Introduction to Space Physics

A Summary Of Notes and References
Related to University of Washington Course ESS 471 Fall 2009
Compiled by Michael McGoodwin, content last updated 12 December 2009

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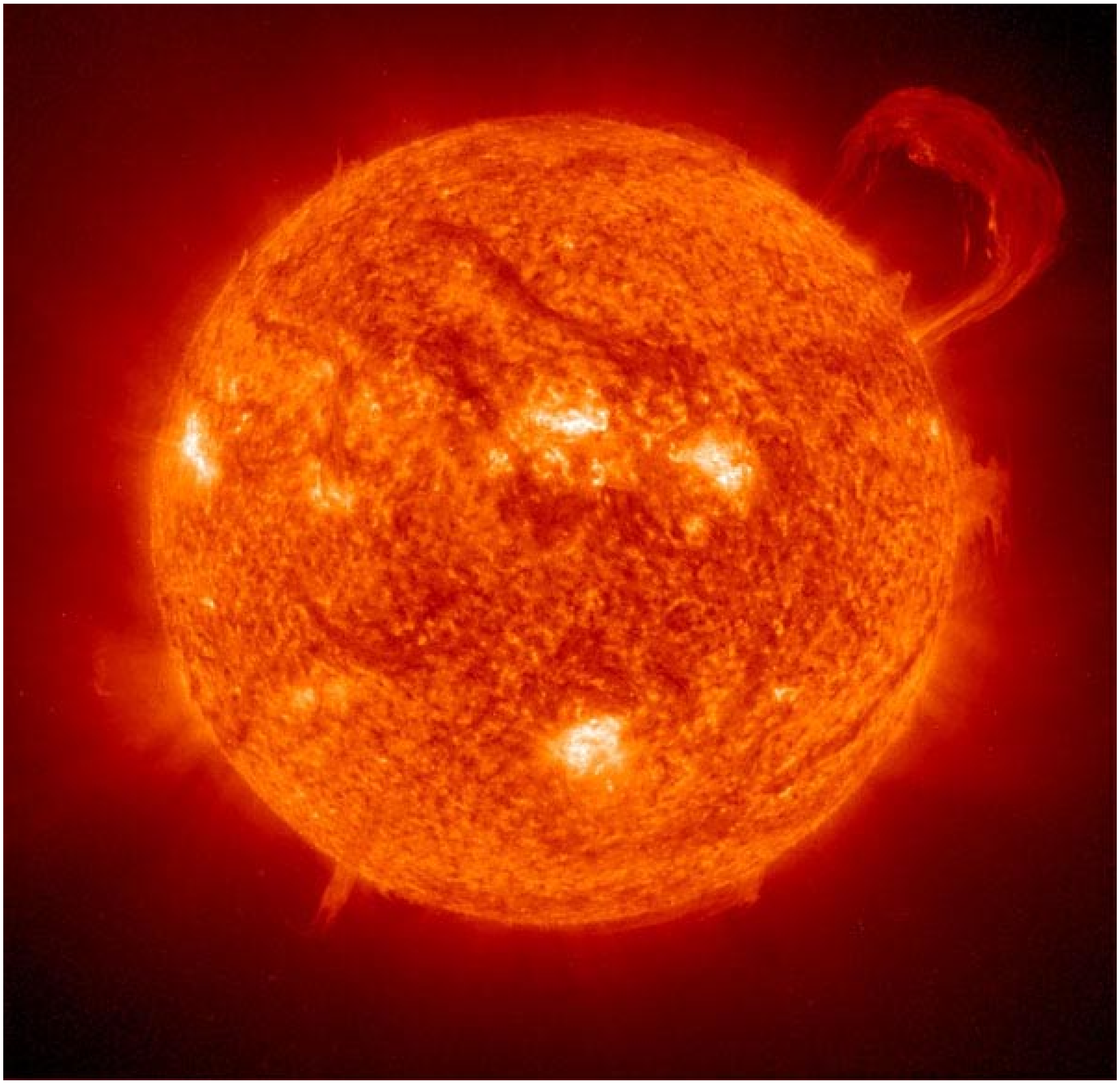
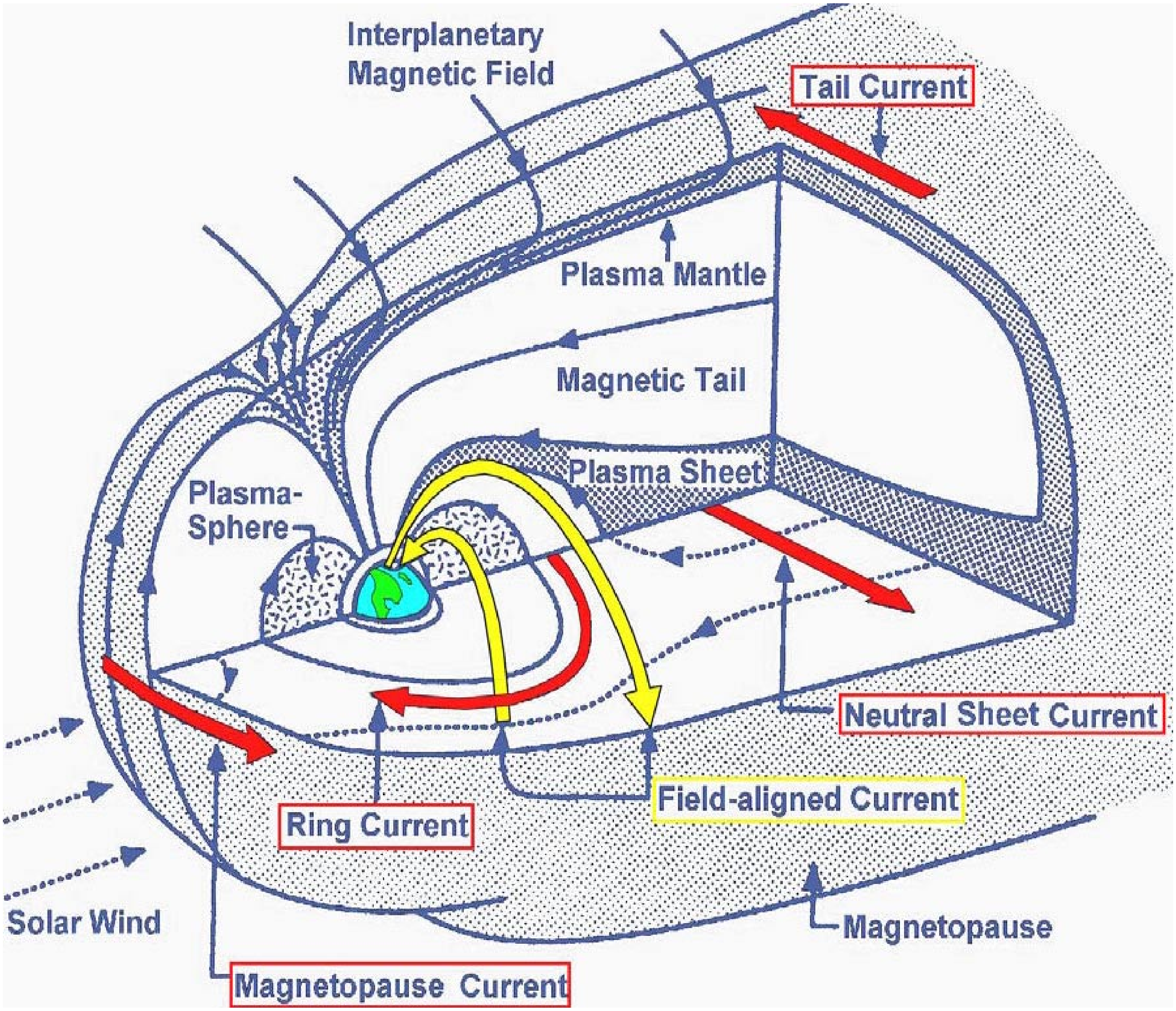


THE SUN IS WHERE THIS STORY BEGINS…
304Å Ultraviolet image of the Sun showing a huge handle-shaped prominence
14 Sept. 1999 (EIT/SOHO/ESA–NASA[1])

[1] Solar Prominence in EIT (Extreme UV Imaging Telescope) of SOHO (Solar & Heliospheric Observatory):
• http://sohowww.nascom.nasa.gov/gallery/images/superprom.html
• http://sohowww.nascom.nasa.gov/gallery/images/large/superprom.jpg



… And The Earth's magnetosphere Is Where The Story Takes Us

Diagram showing incoming solar wind, magnetic fields (blue lines with arrowheads), named electric currents and current sheets (mostly red and yellow), and certain plasma regions and flows (stippled or cross-hatched) (modified slightly by MCM from NOAA 2004 image[2])

[2] http://www.ngdc.noaa.gov/geomag/WMM/data/TRWMM_2005.pdf

Introduction

I compiled this summary to assist in learning materials relevant to the study of Space Physics[3]—the subject of University of Washington course ESS 471, as presented in fall 2009.

This course is taught by Professor Robert H Holzworth ("RHH")[4]. I appreciate Professor Holzworth's expertise and enthusiasm, his class dog, and his willingness to allow me to audit his course. My apologies for not yet having taken the time to become better acquainted with the scope of his extensive research. When I quote or paraphrase RHH, I am referring to his oral lectures, the PDF versions of his lectures, and his website[5] including his "Key Concepts in Solar Terrestrial Physics" document.

A major theme of the course is following the energy from its source in the core of the Sun to its impacts in the Earth's magnetosphere and Earth atmosphere (but limited here primarily to the ionosphere). The emphasis is primarily on ionization and space plasmas, and electrical and/or magnetic physical phenomena, including lightning and transient luminous events. It is not an atmospheric science course, and only limited mention is made of the effects of the Sun on the Earth's mesosphere, troposphere, and biosphere. This subject once was termed *Solar-Terrestrial Physics*, but the term has been generalized to include other planets and other planetary systems.

I am a retired physician and merely an auditing student, and claim no expertise in this field. The materials here represent selected key concepts assembled for the most part from various Web sources as well as the lecture notes, the textbook, and the assigned materials. No assumptions are made regarding the ultimate authoritativeness of Web sources utilized, particularly Wikipedia, although I believe such sources can frequently provide helpful overview perspectives and links to more scholarly materials. Note that links (URLs) shown in footnotes are "live" and can be followed by clicking on them in PDF documents such as this.

The textbook used in this course in 2009 was Margaret G Kivelson and Christopher T Russell, *Introduction to Space Physics*, Cambridge University Press, 1995—this is abbreviated below as *ISP*. It is not feasible to fully summarize the extensive material in this text, and we did not actually discuss all chapters. The book is quite detailed and mathematical, but seems to be in need of updating and better integration of the chapters by different authors that deal with overlapping material. However, it probably accurately reflects the fact that this is a rapidly evolving field undergoing intense research, one in which not all questions have been neatly resolved and for which controversy and considerable uncertainty remains. The textbook would also benefit from a detailed and preferably online glossary as well as a more comprehensive index. Some useful websites of general interest and relevance include:

- Timeline of the history of Solar-Terrestrial physics [6]
- NOAA's National Geophysical Data Center page on Solar-Terrestrial physics [7]
- NASA's Solar physics Group Sun facts [8]
- Spaceweather.com[9]
- NOAA Space Weather Prediction Center[10]
- Geomagnetism (NGDC)[11]

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[3] Definition of Space Physics (http://www.geophys.washington.edu/Space/):
The UW Space and Planetary Science department defined Space Physics in 2000 as: "the study of ionized gas in the earth's environment and its interaction with the neutral atmosphere and with natural and manmade boundaries [such as the magnetopause]. When long range electric and magnetic forces dominate the evolution of a volume of ionized gas it is referred to as a plasma. Space physics research at the University of Washington covers topics from very weakly ionized gas, such as that of the earth's lower and middle atmosphere, to the plasmas of interplanetary space which are nearly fully ionized. Understanding space physics involves learning about a multiply connected set of ionized gas phenomena stretching from the sun to the surface of the earth and the other planets."
[4] RHH webpage and selective bibliographies:
• http://earthweb.ess.washington.edu/dwp/people/profile.php?name=holzworth--robert
• http://earthweb.ess.washington.edu/holzworth/
• http://myprofile.cos.com/holzworr79
[5] http://earthweb.ess.washington.edu/holzworth/ess471-503/welcome.html
[6] http://measure.igpp.ucla.edu/solar-terrestrial-luminaries/timeline.html
[7] http://www.ngdc.noaa.gov/stp/
[8] http://solarscience.msfc.nasa.gov/
[9] http://spaceweather.com/
[10] http://www.swpc.noaa.gov/SWN/

When I have taken material or diagrams from Wikipedia or other Web sources, I have always shown a URL citation, usually in a footnote. However, as this summary was somewhat hastily assembled for personal study, I may not have always remembered to set off extracted materials with quotation marks. In many cases, I have adapted or paraphrased the material extracted from these external sources. Readers incorporating any of these materials into their own writings are advised to consult the sources and citations provided to obtain exact quotes so that the sources can be properly attributed. (URLs are of course expected to go out-of-date with time, and I will not attempt to keep the links current.) I have included only a few diagrams and images taken from the Web due to space limitations and copyright concerns—most are from NASA, NOAA, and other US governmental sources, or Wikipedia—but I have tried to point out where the interested reader might find other useful diagrams and multimedia materials. Inside quoted material, I have embedded editorial comments, clarifications, and questions of my own enclosed in square brackets. I have also tried to mention areas about which I remain personally uncertain.

As noted below, I have not taken the time or do not have the background to understand fully all of the mathematics and details underlying this subject matter. I'm sure if I took sufficient time, I would find better references to quote and cite, and would understand this subject matter better. My personal goal has been to assimilate many of the important points, qualitatively if not always quantitatively, and to be aware that (as with General Relativity) great minds exist that can derive and manipulate the more abstruse mathematical details. Many of the mathematical details that have been omitted from this summary may be found in some of the references I have provided. This has been a truly fascinating learning experience involving an important realm of existence about which I previously knew very little.

Constructive corrections, clarifications, and amplications would always be appreciated. Send these to:
MCM at McGoodwin period NET (please convert to standard format when using)

Vector Calculus: Terminology, Symbols, Definitions, and Selected Theorems

This is a limited survey. In general, symbols other than subject headings that are shown in bold-face are vectors rather than scalars.

Some Handy Characters and Symbols Used in This Summary:
Greek letters: αβγδΔ∏πζεηνθκΛλμρ∑στφΦχψΩω
Mathematical & Misc. Symbols: °≈≠≡∂√•∫±♦¶⇒∠∝∇∗×^⊥||⊙⊕

Vector Dot-Product: The dot product[12] designated $\mathbf{a} \cdot \mathbf{b}$ of two vectors in n-dimensional space $\mathbf{a} = [a_1, a_2, \ldots, a_n]$ and $\mathbf{b} = [b_1, b_2, \ldots, b_n]$ is defined as:

$$\mathbf{a} \cdot \mathbf{b} = \sum_{i=1}^{n} a_i b_i = a_1 b_1 + a_2 b_2 + \cdots + a_n b_n$$

This is a *scalar* quantity. In Euclidean geometry, $\mathbf{a} \cdot \mathbf{b} = |\mathbf{a}||\mathbf{b}|\cos\theta$ where $|\mathbf{a}|$ and $|\mathbf{b}|$ denote the length of **a** and **b** and θ is the angle between them. The dot product of two orthogonal vectors is always zero because cos 90° is 0. The dot product is also called the direct or scalar product.

Vector Cross-Product: the cross product[13] designated $\mathbf{a} \times \mathbf{b}$ is a vector perpendicular (orthogonal) to the plane formed by vectors **a** and **b** and having magnitude equal to the area of the parallelogram that the vectors span (i.e., that have **a** and **b** as sides). The direction in a right-handed coordinate system is given by the *right hand rule*, for instance with **a** oriented along the index finger, **b** along the middle finger, and the cross product **c** oriented along the thumb. (Because of this dependence of direction on handedness, the cross product is called a *pseudovector*.) The magnitude of $\mathbf{a} \times \mathbf{b}$ is $|\mathbf{a}|\cdot|\mathbf{b}|\sin\theta$, where θ is the angle between **a** and **b**. The magnitude is the area of the *parallelogram* with sides $|\mathbf{a}|$ and $|\mathbf{b}|$ and forming angle θ. The cross product of two vectors is also called the skew or vector product. The cross product of parallel vectors has magnitude 0 because sin θ is 0.

Given vectors $\mathbf{a} = a_1\mathbf{i} + a_2\mathbf{j} + a_3\mathbf{k}$ or (a_1, a_2, a_3) and $\mathbf{b} = b_1\mathbf{i} + b_2\mathbf{j} + b_3\mathbf{k}$ or (b_1, b_2, b_3), then
$\mathbf{a} \times \mathbf{b} = (a_1, a_2, a_3) \times (b_1, b_2, b_3) = (a_1\mathbf{i} + a_2\mathbf{j} + a_3\mathbf{k}) \times (b_1\mathbf{i} + b_2\mathbf{j} + b_3\mathbf{k})$, or
$\mathbf{a} \times \mathbf{b} = (a_2b_3 - a_3b_2)\mathbf{i} + (a_3b_1 - a_1b_3)\mathbf{j} + (a_1b_2 - a_2b_1)\mathbf{k} = (a_2b_3 - a_3b_2 , a_3b_1 - a_1b_3 , a_1b_2 - a_2b_1)$, or

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[11] http://www.ngdc.noaa.gov/geomag/
[12] http://en.wikipedia.org/wiki/Dot_product
[13] http://en.wikipedia.org/wiki/Vector_cross_product

$$\mathbf{a} \times \mathbf{b} = \det \begin{bmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{bmatrix}.$$

where det = determinant[14]. See the *rule of Sarrus*[15] for calculating 2x2 and 3x3 determinants. Cross-product calculations can also be done with *matrix notation*.

The *Index notation* using the Levi-Civita[16] symbol ε (which has possible values 0 and ±1) is shown as follows:

$$\mathbf{a} \times \mathbf{b} = \mathbf{c} \Leftrightarrow \ c_i = \sum_{j=1}^{3} \sum_{k=1}^{3} \varepsilon_{ijk} a_j b_k$$

where ε_{ijk} is

+1 if (i, j, k) is one of [(1,2,3), (3,1,2), or (2,3,1)],
−1 if one of [(3,2,1), (1,3,2), or (2,1,3)], and
0 otherwise (components for which an index is repeated).

Del: In vector calculus, Del[17] is a shorthand vector differential operator represented by the nabla symbol ∇ (nabla is the Greek word for a Hebrew harp). Its use was introduced by William Rowan Hamilton in 1837. ∇V is pronounced "Del V". Del can operate on scalar or vector fields. It is non-commutative. In general, for any n-dimensional space with dimensions i=1 to n where e_i represent unit vectors:

$$\nabla = \sum_{i=1}^{n} \vec{e}_i \frac{\partial}{\partial x_i}$$

or in Einstein notation,

$$\nabla = \vec{e}_i \, \partial_i.$$

The symbol ∂ is read as "partial".

Gradient (Grad): The vector derivative ∇f of a *scalar* field f is a *vector* called the gradient[18], abbreviated Grad, represented as

$$\nabla f = \frac{\partial f}{\partial x}\hat{\mathbf{x}} + \frac{\partial f}{\partial y}\hat{\mathbf{y}} + \frac{\partial f}{\partial z}\hat{\mathbf{z}}$$

or **grad**(f).

It always points in the direction of greatest increase of f, and it has a magnitude equal to the maximum rate of increase at the point, just like a standard derivative.

Divergence (Div): The divergence[19] of a *vector* field

$$\vec{v} = v_x\hat{\mathbf{x}} + v_y\hat{\mathbf{y}} + v_z\hat{\mathbf{z}}$$

is a *scalar* function that can be represented as

$$\operatorname{div} \vec{v} = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = \nabla \cdot \vec{v}$$

or div(**V**). The divergence is a measure of that field's tendency to converge on or repel (diverge) from a point. It expresses the extent to which the vector field flow behaves like a source or a sink at a given point. A vector

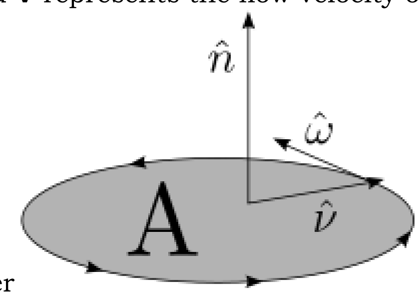
[14] http://en.wikipedia.org/wiki/Determinant
[15] http://en.wikipedia.org/wiki/Rule_of_Sarrus
[16] http://en.wikipedia.org/wiki/Levi-Civita_symbol
[17] http://en.wikipedia.org/wiki/Del
[18] http://en.wikipedia.org/wiki/Gradient
[19] http://en.wikipedia.org/wiki/Divergence

field with constant zero divergence is called *incompressible*. Gauss's law for Magnetism (see below) holds that the divergence of the magnetic induction ∇·B = 0.

Divergence Theorem: The intuition that the sum of all *sources* [of outward flows] minus the sum of all *sinks* should give the net flow outwards of a region is made precise by the divergence theorem[20] (aka Gauss or *Ostrogradsky-Gauss theorem*). The divergence theorem is a conservation law which states that the volume total of all sinks and sources, the volume integral of the divergence, is equal to the net flow across the volume's boundary:

$$\iiint\limits_V (\nabla \cdot \mathbf{F})\, dV = \oint\!\!\!\!\oint\limits_{\partial V} \mathbf{F} \cdot \mathbf{n}\, dS.$$

Curl: The curl[21,22] (or **rotor**) of a vector field **F** is a vector operator designated by ∇×**F** (read "Del cross F") or *curl*(**F**) that describes the rotation of the vector field. At every point in the field, the curl is represented by a *vector*. The attributes of this vector (length and direction) characterize the rotation of the field at that point. The direction of the curl is the axis of rotation, as determined by the right-hand rule, and the magnitude of the curl is the magnitude of rotation. If the vector field **V** represents the flow velocity of a moving fluid, then the curl is the circulation density of the fluid. Consider



for a vector field **F** and the definition

$$(\nabla \times \mathbf{F}) \cdot \hat{\mathbf{n}} \overset{\text{def}}{=} \lim_{A \to 0} \frac{\oint_C \mathbf{F} \cdot d\mathbf{r}}{A}$$

According to the right-hand rule convention, the curve C along which the closed line integral is taken is traced so that the enclosed area is always to the left. In this example:

> A = an infinitesimal area element of area A in a plane orthogonal to unit vector **n** around which the closed line integral is made as shown;
> C = the closed curve enclosing A and along which the closed line integral is made;
> **v** = an outward pointing in-plane vector oriented normal (perpendicular) to a particular point on the curve C and providing the direction along the "index finger";
> **ω** is perpendicular to **v** and tangent to C where they intersect, and represents the rotation direction of the integration (along the "middle finger");
> **n** = a unit vector (along the "thumb") on which the curl vector is projected; and
> **dr** = an infinitesimal vector differential line interval. The formula gives the component of the curl projected on **n**.

A vector field whose curl is zero is called *irrotational*, but if nonzero there is a net rotation. The corresponding form of the fundamental theorem of calculus is the *Stokes theorem*[23] (or *generalized Stokes theorem*, for which a special case is the *Kelvin-Stokes theorem*), which relates the surface integral of the curl of a vector field to the line integral of the vector field around the boundary curve.

Physics of Electrical and Magnetic Fields

This is again a limited survey.

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[20] http://en.wikipedia.org/wiki/Divergence_theorem
[21] http://en.wikipedia.org/wiki/Curl_%28mathematics%29
[22] http://mathworld.wolfram.com/Curl.html
[23] http://en.wikipedia.org/wiki/Stokes%27_theorem

Electric Field E: "Electric field is defined as the electric force per unit charge. The direction of the field is taken to be the direction of the force it would exert on a positive test charge. The electric field is oriented radially outward from a positive charge and radially in toward a negative point charge.[24]" The electric field is expressed in SI units as Newtons [N] per Coulomb [C], or equivalently *volts/m*.

Magnetic Field B (aka **magnetic induction**, **magnetic field density**, or **magnetic flux density**): **B** is a pseudo-vector field measured in teslas (T, the SI unit), gauss (the cgs unit, where 1 gauss = 10^{-4} T), or gammas (1 gamma = 1 nanotestla [nT] = 10^{-5} gauss). Magnetic field lines emanating from a bar magnet by convention emanate outward from the "north pole" and curve around to reenter at the "south pole"[25]. However, the Earth's north magnetic pole has the approximate polarity of a bar magnet's south pole (as it attracts a bar magnet's north pole), and therefore external geomagnetic **B** field lines are considered to dip down and *enter* Earth (roughly vertically) at the geomagnetic north pole, and *exit* from the geomagnetic south pole.

Magnetizing field H (aka **auxiliary magnetic field** or **magnetic field intensity**): is defined as $(\mathbf{B}/\mu_0) - \mathbf{M}$, where $\boldsymbol{M}$ is the magnetization of the material and μ_0 is the **permeability** of free space (or *magnetic constant*). The H-field is measured in ampere per meter (A/m) in SI units, and in oersteds (Oe) in cgs units. In free space,

$$\mathbf{H} = \mathbf{B}/\mu_0.$$

B is the fundamental quantity compared to the derived quantity **H**.

Magnetic Moment and Magnetic Dipole Moment[26]: The magnetic moment of a system is a measure of the strength and the direction of its magnetism. More technically (in physics, astronomy, chemistry, and electrical engineering), the term magnetic moment of a system (such as a loop of electric current, a bar magnet, an electron, a molecule, or a planet) usually refers to its *magnetic dipole moment*, and quantifies the contribution of the system's internal magnetism to the external dipolar magnetic field produced by the system (that is, the component of the external magnetic field that drops off with distance as the inverse cube, see also *ISP* p. 314 and here[27]). Any dipolar magnetic field pattern is symmetric with respect to rotations around a particular axis, therefore it is customary to describe the magnetic dipole moment that creates such a field as a vector with a direction along that axis. In SI, the dimensions of magnetic dipole moment are Area x current, or L^2I (thus m^2A or J/T)...

There can also be quadrupolar, octupolar, and higher-order multipole magnetic moment components[28], for which the variation with angle is greater and the rapidity of falloff of magnetic force is more rapid than for the approximately inverse cube rate of the dipolar component. These higher order components have little effect, for instance, in the Sun's magnetic field at the distance of the outer corona and beyond.

Lorentz Force, Guiding Center, and Guiding Center Drift

A particle having an electric charge q (coulombs) and moving in a pure **B**-field (teslas) with a velocity $\boldsymbol{v}$ (m/s) experiences a force F (newtons) called the **Lorentz force**[29]. In SI units, the Lorentz force equation is

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B})$$

where × denotes the vector cross-product, so the Lorentz force is perpendicular to the plane defined by the velocity **v** and the magnetic field **B**. (According to the *right hand rule*, if q is positive and **v** points along the index finger and **B** points along the middle finger, the direction of **F** points along the thumb. Stated another way, consider a particle travelling in a plane from which a **B** field rises toward the viewer. (This is symbolized by ⊙, as if seeing the tip of an approaching arrow. The symbol ⊗ signifies direction down into the plane away

[24] http://hyperphysics.phy-astr.gsu.edu/hbase/electric/elefie.html
[25] http://en.wikipedia.org/wiki/Magnetic_field
[26] http://en.wikipedia.org/wiki/Magnetic_torque
[27] Magnetic dipole inverse cube falloff:
• http://en.wikipedia.org/wiki/Dipole#Field_from_a_magnetic_dipole
• http://blazelabs.com/inversecubelaw.pdf
[28] http://en.wikipedia.org/wiki/Multipole_expansion
[29] http://en.wikipedia.org/wiki/Lorentz_force

from the viewer, as if seeing the receding feathers on an arrow). Then the particle is seen to deviate to the right[30] (turn clockwise) if positively charged, or to the left (turn counterclockwise) if negatively charged. Thus, "the magnetic field acts to change the motion of a charged particle only in directions perpendicular to that motion (ISP p. 29).

If there is also an electric field **E** (volts/m), the Lorentz force equation is

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

where q**E** gives the *electric force* component. The **v** × **B** component is called the *magnetic force* component (and some persons call only the **v** × **B** component the Lorentz force). The Lorentz Force is no longer grouped with the Maxwell equations[31] but is closely related. In real materials the Lorentz force is inadequate to describe the behavior of charged particles.

The Lorentz force may be used to define and measure the strength of the magnetic field **B**. (*ISP* p. 402 and here[32])

Guiding Center and Guiding Center Drift: According to the Lorentz force **F** = q(**E** + **v** × **B**) and the right-hand rule, and for the moment assuming **E** = 0, for a positively charged particle moving in a plane with a magnetic field B directed up perpendicular to the plane, the particle is accelerated or deflected to the right (causing clockwise rotation) in the plane. For such particle rotation, the *gyro-frequency* (aka *cyclotron frequency* ω_c, expressed in radian s^{-1}) is given by $\omega_c = qB/m$ and the *gyroradius* (*Larmor radius*) for speed v is $\rho_L = v/\omega_c$. Here, q = electric charge, B = magnitude of magnetic induction, m = particle mass.

"In many cases of practical interest, the motion in a magnetic field of an electrically charged particle (such as an electron or ion in a plasma) can be treated as the superposition of a relatively fast circular motion around a point called the *guiding center*[33] [gyrorotation] and a relatively slow **drift** of this point... Generally speaking, when there is a force [such as **E**] on the particles perpendicular to the magnetic field, then they drift in a direction perpendicular to both the force and the field.[34] (Further discussed below with "Particle Motions in the Radiation Belts")

The drift arising from the electric field **E** component is often called the $\vec{E} \times \vec{B}$ or "E-cross-B" drift... Ions (of whatever mass and charge) and electrons both **drift in the same direction and at the same speed**, **so there is no net current** (assuming quasi-neutrality, with no net charge in the sample, and provided there are no collisions, the latter condition not applying in the ionosphere) (*ISP* p. 31 and here[35])

The drift velocity contributed by E-cross-B drift (and more generally by some other unspecified steady force F) is given by[36]

$$\vec{v}_E = \frac{\vec{E} \times \vec{B}}{B^2} \quad \text{and} \quad \vec{v}_f = \frac{1}{q}\frac{\vec{F} \times \vec{B}}{B^2}$$

and these are therefore perpendicular both to **E** and **B**. (For a textbook derivation of the first formula, see here[37].) However, particles of opposite charge rotate in opposite directions about the guiding center. The overall particle motion is a cycloid or trochoid. The **E** force initially results only initially in an acceleration parallel to itself, but the magnetic field deflects the resulting motion in the drift direction of **v**. Once the particle is moving in the drift direction of **v**, the magnetic field deflects it back against the **E** force, so that the average acceleration in the direction of the **E** force after drift is established is zero.

A more general formula for *guiding center drift* v_g (which is incompletely shown here, see also *ISP* p. 307 eqn. 10.5 and RHH lectures) pertains for instance to particles moving in the magnetosphere, and incorporates the following additive components:

(1) the $\mathbf{v}_{\parallel}$ component: This is the velocity of the particle parallel to the **B** field. This component is constant

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[30] http://en.wikipedia.org/wiki/Lorentz_force_law
[31] http://en.wikipedia.org/wiki/Maxwell_equations
[32] http://en.wikipedia.org/wiki/Magnetic_field
[33] http://en.wikipedia.org/wiki/Guiding_center
[34] http://www.absoluteastronomy.com/topics/Guiding_center
[35] http://en.wikipedia.org/wiki/Guiding_center
[36] http://en.wikipedia.org/wiki/Guiding_center
[37] R. J. Goldston, Paul Harding Rutherford. *Introduction to plasma physics*. 1995, 2000. pp 24-6

and unaffected by constant **B**. "In a uniform [**B**] field with no additional forces, a charged particle will gyrate around the magnetic field according to the perpendicular component of its velocity and drift parallel to the field according to its initial parallel velocity [$\mathbf{v}_{\|}$], resulting in a helical orbit.[38]" Note that the gyrorotation does not contribute to the drift.

(2) the **E** × **B** and **F** × **B** components (as given above),

(3) the *gradient drift* (grad-**B** drift) velocity component: This is charge dependent and is given[39] by

$$\vec{v}_{\nabla B} = \frac{\epsilon_\perp}{qB}\frac{\vec{B}\times\nabla B}{B^2}$$

where $\epsilon_\perp = \frac{1}{2}mv_\perp^2$ is the KE from motion with $v_\perp$ = velocity component perpendicular to **B**, and

q = electric charge

Note for instance that as field lines converge toward the pole of the Earth's external magnetic field, a gradient in **B** results.

(4) the *curvature drift* component: This is also charge dependent and is given[40] by

$$\vec{v}_R = \frac{2\epsilon_\|}{qB}\frac{\vec{R}_c\times\vec{B}}{R_c^2 B}$$

where $\epsilon_\| = \frac{1}{2}mv_\|^2$ represents the KE from motion with velocity $v_\|$ component parallel to **B,**

R_c = radius of curvature, and

q = electric charge

Note for instance that particles moving in the curved magnetic field of the Earth experience curvature drift.

Because gradient and curvature guiding center drift are charge dependent, they give rise to a net current (unlike E-cross-B drift, which is charge independent).

The guiding center drift component from the force of gravity is small and can usually be ignored. There are additional potential contributors to the drift velocity not shown here.

Magnetic Confinement, MHD, Other Maxwell Equations, Misc. EM Physics

Magnetic Bottle: A *magnetic bottle*[41] has a generally cylindrically symmetrical B field that is more intense or concentrated at the ends than in the middle bulging region. It has 2 separated symmetrical magnetic mirrors, one at each end, and can trap charged particles. However, particles moving in the parallel (long axis) direction are not reliably trapped and escape from an end.

Magnetohydrodynamics (MHD): MHD is the study of the interaction of magnetic fields and electrically conducting fluids such as plasmas, salt water, or molten metals. "The field of MHD was initiated by Hannes Alfvén, for which he received the Nobel Prize in Physics in 1970."[42] (See also *ISP* p. 41 and 46, and below for useful versions of the Maxwell equations.)

[38] http://en.wikipedia.org/wiki/Guiding_center
[39] ibid.
[40] ibid.
[41] http://en.wikipedia.org/wiki/Magnetic_mirror
[42] http://en.wikipedia.org/wiki/Magnetohydrodynamics

Maxwell-Faraday law[43]: Also called *Faraday's law of induction*[44], this is one of the 4 Maxwell equations. It expresses the fact that a changing magnetic field creates an electric field (and induces, for instance, an *electromotive force* or *emf* in a coiled wire).

$$\nabla \times \mathbf{E}(\mathbf{r},\ t) = -\frac{\partial \mathbf{B}(\mathbf{r},\ t)}{\partial t} \quad \text{or equivalently} \quad \oint_{\partial S} \mathbf{E} \cdot \mathrm{d}\mathbf{l} = -\frac{\partial \Phi_{B,S}}{\partial t}$$

where $\nabla\times$ **E** is the curl of electric field **E** where **E** is a function of position and time
the integral is the line integral of the electric field along the boundary ∂S of a surface S
∂S is always a closed curve
d**l** is a differential vector element of path length tangential to the path/curve
E • dl is a vector dot product
$\Phi_{B,S}$ is magnetic flux through surface S, expressed in webers or volt-seconds,
and given by the integral of a dot product:

$$\iint_S \mathbf{B} \cdot \mathrm{d}\mathbf{A} = \Phi_{B,S}$$

where d**A** = differential vector element of surface area A,
with infinitesimally small magnitude and direction normal to surface S

"When applied to charged particles, this law implies that if a particle experiences time-varying magnetic fields, it will simultaneously be subjected to electrical forces that will change its energy. [Under certain conditions, however,] the particle's magnetic moment will remain constant." (*ISP* p. 32)

With particular application to electrical circuits, this law is also expressed in the form

$$|\mathcal{E}| = \left|\frac{d\Phi_B}{dt}\right|$$

where ΦB is the magnetic flux through a circuit (in webers) and |ε| here is the magnitude of the induced electromotive force (EMF) in volts. A changing B-field induces a current in a conductor which opposes the changing B-field.

This is one of the basic laws of electromagnetism, and is involved in the working of transformers, inductors, and many forms of electrical generators.

Ampère's Circuital law with Maxwell Correction[45]: There are two formulation, one for free charge and current and one for total charge and current (which take into account bound charges). Here I present only the formulation in terms of free charge and current.

Historically, Ampère's original form relates the magnetic field around a closed loop C to the electric current passing through the loop:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J_f}$$

where $\nabla\times$**B** is the curl of **B**
μ_0 is the *magnetic constant*, also called the *permeability of free space*[46], and
$\boldsymbol{J_f}$ is the free current density through the surface S enclosed by the curve or loop C.
This is the differential form—there is also an integral form (not shown here).

The full form of Ampère's law as corrected by Maxwell (and one of 4 Maxwell equations) accounts for the contribution of *displacement current or field* ***D***[47] and therefore polarization of the medium. **D** is defined as

[43] Maxwell-Faraday Equation:
• http://en.wikipedia.org/wiki/Faraday%27s_law_of_induction
• http://en.wikipedia.org/wiki/Maxwell%27s_equations
[44] http://en.wikipedia.org/wiki/Maxwell%27s_equations
[45] Ampère's Circuital law with Maxwell Correction:
• http://en.wikipedia.org/wiki/Amp%C3%A8re%27s_law
• http://en.wikipedia.org/wiki/Maxwell%27s_equations
[46] http://en.wikipedia.org/wiki/Magnetic_constant
[47] http://en.wikipedia.org/wiki/Displacement_current

$\mathbf{D} \equiv \varepsilon_0\mathbf{E} + \mathbf{P}$

where **D** is the displacement current (also termed *electric induction* or *electric flux density*)

ε_0 is the permittivity of free space, and

P is the polarization density of the medium.

The extended Maxwell-Ampère equation in differential form for free charge and current is therefore:

$$\nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{D}}{\partial t} \quad \text{or equivalently} \quad \oint_{\partial S} \mathbf{H} \cdot \mathrm{d}\mathbf{l} = I_{f,S} + \frac{\partial \Phi_{D,S}}{\partial t}$$

where **H** = magnetic H field (also called magnetizing field, or auxiliary magnetic field intensity)

$\nabla \times \mathbf{H}$ is the curl of the magnetic **H** field

$\mathbf{J_f}$ = free current density (i.e., not including bound current)

D = electric displacement field (also called electric induction) usu. expressed in coulomb m^{-2}

the integral is the line integral of the **H** field along the boundary ∂S of a surface S

∂S is always a closed curve

d**l** is a differential vector element of path length tangential to the path/curve of the line integral

H • dl is a vector dot product

$I_{f,S}$ is net free electrical current passing through a surface S (not including bound current)

and given by the integral of a dot product $\iint_S \mathbf{J}_f \cdot \mathrm{d}\mathbf{A} = I_{f,s}$

where d**A** = differential vector element of surface area A,

with infinitesimally small magnitude and direction normal to surface S, and

$\Phi_{D,S}$ is the flux of electric displacement field through any surface S, not necessarily closed,

and given by the integral of a dot product $\iint_S \mathbf{D} \cdot \mathrm{d}\mathbf{A} = \Phi_{D,S}$

Applied to the MHD limit, the displacement current may be ignored and this may be expressed as (ISP p. 46, where **j** is current density):

$\nabla\times\mathbf{B} = \mu_0\mathbf{j}$ or $\mathbf{j} = \nabla\times(\mathbf{B}/\mu_0)$ … (See *ISP* p. 65-6)…

Divergence of j: The current density *j* is divergenceless in MHD: $\nabla\cdot\mathbf{j} = 0$ (*ISP* p. 46). Therefore, all currents must close on themselves and there are neither sources nor sinks of charge in plasmas.

Gauss's Law for Magnetism[48]: This is one of the four Maxwell equations. It is also called divergenceless **B**, and can be expressed in differential or integral forms:

$$\nabla \cdot \mathbf{B} = 0 \quad \text{or equivalently} \quad \oint\!\!\!\oint_{\partial V} \mathbf{B} \cdot \mathrm{d}\mathbf{A} = 0 .$$

Here, the integral is the surface integral over a closed surface S fully enclosing a volume V using differential vector area elements d**A** each normal to the surface . It is equivalent to the statement that magnetic monopoles do not exist. Rather than magnetic monopolar charges, the basic entity for magnetism is the magnetic dipole. This equation states that if "the integral is taken over a surface that completely encloses a spatial volume, no net magnetic flux will cross the surface." (*ISP* p. 45)

Gauss's Law [for Electric Fields][49]**:** This is another of Maxwell's equations, which expressed here in terms of free charge and current) states

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[48] Gauss's Law for Magnetism:
- http://en.wikipedia.org/wiki/Gauss%27s_law and
- http://en.wikipedia.org/wiki/Maxwell%27s_equations

[49] Poisson's Equation or Gauss's Law:
- http://en.wikipedia.org/wiki/Poisson%27s_equation
- http://en.wikipedia.org/wiki/Maxwell%27s_equations

$$\nabla \cdot \mathbf{D} = \rho_f \quad \text{or equivalently} \quad \oiint_{\partial V} \mathbf{D} \cdot \mathrm{d}\mathbf{A} = Q_f(V)$$

where **D** = electric displacement field
$Q_f(V)$ = net free electric charge within the three-dimensional volume V
(not including bound charge)
ρ_f = free charge density (not including bound charge)

In contrast to **B**, the electric displacement field **D** is not divergenceless, recognizing for instance the existence of point electrical charges.

Plasmas and Plasma Physics

This is a very limited partial survey. There is considerable overlap with the previous section.

Plasmas[50] are partially ionized usually neutrally charged gases in which positive and negative charges balance out. Plasmas are the most common of the four states of matter in the visible universe[51]. According to RHH, the KE of particles in most plasmas is much larger than the potential energy (i.e., KE/PE $\gg$ 1) due to nearest neighbor effects. Plasma parameters (common collective properties or characteristics measured in plasmas such as plasma frequency) are summarized here[52].

Temperature and Thermal Particle Velocities in Gases

A temperature in degrees K may be converted to thermal energy expressed in eV (for single particles having 3 translational degree of freedom, such as electrons) by using the Boltzmann constant k = 8.617×10^{-5} eV/K, so that:

Thermal energy KE_{avg} (eV) = $3 \bullet (kT/2) = T \times 8.617 \times 10^{-5}$,
where T is in Kelvin

Room temperature particles at 293 K have a thermal energy of 0.0252 eV = ~1/40 eV.
A temperature of 6000 K is equivalent to an average particle thermal energy of 0.5 eV.
1 eV thermal energy is equivalent to a temperature of about 11604 K[53].

Particles having more than the three basic translational degrees of freedom, such as molecules, have thermal energies of multiples of the $3 \bullet (kT/2)$ value[54].

For an ideal gas, the *most probable thermal speed V_p* (at the peak of the Maxwell speed distribution[55, 56]), which is a function of temperature and of mass, is given by

V_p (m/s) = $(2RT/M)^{1/2}$,
where R = gas constant = 8.3145 J/mol K, M is the particle mass in kg/mol, and T is degrees Kelvin.

The *mean speed* and the *RMS (Root Mean Square) speed* are somewhat higher than V_p.
For *electrons* with M = 5.486×10^{-4} amu = 5.468×10^{-7} kg/mol and room air T = 20 °C = 293.15K,
V_p = 94300 m/s = 94.3 km/s
For *protons* with M = 1.007 amu = 1.007×10^{-3} kg/mol and room air T = 20 °C = 293.15K,
V_p = 2208 m/s = 2.208 km/s
For *atomic nitrogen* with M = 14.01 amu = 0.01401 kg/mol and room air T = 20 °C = 293.15K,
V_p = 590 m/s = 0.590 km/s
For *dry air* (mostly N_2) with nominal M = 29 amu = 0.029 kg/mol and room air T = 20 °C = 293.15K,
V_p = 410 m/s = 0.410 km/s

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50 http://en.wikipedia.org/wiki/Plasma_%28physics%29
51 http://en.wikipedia.org/wiki/Ion
52 http://en.wikipedia.org/wiki/Plasma_parameters
53 http://physics.nist.gov/cuu/Constants/energy.html
54 http://hyperphysics.phy-astr.gsu.edu/HBASE/kinetic/eqpar.html
55 http://hyperphysics.phy-astr.gsu.edu/HBASE/kinetic/kintem.html
56 http://en.wikipedia.org/wiki/Maxwell_distribution#Typical_speeds

Plasma Density, Ionization, Temperature, and Debye Parameters

Each charged particle influences many nearby charged particles, rather than just interacting with the closest particle. The *Debye Screening Length*[57] λ_D is typically short compared to the physical size of the plasma. λ_D, a quantity which is fundamental to plasma physics, is the scale beyond which mobile charge carriers, such as electrons, screen out electric fields in plasmas and other conductors. In other words, it is the distance within which significant charge separation due the presence of a plasma ion can occur. Its value is given by (diagram from same source, and neglecting the contribution of positive ions):

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k T_e}{n_e q_e^2}}$$

where n_e is the density of electrons. The Debye length enters into the formula for the shielded electrostatic potential (*ISP* p. 39):

$$\varphi = q e^{(-r/\lambda_D)} \,/\, (4\pi\varepsilon_0 r)$$

Clearly, the potential φ becomes small when $r \gg \lambda_D$. Representative λ_D values include: Solar core 10^{-11} m, Solar corona 10^{-1} m, solar wind 10 m, magnetosphere 10^2 m, Ionosphere 10^{-3} m ([58] and *ISP* p. 41).

The *Debye Sphere* is a sphere of Debye length radius and holds $N_D = (4/3)\pi n \lambda_D^3$ electron particles. N_D (or less commonly its reciprocal g) is called the *plasma parameter*[59].

Typically, plasma densities are sufficiently low that actual collisions are rare, and electromagnetic interactions dominate over the processes of ordinary gas kinetics.

The *plasma density* usually refers to the *electron density*—the number of free electrons per unit volume.

As plasmas are very good conductors, electric potentials play an important role. The potential as it exists on average in the space between charged particles is called the *plasma potential* or the *space potential*. If an electrode is inserted into a plasma, its potential will generally lie considerably below the plasma potential due to what is termed a *Debye sheath*[60]. The good electrical conductivity of plasmas causes their electric fields to be very small. This results in the important concept of *quasineutrality*: the density of negative charges is approximately equal to the density of positive charges over large volumes of the plasma, but on the scale of the *Debye length* there can be charge imbalance.

The *degree of ionization* (α) of a plasma is the proportion of atoms which have lost (or gained) electrons and therefore become *ions*. α is defined as $\alpha = n_i/(n_i + n_a)$ where n_i is the number density of ions and n_a is the number density of neutral atoms (often referred to as "neutrals"). Natural plasmas often have very low neutral particle densities, and the probability of collisions between charged and neutral particles is low (*ISP* p. 41).

Temperature controls the degree of plasma ionization and is governed by the Saha Ionization equation[61]. Plasma temperatures are commonly measured in Kelvins or eV, and is an informal measure of the thermal kinetic energy per particle. However, plasma constituents are often not at thermal equilibrium and do not adhere to a classic *Maxwell-Boltzman distribution*[62] (see also formula in *ISP* p. 35, including formula for when the plasma has a net velocity). Due to differences in equilibration rates, the "ion temperature" may be very different from (and usually lower than) the "electron temperature". A plasma is sometimes referred to as being *hot* if it is nearly fully ionized, or *cold* if only a small fraction (e.g., 1%) of the gas molecules are ionized. Cosmic plasma temperatures may be as cold as 100 K (for example, in auroras) or lower.

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[57] http://en.wikipedia.org/wiki/Debye_length
[58] http://en.wikipedia.org/wiki/Debye_length
[59] http://en.wikipedia.org/wiki/Plasma_parameter
[60] http://en.wikipedia.org/wiki/Debye_sheath
[61] http://en.wikipedia.org/wiki/Saha_equation
[62] http://en.wikipedia.org/wiki/Maxwell%E2%80%93Boltzmann_distribution

Plasma Frequency and Langmuir Waves

The *plasma frequency*[63] for free electrons of number density n_e is given by

$\omega_{pe} = (n_e e^2/m_e \varepsilon_0)^{1/2}$

This is the natural angular frequency for plasma oscillations (also called "*Langmuir waves*") resulting from charge-density perturbations (*ISP* p. 40). Because this formula contains the electron density and otherwise only physical constants, measuring the plasma frequency experimentally can be used to determine the electron density. (Note: The term *Plasma Response Time* or *Response Time* is often used for the amount of time in ms that a pixel, usually in an LCD monitor, takes to go from black to white and back to black again. I am unsure to what extent this term is applicable to space physics plasmas, though I have found it so used.)

A fascinating frequency-time spectrogram was shown by RHH. It was acquired on 28 February 1979 by the plasma wave subsystem (PWS) of the Voyager 1 mission, and depicts the abrupt change in the sonogram resulting from crossing the *Bow Shock* of Jupiter. (This spectrogram may be found here[64], along with a description and an audio file that allows one to hear the abrupt change.) According to RHH[65], the apparent decrease in plasma frequency is a spectrogram artifact, as the plasma frequency actually jumps up to MegaHz at the transition: "Inside Jupiter's bow shock there is intense low frequency noise, just as there is at Earth, but in the case of Jupiter, the plasma frequency is out of range of this spectrogram. By the way, most people associate the low frequency noise [prior to crossing the Jupiter Bow Shock] with Ion Acoustic waves in the magnetosheath of the planet." Other missions detecting bow shocks have included the AMPTE (Active Magnetospheric Particle Tracer Explorer) spacecraft. RHH showed a slide of a spectrogram made by it as it crossed from the Earth's electron foreshock through the bow shock and into the magnetosheath. This shows a transition from a plasma frequency of ~24 kHz (corresponding to a plasma electron density of 7 cm^{-3}) to broad band noise at the shock. (This graph may be seen in RHH's 1989 paper here[66].)

Mirroring, Frozen-In Fields, and Other Plasma-related Topics

Magnetic Mirroring Force and Mirror Point: When charged particles move in the direction of a changing magnetic field, they experience a force along the field and away from the direction of increasing field (see *Guiding Center Drift* above and *Particle Motions in the Radiation Belts* below). This means that the velocity parallel to the field drops to 0 at the point when $B = mv^2\mu/2$. The opposing force is termed the *mirror force*

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[63] http://en.wikipedia.org/wiki/Plasma_oscillation

[64] Jupiter Bow Shock and Voyager 1 & 2 spacecraft:
http://www-pw.physics.uiowa.edu/plasma-wave/tutorial/voyager1/jupiter/bowshock/text.html:
"The spectrogram shows a narrowband emission near 6 kHz during the early part of the time interval. This emission is seen when the spacecraft is still in the supersonic solar wind upstream of the [Jupiter bow] shock. These emissions are called electron plasma oscillations or Langmuir waves and represent the oscillatory motion of electrons about their equilibrium positions. From the frequency of this band of emissions we can say that the plasma density of the solar wind just upstream of the bow shock is about 0.44 electrons per cm^3... These electrons are moving in the opposite direction of the bulk of the solar wind, hence, we have one stream of electrons moving from the shock towards the sun and another, the solar wind electrons, moving from the sun towards the shock. This situation is not an equilibrium state and, in fact, the two streams represent a source of free energy in the plasma upstream of the shock. The natural response of the plasma to such a situation is to generate an instability known as electron plasma oscillations or Langmuir waves which will tend to scatter the shock-associated electrons and thermalize them, incorporating them back into the normal solar wind population of electrons... The band of electron plasma oscillations [at the crossing] fades out and is replaced by a lower frequency but broader band of emission. This low-frequency, broadband emission is directly associated with the bow shock and, in our analogy with sonic booms, is very similar to the sound waves one hears from a sonic boom. There are a few fairly clearly defined regions within this shock-related noise over the minute or so during which these waves are detected; the waves ramp up in both intensity and bandwidth to an abrupt maximum at about 90 seconds into the interval and subsequently decay over the next minute or so. "

[65] RHH, personal communication, 2009

[66] Earth's electron foreshock and bow shock:
http://www-pw.physics.uiowa.edu/~dag/publications/1989_HighFrequencyElectrostaticWavesNearEarthsBowShock_JGR.pdf

and the point of turnaround is termed the *mirror point*. When responding to a dipole field, this oscillation of particles ("bounce motion") between two mirror points may be combined with a drift motion along a *drift shell* (*ISP* p. 33).

Frozen-in Condition for Magnetic Flux: The approximate MHD version of Ohm's law is $\mathbf{E} + \mathbf{u}\times\mathbf{B} = \eta\mathbf{j}. = \mathbf{j}/\sigma$ where η = resistivity = $1/\sigma$, σ = conductivity, and $\mathbf{u}$ is the plasma velocity. (Both η and σ may in some circumstances be anisotropic and require expression as tensors.) Plasmas have such high conductivity σ that any attempted change in magnetic field induces opposing eddy currents. In collisionless plasmas, the conductivity σ may be so large (i.e., resistivity η so low) that $\mathbf{j}/\sigma$ is effectively 0 and a simplified relationship applies (see *ISP* p. 48):

$$\mathbf{E} = -\mathbf{u}\times\mathbf{B}$$

Magnetic flux[67] Φ_m is defined as the integral of $\mathbf{B}\bullet d\mathbf{S}$ over a surface S through which magnetic flux lines pass. A *flux tube* is a generally tube-like (cylindrical) region of space containing a magnetic field, such that the field at the side surfaces is parallel to those surfaces. Both the cross-sectional area of the tube and the field [strength] contained may vary along the length of the tube, but the *magnetic flux* is always constant [i.e., calculated over surfaces bounded by and contained within the flux tube].[68]" (See here[69] for a mathematical proof.)

"Plasma must flow when there is an electric field. In MHD fluid flow, the magnetic field can be *frozen in* to the fluid." For a surface S in the fluid not parallel to the lines of **B**, the field lines are held in place so tightly that as the surface moves through the system, "the flux through the surface will remain constant even as the surface changes its location and its shape". "As the surface stretches or shrinks, the field lines will move apart or move closer together." "All particles initially on a flux tube will remain linked along a single flux tube as they convect through space." "The plasma is moving, but the frozen-in flux can be thought of as moving with the plasma." (*ISP* p. 48-9) The plasma and the B-field move together.

The frozen-in condition applies for instance to the effect of differential solar rotation by latitude, with the carrying along of wrapped lines of magnetic flux creating a toroidal field (see below).

MHD Waves: This is a potentially complex topic[70] which I have only touched on. These are controlled by pressure and by the EM field. Solutions include (*ISP* p. 51):
(1) *compressional* = *longitudinal waves* [71] (which carry changes of plasma and magnetic pressure and of plasma density, and are apparently for electrons also called *Plasma oscillations* or *Langmuir waves*), and
(2) *shear* = *transverse* = *Alfvén or Alfvénic waves*[72] (which only cause magnetic field lines to bend)

The *Alfvén Speed* is the typical speed to which magnetic forces can accelerate plasma. (ISP p. 67)

Landau Damping: Consider a particle moving at velocity v and a longitudinal plasma wave moving in the same direction with phase velocity v_φ (e.g., the velocity of the wave peaks). If $v > v_\varphi$, the particle is pushing against the wave and slows down, whereas if $v < v_\varphi$, the particle is pushed by the wave and speeds up. This phenomenon creates a region of stability in the parameter space[73]... The damping is collisionless.

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[67] http://en.wikipedia.org/wiki/Magnetic_flux
[68] http://en.wikipedia.org/wiki/Flux_tube
[69] Paul Murray Bellan. *Fundamentals of plasma physics*. Cambridge U. Press. 2006. p. 56
[70] http://en.wikipedia.org/wiki/Waves_in_plasmas
[71] http://en.wikipedia.org/wiki/Magnetohydrodynamics
[72] Alfvén wave:
http://en.wikipedia.org/wiki/Alfv%C3%A9n_wave
"An Alfvén wave in a plasma is a low-frequency (compared to the ion cyclotron frequency) traveling oscillation of the ions and the magnetic field. The ion mass density provides the inertia and the magnetic field line tension provides the restoring force."... "The motion of the ions and the perturbation of the magnetic field are in the same direction and transverse to the direction of propagation."
[73] http://en.wikipedia.org/wiki/Landau_damping

Collisionless Shocks including Bow Shocks: These occur due to the tenuousness or high temperature of a plasma such as the solar wind. Because there are only rare actual (Coulomb[74]) collisions, the resulting deflections are caused by field effects and plasma waves, etc.[75]. Such collisionless shocks do not maintain thermal equilibrium, so that electrons and positive ions may have different temperatures, and non-Maxwellian distributions may arise. (See also *ISP* Chap. 5 for detailed discussion of collisionless shock phenomena beginning p. 135)

According to graphical data presented by RHH, passing through a bow shock irreversibly changes the plasma state (P, T, n_e, and **B**, etc.) A *bow shock*[76] is a non-linear wave in a plasma The speed of propagation of a bow shock is not limited by the plasma properties. To get a shock wave, something has to be travelling faster than the local speed of sound. Depending on the frame of reference, a bow shock arising from a object moving in a stationary medium may propagate ahead of an object (as seen with an explosion from a stationary source causing an advancing shock wave), or it may appear stationary when the medium (e.g., solar wind) is seen to be moving against a stationary object (e.g., the magnetosphere). "Across a shock there is always an extremely rapid rise in pressure, temperature and density of the flow. In supersonic flows, expansion is achieved through an expansion fan. A shock wave travels through most media at a higher speed than an ordinary wave.[77]" "In a planetary magnetosphere, the bow shock is the boundary at which the speed of the solar wind abruptly drops as a result of its approach to the magnetopause.[78]"

Foreshocks: These are particles (and associated waves) that result directly and indirectly from collisionless shocks, and that advance at higher speed than the characteristic shock wave speed in a direction upstream from the shock. The electron and ion foreshocks may occupy differing regions. (*ISP* p. 158-161)

Maxwell Stress Tensor*:* The *tension* or *stress* exerted on charged particles in an electromagnetic field, including apparently along the magnetic field lines in a plasma sheet or in the auroral electrojet, is given by the *Maxwell Stress Tensor*[79]. This computation derives from conservation of momentum considerations. "These units [of each tensor element] can also be seen as units of force per unit of area (pressure), and the ij element of the tensor can also be interpreted as the force parallel to the i-th axis suffered by a surface normal to the j-th axis per unit of area. Indeed the diagonal elements give the *pressure* acting on a differential area element normal to the corresponding axis. Unlike forces due to the pressure of an ideal gas, an area element in the electromagnetic field also feels a force in a direction that is not normal to the element. This *shear* (rather than pressure) is given by the off-diagonal elements of the stress tensor."

Basic Facts about the Sun ⊙ Compared to the Earth ⊕

This data derives in part from here[80,81].

Radius of Sun $R_\odot$ (at equator)[82]: 6.9599×10^8 m = 695,990 km = 432,470 mi = 109 $R_\oplus$

Radius of Earth (R_E or $R_\oplus$ per WGS-84[83])

Mean at Equator: 6.378137×10^6 m = 6,378.137 km

Mean at Poles: 6.356752×10^6 m = 6,356.752 km

Ellipticity of Sun (Flattening[84] or oblateness) = 9×10^{-6} (thus nearly a perfect sphere)

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74 http://en.wikipedia.org/wiki/Coulomb_collision
75 http://www.scholarpedia.org/article/Collisionless_shock_wave
76 http://en.wikipedia.org/wiki/Bow_shock_%28aerodynamics%29
77 http://en.wikipedia.org/wiki/Shock_wave
78 http://en.wikipedia.org/wiki/Bow_shock
79 Maxwell stress tensor:
• http://en.wikipedia.org/wiki/Maxwell_stress_tensor
• http://www.statemaster.com/encyclopedia/Maxwell-stress-tensor
80 http://solarscience.msfc.nasa.gov/
81 http://en.wikipedia.org/wiki/Sun
82 http://solarscience.msfc.nasa.gov/
83 http://en.wikipedia.org/wiki/World_Geodetic_System

Ellipticity of Earth = 0.00335 = ~0.3% (expressed inverted: 1:298)

Distance from Sun to Earth, average (1 Astronomical Unit = AU)[85]:
1.496×10^{11} m = 92.96 million mi = 8.32 lm (light minutes) = 499 ls = 4.8481×10^{-6} parsec = 215 $R_\odot$

Mass of Sun $M_\odot = 1.989 \times 10^{30}$ kg = 333,000 $M_\oplus$

Mass of Earth $M_\oplus = 5.9742 \times 10^{24}$ kg

Density of Sun $\rho_\odot$: [note that 1 gm/cm³ = 10^3 kg/m³]
Mean: 1.408 gm/cm³ = 1.408×10^3 kg/m³ = 0.255 mean ρ_E
Central or Core: up to 150 g/cm³ = 150×10^3 kg/m³ (the core extends to 0.2 to 0.25 $R_\odot$)
Photosphere[86]: 2×10^{-7} g/cm³ = 2×10^{-4} kg/m³ [~1.6×10^{-4} times the Earth sea level atmos. density[87]]
Particle density = ~10^{23} particles m^{-3}
Corona Mean[88]: 1×10^{-15} g/cm³ = 1×10^{-12} kg/m³
Lower Corona[89]: 1×10^{-16} g/cm³
Particle density[90]: $10^{15} - 10^{16}$ particles m^{-3}

Density of Earth ρ_E[91]:

Mean:	5.515 gm/cm³	= 5.515×10^3 kg/m³
Inner Core:	12.8 – 13.1 gm/cm³	= 12.8×10^3 - 13.1×10^3 kg/m³
Mantle:	3.4 – 5.6 gm/cm³	= 3.4×10^3 - 5.6×10^3 kg/m³
Crust:	2.2 – 2.9 gm/cm³	= 2.2×10^3 - 2.9×10^3 kg/m³

Atmosphere (at sea level)[92]: 1.2×10^{-3} gm/cm³ = 1.2 kg/m³
[MCM crude estimate cf. Sun: ~6×10^{26} particles m^{-3}]

Temperature of Sun[93]
Surface (effective black body temperature) = 5770 K = 9,930 °F (*ISP*: 5785 K)
Central or Core = 15,600,000 K = 28,000,000 °F

Luminosity of Sun $L_\odot$[94,95] = 3.846×10^{26} W = 3.846×10^{33} erg/s

Spectral Stellar Classification of Sun (Morgan-Keenan)[96,97]: G2V

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[84] Ellipticity:
http://en.wikipedia.org/wiki/Flattening:
Ellipticity is defined for an ellipsoid with equatorial radius a and polar radius b as (a-b)/a
[85] http://en.wikipedia.org/wiki/Astronomical_unit
[86] http://en.wikipedia.org/wiki/Sun
[87] http://solarscience.msfc.nasa.gov/
[88] http://en.wikipedia.org/wiki/Sun
[89] http://solar-center.stanford.edu/vitalstats.html
[90] http://en.wikipedia.org/wiki/Sun
[91] http://en.wikipedia.org/wiki/Earth
[92] http://en.wikipedia.org/wiki/Earth%27s_atmosphere
[93] http://solarscience.msfc.nasa.gov/
[94] http://solarscience.msfc.nasa.gov/
[95] Luminosity:
http://en.wikipedia.org/wiki/Solar_luminosity:
Luminosity here is total bolometric (wide spectrum) photon radiant energy output, and does not include neutrino radiant energy, which adds 0.1×10^{26} W
[96] Star Spectral classification:
http://en.wikipedia.org/wiki/Spectral_classification:
For the Sun classified as G2V in the Morgan-Keenan classification,
- Letter G indicates a yellowish star with surface T 5,200–6,000 K
- Number 2 indicates two tenths of the range between star classes G and adjacent star class K (orangish)
- Roman Number V indicates the width of certain absorption lines, which correlates with stellar size, so that V indicates a Main Sequence star.

[97] http://en.wikipedia.org/wiki/Hertzsprung%E2%80%93Russell_diagram

Magnitude of Sun:

Absolute: +4.83

Visual (Apparent): -26.74

Elemental Composition of Sun by Mass % or ppm

Photosphere[98] = H 91.0%, He 8.9%; O 774 ppm, C 330 ppm, Ne 112 ppm, N 102 ppm, Fe 43 ppm …

Central[99]= 35% H, 63% He, 2% (C, N, O, etc.)

Age of Sun[100] = 4.57×10^9 yr (cf. 4.54×10^9 yr for Earth[101])

Rate of Mass Conversion to Energy of Sun through Fusion[102]: 4.4×10^9 kg s^{-1} or 9.2×10^{37} protons s^{-1}

Rotation Periods of the Surface of the Sun[103]:

Sidereal equatorial: 24.47 d (rotation period in days to same apparent location as viewed in star frame)

Synodic equatorial: 26.24 d (rotation period in days to same apparent location as viewed from Earth)

Sidereal Carrington (~26 degrees latitude): 25.38 d

Synodic Carrington (~26 degrees latitude): 27.2753 d

Solar Rotation period (an empiric formula by latitude at the surface for data collected 1967 – 1987[104]):

$\omega = 14.713 - 2.396\sin^2(\varphi) - 1.787\sin^4(\varphi)$, where

ω = deg/d sidereal

φ = solar latitude (deg)

This gives sidereal days: 0°→24.47 d, 26°→25.38 d, 30°→25.71 d, 60°→30.22 d, 90°→34.19 d

Total Solar Irradiance (TSI, the not-so-constant "Solar Constant") is the irradiance (W m^{-2}) at all wavelengths of photons (effectively from about 10,000 nm to about 10 nm) at exactly 1 A.U.[105] on a surface perpendicular to the incoming rays:

Mean is about 1366 W m^{-2}

Actual solar irradiance[106] varies due to changing Earth-Sun distance and solar fluctuations from 1,412 – 1,321 W m^{-2}

Tilt of Sun's rotational axis with respect to the plane of Earth's orbit: ~7.25 degrees[107]

Tilt of Sun's magnetic dipole field axis with respect to rotation axis: varies during solar cycle but up to ±(10° – 20°).[108]

Sun rotation direction: Counterclockwise (when viewed from the north)

(this is the same direction that the planets rotate and orbit around the Sun).

Sun Escape Velocity: Escape velocity[109] in general is given by $v_e = (2GM/r)^{1/2}$, where M is the mass of the massive body being escaped from starting at distance from the body's center r, and v_e is the minimum speed required when propulsion ceases at that distance. (This idealized formula ignores the drag of the atmosphere.) For the Sun's surface, the idealized escape velocity is calculated at 617.5 km/s, whereas for the Earth' surface, it is calculated at 11.2 km/s. However, there appears to be a complex relationship between this simplistic solar escape velocity estimate and the velocities actually attained in solar wind. The latter is found to be below v_e at least using estimates from actual measurements near the Sun (at $4R_\odot - 7R_\odot$) using

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98 http://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html

99 http://solarscience.msfc.nasa.gov/

100 http://en.wikipedia.org/wiki/Sun and http://solarscience.msfc.nasa.gov/

101 http://en.wikipedia.org/wiki/Age_of_the_Earth

102 http://en.wikipedia.org/wiki/Sun

103 http://en.wikipedia.org/wiki/Solar_rotation

104 Solar differential rotation:
Snodgrass, H. B. & Ulrich, R. K., "Rotation of Doppler features in the solar photosphere", *Astrophysical Journal*, Part 1 vol. 351, 1990, p. 309-316

105 ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_IRRADIANCE/COMPOSITE.v2.PDF

106 http://en.wikipedia.org/wiki/Solar_irradiation

107 http://solarscience.msfc.nasa.gov/sunturn.shtml

108 http://www.nso.edu/press/newsletter/Tilted_Solar_Magnetic_Dipole.pdf

109 http://en.wikipedia.org/wiki/Escape_velocity

data from the Ulysses probe[110], and certainly solar wind speed is often < v_e (see below) by the time the solar wind has decelerated in travelling to Earth orbit.

Solar Nucleosynthesis (Fusion Reactions)

Fusion reactions take place almost entirely in the core. The Sun overall converts c. 4.4×10^9 kg s^{-1} in proton mass to energy, yielding a total Sun power generation rate from fusion of 3.83×10^{26} W. At the center of the core, the power generation density is estimated[111] at 276.5 W m^{-3} or 0.0175 W kg^{-1}. By comparison, if we assume an average human heat production rate[112] of 1.3 W/kg, the human heat production rate is about 75 times as great (expressed as W/kg) as the Sun's central core, or about 5 times as great (expressed as W m^{-3}).

The conversion of 4 protons (each with mass 1.6726216×10^{-27} kg[113]) to one alpha particle (${}^4_2He^{2+}$ nucleus, with nuclear mass 6.644656×10^{-27} kg[114]) results in a mass deficit of 4.583012×10^{-27} kg, which is equivalent (by $E=mc^2$) to 4.11900577×10^{-12} Joule = 25.71 MeV (using 1eV = 1.60217653E-19 J). This mass deficit is about 0.7% of the mass of the 4 protons. The pp fusion reaction also consumes (annihilates) 2 electrons, releasing their energy as gammas, so the total energy released in fusing 4 protons is 25.71 + 2x0.511MeV = 26.73 MeV. (This final value is that cited for the pp I chain here[115].)

There are several possible pathways for this fusion reaction (rare pathways such as pp IV and pep are omitted here). Power generation by these pathways is consistent with the predictions of the Standard Solar Model. The principle fusion reaction chains in the Sun (and in stars similar in size) are as follows:

The Proton–proton (pp) Chain Reaction

The pp reaction chain[116] generates ${}^4_2He^{2+}$ nuclei from 4 protons and 2 electrons (the latter annihilate with the 2 positrons produced). PP reactions start occurring at temperatures around 4×10^6 K (4 mega-Kelvin or MK). However, the low reaction rate below 10 MK leads to little ${}^4He$ production.

Of the pp branches, the pp I branch (which involves ${}^2_1H$ and ${}^3_2He$ intermediaries) dominates at 10 to 14 MK temperatures. The energy given off is in the form of KE, 5 gamma ray photons, and 2 electron neutrinos (ν_e).

The pp II branch (which involves ${}^7_4Be$ and ${}^7_3Li$ intermediaries) is dominant at temperatures of 14 to 23 MK, whereas the pp III chain (with ${}^7_4Be$, ${}^8_5B$, and ${}^8_4Be$ intermediaries) is dominant if the temperature exceeds 23 MK.

In the Sun, 86% of pp reactions are pp I, 14% of pp reactions are pp II, and 0.11% are pp III. The neutrinos carry away part of the energy produced as follows: 2.0% of energy produced in ppI reactions , 4.0% of ppII energy, and 28.3% of ppIII energy, respectively. These neutrinos do not contribute significantly to the pressure that counters gravitational collapse and maintains hydrostatic equilibrium, nor do they contribute to solar warming of the Earth.

The Carbon Nitrogen Oxygen (CNO) Cycle

The CNO cycle[117] (or Bethe-Weizsäcker-cycle) is the dominant source of energy in stars heavier than about 1.5 $M_\odot$, whereas the proton-proton chain is more important in stars of 1.0 $M_\odot$ or less. The CNO chain reaction starts occurring at approximately 13 MK. At approximately 17 MK, the CNO cycle becomes the dominant source of energy. This occurs in stars with masses at least 1.3 $M_\odot$. Only 1.7% of ${}^4_2He$ nuclei being produced in the Sun come from the CNO cycle (almost all of the remainder are in the pp cycle). Like the pp reaction, the CNO cycles consists of more than one branch. The intermediaries include ${}^{13}_7N$, ${}^{13}_6C$, ${}^{14}_7N$, ${}^{15}_8O$, ${}^{15}_7N$, ${}^{16}_8O$, ${}^{17}_9F$, ${}^{17}_8O$, ${}^{14}_7N$, ${}^{18}_9F$, ${}^{18}_8O$, and ${}^{19}_9F$ (see cited article for details). The several CNO cycles produce C N and O but only as catalytic intermediaries—they do not accumulate at least in the Sun to any significant degree (see

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110 Efimova AI et al. "Solar wind velocity measurements near the sun using Ulysses radio amplitude correlations at two frequencies". *Advances in Space Research*. Volume 35, Issue 12, 2005, Pages 2189-2194
111 http://fusedweb.llnl.gov/CPEP/Chart_Pages/5.Plasmas/Sunlayers.html
112 http://en.wikipedia.org/wiki/Sun
113 http://en.wikipedia.org/wiki/Proton
114 http://en.wikipedia.org/wiki/Alpha_particle
115 http://en.wikipedia.org/wiki/Proton%E2%80%93proton_chain_reaction
116 http://en.wikipedia.org/wiki/Proton-proton_chain
117 http://en.wikipedia.org/wiki/CNO_cycle

solar composition above). The net result of the CNO chain is generation from 4 protons of one ${}^4_2He$, 2 positrons, 2 electron neutrinos, and 1 gamma ray, yielding 26.8 MeV in energy. (This quoted energy figure apparently includes the energy in the electrons which will be annihilated by the positrons, and is close to the overall figure computed for the pp reaction.)

Standard Solar Model (SSM), Solar Convection, and Solar Layers

The SSM is a relatively successful model that assumes that the Sun is spherical, that it is on average at hydrostatic equilibrium (pressure balances gravity), that energy is only produced by nuclear fusion (almost entirely in the core), that energy transport is by radiation, convection, and neutrino losses (conduction is ignored), and that there was initially a homogenous composition. It makes use of four ordinary differential equations of state involving five variables: P (pressure), T (temperature), r (radius), M(r) (mass enclosed at radius r) or density ρ, and L (luminosity), for a given increment dr of solar shell[118,119,120]:

(1) $dP/dr = -Gm_r\rho/r^2$ (Hydrostatic Equilibrium balances pressure and gravity)
where P = pressure (kinetic gas pressure, not radiative)
ρ = density
m_r = mass contained inside the radius r,
G (gravitational constant[121]) = 6.67428×10^{-11} m^3 kg^{-1} s^{-2}

(2) $P = \rho TR/\mu$
where ρ = density
T = temperature,
μ = mean molecular weight (typically about 0.59[122] when including electrons)
R (gas constant[123]) = 8.314 J K^{-1} mol^{-1}

(3a) $dT/dr = -3\kappa\rho L / (16\pi\sigma c r^2 T^3)$ (Radiative energy transport expr. by the temp gradient)

where κ = Rosseland mean opacity[124] of the solar material,
L = luminosity
c = speed of light
σ = Stefan–Boltzmann constant[125], the total Energy radiated by a black body per unit surface area in unit time

(3b) $dT/dr = (1 - 1/\gamma)\cdot(T/P)\cdot dP/dr$ (Convective energy transport expr. by the temp gradient)

where k = opacity of the stellar material
L = luminosity
γ = the ratio of specific heats, C_P/C_V

(4) $dL/dr = 4\pi r^2\rho\varepsilon$ (Conservation of energy)
where *L* = total luminosity (energy time^{-1} area^{-1}) passing through the shell dr at radius *r*,
ε is the energy production rate per unit mass [ergs s^{-1}] within the shell dr at radius r
(The T dS/dt entropy term has been ignored)

The 2002 publication by Kevin France[126] includes helpful graphs showing the SSM predicted values as a function of relative radius $r/R_\odot$ unless otherwise noted. Values modeled include:

Mean molecular weight;
Mass fractions of H (reduced centrally) and He (increased centrally);
Heavy element ratios;
Energy production rate (almost all production occurs in the core inside 0.2 $r/R_\odot$);

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118 http://en.wikipedia.org/wiki/Standard_Solar_Model
119 http://www.ap.stmarys.ca/~guenther/Level01/solar/what_is_ssm.html
120 Kevin France. Standard Solar Model. http://www.pha.jhu.edu/~france/PAPERS/solmodel.pdf
121 http://en.wikipedia.org/wiki/Gravitational_constant
122 http://neutrino.aquaphoenix.com/un-esa/sun/sun-chapter1.html
123 http://en.wikipedia.org/wiki/Gas_constant
124 http://en.wikipedia.org/wiki/Rosseland_mean_opacity
125 http://en.wikipedia.org/wiki/Stefan%E2%80%93Boltzmann_constant
126 Kevin France—Standard Solar Model:
http://www.pha.jhu.edu/~france/PAPERS/solmodel.pdf

Luminosity fraction;
Transition to convection when energy transport by radiation is inadequate;
Mass and Luminosity Fraction;
Density;
Pressure;
Temperature;
Hydrogen fraction;
^{3}He fraction;
^{4}He fraction;
C fraction;
N fraction;
O fraction;
Solar opacity;
Optical depth[127];
Luminosity by mass fraction;
Heavy element abundance; and
Region of maximum energy production (at ~0.1 $r/R_\odot$).

According to France, a region becomes unstable when its density becomes appreciably different than its surroundings, resulting in a buoyancy force. (See *ISP* p. 74 for a calculation showing why the flux tube has lower density than its surroundings and thus this buoyancy arises.) This occurs when the *Schwarzchild stability criterion*[128] is violated (i.e., when the radiative temperature gradient is greater than the adiabatic temperature gradient)—the region becomes unstable and convection begins. In terms of the equations above, the transition to convection occurs when equation 3a gives a higher dT/dr than equation 3b. This is the start of the *convection zone*.

According to RHH, convection cells are unstable when width > depth.

Photosphere: The *photosphere* is the layer below which the Sun is opaque to visible light. The dominant factor contributing to the increase in opacity with depth is the increasing amount of H^- ions (atomic hydrogen with an added electron). H^- ions are strongly light absorbing[129] but their formation emits light. [Solar opacity is a complex topic that I have not adequately reviewed.)

Solar granules[130] "are in the photosphere of the Sun and are caused by convection currents (thermal columns, Bénard cells) of plasma within the Sun's convective zone. The grainy appearance of the solar photosphere is produced by the tops of these convective cells and is called *granulation*. The rising part of the granules is located in the center where the plasma is hotter. The outer edge of the granules is darker due to the cooler descending plasma. In addition to the visible appearance, Doppler shift measurements of the light from individual granules provides evidence for the convective nature of the granules. A typical granule has a diameter on the order of 1,000 kilometers and lasts 8 to 20 minutes before dissipating."

Below the photosphere is a layer of *supergranules.* Supergranules[131] are detectable primarily by detection of magnetic fields using Zeeman splitting[132]. They have "a typical size of about 30,000 km … with a lifetime of about 24 hours. … Its origin is not precisely known." Wave-like properties of solar supergranulation have been reported.[133]—these propagate in a prograde pattern (that is, in the direction of rotation).

Chromosphere: Above the photosphere is the *chromosphere*, a thin layer of the Sun's atmosphere roughly 2,000 kilometers deep. "The chromosphere is more visually transparent than the photosphere. The name

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[127] http://en.wikipedia.org/wiki/Optical_depth
[128] http://lcd-www.colorado.edu/sabrun/StellarConvection_26April08.pdf
[129] http://en.wikipedia.org/wiki/Sun
[130] http://en.wikipedia.org/wiki/Granule_%28solar_physics%29
[131] http://en.wikipedia.org/wiki/Supergranulation
[132] Zeeman effect:
• http://en.wikipedia.org/wiki/Zeeman_effect and
• http://en.wikipedia.org/wiki/Pieter_Zeeman
[133] L. Gizon et al, "Wave-like properties of solar supergranulation" *Nature* **421**, 2 January 2003.

comes from the fact that it has a reddish color, as the visual spectrum of the chromosphere is dominated by the deep red [*Balmer-alpha* or] *H-alpha* spectral line of hydrogen [at 656.281 nm]. The coloration may be seen directly with the naked eye only during a total solar eclipse, where the chromosphere is briefly visible as a flash of color just as the visible edge of the photosphere disappears behind the Moon…. The most common solar feature within the chromosphere are spicules, long thin fingers of luminous gas which appear like the blades of a huge field of fiery grass… Spicules rise to the top of the chromosphere and then sink back down again over the course of about 10 minutes.[134]"

Corona: The temperature abruptly rises in the transition (at about 2500 km) from chromosphere to corona, while atomic hydrogen number density precipitously falls with dissociation into free electrons and protons. (RHH slide citing Withbroe and Noyes 1977). The corona is variable in size but can extend millions of kilometers into space, and is continuous with the solar wind. (There does not appear to be a sharp demarcation separating the outer corona from the adjacent solar wind.)

Shortcomings of the SSM: Some shortcomings of the SSM include the problem of the insufficient experimentally measured neutrino flux (this has been resolved by neutrino oscillations[135]); an excessively low abundance of light elements Li, B, and Be; chemical controversy in the photosphere; and other issues. The SSM does not incorporate the effect of *radiation pressure*, which is thought to be small inside the Sun (but can be the dominant pressure component in the heaviest stars[136]).

Sunspots, Coronal Phenomena, Space and Earth Weather

These important topics are only briefly reviewed here, see Sunspots[137], etc.: For links to Space Weather websites, see links near beginning of this document.

General: A glossary of Sun-related terminology is found here[138]. For high resolution images at multiple wavelengths of flares, loops, prominences, filaments, magnetic flux tubes, coronal mass ejections, etc. involving the solar photosphere, transition region, and corona, see TRACE[139] images (mission launched 1998). A useful set of images here (Active Region 9017 taken at 14:01 UT on June 2, 2000) shows a 10^6 K flare and loops extending between two sunspots at 4000 K surrounded by the 6000 K photosphere.

Solar and Heliospheric Observatory (SOHO), and Missions to the Lagrangian Points: This important spacecraft was launched in 1995 and continues to capture real-time solar data. Good images can also be seen for the Solar and Heliospheric Observatory (SOHO) mission here[140]. It is "one of three spacecraft currently in the vicinity of the Earth-Sun [L1 Lagrangian point], a point of gravitational balance located approximately 0.99 astronomical unit (AU)s from the Sun and 0.01 AU from the Earth.[141]" "The Sun–Earth [L1 Lagrangian point] is ideal for making observations of the Sun. Objects here are never shadowed by the Earth or the Moon. The Solar and Heliospheric Observatory (SOHO) is stationed in a Halo orbit at L1… At the L1 point, the orbital period of the object [e.g., SOHO] becomes exactly equal to the Earth's orbital period [about the Sun].[142]" "…The SOHO satellite is not exactly at L1 as this would make communication difficult due to radio interference generated by the Sun, and because this would not be a stable orbit. Rather it lies in the (constantly moving) plane which passes through L1 and is perpendicular to the line connecting the sun and the Earth. It stays in this plane, tracing out an elliptical orbit centered about L1. It orbits L1 once every six months, while L1 itself orbits the sun every 12 months as it is coupled with the motion of the Earth. This keeps SOHO at a good position for communication with Earth at all times.[143]" See here[144] for detailed

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[134] http://en.wikipedia.org/wiki/Chromosphere
[135] http://en.wikipedia.org/wiki/Neutrino_oscillation
[136] http://en.wikipedia.org/wiki/Radiation_pressure
[137] http://en.wikipedia.org/wiki/Sunspot
[138] http://solar-center.stanford.edu/gloss.html
[139] http://trace.lmsal.com/
[140] http://sohowww.nascom.nasa.gov/
[141] http://en.wikipedia.org/wiki/SOHO_spacecraft
[142] http://en.wikipedia.org/wiki/Lagrange_point
[143] http://en.wikipedia.org/wiki/SOHO_spacecraft
[144] http://www.physics.montana.edu/faculty/cornish/lagrange.pdf

calculations for the Lagrangian Points L1 through L5. L1 is about 1.5×10^6 km closer to the Sun than is the Earth.

"The L2 point of the Earth-Sun system is home to the WMAP spacecraft, and (perhaps by the year 2011) the James Webb Space Telescope.[145]"

Magnetic Reconnection

"Magnetic reconnection is the process whereby magnetic field lines from different magnetic domains are spliced to one another… It is a violation of an approximate conservation law in plasma physics, and can concentrate mechanical or magnetic energy in both space and time. Solar flares, the largest explosions in the solar system, may involve the reconnection of large systems of magnetic flux on the Sun, releasing, in minutes, energy that has been stored in the magnetic field over a period of hours to days. Magnetic reconnection in Earth's magnetosphere is one of the mechanisms responsible for the aurora… The most common type of magnetic reconnection is *separator reconnection*, in which four separate magnetic domains exchange magnetic field lines…[146]" A technical presentation on solar CME's that depicts some of the details of the postulated reconnection events is available here[147].

Magnetic reconnection is also termed *magnetic merging*. Reconnection is depicted as an *X-type* (or *X-line*) *configuration*. The field lines forming this X are called the *separatrix* (plural: *separatrices*), and these lines separate four regions of differing magnetic fields. The center point (or line if extended in 3 dimensions) formed at the intersection of the separatrices is called the *magnetic neutral point* or *neutral line*[148]. Magnetic reconnection can both realign magnetic fields and release magnetic energy, accelerating particles.

Relation of Current Sheets to Magnetic Reconnection: "A *current sheet* is an electric current that is confined to a surface, rather than being spread through a volume of space. Current sheets feature in magnetohydrodynamics (MHD)… If there is an electric current through part of the volume of [an electrically conductive fluid], magnetic forces tend to expel it from the fluid, compressing the current into thin layers that pass through the volume… Current sheets in plasmas store energy by increasing the energy density of the magnetic field. Many plasma instabilities arise near strong current sheets, which are prone to collapse, causing magnetic reconnection and rapidly releasing the stored energy. This process is the cause of solar flares and is one reason for the difficulty of magnetic confinement fusion, which requires strong electric currents in a hot plasma.[149]" (The *Heliospheric current sheet*[150] *is* further discussed below.)

Sunspots—Size, Frequency, Patterns, and Effects on Earth Climate

Sunspots are up to 20 Mm in size (*ISP* p. 71). "A sunspot is an area on the Sun's surface (photosphere) that is marked by intense magnetic activity, which inhibits [outward] convection, forming areas of reduced surface temperature. They can be visible from Earth without the aid of a telescope." [MCM: I have personally experienced this on a hazy day.] The temperatures of umbras are 4,000 K according to TRACE, and *ISP* p. 71 estimates 4100 K. The contrast with the surrounding material at about 5,800 K leaves [the cooler portions] visible as dark spots, as the intensity of light from a heated black body [is proportional to T^4]. Despite their apparent darkness, "If a sunspot were isolated from the surrounding photosphere it would be brighter than an electric arc.[151]"

"Sunspots, being the manifestation of intense magnetic activity, host secondary phenomena such as coronal loops and reconnection events. Most solar flares and coronal mass ejections originate in magnetically active regions around visible sunspot groupings. Similar phenomena indirectly observed on stars are commonly called starspots and both light and dark spots have been measured…. Sunspot populations quickly rise and

[145] http://map.gsfc.nasa.gov/mission/observatory_l2.html
[146] http://en.wikipedia.org/wiki/Magnetic_reconnection
[147] http://cdaw.gsfc.nasa.gov/geomag_cdaw/data/presentation/Siscoe_CDAW/Siscoe_CDAW.ppt
[148] http://www-spof.gsfc.nasa.gov/Education/bh2_5.html
[149] http://en.wikipedia.org/wiki/Current_sheet
[150] http://en.wikipedia.org/wiki/Heliospheric_current_sheet
[151] http://en.wikipedia.org/wiki/Sunspot

more slowly fall on an irregular cycle about every 11 years[152]" [thereby attaining the *Solar Maximum* and *Solar Minimum*]…

Sunspots were rarely observed during the *Maunder Minimum*[153] [c. 1645 – 1715, during the reign of France's King Louis XIV]. This coincided with the middle (and coldest) part of a period of cooling known as the Little Ice Age…" The correlation of low solar sunspot activity with lower Earth temperatures as in the Maunder Minimum has been a topic of great interest and is not fully understood. Some possible contributory factors for this *Sun/Climate interaction* according to review[154] by GC Reid include:

• Variations In Total Irradiance: "The general conclusion of these estimates is that the Sun's total irradiance has probably varied by somewhere between 0.2 and 0.6% over the 300-year period, and that this would have been sufficient to account for the cooling of the Little Ice Age, which has been estimated to have been about 0.5 to 1 °C on a global basis.";
• Variations In UV Spectral Irradiance; and
• Variations In The Solar Wind And Energetic Particles.

RHH mentions another possible mechanism for the Maunder Minimum, namely that the correlation may involve *cirrus clouds*. These clouds can increase infrared absorption preventing re-radiation into space (thus promoting warming), However, the degree to which they also reflect incoming sunlight (increasing albedo and promoting cooling) is a confounding factor which has apparently been difficult to model[155].

A sunspot often has a dark cool central *umbra* and a surrounding warmer *penumbra*. The magnetic field in a sunspot is most intense in the umbra, where it is oriented more perpendicular to the surface and ranges as high as 2000 – 3600 Gauss. (This compares to much smaller values of only 0.1 to 100 G outside sunspots.) It is generally higher for larger sunspots. The flux tubes of the penumbra are more bent over toward the surface and have lower magnetic field strength. The maximum field strength in the umbra tends to decrease with higher penumbra to umbra radius ratio.[156]

The polarity of the Sun's magnetic field reverses approximately each 11 years (along with the maxima and minima of sunspots), and returns to the original polarity approximately each 22 years (the latter more regularly than the former, but predictions are never exact)[157]. A graphical prediction of the future solar cycle is shown here[158]. One pole reverses one year ahead of the other.

"… It appears that sunspots are the visible counterparts of magnetic flux tubes in the sun's convective zone that get "wound up" by differential rotation. If the stress on the tubes reaches a certain limit, they curl up like a rubber band and puncture the sun's surface. Convection is inhibited at the puncture points; the energy flux from the sun's interior decreases; and with it surface temperature."[137] Sunspots often appear in *bipolar* pairs, presumably corresponding to the two limbs of the erupting loop of magnetic flux tubes, but may be unipolar. (See Babcock model below)

"… Observations using the Zeeman effect show that prototypical sunspots come in pairs with opposite magnetic polarity. From [11-year] cycle to cycle, the polarities of leading and trailing (with respect to the solar rotation) sunspots change from north/south to south/north and back. [The overall sunspot cycle is more accurately said to be 22 years.] Sunspots usually appear in groups (and are counted relative to solitary sunspots using the Wolf number[159])… Sunspot lifetime is about two weeks."

"Sunspots appear mostly in the low latitudes near the solar equator. In fact they almost never appear closer than 5 or further than 40 degrees latitude, north or south. As each sunspot cycle progresses, the sunspots

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[152] ibid.
[153] http://en.wikipedia.org/wiki/Maunder_Minimum
[154] Reid GC "Solar Variability and the Earth's Climate: Introduction and Overview " *Space Science Reviews*. Volume 94, Numbers 1-2 / November, 2000
[155] http://en.wikipedia.org/wiki/Cirrus_cloud
[156] Sunspots and Magnetic Fields:
• C. L. Jin et al. "The Relationships of Sunspot Magnetic Field Strength with Sunspot Area, Umbral Area and Penumbra-Umbra Radius Ratio". *Astrophys Space Sci* (2006) 306:23–27 and
• http://www.ips.gov.au/Category/Educational/The%20Sun%20and%20Solar%20Activity/Sunspots/Sunspot_Magnetic_Fields.pdf
[157] http://solarscience.msfc.nasa.gov/papers/hathadh/HathawayWilsonReichmann1994.pdf
[158] http://solarscience.msfc.nasa.gov/images/ssn_predict_l.gif
[159] http://en.wikipedia.org/wiki/Wolf_number

gradually start to appear closer and closer to the equator. The resulting scatter distribution described by Maunder in 1904 is called a *butterfly diagram*[160].

"*Plages* are bright cloud-like features found around sunspots that represent regions of higher temperature and density within the chromosphere.[161]"

Coronal Phenomena: Loops, Flares, CMEs, Prominences, Holes, etc.

Coronal Loops: "Coronal loops are the basic structures of the magnetic solar corona. These loops are the closed-magnetic flux cousins of the open-magnetic flux that can be found in coronal hole (polar) regions and the solar wind. Loops of magnetic flux well up from the solar body and fill with hot solar plasma. Due to the heightened magnetic activity in these coronal loop regions, coronal loops can often be the precursor to solar flares and coronal mass ejections (CMEs). Solar plasma feeding these structures is heated from under 6000K to well over 1×10^6 K… Often, the solar plasma will fill these loops from one foot point and drain from the other… Coronal loops may have lifetimes in the order of *seconds* (in the case of flare events), *minutes, hours or days*. Usually coronal loops lasting for long periods of time are known as steady state or quiescent coronal loops, where there is a balance in loop energy sources and sinks… Coronal loops have become very important when trying to understand the current coronal heating problem. Coronal loops are highly radiating sources of plasma and therefore easy to observe by instruments such as TRACE…[162]" "Coronal loops form the basic structure of the lower corona and transition region of the Sun. These highly structured and elegant loops are a direct consequence of the twisted solar magnetic flux within the solar body. The population of coronal loops can be directly linked with the solar cycle, it is for this reason coronal loops are often found with sunspots at their footpoints… Closed flux must be *filled with plasma* before it can be called a *coronal loop*… Many scales of coronal loops can be observed [extending to the transition region or well into the corona.] ",[163]

Solar Flares: "Solar flares are intense, short-lived releases of energy. They are seen as bright areas on the Sun in optical wavelengths and as bursts of noise in radio wavelengths; they can last from *minutes to hours*. Solar Flares are our solar system's largest explosive events. The primary energy source for flares appears to be the tearing and *reconnection* of strong magnetic fields. They radiate throughout the electromagnetic spectrum, from gamma rays to x-rays, through visible light out to kilometer-long radio waves.[164]"

The complex composite spectrum of a large solar flare on 6 March, 1989 is shown here[165], including its evolution with time. (The annotations on the graph are partly illegible.) This flare produced—in addition to radio, infrared, visible light (1.65 - 3.1 eV), and UV (3.1 - 124 eV) radiation, etc.—higher energy EM photon radiation including:
(1) *soft x-rays* (variously defined but generally between 120 eV and 12 keV [compared to 1/40 eV for the thermal energy of atoms at room temperature]), typically *thermal bremsstrahlung* [166] or *braking radiation* in which the radiation is produced by the hot plasma as the electrons are deflected in the Coulomb field of the ion nuclei);
(2) *hard x-rays* (greater than 10 or 12 keV, some of which is due to *nonthermal bremsstrahlung*, thought to be from electrons that have been accelerated to much higher energies than those found in the ambient plasma), and
(3) *gamma rays* (with energies typically in the MeV range and arising from nuclear and positron reactions).

The energy released can be as high as 6×10^{25} joules (6×10^{32} ergs) over a few minutes or tens of minutes, whereas smaller events may last only a few seconds. When sunspots are more prevalent, the incidence of flares also increases. They are classified according to the peak flux (W/m^2) of 100 to 800 picometer X-rays as

[160] Maunder butterfly diagram:
• http://cse.ssl.berkeley.edu/segwayed/lessons/sunspots/ and
• http://en.wikipedia.org/wiki/Edward_Walter_Maunder
[161] http://csep10.phys.utk.edu/astr162/lect/sun/prominences.html
[162] http://en.wikipedia.org/wiki/Corona
[163] http://en.wikipedia.org/wiki/Coronal_loop
[164] http://www.swpc.noaa.gov/primer/primer.html
[165] http://hesperia.gsfc.nasa.gov/hessi/flares.htm
[166] http://en.wikipedia.org/wiki/Bremsstrahlung

measured for instance by the Geostationary Operational Environmental Satellite (GOES) satellites[167]. (Flares are also being monitored by Yohkoh, RHESSI, Hinode, and other spacecraft.)

"Solar flares strongly influence the local space weather of the Earth. They produce streams of highly energetic particles in the solar wind and the Earth's magnetosphere that can present radiation hazards to spacecraft and astronauts. The soft X-ray flux of X class flares increases the ionisation of the upper atmosphere, which can interfere with short-wave radio communication and can increase the drag on low orbiting satellites [due to expansion of the atmosphere], leading to orbital decay. Energetic particles in the magnetosphere contribute to the aurora borealis and aurora australis... Solar flares release a cascade of high energy particles known as a proton storm... [MCM: Is this a CME?] The proton storms ... present a hazard to astronauts during interplanetary travel. Most proton storms take two or more hours from the time of visual detection to reach Earth's orbit. A solar flare on January 20, 2005 released the highest concentration of protons ever directly measured, taking only 15 minutes after observation to reach Earth, indicating a velocity of approximately one-half light speed[168]."

See also here[169]: The protons from this flare had energies higher than 100 MeV. "On the moon ... an astronaut protected by no more than a space suit [exposed to this proton flux] would have absorbed about 50 rem of ionizing radiation.[170]" This would be a harmful but not generally lethal exposure.

See also *ISP* p. 82 for a highly technical discussion of mechanisms for flare development.

Coronal Mass Ejections (CMEs): "The outer solar atmosphere, the corona, is structured by strong magnetic fields. Where these fields are closed [by magnetic reconnection events], often above sunspot groups, the confined solar atmosphere can suddenly and violently release bubbles or tongues of gas and magnetic fields called coronal mass ejections. A large CME can contain 10^{16} grams (a billion tons) of matter that can be accelerated to several million miles per hour in a spectacular explosion. Solar material streaks out through the interplanetary medium, impacting any planet or spacecraft in its path. CMEs are sometimes associated with flares but usually occur independently.[171]"

"The average properties of CMEs observed during 1996–2003 were tabulated by Gopalswamy et al... who found mean values of ~7 x 10^{14} g for the mass [ejected], ~483 km/sec for the velocity, and ~5 x 10^{29} ergs [5 x 10^{22} J or 12,000,000 megatons] for the kinetic energy [of the ejected mass].[172]" According to an RHH slide, a solar "flare" can release 10^{30} ergs. NASA states that a solar "flare" can be up to 10^{32} erg[173]. [MCM: I am unclear if these statements fully distinguish between solar flares and CMEs—the distinction remains unclear to me. However, *ISP* p. 127 states, "We are thereby led to the interesting possibility that mass ejections are driven by changes in the very large scale magnetic fields that occur within coronal structures, such as helmet streamers, and have only a coincidental relationship to the smaller-scale magnetic fields that seem to be involved with solar flares."]

"This is how a proton storm develops [on Earth]: It begins with an explosion, usually above a sunspot... From Earth we see a flash of light and X-rays. This is the 'solar flare', and it's the first sign that an explosion has occurred... If the explosion is powerful enough, a billion-ton cloud of gas billows away from the blast site. This is the coronal mass ejection or 'CME'. CMEs are [usually] relatively slow. Even the fastest ones, traveling one to two thousand km/s, [usually] take a day or so to reach Earth. You know a CME has just arrived when you see auroras in the sky... Protons are guided by magnetic force fields so, on January 20th [2005], there was a superhighway for protons leading all the way from sunspot 720 to our planet.[174]" [The same article reports that "... minutes after the January 20th flare, a swarm of high-speed protons surrounded Earth and the Moon. Thirty minutes later, the most intense proton storm in decades was underway."] The duration of a CME appears to be in the range of 10 minutes to 20 hours[175].

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167 http://www.spaceweather.com/glossary/flareclasses.html
168 http://en.wikipedia.org/wiki/Solar_flare
169 http://science.nasa.gov/headlines/y2005/10jun_newstorm.htm
170 http://www.nasa.gov/mission_pages/stereo/news/stereo_astronauts_prt.htm
171 http://www.swpc.noaa.gov/primer/primer.html
172 http://authors.library.caltech.edu/14258/1/MEWaipcp08.pdf
173 http://hesperia.gsfc.nasa.gov/sftheory/flare.htm
174 http://science.nasa.gov/headlines/y2005/10jun_newstorm.htm
175 http://journals.cambridge.org/production/action/cjoGetFulltext?fulltextid=310316

Solar Prominences and Filaments: The term *Solar Prominence*[176] refers to "A large structure visible off the solar limb, extending into the chromosphere or the corona, having a typical density much higher than and temperatures much colder than the ambient corona. When seen against the solar disk these manifest as dark absorption features referred to as *filaments*.[177]" Another source states "One of the largest individual magnetic features on the Sun is the quiescent prominence. Quiescent prominences form on the timescale of a day, typically remain unchanged for up to a month, and often end their existence through an eruption as part of a coronal mass ejection (CME). Prominences are located in the corona and consist of plasma that has parameters comparable to that of the chromosphere: they are cold and dense compared to the surrounding corona. Despite the fact that prominences have been observed for decades, they are still not well understood.[178]" *ISP* (p. 74) discusses prominences, stating they are huge vertical sheets of plasma, and describes the twisted-flux-tube model for why they erupt when the twist is too great... See here[179] for a large prominence observed in 1999 by SOHO, using the 304Å =3040 nm emission of "He II" [doubly ionized helium, not the superconducting phase]. [MCM: I remain somewhat unclear on the distinction between prominences and flares and CMEs.]

Coronal Heating: The mechanism of heating of the corona is thought to be magnetic (ISP p. 79), but the mechanism remains uncertain. "Many coronal heating theories have been proposed, but two theories have remained as the most likely candidates, *wave heating* and *magnetic reconnection (or nanoflares)*. Through most of the past 50 years, neither theory has been able to account for the extreme coronal temperatures. Most solar physicists now believe that some combination of the two theories can probably explain coronal heating, although the details are not yet complete"[180].

The waves being considered might be Alfvén waves[181] or magneto-acoustic waves. Although Alfvén waves were demonstrated in the solar corona in 2007, the authors concluded that "An estimate of the energy carried by the [Alfvén] waves that we spatially resolved indicates that they are too weak to heat the solar corona; however, unresolved Alfvén waves may carry sufficient energy.[182]"

Another view states, "...solar physicists have identified small patches of magnetic field covering the entire surface of the Sun... Scientists now think that this magnetic carpet is probably a source of the corona's heat... It's a fairly inefficient source of energy, but the sheer number of these small magnetic patches on the surface of the Sun makes the process a viable solution to the 50 year old problem of what heats the solar corona[183]..."

Coronal Holes: "Coronal holes are variable solar features that can last for weeks to months. They are large, dark areas when the Sun is viewed in x-ray wavelengths, sometimes as large as a quarter of the Sun's surface. These holes are rooted in large cells of unipolar magnetic fields on the Sun's surface; their field lines extend far out into the solar system. These open field lines allow a continuous outflow of high-speed solar wind. Coronal holes have a long-term cycle, but the cycle doesn't correspond exactly to the sunspot cycle; the holes tend to be most numerous in the years following sunspot maximum. At some stages of the solar cycle, these holes are continuously visible at the solar north and south poles.[184]"

Auroras (Aurorae) and Connection with the Sun: "The aurora is a dynamic and visually delicate manifestation of solar-induced geomagnetic storms. The solar wind energizes electrons and ions in the magnetosphere. These particles usually enter the Earth's upper atmosphere near the polar regions. When the particles strike the molecules and atoms of the thin, high atmosphere, some of them start to glow in

[176] http://en.wikipedia.org/wiki/Solar_prominence
[177] http://www.websters-online-dictionary.org/so/solar+prominence.html
[178] http://www.iop.org/EJ/article/0004-637X/510/1/444/38023.web.pdf
[179] http://apod.nasa.gov/apod/image/0905/sunprom3_soho_big.jpg
[180] http://en.wikipedia.org/wiki/Corona
[181] http://en.wikipedia.org/wiki/Alfv%C3%A9n_wave
[182] http://www.sciencemag.org/cgi/content/abstract/317/5842/1192
[183] http://imagine.gsfc.nasa.gov/docs/science/mysteries_l1/corona.html
[184] http://www.swpc.noaa.gov/primer/primer.html

different colors. Aurora begin between 60 and 80 degrees latitude. As a storm intensifies, the aurora spread toward the equator. During an unusually large storm in 1909, an aurora was visible at Singapore, on the geomagnetic equator. The aurora provide pretty displays, but they are just a visible sign of atmospheric changes that may wreak havoc on technological systems.[185]" See additional discussions below.

Helioseismology

This is a technical subject which I have only skimmed. Helioseismology[186,187,188,189] is "the science studying wave oscillations in the Sun… These are primarily sound and buoyancy waves, the resulting motions of which are sought by studying spectral Doppler shifts.

The sources of agitation causing the solar waves that we observe are processes in the larger convective region… On the Sun's surface, the waves appear as up and down oscillations of the gases, observable as Doppler shifts of spectral lines. If one assumes that a typical visible light solar spectral line has a wavelength of about 600 nanometers and a width of about 10 picometers, then a velocity of 1 meter per second shifts the line about 0.002 picometers… In helioseismology, the observational goal is to measure shifts of a spectrum line to an accuracy of parts per million of its width. Identifying oscillation modes is the mainstay of the helioseismologist's work.

The Sun acts as a *resonant cavity*, and there are three different kinds of waves, differentiated by the nature of the restoring force. These three waves have

p modes [*acoustic* or *sound waves* due to fluctuations in *pressure*],
g modes [*internal gravity* or *buoyancy waves* due to fluctuations in *density*], and
f modes [*surface gravity waves*]…

In contrast to the solid Earth, solar waves have practically no shear component (s-waves). *Alfvén or Alfvénic waves*[190] however are transverse solar waves and these have recently been demonstrated in the corona.[191]

"Acoustic [p] waves become trapped in a region bounded on top by a large density drop near the surface [i.e., the photosphere], and bounded on the bottom by an increase in sound speed [the inward turning point] that [totally] refracts a downward propagating wave back toward the surface. A *standing wave* is created.

Physically and mathematically, one can understand the oscillation modes using *spherical harmonics*[192]. The determining parameters are

l (the spherical harmonic *degree)*, and
m (the *azimuthal order)*.

Some authors also mention a third parameter, *n* [the ?radial order], but apparently this is not usually applicable here…

A *node* or *nodal line* is a circle on the sphere along which the oscillation is 0—these may be oriented latitudinally or longitudinally (great circles). There are $\ell-|m|$ latitudinally-oriented nodal lines or circles, whereas there are $|m|$ longitudinally-oriented nodal great circles or 2|m| N-S nodal lines.

The p waves have a period of typically 5 min (3.3 milliHz or mHz, range 2 - 7 milliHz). They have amplitudes of hundreds of kilometers at the surface and are readily detectable with Doppler imaging.

The g mode waves have a period of several hours or 0-4 mHz (per RHH and Christensen-Dalsgaard Fig. 3, etc.) They are confined below the convection zone, are thought to have residual amplitudes of only

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185 Ibid.
186 http://soi.stanford.edu/results/heliowhat.html
187 http://gong.nso.edu/info/helioseismology.html
188 Helioseismology:
Christensen-Dalsgaard, J. Helioseismology. *Rev.Mod.Phys.* 74:1073-1129, 2003 [a large review paper]. http://arxiv.org/abs/astro-ph/0207403
189 http://en.wikipedia.org/wiki/Helioseismology
190 http://en.wikipedia.org/wiki/Alfv%C3%A9n_wave
191 http://www.sciencemag.org/cgi/content/abstract/317/5842/1192
192 http://en.wikipedia.org/wiki/Spherical_harmonics

millimeters at the photosphere, and are difficult to detect (see Fig. 1 here[193].) The *buoyancy frequency* is applicable to the atmosphere of the Sun or Earth or to fluid bodies such as oceans, and is expressed by two forms of the Brunt–Väisälä frequency [194].

2D cross-sectional graphs depicting the different rates of rotation of parts of the Sun with respect to Latitude and Depth are given in Fig. 3 of this article[195] and Fig. 1 of this article[196].

Solar Magnetic Field and Babcock's Heuristic Model

The differential rotation of the Sun at varying latitudes is thought to deform what would otherwise be a *poloidal*[197] solar magnetic field into a *toroidal* field. A poloidal pattern is produced by a stationary dipole magnet, or what we observe as the Earth's field, and has radial and longitudinally-oriented (i.e., *meridionally* or North-South oriented) components, but not latitudinally-oriented (azimuthal) components. A *toroidal*[198] field has field lines which have a substantial latitudinally-oriented (East-West) component, and may lack radial components. NASA has produced an interesting movie of the evolution of the Sun's toroidal field[199].

Discussion in this section applies to magnetic fields at the Sun's surface (photosphere) and in somewhat deeper layers (part of convection zone), but not to the magnetic field in the solar wind beyond $4R_{\odot}$ (discussed below).

The 1961 *Horace Babcock Heuristic Model or Theory of the Solar Cycle*[200] (a still incompletely formulated qualitative model, summarized here by RHH) suggests a mechanism for how this differential solar rotation accounts for sunspot dynamics and certain magnetic phenomena. When the frozen-in magnetic **B** fields become sufficiently wound up, forming a toroidal field that becomes twisted and of critical intensity, flux ropes or loops break through the photosphere (from convection and buoyancy), creating bipolar *sunspot groups*, seen first (in the sunspot cycle) at higher latitudes and progressing to lower latitudes close to the equator… The leading spot is the same polarity as the hemisphere of origin, and tends to migrate[201] toward the equator and mingle with and be cancelled out by similar leading sunspots with opposite polarity arising on the opposite side of the equator. According to RHH, some opposite polarity [perhaps from trailing sunspots] migrates toward the poles and contribute to the eventual pole reversal. [The overall pattern of changing magnetic field is depicted here[202], including a useful color Magnetic Butterfly diagram (and a movie). A map of the average polarity by latitude of the surface of the Sun from 1980 to 2000 is included.] The continued differential rotation unwinds the field, so Babcock's process is a kind of relaxation oscillator.

The reversal of the polarity of the Sun's field does not appear to be well understood. According to Hathaway, "The poles end up flipping because these flows [associated with sunspot migration] transport south-pointing magnetic flux to the north magnetic pole, and north-pointing flux to the south magnetic pole."

Spectroscopic and Doppler Measurements of Solar Emissions

Spectral Lines and Hydrogen Series: Doppler measurements of velocities pertaining to the Sun are made on emission and absorption lines arising from electron transitions in various elements[203]. For example, the

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[193] Solar g-mode vibrations:
T.Appourchaux, et al. The quest for the solar g modes. *Astronomy and Astrophysics Review*. Submitted Oct. 2009. http://arxiv.org/abs/0910.0848

[194] http://en.wikipedia.org/wiki/Brunt%E2%80%93V%C3%A4is%C3%A4l%C3%A4_frequency

[195] Helioseismology:
Di Mauro MP. Helioseismology. *Astrophys. Space Sci. Trans.*, 4, 13-17, 2008.
http://www.astrophys-space-sci-trans.net/4/13/2008/astra-4-13-2008.html

[196] http://solarphysics.livingreviews.org/open?pubNo=lrsp-2005-1

[197] http://en.wikipedia.org/wiki/Toroidal_and_poloidal

[198] http://www.encyclopedia.com/doc/1O13-toroidalfield.html

[199] http://svs.gsfc.nasa.gov/vis/a000000/a003500/a003521/index.html

[200] http://en.wikipedia.org/wiki/Babcock_Model

[201] http://solarscience.msfc.nasa.gov/images/BFLY.pdf

[202] http://solarscience.msfc.nasa.gov/dynamo.shtml

[203] http://en.wikipedia.org/wiki/Astronomical_spectroscopy

hydrogen spectrum is described as follows[204]. The *Balmer-alpha* ("Hα") line of the *Balmer series* occurs in hydrogen (according to the Bohr model) for the transition in principle quantum number from n=3 to n′=2. This is the lowest energy and therefore longest wavelength emission in the Balmer series, located in the visible red at 6562.8 Å (656 nm). Other Balmer series transitions arise from transitions from higher starting n values to n′=2, giving H-beta (486 nm), H-gamma (434 nm), H-delta (410 nm), etc., which are in blue and violet regions (and the series continues into ultraviolet). The hydrogen *Lyman series* begins with Lyman-alpha, falling from n=2 to n′=1 (122 nm) and extends to even shorter UV wavelengths. The *Paschen series* (with n′ = 4) is entirely in the infrared.

21 cm Line: An interesting spectroscopic "line" of more general astronomical use (apparently less so in solar spectroscopy) is the *21-cm wavelength line*[205] which is in the radio region of the EM spectrum. "The hydrogen in our galaxy has been mapped by the observation of the 21-cm wavelength line of hydrogen gas. At 1420 MHz, this radiation from hydrogen penetrates the dust clouds and gives us a more complete map of the hydrogen than that of the stars themselves since their visible light won't penetrate the dust clouds. The 1420 MHz radiation comes from the transition between the two levels of the hydrogen 1s ground state, slightly split by the interaction between the electron spin and the nuclear spin. The splitting is known as hyperfine structure[206]."

Doppler Shift: For non-relativistic speeds $v \ll c$ (appropriate for solar study), *Doppler shift*[207] is expressed as approximately (i.e., the major part of a series expansion) as

$\Delta f = -(v_{s,r}/c)f_0 = -v_{s,r}/\lambda_0$, where

$v_{s,r}$ is the velocity of the source relative to the receiver
(negative when the source is moving towards the receiver, positive when moving away)

c is the speed of light (e.g. 3×10^8 m/s for electromagnetic waves in a vacuum)

λ_0 is the wavelength of the transmitted wave in the reference frame of the source.

Solar Wind

The solar wind was suspected from geomagnetic storms, auroral activity, and the pointing away from the Sun of a comet's tail, etc. The solar wind was first directly detected by Soviet spacecraft Luna 1 (1959), 2, and 3, etc. and subsequently by Mariner 2 (1962).

General Properties of the Solar Wind at 1 A.U. (Earth's Orbit)

The following information is primarily taken from *ISP* p. 92-3 or as cited. Many of these quantities are representative averages, but instantaneous values vary widely, especially when associated with geomagnetic substorms and storms.

Electrons number density = 7.1 cm^{-3}
Proton number Density = 6.6 protons cm^{-3}
Proton flux density =~3.0×10^8 protons cm^{-2} s^{-1}
Alpha Particle number density ($^4_2He^{2+}$) number density = 0.25 cm^{-3}
Other positive ions including $^4_2He^+$ and $^3He^{1+}$ have much smaller number density.

Average solar wind flow speed (nearly radial in direction) = 450 km s^{-1} (range is 200 to more than 1000 km s^{-1})
Proton Temp = 1.2×10^5 K
Electron Temp = 1.4×10^5 K
Magnetic induction field (**B**) = 7 nT (7×10^{-5} Gauss; highly variable)
Kinetic energy = 0.6 erg cm^{-2} s^{-1}
Radial momentum flux = 2.6×10^{-9} pascal (mostly carried by the protons)

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204 http://en.wikipedia.org/wiki/Hydrogen_spectral_series
205 http://en.wikipedia.org/wiki/Hydrogen_line
206 http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/h21.html
207 http://en.wikipedia.org/wiki/Doppler_shift

Derived solar wind quantities at 1 A.U. include:
Gas pressure = 30 pPa [computed by $nk(T_p+T_e)$]
Speed of Sound = 60 km s^{-1} (thus solar wind flow speed is highly *supersonic*)
Alfvén speed = 70 km s^{-1} (*ISP*: "comparable to the sound speed")
Magnetic Pressure = 15 pPa (pressure exerted by the magnetic field, which is comparable to the gas pressure)
Proton gyroradius = 80 km
Travel time to Earth = $3.5x10^5$ s (about 4 days)
Kinetic Energy (non-relativistic non-thermal) for solar wind electrons with bulk speed 450 km s^{-1} = 1.15 eV
Kinetic Energy (non-relativistic non-thermal) for solar wind protons with bulk speed = 450 km s^{-1} = 2115 eV

Thus the solar wind is hot, tenuous, almost completely ionized, and fast moving. It holds a weak magnetic field oriented (at 1 A.U.) "in a direction nearly parallel to the ecliptic plane … but at 45° to the line from the sun to the [Earth] observer" (*ISP* p. 93) [MCM: This statement is somewhat misleading and requires clarification provided below under *Geomagnetic Storms* and *Heliospheric Current Sheet*.]

The solar wind carries mass away from the Sun (in all directions) at $1.6x10^{12}$ g s^{-1}, and energy at $1.8x10^{27}$ erg s^{-1}. (which is $<10^{-6}$ of the overall energy flux from the Sun). (*ISP* p. 91-96) "Other stars have much stronger stellar winds that result in significantly higher mass loss rates.[208]"

Origin of the Solar Wind

"The solar wind is a stream of charged particles ejected from the upper atmosphere of the sun. It consists mostly of electrons and protons with energies of about 1 keV… These particles are able to escape the sun's gravity, in part because of the high temperature of the corona, but also because of high kinetic energy that particles gain through a process that is not well understood [MCM: but is thought to include magnetic interactions and *reconnection*]… The Sun's corona … is heated to over a million degrees Celsius. As a result of thermal collisions, the particles within the inner corona have a range and distribution of speeds described by a Maxwellian distribution. The mean velocity of these particles is about 145 km/s, which is well below the solar escape velocity of 618 km/s. However, a few of the particles will achieve energies sufficient … to feed the solar wind. At the same temperature, electrons, due to their much smaller mass, obtain escape velocity and build up an electric field which tends to further accelerate [positive] ions … away from the Sun…. By the 1960s it was clear that thermal acceleration alone cannot account for the high speed of solar wind. An additional unknown acceleration mechanism is required, and likely relates to magnetic fields in the solar atmosphere[209]…"

"Alfvén waves in principle can transfer energy from the Sun's surface up through its atmosphere, or corona, into the solar wind. Because of this, powerful magnetic Alfvén waves in the electrically charged gas near the Sun have always been a leading candidate as a force in the formation of solar wind… In the solar atmosphere, Alfvén waves are created when convective motions and sound waves push magnetic fields around, or when dynamic processes create electrical currents that allow the magnetic fields to change shape or reconnect… Using Hinode's high resolution X-ray telescope, a team … was able to peer low into the corona at the Sun's poles and observe record numbers of *X-ray jets*. The jets are fountains of rapidly moving hot plasma. Previous research detected only a few jets daily. With [spacecraft] Hinode's higher sensitivity, Cirtain's team observed an average of 240 jets per day. They conclude that *magnetic reconnection*, a process where two oppositely charged magnetic fields collide and release energy, is frequently occurring in the low solar corona. This interaction forms both Alfvén waves and the burst of energized plasma in X-ray jets.[210]"

The Slow and Fast Solar Wind Components

"The solar wind is divided into two components, respectively termed the *slow solar wind* and the *fast solar wind*. The *slow solar wind* has a velocity of about 400 km/s , a temperature of $1.4–1.6×10^5$ K and a composition that is a close match to the corona. By contrast, the *fast solar wind* has a typical velocity of 750 km/s, a temperature of $8×10^5$ K and it nearly matches the composition of the Sun's photosphere. The slow solar wind is twice as dense and more variable in intensity than the fast solar wind…

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[208] http://en.wikipedia.org/wiki/Solar_wind
[209] http://en.wikipedia.org/wiki/Solar_wind
[210] http://www.astronomy.com/asy/default.aspx?c=a&id=6377

The *slow solar wind* appears to originate from a region around the Sun's equatorial belt that is known as the "*streamer belt*". Coronal streamers extend outward from this region, carrying plasma from the interior along closed magnetic loops. Observations of the Sun between 1996 and 2001 showed that emission of the slow solar wind occurred between latitudes of 30–35° around the equator during the solar minimum (the period of lowest solar activity), then expanded toward the poles as the minimum waned. By the time of the solar maximum, the poles were also emitting a slow solar wind…

The *fast solar wind* is thought to originate from coronal holes, which are [relatively dark] funnel-like regions of open field lines in the Sun's magnetic field. Such open lines are particularly prevalent around the Sun's magnetic poles. The plasma source is small magnetic fields created by convection cells in the solar atmosphere. These fields confine the plasma and transport it into the narrow necks of the *coronal funnels*, which are located only 20,000 kilometers above the photosphere. The plasma is released into the funnel when these magnetic field lines reconnect.[211]" Details and good diagrams of these coronal funnels may be seen from SOHO/MDI/SUMER data here[212]. RHH states that the main source of the solar wind are the coronal holes.

Another view: "The solar wind streams off of the Sun in all directions at speeds of about 400 km/s… The solar wind is not uniform. Although it is always directed away from the Sun, it changes speed and carries with it magnetic clouds, interacting regions where high speed wind catches up with slow speed wind… The solar wind speed is high (800 km/s) over coronal holes [which are associated with "open" magnetic field lines and are often found at the Sun's poles] and low (300 km/s) over [helmet] streamers . These high and low speed streams interact with each other and alternately pass by the Earth as the Sun rotates…[213]"

Helmet Streamers are "large cap-like coronal structures with long pointed peaks that usually overlie sunspots and active regions. We often find a prominence or filament lying at the base of these structures. Helmet streamers are formed by a network of magnetic loops that connect the sunspots in active regions and help suspend the prominence material above the solar surface. The closed magnetic field lines trap the electrically charged coronal gases to form these relatively dense structures. The pointed peaks are formed by the action of the solar wind blowing away from the Sun in the spaces between the streamers.[214]" Helmet streamers are readily apparent in solar eclipses as prominent glowing streamers with wispy margins[215]. (See also *ISP* p. 117)

In addition to fast and slow components as above, CMEs add transient winds of a wide range of speeds[216].

The Sun's plasma exosphere (which is continuous with the solar wind) and disturbances propagating in it are Super-Alfvénic (i.e., their velocity exceeds the locally prevailing velocity of Alfvén waves).[217,218]

RHH included a diagram showing how the Hakamada-Akasofu-Fry (HAF) Kinematic Solar Wind Model predicts the propagation of disturbances in the solar wind[219] in the outer heliosphere. The normal orderly spiral wave fronts are overtaken by shock events and compression waves etc. propagating at higher speeds. This phenomenon is also depicted in his diagram from Pizzo 1978 for co-rotating and transient flow, and *ISP* p. 124. A flare-associated transient flow may have greater velocity than the solar wind and can create a compression wave with non-radial flow and other discontinuous phenomena.

A good tutorial of these interactions is given here[220]. This PDF includes diagrams of the solar wind arriving at the garden hose angle, the foreshock boundary, the deformation of the magnetosphere, and a 3D diagram of various electrical currents.

Ulysses Solar Orbiting Spacecraft and Polar Observations

The Ulysses spacecraft[221] was active from 1990 – 2009 and was designed in part to study *Solar Wind Observations Over the Poles of the Sun* (SWOOPS). (In diagrams that are referenced below, IMF=*Interplanetary*

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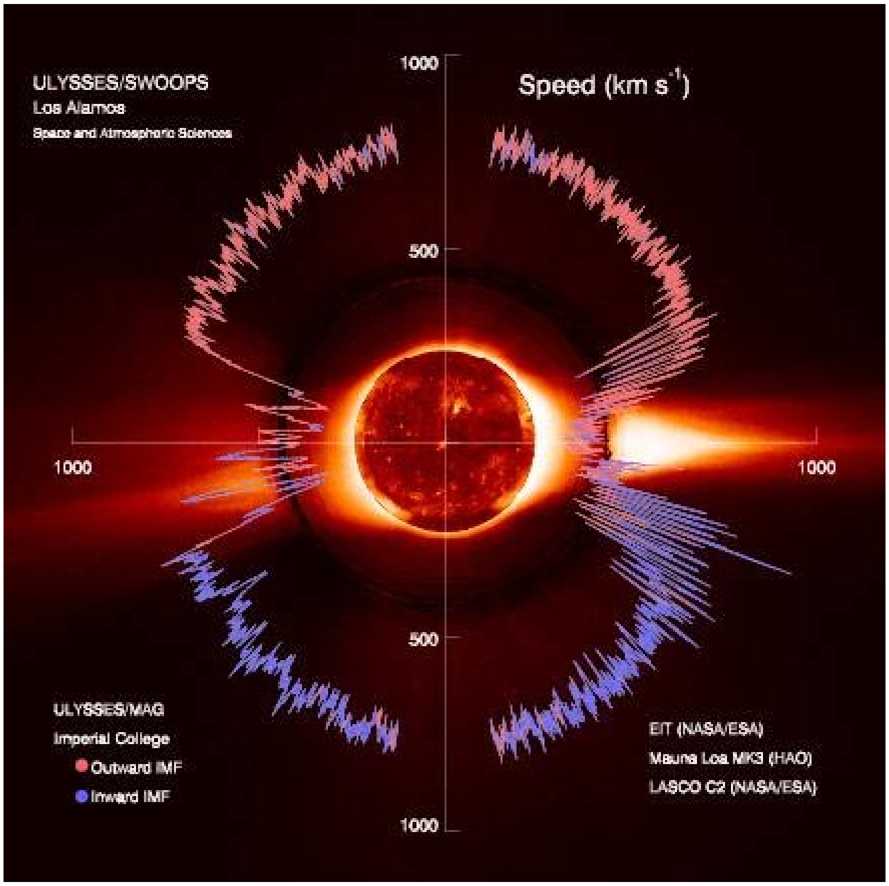
211 http://en.wikipedia.org/wiki/Solar_wind
212 http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=36998
213 http://solarscience.msfc.nasa.gov/SolarWind.shtml
214 http://solarscience.msfc.nasa.gov/feature3.shtml#Helmet%20Streamers
215 http://en.wikipedia.org/wiki/Helmet_streamer
216 http://stereo.nrl.navy.mil/orig_stereo/stereosdtreport.pdf
217 http://www.aanda.org/index.php?option=article&access=bibcode&bibcode=2005A%2526A...440L..29TFUL
218 http://physics.aps.org/articles/v1/42
219 http://adsabs.harvard.edu/abs/2004AGUFMSA51B0237F
220 http://dawn.ucla.edu/ssc/tutorial/solwind_interact_magsphere_tutorial.pdf

Magnetic Field)[222]; LASCO=Large Angle and Spectrometric Coronagraph of SOHO; EIT=Extreme ultraviolet Imaging Telescope of SOHO; SOHO=Solar and Heliospheric Observatory spacecraft.)

Some composite findings pertaining to the solar wind include:

• *Particle Density*: is substantially greater in the equatorial compared to the polar regions[223].
• *Proton Speeds*: are substantially higher (~750 km s^{-1}) in the polar regions compared to the equatorial regions (~300-400 km s^{-1}).
• *Temperature*: The corona is also seen to be considerably hotter above 45 degrees latitude[224] compared to near the equator.



SOLAR WIND SPEED AND IMF ORIENTATION (IN/OUT) AS A FUNCTION OF SUN LATITUDE
(composite data from Ulysses/SWOOPS + EIT & LASCO instruments aboard SOHO + Mauna Loa ground data[225])

Heliosphere and Vicinity

Heliosphere: The *heliosphere* is a bubble in the interstellar medium created by interaction with the solar wind. Rather than having a comet-like shape, the heliosphere appears to be bubble-shaped according to data from Cassini's Ion and Neutral Camera (MIMI / INCA)[226]. Structures encountered in and adjacent to the Heliosphere, travelling from out to in, include:

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[221] Ulysses/SWOOPS spacecraft:
• http://en.wikipedia.org/wiki/Ulysses_%28spacecraft%29 and
• http://swoops.lanl.gov/
[222] http://www.spaceweather.com/glossary/imf.html
[223] http://swoops.lanl.gov/polar_plots/polar_density.html
[224] http://swoops.lanl.gov/polar_plots/polar_temp.html
[225] http://swoops.lanl.gov/lasco_swoops.html
[226] http://www.sciencedaily.com/releases/2009/10/091016101807.htm

Sun Bow Shock: Further out from the Sun than the heliopause is the postulated *bow shock,* a turbulent region caused by the pressure of the advancing heliopause against the interstellar medium (also called the Very Local Interstellar Medium or VLISM). It is at about 230 – 300 A.U.[227] in our Solar System, therefore beyond the Kuiper Belt (which is at 30 – 50 A.U.)[228] No spacecraft has reached this.

[Outer] Heliosheath: "The region inside the bow shock and outside the heliopause.

Heliopause: The solar wind interacts with the *interstellar medium* at the *heliopause*. The heliopause is the outer surface of the heliosphere, the theoretical boundary where the Sun's solar wind is no longer great enough to push back the winds presumably arising from surrounding stars[229]. It is the surface at about 125 – 185 A.U. from the Sun where the interstellar medium and solar wind pressures balance. No spacecraft has yet reached this surface, though Voyager 1 and 2 will eventually cross it.

[Inner] Heliosheath: "The region of the heliosphere inside the heliopause and beyond the termination shock. Here the wind is slowed, compressed and made turbulent by its interaction with the interstellar medium. Its distance from the Sun is approximately 80 to 100 astronomical units at its closest.[230]"

Termination Shock: The *termination shock* is the surface in the heliosphere beyond which the solar wind slows down to subsonic speed (with respect to the stars) due to interactions with the local interstellar medium. Voyager 1 and 2 have both reached this surface at about 94.1 and 83.7 A.U. respectively[231,232]. Although the terminology is sometimes confused in the literature, this is not the same as the postulated and more peripheral bow shock. (See also *ISP* p. 109)

Heliospheric Current Sheet, Parker Spiral, Garden Hose Angle, and Ballerina Skirt

This section discusses the large-scale structure of the magnetic field in the solar wind environment. The orientation of the magnetic field at the Sun's surface, in the corona, and in the solar wind is truly one of the most confusing and difficult topics I have encountered in this course. It is important to make clear the distance from the Sun's surface for which the magnetic field is being modeled and to recognize that a variety of models have been presented at various scales and at various distances from the Sun or Earth. The following discussion ignores the slow changing of the Sun's magnetic field over the 22 year cycle (discussed earlier). Current sheets are also discussed above.

Parker Spiral: The parcels of solar wind initially radiate radially outward from the Sun, but the rotation of the Sun imparts an Archimedean spiral locus to the successive parcels arising from any particular point on the Sun. This spiral is the so-called **Parker Spiral**[233]. The large-scale solar wind structures exhibit the spiral shape, and form an angle with respect to the axis connecting the Sun and Earth of about 45 degrees—an angle termed the **Garden Hose angle.**

B field: The *frozen-in B field*, which is carried along by these plasma parcels, participates in the spiral pattern. "Solar-wind observations accumulated over long time intervals in the mid-1960s indicated that the polarity of the field was organized in a very simple pattern. The field would point predominantly outward from or inward toward the sun (along the average direction of the field lines at ~45° to the radial direction) for about a week at a time and then change in a relatively short time to the opposite polarity. This pattern was found to repeat, with only minor changes, with a period of 27 days. (*ISP* p. 119)". [However, it is somewhat

[227] Heliosphere and Heliopause:
• http://antwrp.gsfc.nasa.gov/apod/ap020624.html and
• http://www.atnf.csiro.au/pasa/17_1/cairns/paper/node1.html
[228] http://solarsystem.nasa.gov/planets/profile.cfm?Object=KBOs
[229] http://en.wikipedia.org/wiki/Heliosphere
[230] http://en.wikipedia.org/wiki/Heliosphere#Heliosheath
[231] http://www.nasa.gov/vision/universe/solarsystem/voyager_agu.html
[232] http://www.planetary.org/news/2008/0710_30_Years_into_its_Journey_Voyager_2.html
[233] http://en.wikipedia.org/wiki/Parker_spiral

oversimplified to say that the magnetic field of the solar wind—also called the IMF—itself assumes an angle at the Earth's magnetosphere of 45 degrees. In fact, it can take on any orientation, discussed further below.] At the Sun's surface, the magnetic field is partially toroidal with a substantial azimuthal component. The polarity reverses at the magnetic equator. The frozen-in magnetic field in the solar wind becomes more and more toroidal and azimuthal (due to the spiraling effect) and thus less radial in orientation as distance from the Sun increases (*ISP* p. 108).

Simple Solar Magnetic Field Model: A very simplified model for the Sun's magnetic field structure in the corona is discussed at *ISP* beginning on p. 104. This calculation assumes a radial orientation for the magnetic field lines as they emerge at the solar surface, an assumption that seems at first glance unrealistic, but read on. The frozen-in B Field lines of the solar wind arising closer to the Sun become more tightly wound with distance. By the time the solar wind reaches the Earth (at 1 A.U.), magnetic field lines frozen in to solar wind plasma are embedded in a spiral configuration, the *Parker Spiral*, which forms an angle with respect to the x-axis connecting the Sun and Earth of about 45 degrees, the so-called *garden hose angle*. (*ISP* p. 108, fig. 4.6). More accurate MHD models present marked computational difficulties (*ISP* p. 110).

Pneuman and Kopp 1971 Model: According to a more complex but still simplified MHD model of the coronal structure (*ISP* p. 114-117 etc., the model of Pneuman and Kopp 1971[234]), the dipolar magnetic field lines form closed loops if they originate at solar latitudes of less than about 45° (above or below the solar equator). However, those arising greater than about 45° are open field lines that may curve around the closed region to some extent but eventually extend far into space in all directions, at least beyond a heliocentric distance of about 2 $R_\odot$. Those lines that arise at approximately 45° skim around the closed field region and then become parallel and *radially directed*, and these nearly meet along the solar dipole equator. The pointed overall pattern that these lines assume resembles a large helmet streamer. Because they have arisen from opposite regions of the dipole, these nearly-equatorial lines must have opposite polarity despite their close proximity. This condition implies a thin interposed region of high electric current density $\mathbf{j} = (1/\mu_0)\nabla\times\mathbf{B}$. The current **j** given by the curl of **B** must be normal to the plane holding the field lines under consideration in this model.

Therefore, a **current sheet** is predicted which encircles the dipole of the Sun (i.e., it is predominantly azimuthally oriented). This current is termed the **Solar-Interplanetary Current Sheet** or the **Heliospheric Current Sheet**[235] or the **Neutral Current Sheet**[236], and it separates the fields and plasma flows that originated from opposite ends of the dipole field. The Heliospheric Current Sheet extends far into space and is the surface—corresponding to the Sun's magnetic equator—within the Solar System where the polarity of the Sun's magnetic field abruptly changes direction. The plane of the oscillating heliospheric current sheet is likened to an undulating **ballerina's skirt**—it assumes a 3-D spiral shape called the *Parker Spiral*[237]. "The heliospheric current sheet rotates along with the Sun once every 27 days, during which time the peaks and troughs of the skirt pass through the Earth's magnetosphere, interacting with it....[238]" It is this structure especially that I refer to as a large-scale structure in the solar wind environment. "A small electrical current flows within the sheet, about 10^{-10} A/m². The thickness of the [heliospheric] current sheet is about 10,000 km.[239]" However, the amplitude of the oscillations in the ballerina skirt are much greater.

Evidence for the Undulating Ballerina Skirt: The IMF encountered at 1 A.U. at the Earth is discussed further below. RHH presented a slide of 1979 data (origin unknown) showing how the IMF abruptly changes in $\mathbf{B_Z}$ and in the direction given by the Phi angle, the latter abruptly changing from values fluctuating around 135 degrees to values fluctuating around 315 degrees and then back again, during the 27 day solar rotation cycle. RHH states that phi is an angle in the plane perpendicular to $\mathbf{B_Z}$ that contains the GSM-x axis—phi is the angle formed between the **B** field component projected in this plane and the GSM-x axis. He states that this data demonstrates the ballerina skirt phenomenon whereby the Earth is exposed to abrupt changes in IMF polarity as the Sun rotates.

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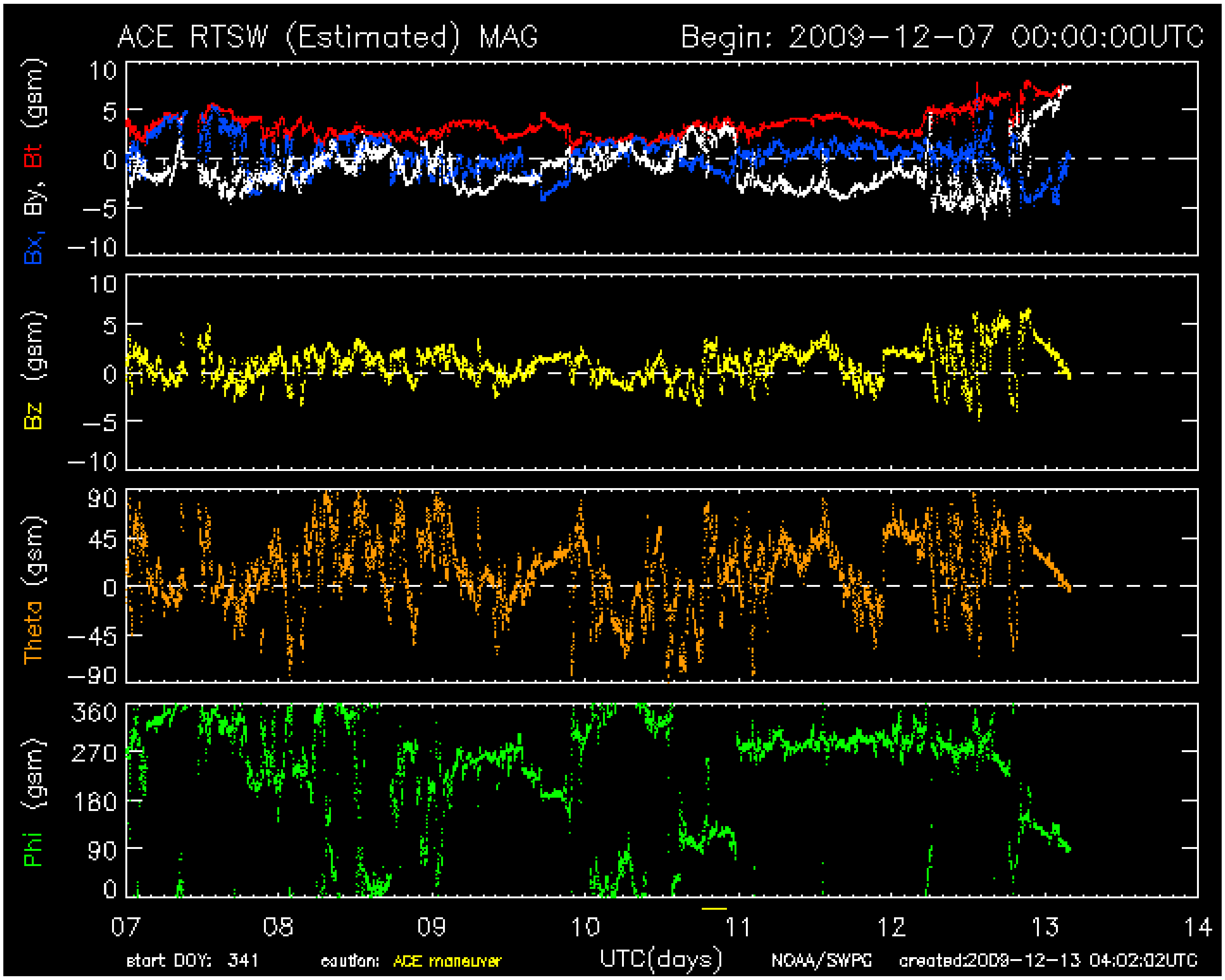
[234] Pneuman GW, Kopp RA. "Gas-Magnetic Field Interactions in the Solar Corona" *Solar Physics*, Volume 18, Issue 2, pp.258-270.
[235] Heliospheric current sheet:
• http://www.aanda.org/articles/aa/pdf/2001/34/aah2814.pdf and
• http://en.wikipedia.org/wiki/Heliospheric_current_sheet
[236] http://helios.gsfc.nasa.gov/gloss_op.html
[237] http://en.wikipedia.org/wiki/Parker_spiral
[238] http://en.wikipedia.org/wiki/Heliospheric_current_sheet
[239] ibid.

Recent solar wind **B** data may be seen in the current ACE (Advanced Composition Explorer) data plots[240]. The graphs shown below use GSM data: B_X, B_Y, B_Z, B_T (total magnetic field), Theta (GSM latitude), and Phi (GSM longitude). RTSW = Real Time Solar Wind. The GSM coordinate system parameters are defined in the footnotes. Phi can be seen to vary dramatically in the sample plot below, but the magnetic field strength is rather modest:



Sample 7-day plot of ACE real-time solar wind magnetic field orientation and magnitude data (Explained and source cited above; NOAA 2009)

The Radial Heliospheric Current Sheet Component: Although the simpler model predicts an azimuthal current, analysis based on a more complex simulation concludes: "Another consequence of solar rotation and magnetic field line twisting was predicted by Alfvén (1981). The spiral form of the magnetic field lines means that there is a significant *radial* component of the electric current in the sheet, along with the azimuthal component… The only way to satisfy the electric current continuity is to close the radial electric current by field-aligned currents at the polar region of the sun. The total strength of the *radial* current is ~3×10^9 amperes.[241]" [Note: The article in Wikipedia as of 12/7/2009 on the Heliospheric Current Sheet incorrectly

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[240] Solar Wind magnetic field orientation and strength measured by ACE:
• http://www.ssg.sr.unh.edu/mag/ACE.html Home page
• http://www.swpc.noaa.gov/ace/MAG_7d.html Recent 7 day plot
• http://www.srl.caltech.edu/ACE/ASC/browse/browse_info.html#mag Defines coordinates as:
B_{gsm} z = Z-component of magnetic field, in GSM coordinate system
B_{gsm} phi (GSM Longitude) = The angle in degrees with 0 at B_x and + toward B_y (0 to 360 degrees)
B_{gsm} theta (GSM Latitude) = The angle in degrees with 0 at B_x/B_y plane and + toward B_z (-90 to +90 degrees)
[241] http://www.aanda.org/articles/aa/pdf/2001/34/aah2814.pdf

quoted this article's estimate of radial current as being the total sheet current.[242] I have not yet found a clearly valid estimate of the total current sheet current, and none is provided in the 1971 Pneuman and Kopp article.]

Outside the termination shock, the orderly spiral structure in the expanding solar wind appears disrupted by turbulent flow in the heliosphere. (See RHH slide labeled "Figure 5.2 One possible model of the heliosphere", source unstated.)

Cosmic Rays and Their Connection with Sunspots and Atmospheric Ionization

For general summaries on cosmic rays, see these sources[243]. The level of sunspot activity (and solar wind intensity) correlate inversely with cosmic ray flux as monitored by neutron detectors such as the Climax Neutron Monitor (located in a high altitude underground mine near Leadville, Colorado)[244]. Cosmic rays are mostly protons (90%) and alpha particles (~10%), with <1% being heavier nuclei and electrons. Those of moderate energy are readily deflected by the magnetosphere. "When the number of sunspots is high, the galactic cosmic ray flux is low, and vice versa.[245]" Cosmic rays also exhibit "Forbush decreases" (named for Scott Forbush) as a result of solar CMEs, an effect that can be observed near-simultaneously at widely separated sites on Earth.

The term "Cosmic ray" is a misnomer because they usually are single particles, not rays. A single galactic cosmic ray particle can have energy in excess of 10^{20} erg. (One cosmic ray particle, probably a proton, had energy of $3x10^{20}$ eV, equivalent to the KE of a 142 g hardball baseball traveling at 96 km/h.) Such extremely high energy cosmic rays are not deflected by the magnetic field. However, the energy of most cosmic rays is between 10^7 eV and 10^{10} eV.[246] [A graph[247] shows a steady decrease in flux density of cosmic rays over the range of 10^9 to 10^{20} eV.]

Atmospheric Ionization: The ionosphere is said to owe its ionization to solar EUV and solar X-rays, though "during the night cosmic rays produce a residual amount of ionization.[248]" A slide shown by RHH (origin unknown) shows a steady rise of electron number density in #/cm^3 from 50 to about 250 km or 300 km. The number density over this range drops substantially during the night.

Cosmic rays are the primary source of ions in the atmosphere of the Earth below 50 km[249,250]. According to an RHH slide presenting Neher's data, the peak rate of cosmic ray ionization below 50 km appears to be about 50 ions cm^{-3} s^{-1}, occurring at an altitude of about 15 km, and this peak rate is maximal at times of minimal sunspot activity, and also greater at higher compared to lower latitudes. This peak rate of ion production corresponds with the peak ion number density[251] over the same altitude range below 50 km. An RHH slide labeled "Fig. 1. Schematic Representation of the atmospheric ionized component" (origin unknown) shows a relative peak in the charged particle concentration at about 15 – 20 km in the Cosmic Ray Layer with a value by inspection of around 8,000 charged particles cm^{-3}. (In contrast, the lowest or "D" layer of the *ionosphere* is above 50 km.)

Energy Fluxes Incident on the Earth: The energy fluxes at the Earth (presumably at the edge of the atmosphere) according to RHH are (rounded and slightly modified)

Sunlight:	$1.4x10^6$ ergs cm^{-2} s^{-1}	(converted from 1366 w m^{-2})
Cosmic Rays:	$3.0x10^{-3}$ ergs cm^{-2} s^{-1}	(same value is given here[252])

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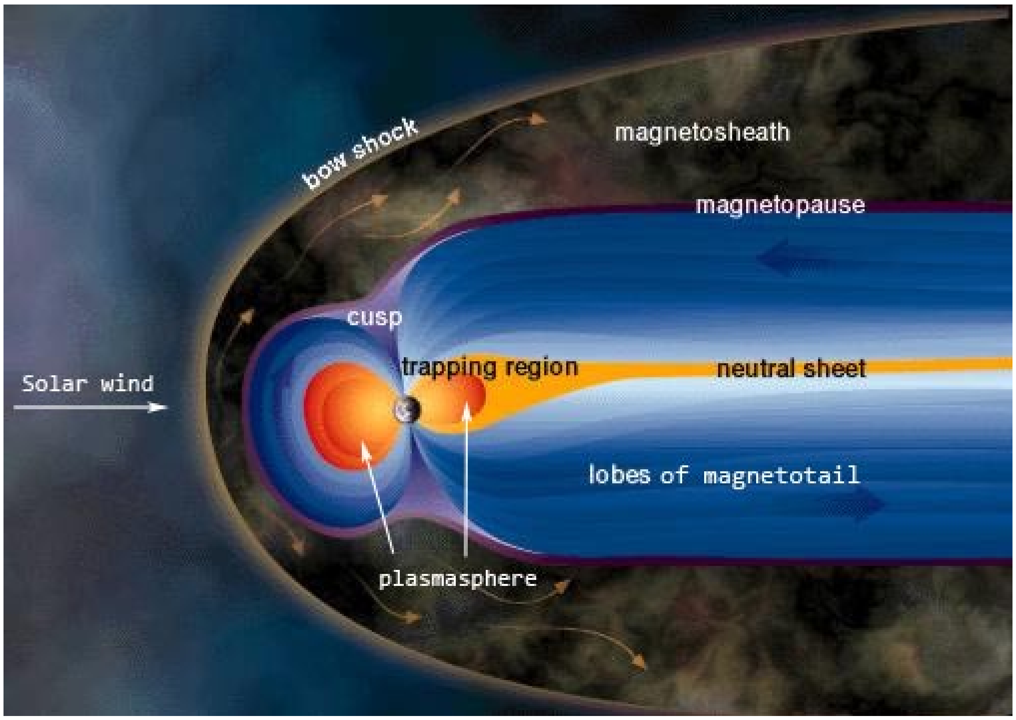
242 http://en.wikipedia.org/wiki/Heliospheric_current_sheet
243 Cosmic Rays:
• http://imagine.gsfc.nasa.gov/docs/science/know_l1/cosmic_rays.html and
• http://en.wikipedia.org/wiki/Cosmic_ray
244 Cosmic rays versus Sunspot activity:
• http://ulysses.sr.unh.edu/NeutronMonitor/Misc/neutron2.html and
• http://sgd.ngdc.noaa.gov/sgdpdf/0203/Cosmic_Ray_Means_Climax_0203.pdf
245 http://se.crd.yerphi.am/Solar_Wind__Heliosphere__and_Cosmic_Ray_Propagation
246 http://en.wikipedia.org/wiki/Ultra-high-energy_cosmic_ray
247 http://www.chicos.caltech.edu/collaboration/education/spectrum.html
248 http://en.wikipedia.org/wiki/Ionosphere
249 http://ecrs2008.saske.sk/dvd/s1.14.pdf
250 http://www.nap.edu/openbook.php?record_id=898&page=167
251 http://www.nap.edu/openbook.php?record_id=898&page=167
252 http://www.accessmylibrary.com/article-1G1-92139392/energy-flux-cosmic-rays.html

Starlight:	1.8x10^{-3} ergs cm^{-2} s^{-1}	(cf. 1.8×10^{-2} erg cm^{-2} s^{-1} computed here [253] for our galaxy)
Nebular light:	1.8x10^{-5} ergs cm^{-2} s^{-1}	(cf. 3.5×10^{-5} erg cm^{-2} s^{-1} Ibid. for external galaxies)
Radio waves:	5.0x10^{-8} ergs cm^{-2} s^{-1}	(not sure if this is solar radio flux or where measured etc.)

Earth's Magnetosphere, Interaction with Solar Wind, and Electric Currents

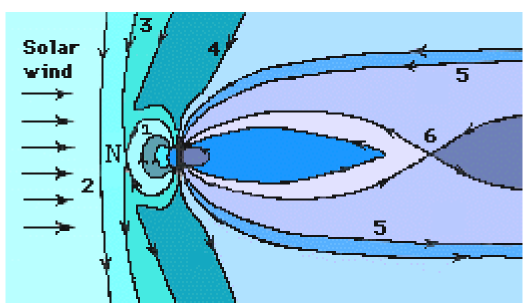
This is a very complex topic which I have partly reviewed only qualitatively. The many components and interactions of the magnetosphere are difficult to separate into neat subtopics. The various electrical currents present in the magnetosphere and ionosphere are mentioned at several locations—search for '*current*' to see all descriptions. Magnetic reconnection plays a major role in the magnetospheric phenomena.



Earth Magnetosphere and Environs

Diagram showing arriving solar wind; bow shock; magnetosheath (with turbulent particle flow [yellow]); magnetopause [purple] bounding magnetosphere [mostly blue]; polar cusps; magnetotail Lobes [blue]; plasmasphere and radiation belts [red-orange]); and neutral sheet [yellow]

(NASA/ESA 2004, modified by MCM[254])



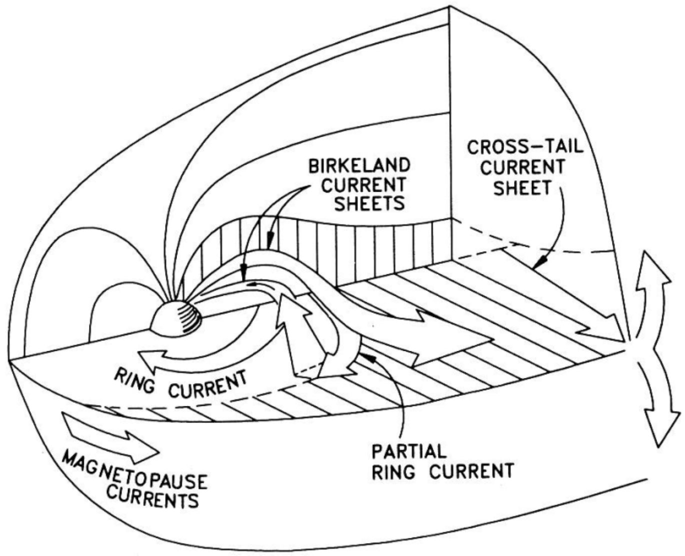
Magnetospheric magnetic reconnection

Diagram showing reconnection occurring at the Sun side "N", and in the magnetotail at the neutral line labeled "6" (NASA, 2001)[255]

[253] Starlight intensity:
J Pecker and J Narlikar. "Stellar and extragalactic radiation at the Earth's surface". Journal of *Astrophysics and Astronomy*. Volume 27, Number 1 / March, 2006

[254] http://www-istp.gsfc.nasa.gov/istp/outreach/theretohere.html

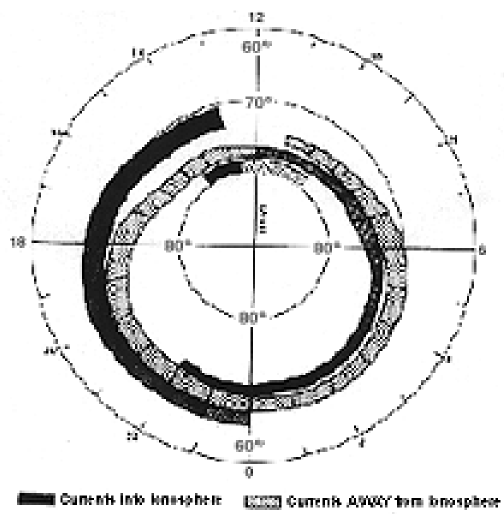
[255] http://www-istp.gsfc.nasa.gov/Education/wtail.html



Magnetospheric Electric Current Sheets

Sketch of various electric currents including Birkeland field-aligned currents flow from/to the magnetotail and ionosphere (NASA, 2006[256])

(See also earlier image, page 3)



Current Sheets in the Circumpolar Ionosphere

NASA Triad spacecraft data mapping the average "footprints" of field-aligned current sheets in the polar ionosphere, including their intricate overlap of flows in opposite direction at midnight ("0"). Sunward is at top, magnetic pole at center, black is current entering the ionosphere from above, gray is current exiting the ionosphere to space.
(NASA 2001[257], further discussed below)

Coordinate Systems and Display Orientations: The Earth's magnetosphere is often and preferentially represented in the *Geocentric Solar Magnetospheric (GSM)*[258] coordinate system. It is shown in the GSM either

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[256] Magnetospheric currents:
http://en.wikipedia.org/wiki/File:Currents.jpg (public domain NASA image by David P. Stern)

[257] http://www-spof.gsfc.nasa.gov/Education/wcurrent.html

[258] GSM Coordinate Systems:
• http://sscweb.gsfc.nasa.gov/WebServices/1/public/api/gov/nasa/gsfc/spdf/ssc/CoordinateSystem.html: The Geocentric Solar Magnetospheric (GSM) Coordinate System "has its X-axis from the Earth to the Sun. The Y-axis is defined to be perpendicular to the Earth's magnetic dipole so that the X-Z plane contains the dipole axis. The positive Z-axis is chosen to be in the same sense as the northern magnetic pole." and
• *ISP* p. 536-7: When the north magnetic pole is tilted toward the sun, the *dipole tilt angle* is termed positive. This coordinate system "rocks about the solar direction with a 24-hr period" as well as a 24 yearly period
• See http://www.spenvis.oma.be/spenvis/help/background/coortran/coortran.html#GSM for an animation.

viewed in the so-called *noon-midnight meridian plane* (with Earth's N at top, S at bottom, tail usually to the right), or in an "*equatorial view*" seen from well above the North polar region (a view which appears to be usually defined loosely). Note that in the GSM system, the magnetic dipole axis of the Earth is not oriented perpendicular to the X_{GSM} axis or parallel to the Z_{GSM} axis, but lies in the X-Z plane.

The Earth's magnetic field vector **B**(F) of the dipole magnetic field at the surface may be said to have magnitude F. It can be expressed as the vector sum of orthogonal *geographic* components (which are not the same as GSM coordinates, a potential source of confusion):
• **Z** (vector component pointing to Earth's geographic rotational center).
• **X** (vector component pointing to the geographic North, perpendicular to **Z**),
• **Y** (vector component pointing to geographic East, perpendicular to **Z** and **X**), and

The Earth's local magnetic field vector **B**(F) may also be expressed by:
• **H** (the horizontal field component, in a plane perpendicular to **Z** defined above and therefore locally tangent to the Earth's surface at the point of measurement, a component which is the vector sum of **X** and **Y** vector components defined above),
• *Declination D* (the angle in the horizontal plane formed between **H** and **X**), and
• *Inclination I* (the angle formed between the horizontal field component **H** and **B**.) (*ISP* p. 403)

Solar-Quiet (Sq) Variation: There is a normal diurnal variation in the **X**, **Y**, and **Z** components of B termed the *Solar-Quiet variation* or *S_q variation* which depends on local time and latitude. (The term "quiet" refers to a baseline level of activity when no storms or substorms are present.) Graphs depict two vortices ("cells") of current circulation on the day side of the Earth, rotating around foci located at about 30 degrees magnetic latitude (*ISP* fig. 13.4 and also here[259]). *S_q variation* is thought to arise from the ionospheric equatorial electrojets whose positions are fixed with respect to the Sun but below which observing Earth stations move into and out of position by Earth's rotation. They are related to solar heating of and resulting winds in the ionosphere (*ISP* p. 404-5)…

Earth's Magnetic B Field Strength: The strength of the intrinsic **B** field at the Earth's surface ranges from less than 30 microteslas = 30,000 nT = 0.3 gauss in the region of the magnetic equator, to over 60 microteslas = 60,000 nT = 0.6 gauss around the magnetic poles[260].
The Earth's dipole field strength, like other dipole fields (ignoring distortions caused by the solar wind), falls off approximately as the inverse cube of the distance[261], in contrast to the inverse square falloff of gravitational or electrical field strength from a point mass or charge.

Magnetosphere: This is the region in space dominated by the magnetic field of the Earth (or correspondingly of another magnetized planet). Structures encountered in and adjacent to the Earth's magnetosphere, from out to in, include the following:

Earth's Foreshock: "Earth's foreshock … is the region upstream from the bow shock that is downstream of the 3-D bundle of magnetic field lines tangent to the shock.[262]" (See also a good diagram including spiraling wavefronts here[263] as well as *ISP* appendix 5b depicting non-overlapping electron and positive ion foreshock regions.)

Earth Bow Shock: "In a planetary magnetosphere, the bow shock is the boundary at which the speed of the solar wind abruptly drops as a result of its approach to the magnetopause. The best-studied example of a

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259 http://geomag.usgs.gov/intro.php#ionosphere
260 http://en.wikipedia.org/wiki/Earth%27s_magnetic_field
261 Magnetic dipole field falloff as inverse cube:
• http://blazelabs.com/inversecubelaw.pdf and
• http://en.wikipedia.org/wiki/Magnetic_moment
262 http://www.atnf.csiro.au/pasa/17_1/cairns/paper/node4.html
263 http://www.atnf.csiro.au/pasa/17_1/cairns/paper/node1.html

bow shock is that occurring where the solar wind encounters the Earth's magnetopause, although bow shocks occur around all magnetized planets. The Earth's bow shock is about 100-1000 km thick and located about 90,000 km (55,923 miles) from the Earth [i.e., at about 13 - 14 R_E]. The defining criterion is that the bulk velocity of the fluid (in this case, the solar wind) drops from 'supersonic' [i.e., *super-Alfvénic*] to 'subsonic'. The particles making up the solar wind follow spiral paths along magnetic field lines... At the bow shock, the bulk forward velocity of the wind (which can be seen as the velocity of the points [guiding centers] on the field lines about which the particles gyrate) drops below the speed at which the particles are corkscrewing.[264]"

This bow shock is an example of a *collisionless shock* for which electrons and positive ions may have different temperatures, etc. (see above and *ISP* chapter 5).

The bow shock and the magnetopause change in shape and in distance to Earth with solar CMEs, see for example the movie of data from July 14, 2000 the ACE spacecraft (per RHH) here[265].

Earth Magnetosheath: The region of space between the bow shock and the magnetopause of a planet's magnetosphere. "The regularly organized magnetic field generated by the planet becomes weak and irregular [turbulent] in the magnetosheath due to interaction with the incoming solar wind, and is incapable of fully deflecting the highly charged particles [in contrast to the magnetopause]. The density of the [incoming] particles in this region is considerably lower than what is found beyond the bow shock, but greater than within the magnetopause...[266]"

Earth Magnetopause: "The outermost boundary of the region controlled by [or dominated by] a planet's magnetic field. It separates the magnetosheath [beyond] and the magnetosphere [within]. It is the location where the outward magnetic pressure of a planet's magnetic field is counterbalanced by the pressure of the solar wind plasma[267]." Its distance from the Earth on the Sun side is about 10 R_E.

Magnetosphere Reconnection, Currents Sheets, and the Magnetotail (Geomagnetic Tail): "Reconnection is the primary means by which distinct plasma regions are able to interact and exchange mass, momentum, and energy (*ISP* p. 284)." Magnetic reconnection occurs initially at the sunward (dayside) forward edge of the magnetopause as it interacts with the incoming solar wind (*ISP* p. 243).

A net electric charge current arises at the magnetopause because (according to a simple model) Lorentz-deflected protons have greater inertia than deflected electrons... (*ISP* fig. 9.2 p. 230). In the sunward dayside "nose" part of the magnetopause (i.e., the part located closer to the Sun than the *cusp*[268] region of the Earth's field), the current flows eastward or toward dusk (as expected for the Lorentz force on protons) when facing away from the Sun (i.e., it flows counterclockwise when viewed down from above the magnetic equatorial plane). This is the so-called *Chapman-Ferraro current* (*ISP* p. 229 and 289). RHH states, "Most solar wind plasma reflects off earth's B-field and flows around [in the form of the] Chapman-Ferraro current." There are also *Birkeland field-aligned currents* (see below), as well as *ring currents* and *partial ring currents* (which flow essentially clockwise when seen from above the magnetic equatorial plane, *ISP* p. 289 and p. 409 and see below).

The *Partial ring current* "flows near the equatorial plane principally near dusk, closing through the ionosphere, to which it is linked by field-aligned currents..." (*ISP* p. 409). The partial ring segment of the current is centered at midnight (Wolf 2007, figs. 3 and 7). However, "the basic shape of the main-phase partial ring current in Earth's inner magnetosphere ... is difficult to establish through in situ measurements by a single spacecraft. (Wolf 2007, p. 298)" and theoretical modeling appears to remain in flux.

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[264] http://en.wikipedia.org/wiki/Bow_shock
[265] Fluctuations in magnetopause and bow shock during geomagnetic storms:
• http://pixie.spasci.com/DynMod/movie20000715shue.gif and
• http://pixie.spasci.com/DynMod/mpbs20000714_15.html
[266] http://en.wikipedia.org/wiki/Magnetosheath
[267] http://en.wikipedia.org/wiki/Magnetopause
[268] Magnetosphere charged particle motion:
• http://en.wikipedia.org/wiki/Magnetosphere_particle_motion and
• http://www-spof.gsfc.nasa.gov/Education/wmpause.html

Substorm currents are "a diversion of the tail current that also links into the ionosphere through field-aligned currents (*ISP* p. 409)."

The *geomagnetic tail* is an extensive region that expands downwind from the Earth to a maximum diameter of about 60 R_E (thus, its radius equals 30 R_E) attained at a distance from Earth of about 150 R_E and continuing at least to 200 R_E. The position of the tail fluctuates in the GSE-y direction by at least its own radius, thus by about 30 R_E (*ISP* p. 236, where GSE = Geocentric Solar Ecliptic coordinate system). On the magnetopause N and S surfaces is an eastward current (dusk to dawn looking sunward, *ISP* p. 229). The tail is divided into *North* and *South lobes*, which are separated by a *plasma sheet*. Embedded in this plasma sheet is the *cross-tail [cross tail] [neutral sheet] current* (*ISP* p. 229 and 289), which is moving westward as one faces the Sun from the tail (i.e., from dawn to dusk). It carries 10^6 A for each 5 R_E increase in distance from the Earth. It forms by *magnetic reconnection* where opposing magnetic flux lines are annihilated or become "cut" and "reconnected" (*ISP* p. 239-43). This sheet current completes the circuit for the currents flowing to the east (dusk to dawn) along the magnetopause boundaries of the North and South lobes of the magnetotail. (See *ISP* chapter 9 and fig. 1.18 for more details.)

According to RHH and *ISP* p. 242-3 and 292, reconnection in the tail closes the current cycle and injects heated plasma into the inner magnetosphere. When this current is diverted toward the Earth, it may help to explain the ionospheric *auroral electrojet* currents observed during *substorms* (*ISP* p. 234). Another source states, "The extended magnetotail results from energy stored in the planet's magnetic field. At times this energy is released and the magnetic field becomes temporarily more dipole-like. As it does so that stored energy goes to energize plasma trapped on the involved magnetic field lines. Some of that plasma is driven tailward and into the distant solar wind. The rest is injected into the inner magnetosphere where it results in the aurora and the ring current plasma population. The resulting energetic plasma and electric currents can disrupt spacecraft operations, communication and navigation.[269]"

"...It was estimated that about 1-2% of the solar wind energy impinging on the magnetopause cross-section is tapped by internal processes of the magnetosphere. In the neutral atmosphere of the Earth, energy is usually transmitted by two mechanisms: by large-scale circulating flows which *convect* heat from the ground upwards, and by radiation which takes a more direct path. The magnetosphere, too, may transmit energy both by *convective flows* and by a more direct route, involving field-aligned currents.[270]"

The small electric **E**-field of the distant magnetotail was studied using Apollo 15 and 16 subsatellites in orbit about the Moon (therefore approximately 62 R_E from Earth), looking at E-cross-B drift of electrons as the Moon's shadow region was entered... Values of 0.02 mV/m (the lower limit of sensitivity of the method) to 2 mV/m were found, with a typical value being 0.15 mV/m, and these values were said to agree with the prevailing model of the magnetosphere[271].

[The region of the tail lobes] "is almost empty of plasma—typical density 0.01 ion/cubic cm., the 'best vacuum' in the Earth's vicinity—but it contains a relatively strong magnetic field which, since it fills a large volume, can store appreciable magnetic energy. Many believe that this is the storehouse from which substorms draw their energy, releasing it quite rapidly. Further down the tail the plasma density increases, as ions from the boundary layers infiltrate the lobes.[272]"

Open and Closed Magnetosphere Models: The *Chapman-Ferraro closed magnetosphere model*[273] from the 1930s allowed no mixing of magnetic field lines in the solar wind and the magnetosphere. The B field embedded in the solar wind near the Earth has a strength of about 5-7 nanoteslas (nT). This is a weak field compared to that at the Earth's surface (30,000-60,000 nT or 0.3-0.6 G). Nevertheless, in this model, when the solar wind and magnetosphere meet, they "do not mix, but instead they form distinct regions separated by a thin boundary. The solar wind thus confines the Earth's magnetic field to a cavity surrounding the planet, forming the Earth's magnetosphere... A sheet of electrical current must flow in the plasma in this interface, called the Chapman-Ferraro current... Across the [bow] shock the flow is slowed, compressed, and heated, forming a layer of turbulent plasma outside the magnetopause called the magnetosheath. Inside the [magnetospheric] cavity... the terrestrial plasma will approximately rotate with the Earth ... because the

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[269] http://en.wikipedia.org/wiki/Magnetosphere
[270] http://www-spof.gsfc.nasa.gov/Education/bh2_4.html
[271] http://adsabs.harvard.edu/abs/1975JGR....80.3217M
[272] http://www-spof.gsfc.nasa.gov/Education/wms2.html
[273] http://www.agu.org/sci_soc/cowley.html

Earth's field lines are frozen into the ionospheric plasma." In this closed model, only at the *cusp* is there a potential route for solar wind particles to enter the magnetosphere.

In contrast, the now more widely accepted *Dungey open magnetosphere model* (discussed here[274], see also *ISP* p. 243) improves on the closed model. It has the geomagnetic and interplanetary magnetic fields join together by *magnetic reconnection*, both at the sunward "nose" of the magnetosphere and in the tail. This provides a mechanism for the injection of energetic solar wind plasma into the magnetosphere and ionosphere... The large-scale bulk flow of magnetospheric plasma away from and back toward the Earth that is driven by the solar wind and reconnection is termed *convection*, a term which arose in connection with the *double-vortex flow pattern* seen in the auroral zone (see *ISP* fig. 9.11 and here[275]). The double-vortex flow pattern loosely resembles the swirling vortex pattern seen with thermal convection, but is unrelated to it. The ionosphere "develops twin flow vortices with open field lines that flow away from the Sun over the polar cap and closed field lines that flow toward the Sun at lower latitudes. Typical ionospheric flow speeds are several hundred meters per second... The most important feature of the magnetosphere-ionosphere flow, however, is that its strength is modulated by variations in the direction and strength of the interplanetary magnetic field [in the solar wind]." [MCM: I find this model and the discussion of it difficult to understand.] According to RHH, the magnetospheric convection of Dungey begins in the nose of the magnetosphere and closes in the tail, "making a complete circulation pattern, allowing solar wind plasma and energy to enter the magnetosphere".

Field-Aligned Currents (Birkeland Currents and Current Sheets): In contrast to the *Chapman-Ferraro current* on the magnetopause (which is oriented generally perpendicular to Earth's **B**), the field aligned currents move along magnetospheric **B** field lines. "A *Birkeland current* is a specific magnetic field aligned current in the Earth's magnetosphere which flows from the magnetotail [cross-tail current] towards the Earth on the dawn side and in the other direction on the dusk side of the magnetosphere. [MCM: This proves to be an oversimplified view, see below, but is the model depicted in a simple RHH slide.] Lately, the term *Birkeland currents* has been expanded by some authors to include magnetic field aligned currents in general space plasmas. [These currents] ... create the aurora borealis and australis. The currents are closed [i.e., the circuit completed] through the *auroral electrojet*, which flows [roughly] perpendicular to the local magnetic field in the ionosphere. Auroral Birkeland currents can carry about 1 million amperes... They can heat up [and expand] the upper atmosphere which results in increased drag on low-altitude satellites[276]." "Electrojets are Hall currents carried primarily by electrons at altitudes from 100 to 150 km. In this region the electron gyro frequency (Larmor frequency) is much greater than the electron-neutral collision frequency.[277]"

"When separated into categories depending upon their scale size and interplanetary conditions, the Birkeland currents can be described in terms of specific patterns. For example, the large-scale (spatial features larger than 50 km) Birkeland currents persist in predictable patterns when the interplanetary magnetic field (IMF) is either strongly northward or southward [i.e., B_Z, the Z_{GSM} component, dominates]. When the IMF is southward, the Birkeland currents flow in two concentric circles around the geomagnetic pole often referred to as 'region 1' (at the poleward [inner] side) and 'region 2' at the equatorward [outer] side. The *region 1* Birkeland currents flow into the auroral zone on the [dawn and] morning side and away from the auroral zone on the afternoon [and dusk] side. The 'region 2' Birkeland currents flow in opposite directions of the 'region 1' system [i.e., into the ionosphere on the afternoon/dusk side and out on the dawn/morning side]. During periods of strongly northward IMF [B_Z, the Z_{GSM} component, dominates and is directed northward], a different large-scale Birkeland current system dominates in the sunlit polar region which has been referred to as the 'NBZ' [i.e., Northward B_Z] system. These general patterns appear to exist over a wide range of geophysical conditions, indicating that they are related to a fundamental coupling process between the Sun and Earth[278]." A model for explaining Birkeland currents is presented in *ISP* p. 321-2.

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[274] Closed vs. open magnetosphere models:
• http://ion.le.ac.uk/education/magnetosphere.html and
• http://www-spof.gsfc.nasa.gov/Education/wmpause.html and
• http://www.agu.org/sci_soc/cowley.html
[275] http://www-spof.gsfc.nasa.gov/Education/bh2_4.html
[276] http://en.wikipedia.org/wiki/Birkeland_current
[277] http://en.wikipedia.org/wiki/Electrojet
[278] Potemra TA. "Birkeland currents in the earth's magnetosphere". *Astrophysics and Space Science*, vol. 144, no. 1-2, May 1988.

According to RHH, at regions of E field reversals (the separatrix between open and closed polar region field lines), a charge distribution builds up which drives Region 1 currents… (I have not mastered these details.) Region 2 currents according to RHH result from partial ring currents leading to buildup of positive charge at dusk and negative charge at dawn, causing a current to flow down on the dusk side and up on the dawn side.

Birkeland currents were inferred by explorer and physicist Kristian Birkeland in 1908, along with *auroral electrojets*. Birkeland discovered that when the aurora appeared, the needles of magnetometers were deflected, indicating a flowing electric current overhead.

It was later inferred that large electric currents in the ionosphere associated with auroras flowed in the east to west directions along the auroral arc from the dayside towards midnight, and these were later named '*auroral electrojets*'...[279] These auroral electrojets did not simply follow a straight line return path over the pole to connect up the incoming and outgoing Birkeland current sheets. Instead, as the 1973 navy satellite Triad reported, the current "found an alternate way: it flowed in the ionosphere a few hundred miles equatorward and then headed out again to space.[280]" MCM: In fact, a complex footprint of clockwise and counterclockwise large-scale current flows were found in the polar ionosphere, centered roughly about the magnetic pole and intricately overlapping at midnight. (See diagram above and on the webpage last cited, taken from 1976 Triad data reported by Iijima and Potemra, and also *ISP* p. 303, and here[281].) The ionosphere electrical currents are seen to flow in directions that connect up the downward with the upward Birkeland currents (ISP fig. 10.18a and 10.18c).

RHH showed a slide indicating that magnetospheric tension along magnetic field lines is given by the *Maxwell Stress Tensor* (see above). Slides of parallel electric fields and electrojets in the northern auroral zone were also shown (which I do not quite understand). Apparently the field-aligned currents become complex and disordered during substorms.

"Bright auroras are generally associated with Birkeland currents ... which flow down into the ionosphere on one side of the pole and out on the other. In between, some of the current connects directly through the ionospheric E layer (125 km); the rest ("region 2") detours, leaving again through field lines closer to the equator and closing through the "partial ring current" carried by magnetically trapped plasma. The ionosphere is an ohmic conductor, so such currents require a driving voltage, which some dynamo mechanism can supply. Electric field probes in orbit above the polar cap suggest voltages of the order of 40,000 volts, rising up to more than 200,000 volts during intense magnetic storms.[282]"

"Observed [electric] potential drops of as much as several kilovolts are frequently observed along auroral field lines. The most dramatic effects of these [electric] potential drops is acceleration of downcoming plasma-sheets electrons to energies above those characteristic of the normal plasma sheet, and such electrons are responsible for most bright auroral forms (*ISP* p. 325)."

"Birkeland currents are also one of a class of plasma phenomena called a *z-pinch*, so named because the azimuthal magnetic fields produced by the current pinches [self-constricts] the current into a filamentary cable. This [cable] can also twist, producing a helical pinch that spirals like a twisted or braided rope, and this [twisted cable configuration] most closely corresponds to a Birkeland current[283]..."

Spacecraft crossing these sheets encounter a reversal of the associated **B**-field, which is perpendicular to the current flow by Ampère's circuital law. RHH showed representative 1981 B-field data published by Sugiura et al. documenting such a pass.

Flux Transfer Events: "A flux transfer event (FTE) occurs when a magnetic portal opens in the Earth's magnetosphere through which high-energy particles flow from the Sun. This connection, while previously thought to be permanent, has been found to be brief and very dynamic. The European Space Agency's four Cluster spacecraft and NASA's five THEMIS probes have flown through and surrounded these FTEs,

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[279] http://en.wikipedia.org/wiki/Aurora_%28astronomy%29
[280] http://www-spof.gsfc.nasa.gov/Education/wcurrent.html
[281] Field-aligned currents:
• Potemra TA. op cit. and
• Potemra TA. "Field-aligned (Birkeland) currents", *Space Science Reviews*. Volume 42, Numbers 3-4 / December, 1985. (see Figure 3)
[282] http://en.wikipedia.org/wiki/Aurora_%28astronomy%29
[283] http://en.wikipedia.org/wiki/Birkeland_current

measuring their dimensions and identifying the particles that are transferred between the magnetic fields.[284]" "Tons of high-energy particles may flow through the opening before it closes again... The connections are not steady at all. They are often brief, bursty and very dynamic.... Approximately every eight minutes, the two fields [Earth's and Sun's magnetic field] briefly merge or "reconnect," forming a portal through which particles can flow. The portal takes the form of a magnetic cylinder about as wide as Earth [MCM: This article depicts possible magnetic topologies for FTEs such as *ropes*, *cylinders*, and *bubbles*.][285]" RHH showed a slide of the 1980s data from the International Sun-Earth Explorer (ISEE) spacecraft as it crossed these events. (See also *ISP* p. 270 regarding FTEs.)

Plasmasphere and the Van Allen Trapped Radiation Belts

Plasmasphere

This is a cool and neutral plasma consisting of both ions and electrons. "The plasmasphere, or *inner magnetosphere* is a region of the Earth's magnetosphere consisting of *low energy* (cool) plasma. It is located above the ionosphere. The outer boundary of the plasmasphere is known as the *plasmapause*, which is defined by an order of magnitude drop in plasma density... The plasmasphere was discovered in 1963 by Don Carpenter from the analysis of VLF whistler wave data (see more below)... Recent satellite observations have shown that density irregularities such as plumes or biteouts may form[286]."

The outer edge of the plasmasphere (plasmapause) is demarcated by a rapid drop in particle number density. In quiet geomagnetic times, this transition occurs at L value of about 5-6 R_E, but the boundary shrinks to 3-4R_E during times of high geomagnetic activity (high K_p, where K_p is a planetary index of geomagnetic activity ranging from 0 to 9 and explained here[287]). Note that *geostationary orbits* are at a geocentric distance of about 6.6 R_E (*ISP* p. 293).

The plasmapause is seen in equatorial view to *bulge* outward between dusk and midnight (maximal at about 18 – 21 Magnetic Local Time=MLT), a bulge which is more pronounced and more noonward[288] for higher K_p [i.e., magnetospheric activity]. This empirical observation has been made with *whistler* data (*ISP* p. 300). While I do not fully understand the theory explaining this (see *ISP* p. 316 and Fig. 10.25 and the 2007 article by Wolf), it appears that the bulge of the cold particles in the plasmasphere on the dusk side results from a relative paucity of cold [$\ll$ 1 keV] inflowing E-cross-B drift convection plasma flow lines in this region. The convection and co-rotation processes both cause eastward drift toward the Sun on the dawn side and magnetic field lines lie close together there, but convection and co-rotation oppose each other on the dusk side. This leads to a plasmaspheric "*forbidden region*" inside a boundary ("separatrix" or *Alfvén layer*[289]) such that convecting cold plasma from the tail cannot cross into this region. This apparently allows the plasmasphere to bulge out in this region. In contrast, the separatrix or *Alfvén layer* on the dawn side lies much closer to Earth and prevents a dawn side bulge.

RHH summarizes, the plasmasphere is high density, low energy, and co-rotates with the Earth. The co-rotation (also spelled co-rotation) is because Earth is magnetized, rotates, and has a conductive ionosphere. [However, see below regarding deviation from co-rotation.]

Actual images of the plasmasphere made by NASA's IMAGE spacecraft, including those by the Extreme UV imager (EUV = 30.4-nm photons from Helium) may be seen here[290]. A good diagram may be seen here[291].

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[284] http://en.wikipedia.org/wiki/Flux_transfer_event
[285] http://science.nasa.gov/headlines/y2008/30oct_ftes.htm?list179029
[286] http://en.wikipedia.org/wiki/Plasmasphere
[287] http://www.ngdc.noaa.gov/stp/GEOMAG/kp_ap.html
[288] Plasmapause bulge:
http://www.aeronomie.be/plasmasphere/pdf/Meeting_IASB_PLS_24_25FEB2003/Talk_IASB_PLS_24_25FEB2003_Laakso_Polar.pdf
[289] Alfvén layer:
R.A. Wolf et al. "How the Earth's inner magnetosphere works: An evolving picture". *Journal of Atmospheric and Solar-Terrestrial Physics*. Volume 69, Issue 3, March 2007.
[290] http://pluto.space.swri.edu/image/index.html
[291] http://www.windows.ucar.edu/tour/link=/janet/earth_plasmasphere_jpg_image.html

“[The lower limit of the plasmasphere] is located just outside the upper ionosphere…. The atmospheric gas density becomes low enough to support the conditions for a plasma [formed by solar UV ionization]... at about 90 kilometers above Earth's surface... More and more electrons begin to escape outward... [and] ... lighter ions of hydrogen, helium and oxygen are able to escape from the ionosphere... For a planet like Earth with a strong planetary magnetic field, these outward moving particles [including electrons] remain trapped near the planet unless other processes further draw them away and into interplanetary space... This "donut shaped" region of cold (about 1 eV per particle) plasma encircling the planet is called the plasmasphere... [The plasmasphere or plasmapause] shrinks in size with increased space weather activity and expands or refills during times of inactivity. As it shrinks with increasing activity, some of the plasmasphere is drawn away from its main body (plasmaspheric erosion) in the sunward direction toward the [magnetopause]... The plasmasphere takes 27 hours on average to do a full rotation.[292]” This data (from the NASA satellite IMAGE) shows therefore that the plasmasphere does not exactly co-rotate with the Earth (which of course takes 24 hours for a full rotation).

“The base of the plasmasphere, which is the same as the top of the ionosphere, is about 1000 kilometers from the Earth's surface. The temperature in the plasmasphere is generally between 6,000K and 35,100K...[293]” [MCM: A temperature of 6,000K is equivalent to an average single thermal particle energy of 0.5 eV, and an average energy of 1 eV is found at a temperature of 11,604K.]

“Early in the exploration of the near-Earth space environment it was recognized that magnetic reconnection and other coupling processes would cause drag between Earth's magnetosphere and the streaming solar wind, forcing the outermost layer of the magnetosphere to flow anti-sunward... This necessitates a sunward return flow on closed field lines in the interior of the magnetosphere, corresponding to dawn-to-dusk electric field across the magnetospheric tail. Termed “magnetospheric convection” and initially based on somewhat indirect observational evidence, this concept remained controversial for several years until finally settled by increasingly direct measurements of the ionospheric signatures of the magnetospheric convection, particularly spacecraft measurements of dawn–dusk electric fields over the polar caps (representing anti-sunward convection) and dusk–dawn fields in the auroral zones (sunward return flow)...

“Initial quantitative models of sunward convection were based on the simplifying assumption that the electric field consisted of the superposition of a spatially uniform field directed from dawn-to-dusk in the magnetospheric equatorial plane and a radially inward-directed electric field caused by Earth's rotation... Low-energy particles (energies much less than 1 keV) essentially execute ExB drift, with their energy-dependent gradient and curvature drifts being negligible. Under these conditions, electric equipotentials correspond to instantaneous drift paths. The *Alfvén layer* is defined to be the separatrix between two sets of drift trajectories, one comprising open drift paths extending from the magnetospheric tail to the dayside magnetopause and another, nearer set consisting of closed drift paths, encircling the Earth. On the dawn side, sunward convection and eastward co-rotation are in the same direction, while on the dusk side they oppose each other, producing a null point. Inside the Alfvén layer, flow speeds are then lower on the dusk side, implying that the equipotential flow lines are spread out there. This means that the Alfvén layer for low-energy particles is located furthest from Earth near local dusk and closest near local dawn.[294]” [See the Wolf 2007 article cited.]

Shielding: “The sustained application of a dawn-dusk electric field causes region-2 Birkeland currents and a dusk–dawn shielding electric field…” (Wolf 2007 p. 289)

Additional phenomena: discussed or mentioned by Wolf 2007 as items of current study include: “polarization jets” = “subauroral ionization drift” (PJ/SAID, occurring during magnetic storms and substorms), effects of the “sub-auroral polarization streams (SAPS)” on the plasmapause, plasmaspheric plumes associated with ionospheric “Storm-Enhanced Density” (SED) events, plasmaspheric shoulders and overshielding, sub-co-rotation of the quiet-time plasmapause, and smaller-scale events such as “fingers, crenulations, channels, and notches.”

For hot particles drifting in from the tail, the Alfvén layer extends further out on the dawn side for positive particles whereas it extends further out on the dusk side for negative particles (see 2007 Wolf article and *ISP* p. 318). Correspondingly, incoming positive ions penetrate close to Earth on the dusk side and incoming

[292] http://plasmasphere.nasa.gov/regions.html
[293] http://www.windows.ucar.edu/tour/link=/janet/earth_plasmasphere_jpg_image.html
[294] Earth's inner magnetosphere:
R.A. Wolf et al. “How the Earth's inner magnetosphere works: An evolving picture”. *Journal of Atmospheric and Solar-Terrestrial Physics*. Volume 69, Issue 3, March 2007.

electrons penetrate closer to Earth on the dawn side. More energetic plasma-sheet particles *cannot* penetrate as close to the Earth as can the less energetic particles (*ISP* p. 318). But penetration is greater and deeper during times of strong convection (magnetic storms), and result in stronger auroras at lower ionospheric latitudes, expanding the *auroral zone*.

The process in which fluctuating fields spread the L shells of particles that drift near the Alfvén layer is called *radial diffusion* (*ISP* p. 319). This reduces the radial gradients of the distribution functions at fixed μ and J.

Trapped Radiation (Van Allen) Belts

These belts describe highly energetic "hot" particles, but partially overlap the plasmasphere consisting of cold particles. "The Van Allen radiation belt is a torus of energetic charged particles (plasma) around Earth, which is held in place by Earth's magnetic field. This field is not uniformly distributed around the Earth. On the sunward side, it is compressed because of the solar wind, while on the other side it is elongated to around three R_E [or more]… It is split into two distinct belts, with energetic electrons forming the outer belt and a combination of protons and electrons creating the inner belt. In addition, the belts contain lesser amounts of other nuclei, such as alpha particles. The Van Allen belts are closely related to the polar aurora where particles strike the upper atmosphere and fluoresce… The existence of the belt was confirmed by the Explorer 1 and Explorer 3 missions in early 1958, under Dr James Van Allen at the University of Iowa… The term Van Allen belts refers specifically to the radiation belts surrounding Earth; however, similar radiation belts have been discovered around other planets. The Sun does not support long-term radiation belts. The Earth's atmosphere limits the belts' particles to regions [beginning above an altitude of] 200 – 1,000 km, while the [outer limits of the] belts do not extend past 7 R_E . The belts are confined to an area which extends about 65° [on either side of] the celestial equator.[295]"

"The large **outer radiation belt** extends [from] three to ten R_E above the Earth's surface. Its greatest intensity is usually around 4 – 5 R_E… Radiation belt electrons are also constantly removed by collisions with atmospheric neutrals, losses to magnetopause, and the outward radial diffusion. The outer belt consists mainly of *high energy (0.1 – 10 MeV) electrons* trapped by the Earth's magnetosphere. The gyroradii for energetic protons would be large enough to bring them into contact with the Earth's atmosphere. The electrons here have a high flux, and at the outer edge (close to the magnetopause), where geomagnetic field lines open into the geomagnetic 'tail', the flux of energetic electrons can drop to the low interplanetary levels within about 100 km (a decrease by a factor of 1,000).[296]" The plasmapause or outer boundary of the plasmasphere tends to correlate with the inner boundary of the outer radiation belt[297]. "The outer belt electrons are injected from the geomagnetic tail following *geomagnetic storms*, and are subsequently energized though wave-particle interactions.[298]"

"The **inner Van Allen [Radiation] Belt** extends [over an altitude range of] 100 to10,000 km (0.01 to 1.5 R_E) above the Earth's surface, and contains high concentrations of *energetic protons* with energies *exceeding 100 MeV* and *electrons in the range of hundreds of keV*, trapped by the strong (relative to the outer belts) magnetic fields in the region… It is believed that protons of energies exceeding 50 MeV in the lower belts at lower altitudes are the result of the beta decay of neutrons created by cosmic ray collisions with nuclei of the upper atmosphere. The source of lower energy protons is believed to be proton diffusion due to changes in the magnetic field during geomagnetic storms… Due to the slight offset of the belts from Earth's geometric center, the inner Van Allen belt makes its closest approach to the surface [of the Earth] at the *South Atlantic [Magnetic] Anomaly*."[299] Put another way, the bounce mirror point lies closest to the Earth's surface at the South Atlantic Magnetic Anomaly, and high energy charged particles are inserted into the atmosphere there. It is currently centered near Brazil and represents a hazard to satellites, other spacecraft, much less likely to aircraft.[300] The magnitude of the surface magnetic field in this region is the lowest found on Earth (according to a model diagram presented by RHH, elsewhere reported to be 22,850 nT[301]). The measured fluxes of

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[295] http://en.wikipedia.org/wiki/Van_Allen_radiation_belt
[296] Ibid
[297] http://www.johnstonsarchive.net/physics/RBtutorial.pdf
[298] http://en.wikipedia.org/wiki/Van_Allen_radiation_belt
[299] Ibid
[300] http://en.wikipedia.org/wiki/South_Atlantic_Anomaly
[301] South Atlantic magnetic anomaly:
Trivedi NB, et. al. "Geomagnetic phenomena in the South Atlantic anomaly region in Brazil" *Advances in Space Research* 36 (2005) 2021–2024

"precipitating" high energy (5 - 45 MeV) protons at 750 km (and of 80 MeV protons at 1336 km) are correspondingly maximal in this same area. Satellite Topex exhibits the densest concentration of *Single Event Upsets* in this area as well—in fact over 90% of SEUs encountered[302]. (SEUs = "a change of state caused by ions or electro-magnetic radiation striking a sensitive node in a micro-electronic device."[303])

"There is no clear distinction between these [radiation] belts and the 'ring current particles'. In fact, there is a strong overlap in the terminology ... The plasmasphere coexists in approximately the same region of space as the radiation belts. (*ISP* p. 297 - 298)"

According to RHH, the ring current comprises the second largest energy reservoir in the magnetosphere (the largest being the geomagnetic tail).

An interesting but somewhat confusing video of the relationship of the COLD plasmasphere/plasmapause and the HOT radiation belts is available here.[304] The text states " Radiation Belts and Plasmapause Fluctuate Under Solar Storm. Under the wave of energetic particles from the Halloween 2003 solar storm events, the Earth's radiation belts underwent significant changes in structure... In this visualization, we see the interaction of the radiation belts ..., the plasmapause ... and magnetopause..."

A detailed article on the radiation belts is seen here[305], and Figure 10 showing estimated **radiation dosages** in rads as a function of the amount of aluminum shielding employed. Although the time period of exposure is not obvious, the graph shows impressive radiation dosages of up to more than 10^7 rads. According to a NASA graphic[306], the unshielded absorbed radiation dose rate in the most intense regions of the inner and outer belts is up to 0.01 - 0.05 Rad s^{-1}. Astronauts flying to the moon through these belts (on a hypothetical path that does not deliver maximal radiation) without any shielding would receive 11 Rads. However, Apollo astronaut actually received less than 2 Rads for their entire round trip, according to dosimeters they carried. By comparison, acute whole body radiation doses of 100 rad (1 Gy) may cause acute radiation syndromes, and acute dosages of 600 rads (6 Gy) are almost always lethal to humans. The radiation belts around Jupiter have a million times higher radiation intensity compared to Earth's, and radiation will affect efforts to explore for instance its icy moon Europa for signs of life[307].

Particle Motions in the Radiation Belts: See discussion above about Guiding Center Drift. This complex analysis of particle motions is used to explain how charged particles—both electrons and positive ions—are trapped in the radiation belts by the effects of the magnetic field. Their complex motion consists of multiple components which differ in velocity, scale, and direction. (See *ISP* p. 307-8, including Fig. 10.21 for representative values of the respective frequencies for these motions plotted against KE and L.)

- *Gyromotion about B Field Lines*: Particles rotate (gyrate) rapidly about magnetospheric **B**-field lines at the cyclotron or gyro-frequency (Larmor frequency) and at a distance of the Larmor gyroradius from the guiding center. This is an adiabatic process in which no work is done. The quantity μ, the magnetic moment of the particle's gyromotion, is shown to be *adiabatic invariant* and is termed the *first adiabatic invariant* (*ISP* p. 308). The gyroperiods for protons range from about 1 ms at low altitude to 2 s at 10 R_E, and gyroradii range widely from 0.05 km to thousands of km, depending on R_E and eV (*ISP* p. 306). The gyroperiod and gyroradii for electrons are substantially smaller—for example, the electron gyroperiod is 1/1836 of the proton gyroperiod for the same B.

- *Bounce Motion along B Field Lines*: The magnitude of **B** increases with greater distance from the magnetospheric equator as field lines converge. For a particle starting at a pitch angle α_0 with respect to **B** (and regardless of its charge, energy or mass according to RHH), grad-B drift forces arise which increase $\perp$ to B and decrease parallel to B. Eventually a mirror point is reached where $v_\parallel$ falls to zero, and the particles reflect back so that $v_\parallel$ now is in the opposite direction. This reversal of course is termed *mirroring*. This is also an adiabatic process and no work is done. A *second adiabatic invariant*,

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302 http://radhome.gsfc.nasa.gov/radhome/papers/chris.htm
303 http://en.wikipedia.org/wiki/Single_event_upset
304 Plasmasphere/plasmapause versus the radiation belts:
• http://visibleearth.nasa.gov/view_rec.php?id=14578 and
• http://veimages.gsfc.nasa.gov/14575/magnetoplasma_Oblique_320x240.mpg
305 http://www.spenvis.oma.be/spenvis/help/background/traprad/traprad.html
306 http://spacemath.gsfc.nasa.gov/weekly/3Page7.pdf
307 http://www.astrobio.net/exclusive/3010/hiding-from-jupiters-radiation

J, is associated with bounce motion (*ISP* p. 309). The period for bounce motion is slower than the gyration period, with much of the time spent near the mirror points. For protons, the bounce period is about 600 times the gyromotion period, and for electrons, the bounce period is about 25,000 times the gyromotion period.

- *Drift Motion Perpendicular to B Field Lines (Longitudinal Drift)*: An **E** field imparts an E-cross-B drift, which is charge and energy independent and of course perpendicular to B as well as to E. In addition, drift perpendicular to B arises from *grad-B drift* and *curvature drift*, which are typically in the same direction. The longitudinal drift period (the time needed to encircle the Earth) for protons is about 1/360,000 of the gyromotion period, yielding a frequency in the milliHz range. Electrons have similar grad-B drift and curvature drift (they are independent of mass for a given energy). There is also an associated *third adiabatic invariant* Φ (*ISP* p. 50) which however is "often not conserved in practical applications"[308]) and is not mentioned in *ISP* chapter 10.

The longitudinal drifts cause positive particles to drift westward (clockwise from above) in the Earth's dipole field, and negative particles to drift eastward (counterclockwise), so that there is a net westward positive current J circling the Earth. This *ring current* tends to decrease the strength of the northward B field observed at low latitudes (see discussion with *Geomagnetic Storms*). Note that the direction of the ring current is opposite to that further out in the nose of the magnetopause. (See for example *ISP* p. 22, figure 1.18.)

Particles can persist in the radiation belts for many hundreds of years.

The lack of precisely central positioning of the Earth's dipole leads to the South Atlantic Magnetic Anomaly mentioned above (*ISP* p. 312). There, the field strength B is weakest, and the magnetic mirrors of the inner belt lie closest to the Earth's surface, so that particles there are more likely to be lost into the atmosphere. Another result of this asymmetry is *Drift-Shell splitting* (*ISP* p. 312-3)…

The equation for a pure magnetic dipole field line (*ISP* p. 166) is

$$r = r_0 \sin^2\theta,$$

where r_0 is the distance to the field line at the magnetic equator, r is the distance to a given point on the field line, and θ is the angle formed between the magnetic field direction at that point on the line and the equatorial plane (i.e., $\theta = 90°$ for a point on the equator). Equivalently,

$$r = L\, R_E \cos^2\lambda,$$

where $L \equiv r_0 / R_E$ [i.e., the relative distance at the magnetic equator] and λ is the magnetic latitude.

The *Invariant latitude* Λ is the latitude where a field line reaches the surface of the Earth ($r = R_E$), and is given for a given L shell by

$$\Lambda \equiv \cos^{-1}(1/L)^{1/2}$$

For a given *L shell* (the torus satisfying this value of L), if the mirror point is < ($1\ R_E$ + 100 km), then the particles have a high probability of being lost in the atmosphere. The higher the starting value of $v_\perp$ relative to $v_\parallel$, the lower the latitude at which the particle will mirror bounce (and therefore the less chance there will be of loss). If a particle has starting motion lying within the *bounce loss cone* in velocity phase space (determined by $v_\perp$ being sufficiently small relative to $v_\parallel$), "then its mirror point will fall below the surface of the planet (actually, below the thickening atmosphere at about 100 km altitude) and it will be lost before completing a full cycle of bounce motion.[309]"

Particles can also be said to lie in a *drift loss cone* if they are not currently within a bounce loss cone, but, when they drift to a different longitude where they will be in a bounce loss cone (as a result of the asymmetry of the dipole field)—as before, they become lost on bouncing too close to Earth[310]. More compactly stated, RHH describes the drift loss cone as the largest angle α_e at the equator which equals the bounce loss cone angle at some longitude.

The presence of waves and other instabilities can affect these idealized particle pitch angle analyses, and result in a random diffusion of particles from larger to smaller pitch angles, leading to additional particles becoming lost.

[308] http://en.wikipedia.org/wiki/Adiabatic_invariant
[309] http://www.altfuels.org/sampex/losscone/index.html
[310] ibid.

Plasma Sheet and Plasma-Sheet Boundary Layer

Beyond the outer radiation belt and plasmasphere, we encounter in the near tail the *inner plasma sheet* (also discussed above). It consists of hot particles, both ions and electrons, with number densities of 0.1 to 1 cm^{-3} and symmetrical velocity distributions (thus slow bulk flow) (*ISP* p. 291). Typical particle energies are 0.6 keV for electrons and 5 keV for protons[311]. NASA states, "Separating the two tail lobes is the *plasma sheet*, a layer of weaker magnetic field and denser plasma, centered on the equator and typically 2-6 Earth radii thick. Unlike field lines of the tail lobes, those of the plasma sheet do cross the equator, though they are quite stretched out. A weak magnetic field means that the plasma is less restrained here than nearer to Earth, and on occasion it sloshes or flaps around."[312]. The *inner plasma sheet* is closer and contributes convecting particles. The inner plasma sheet shows preferential flow of electrons to the dawn side and of positive ions to the dusk side, creating a current which contributes to the *partial ring current* and to the buildup of a dusk–dawn shielding electric field. (RHH; Wolf 2007 p. 289). The *neutral line* of magnetic reconnection in the neutral plasma sheet is considered to be the equatorial boundary between closed and open magnetic field lines. Sunward from the neutral line, the neutral sheet though stable in quiet times is unstable during substorms and is prone to form new and closer-in zones of magnetic reconnection (neutral lines).[313]

The term "*neutral plasma sheet*" is rather confusing to me and needs clarification. In the heliosphere, it is mentioned as follows: "[The polarity of magnetic field B_φ] is assumed to be reversed, from the northern to the southern hemisphere, hence a *neutral plasma sheet* is formed in the ecliptic plane in the heliosphere.[314]" It appears that the word "neutral" refers to the relatively low magnetic field. The phrase may also be used to refer to either the zone of reconnection at the neutral line in the plasma sheet[315] or the flatter part of the plasma sheet found in the more distant tail beyond the more lenticular-shaped near-Earth part and separating the tail lobes[316].

The *Plasma Sheet Boundary Layer* (*distant plasma sheet*) has ions with velocities of hundreds of km s^{-1}, with thermal energies being small compared to flow energies. Some are streaming earthward and some tailward. Densities are 0.1 cm^{-3} It lies on closed magnetic field lines. "The counterstreams [flowing earthward] tend to be unstable to various plasma waves, which eventually convert the streaming energy to thermal energy, creating the hot slow-flowing plasma sheet." (*ISP* p. 291-2) How this layer relates to the "neutral plasma sheet" is unclear to me. Moreover, "It is not clear that … the plasma-sheet boundary layer exists during quiet conditions associated with a northward IMF (*ISP* p. 432).

The *Tail lobes* have ions with <0.1 cm^{-3} density and probably open field lines. Few particles have energies of as much as 5 keV and few return toward Earth. (*ISP* p. 291) NASA states, "However, in the tail itself the earthward [particle convection] flow has been harder to confirm and seems to be rather irregular, coming in fits and bursts, especially during magnetic substorms.[317]"

Ionosphere, Coupling with Magnetosphere, Magnetic Substorms and Storms

The Earth's atmosphere[318] has layers defined in part by temperature behavior: *Troposphere* (0 to 7 – 17 km), *Stratosphere* (17 to 50 – 55 km), *Mesosphere* (50 to 80 – 85 km), *Thermosphere* (85 to 350 – 800 km), and *Exosphere* (above 350 – 800 km). The *Ionosphere* overlaps parts of the exosphere and thermosphere, and even the mesosphere.

Earth Ionosphere

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[311] http://www.windows.ucar.edu/tour/link=/glossary/plasma_sheet.html&edu=high
[312] http://www-spof.gsfc.nasa.gov/Education/wtail.html
[313] Burch JA. "The Magnetosphere" in *The upper atmosphere and magnetosphere*. Assembly of Mathematical and Physical Sciences (U.S.), Geophysics Study Committee. 1977. p. 52
[314] H. Washimi, et al. "MHD structure of the heliosphere and its response to the 11-year solar cycle variations." *Advances in Space Research*, Volume 23, Issue 3, 1999, Pages 551-560
[315] http://adsabs.harvard.edu/abs/1974IJRSP...3..407K
[316] http://www.springerlink.com.offcampus.lib.washington.edu/content/r6215512nj542647/
[317] http://www-istp.gsfc.nasa.gov/Education/wtail.html
[318] http://en.wikipedia.org/wiki/Earth%27s_atmosphere

Ionosphere Layers: The ionosphere begins at the **D layer** at 50 – 90 km, which is most apparent in its radio wave absorption occurring during the day. "Ionization here is due to Lyman series-alpha hydrogen radiation at a [EUV] wavelength of 121.5 nm ionizing nitric oxide (NO). In addition, when the sun is active with 50 or more sunspots, hard X-rays (wavelength < 1 nm) ionize the air (N_2, O_2).[319]"

The **E layer** is the middle layer at 90 km – 120 km. "Ionization is due to soft X-ray (1-10 nm) and far ultraviolet (UV [10 nm – 121 nm or 200 nm depending on definition]) solar radiation ionization of molecular oxygen (O_2).[320]"

The **F layer** or region, also known as the Appleton layer, is 120 km to up to 1000 km where it merges with the inner plasmasphere (an ill-defined region also termed the *exosphere*). [MCM: I am unsure exactly how the upper boundary of the ionosphere is defined, but some definitions relate it to its effects on radio waves.] It contains a plasma of electrons and ions, which are created by solar extreme UV (EUV, 10 – 121 nm).

Ionospheric structure may be considered from the point of view of electron density, thermal structure, and ion density and source. One graph presented by RHH shows that at altitudes below about 85 km, the so-called *Cosmic ray layer*, there are many ions including negative ions. Above 85 km—the *Solar EUV layer*—free electrons are prevalent.

See lecture notes graph "Fig. 1.1. Nomenclature of atmospheric regions based on profiles of electrical conductivity, neutral temperature, and electron number density" (graph origin unknown, partly shown here[321]). Here, "neutral temperature" refers to the temperature for neutral particles (rather than for electrons, protons, etc.), and electron number density is plotted only for the ionosphere[322] (and is seen to peak at ~10^{12} m^{-3} or 10^6 cm^{-3} at around 300 km.)

Ionospheric Conductivity Variation and Anisotropy, and Electrojets: The ionosphere is Ohmic and electric currents follow Ohms law:

$J = \sigma E$ where

J = Total current density
σ = Electrical conductivity (which may be scalar or a tensor)
E = Electric field

The scalar conductivity[323] $\sigma \equiv J/E$. For a resistive medium, this is the [Lyman] Spitzer conductivity, given by

$\sigma = ne^2/m\nu$ where

n = number density
e = charge
m = mass
ν = collision frequency

The SI units of conductivity are S m^{-1} where S = siemens, and *conductivity* integrated over distance is in S.

The atmospheric conductivity[324] is scalar up to about 85 km, a region termed the "neutral atmosphere" or "lower atmosphere". At higher altitudes (the "dynamo region" or "middle atmosphere", and the "magnetosphere"), conductivity $\boldsymbol{\sigma}$ is anisotropic, has multiple components, and behaves as a rank-2 tensor… Conductivity components include $\sigma_F = \sigma_0$ = longitudinal (aka *parallel* or *direct*, parallel to the magnetic field), $\sigma_1 = \sigma_P = \sigma_{Pedersen}$ (perpendicular to the magnetic field but parallel to the electric field), and $\sigma_2 = \sigma_H = \sigma_{Hall}$ conductivity[325] (perpendicular to both the magnetic field and the electric field). (The name Pedersen is sometimes misspelled Peterson or Petersen).

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319 http://en.wikipedia.org/wiki/Ionosphere
320 Ibid.
321 The Earth's Electrical Environment (1986)
http://www.nap.edu/openbook.php?record_id=898&page=214
322 http://en.wikipedia.org/wiki/Ionosphere
323 http://en.wikipedia.org/wiki/Electrical_conductivity
324 Middle Atmosphere Conductivity:
Holzworth RH. "Electric Fields in the Middle Atmosphere" 1987 *Phys. Scr.* T18 298-308 doi: 10.1088/0031-8949/1987/T18/030
325 Della-Rose DJ. "A graphical interpretation of the electrical conductivity tensor".
doi:10.1016/j.jastp.2004.11.003 *Journal of Atmospheric and Solar-Terrestrial Physics*. Vol 67 March 2005

Explanation: Below some altitude ~85 km, particles are much more likely to collide than to complete a gyrorotation (gyrofrequency $\Omega_s \ll$ collision frequency ν_s), and scalar conductivity σ_1 applies. Above 300 km, particles rarely collide and motions of all species are governed entirely by collisionless forces. But in the middle zone 85 - 300 km (another RHH slide also says this region occurs 85 - 120 km), motions are complex, because positive ions may differ from electrons in their interactions due to differing gyroradii and gyrofrequencies, etc... In this domain,

$$\Omega_e \gg \nu_e \text{ but } \Omega_i \ll \nu_i$$

where Ω are gyrofrequency, e = electrons and I = positive ions. The electrons therefore exhibit an **E**×**B** (E cross B) drift, but positive ions do not, and a Hall current results in the -**E**×**B** direction (negative because of the electron's charge)... Peak overall ionospheric conductivity occurs at about 100 km[326].

The electric field **E** consists of components $\mathbf{E}_\parallel$ (parallel to B) and $\mathbf{E}_\perp$ (in the plane perpendicular to **B**). The resulting current **J** does not lie along **E** but has components $\mathbf{J}_\parallel = \boldsymbol{\sigma}_0\mathbf{E}_\parallel$ (current parallel to **B** and $\mathbf{E}_\parallel$), $\boldsymbol{\sigma}_1\mathbf{E}_\perp$ (current perpendicular to **B** and parallel to $\mathbf{E}_\perp$), and $\boldsymbol{\sigma}_2\mathbf{E}_\perp$ (current perpendicular to both **B** and to $\mathbf{E}_\perp$). Because $\boldsymbol{\sigma}_2$ and $\boldsymbol{\sigma}_1$ have similar magnitude, the component of J lying in the perpendicular plane, namely $\mathbf{J}_\perp$, is angled at about 45 degrees with respect to $\mathbf{E}_\perp$ in the horizontal plane. See *ISP* fig. 10.18(c), which depicts the horizontal auroral ionospheric "electrojet" current pattern. It is angled with respect to the horizontal electric field shown in *ISP* fig. 10.18(d). (See the articles cited here[327] for quantitative aspects, and RHH also provides a quantitative derivation, details omitted here.)

A more equatorial ionospheric current system (*ISP* fig. 13.4) is termed the *equatorial electrojet*. It exhibits current circulations lying above and below the equator. These circulate in opposite directions so that both are directed east ("dawn to dusk") close to the equator. (These double vortex circulations are not the same as auroral zone double vortex seen with "convection".)

Ionospheric Convection Pattern: Graphs of the polar region electric potential show a 2-cell "convection" pattern: the cell on the dusk side of the pole being somewhat larger than on the dawn side. (See RHH slides and here[328] Fig. 1.) The article cited shows how these convection patterns increase in size (extend to lower latitude) and in electric field strength during a substorm. It also depicts polar maps of Pedersen and Hall conductivity—which show greater conductivity present on the night side. See here[329] for the SuperDARN [Super Dual Auroral Radar Network] Real-time Global Ionospheric Convection Map, which is continuously updated.

Geomagnetic Substorms

In contrast to full-blown geomagnetic storms, these are less intense and last only a few hours, and are more frequent than geomagnetic storms. The concept of a widespread substorm—including the onset, expansion phase, and recovery phase—and presenting as an oval of auroras surrounding the north magnetic pole was introduced by Akasofu[330]. (See his 1964 article, *ISP* p. 421, and here[331] for details.) His model has subsequently been modified (*ISP* p. 426).

Substorms typically begin with a increase in *southward-directed IMF B_Z* (Interplanetary Magnetic Field, *ISP* p. 405 – 7), which partially cancels the external magnetospheric **B** field[332] by reconnection and compresses the sunward magnetosphere. A rise in dynamic solar wind pressure is also seen. Soon after, the horizontal component **H** of the magnetic field becomes perturbed due to concentrated electrojet ionospheric currents flowing in channels of high conductivity at ~120 km, and bright auroral displays develop. Typical magnetic field **H**-component electrojet disturbances (*ISP* p. 406] are 200 - 2000 nT in amplitude (compared to 60,000 nT for Earth's polar magnetic field), and these disturbances last 1 - 3 hours. Substorm auroral electrojet

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[326] http://www.faculty.iu-bremen.de/course/fall03/GeneralGeoAstro1/space/gga1s-ionosphere.pdf
[327]Ionospheric Conductivity Quantitation:
• http://wdc.kugi.kyoto-u.ac.jp/ionocond/exp/icexp.html and
• http://geomag.org/info/Geomag_tutorials/Maus_ionospheric_conductivity.pdf
[328] http://www-ssc.igpp.ucla.edu/gem/poster/weimer/substorm/
[329] http://superdarn.jhuapl.edu/rt/map/index.html
[330] Akasofu SI. "The development of the auroral substorm". *Planetary and Space Science*. Vol. 12, pp. 273-282. 1964.
[331] http://www.nasa.gov/mission_pages/themis/auroras/substorm_history.html
[332] http://science.nasa.gov/headlines/y2000/ast02mar_1m.htm

indices, particularly *AU*, *AL*, and *AE*, are "relatively uncontaminated by effects of the ring current", and may be used to quantitate the degree of the substorm (*ISP* p. 455). In contrast, the D_{st} *index*, which reflects ring current, is apparently less useful in substorms.

RHH's "full picture" of the substorm sequence is as follows: The increase in $\mathbf{B_Z}$ [the Z_{GSM} component of B] southward → enhanced [magnetopause] reconnection → Region 1 currents [driven by magnetopause charge separation] → build up of tail energy → enhanced tail reconnection [including pinching off plasmoids and moving reconnection point closer to Earth] → injection of heated plasma into plasma sheet → Partial ring current [piling up excess positive ions on dusk and negative electrons on dawn] → shielding **E**-field (Alfven field) → cold plasma flows around co-rotating plasmasphere → energetic plasma makes ring current → region 2 current [driven by partial ring current, which go down to ionosphere on dusk side and up on dawn side]. Ring current particles eventually pitch-angle scatter and go into the loss cone.

RHH: The magnetic field lines closest to the pole inside the auroral zone are open field lines connecting to the tail and solar wind, whereas lower latitude polar region field lines are closed. At the separatrix of magnetic open and closed field lines where **E** field reversals occur [?], there is a charge distribution (by Gauss's Law) which can drive currents through the ionosphere. [I don't quite get this.]

During a substorm, "energy is rapidly released in the magnetospheric tail. During substorms, in the polar regions, aurora becomes widespread and intense, also much more agitated, and the Earth's magnetic field is disturbed. Out in space, ions and electrons flow in much greater numbers and at higher energies, and changes in the magnetic field are much more profound than those seen at Earth.... On Earth the most visible sign of a substorm is a great increase of polar auroras in the midnight auroral zone. At ordinary times, quiescent auroral arcs are often seen there, but following the onset of a substorm, they intensify, move rapidly (mostly poleward) and expand, until they may cover much of the sky.[333]"

"Much more profound changes are observed in space [from a substorm]. Satellites in synchronous orbit which find themselves near midnight when a substorm erupts may see the magnetic field drop by half, and their on-board detectors in general register the arrival of many ions and electrons with (typically) [energies of] 5-50 keV. These particles *can affect a spacecraft*, and in particular, the electrons may charge it negatively to hundreds and even thousands of volts, which could interfere with normal operations. With over 200 communication satellites inhabiting the synchronous orbit, there is obviously a good reason for studying substorm effects there. Still further out, in the plasma sheet, very fast flows of plasma are often seen, typically at 100-1000 km/sec; the plasma particles also seem to have higher energies than normal, and magnetic fields change rapidly and erratically.... What seems to happen is that magnetic field lines of the tail are first stretched tailwards [away from the Earth] and are then released, in a way frequently compared to the stretching and rebounding of a slingshot. As the lines bounce back [toward Earth], they propel and energize ions and electrons in the midnight region, at typical distances of 6-15 RE…" The rate of reconnection increases on the Sun side of the magnetosphere and the Earth's magnetic field weakens near noon, "allowing the solar wind to push its way closer to Earth… When the interplanetary magnetic field (IMF) is 'southward', the 'nose' of the magnetosphere is seen to be (on the average) about 1 R_E further earthwards than with 'northward' IMF, out of a mean distance of 10-11 R_E… More of the magnetic field is drawn into the tail, and the tail lobes expand, storing additional magnetic energy in them. It is widely believed that the expanded lobes are the main storehouse of energy which powers the substorm. Sometimes, in 'clean' substorms when the IMF suddenly 'turns southward' after a long quiet period, one can observe this reservoir of energy [in the tail] charging up, as the tail field intensifies and magnetic field lines in synchronous orbit become increasingly stretched tailwards, slingshot-like. This 'growth phase' typically lasts 40 minutes… The exact way in which this [reservoir of] energy is released, and the 'trigger' which starts the process, are still subjects of debate and controversy. But it is widely held that the critical event is the formation of an X-shaped neutral point, or more accurately, a *neutral line* extending some distance across the tail. That is not the distant neutral point of Dungey's theory, but an additional one formed quite close to Earth, at a distance of 15 to 30 R_E… Magnetic reconnection then begins… The broken and reconnected halves of lobe field lines form two new lines. The one on the earthward side, essentially a stretched terrestrial line, rebounds earthward, just like a released slingshot. The other one is connected tailwards, and because it no longer has any connection to Earth, it is expelled down the tail… It forms a sort of a plasma bubble known as a *plasmoid*… The magnetic energy taken from the tail lobes also reappears in different forms… Some is turned to heat… it raises the velocity and hence the energy of plasma ions and electrons… The plasma most likely to be heated in this process [comes] from the tail lobes, whose plasma is extremely rarefied … [and so] … the amount each [field line] receives may be quite big… Some of the converted energy ends up driving electric currents, in a circuit

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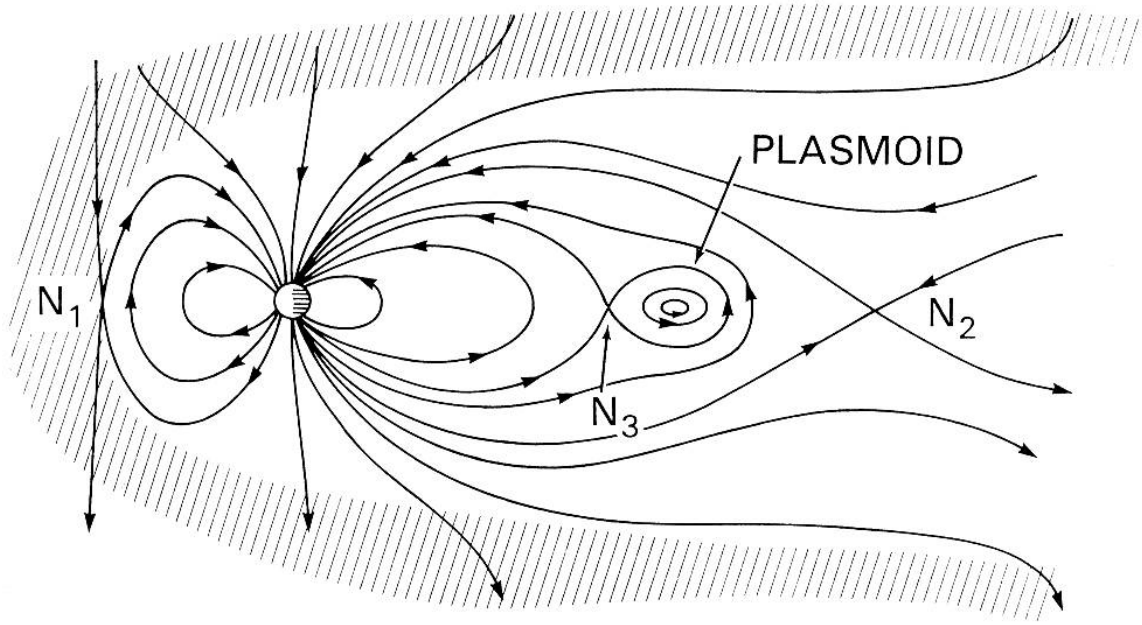
[333] http://www-spof.gsfc.nasa.gov/Education/wsubstrm.html

linking the plasma sheet and Earth. The connecting links are magnetic field lines, which can conduct electric currents quite well, since ions and electrons attached to field lines slide rather easily along them. [Some of the usual dawn to dusk plasma sheet ring current flow is diverted earthwards, starting on the dawn side, passing through the ionosphere as a Region 1 current and returning on the dusk side.] Much [of this] is guesswork...[334]."



Magnetospheric sites of magnetic reconnection
(1) at sunward margin of Earth's magnetosphere ("N_1"), where the $\mathbf{B_Z}$ (the Z_{GSM} magnetic field component) of the solar wind has become strongly southward (typical of substorms);
(2) at the usual site of reconnection in the magnetotail ("N_2"); and
(3) at a substorm-induced additional closer-in site "N_3", where a pinching-off a plasmoid is in progress.
(diagram from Wikipedia[335])

McPherron suggests that the sudden onset of explosive "dissipation" of energy stored in the tail during a substorm (for which $\mathbf{B_Z}$, the Z_{GSM} component, has been more southward than usual) occurs when the $\mathbf{B_Z}$ field suddenly becomes more northward (corresponding to a more negative AL index) or there is a sudden increase in solar wind dynamic pressure pulse, or both. However, the exact cause of the triggering event for the explosive phase of a substorm is unknown (*ISP* p. 419).

McPherron describes in detail the *Near-Earth Neutral-Line Model* for the sequence of substorm plasmoid formation in *ISP* p. 437.

Geomagnetic Storms

A magnetic storm is a period of rapid magnetic field variation which may be caused by arrival of a solar CME, or the IMF taking on a prolonged southward orientation[336], longer than that seen with substorms. (USGS states, "In the complicated flow of the solar wind, the interplanetary magnetic field can take on virtually *any orientation*, but sometimes it assumes a southward orientation.[337]" (MCM: It is therefore probably an oversimplification to refer to the orientation of the IMF as being at 45°, as is often stated with discussion of the Garden Hose Angle, Parker Spiral, etc.) These worldwide events are more intense than geomagnetic substorms and last days to weeks, but occur much less often than substorms. "During magnetic storms

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[334] ibid.
[335] http://en.wikipedia.org/wiki/Magnetosphere
[336] http://geomag.usgs.gov/faqs.php
[337] http://geomag.usgs.gov/intro.php

intense substorms are generally observed in the polar regions. 'Storms' distinguish themselves by injecting appreciable numbers of ions and electrons from the tail into the outer radiation belt, and their world-wide magnetic disturbance reflects a rapid growth of the *ring current*. Substorms usually do not inject as many particles. It might thus be that magnetic storms are merely sequences of very intense substorms, but additional factors are also involved—in particular, magnetic storms require external stimuli such as the arrival of a shock front or a fast stream in the solar wind.[338]" These ring currents are in the inner magnetosphere, and in magnetic storms are seen as a dramatic increase especially in the inner ring current at $L < 4\ R_E$. The particles consist of H^+ and O^+.[339]

When the southward IMF field is juxtaposed with the northward leading magnetosphere field, "this juxtaposition of oppositely-oriented field lines is an unstable situation, one which mathematically is identical to a shear-flow instability in fluid mechanics. With a little bit of diffusion, brought about by electrical resistance, the interplanetary magnetic field can connect onto the Earth's field. Then, particles from the Sun, which would otherwise be deflected by the Earth's field, can stream along these continuously-connected field lines and enter into the magnetospheric cavity... The tail of the magnetosphere is further stretched as well. In the equatorial plane of the magnetotail, and with this stretching of the field lines, we have a second place where neighboring field lines have opposite orientation... As before, with a little diffusion we obtain reconnection, causing part of the magnetic field, and the plasma in which it is embedded, to break off from the rest of the geomagnetic field and float down the tail... Simultaneously, the inner field lines recoil and accelerate the plasma particles within the magnetosphere, giving rise to an enhancement of electric currents. All of this, of course, describes a highly dynamic process, which causes the magnetic field measured at the Earth's surface to become extremely active.[340]" The Earth's magnetic field can undergo a complex oscillation.

Storms typically begin with a sudden increase in magnetic field (in the same direction as Earth's external **B**, *ISP* fig. 13.6) and in D_{st} lasting 1 - 5 hours, followed by a highly disturbed decrease in D_{st} over the entire Earth during the *main phase* of a storm (lasting about a day), and this is followed by a long *recovery period* that may take 5 days to more than a month (*ISP* p. 406-7). They are less frequent than geomagnetic substorms: storms with D_{st} of 50 - 150 nT occur monthly, whereas only at most a few per year exceed 500 nT.

The *D_{st} index* (*Disturbed Storm Time index*) is defined as "the instantaneous worldwide average of the equatorial **H** [horizontal magnetic] disturbance". It is "a measure of the strength of the [equatorial] ring current" from a network of near-equatorial geomagnetic observatories which compares measured values to quiet diurnal variation, utilizes Fourier analysis retaining only low harmonics, etc... It takes as its value the "average around the world of the adjusted residuals..." (*ISP* p 407 and p. 456-7 and described more fully here[341]), typically expressed as nT. The more negative is D_{st}, the greater the induced ring current's magnetic field opposing the normal dipolar Earth magnetic field and the greater the ongoing storm intensity. D_{st} indices are "derived from hourly scalings of low-latitude horizontal magnetic variation. They show the effect of the globally symmetrical westward flowing high altitude equatorial ring current...[342]". *D_{st} index* can be estimated from the auroral electrojet *AL index*[343].

The graph of D_{st} for a large geomagnetic storm in 8 – 10 Nov. 1991 (dropping to -354 nT and attributed to the eruption of a quiescent solar filament[344]) may be seen here[345]. The largest storm ever recorded (dropping to D_{st} = -589 nT), occurred in 13-15 March 1989 and is graphed here[346]. It caused the collapse of the Hydro-Québec power grid[347].

"The ring current causes large decreases in the H [horizontal magnetic field] component over most of the earth's surface.... Some magnetic storms are preceded by an initial phase of enhanced H component in ground magnetometer records. This effect is unrelated to the ring current and is caused by an enhancement

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[338] http://www-spof.gsfc.nasa.gov/Education/wsubstrm.html
[339] http://pluto.space.swri.edu/IMAGE/glossary/ring_current.html
[340] http://geomag.usgs.gov/intro.php
[341] http://wdc.kugi.kyoto-u.ac.jp/dstdir/dst2/onDstindex.html
[342] http://www.ngdc.noaa.gov/stp/GEOMAG/dstcont.shtml
[343] Ga-Hee Moon, et al. "Estimation of the Dst index based on the AL index" *Advances in Space Research* Volume 37, Issue 6, 2006, Pages 1148-1151
[344] http://www.agu.org/pubs/crossref/2009/2008JA013232.shtml
[345] http://wdc.kugi.kyoto-u.ac.jp/dst_final/f/dstfinal199111.html
[346] http://wdc.kugi.kyoto-u.ac.jp/dst_final/f/dstfinal198903.html
[347] http://en.wikipedia.org/wiki/March_1989_geomagnetic_storm

of the magnetopause current. Many magnetic storms follow solar flares or coronal mass ejections… This compression of the field is called a *sudden impulse*." (*ISP* p. 429 - 430).

The *Dessler-Parker-Sckopke (DPS) equation* relates the total energy content stored in the equatorial ring current to the magnetic field depression at the Earth's center and approximately to D_{st}. Russell reports a simple result: B_{tot}[nT] = $3.6\text{x}10^{-14}$ W_{tot} [J] or equivalently, W_{tot} [J] = D_{st} x $2.78\text{x}10^{13}$ x B_{tot}[nT], where W is stored kinetic energy. For a storm with D_{st}= 100 nT depression, the total ring current energy is calculated to be $2.8\text{x}10^{15}$ J (*ISP* p. 312, and here[348]; also similar methodology here[349]). Limitations of this method are discussed here[350].

"Large magnetic disturbances are also observed [in *substorms*], up to 1000 nT… in the auroral zone. The world-wide disturbance observed in a *magnetic storm* of respectable size may only reach 100 nT, but then, its source is much more distant, namely, the ring current which circles the Earth at distances of tens of thousands of kilometers. The electric currents associated with the substorm, on the other hand, come down to the ionosphere, only about 130 km above the ground.[351]"

A NASA color movie—showing a CME erupting on the Sun and progressing to cause a geomagnetic storm—may be found here[352]. It depicts the flow curving around the bow shock and magnetopause, reconnecting at the tail, and flow toward the Earth in convection currents and in field-aligned currents that enter the auroral zones and produce auroras.

The potentially deleterious and hazardous effects of magnetic storms are described as follows[353]:
(1) "Because the ionosphere is heated and distorted during storms, long-range radio communication, which relies on sub-ionospheric reflection, can be difficult or impossible, and global-positioning systems (GPS), which relies on radio transmission through the ionosphere, can be degraded."
(2) "Ionospheric expansion can enhance satellite drag and thereby make their orbits difficult to control."
(3) "Satellite electronics can be damaged through the build up and subsequent discharge of static-electric charges."
(4) "Astronaut and high-altitude pilots can be subjected to increased levels of radiation."
(5) On the ground, enhanced pipe-line corrosion, and electric-power grids can experience voltage surges that cause blackouts.

Auroras

Most auroras occur at an altitude of about 100 km (*ISP* p. 478). I have skipped many parts of the *ISP* aurora Chapter 14, including effects on radio waves.

Colors: A good graph of auroral emission intensities versus altitude (100 – 300 km) is found on *ISP* p. 472, and the physical chemistry is explored in the preceding pages.

"The composition and density of the atmosphere and the altitude of the aurora determine the possible light emissions… The upper atmosphere consists of air just like the air we breathe. At very high altitudes there is *atomic oxygen* in addition to normal air, which is made up of molecular nitrogen and molecular oxygen. The energetic electrons in aurora are strong enough to occasionally split the molecules of the air into nitrogen and oxygen atoms. The photons that come out of aurora have therefore the signature colors of nitrogen and oxygen molecules and atoms. Oxygen atoms, for example, strongly emit photons in two typical colors: **green** and **red**. The red is a **brownish red** that is at the limit of what the human eye can see, and although the red auroral emission is often very bright, we can barely see it… Since there is more atomic oxygen at high altitudes, the red aurora tends to be on top of the regular green aurora. The colors that we see are a mixture of all the auroral emissions. Just like the white sunlight is a mixture of the colors of the rainbow, the aurora is a mixture of colors. The overall impression [for usual auroras] is a **greenish-whitish** glow. Very intense

[348] http://dawn.ucla.edu/personnel/russell/papers/COSPAR_predict/
[349] Van Zele MA et al. "The equatorial ring-current energy during magnetic storms as related to Dst activity indices". *Journal of Atmospheric and Terrestrial Physics*. Volume 57, Issue 6, May 1995, Pages 719-724 .
[350] Liemohn MW. "Yet another caveat to using the Dessler-Parker-Sckopke relation." *Journal Of Geophysical Research*, Vol. 108, NO. A6, 2003
[351] http://www-spof.gsfc.nasa.gov/Education/wsubstrm.html
[352] http://helios.gsfc.nasa.gov/CME.mpg
[353] http://geomag.usgs.gov/faqs.php

aurora gets a **purple** edge at the bottom. The purple is a mixture of blue and red emissions from nitrogen molecules... The **green** emission from oxygen atoms has a peculiar thing about it.. Only after about a 3/4 second does the excited atom return to the ground state to emit the green photon. For the red photon it takes almost 2 minutes! If the atom happens to collide with another air particle during this time, it might just turn its excitation energy over to the collision partner, and thus never radiate the photon. Collisions are more likely when the atmospheric gas is dense, so they happen more often the lower down we go. This is why the red color of [atomic] oxygen only appears at the very top of an aurora [around 300 km], where collisions between air molecules and atoms are rare. Below about 100 km (60 miles) altitude even the green color doesn't get a chance. This happens when we see a purple lower border: the green emission gets quenched by collisions, and all that is left is the blue/red mixture of the molecular nitrogen emission.[354]"

"Oxygen is responsible for two primary auroral colors: *green-yellow* wavelength of 557.7 nanometers (nm) is most common, while the deep red 630.0 nm light is seen less frequently. Nitrogen in an ionized state will produce *blue* light [427.8 nm], while neutral nitrogen molecules create *purplish-red* auroral colors. For example, nitrogen is often responsible for the purplish-red [or magenta] lower borders and rippled edges of the aurora.[355]"

Red Aurora Origin and Notable Historical Occurrences: The red aurora is a pure red diffuse aurora seen during strong geomagnetic events. The red is from the excited *atomic oxygen* $O(^1D)$ emission at 630 nm [deep or blood-red], which is observed only at high altitude[356,357].

"In a typical auroral display, the light is a mixture of many colors. There's actually a fair bit of *blue*, but the human eye doesn't pick it up very well. We see much better in the *green* part of the spectrum, and there is a strong *yellowish-green* component [at 557.7 nm] in the light of a usual aurora, so we often see *green* displays. *Green* auroras, and green auroras with a *reddish lower border*, occur at an altitude near 100 kilometers (60 miles) above the earth...[358]"

"On the nights of March 12 and 13 [1989], many Alaskans saw ... a stunning display of the northern lights with great patches of red aurora... Three days earlier on the sun, enormous flares had erupted. Thursday's flare [in 1989], extending 70,000 miles into space, was one of the largest ever recorded... Rare, *all-red auroras* occur much higher, at 300 to 500 kilometers altitude and are associated with a large influx of electrons. These electrons are moving too slowly to penetrate deeply into the atmosphere: they actually have less energy than the electrons that create more common auroras. At this high altitude, the electrons lose their energy only to ... oxygen atoms. The process produces light as pure as that from a laser; there's no mixture of colors to confound the eye. Instead, light is produced at exactly 6300 and 6364 angstrom units on the spectrum, and we see *true red* aurora... It is associated with intense solar activity... The most impressive red aurora visible in North America during the last half-century occurred on February 11, 1958. And it really was visible in North America, seen in California and even Florida...[359]"

"February 11, 1958: The most spectacular display of the rarest Aurora Borealis was observed throughout North America. The Great Red Aurora caused an intense red light in the sky that even made the snow appear red in Alaska. It was so intense that it disrupted radio communication between the U.S. and the rest of the world.[360]" "In the Middle Ages a glowing red aurora over middle latitudes was seen by some Europeans as an omen of bloody battle or other impending doom.[361]"

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[354] http://odin.gi.alaska.edu/FAQ/
[355] http://www.eoearth.org/article/aurora_borealis
[356] http://www.rsbs.anu.edu.au/O2/O2_1_%20ElectronicConfig.htm
[357] http://www.atoptics.co.uk/highsky/auror3.htm
[358] http://www.gi.alaska.edu/ScienceForum/ASF9/918.html
[359] ibid.
[360] http://www.nasa.gov/exploration/thismonth/this_month_feb08.html
[361] http://science.nationalgeographic.com/science/space/universe/auroras-heavenly-lights.html

Discrete and Diffuse Auroras: The diffuse auroras (lacking structure) tend to be at the equatorward side of the auroral oval, whereas the discrete auroras (having east-west bands of luminosity) are further toward the pole and predominantly in the evening sector (*ISP* p. 420 and here[362]).

Jupiter and Saturn Aurora: Auroras are not confined to Earth but are seen on other planets having magnetospheres and atmospheres, including Jupiter[363] and Saturn[364,365]. (Their magnetospheres are discussed in *ISP* chapter 15. Jupiter's magnetic moment is about 20,000 times that of Earth.)

Auroral Oval: "The disturbances know as substorms are most clearly seen in the *auroral ovals*… [An auroral oval when viewed directly overhead] becomes a *circle* of about 20° radius centered about a point located 4° tailward of the instantaneous location of the dipole axis… In geographic coordinates, however, it is oval-shaped…" (*ISP* p. 420 and here[366]). "Cameras aboard satellites can look down at the aurora... What they see is a roughly circular strip, centered a little nightward of the magnetic pole, known as the *auroral oval*. During large magnetic storms the oval grows in size and may even reach the population centers of Europe and America… The narrow *auroral oval* gives the instantaneous shape of the aurora. The *auroral zone* ... is much more smeared out, because it is the long term statistical average of many aurora observations… Field lines starting from points of the dark region inside the auroral oval, which includes the magnetic pole, extend to even greater distances.[367]"

Polar Rain of Electrons: "Early researchers, who believed auroral electrons came from the Sun ... could not understand why the aurora was absent from the vicinity of the magnetic pole itself. From satellite data we now know that field lines inside the oval extend to the 'tail lobes'… Ultimately they probably lead into the solar wind, somewhere far on the nightside of the Earth… One expects very little plasma to come from that direction… Yet something does flow earthwards on those field lines, a thin *polar rain of fast electrons* with energies around 500 eV… Electrons of 500 eV are a completely different population [than solar wind electrons having about 1 – 2 eV], easily able to outrace the solar wind and follow field lines in any direction. They are too few to produce a visible aurora, but instruments aboard satellites readily observe them. They provide the best evidence that the tail lobes [of the magnetosphere] are indeed connected to the solar wind[368]." The high velocities are thought to result from magnetic X-line reconnection[369].

Atmospheric Electricity

Below 50 km, ions are produced mainly by cosmic rays—above 100 km they are mainly produced by solar EUV and solar X-rays. (See discussion above about Cosmic rays and ionization.) The peak rate of production and peak number density below 50 km are at about 15 km as previously discussed.

Some aspects of lightning etc. are off-topic for this Space Physics course, which is primarily concerned with space plasma environments, and are therefore mentioned only briefly. The textbook, *ISP*, does not discuss processes below the ionosphere.

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[362] Cogger LL et al "High space and time resolution ultraviolet auroral images from the Viking spacecraft" 1988 *Phys. Scr.* 37 432-436.
[363] Jupiter aurora:
• http://www.space.com/scienceastronomy/solarsystem/cassini_hubble_010311.html and
• http://www2.jpl.nasa.gov/galileo/hst6.html
• http://www.nature.com/nature/journal/v415/n6875/full/4151003a.html
[364] http://www.nasa.gov/mission_pages/cassini/media/cassini-20081112.html
[365] Stallard T et al, "Jovian-like aurorae on Saturn". *Nature* 453, 1083-1085 (19 June 2008)
[366] Holzworth RH and Meng CI. "Mathematical representation of the auroral oval" *Geophysical Research Letters*, Vol. 2, No. 9, Pages 377–380, 1975.
[367] http://www-spof.gsfc.nasa.gov/Education/wpcap.html
[368] ibid.
[369] http://adsabs.harvard.edu/abs/2006GeoRL..3319105A

Benjamin Franklin: was an important scientist in advancing knowledge about atmospheric electricity. His proposed Sentry Box experiment was carried out by D'Alibard (Thomas-François D'Alibard or Dalibard) in 1752 by extracting electricity from a low cloud[370]. He invented the lightning rod, saving many buildings and ship masts from lightning damage. His *Franklin chimes*—which were attached to a lightning rod and caused a brass ball to oscillate noisily between two bells—could demonstrate rising atmospheric charge (but were dangerous to have in the house!) What is the best tip shape for a lightning rod, sharp or blunt?—the answer remains somewhat unclear[371].

Global Atmospheric Electrical Circuit

Louis Guillaume Le Monnier (or Lemonnier) discovered *Fair Weather Electricity*, also called the *Fair Weather Current*[372]. Specifically, in 1752 he "reproduced [the proposed] Franklin [kite] experiment with an aerial, but substituted the ground wire with some dust particles (testing attraction). He went on to document the fair weather condition, the clear-day electrification of the atmosphere, and the diurnal variation of the atmosphere's electricity. G. Beccaria (1775) confirmed Lemonnier's diurnal variation data and determined that the atmosphere's charge polarity was positive in fair weather.[373]" (See also here[374].) This electrification is termed the *vertical atmospheric electric field*, or *potential gradient*, and it results in a current.

"Atmospheric electricity abounds in the environment; some traces of it are found less than four feet from the surface of the earth, but on attaining greater height it becomes more apparent… The air above the surface of the earth is usually, during fine weather, positively electrified, or at least … it is positive with respect to the earth's surface, [which is] relatively negative.[375]"

The positive charge in the air results in a continuous current to ground. A slide of RHH shows that the mean total [positive plus negative charges] air to earth current "density", as measured by Gringel et al at Laramie Wyoming in 1978, was found to be essentially constant for altitudes of 10 to 30 km, measuring $j_v = (5.1 \pm 0.3)$ pA m^{-2}. Additional slides by RHH show atmospheric *conductivity* rising steadily in the middle atmosphere and the ionosphere (up to the top of the curve at about 100 – 125 km). Several additional lines of data are presented affirming that conductivity rises with altitude at least from about 20 to 70 km. The electric field is seen to vary somewhat about a mean value as one ascends. (See further discussion of properties below.)

A detailed review of the *Global Atmospheric Electrical Circuit* and climate, as proposed by C. T. R. Wilson, is presented here[376] (though I have only glanced at it) and in an online textbook[377] (which covers many other topics in the Earth's Electrical Environment). This model posits a negative Earth and positive charge accumulation in the atmosphere, which arises from storm clouds, leading to a Fair Weather Current… There is a robustly demonstrated diurnal variation in the atmospheric electrical current, with maximal average current seen in the afternoon and evening in many places. It was suggested that this is related to thunderstorms arising typically in the afternoon over unevenly distributed land masses. RHH has studied aspects of this phenomenon[378]. Apparently the variation, as discussed only very briefly, has been found to have a planetary scale, so more study is needed, and the cause of the variation remains a topic of active research…

A table of properties of the Global Circuit may be seen here[379]. Estimates are as follows: The current *above* a thunderstorm to the ionosphere averages 0.5 to 1 A. The total integrated global current of positive charge to ground is 750 [1000 per RHH] to 2000 A. This translates to an average fair weather current density of 1 – 2.5 [2 per RHH] pA m^{-2}. The global fair weather charge transfer is 90 C km^{-2} y^{-1}. The total integrated global resistance to this flow from ionosphere to ground is estimated at only 100 Ω (per RHH) to 200 Ω. The electrical gradient in these fair weather conditions is 70 – 400 V/m depending on location, and RHH indicates

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370 http://en.wikipedia.org/wiki/D%27alibard
371 http://en.wikipedia.org/wiki/Lightning_rod
372 http://science.nasa.gov/newhome/headlines/essd15jun99_1.htm
373 http://en.wikipedia.org/wiki/Fair_weather_condition
374 http://en.wikipedia.org/wiki/Atmospheric_electricity
375 ibid.
376 http://arxiv.org/pdf/physics/0506077
377 http://www.nap.edu/openbook.php?record_id=898&page=206
378 Holzworth RH. "Hy-Wire Measurements of Atmospheric Potential." Journal Of Geophysical Research, Vol. 89, NO. D1, PAGES 1395–1401, 1984.
379 http://www.nap.edu/openbook.php?record_id=898&page=211

that the potential difference from ionosphere to ground is on the order of 100,000 V. (Of course, the potential difference between thunderclouds and ground is much higher.)

As seen in a complex slide shown by RHH (source not stated, my interpretation somewhat uncertain), atmospheric conductivity increases with increasing altitude up to the ionosphere, is greater in the day than at night, and is greater on disturbed PCA (increased *Polar Cap Absorption*[380]) days compared to quiet days. Polar Cap Absorption refers to increased radio wave absorption resulting in disrupted communications—this arises in the lower ionosphere and is related to increased solar flares and geomagnetic activity, etc. (See also earlier discussions about upper atmosphere conductivity.)

Another slide of RHH[381] shows how the vertical conduction current rising from the top of a thundercloud to the ionosphere begins vertically and then fans out approaching the ionosphere as it joins in the Global Electric Circuit.

Charge Separation, Thunderstorms, and Lightning

Charge separation in the atmosphere takes place in three ways[382]:
• *Thermodynamically*: In a thundercloud, small ice crystals or snowflakes form from water vapor. These collide with rime-growing *graupels*. *Graupel*[383] or "soft hail" consists of soft porous fragile 2-5 mm (or larger) icy objects formed by accretion and freezing of droplets of supercooled water onto snow crystals. (Supercooled droplets tend to maintain this state due to high surface tension opposing the expansion which accompanies freezing.) The collision of ice crystals with graupel having a quasi-liquid outer coating leads to a transient meniscus formation, which breaks off… The snow crystals carry off positive charge, and the graupels negative charge (the microscopic mechanism is not yet well known). Convection in the thundercloud carries the small positively charged ice crystals to the cloud top, whereas the heavier negatively-charged graupels staying in the mid-cloud. A macroscopic [electrical] dipole structure forms in the thundercloud, with positive above and negative at the base of the cloud. This is the so-called ice-ice non-inductive charging mechanism, a process studied at the UW by Marshall Baker (see here[384] and good review article here[385]). The potential difference is $10^8 – 10^{10}$ volts! This process happens at the -10 to -20 °C isotherm. Ice is a poor conductor, and below -40 °C spontaneous freezing occurs, interrupting this process.
• *By radiation ionization*: Cosmic ray and radioactivity decay radiation ionize air, and equal numbers of molecular-size positive and negative small ions are formed; air becomes (weakly) electrically conductive. Small ions are also attached to airborne dust (aerosol), which thus regularizes the number of small ions.
• *By collision ionization*: Lightning and other discharges in the thundercloud ionize air temporarily into electrically conducting channels.

Thunderstorms are depicted in many movies under "Florida Thunderstorms" and otherwise on YouTube.com, etc…

Lightning: A high voltage ionizing *discharge* such as lightning requires a high voltage producing a strong electric field, target particles to ionize (it cannot occur in a vacuum), and sufficient distance between particles to allow electrons to accelerate sufficiently to cause ionization upon striking their targets. [I have not reviewed this complex topic in greater detail.]

The mechanism of charge separation leading to lightning is discussed above. The sequence of events with lightning is discussed here[386], and will only be briefly mentioned now. "An initial bipolar discharge, or path of ionized air, starts from a negatively charged mixed water and ice region in the thundercloud. Discharge

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380 http://www.springerlink.com/content/w4047265235xn341/
381 Tzur and Roble. "The interaction of a dipolar thunderstorm with its global electrical environment". Jun 30, 1985. *Journal of Geophysical Research*, 90, 5989-599, p. 5993
382 http://dev.space.fmi.fi/~makelaa/fairw.html
383 http://en.wikipedia.org/wiki/Graupel
384 Ziegler CL et al. "A Model Evaluation of Non-inductive Graupel-Ice Charging in the Early Electrification of a Mountain Thunderstorm." *Journal Of Geophysical Research*, Vol. 96, No. D7, Pages 12,833–12,855, 1991
385 Saunders C. "Charge Separation Mechanisms in Clouds" Space Science Reviews. Volume 137, Numbers 1-4 / June, 2008
386 http://en.wikipedia.org/wiki/Lightning

ionized channels are known as *leaders*. The negatively charged leaders, generally a "*stepped leader*", proceed downward in a number of quick jumps (steps). Each step is on the order of 50 to 100 ft (15 to 30 metres) long but may be up to 165 ft (50 m). As it continues to descend, the stepped leader may branch into a number of paths. The progression of stepped leaders takes a comparatively long time (hundreds of milliseconds) to approach the ground. This initial phase involves a relatively small electric current…, and the leader is almost invisible when compared with the subsequent [return stroke] lightning channel… When a stepped leader approaches the ground, the presence of [induced] opposite charges on the ground enhances the strength of the electric field. The electric field is strongest on ground-connected objects whose tops are closest to the base of the thundercloud, such as trees and tall buildings. If the electric field is strong enough, a conductive discharge (called a *positive streamer*) can develop from these points [arising from the ground]… As the field increases, the positive *streamer* may evolve into a hotter, higher current leader which eventually connects to the descending stepped leader from the cloud. It is also possible for many streamers to develop from many different objects simultaneously, with only one connecting with the leader and forming the main discharge path… Once a channel of ionized air is established between the cloud and ground this becomes a path of least resistance and allows for a much greater current to propagate from the Earth back up the leader into the cloud. This is the *return stroke* and it is the most luminous and noticeable part of the lightning discharge…. An average bolt of negative lightning [leader] carries an electric current of 30 kiloamperes (kA), and transfers a charge of five coulombs and 500 MJ of energy. Large bolts of [negative] lightning can carry up to 120 kA and 350 coulombs. The voltage is proportional to the length of the bolt… An average bolt of positive lightning (the return stroke) carries an electric current of 300 kA or about 10 times that of negative lightning… Lightning leader development is not just a matter of the electrical breakdown of air, which is about *three million volts per meter*. The ambient electric fields required for lightning leader propagation can be one or two orders of magnitude less than the electrical breakdown strength. The potential gradient inside a well-developed return-stroke channel is in the order of hundreds of volts per meter [rather than millions of volts per meter] due to intense channel ionization, resulting in a true power output in the order of a megawatt per metre for a vigorous return stroke current of 100 kA. The average peak power output of a single lightning stroke is about a terawatt (10^{12} W) and the stroke lasts for around 30 microseconds…[387]"

The *Fermi Gamma-ray Space Telescope*[388], launched June 11, 2008, and engaged in looking for gamma ray bursts, found extremely intense bursts arising apparently from the Earth. The World Wide Lightning Location Network (WWLLN[389], directed by RHH) showed that these bursts are associated with Lightning: "During two recent lightning storms, Fermi recorded gamma-ray emissions of a particular energy [511 keV] that could have been produced only by the decay of energetic *positrons*, the antimatter equivalent of electrons.[390]" Such bursts are termed *Terrestrial Gamma-ray Flashes* (TGFs)[391], as opposed to gamma ray bursts arising from the Sun, Milky Way, or outside the Milky Way[392]. But how exactly are these positrons formed?

Radio Atmospherics including Whistlers

Lightning is associated with radio atmospherics or *sferics*[393] (impulses of broad-band radio EM radiation termed *radio atmospherics*) and *whistlers*. Other named sferics include static, tweeks, hiss, discrete transient emissions, periodic emissions, chorus, quasi-periodic emissions, triggered emissions, etc.[394].

Whistlers[395] start as sferics in the range of 1 to 30 kHz, thus in the *Very low frequency VLF* radio frequency part of the EM spectrum, with a maximum intensity usually at 3 to 5 kHz. The VLF radio noise travels to some extent along the Earth–Ionosphere "waveguide", is injected into the ionosphere at some point, and becomes coupled into and travels along paths ("*Whistler ducts*") paralleling magnetospheric field lines that extend far beyond the ionosphere. Why whistler radiation is contained and propagated along these

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387 ibid.

388 http://fermi.gsfc.nasa.gov/

389 WWLLN and TGFs:

• http://wwlln.net/ (general info)

• http://wwlln.net/publications/bryna.hazelton.2009GRL2008GL035906.pdf (correlation with TGFs)

390 http://www.sciencenews.org/view/generic/id/49288/title/Signature_of_antimatter_detected_in_lightning

391 http://en.wikipedia.org/wiki/Terrestrial_gamma-ray_flashes

392 http://en.wikipedia.org/wiki/Gamma-ray_burst

393 http://en.wikipedia.org/wiki/Radio_atmospheric

394 http://www.loscrittoio.it/Pages/MM-0700.html

395 http://en.wikipedia.org/wiki/Whistler_%28radio%29

magnetospheric ducts is complex, has been a topic of extensive investigation, and remains controversial in its details, but is thought to be due to reflective boundaries "formed by inhomogeneities of the electron density… At the other end of the field line, the signal crosses the (conjugate) ionosphere and propagates to the observing site… It may also be reflected strongly in the conjugate ionosphere and thus propagate several times through the magnetosphere (forming multi-hop whistlers)…There is an upper frequency limit for the [whistler] propagation, being $f_H/2$, half the local electron gyro frequency f_H[396]." Another author also states the upper frequency cutoff for whistlers is "the local electron plasma frequency or gyrofrequency, whichever is less"[397].

When whistler VLF EM waves are transduced to sound waves of the same frequency, they sound like a musical descending tone that lasts for a second or more. The descending frequency pattern results from faster travel time of higher vs. lower frequency VLF radiation. Audio examples of whistlers can be heard here[398].

I am unclear why whistlers often exhibit such a relatively pure (albeit descending) musical frequency. Perhaps (I speculate) this is some sort of resonance in the whistler tube waveguide akin to the Schumann resonance frequencies arising in the Earth–ionosphere waveguide cavity[399], but I have not looked into this topic in detail.

"Whistlers are categorized according to *hops*. One hop equals a single traverse between conjugate regions [of magnetospheric field lines]. A *one hop whistler* is generated by lightning in the opposite hemisphere [N or S] from the listener. It has traversed the magnetosphere just once and as a consequence, it tends to be a high pitched whistler of short duration. Since the causative sferic is very far away, it [the sferic] is rarely heard in association with single hop whistlers. *Two hop whistlers* are produced by lightning in the same magnetic hemisphere as the listener. The signal has traveled to the opposite hemisphere [N or S] and echoed back to the region of its origin. Subject to roughly twice the dispersion of a single-hop whistler, its duration is much longer than its one-hop cousin. Causative sferics can often be heard in very distinct association with 2-hop whistlers. Delays of 1.5 to 3 seconds between sferic and [2-hop] whistler are typical. Odd order hops (1, 3, 5, etc.) indicate opposite hemisphere lightning while even order progressions (2, 4, 6, etc.) follow from same hemisphere lightning. On occasion, whistlers generate multiple echoes or progressions known as echo trains. While trains exceeding about a dozen echoes are uncommon, progressions of more than 100 have been observed on rare occasions.[400]"

In a graph RHH provided of Winckler data, the sferic occurs first, followed in 2 or 3 ms by the lightning cloud-to-ground sky flash, followed a few ms later by the sprite (see below).

An RHH slide (source unknown) shows a sferic followed by a one-hop whistler and a more slowly descending 3-hop "echo" whistler. (This appears to be an exception to the above statement that the initiating sferic is not usually observed with odd-numbered whistlers.) Another RHH slide (source unknown) shows "*nose whistlers*"—these start at a mid-frequency and then evolve with ascending and descending frequency components (therefore shaped in a spectrogram somewhat like a nose facing toward lower time). A number of additional slides relating to whistlers, some of RHH data[401], were also shown (not all of which I understand fully). These include the sequence of changes in the ionosphere with lightning strokes: the visible light pulse; the E field changes including whistlers; and the more slowly rising and falling changes in the B field. WIPP rocket data [Wave Induced Particle Precipitation=WIPP, Wallops Island, 1987] was shown demonstrating increasing delays in arrival of whistler-like VLF radiation (or electrical field changes) with increasing altitude following the detection of the lightning event by the NLDN (*National Lightning Detection Network*)… An interesting diagram of 3-D patterns apparently of VLF radiation propagation along magnetospheric field lines was shown (origin unknown)—some of the propagation continues toward the tail without returning to Earth.

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396 Verö J, et al. "Whistler ducts and geomagnetic pulsation resonant field line shells near L = 2—are they identical? " *Journal of Atmospheric and Solar-Terrestrial Physics* Volume 59, Issue 14, September 1997, Pages 1855-1863

397 http://arxiv.org/pdf/0906.0429

398 http://spaceweather.com/glossary/inspire.html

399 http://en.wikipedia.org/wiki/Schumann_resonances

400 http://www.loscrittoio.it/Pages/MM-0700.html

401 Ya Qi Li, Holzworth RH, et al, "Anomalous Optical Events Detected by Rocket-Borne Sensor in the WIPP Campaign", *J. Geophys. Res.*, 1991, 96(A2), 1315–1326.

Transient Luminous Events (TLEs)

See video and composite diagram here[402] and high res video (probably montaged) here[403], plus *tendrils* especially well depicted here[404].

Some of these events were first seen in the 1950s, but were controversial and remained dubious, like "ball lightning"[405]. Eventually they were described in scientific publications in the 1990s and gradually gained acceptance. TLEs are secondary phenomena that occur in the upper atmosphere in association with underlying thunderstorm activity, and include[406]:

• *Red Sprites*: These are flashes of bright red light that occur in the upper mesosphere well above storm systems up to about 90 km. They are "massive but weak luminous flashes that appear directly above an active thunderstorm system and are coincident with cloud-to-ground [CG] or intracloud lightning strokes. Their spatial structures range from small single or multiple vertically elongated spots, to spots with faint extrusions above and below, to bright groupings which extend from the cloud tops to altitudes up to about 95 km. Sprites are predominantly red. The brightest region lies in the altitude range 65 – 75 km, above which there is often a faint red glow or wispy structure that extends to about 90 km. Below the bright red region, blue *tendril*-like filamentary structures often extend downward to as low as 40 km. Sprites rarely appear singly, usually occurring in clusters of two, three or more. Some of the very large events ... seem to be tightly packed clusters of many individual sprites. Other events are more loosely packed and may extend across horizontal distances of 50 km or more and occupy atmospheric volumes in excess of 10,000 cubic km... High speed photometer measurements show that the duration of sprites is only a few ms. Current evidence strongly suggests that sprites preferentially occur in decaying portions of thunderstorms and are correlated with large positive cloud-to-ground lightning strokes. The optical intensity of sprite clusters, estimated by comparison with tabulated stellar intensities, is comparable to a moderately bright auroral arc. The optical energy is roughly 10 – 50 kJ per event, with a corresponding optical power of 5 – 25 MW. Assuming that optical energy constitutes 1/1000 of the total for the event, the energy and power are on the order of 10 – 100 MJ and 5 – 50 GW, respectively.[407]" "They are rarely seen with the human eye, so they are most often imaged with highly sensitive cameras.[408]"

"Sprites may be horizontally displaced by up to 50 km from the location of the underlying lightning strike, with a time delay following the lightning that is typically a few milliseconds [see RHH slide of Winckler 1994 data], but on rare occasions may be up to 100 milliseconds... Sprites are sometimes, but not always, preceded, by about 1 millisecond, by a *sprite halo*, a pancake-shaped region of weak, transient optical emissions approximately 50 kilometres (31 mi) across and 10 kilometres (6.2 mi) thick. The halo is centered at about 70 kilometres (43 mi) altitude above the initiating lightning strike. These halos are thought to be produced by the same physical process that produces sprites, but for which the ionization is too weak to cross the threshold required for streamer formation.[409]" They have been observed from the ground, including by Walter Lyons[410] at Yucca Ridge near Ft. Collins, who looks across the flat terrain of Eastern Colorado in the direction of thunderstorms that are in Kansas and Nebraska 100 to 300 miles away and therefore positioned below the horizon [411].

• *Blue Jets*: These are "a second high altitude optical phenomenon, distinct from sprites, observed above thunderstorms using low light television systems. As their name implies, blue jets are optical ejections from the top of the electrically active core regions of thunderstorms. Following their emergence from the top of the thundercloud, they typically propagate upward in narrow cones of about 15 degrees full width at vertical

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402 http://www.esa.int/esaMI/Celsius/SEM60KC4VUE_1.html
403 http://esamultimedia.esa.int/images/ISS/2005-09-27_Lighting_story/ISS-lyn.avi
404 http://quicktime.oit.duke.edu/news/sprites.mp4
405 http://en.wikipedia.org/wiki/Ball_lightning
406 http://en.wikipedia.org/wiki/Transient_luminous_event
407 http://elf.gi.alaska.edu/
408 http://www.nssl.noaa.gov/primer/lightning/ltg_tle.html
409 http://en.wikipedia.org/wiki/Sprite_%28lightning%29
410 Observations of Red Sprites by Walter Lyons:
• Lyons WA. "Characteristics of luminous structures in the stratosphere above thunderstorms as imaged by low-light video". *Geophysical Research Letters*, Vol. 21, No. 10, Pages 875–878, 1994
• http://ams.confex.com/ams/pdfpapers/65547.pdf
411 http://www.physorg.com/pdf10961.pdf

speeds of roughly 100 km/s (Mach 300), fanning out and disappearing at heights of about 40 – 50 km. Their intensities are on the order of 800 kR [kilo-rayleigh] near the base, decreasing to about 10 kR near the upper terminus. These correspond to an estimated optical energy of about 4 kJ, a total energy of about 30 MJ, and an energy density on the order of a few mJ/m^3. Blue jets are not aligned with the local magnetic field.[412]" "Blue jets emerge from the top of the thundercloud, but are not directly associated with cloud-to-ground lighting… Blue jets last a fraction of a second and have been witnessed by pilots.[413]" [The *rayleigh*, a unit of luminous flux, is defined as 10^{10} photons per second in a column of 1 square meter area, and is used to express air glow of the night sky (typically 250 R) and auroras (up to 1000 kR)[414]. (See also *ISP* p. 475.]

• *ELVES*: [plural of *ELVE*, a somewhat strained acronym for *E*(mission of) *L*(ight and) *V*(ery low-frequency perturbations from) *E*(lectromagnetic pulse sources]. "Elves are rapidly expanding disk-shaped regions of glowing that can be up to 300 miles across. They last less than a thousandth of a second, and occur above areas of active cloud to ground lightning. Scientists believe elves result when an energetic electromagnetic pulse extends up into the ionosphere. Elves were discovered in 1992 by a low-light video camera on the Space Shuttle.[415]"

Other TLEs have also been mentioned. *Halos* for instance are horizontal featureless emissions of reddish light immediately preceding sprites arising in the same location.

Electrical Model for TLEs: The buildup of charge in a thundercloud is described in the *Quasi-Electrostatic Field Model*, positive charge at the top, and negative at mid or lower levels (both within the cloud). A negative shielding layer builds up electrostatically immediately above a thundercloud in response to the upper cloud accumulation of positive charge. The positive cloud charge is discharged by CG [charge to ground] lightning, but the negative shielding layer persists longer and is unbalanced. It therefore induces a positive high-altitude charge accumulation or polarization at about 90 - 100 km (RHH terms this *atmospheric polarization*). A strong E field develops, and sprites arise as current passing between these two oppositely charged layers.

However, data cited by RHH of Cummer et al 1999 (article not identified) is said to indicate that the *charge moment* (expressed in C km) for sprites can be substantially smaller than the charge moment required to produce conventional lightning breakdown at 50 km, and that horizontal currents and additional phenomena including may be involved…

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412 http://elf.gi.alaska.edu/
413 http://www.nssl.noaa.gov/primer/lightning/ltg_tle.html
414 http://en.wikipedia.org/wiki/Rayleigh_%28unit%29
415 ibid.