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INTERPLANETARY PLASMA AND HELIOSPHERE

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TRIENNIAL REPORT 2006 - 2009

1. Introduction

Commission 49 covers research on the solar wind, shocks and particle acceleration, both transient and steady-state, e.g., corotating, structures within the heliosphere, and the termination shock and boundary of the heliosphere.

The present triennial report is particularly rich in important results and events. The crossing of the solar wind termination shock by *Voyager 2* in 2007 is a highlight and a milestone that will certainly have important consequences for astrophysical processes in general (Section 7). The fiftieth anniversary of the *International Geophysical Year* (1957–1958), which is also the fiftieth anniversary of the birth of the Space Age, was marked not only by celebrations and a strong Education and Public Outreach Program, but also by efforts in coordinating present observations and in starting new scientific programs, particularly implying developing countries (Section 8). Studies of solar energetic particles (Section 3) and the related radio bursts (Section 4) benefited from new data from a number of spacecraft. The *STEREO* mission was launched in October 2006 and has obtained new results on 3-D aspects of the inner heliosphere. Meanwhile, solar cycle 24 is expected to become active soon, following what is already the deepest solar minimum of the space age.

Heliospheric compositional signatures will be presented in Section 5, and Interplanetary Scintillation results and developments in Section 6.

One of the highlights of this present period is definitely the completion in 2008 of the *Ulysses* mission, after almost 18 years of scientific successes and discoveries. *Ulysses* marks a giant step in the exploration of the Heliosphere and the next Section will give a very brief summary of its results.

2. Ulysses

Richard G. Marsden, Ulysses Mission Manager
ESA/ESTeC (SRE-SM), P.O. Box 299, NL-2200AG Noordwijk, Netherlands
<Richard.Marsden@esa.int>

2.1. Introduction

The joint ESA-NASA *Ulysses* space mission is probing the most fundamental processes of our solar system from a unique, out-of-ecliptic orbit. Its principal scientific goal is to conduct as complete a survey as possible of the heliosphere within ~ 5 AU of the Sun at all solar latitudes and under a wide range of solar activity conditions. *Ulysses* was launched in October 1990, and was initially foreseen to have a 5-year lifetime. The mission has been so successful, however, that ESA and NASA have extended its operational phase a number of times, permitting three surveys of the Sun's polar regions. Nevertheless, the diminishing output from the spacecraft's power source will probably bring this historic mission to a close before the end of 2008.

2.2. *Ulysses* through the solar cycle

Ulysses orbits the Sun once every 6.2 yr in a plane that is nearly perpendicular to both the ecliptic and the solar equator. This, together with the longevity of the mission, has allowed *Ulysses* to characterize the heliosphere in 'four dimensions', i.e., three spatial dimensions and time. Solar variability, which drives many of the phenomena being investigated by *Ulysses*, occurs on a wide variety of time-scales. In the context of global heliospheric studies, two are particularly relevant: the 11-yr solar activity (sunspot) cycle, and the 22-yr magnetic (Hale) cycle. Fortuitously, the orbital period of *Ulysses* corresponds roughly to the time it takes the Sun to go from the minimum to the maximum of its activity cycle. When *Ulysses* first flew over the Sun's polar regions in 1994 and 1995, solar activity was close to minimum, providing a view of the 3-dimensional heliosphere at its most simple (Balogh *et al.* 2001, and references therein). Fast solar wind from the polar regions flowed uniformly to fill a large fraction of the heliosphere; variability was confined to a narrow region around the solar equator (McComas *et al.* 2000). When *Ulysses* returned to high latitudes in 2000 and 2001, things were very different (Balogh *et al.* 2008, and references therein). Solar activity was close to maximum and transient features were dominant. Solar wind streams from the poles appeared indistinguishable from streams at low latitudes (McComas *et al.* 2003). Amid all this apparent chaos, *Ulysses* found that the reversal of the heliospheric magnetic field polarity, which occurs every 11 yr, happens in an unexpectedly simple fashion. The main component of the field is a dipole, and this appears to simply rotate through 180 degrees to accomplish the reversal (Smith 2008). Given the complexity of the field reversal at the solar surface, this is surprising. At the time of the third polar passes, in 2006–2007, solar activity was once again close to minimum, although there were important differences when compared with the 1st high-latitude passes. In particular, the solar wind and magnetic field measured by *Ulysses* were noticeably weaker than before (McComas *et al.* 2008; Issautier *et al.* 2008; Smith & Balogh 2008).

2.3. Scientific 'firsts' from *Ulysses*

(a) The first direct measurements of interstellar dust and neutral helium gas: Astronomical observations suggest that the Sun is presently moving through a warm, tenuous interstellar cloud made of dust and gas, one of several that make up our local galactic neighbourhood. Using instruments on board *Ulysses*, it has been possible to make direct measurements of dust grains and neutral helium atoms from the local cloud that

penetrate deep into the heliosphere for the first time (Gruen *et al.* 1993; Witte *et al.* 1993). These measurements have allowed the determination of the flow direction of the dust and gas, as well as the density and temperature of the neutral helium and the mass distribution of the dust particles.

(b) First high-precision measurements of rare cosmic-ray isotopes (e.g., ^{36}Cl and ^{54}Mn): Together with the interstellar neutral gas and dust, cosmic-ray particles are the only sample of material from outside the heliosphere that is available for direct in-situ study. *Ulysses* carries an instrument that has been able, for the first time, to make the precise measurements of rare cosmic-ray isotopes needed to test current theories of cosmic ray origin (Connell 2001).

(c) First measurements of so-called ‘pickup’ ions of both interstellar and near-Sun origin: Pickup ions are created in the heliosphere when neutral atoms become ionized by charge-exchange with solar wind ions or by photo-ionization. Measurements of pickup ions by *Ulysses* have led to a wide range of discoveries (Gloeckler *et al.* 2001). New sources of pickup ions have been discovered. Solar wind particles appear to become embedded in dust grains near the Sun, and are subsequently released to form a pickup ion population known as the ‘inner source’. Comets emit neutrals that form pickup ions, from which the composition of the comet can be determined. *Ulysses* has made detailed measurements of interstellar pickup ions, created when interstellar neutral gas becomes ionized. Interstellar neutral gas is a sample of the local interstellar medium and thus the composition of the Galaxy in the present epoch, as opposed to when the solar system was formed 4.5 billion years ago. The isotope ^3He was measured in the interstellar pickup ion population by *Ulysses*, providing an important constraint on the evolution of matter in the universe.

(d) First observations of solar energetic particles over the solar poles: A fundamental *Ulysses* discovery is that energetic charged particles are able to move much more easily in latitude than was imagined prior to launch (Lario & Pick 2008). Large latitudinal excursions in the direction of the heliospheric magnetic field were not anticipated, and it was therefore assumed that charged particles would not be able to move easily in latitude. Surprisingly, during its first solar minimum polar pass, *Ulysses* observed particles accelerated at corotating interaction regions (CIR) well above the latitude at which the CIRs themselves occurred. Similarly at solar maximum, *Ulysses* detected large numbers of energetic particles over the solar poles, far away from the location of the solar activity that created them. Either the particles are transported across the magnetic field, or the field lines themselves undergo large excursions, enabling low-latitude sources to be connected to high latitudes. Which of these processes dominates is still a matter of debate.

2.4. *Ulysses* scientific achievements 2005–2008

Specific achievements of the *Ulysses* mission during the period covered by this report include:

- The development of a global picture of the 3-D solar wind at minimum and maximum for use in modeling the heliospheric interface with the interstellar medium.
- Showing that the magnetic flux in the heliosphere in solar cycle 23 is different from earlier cycles (weaker) (Smith & Balogh 2008).
- Showing that, from a 3-D heliospheric perspective, solar cycle 23 is in many ways different from earlier cycles.
- The discovery that the invariance of the radial magnetic field with heliolatitude, shown earlier to exist at sunspot minimum, also exists at sunspot maximum (Smith 2008).
- Acquiring observations leading to new theories for the origin of slow solar wind.

- The cataloging of abundance signatures in ICMEs.
- The discovery of the ubiquitous presence of suprathermal tails in the energy distributions of solar wind ions, leading to new models of particle acceleration (Fisk & Gloeckler 2007).
- Mapping the changing 3-D energetic particle environment between solar minimum and maximum (Lario & Pick 2008).
- The discovery of the shift in flow direction of interstellar dust in the heliosphere beginning in 2005 (Krueger *et al.* 2007).
- The discovery of in-situ magnetic reconnection in the solar wind at all heliospheric distances sampled by *Ulysses* (Gosling *et al.* 2006).

This brief summary has not been able to do justice to the full range of science to which *Ulysses* has made lasting contributions. Nevertheless, it illustrates the fundamental new insights that have been obtained through *Ulysses* into the global behaviour of the heliosphere.

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3. Solar energetic particles

Hilary V. Cane

Astroparticle Physics Laboratory, NASA/GSFC, Greenbelt MD, USA

<hilary.cane@utas.edu.au>

During the period 2006 - 2008, at the end of cycle 23, the Sun was quiet except for some intense activity in December 2006. Spacecraft launched in the mid-1990s to early 2000's to make observations of the Sun, the solar wind, and solar energetic particles (SEPs), (*Wind*, *SOHO*, *ACE*, *RHESSI*), were still providing data and were augmented by the launch of *Hinode* and the two *STEREO* spacecraft in 2006. *STEREO* observations will provide additional information about the role of flare processes in large SEP events. It is clear from particle observations that such processes, related to magnetic reconnection, provide

part of the SEP source population (Desai *et al.* 2006). However, it is not clear whether the numerous, small SEP events provide Fe-rich, ^3He -rich seed particles for the coronal mass ejection (CME) driven shocks (Tylka & Lee 2006) or whether the particles with enhanced abundances seen in large events come directly from the associated flare (Cane *et al.* 2006). Electron observations are also not definitive (Kahler 2007). Unfortunately in December 2006 the *STEREO* spacecraft were essentially at the same location and could not provide different viewpoints of the abundances in the SEP events that occurred at this time.

The ionic charge is an important diagnostic of SEP source regions but unfortunately measurements are not available for the majority of events and then only by indirect methods at the high energies ($>\sim 25$ MeV) that are most important for understanding processes occurring close to the Sun. A new indirect method for determining ionic charge has recently been presented by Sollitt *et al.* (2008). It uses a scaling of charge state to decay time. For the largest events, data from the *SAMPEX* spacecraft can provide charge states for high energies. The comprehensive results are not yet published. On the other hand extensive analyses have been made of the charge state measurements at energies <1 MeV/nuc returned from the *sepica* instrument on *ACE*. A review is presented by Klecker, Möbius & Popecki (2007). The important result is that the charge states are energy dependent. Modeling efforts that include stripping processes and particle propagation are continuing (e.g. Dröge *et al.* 2006, Kartavykh *et al.* 2008).

Understanding propagation processes is clearly important for interpreting observations that are primarily made at 1 AU. Interplanetary scattering must be understood if we are to make correct deductions concerning the time and location of the release of particles at the Sun (e.g., Kahler and Ragot 2006). It has also been proposed that interplanetary scattering can account for abundance ratios changing with time in individual events at a fixed energy/nuc (Mason *et al.* 2006). Particle guiding within and reflection at interplanetary structures are aspects that also need to be considered (e.g. Sáiz *et al.* 2008, Tan *et al.* 2008, Kocharov *et al.* 2008). Recent studies suggest that azimuthal spreading of particle distributions also takes place in the low corona (Wibberenz and Cane 2006, Klein *et al.* 2008) as had been proposed decades earlier.

Modeling of the shock acceleration of SEPs is ongoing and becoming more detailed with increased computing power. One aspect that is of particular interest is how quickly a shock in the low corona can accelerate high energy particles. Two studies suggest that proton energies >100 MeV may be achieved within minutes (Vainio & Laitinen 2007, Ng & Reames 2008).

Studies of small SEP events are also ongoing. Mason (2007) has recently summarised the results from the ULEIS experiment on *ACE*. The spectra of ^3He and ^4He have been modeled by assuming stochastic particle acceleration by turbulent plasma waves (Liu, Petrosian & Mason 2006). Several authors have studied the source regions of ^3He -rich events (Wang, Pick and Mason 2006, Nitta *et al.* 2006, 2008). These events are often associated with coronal jets that are likely to be signatures of magnetic reconnection between closed and open field lines.

The link between particles accelerated at the Sun, as evidenced by associated electromagnetic emissions, and particles detected in situ is still tenuous. However observations of the January 2005 flares from *RHESSI* have supported earlier studies that found that spectral hardening in X-rays is indicative of an event that produces interplanetary particles (Saldanha, Krucker & Lin 2008). On the other hand, comparisons between electron

spectral indices deduced from X-ray observations with those measured in space do not always agree (Krucker *et al.* 2007).

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4. Interplanetary radio bursts

Natchimuthuk Gopalswamy

NASA/GSFC, Greenbelt MD, USA

<nat.gopalswamy@nasa.gov>

4.1. Type II radio bursts and shocks

The close connection among Type II radio bursts, large solar energetic particle (SEP) events, and interplanetary (IP) shocks has been examined in more detail in many recent works (Gopalswamy 2006; Cliver & Ling 2007; Cliver 2008; Gopalswamy *et al.* 2008a,b). The SEP associated rate increases with the speed and width of coronal mass ejections (CMEs) that produce type II radio bursts in the decameter-hectometric (DH) wavelength domain. In particular, presence of DH type II seems to be a necessary condition for the production of SEP events but not the type III radio bursts at low frequencies (~ 1 MHz) (Cliver 2008). The three phenomena have a common cause, viz., fast and wide CMEs (speed ≥ 900 km/s and width ≥ 60 degrees). Deviations from this general picture are observed as (i) lack of type II bursts during many fast and wide CMEs and IP shocks; (ii) slow CMEs associated with type II radio bursts and SEP events; and (iii) lack of SEP events during many type II bursts (Gopalswamy 2008). Most of the deviations can be accounted for by the large variation of the Alfvén speed in the corona, ranging from about 400 km/s to 1600 km/s. A large number of fast and wide CMEs that did not produce type II radio bursts in fact came from behind the limb, which may indicate a visibility problem.

Thejappa *et al.* (2007) performed Monte Carlo simulation of the directivity of interplanetary types II and III radio bursts occurring at 120 kHz. They find that the scattering by random density fluctuations extends the visibilities of fundamental and harmonic components from 18 degrees to 90 degrees, and from 80 degrees to 150 degrees, respectively. They also reported the simultaneous observation of bursts by *Ulysses* and *Wind* spacecraft separated by more than 100 degrees. Scattering and refraction seem to play a major role in making the bursts visible over a wide range of angles.

Pulupa & Bale (2008) studied the source regions of interplanetary (IP) type II radio bursts associated with shock-driving interplanetary CMEs (ICMEs). Immediately prior to the arrival of each shock, electron beams along the interplanetary magnetic field and associated Langmuir waves are detected, implying magnetic connection to a quasi-perpendicular shock front acceleration site. The presence of a foreshock region requires nonplanar structure on the shock front. Using *Wind* burst mode data, the foreshock electrons are analyzed to estimate the dimensions of the curved region. Ledenev *et al.* (2007) showed that the longitudinal wave spectrum, excited in the solar wind plasma, extends with the increase of the refractive index to values > 10 . This explains the broad band of emission, the constant value of the average ratio of frequency-band to radio emission frequency from interplanetary shock wave fronts. They were able to estimate the electron beam density and amplitude of Langmuir waves at the shock. The spectrum of radio emission was shown to be determined by the spectrum of Langmuir waves excited upstream of the interplanetary shock wave by heated electrons escaping from the shock wave front.

The type II burst of 2001 May 10 was tracked to very low frequencies using *Ulysses* radio data (Hoang *et al.* 2007). The associated shock was also observed in situ at *Ulysses* but the type II radio emission was observed for more than a day prior to the arrival of an interplanetary shock at *Ulysses*. By accurately subtracting the thermal noise background from the observed emission intensity they were able to deduce the type II brightness temperatures at the fundamental and harmonic near the shock crossing. The measured brightness temperature of the type II harmonic emission reached a peak a value of $\approx 3 \times 10^{13}$ K just after the shock crossing at *Ulysses*.

Since type II bursts are good indicators of shocks, Oh *et al.* (2008) selected a set of 31 IP shocks associated with *Wind*-WAVES type II radio bursts and studied the kinematics of the shocks. They found that the mean acceleration of the IP shocks between the Sun and Earth to be about -1.02 m s^{-2} , which is smaller than the values obtained for CMEs. Using the constraints imposed by the low-frequency radio emissions generated by shocks driven by CMEs, the measured 1 AU transit times and the calculated in situ shock speeds, together with the required consistency with the white-light measurements, Reiner *et al.* (2007a) analyzed the interplanetary transport of 42 CME/shocks observed during solar cycle 23 to determine when, where, and how fast CMEs decelerate as they propagate through the corona and interplanetary medium. They found some notable correlations between the parameters that characterize the deceleration of these CMEs to 1 AU.

Kahler *et al.* (2007) found evidence for a class of shock-accelerated 'near relativistic' electron events based on particle and *Wind*-WAVES data. They compared the inferred injection times of 80 near-relativistic electron events observed by the *Wind*-3DP electron detector with 40-80 MHz solar radio observations and found no single radio signature characteristic of the inferred electron injection times. About half of the events were associated with metric or DH type II bursts, but most injections occurred before or after those bursts. Electron events with long (≥ 2 hr) beaming times at 1 AU were preferentially associated with type II bursts, which led to their conclusions on the source of the electrons.

Sakai & Karlicky (2008) performed particle-in-cell simulations of shocks to explain the band splitting of type I solar radio bursts. Near the shock front, they found some protons reflected and accelerated. The reflected protons dragged the background electrons to keep the charge neutrality, resulting in electron acceleration. The accelerated electrons excited electrostatic waves. The resulting radio emission occurred near the fundamental and second harmonic of the local plasma frequency. The band splitting of the type II burst was found to be dependent on the direction of propagation of the shock.

4.2. Type III radio bursts

Investigations on the type III bursts concentrated on the analysis of storm events. Reiner *et al.* (2007b) reported the detection of circular polarization ($\sim 5\%$) in solar type III radio storms at hectometric-to-kilometric wavelengths. The sense of the polarization is maintained for the entire duration of the type III storm (usually many days). For a given storm, the degree of circular polarization was found to peak near central meridian crossing of the associated active region. At a given time, the degree of circular polarization was found to generally vary as the logarithm of the observing frequency. These observations may provide important information on the magnitude and radial dependence of the solar magnetic field above active regions.

Using long-term observations from the *Geotail* and *Akebono* satellites, Morioka *et al.* (2007) studied the individual bursts in the type III storm ('micro-type III') radio bursts. The average power of the micro type III bursts were found to be about 6 orders of magnitude below that of normal type III bursts. They were able to identify the active regions responsible for the micro-type III bursts by examining the concurrence of their development and decay with the bursts. It was found that both micro and ordinary type III bursts can emanate from the same active region without interference, indicating the coexistence of independent electron acceleration processes. One of interesting findings was that the active regions responsible for micro-type III bursts seem to be located close to coronal holes.

4.3. Conclusions

The Radio and Plasma Wave Experiment (WAVES) experiment on the *Wind* spacecraft has made the frequency coverage nearly complete for investigating interplanetary radio bursts. This led to the clarification of many issues regarding the connection of radio bursts with CMEs. A similar experiment on the twin *STEREO* spacecraft (S/WAVES) will enhance our understanding of the interplanetary radio bursts by providing two view points to the radio sources (Bougeret *et al.* 2008). The S/WAVES instrument includes a suite of state-of-the-art experiments that provide comprehensive measurements of the three components of the fluctuating electric field from a fraction of a hertz up to 16 MHz. The instrument has a direction finding or goniopolarimetry capability to perform 3-D localization and tracking of radio emissions associated with streams of energetic electrons and shock waves associated with CMEs. Currently the separation between the two spacecraft is sufficient to show the directivity of radio bursts.

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5. Heliospheric compositional signature

Rudolf von Steiger

International Space Science Institute, Bern, Switzerland

<rvsteiger@issibern.ch>

5.1. Introduction

The primary motivation for solar wind composition studies is twofold: On the one hand we seek to determine the composition of the outer convective zone of the Sun (as represented by the photosphere) in order to infer the composition of the protosolar nebula, as this represents the baseline from which the entire solar system was formed some 4.6 Gy ago (cf. von Steiger 2001, and references therein). On the other hand composition differences between different solar wind types (or other reservoirs) are indicative for the conditions and processes where these reservoirs originate. Thus composition studies naturally fall into two different types: charge state composition and elemental composition. Charge state composition, i.e., the distribution of the different charge states of a single element, probes the conditions and processes in the corona at a temperature of the order of 10^6 K, whereas elemental composition, i.e., the abundances of the elements summed over all charge states, probe the conditions and processes in the chromosphere and lower transition region at a temperature of the order of 10^4 K. Observations using composition instrumentation such as the SWICS instruments on the *Ulysses* and the *ACE* missions have revealed that both charge state composition and elemental composition are somehow related to the solar wind state, the most obvious feature being an anti-correlation of the charge state ratio O^{7+}/O^{6+} and the solar wind speed, v .

5.2. Charge state composition

The charge states of heavy ions observed in the solar wind are indicative of the coronal temperature at the altitude in the corona where the collision time scale equals the expansion time scale. Since the ionisation/recombination rates with hot electrons are temperature dependent each ion pair freezes in at a different altitude in the corona. In fast streams from coronal holes the charge states of each element are well represented by a single temperature. This fact was first used by Geiss *et al.* (1995) to obtain a temperature profile in the south polar coronal hole from charge states observations observed with *Ulysses*-SWICS in the southern high-speed stream. The single freezing-in temperature per element could also be used to infer that the coronal hole is thermally homogeneous to less than $\pm 100\,000$ K.

Charge state distributions obtained outside fast streams are quite different from the single-temperature ones found within. They not only have a significant excess of higher charge states, but they are also broader, indicating a mixture of sources at different, on

average higher, temperatures. This has led Zurbuchen *et al.* (2002) to conclude that the slow solar wind is made up from a continuum of dynamic states. An excess of the highest charge states of each element is due to interplanetary coronal mass ejections (ICMEs); in fact, the average charge state of iron ions has been established as a very reliable ICME signature (Lepri and Zurbuchen 2004; Zurbuchen & Richardson 2006).

The direct observation of iron charge states on *Ulysses* has led to a discrepancy with *SoHO*-SUMER remote observations: Based on observations of the 1242 Å line formed by Fe XII (i.e., Fe¹¹), Wilhelm *et al.* (1998) inferred a coronal electron temperature of just barely 1 MK at the base of a coronal hole and decreasing with altitude. This is at variance with the *Ulysses*-SWICS observation of 25% of all iron ions in the 11+ charge state, indicating a temperature of 1.23 MK at 3–4 R_{\odot} . The discrepancy has yet to be resolved (von Steiger *et al.* 2001).

5.3. Elemental composition

It has been known for some time known that the first ionisation potential (FIP) fractionation factor $f = (X/O)_{\text{SW}}/(X/O)_{\odot}$ (with X/O the abundance ratio of a low-FIP element X relative to oxygen) is about 3–5 in the slow solar wind, but significantly lower than that in the fast streams from coronal holes. With *Ulysses* it was found that the slow solar wind is so variable in elemental composition (and in most other parameters as well), to the point that it becomes hardly meaningful of speak of an average FIP fractionation factor there. Daily averages of the Mg/O abundance ratio reach from only little more than the photospheric value $\text{Mg}/\text{O}_{\odot} = 0.074$ (Grevesse *et al.* 2007) to about 4 times that value. Analyses at higher time resolutions seem to indicate even higher FIP fractionation factors at shorter time scales, but these are difficult to ascertain since statistical variability also increases. It seems that the highest FIP factors are found at low latitudes, which helps to explain why fractionation factors found with *Ulysses* are generally smaller than the previously reported factor of $f = 3$ –5. These factors were of course obtained at low latitudes, while the smaller *Ulysses* result is an average over all latitudes. The variability of the slow solar wind fits well with the Fisk field model, according to which the slow wind stems from closed loops reconnecting with open field lines as they wander along the solar streamer belt (Fisk *et al.* 1998). The natural age variability of these loops together with the fact that the FIP fractionation factor correlates with their ages (Widing & Feldman 2001) readily accounts for the observed variability.

It can be argued that the composition of the fast polar streams is as close as we can get to the solar composition with in-situ observations. This is particularly important for elements such as neon that cannot be observed by remote sensing in the photosphere for lack of transitions in the relevant energy range. The ‘solar’ neon abundance given in tables such as the one of Grevesse *et al.* (2007) is not really a solar value, but an approximation thereof obtained from other sources such as remote sensing of the corona or solar energetic particles. Bahcall *et al.* (2005) have used this ignorance to argue that the solar neon abundance might be higher by a factor of 2.5–3 (0.4–0.5 dex) than this estimate in order to reconcile the helioseismology results with the latest values of solar abundances, in particular of CNO, as if the neon abundance were a freely disposable parameter. But the solar wind value of neon observed with *Ulysses*-SWICS ought to be taken into account, and it makes such a high neon abundance seem quite unlikely. Von Steiger *et al.* (2000) find $\text{Ne}/\text{O} = 0.083$ in fast streams but caution that this is a difficult measurement since neon occurs in the single charge state Ne^{8+} that lies close to the most abundant of the heavy ions, O^{6+} . Nevertheless, a recent independent analysis (Gloeckler & Geiss 2007) seems to confirm this low value of Ne/O . The value is even lower than the solar estimate of Grevesse *et al.* (2007), $\text{Ne}/\text{O} = 0.15$, which makes it very difficult to

believe that the real solar value could be as high as $\text{Ne}/\text{O} = 0.4$ like it would be needed for the helioseismology results to fit. The solution of this conundrum is as yet outstanding; it may well lie in the abundances of other elements than just the one of neon.

5.4. Correlation between composition and kinetic parameters

The anti-correlation of $\text{O}^{7+}/\text{O}^{6+}$ and v mentioned above was studied in some detail in a pair of papers (Gloeckler *et al.* 2003; Fisk 2003). During a 166 d time period around the solar minimum in 1996–1997, Gloeckler *et al.* (2003) first determine a correlation $v = 144/T - 88$, where v is the solar wind speed in km/s and T is the freezing-in temperature from oxygen charge states in MK. The correlation is found to be very tight except at times when an ICME passes by. On the other hand, Fisk (2003) derives a theoretical relation between coronal electron temperature and terminal solar wind speed squared (i.e., its energy) of the form $v^2/2 = C_1/T + C_2$, where $C_{1,2}$ are constants. The theory is based on the picture of open field lines migrating across the solar surface by successively reconnecting with closed loops and thus displacing themselves by the separation of the loop's footpoints. Each of these reconnection events releases energy and mass onto the open field line, i.e., into the corona and solar wind. In turn, these two quantities determine the final energy of a solar wind parcel, or v^2 . The quantities can be determined using solar observations or estimates of typical loop heights and other solar quantities, thus determining the constants $C_{1,2}$. Note that only C_1 involves quantities that are not determined in a straightforward manner, while $C_2 = -GM_\odot/r_\odot = -(437 \text{ km/s})^2$ is simply the gravitational potential at the solar surface and thus unadjustable. Fitting their data to Fisk's $V^2 \propto 1/T$ relation, Gloeckler *et al.* (2003) find an equally satisfying fit (again with the ICME periods removed) as for $V \propto 1/T$. It is noteworthy that this fit yields an intercept value very close to the unadjustable constant C_2 and has the added benefit of a physical underpinning. This can finally be used to reverse the relation and ask about the loop heights with which the migrating field lines reconnect. In the quiet Sun, loop heights were found to show a strong dependence on latitude, reaching up to $\sim 100\,000$ km at low latitudes; conversely, in polar coronal holes the lowest heights of $\sim 15\,000$ – $30\,000$ km were observed with minimum fluctuation and no dependence on latitude.

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6. Interplanetary scintillation and solar wind studies

P. K. Manoharan,

Radio Astronomy Centre, NCRA-TIFR, Udhagamandalam (Ooty), India.

<mano@wm.ncra.tifr.res.in>

6.1. Introduction

Interplanetary scintillation (IPS) is caused when planar wave fronts from a compact radio source (e.g., radio galaxy or quasar) pass through the solar wind. As we see in the following, IPS measurements are an essential means to probe the 3-D heliosphere in density turbulence and flow speed and to establish the connection between the solar phenomena and interplanetary consequences.

6.2. Propagation and radial evolution of CMEs

In a study to understand the radial evolution of 30 large CMEs, IPS images obtained from the Ooty Radio Telescope (ORT) along with white-light images from *SOHO*-LASCO have made it possible to track CMEs in the inner heliosphere. Results indicate that each CME tends to attain the speed of the ambient solar wind at 1 AU or further out of the Earth's orbit and the net acceleration imposed on a CME is determined by its initial speed and properties of the solar wind encountered on its way. Further, the radial evolution of CMEs between the Sun and 1 AU confirms the combined influence of *expansion* of the CME (i.e., the magnetic energy possessed by the CME in supporting the propagation) and *aerodynamical drag force* (i.e., interaction between CME and solar wind) at different regions of the inner heliosphere (Manoharan 2006).

In another study, IPS measurements made with the multi-antenna system operated by the Solar-Terrestrial Environment Laboratory (STEL) reveal the 3-D structure and evolution of an intense CME on October 28, 2003. This study shows that the high-density cloud associated with the above CME propagates with a speed much lower than the IP shock. Further, the IP disturbance assumes a loop-shaped distribution, which is in good agreement with the simultaneous white-light observations made with the Solar Mass Ejection Imager (SMEI). It is considered that the loop-shaped structure has resulted from the coronal ejecta confined within the magnetic flux rope, since the location and direction of the loop are consistent with the flux rope geometry inferred from the cosmic ray and *in situ* observations (Tokumaru *et al.* 2005).

The above result suggests that IPS enhancements can indicate plasma in front of the shock and also the CME ejecta behind it. While a CME observed by the coronagraph usually consists of three parts (frontal loop, cavity and core), an interplanetary CME observed *in situ* often shows a two-part structure which lacks dense material in its inner part. This discrepancy may be ascribed to limited spatial coverage of *in situ* observations. The present result is considered as observational evidence to indicate that the core material can survive and travel much farther than the field-of-view of the coronagraph (Tokumaru *et al.* 2007).

In an attempt to study the evolution of fast CMEs, speed estimates of CMEs from the following methods have been examined, radio type II bursts, white-light data, and Ooty IPS images. This study highlights the difficulties of making velocity estimates from radio observations using solar atmospheric density models, particularly under disturbed coronal conditions (Pohjola *et al.* 2007).

Another study to analyze events on October 28 and 29, 2003, using the IPS at STEL and other solar and interplanetary data, suggests that understanding the physical features of shock propagation is of great importance in improving the prediction efficiency (Xie *et al.* 2006). In a measurement-based MHD simulation study, the simulated interplanetary

shocks are compared with the near-Earth measurement, and the well produced shock arrivals to the Earth implied the ability of the cooperation of the cone-model, the IPS-analysis and MHD simulation. It is found that the second interplanetary disturbance propagated faster in the rarefaction region of the first event, implying that the multi-event simulation is important to enhance the simulation model (Hayashi, Zhao, & Liu 2006).

The tomographic reconstruction of STEL IPS data of a CME from May 2005 has provided an excellent model fit to the EISCAT/MERLIN observation. The above sets of data show that an adjacent fast stream appears significantly deviated from the radial direction (Breen *et al.* 2008). In a follow-up study of a CME in May 2007, IPS observations from EISCAT and the heliospheric imagers on the *STEREO* spacecraft show that IPS could reveal small-scale structure within the CME front which was not resolved by the white-light imager (Dorrian *et al.* 2008). Simultaneous observations at 500 MHz, 928 MHz and 1420 MHz with baselines of up to 1200 km have been carried out. The results are found to be consistent between single- and dual-frequency correlations, allowing the range of observations possible with the EISCAT system to be expanded (Fallows *et al.* 2006).

6.3. Solar cycle evolution

The solar wind measurements at Ooty over the solar cycle 23 provide the large-scale changes of latitudinal features of the solar wind density turbulence and speed. The Ooty 'latitude-year' plots show systematic changes of high speed flow from coronal hole (and its associated low-level of density turbulence). The drifting of density structures from high to low latitudes, as revealed by this study, are effected by the gradual movement of *magnetically-concentrated* coronal holes, in association with the reversal of solar magnetic field. The latitudinal results are consistent with the evolution of warping of the current sheet between the ascending and declining phases of the solar cycle. The high speed streams from these migrating coronal holes cause recurrent interaction regions, which are dominant during the year 2003 (Manoharan 2007).

6.4. Coronal magnetic field and fast/slow solar wind flows

It is crucial to understand the physical parameters, which determine the acceleration of solar wind from different coronal sources. In an investigation from STEL IPS made during the minimum phase of the solar cycle, combined with the extrapolated magnetic field data, it is found that the ratio between photospheric magnetic field (B) and the flux expansion factor (f) shows a considerably higher correlation with the solar wind velocity than an individual parameter of B or f (Fujiki *et al.* 2005; Kojima *et al.* 2007).

A study based on the modeling of structure functions from angular/spectral broadening observations and velocity measurements from IPS observations shows that the near-Sun solar wind is dominated by effects associated with obliquely propagating Alfvén/ion cyclotron waves. The modeling of IPS velocities reveals that the large parallel velocity spread and upward bias to the mean velocity observed near the Sun are a direct result of the density fluctuations associated with Alfvén waves along an extended line of sight (Harmon and Coles 2005).

Simultaneous observations between EISCAT and MERLIN, of baselines of up to 2000 km, suggest that two modes of fast solar wind may exist with the fastest mode above the polar regions and slower flow above equatorial extensions of the polar coronal holes (Fallows *et al.* 2007; Bisi *et al.* 2007). The mass flux measurements from *SOHO*-SWAN and mass flux estimates using *LASCO*-C2 density and IPS velocity show that the fast solar wind reaches its terminal velocity at $\sim 6 R_{\odot}$ and expands with constant velocity beyond this distance. On the contrary, the slow solar wind attains only half of its

terminal value at the above distance and is thus accelerated farther out (Quémerais *et al.* 2007).

Studies of IPS observations from STEL combined with different space missions data suggest that solar wind disappearance events (e.g., 11 May 1999 event as well as events occurred during 2002) are highly non-radial and associated with unipolar solar wind flows that originate at the boundaries of large active regions and coronal holes located at the central meridian (Janardhan *et al.* 2008; Janardhan, Tripathi & Mason 2008).

6.5. SMEI and IPS measurements - 3-D reconstruction

One of the goals of the Solar Mass Ejection Imager (SMEI) team is to provide the analyses for as many events as possible and for this a semi-automated system has been set up to provide the photometric results from SMEI (February 2003 - to date; refer to <smei.ucsd.edu/>). The reader may also refer to the review by Webb *et al.* (2006) for general observations of interplanetary CMEs by SMEI. A high-resolution analysis has allowed the 3-D reconstruction of not only the more dense regions of the CMEs observed in SMEI, but also the density enhancements behind the largest CME-driven shocks (Jackson *et al.* 2006).

The 3-D velocity reconstructions of IPS and SMEI data during 6-10 November 2004 clearly show CME structures. Ooty IPS shows very high correlations with *in situ* velocities during this complex interval of solar activity that are unparalleled at this temporal resolution (Bisi *et al.* 2008).

6.6. Cometary scintillation

The occultation of compact radio quasar B0019-000 by the plasma tail of comet 73P/Schwassmann-Wachmann 3-B (May 2006) has been made using the ORT, at 327 MHz. The intensity scintillation of this source shows significant increase compared to that of the control source located outside the comet tail. Further, the power spectra of intensity fluctuations show gradual changes as the target source approached the central part of the comet tail. At the point of closest distance to the comet, the spectrum reveals an enhanced level of turbulence both at large-scale (~ 500 km) and at small-scale (~ 50 km) portions of the spectrum. A density turbulence spectrum of two spatial scale sizes can explain the temporal evolution of the power spectrum during the occultation (Roy, Manoharan & Chakraborty 2007).

6.7. New IPS arrays

IPS studies are gaining more and more importance. For example, a new large antenna has been added to the multi-antenna IPS system at STEL, Japan. Further, new IPS arrays are being constructed at widely separated geographical longitudes, which will enable the continuous monitoring of the IP medium. The upcoming Low Frequency Array (LOFAR), in the frequency range 10 - 240 MHz, has plans to carry on IPS studies. Briefings of some of the new arrays are given below.

Pushchino Radio Telescope: A specialized antenna system for monitoring IPS at 110 MHz was installed at Pushchino Radio Astronomy Observatory, Lebedev Physical Institute, Russia, during 2006 (Shishov *et al.* 2008). It includes 16-beam array (each beam $\sim 1^\circ \times 0.5^\circ$), which allows to observe a few hundreds of radio sources per day at flux density 0.2 Jy and above. The preliminary observations with the above telescope indicate a quiet state of interplanetary plasma during 2006–2007.

Mexican Array Radio Telescope: This dedicated IPS array, located at Michoacan, about 350 km north-west of Mexico (19.8°N , 101.7°W), is nearing completion. It consists of 64×64 full wavelength dipole array, operating at 140 MHz, occupying 980 m^2

(E-W 70 m × N-S 170 m) (Gonzalez-Esparza *et al.* 2006). This array supports a multiple-beam system (www.mexart.unam.mx/).

Murchison Widefield Array: This new radio array, under construction in Western Australia, consists of 512 antenna tiles, each of 4x4 array of crossed vertical bowtie dipoles, operating in the frequency range 80-300 MHz. The MWA plans to participate in the global IPS network. Its Faraday rotation measurement of radio sources (e.g., Jensen & Russell 2008), combined with IPS tomography, will provide the 3-D magnetic field of propagating CMEs and IP medium (www.haystack.mit.edu/ast/arrays/MWA).

Miyun Radio Telescope: A new IPS observing system is being setup at National Astronomical Observatories, China, to record simultaneous dual frequency data at bands of 327/611 MHz and 2.3/8.4 GHz (Zhang 2007).

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7. The termination shock and heliospheric boundary

Rosine Lallement

Service d'Aéronomie du CNRS, BP 3, 91371 Verrières-le-Buisson, France

rosine.lallement@aerov.jussieu.fr

7.1. Introduction

The three years covered by the previous report had been exceptional for the heliospheric community: the events during the last three years covered by this report are even more spectacular. After the crossing of the solar wind termination shock by *Voyager 1* in

December 2004, the crossing of the shock by *Voyager 2* in August 2007 is not only a milestone in the history of space exploration, but its associated discoveries will certainly have important consequences for astrophysical plasmas in general. Following the two events is now beginning a new exciting period of exploration of the transition region between the solar wind and the interstellar medium, and hopefully to the *in situ* exploration of the ambient galactic medium. Fortuitously, fundamental and complementary information on the boundary of the heliosphere has been also provided by other spacecraft, by means of the detection of energetic neutral atoms (ENAs) from the heliosheath. All these results provide an ideal context for the launch of the *IBEX* mission, scheduled for October 2008, and entirely devoted to ENAs. All *in situ* and remote sensing observations will be combined in an unprecedented way.

7.2. *Voyager 2* historical termination shock crossing

Thirty years after her launch, *Voyager 2* crossed the heliospheric termination shock of the solar wind several times during about 24 hours on 31 August 2007 at a distance of 83.7 AU from the Sun. The shock oscillates in and out in response to solar wind variations, which explains the multiple crossings. These crossings have been recorded by all instruments, including very fortunately the plasma analyser, whose analogon on board *Voyager 1* had stopped to function long before the *Voyager 1* crossing. Those exceptional and unprecedented data are presented by Jokipii (2008) and discussed in a special issue of *Nature*.

Richardson *et al.* (2008) show the very sharp transitions of the thermal plasma at the shock crossings. An enormous surprise is the low temperature (100 000 K) of the post-shock core plasma, which implies that this core plasma is still supersonic after the shock (!), and that most of the upstream solar wind energy is transferred to minor species, (see below) and not to the core. They also show from solar wind measurements that the strong heliosphere asymmetry implied by *Voyager 2* and *Voyager 1* crossings at 94 and 84 AU respectively is only partially due to temporal effects (solar wind pressure variations which move in and out the shock) and is linked to a real permanent asymmetry due to an inclined interstellar magnetic field, as suggested by neutral species measurements (Lallement *et al.* 2005) and *Voyager* radio and Termination Shock Particles (TSP) directional properties (Opher *et al.* 2006).

Gurnett & Kurth (2008) describe the intense plasma waves recorded at the termination shock, electron oscillations first upstream of the shock, then broadband electrostatic waves right at the shock. They compare these new data with the spectra observed at planetary bow shocks. A number of similarities are observed, but some of the differences remain to be explained. These data are mandatory for the understanding of the shock formation and temporal behaviour.

Burlaga *et al.* (2008) show the magnetic field intensity and direction along three crossings and very precise measurements of the shock foot, ramp and overshoot characteristics and thickness. These structures and the processes of quasi-perpendicular shock decrease and reformation predicted by simulations (e.g., Lembege & Savoini 1992) have been beautifully demonstrated. On the other hand, the data show that the magnetic field fluctuation spectrum is found to be transformed from a lognormal to a normal distribution as the solar wind passes through the heliosphere termination shock, which is unexpected and under study (Chen *et al.* 2008).

Decker *et al.* (2008) show the unique measurements of the low energy charged particle instrument, that cover energies between a few keV and a few MeV. These low energy accelerated particles play a central role in the new picture that emerges from the *Voyager 2* and *Voyager 1* measurements. The data (see also Decker *et al.* 2005) show that their

total pressure is largely above the solar wind pressure, that they keep the same spectral index before and after the shock, despite the very strong increase in their fluxes, and that their composition is identical to the composition of the pickup ions (interstellar species after they have been ionized and convected in the solar wind, that form a suprathermal distribution). Fisk *et al.* (2006) have suggested that these particles, i.e., core pickup ions and their suprathermal tails formed in solar wind shocks and turbulence, are the main actors at the shock and follow a classical Rankine-Hugoniot compression. Most of the solar wind kinetic energy is thus used to heat these TSPs, while the core solar wind receives very little.

Stone *et al.* (2008) analyze the data of the higher energy particle telescopes, namely (i) the high energy tails of the previous species; (ii) the 10–100 MeV anomalous cosmic rays; and (iii) the ≤ 100 MeV galactic cosmic rays. The biggest surprise is, as for *Voyager 1*, the absence at the shock of a maximum of the ACR fluxes, which contradicts standard shock acceleration as their source mechanism. Are the ACR's accelerated further in the heliosheath, as suggested by several previous works (e.g., Ferreira *et al.* 2007) or along the shock flanks (McComas & Schwadron 2006)? Galactic cosmic ray helium shows a surprisingly small gradient which suggests that the true galactic intensity may be lower than expected, or that there is a stronger gradient outside, something equally unexpected.

7.3. *The heliospheric shock entirely mediated by non-thermal ions: confirmation by heliosheath ENAs*

The new technique of ENA imaging is now providing a number of new diagnostics. The ASPERA instrument on board *Mars-Express* (ESA) is detecting energetic neutrals of both Martian and non-planetary origin. Galli *et al.* (2006) and Wurz *et al.* (2008) have measured the 0.2–2 keV spectra of the non-planetary ENAs, identified as neutrals created by charge-exchange between heliosheath protons and interstellar neutrals. More recently, the electron instruments on board the two NASA *STEREO* spacecraft have unexpectedly detected neutral particles from a large fraction of the sky, with a maximum from the front of the heliosphere. Neutral particles are identified when they do not follow the electro-magnetic fluctuations recorded in parallel. Wang *et al.* (2008) present their 3–20 keV spectra and directional fluxes, and argue based on spectral slopes and fluxes that these neutrals are formed by charge exchange between interstellar neutrals and the low energy tail of the heliosheath energetic particles detected by the *Voyagers*. A knee in the spectra at 10–12 keV is indeed clearly seen, which is very likely the counterpart in the shocked and heated heliosheath of the well known 4 keV knee in the solar wind pickup ion spectra that separates core pickup ions from their suprathermal tail. These data provide first partial maps of the heliosheath and confirm the *Voyager* findings, i.e., the transfer of most of the solar wind energy (more than 70%) to a minority of high energy particles, the upstream pickup ions and their suprathermal tails. The big surprise is the directionality. Instead of a broad maximum from the longitude corresponding to the front of the heliosphere, two maxima of the neutral fluxes are detected, one within 10 degrees longitude on one side of the interstellar wind direction, and one shifted by about 25 degrees longitude on the opposite side. The direction of this secondary flow corresponds to some previous measurements discussed by Collier *et al.* (2004), especially *SOHO-CELIAS* and *IMAGE-LENA* ENAs.

There is now a strong debate about the origin of the secondary maximum. Is it linked to the strong asymmetry of the heliosphere under the magnetic field influence, with shock heating and resulting energetic particles densities being function of the location? Is it solely due to temporal effects (solar wind pressure variations)? Is it due to the existence of a secondary interstellar flow? Fortunately the forthcoming *IBEX* mission (McComas

2008) will be able to answer these questions. *IBEX* will image energetic neutrals with unprecedented energy and spatial resolution. If the secondary flow is linked to the distortion of the heliosphere under the influence of the interstellar magnetic field, one can deduce from interstellar neutral hydrogen deflection and radio measurements that the secondary maximum must be located at high positive latitude. *IBEX* will also allow to determine the entire spectra of the heliosheath particles and follow their variability.

7.4. Conclusion: lessons from the heliospheric boundary exploration

The heliosphere boundary is a unique laboratory for the study of interstellar shocks and cosmic ray production, and answering the questions raised by the current exploration is as a consequence of fundamental importance in astrophysics. Astrospheres formed around other stellar-type stars are already shown by means of absorption spectroscopy to possess properties similar to those of our heliosphere (Wood *et al.* 2007), but there are many other structures around objects moving in interstellar plasma such as stellar winds and supernovae bubbles (confirmed production sites of galactic cosmic rays), the study of which will gain from the new findings. In particular, the role of the neutral interstellar gas fraction is found to be essential, through the neutral mass loading, pickup ion production, convection and acceleration. Their fundamental role and influence on the shock seem now to be well established. A number of major questions remain: - Where are the ACR's accelerated? - What is the origin of the double structure of the ENA's? It is impossible here to refer to the numerous works currently published and motivated by the results of the last five years and here we have focused on the recent data.

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8. The International Heliophysical Year 2007–2008

Nat Gopalswamy

NASA/GSFC, Greenbelt MD, USA

<nat.gopalswamy@nasa.gov>

8.1. *Introduction*

The *International Heliophysical Year* (IHY) commenced in February 2007, marking the fiftieth anniversary of the *International Geophysical Year* (IGY, 1957–'58). Like the IGY, the objective of the IHY is to discover the physical mechanisms that link Earth and the heliosphere to solar activity. The IHY will focus on global effects but at a much greater physical scale (from Geophysics to Heliophysics) that encompasses the entire solar system and its interaction with the local interstellar medium.

The IHY activities are centered around four key elements: Science (coordinated investigation programs or CIPs conducted as campaigns to investigate specific scientific questions), Observatory Development (an activity to deploy small instruments in developing countries), Public Outreach (to communicate the beauty, relevance and significance of the space science to the general public and students), and the IGY Gold Program (to identify and honor all those scientists who worked for the IGY program). This report concerns the science activities and the observatory development programs.

8.2. *IHY and the United Nations Basic Space Sciences Initiative*

The IHY organization has joined hands with the United Nations Office of Outer Space Affairs to promote heliophysical science activities throughout the world by deploying scientific instruments in the developing countries. Under this collaborative program known as the United Nations Basic Space Sciences (UNBSS) initiative, scientists from developed countries or those who are willing and able, donate small instruments to developing countries for studying heliophysical processes. These deployments will serve as nuclei for a sustained development of scientific activities in the host countries (Davila *et al.* 2008). The IHY/UNBSS instrument concepts can be grouped as follows:

- (i) Solar Telescope Networks,
- (ii) Ionospheric Networks,
- (iii) Magnetometer Networks, and
- (iv) Particle Detector Networks.

Extensive data on space science have been accumulated by a number of space missions. Similarly, long-term data bases are available from ground-based observations. These data can be utilized in ways different from originally intended for understanding the heliophysical processes. Most of the networks are in progress, and some of them are close to completion. The networks are designed such that observations can be made continuously. For example, the Compound Astronomical Low-cost Low-frequency Instrument for Spectroscopy and Transportable Observatory (CALLISTO) network (PI: Arnold Benz, ETH Zürich, Switzerland) covers the whole globe so the Sun can be observed continuously.

The IHY/UNBSS instrument program is supported by a series of workshops. The primary activities during the workshops can be summarized as follows:

- (1) Scientists from developing and developed countries meet face-to-face to discuss collaborative projects under the UNBSS program,
- (2) Scientific instrument host groups provide descriptions of the sites for instrument deployment and the facilities available for hosting the instrument,
- (3) Potential providers of scientific instruments describe their instruments and the key requirements in terms of infrastructure for a successful deployment and continued operation,
- (4) Progress reports after the previous workshop are presented and discussed, and
- (5) Several participants provide the necessary scientific background through a series of tutorial talks.

The first IHY/UNBSS Workshop on Basic Space Science was held in Abu Dhabi and Al-Ain, United Arab Emirates during 20-23 November, 2005. Workshop participants

represented 44 countries, including a significant portion of North Africa and the IHY-West Asia region. The Second IHY/UNBSS Workshop was held from 27 November - 1 December 2006 in Bangalore, India and was sponsored by UN, NASA and several institutions in India. After several sessions on background science topics, presentations by the instrument donors on the current progress and future plans for the deployment projects were made. Proceedings of the second workshop was published in the Bulletin of the Astronomical Society of India (vol. 35, December 2007). The volume contains 39 articles covering the entire range of IHY science. The third UNBSS meeting took place in Japan in June 2007, which combined both IHY and astronomy activities. Twenty two publications will soon appear in *Earth, Moon and Planets*. The fourth IHY/UNBSS workshop was held in Sozopol, Bulgaria in June 2008. In addition to the traditional activity, this workshop included first results from the IHY science activities. Papers presented in this workshop will be published in the on-line journal *Sun and Geosphere*. The final IHY/UNBSS workshop will take place in South Korea in September 2009.

8.3. *Science: Coordinated Investigation Programs*

The building blocks of the IHY science program are the Coordinated Investigation Programs (CIPs). The CIPs are essentially autonomous investigations proposed and executed by self-selected groups of scientists that span the range of IHY science. The CIPs have been grouped into seven 'Disciplines': Solar; Heliospheric/Cosmic Rays; Magnetospheres; Ionized atmospheres; Neutral atmospheres; Climate; Meteors/Meteoroids/ Interstellar Dust. One of the major achievements of IHY has been establishing more than 60 CIPs, each one involving a large number of international scientists. The CIPs will continue even after IHY ends formally in the Spring of 2009.

The Whole Heliosphere Interval (WHI) is one of the CIPs. It is an internationally coordinated observing and modeling effort to characterize the 3-dimensional interconnected solar-heliospheric-planetary system. The campaign to characterize this 'heliophysical' system was conducted during solar Carrington Rotation 2068 (20 March–16 April 2008). The previous and following rotations were also included for comparison purposes. Observers, theorists and modelers met for a workshop during 26–29 August 2008 in Boulder, CO, USA. A wealth of information on the quiet heliosphere as well as transient events has been accumulated and the analyses have been initiated during the workshop. One of the first comparisons made was between the appearance of the Sun during the solar minimum in 1996 (Whole Sun Month campaign) and the current solar minimum (2008). In August 1996, the new cycle (23) had already started, which continued to be present in 2008. Even though there are indications that cycle 24 has started in December 2007, the old cycle activity is still dominant. Comparisons were also made in the polar region using *Ulysses* data from the two minima. Many coronal mass ejections were also observed and their study assumed new significance because of the availability of data from the twin *STEREO* spacecraft.

WHI occurred during solar minimum, which optimizes our ability to characterize the 3-D heliosphere and trace the structure to the outer limits of the heliosphere. With the *Ulysses* spacecraft over the northern pole of the Sun, and the twin *STEREO* spacecraft in a configuration optimal for 3-D view of the Sun and inner heliosphere, there are some unique possibilities to understand the heliophysical processes. This is augmented by the observations from *SOHO*, *Wind* and *ACE* missions at Sun-Earth L1 point. The five *THEMIS* spacecraft will likewise be in an ideal configuration to perform 3-D studies of the Earth's magnetosphere.

8.4. *IAU Symposium No. 257*

The IAU Symposium No. 257 on *Universal Heliophysical Processes* was held in Ioannina, Greece, 15–19 September 2008. The symposium is cosponsored by the IHY program and the University of Ioannina. The focus of IAU Symposium No. 257 was on the universality of physical processes in the region of space directly influenced by the Sun through its mass and electromagnetic Emissions: the heliospace. The symposium also attempted to consolidate the knowledge gained in space science over the past fifty years since the birth of this discipline in 1957. The topics of discussion include: Solar sources of heliospheric variability; Origin, evolution and dissipation of magnetic structures; Planetary atmospheres, ionospheres, and magnetospheres, Plasma processes: flows, obstacles, circulation; Energetic particles in the heliosphere; Heliophysical boundaries and interfaces including shock waves; Reconnection processes; Turbulence in heliospace; Physical processes in stellar systems. The symposium had nearly 100 papers presented as keynote addresses, invited talks, contributed talks, and posters. Proceedings of the symposium will be published by Cambridge University press within six months (Gopalswamy & Webb 2009).

8.5. *The IHY Schools Program*

The IHY Schools Program was designed to provide a broad exposure of the universal processes in the heliospace to you scientists and graduate students throughout the world. The School program is designed to be synergistic with the IHY/UNBSS program. International schools have now been successfully conducted in North America (Boulder, CO, USA, August 2007), Asia-Pacific I (Kodaikanal Solar Observatory, India, December 2007), and Latin America (Sao Paulo, Brazil, February 2008). Two more schools are being planned for 2008: Asia-Pacific II in Beijing, China, 20-31 October, and Africa School in Enugu, Nigeria, 10–22 November. A book containing the lectures of the Kodaikanal IHY school is in preparation and will be published by Springer (Gopalswamy, Hasan, & Ambastha 2009). A book will also be published for the proceedings of the American IHY school in Boulder.

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9. Closing remarks

The word ‘Heliophysics’ was coined very recently. Heliophysics encompasses the study of the system composed of the Sun’s Heliosphere and the objects that interact with it. This is precisely the scope of Commission 49; it can give us first hand knowledge on fundamental astrophysical processes, from microscopic scales to the scale of the heliosphere: turbulence, reconnection, shocks, particle acceleration, abundances, scale coupling.

The topic of dusty plasmas in the Heliosphere could not be covered in this report, despite important results. Several analyses are still ongoing at the time of this report, but preliminary results suggest that studies relating to nano-particles and their discovery in the solar wind will probably be one of the highlights of the next triennial report in this field.

Jean-Louis Bougeret
president of the Commission