J. Astrophys. Astr. (2000) **21**, 431–437

Heliospheric Magnetic Fields, Energetic Particles, and the Solar Cycle

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Abstract. The heliosphere is the region filled with magnetized plasma of mainly solar origin. It extends from the solar corona to well beyond the planets, and is separated from the interstellar medium by the heliopause. The latter is embedded in a complex and still unexplored boundary region. The characteristics of heliospheric plasma, fields, and energetic particles depend on highly variable internal boundary conditions, and also on quasi-stationary external ones. Both galactic cosmic rays and energetic particles of solar and heliospheric origin are subject to intensity variations over individual solar cycles and also from cycle to cycle. Particle propagation is controlled by spatially and temporally varying interplanetary magnetic fields, frozen into the solar wind. An overview is presented of the main heliospheric components and processes, and also of the relevant missions and data sets. Particular attention is given to flux variations over the last few solar cycles, and to extrapolated effects on the terrestrial environment.

Key words. Heliosphere—heliopause—termination shock—solar cycle—energetic particles—interplanetary neutrals—anomalous component—cosmic rays—interplanetary magnetic fields.

1. Introduction

Heliospheric processes are mostly, but not exclusively controlled by solar activity that, in turn, reflects internal solar dynamics. Up to radial distances of 10 to 15 AU, solar wind (SW) streams directly control heliospheric structure. Fast streams from coronal holes interact with the slow wind; as a result, merged interaction regions (MIRs) appear which finally produce global merged interaction regions (GMIRs) in the distant heliosphere. Around solar minimum, during periods of stable coronal structure, forward and reverse shocks develop at the interfaces beyond 1 AU, and form corotating interaction regions (CIRs). Frozen-in magnetic fields are of solar origin, and alternating between inward and outward polarity sectors in the equatorial region, while both polar regions are unipolar. The two polarities are separated by the heliospheric current sheet (HCS), the heliospheric extension of the coronal neutral line.

Farther from the Sun, external influences become more competitive. Neutral atoms from interstellar space penetrate deep into the heliosphere before being ionized by charge exchange and solar UV radiation, and are then carried out by magnetic fields frozen into the solar wind; such pick-up (PU) ions get accelerated at the SW termination shock (TS), and can then access the inner solar system again as mainly singly charged anomalous cosmic rays (ACRs). With increasing energy, fully ionized galactic cosmic rays (CRs) can also access the inner heliosphere. In addition to the SW and the ionized component of the local interstellar medium (LISM), each of the PU, ACR and CR components influence the position and structure of the heliospheric boundary region. Reconnection between interstellar and heliospheric fields may also modify the boundary. Those distant processes, however, have only minute effects at 1 AU in comparison to SW ram pressure and local magnetic fields. The main role of high-energy particles in heliospheric studies is to provide information on heliospheric structure and on acceleration and propagation processes. As remote sensing of plasma processes is difficult, this is an important role. With increasing particle energy, information on larger and larger features of the heliosphere is gained.

The extent of external influences on heliospheric and possibly even on solar behaviour is a non-trivial problem. Interstellar conditions are expected to change rather slowly, thus at least the variable component of the influence should be small. There have been claims that planetary motion may assist in synchronizing the clock of the solar dynamo, even if the energy densities of the mass motions involved in the dynamo action vastly exceed planetary effects. On longer terms, the changing interstellar environment may certainly influence the extent of the heliosphere, and some back-reaction of those boundary conditions on SW sources and on flare and CME structure might result. Although SW is supersonic and excludes direct hydrodynamical inward propagating effects, it might be that energetic particles, supersonic thermal and suprathermal electrons, or magnetic fields provide some subtle ways of influencing the inner boundary of the heliosphere.

Magnetic fields and energetic particles, and their cyclic behaviour will be reviewed with particular emphasis on recent space-based measurements. Possible long-term effects of the variability of the Sun and of its galactic environment will also be discussed.

2. Heliospheric data sources

2.1 *Ground-based observations*

Prior to the advent of space age, variation of galactic CR intensity with solar activity provided the first clue for the presence of a changing magnetic shield between Earth at 1 AU and the distant galactic environment. For a vivid recollection on those early days, see J. A. Simpson's report (1985). It soon became known that CR intensity (as measured by secondary particles at sea level or higher in the atmosphere) is reduced not only during the general periods of sunspot maxima, but also short-term decreases (Forbush-decreases) appear after some bursts of solar activity, often also associated with geomagnetic disturbances. A rarer type of intensity changes called ground-level events (GLEs) is associated with solar energetic particles of sufficiently high energy (typically several GeV), so that secondaries can reach ground level. Since the early 40s about 60 such GLEs have been detected. Ground-based observations of magnetic field variations also provided important clues for the understanding of magnetospheric current systems and for their dependence on solar variability, and also for heliospheric fields.

The monitoring of CR flux levels by an extensive network of neutron and muon monitors still contributes to the understanding of both solar and global heliospheric processes. Recording of intensity variations of GeV to tens of GeV CR particles is more efficient by ground-based monitors than by space instruments, due to the much smaller size of the latter. Also, the terrestrial magnetosphere as a powerful magnetic analyzer helps to reconstruct the energy spectrum and the directional distribution for solar events. Neutron monitor data can be accessed through the cosmic ray pages of several groups active in that field (e.g. Chicago, Moscow, Yakutsk).

2.2 *Near-Earth missions*

IMP-8, launched in October 1973, has monitored local interplanetary (and to some extent also magnetospheric) conditions ever since. It has provided a 1 AU baseline e.g. to the Pioneer, Voyager, Helios, and Ulysses deep-space missions. The mean orbital radius of IMP-8 is about 35 Earth radii, with some variation during the mission, and it spends about 7 to 8 days of its 12.5 day orbit in the SW. After more than 26 years, most IMP-8 instruments still work well, performing at least part of their original tasks. Data from IMP-8 now cover 3 solar minima, and are in progress to cover the 3rd maximum. SW plasma parameters, magnetic fields, and energetic particles have been almost continuously covered during the past 26 years, and most data bases are accessible e.g. through the search machines CDAWeb, OMNIWeb and COHOWeb; COHOWeb also contains a wide range of other heliospheric spacecraft data in an easily (also graphically) accessible form. A recent review on IMP-8 performance, with the description of experiments and data sets as well as correlative studies with L1-based spacecraft, can be found in Paularena & King (1999).

SAMPEX, on low Earth orbit, should be mentioned for its ACR results. Mostly singly charged ACR ions, of interstellar neutral atom origin, have been detected since 1992 by extensively using the Earth's magnetosphere as a magnetic analyzer. Also, ACRs trapped inside magnetospheric radiation belts (after losing one or more additional electrons in the residual atmosphere) have been much studied.

Still close to 1 AU, on halo orbit around the L1 Lagrangian point upstream of Earth, was ISEE-3 between 1978 and 1982. It was the first spacecraft on that orbit, and studied SW, magnetic fields and low-energy particles undisturbed by terrestrial effects. The Wind spacecraft, launched in 1994, has also spent some time around that point. SOHO, launched late 1995 and ACE, launched in 1997 are now on similar orbits, their main objectives being observation of the Sun, and of SW and energetic particle composition, respectively.

2.3 *Deep-space missions*

The missions with utmost impact on both planetary and outer heliospheric research were the Pioneer and Voyager deep-space probes. Pioneer-10 was launched in 1972, Pioneer-11 in 1973, Voyager-1 and Voyager-2 both in 1977. While the Pioneer program was formally terminated in 1997, Pioneer-10 is still tracked. Since the last planetary encounter in 1989, all four probes have explored the distant heliosphere. Voyager-1, now farthest from the Sun, reached a heliocentric distance of 76 AU just at the time of the Kodaikanal IAU Colloquium. Both Voyagers are hoped to survive until 2015 or even 2020, and are now involved in the Voyager Interstellar Mission. Both are expected to pass the TS (Voyager-1 perhaps soon), and Voyager-1 should also cross the heliopause and provide *in situ* information from the LISM. Both Voyagers are heading upstream into the streaming LISM, while Pioneer-10 moves downstream.

The near-ecliptic region of the inner heliosphere between 0.29 and 1 AU was explored by the two Helios spacecraft (Helios-1: 1974–86, Helios-2: 1976–80). The range covered was important for a better *in situ* coverage of the radial development of SW structure and turbulence (Schwenn & Marsch 1991; Horbury 1999).

The heliosphere at both low and high latitudes has been covered between about 1.3 and 5.4 AU by Ulysses, launched in 1990. South and North polar passes in 1994 and 95 preceded solar minimum, while the 2000 and 2001 polar passes will cover solar maximum. Ulysses is the first mission with a real 3D coverage of the inner heliosphere. The first *fast latitude scan* from 1994 to 95 provided a snapshot of the latitudinal structure at a time when temporal changes in the heliosphere were relatively slow. The next similar snapshot is expected to provide information on a more dynamical 3D structure of the heliosphere near solar maximum.

3. Large-scale heliospheric structure

The core of the heliosphere is the supersonic SW bubble emanating from the rotating solar corona. Frozen-in Archimedean spiral magnetic field lines thread the bubble, mapping out the polarity of the radial field components from the 'source surface' of the SW (at about 3 solar radii, so that field lines are mostly open) to the whole bubble and also to the inner, subsonic heliosheath. The superexpansion of the fast polar wind extends the latitudinal spread of unipolar coronal hole fields, leaving but a relatively narrow ecliptic latitude bin with alternating field directions at solar minima. Solar wind speed in that 'streamer belt' region is about a factor of 2 lower than at high latitudes. Opposite polarities are separated by a wavy current sheet that has a simple geometry at solar minima, but becomes more tilted and topologically complex at solar maxima. In the streamer belt, alternating slow and fast SW streams form corotating inward and outward propagating shocks.

The distant heliosphere and its boundary region remind of the terrestrial magnetosphere and its upstream and downstream extension: the bow shock, the magnetosheath and the magnetotail. Analogous structures are, however, scaled up by a factor of about 10^5. There are also several important differences. The SW streams past the magnetosphere much faster than the LISM does past the heliosphere, and there is no terrestrial analogue of the supersonic SW bubble surrounding the Sun. The SW is fully ionized, while the LISM is only partially ionized. The terrestrial magnetic field is much more regular, giving rise to radiation belts.

The heliocentric distance to the TS in the upstream direction is expected to be between 80 and 100 AU. So far, none of the distant heliospheric probes has crossed that boundary. The solar wind plasma is separated from the ionized component of the streaming interstellar medium by the heliopause. From considerations of pressure equilibrium with the ionized component of the LISM, the heliosphere is expected to extend to 100–130 AU in the upstream (nose) direction. Its downstream extension, the heliotail, is probably thousands of AU in length (which is still only about 1 per cent of the distance to the nearest star). The heliosphere is surrounded by the heliosheath (or outer heliosheath), the interstellar plasma streaming past the heliopause, diverted by the SW plasma and magnetic field pressure. The fairly weak bow shock is expected to be strongest in the direction of the nose of the heliosphere.

The LISM feeds neutral gas into the heliosphere, while the ionized component provides external pressure for confinement. The heliosphere is embedded in a warm interstellar cloudlet called the local cloud or 'local fluff'. It extends to no more than a few pc, and may be an evaporative extension of the 'squall line', a structure of denser clouds in the direction of the galactic centre. Gas in the anticentre direction is more dilute and more uniform. For a detailed review of our interstellar environment see Frisch (1995).

Magnetic reconnection on the heliopause may arise both with the interstellar field and between alternate stripes of oppositely directed magnetic fields, 'painted' onto the heliopause by the expansion of the substagnation region upstream of the termination shock. As the interstellar flow happens to be close to the ecliptic, convected 'streamer belt' solar fields should change sign at least twice per solar rotation in that region. Unipolar northern and southern fields are mapped into deeper layers, with reversal of the field only once per solar cycle.

4. Cyclicity of fields and particles

Solar-heliospheric magnetic fields have a 22-year periodicity. For many solar and heliospheric phenomena the sign of the field is of secondary importance, but that is not the case for the heliospheric access of predominantly positively charged particles arriving from the galaxy. Drifts due to density gradients and field line curvature reverse their direction for opposite field polarity. When northern solar polarity is outward (such as in the 90's), CR protons drift in from the poles toward the HCS, while for opposite fields the inward drift is mainly along the HCS. Diffusion, convection and adiabatic energy losses in the expanding SW all reduce CR intensity with decreasing solar distance, but, except for solar maximum periods, the large-scale pattern is largely determined by drift effects. This is particularly so in the distant heliosphere.

Recent IMP-8 and Voyager observations revealed that while low-energy (10 to 200 MeV) CR and ACR intensity at Earth almost completely recovered to the 1987 levels by the 1996 activity minimum, outer heliospheric fluxes remained much lower. The difference probably comes from the drift effect at the Voyagers, while at Earth the other modulation effects predominate. Near solar maxima, fields are more disordered and drift effects less important. Shielding by turbulent magnetic shells arising from particularly intense sequences of CMEs then causes long-lasting intensity decreases. In the inner heliosphere, CIRs also contribute both to the modulation (reduction) of CR and ACR fluxes, and to the acceleration of low-energy (MeV) fluxes. For more detail, see several contributions in two proceedings of recent ISSI workshops (ed. By Fisk *et al.* 1998 and by Balogh *et al.* 1999).

At 1 AU, most of the low-energy (< 10–20 MeV) protons are of solar-heliospheric origin. Their hourly (or daily) mean fluxes vary by several orders of magnitude, even at solar minima. Medians of the daily flux distributions increase by about a factor of 40 to 50 from the 1975–77 solar minimum to the 1979–81 maximum, and by 80 to

100 from 1985–87 to 1989–91. Median fluxes are more or less in phase with solar activity, while CR fluxes are in counterphase.

Very low-level fluxes at about 1 MeV proton energies are only seen around solar activity minima. Transition periods between their presence and absence are fairly sharp. The lowest levels measured are sometimes determined by 'instrumental background' caused e.g. by inefficient active shielding of the detectors. It appears, however, that a genuine energy-dependent baseline of those low-level fluxes exists, which is different for each cycle. The level at about 1 MeV was lowest around the 1986 solar minimum, and considerably higher around 1976. The 1996 level is in between. The baseline flux level increases with decreasing energy, opposite to what would be expected from CRs or ACRs adiabatically decelerated in the expanding SW. A solar and/or CIR origin is more likely to explain this observation.

5. Long-term effects

Energy releases in large solar events give rise to huge shocks and radiation increases in interplanetary space. Such events may endanger human life and technology in space, but indirectly may also damage power lines and oil pipelines. It is an important question whether much more powerful solar events occur often enough on geological time scales to affect atmospheric and biospheric processes, and be competitive with meteor impacts and sudden changes in the interstellar environment of the solar system (e.g. with nearby supernova explosions).

Wdowczyk & Wolfendale (1977) called attention to the dangers inherent in the flat integral spectra of solar energy releases observed over about 20 years. The logarithmic slope was estimated to be around –0.5. If that slope continued, several dramatic solar energy releases should be expected on geologically short time scales. In fact, for 10 times longer observation time the largest event would then be about 100 times more energetic, thus long-term mean fluences would be dominated by the largest events.

Luckily, better statistics and additional information available today provide a more optimistic forecast. A power-law function with exponential steepening was recently found by Nymmik (1999), making large events even rarer than predicted by the log-normal model of Feynman *et al.* (1993). Radiation history of lunar regolith (e.g. Reedy 1996), influenced by solar particle fluences over the last 1 Myr, as well as meteoritic and other samples provide now a strong argument against the predominance of very large solar events.

6. Conclusions

Our Sun's environment is but one of the billions of stellar environments in our galaxy. Some of them might be quite similar to ours, some others very different. Ours is, however, the only one we have direct access to. We hope it reflects universal processes as a droplet of water reflects the sea. It is amazing how much of its complexities have already been uncovered, and how many secrets it still holds. The quest is endless. One may recall Mahatma Gandhi's words as given in N. K. Bose's book (1948): "The goal ever recedes from us. The greater the progress the greater the recognition of our unworthiness. Satisfaction lies in the effort, not in the attainment."

Acknowledgements

The organizers are gratefully thanked for their help and hospitality, and IAU for financial support. Travel support of Hungarian national grant *OTKA-T-030078* is acknowledged. The International Space Science Institute (ISSI) in Bern is thanked for supporting a project related to the present research.

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