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by Sten Odenwald
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by George Gloeckler
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by Tim Bastian
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Observations of solar and stellar eruptions, flares, and jets

by Hugh Hudson
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Observations of solar and stellar eruptions, flares, and jets

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Models of coronal mass ejections and flares

by Terry Forbes
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Shocks in heliophysics

by Merav Opher
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Fig. 7.4. Meridional cut from a heliosphere simulation including the plasma and the neutral H atoms (Opher, 2009). The contours are the plasma temperature. The blue region is the region beyond the heliopause; the red the heliosheath and the green the region upstream the termination shock. The black lines are the interstellar magnetic field; and the grey lines are the plasma streamlines. The (projected) trajectories of the Voyager spacecraft 1 and 2 are also indicated.
Shocks in heliophysics

Fig. 7.5. Shock reference frames: a) normal-incident and b) de Hoffman-Teller frame.
Fig. 7.6. Substructure terminology of supercritical, fast mode, collisionless shock layer (from Scudder et al., 1986).
Fig. 7.7. Crossing of the termination shock by Voyager 2. Daily averages of solar wind speed $V$ (a), density $N$ (b), temperature $T$ (c), east-west flow angle (d), north-south flow angle (e) and magnetic field magnitude (f). Flow angles are in the RTN coordinate system, where R is radially outwards, T is parallel to the plane of the solar equator and positive in the direction of the Sun’s rotation, and N completes a righthanded system. The east-west angle is the angle in the R-T plane and the north-south angle is the angle out of the R-T plane. The dashed line shows the termination shock crossing, where the speed decreases by a factor of about two, the density increases by a factor of two, the proton temperature increases to near 100,000 K, and the flow is deflected consistent with flow away from the nose direction of the heliosphere, that is, the direction toward the local interstellar medium flow. (From Richardson et al., 2008)
Fig. 7.8. Representative profiles of 20 MeV proton events for different positions of the observatory with respect to a shock. The draping of the field lines around the ejecta is only a suggestion. From Cane et al. (1988).
Particle acceleration in shocks

by Dietmar Krauss-Varban
Fig. 8.1. Iso-contours of shock heating, expressed as the ratio between downstream to upstream ion temperature $T_{i2}/T_{i1}$, as a function of shock-normal angle $\theta_{Bn}$ (fixed $M_A = 2$) and Alfvén Mach number $M_A$ (fixed $\theta_{Bn} = 45^\circ$) for low $\beta$ plasmas. Derived from standard Rankine-Hugoniot conditions for fast shocks, assuming a specific heat ratio $\gamma = 5/3$. The graphs show that for a wide range of angles, there can be very substantial downstream heating at sufficiently low plasma $\beta$, as present in much of the solar corona. Such extreme heating may help form a seed population for further acceleration.
Particle acceleration in shocks

Fig. 8.2. Difference between normal-incidence frame (NIF) and de Hoffman-Teller frame (HTF) at fast-mode shocks. The NIF is the shock frame in which the upstream flow is aligned with the shock normal. As a consequence, the upstream out-of-plane motional electric field is non-zero and, from Maxwells equations in steady state, actually the same downstream. Transformation to the HTF is along the plane shock surface until the upstream flow vector coincides with the magnetic field. Therefore, the motional electric field vanishes, and the description of particle motion simplifies to energy and magnetic moment conservation. When back-transforming to the NIF, one discovers that reflected particles have attained a speed close to twice the transformation velocity VHT, which evidently becomes very large for nearly perpendicular shocks.
Fig. 8.3. Example of a two-dimensional (2-D) hybrid simulation of the solar wind–magnetosphere interaction (from Krauss-Varban et al., 2008). Shown are contours of the magnetic field lines (upstream IMF angle $\theta = 45^\circ$) and the normalized parallel ion temperature $T_\parallel$, as a proxy of ion acceleration. As well-documented in many observations of the Earth’s bow shock, the ion foreshock starts close to $\theta_{\text{Bn}} = 45^\circ$ with energized and backstreaming ions, and simultaneous excitation of waves (visible in the field line undulations). Conversely, at this scale, and with the number of pseudo-particles used in the simulation, there are virtually no upstream ions at larger shock-normal angles.
Fig. 8.4. Scatter-plot of all interplanetary, forward-propagating fast-mode shocks observed with the ACE satellite and in the ACE magnetometer database, in the period 1998 to 2003 ($M_A$ and $\theta_{Bn}$ as reported from the ACE magnetometer team database). Top: ordering with shock-normal angle $\theta_{Bn}$. Bottom: ordering with $1.0 - \cos(\theta_{Bn})$, which takes into account the solid angle viewing statistics. Even in this corrected plot, one can see a slight preference for oblique angles, as expected from the solar wind Parker spiral. More importantly, it is evident that most IP shocks are rather slow. And, while they typically will have a detectable energetic particle environment, the associated energy range and fluxes are of little interest in the context of detrimental Space Weather effects, except for the rare, higher $M_A$ cases. (from Gosling et al., 1984)
Fig. 8.5. Sketch of upstream proton distributions (perpendicular and parallel to the ambient magnetic field) in the shock frame from planar, 2-D hybrid shock simulations at quasi-parallel ($\theta = 30^\circ$) and oblique ($\theta = 60^\circ$) angles. As in many documented observations of the Earths bow shock and at sufficiently high Mach number IP shocks, at quasi-parallel shock-normal angles, protons cannot only easily travel upstream and generate waves, but they also easily scatter in these self-generated waves to form a diffuse distribution that forms a contiguous cloud of both upstream ($v_\parallel > 0$) and downstream-directed ($v_\parallel < 0$) particles. Conversely, at oblique shocks, only a highly-dilute upstream-propagating beam with enhanced perpendicular energy is found, and even that can only be seen with very good particle statistics, in simulations. Unlike the quasi-parallel shock, a higher Mach number does not help initially, but typically makes it more difficult for ions to make it upstream, in the first place.
Fig. 8.6. Magnetic field line contours and (a) total magnetic field, and (b) parallel temperature $T_\parallel$ normalized to upstream in a subset of a 2-D hybrid simulation of an oblique shock ($\theta = 50^\circ$; from Krauss-Varban et al., 2008). It can be seen how compressional waves generated by dilute beams disrupt the shock and change the local $\theta_0$, in turn allowing more upstream wave and particle production than expected at the oblique shock. This process appears to enhance upstream energetic proton fluxes by two to three orders of magnitude.
Energetic particle transport

by Joe Giacalone
Fig. 9.1. An illustration of the energy spectrum of cosmic rays in the heliosphere based on spacecraft observations. A phenomenological description of the various types of energetic particles indicated in this figure is given in Section 9.1 (see also Fig. 3.1).
Fig. 9.2. The cosmic-ray spectrum observed at Earth’s orbit.
Fig. 9.3. The intensity of energetic protons as a function of time for a solar-energetic particle event associated with a coronal mass ejection on 10/19/1989.
Fig. 9.4. Various representations of the orbit of a single proton moving in an irregular magnetic field, that contains a variety of scales, including those that are comparable to the gyroradius of the proton. The upper left plot shows the cosine of the pitch angle as a function of time, and the lower left plot shows the position along the direction of the average magnetic field (z direction), as a function of time. The right plot shows the position of the particle as projected onto the x-z plane.
Fig. 9.5. The trajectories of two electrons moving in a spatially irregular (but static in time) magnetic field. In the upper left plot, the magnetic field depends on only two spatial coordinates, in which case theory requires that the particle remains within one gyroradius of a particular field line, which is the case. In the right panel, the field depends on all three spatial coordinates and the electron is not strictly tied to the same magnetic line of force.
Fig. 9.6. The inferred value of the ratio of perpendicular to parallel diffusion coefficients for energetic ions, based on the observed particle streaming direction and magnetic field, during the passage of a corotating interaction region as seen by the Wind spacecraft at 1 AU (adapted from Dwyer et al., 1997).
Energetic particle transport

Fig. 9.7. The cross-field diffusion coefficient based on three different analytical approximations (curves) and numerical simulations (filled-in circle symbols).
Fig. 9.8. Individual charged particles with different energies (as indicated) moving in an irregular magnetic field (grey lines). This figure is from Giacalone and Jokipii (1999).
Fig. 9.9. The observed power spectrum of the latitudinal component of the interplanetary magnetic field (from Jokipii and Coleman, 1968).
Fig. 9.10. Solution to the one-dimensional diffusion equation for a point-source release at a position 1 AU away from an observer: \( f(1, t) \) from Eq. (9.25).
Fig. 9.11. A solar energetic particle (SEP) event, associated with an impulsive solar flare, seen by ACE/ULEIS. Each dot represents the detection of a particle by the detector. Two distinct events are shown. Figure adapted from Mazur et al. (2000).
Fig. 9.12. An illustration a possible interpretation of the intermittent intensity variations seen within the events shown in Fig. 9.11. The plots show 5 magnetic field lines, 3 of which are populated with field lines at $t = 0$ (far left panel), and the other 2 are not. An observer is indicated towards the upper part of each plot. As the observer moves passed various field lines which are advected with the solar wind flow, it sometimes sees energetic particles and sometimes not, depending on whether the field lines it is presently seeing is connected to the source.
Fig. 9.13. Climax neutron monitor daily count rate of neutrons produced by the interaction of a primary cosmic ray with Earth’s atmosphere. The meaning of A is defined in Fig. 9.14.
Fig. 9.14. Drift motion of cosmic rays in the heliosphere for two different solar magnetic-polarity cycles. The two polarities of the solar magnetic field are separated by the heliospheric current sheet. The value of $A > 0$ during the period in which the solar magnetic field is outward in the north and inward in the south. The termination of the solar wind is also shown.
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Energy conversion in planetary magnetospheres

by Vytenis Vasyliunas
Fig. 10.1. Schematic time history of geomagnetic field variation for two characteristic magnetic storms. Time range: several days. Vertical variation range: $\sim 100 - 200\text{nT}$. SSC: storm sudden commencement. SO: storm onset. The top panel shows the storm development in response to a characteristic interplanetary coronal mass ejection (ICME), and the bottom panel that for the passage of a corotating interaction region (CIR). (Figure adapted from Tsurutani et al., 2006)
Fig. 10.2. Schematic diagram of an auroral substorm. View from above the north pole, circles of constant geomagnetic latitude, Sun toward the top (Akasofu, 1964)
Fig. 10.3. (a) Left: deformation of magnetotail field by external plasma flow. Solid lines: magnetic field lines. Dashed arrows: plasma flow direction. Dotted line: magnetopause. (b) Right: deformation of planetary magnetic field by torque from magnetospheric plasma element (black sphere). Solid line: actual magnetic field line. Dashed line: undistorted magnetic field line. Arrow on planet’s surface: direction of rotational motion.
Energy conversion in planetary magnetospheres

Fig. 10.4. (Simplified) general energy flow chart for planetary magnetospheres and ionospheres. Rectangular boxes: energy reservoirs. Rounded boxes: energy sinks. Lines: energy flow/conversion processes. (Note: only the energy-flow paths are shown, not the mass-flow paths.)
Fig. 10.5. Possible changes of the magnetic field topology in the magnetotail of a solar-wind-dominated magnetosphere. The diagram (from Vasyliunas, 1976) is shown rotated to facilitate comparisons with diagrams of filament eruptions in, e.g., Chapter 6: the solar wind here blows from bottom to top, rather than from left to right as in the original and in the analogous figures of Chapter 10 in Vol. I. Each panel in the sequence shows a side view of the magnetic field (left), the outline of the X lines seen from above the north pole (right), and a top-down view of the mapping of the reconnection region onto the Earth (top)
Energization of trapped particles

by Janet Green
Energization of trapped particles

Fig. 11.1. Schematic depiction of Earth’s electron radiation belts courtesy of the NASA/Goddard Space Flight Center Scientific Visualization Studio.
Fig. 11.2. Schematic diagram showing the Lorentz force as a particle moves into the magnetic field gradient at Earth’s poles.
Fig. 11.3. Schematic diagram for the gradient-B drift.
Energization of trapped particles

Fig. 11.4. Schematic diagram of particle motion in a dipole magnetic field.
Energization of trapped particles

Fig. 11.5. Radiation-belt electron flux ($10 \log(\text{counts/sec})$) as measured by the Proton Electron Telescope (PET) Elo channel that measures electrons with energies $> 1.5$ MeV on the SAMPEX satellite. The data are averaged in $0.25L$ and 1 day bins.

Fig. 11.6. Radiation-belt proton flux (number per cm$^2$-s-str on a logarithmic scale) from the SEM-2 instrument that measures protons with energies between 2.5 and 6.9 MeV on the NOAA-15 satellite. The data are averaged in $0.2L$ and 1 day bins.
Energization of trapped particles

Fig. 11.7. Schematic diagram of an electron in drift resonance with a ULF wave. The left panel shows two electrons labeled e1 and e2, the direction of the wave electric field, and the direction of the particles EXB drift at time $t=0$. The right panel shows the same properties half a wave period and electron drift period later.
Fig. 11.8. Schematic diagram showing how a distribution of electron spreads in L where the black circle represents Earth and the light circle represents the drift path about Earth. Electrons spread uniformly towards and away from Earth.
Energization of trapped particles

Fig. 11.9. Schematic diagram showing how a distribution diffuses in pitch angle and energy while interacting with a VLF wave.
Fig. 11.10. Schematic diagram showing the adiabatic motion and flux decrease observed by a satellite caused by the “Dst effect.” The blue circle represents Earth. The left most box represents the spectrum of electron flux versus energy at a position initially Earthward of the satellite. The right most box shows how that spectrum appears after the electrons move outward to the position of the satellite. The entire spectrum shifts to lower energy generally resulting in a measured flux decrease at constant energy.
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Flares, CMEs, and atmospheric responses

by Tim Fuller-Rowell and Stanley C. Solomon
Fig. 12.1. Ionospheric properties during a geomagnetic storm. The upper panel shows a comparison of CHAMP neutral density measurements at 400 km altitude with a numerical simulation, for a stormy period in January 2005. The lower panels show, from top to bottom, estimates of auroral power, Joule heating in the Northern and Southern hemispheres, kinetic energy deposition, and nitric oxide infrared cooling rates (courtesy of M. Fedrizzi).
Fig. 12.2. Statistical pattern of auroral energy input derived from TIROS/NOAA satellite data during a single transit of the polar region (from Evans et al., 1988).
Flares, CMEs, and atmospheric responses

Fig. 12.3. Simulated response of the $F$-region plasma densities (left) and neutral winds and temperature (right) at the peak of the storm event at 1:30 UT on 2005/01/08 in the Southern hemisphere. Both represent the response in the upper thermosphere and ionosphere at about 300 km altitude. Peak neutral winds are in excess of 800 m/s (courtesy of M. Fedrizzi).

Fig. 12.4. Neutral winds in the lower thermosphere at around 140 km altitude at the peak of the storm at 1:30 UT on 2005/01/08 in the Southern hemisphere (right), and at the same UT on the quiet day preceding the storm (left). Winds in the lower thermosphere increase dramatically in response to the storm, but peak magnitudes are about half those at 300 km. Lower thermosphere winds driven by the storm also tend to be slower to dissipate, sometimes acting as a "flywheel" driving Poynting flux upward from the thermosphere/ionosphere to the magnetosphere (courtesy of M. Fedrizzi).
Fig. 12.5. Simulation of the response of the neutral winds at mid and low latitudes at 250 km altitude, shortly after a sudden increase in high-latitude Joule heating. The region within 50° of the geographic equator is shown at 15 UT, three hours after the increase in high-latitude magnetospheric forcing, equivalent to a $K_p \sim 7$. Wind surges of $\sim 150$ m/s are produced, mainly on the night side.
Fig. 12.6. Numerical simulations of the equatorward extent of the "composition bulge" at 12:00 UT, for equivalent storms in the Northern hemisphere for summer (left), winter (middle), and equinox (right). The seasonal circulation assists the transport to low latitudes in the summer hemisphere and inhibits the transport in winter.
Fig. 12.7. Changes in the column-integrated O/N$_2$ ratio during the November 2003 Halloween storm (from review by Crowley et al., 2008; after Meier et al., 2005). The data are from the GUVI instrument on the TIMED satellite (Paxton et al., 1999). Five days of GUVI data are plotted as individual dayside orbits and assembled as a montage, time runs from right to left. The storm event on day 324 causes a decrease in the column integrated O/N$_2$ in both hemispheres. The Southern hemisphere depletion penetrates further equatorward as expected from the transport effect of the global seasonal circulation.
Fig. 12.8. The storm-time response of the ionosphere reveals both seasonal and local-
time (LT) dependencies. The figure shows the diurnal variation of the natural log-
arithmetic of the ratio of the storm-to-quiet peak $F$-region plasma density, $NmF2$, at
Argentine Islands (65°S) for 1971-1981. For reference, a decrease of 0.5 indicates a
decrease in the plasma density by 40% (from Rodger et al., 1989).
Fig. 12.9. Illustration of the large enhancement “bulge” in TEC at mid latitudes during a geomagnetic storm, and showing the plume of plasma (storm-enhanced density, or SED) connecting the bulge to the high latitudes (courtesy of J. Foster).
Fig. 12.10. Order of magnitude increases in over-the-satellite electron content (OSEC) above 400 km during the Halloween storm of 28 October 2003 as measured by the CHAMP satellite (from Mannucci et al., 2005).
Fig. 12.11. Satellite observations of the erosion of the plasmasphere during a storm, from observations by the IMAGE satellite before and after the Halloween storm of 28 October 2003 (courtesy of J. Goldstein). The plasmaspheric tail, or plume, can be seen in the dusk section during the storm event.
Fig. 12.12. Vertical plasma drift measured at the Jicamarca incoherent scatter radar facility in Peru on the magnetic equator (from Fejer et al., 2007) for a storm in November 2004. The thin line is the quiet day climatological drift.
Fig. 12.13. Example of GOES XRS measurements during a large (X1.5) solar flare.
Fig. 12.14. Inferred flare enhancement spectrum in the soft X-ray region during the major flare on 28 October 2003, from Rodgers et al. (2006). This is an estimate of the amount of solar photon flux produced by the flare alone, i.e., the underlying pre-flare spectrum has been subtracted.
Fig. 12.15. Solar emission spectrum near the peak of the 28 October 2003 flare obtained from measurements by the TIMED/SEE instrument, compared to a spectrum obtained shortly before the event.
Fig. 12.16. Measurements from instruments on the SORCE satellite (Woods et al., 2004, 2008) showing the time dependence of flare enhancements in various spectral regions (from Woods et al. 2008).
Fig. 12.17. Energy deposition in the upper atmosphere as a function of wavelength and altitude during a solar flare.
Fig. 12.18. Model calculation of electron density enhancement in the $E$ region at high solar zenith angle (at the Sondrestrom radar site in Greenland) for the 28 October 2003 flare, using the spectrum shown in Figure 12.15 as input to a photoionization/photo-electron model. Black, lower-density curve: pre-flare; grey, higher-density curve: flare. The enhancements seen are commensurate with radar observations of the flare effect.
Flares, CMEs, and atmospheric responses

Fig. 12.19. Comparison of total electron content enhancements during the 28 October 2003 flare, observed by the global network of differential GPS stations, and modeled using the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM). Total electron content is the vertically-integrated column electron content in units of $10^{16} \text{m}^{-2}$.
Flares, CMEs, and atmospheric responses

Fig. 12.20. Thermospheric density enhancements measured by accelerometers on the CHAMP satellite (altitude ∼400 km) and GRACE satellite (altitude ∼490 km) during the 28 October 2003 flare (Sutton et al., 2006).
Fig. 12.21. Calculated enhancement and recovery of key thermospheric parameters in response to the 28 October 2003 flare using the NCAR TIE-GCM. Panel 1: neutral temperature at 400 km; panel 2: neutral mass density at 400 km; panel 3: electron density at 300 km; panel 4: nitric oxide density at 110 km. All calculations are at 12 noon local time at the equator.
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Energetic particles and manned spaceflight

by Stephen Guetersloh and Neal Zapp
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Energetic particles and technology

by Alan Tribble
Fig. 14.1. Spacecraft floating potential vs. grounding options (from Tribble, 2000).
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Fig. 14.2. Spacecraft charging in the geosynchronous environment at times of ICME-induced magnetic storms (from Tribble, 2003).
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Fig. 14.4. International Space Station trapped-radiation environment (left) and total dose vs. shielding depth (right).
Fig. 14.5. Metal-oxide semiconductor field-effect transistor (MOSFET).
Energetic particles and technology

Fig. 14.6. The galactic cosmic ray annual fluence ($A$ is the atomic mass number; $A\text{MeV}$ is energy per nucleon). From Wilson et al. (1997).
Fig. 14.7. Examples of monthly fluence of particles from solar particle events. From Wilson et al. (1997).
Fig. 14.8. Characteristic energetic particle fluxes as a function of the linear energy transfer (LET) of these particles, for the galactic cosmic ray (GCR) background and for different solar particle events (SPEs). In order to estimate the frequency of an interaction (e.g., upset, latchup, ...) within a device for a given type of SPE or GCR background, one first identifies the threshold value of LET where the interaction will occur (this is usually obtained from the manufacturer). Then one multiplies the integral flux $F_{\text{case}}$ value corresponding to the LET threshold by the duration $\delta t$ of the event or time interval in question and by the solid angle $\delta \omega$ from which the particles can reach the device: $f_{\text{case}}(LET) = F_{\text{case}} \delta t \delta \omega$. 