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INTERPLANETARY PLASMA AND HELIOSPHERE

PLASMA INTERPLANÉTAIRE ET HÉLIOSPHÈRE

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TRIENNIAL REPORT 2009-2012

1. Introduction

Commission 49 (Interplanetary Plasma and Heliosphere) is part of IAU Division II (Sun and Heliosphere). The research topics include large-scale solar disturbances such as coronal mass ejections (CMEs), shocks, and corotating interaction regions (CIRs) propagating into the heliosphere. The disturbances propagate through the solar wind, which essentially defines the heliosphere. The solar disturbances provide large-scale laboratory to study plasma processes over various time and spatial scales, the highest spatial scale being the size of the heliosphere itself (∼ 100 AU). These solar disturbances are related to solar activity in the form of active regions and coronal holes. Solar eruptions are accompanied by particle acceleration and the particles can be hazardous to life on earth in various ways from modifying the ionosphere to damaging space technology and increasing lifetime radiation dosage to astronauts and airplane crew. Particle acceleration in solar eruptions poses fundamental physics questions because the underlying mechanisms are not fully understood. One of important processes is the particle acceleration by shocks, which occurs throughout the heliosphere. The heliosphere has both neutral and ionized material, with interesting interaction between the two components.

The present triennial report covers a very interesting period marked by rapid explosion of research in the heliophysical processes, thanks to the wide range of observing facilities from space and ground. This period witnessed the two important milestones in the effort of sending mission to the Sun: the approval of the Solar Orbiter and Solar Probe Plus. When these missions come online, they will provide ground truth for a number of theories and greatly enhance our understanding of the near-Sun plasma and magnetic field. The triennial period also witnessed the formal conclusion of the International Heliophysical Year, although the efforts are continuing in the form of the International Space Weather Initiative (ISWI) program (www.iswi-secretariat.org). One of the IHY Coordinated Investigations Programs on the Whole Heliospheric Interval evolved into the IAU Symposium 286 on “Comparative Magnetic Minima: Characterizing quiet times in the Sun and stars” coordinated through Divisions II and IV and some of their associated commissions. The meeting was held during 3 − 7 October 2011 in Mendoza, Argentina. The ISWI program has been deploying instruments to study solar shocks, particles from the Sun and our galaxy, geospace processes, and others in collaboration with the United Nation's Office of Outer Space Affairs. ISWI recently crossed a milestone: ISWI instruments have been deployed in 101 countries. Two Space science summer schools were organized, one in Bahir Dar, Ethiopia (2010) and the other in Tatranska-Lomnica, Slovakia (2011). The Scientific Committee on Solar Terrestrial Physics (SCOSTEP, http://www.yorku.ca/scostep/) launched the second phase of the Climate and Weather of the Sun-Earth System (CAWSES -II). The CAWSES-II program is in full swing attempting to answer four basic questions: What is the solar influence on climate? How will geospace respond to an altered climate? How does short-term solar variability affect the geospace environment? What is the geospace response to variable inputs from the lower atmosphere?

One of the highlights of this present period is the launch of the Solar Dynamics Observatory (SDO) mission in February 2010. The SDO mission provides data of unprecedented quality to make progress in understanding the irradiance, magnetism, and atmospheric dynamics of the Sun, complementing the information provided by other missions such as SOHO, STEREO, and Hinode. Wind, ACE and SOHO continue to provide information on solar disturbances at 1 AU, which can be combined with the near-Sun observations obtained by remote-sensing for understanding the heliospheric propagation of solar disturbances. The STEREO mission was in a unique quadrature configuration during 2010 – 2011 with spacecraft along the Sun-Earth line providing unprecedented 3-D view of coronal mass ejections, which are the most energetic phenomenon in the heliosphere.

Section 2 provides a discussion on the small-scale density structures in the heliosphere. Section 3 describes recent results on dust and dust interactions in the interplanetary medium. Section 4 highlights recent results on solar eruptions and their heliospheric consequences. Information on recent reviews on CMEs and the heliospheric aspects of CMEs are presented in section 5. Use of the interplanetary scintillation technique to study various aspects of the three-dimensional heliosphere is presented in section 6. Section 7 highlights results on the energetic particles from the Sun and galactic cosmic rays. Section 8 presents a summary of recent results from studies on the outer heliosphere.

2. A View of the Heliosphere at Small Scale

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The large scale structures of the interplanetary medium and spatial environment of the planets are deeply constrained by numerous microphysical processes. Langmuir waves are at the origin of the most intense radio emissions observed in the heliosphere. They also efficiently couple with the electron dynamics. For these crucial roles, they have deserved a lot of attention for many years, and in particular in the last years owing to the new measurements allowed by STEREO/WAVES. We present here the most outstanding results in this field obtained during the last four years.

2.1. *Role of Density Fluctuations in the Dynamics of Langmuir Waves*

The density fluctuations are thought to play an important role in the beam-Langmuir waves dynamics. Density wells result from the turbulent cascade of energy, from large to small scales. For many years, *in situ* electric field measurements in the solar wind and planetary environment (like the terrestrial foreshock) have revealed the presence of many intense, localized Langmuir wavepackets. In the last years new progresses in the understanding of the role of the density fluctuations on the dynamics of the waves have been achieved.

The Intense Langmuir Solitons (ILS) are localized Langmuir wavepackets of a few mV/m. They have been interpreted as eigenmodes of electron density cavities (Ergun *et al.* 2008; Malaspina & Ergun 2008). The cavity length have been estimated to peak at about 5 to 10 km (Malaspina *et al.* 2010a). Two models have been proposed to explain the formation of such wavepackets.

In a first approach, the growth of the Langmuir wave is sufficiently moderate so that the density fluctuations constrain the waves to directly develop as an eigenmode of the cavity. As described by Hess *et al.* (2010), larger and deeper cavities favor the Langmuir wave generation. Following a more recent study (Hess *et al.* 2011), both quasi-planar Langmuir waves and eigenmodes should be present in the solar wind, the latest showing a higher amplitude. The authors proposed an analytic formulation of the size and amplitude distribution of the eigenmode wavepackets over a large range of distance to the Sun, in particular close to it. Future missions like the Solar Orbiter or the Solar Probe Plus should be able to test this model.

A second approach to explain the presence of cavities eigenmodes was developed by Zaslavsky *et al.* (2009). In their model, the growth rate of Langmuir waves is supposed to be strong. The waves would be constrained by the presence of density fluctuations not in the growing phase (as the previous model) but during the coalescence phase, when the waves reach saturation.

Density fluctuations also play a key role in the Earth environment, in particular to explain the Langmuir waves strength distribution in the terrestrial foreshock. Indeed, Malaspina *et al.* (2009) deduced that the maximum foreshock Langmuir field strength falls with distance to the foreshock via a power law. Comparing STEREO/WAVES measurements with theoretical models, they concluded that scattering of Langmuir waves by density fluctuations is mandatory to reproduce such a behavior. Finally, LaBelle *et al.* (2010) also invoke the linear growth of Langmuir waves in an homogeneous medium to explain the highly modulated electric waveforms observed in the Earth polar cusp.

2.2. *Langmuir Waves: from Linear to Nonlinear Plasma Physics*

For the electromagnetic radiation to serve as a tool for the diagnostic of the interplanetary medium, the local processes at the origin of such radiation must be known with great details. Two lines of thought are currently debated. The first relies on the classical model of Ginzburg & Zheleznyakov where nonlinear waves coupling generated EM emission at twice the local plasma frequency. Observational evidences of such wave coupling have been presented by Henri *et al.* (2009) in the frame of interplanetary Type III radio bursts. Numerical Vlasov simulations have reinforced their observations. Henri *et al.* (2010) have indeed shown that the energy levels of the observed waves are in good agreement with the threshold of the parametric decay for *non monochromatic* waves.

In a recent work Malaspina *et al.* (2010b) proposed an alternative process to the classical model to explain the $2f_p$ radiation observed during Type III radio bursts. Intense localized Langmuir wavepackets trapped in density wells would drive secondary order currents that oscillate at twice the plasma frequency, producing an electromagnetic radiation at this frequency. Such antenna-like mechanism produces electric field amplitude compatible with STEREO/WAVES observations within an order of magnitude.

The nonlinear evolution of waves is usually classified in terms of "weak" and "strong" turbulence. The typical structures of the strong turbulence like the Langmuir solitons are usually thought to be absent of the interplanetary medium where conditions typical of the weak turbulence prevailed. However, Henri *et al.* (2011b) have demonstrated that the transition toward strong turbulence can also be a consequence of an initial weak turbulence inverse cascade. This result may encourage space physicists to revisit the waveform data in space plasma environments.

Langmuir waves are also observed inside small magnetic depression called magnetic holes. In a recent study Briand *et al.* (2010) have shown that the polarization of the waves is compatible with Langmuir/z-mode waves. Through combined observations of STEREO and CLUSTER they have also demonstrated that the presence of a pronounced electron strahl is required for the generation of Langmuir waves and that the electron distribution function inside the magnetic hole is more isotropic compare to outside the hole. Thus, important wave-particles interactions must take place in such environment. To go further in the understanding of such processes, kinetic numerical simulations are required.

2.3. *Langmuir Waves: an Efficient Tool for Particle Measurements*

In the last years, several studies have shown how Langmuir wave analyses can advantageously complete particles instruments measurements to locally infer density fluctuations, electron beam speed and/or electron temperature at high frequencies.

While the power spectrum describing the turbulent cascade is well known along the inertial range, it is still a source of large debate in the dissipation range. In particular, at electron scale the measurements are very difficult. Langmuir waves can give some information about the density fluctuations observed at "high" frequencies, if not in standard quiet solar wind conditions, at least in several other environments like the terrestrial foreshock.

Langmuir waves are very bursty: fluctuation of the order of tens of milliseconds are perfectly observed. In particular the Time Domain Sampler mode of STEREO/WAVES provides for the first time long time duration waveforms (about 130 msec compared to the 17 msec of the WIND/WAVES instrument). Malaspina *et al.* (2010a) interpret these fluctuations as a signature of local, small scale density variations of the plasma. They thus extend the power spectrum of density fluctuations in the solar wind by an order of magnitude toward the high frequencies compare to former studies.
When the Langmuir wave energy is large enough (typically $\geqslant 10^{-2}$), the pondemorotrice force can explain the formation of electron density fluctuations. Owing to its specific antenna mounting, the TDS mode of STEREO/WAVES allows for the measurement of both strong Langmuir electric field and density fluctuations on short time scale (a few milliseconds). Using STEREO as a density probe, Henri *et al.* (2011a) have provided the first observational evidence for ponderomotive effects in the solar wind. They have estimated the density fluctuations in the foreshock to be in the range 50 to 500 Debye lengths.

The determination of the beam speed is often difficult due to the reduced time resolution of the instruments. Malaspina *et al.* (2011) proposed to use the polarization of the Langmuir waves to deduce this velocity. They showed that the polarization of the waves perpendicular to the local magnetic field is more pronounced as the electron beam speed increases. Langmuir/z-mode propagating in a fluctuating density medium may explain such behavior: the small wavenumber associated with a high beam speed can be reduced to even lower values by density fluctuations, increasing the possibility for strong polarization. Thus, the measurement of the Langmuir waves polarization could provide a new method to deduce electron beam speed and density fluctuations.

Among the many questions regarding the interplanetary shocks, one is particularly well addressed by Langmuir wave measurements. It concerns the localization of the Type II emission generation: is this emission generated at the nose of the shock or on the trailing edge? Since Type II radio emissions take their free energy from accelerated electron beams, the detection and localization of Langmuir waves is a good indicator to answer this question. Pulupa *et al.* (2010) studied the physical conditions for the development of Langmuir waves activity upstream of a shock, providing thus new keys to study the dynamics of the shocks both some an observational point of view than a numerical one.

3. Cosmic Dust in the Heliosphere

The two major cosmic dust components in the heliosphere are the interstellar and interplanetary dust particles. The trajectories of interstellar dust particles that enter the heliosphere are influenced by the heliospheric magnetic field (see Sect. 3.1). Interplanetary dust particles form by fragmentation of comets, asteroids and meteroids, the latter being fragments of the two former parent objects. Heliospheric interactions of the interplanetary dust are recently studied especially for the nanodust among the interplanetary dust (see Sect. 3.2). Cosmic dust in the heliosphere also interacts with electrons, ions and neutrals in the interplanetary medium, but observational results are rare (see Sect. 3.3).

3.1. *Interstellar Dust in the Heliosphere*

The motion of the Sun and the heliosphere relative to the surrounding interstellar medium and its containing Local Interstellar Cloud (LIC) causes a flux of interstellar dust into the solar system. This LIC dust is the only dust component measurable in the Solar System that was not previously incorporated in larger Solar System objects.

3.1.1. *Observations*

Interstellar dust in the heliosphere was measured in detail during the Ulysses mission that orbited the Sun in high inclination orbit during almost three revolutions between about 1.3 and 5.4 AU. Krüger *et al.* (2010) published the final Ulysses dust data covering measurements of the last 3 years and comparing them to previous observations. The dust experiment provided 6719 dust data sets recorded of particles with masses 10^{-19} kg $\leqslant$ m $\leqslant$ 10^{-10} kg, a large fraction being classified as interstellar dust. During the mission Ulysses passed the same latitudes during different phases of the solar cycle and by comparing specific measurement intervals where a large faction of interstellar dust was observed Krüger *et al.* (2010) found that the impact rate of interstellar grains varied by more than a factor of two. This variation is commonly assumed to be primarily due to the change of the solar cycle. They also find a change in flux direction that was already noted in earlier observations. Krüger & Grün (2009) report, that while until 2004, the measured interstellar dust flow direction was close to the mean apex of the motion of the Sun through the LIC, this seems to be shifted later by approximately 30 degree away from the ecliptic. Detailed model calculations are needed to explain to what extent the shift is due to a shift of the initial flux into the solar system and to what extent it is due to the influence of Lorentz force onto the ISD within the heliosphere. Very recently the plasma wave instruments onboard the two STEREO spacecraft observe impacts of interstellar dust (Zaslavsky *et al.* 2011). The STEREO measurements provide a data set of interstellar dust flux near 1 AU during more than 3 years.

3.1.2. *Model Calculations*

New calculations are made to follow the trajectories of interstellar dust into and around the heliosphere. Slavin *et al.* (2010) calculate the entry of tiny interstellar dust into the heliosphere and find that the inclination of the interstellar magnetic field relative to the inflow direction generates an asymmetric distribution of the larger interstellar dust that crosses the heliopause (with sizes of the order of 0.1 micrometer). Sterken *et al.* (2011) present simulations of the interstellar dust trajectories within the heliosphere. Their model accounts for the influence of solar radiation pressure force and Lorentz force in the interplanetary magnetic field and they present the resulting dust densities, dust fluxes and flux directions. The developed tools can now be used for predicting the fluxes of interstellar dust at spacecraft locations.

3.1.3. *Review Papers*

Recent review papers address several different aspects of interstellar dust in the heliosphere. Krüger & Grün (2009) review the different measurements of interstellar dust with dust experiments on board spacecraft. Mann (2010) reviews the recent studies of interstellar dust in the solar system, discusses the entry of dust into the solar system and the comparison of derived properties to dust models: the current measurements suggests similarities in the composition of dust in the local interstellar cloud and pristine cometary dust; comparing different published meteor studies suggests that as to date there is no clear identification of interstellar meteors. Two other reviews consider the physics of the local interstellar cloud surrounding the heliosphere and the medium at the boundaries of the heliosphere — (Frisch *et al.* 2009, 2011). These two latter works take into account absorption line data that allow constraining the gas distribution surrounding the heliosphere, as well as pick-up ion observations that provide information on the neutral gas entering the heliosphere.

3.2. *Nanodust in the Interplanetary Medium*

Observations by the STEREO mission show for the first time that nanodust also exists widely distributed in the interplanetary medium (Meyer-Vernet *et al.* 2009). The detection of the nanodust is possible, because of its high impact speed onto the spacecraft (Meyer-Vernet *et al.* 2010). The nanodust most likely forms during collisions of larger dust in the inner solar system, is accelerated in the solar wind and observed near Earth orbit when moving outward. Czechowski & Mann (2010) have suggested a possibly scenario to generate the nanodust fluxes that are observed near 1 AU: the nanodust forms by collisional fragmentation of larger dust particles inside 1 AU. Initial velocities are close to that of Keplerian motion. Dust particles with a charge to mass ratio Q/m of the order of $10^{-4} - 10^{-5}$ e/m$_p$ (e=elementary charge, m$_p$=the proton mass) are either trapped in orbits with perihelia very close to the Sun and destroyed by sublimation and sputtering. Or they are ejected outward and accelerated to high velocities, of the order of 300 km/s. The charge to mass ratio of $10^{-4} - 10^{-5}$ e/m$_p$ for which acceleration is effective corresponds to dust with radii $3 - 10$ nm (if the charging of larger dust can be extrapolated to the nanometric size). The trajectory calculations can explain the acceleration of the nanodust, while it is still open what causes the flux variations. While an error occurred in the published flux estimate (Czechowski & Mann 2011) the observed and estimated fluxes are within an acceptable range given the large uncertainties of the parameters that enter the problem. STEREO has now observed nanodust during 3 years and at the same time has also observed larger dust particles (Zaslavsky *et al.* 2011).

Interactions with the solar wind are also observed for the streams of nanodust that are ejected from the magnetospheres of Jupiter and Saturn. Hsu *et al.* (2010) studied the Jupiter and Saturn streams based on Cassini measurements and found that the detection patterns of the stream particles are correlated with the interplanetary magnetic field changing the stream direction and the strength of the stream. Similarly Flandes *et al.* (2011) argue based on a comparison of dust, magnetic field and solar wind measurements onboard Ulysses that the dust streams are affected by variations in the interplanetary magnetic field.

The dust formation by collisional fragmentation is a common process in the interplanetary dust cloud as well as in the interplanetary medium. The nanodust has different physical properties compared to larger particles. Extrapolating the collisional fragmentation laws to small-sized fragments therefore has a lower limit. This small size limit is not determined yet. The formation and observation of nanodust in the solar system is the content of a book with 9 different contributions, to be published by Springer in 2012 (Mann *et al.* 2012).

3.3. *Dust Interactions in the Interplanetary Medium*

While the dust is clearly influenced by the presence of the solar wind, current observations show no evidence for the influence of the dust particles on the solar wind on large scales. An exception are possibly the inner source pick-up ions that are observed in the solar wind with Ulysses (see Gloeckler *et al.* 2010 for the most recent results). Dust interactions with the solar wind produce neutral gas or ions in low charge states and dust destruction by mutual collisions, sublimation and sputtering provides a source of electrons and ions. Quantitative discussion of these processes (Mann *et al.* 2010b, 2010a) has shown that the inner source pick-up ions are possibly generated by dust, while other interactions are so far not clearly confirmed by observations (Mann *et al.* 2011). Recent studies have considered the influence that the presence of dust has on the solar wind. Russell *et al.* (2010) claims, for instance that the presence of dust particles causes field enhancements in the solar wind, however without providing a detailed description of the mechanism.

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4. Solar Eruptions and Their Interplanetary Manifestation

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4.1. *Introduction*

Solar eruptions provide important tools to probe the interplanetary medium. Of particular importance are the type III and type II bursts because these bursts are produced by electron beams and shock waves, respectively propagating through the interplanetary medium. Type III bursts can occur with and without an associated CME. The radio dynamic spectra provide information on the speed of the electron beam and the shock if we have independent information on the density variation in the corona and IP medium. Analyzing the radio dynamic spectrum in conjunction with the eruption information from coronagraphic observations, one can derive the large-scale structure of the interplanetary magnetic field as well as its strength.

4.2. *Type III Bursts*

Cairns *et al.* (2009) presented a method for extracting the density profile of the corona from the time-varying frequencies of type III radio bursts in the frequency range 40–180 MHz. They found that wind-like regions (density falling off as the square of the heliocentric distance) occur quite often below ~ 2 Rs. This is different from the typical behavior where a much steeper index derived from eclipse observations. These authors provide a simple physical interpretation involving conical flow from a localized source (e.g., UV funnels observed near the photosphere). Cairns *et al.* (2009) were able to demonstrate this using the linear relationship found between the inverse frequency and time known in at much lower frequencies.

Reiner *et al.* (2009) made use of the stereoscopic view provided by the twin STEREO and the Wind spacecraft to make multipoint measurements of type III radio burst sources by three-spacecraft triangulation measurements. Using three-point measurements of the beaming characteristics for two type III radio bursts, these authors found that individual type III bursts exhibit a wide beaming pattern that is approximately beamed along the direction tangent to the Parker spiral magnetic field line at the source location. In another work involving ray tracing calculations, Thejappa & MacDowall (2010) showed that the radio emission from a localized source escapes as direct and reflected waves along different paths and that the reflected waves experience higher attenuation and group delay because they travel longer path lengths in regions of reduced refractive index. These authors were able to discern the direct and reflected components of a type III event observed by the STEREO spacecraft and found that the sources are located between the turning point of the ray and the harmonic plasma layer.

4.3. *Type II Bursts*

While the source of type III bursts has been more or less accepted to be the flare reconnection, the source of type II producing shocks has been controversial. Flare blast waves and CME-driven shocks have been the competing processes, but recent observations seem to indicate a CME origin. One of the major arguments in this direction has been the universal drift rate spectrum of the type II bursts, which has an index around 2 over the entire wavelength range of type II bursts (Gopalswamy *et al.* 2009a). If individual wavelength domains are considered, it was found that the power law index is < 2 at metric wavelengths (corresponding to the inner corona) and > 2 at kilometric wavelengths (far away from the Sun). These deviations can be explained by the increasing in shock speed near the Sun as a part of the eruption process and the declining speed in the interplanetary medium due to the drag force. However, there have been reports of occasional type II bursts associated with slow CMEs (Magdalenić *et al.* 2010; Nindos *et al.* 2011). One explanation is to attribute the type II shock to the impulsive increase of the pressure in the flare region (Magdalenić *et al.* 2010; Nindos *et al.* 2011). The other explanation is to attribute the slow CME association to the variability of Alfven speed in the corona that can vary over a factor of 4 (Gopalswamy *et al.* 2008) because the Alfven speed in the inner corona can be as low as 200 km/s, which is low enough for the slow CMEs to drive a shock. Furthermore, direct observation of shock formation in SDO/AIA images precisely coinciding with the appearance of a type II burst clearly shows the shock overlying the CME at a heliocentric distance of 1.2 solar radii (Gopalswamy *et al.* 2011). Multiple type II bursts observed in some events have also been interpreted as the flare and CME driving two different shocks causing two different type II bursts. However, the two type II bursts can be explained by a single CME (Gopalswamy *et al.* 2009a; Cho *et al.* 2011).

4.4. *EUV Waves*

EUV wave transients associated with CMEs have been studied extensively over the past decades, thanks to the excellent data from SOHO's Extreme-ultraviolet Imaging telescope (EIT), STEREO's EUV Imager (EUVI), and recently SDO/AIA. The physical nature of these so-called "EUV waves" has not been fully understood. It is natural to expect them to be MHD waves and/or shocks depending on the speed of the driving CME. When the EUV waves are associated with type II bursts, the EUV waves are expected to be shocks because the type II bursts are produced by CME-driven shocks. When there is no type II burst, the EUV wave may be a weak shock or simply fast-mode wave. EUV waves have also been interpreted as signature of magnetic reconfiguration due to the expansion of the associated CME into the ambient magnetized plasma. In addition to the association with type II bursts, wave reflection from a coronal hole (Gopalswamy *et al.* 2009b) also supports the wave interpretation. Veronig *et al.* (2010) presented clear evidence from STEREO/EUVI that the wave is a dome-shaped spherical wave surrounding the CME (see also Temmer *et al.* 2011). Chen & Wu (2011) interpret an EUV event using SDO/AIA data as consisting of a fast mode wave followed by a slower disturbance. They identify the slower wave with the EIT wave, while the leading one as the fast mode wave (Moreton wave). Warmuth & Mann (2011) analyzed a set of 176 EUV waves observed by SOHO/ EIT and STEREO/EUVI and found that the waves fall into three classes: 1) initially fast waves ($v \geqslant 320$ km s^{-1}) that show pronounced deceleration, 2) waves with moderate ($v \approx 170-320$ km s^{-1}) and nearly constant speeds, and 3) slow waves ($v \leqslant 130$ km s^{-1}) showing a rather erratic behavior. They concluded that class 1 waves are nonlinear large-amplitude waves or shocks that propagate faster than the ambient fast-mode speed and subsequently slow down due to decreasing amplitude. Class 2 waves are linear waves moving at the local fast-mode speed. Class 3 waves may be disturbances that could be attributed to magnetic reconfiguration. They suggest that a single model cannot explain all the three classes of EUV waves, a conclusion shared by others (Zhukov 2011; Gallagher *et al.* 2011).

4.5. *White-light Signatures of CME-driven Shocks: Four-part CME Structure*

Although there have been attempts to search for white-light features of the shocks in the past (Sheeley *et al.* 2000; Vourlidas *et al.* 2003), the diffuse feature has been recognized as a shock manifestation only recently (Gopalswamy 2009; Gopalswamy *et al.* 2009a; Ontiveros & Vourlidas, 2009; Gopalswamy, 2010; Eselevich & Eselevich, 2011). In coronagraphic difference images, one observes a diffuse feature surrounding the bright feature identified as the CME flux rope. The bright and diffuse structures are sometimes referred to as the main body and whole CME (Michalek *et al.* 2007, Gopalswamy *et al.* 2008; Yashiro *et al.* 2008). The diffuse feature surrounding the flux rope is identified with the compressed plasma known as shock sheath. The shock itself is too thin to be observed in coronagraphic images. The diffuse structure is only observed in relatively fast CMEs. Thus, fast CMEs have an additional shock sheath structure and hence should be referred to as CMEs with a four-part structure. More recently, a shock was identified very close to the Sun, using EUV images obtained by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO). The eruptive prominence, the flux rope, and the shock sheath can all be tracked within the SDO/AIA field of view (Kozarev *et al.* 2011; Ma *et al.* 2011; Gopalswamy *et al.* 2011).

Identification of the shock sheath surrounding the CME flux rope has opened up new opportunities to derive the shock and ambient medium properties. The shock strength can be measured in terms of the density compression ratio downstream to upstream using brightness jump in the diffuse feature (Ontiveros & Vourlidas 2009; Eselevich & Eselevich 2011; Bemporad & Mancuso 2011). Bemporad & Mancuso (2011) used the compression ratio to infer the Alfvén Mach number at various locations of the shock front. They conclude that the CME-driven shocks could be efficient particle accelerators at the initiation phases of the event, while at later times they progressively loose energy, also losing their capability to accelerate high-energy particles. Gopalswamy & Yashiro (2011) introduced a new technique to measure the coronal magnetic field strength in the heliocentric distance range $6-23$ solar radii using the shock standoff distance and the CME radius of curvature in the SOHO and STEREO coronagraphic images. Assuming the adiabatic index, they determined the Alfvén Mach number, and hence the Alfvén speed in the ambient medium using the measured shock speed. By measuring the upstream plasma density using polarization brightness images, they obtained the magnetic field strength upstream of the shock. The estimated magnetic field decreased from ∼ 48 mG around 6 Rs to 8 mG at 23 Rs. The radial profile of the magnetic field can be described by a power law in agreement with other estimates at similar heliocentric distances. This is a new technique, which provides a means of estimating the magnetic field in the heliospheric region that will be probed by the Solar probe Plus. This technique was also applied to the SDO/AIA data for shock-driving CMEs associated with metric type II radio bursts. Obtaining the upstream parameters from the type II band-splitting, Gopalswamy *et al.* (2011) derived the coronal magnetic field very close to the Sun (1.5 Rs) to be ∼ 1.3 G. Recently, Maloney & Gallagher (2011) extended the stand-off distance measurement to 120 Rs, using observations from the STEREO Heliospheric Imager. This, coupled with the HELIOS observations from the past, provides an opportunity to estimate the magnetic field strength throughout the inner heliosphere.

4.6. *Variability in CME-driven Shocks at 1 AU*

One way to find out whether a CME drives a shock or not is to look at its radio emission properties (Gopalswamy *et al.* 2010). CME-driven shocks emitting type II radio bursts are known as radio-loud (RL) events as opposed to radio-quiet (RQ) events in which the shocks do not produce the bursts. Starting with the 200+ shocks detected at L1 by one or more of Wind, SOHO, and ACE spacecraft, the associated CMEs were grouped into RL and RQ events. When the CME properties were compared for the two groups, there were significant differences. The CME speeds were very different for the RL and RQ CMEs, while the corresponding IP shock speeds were similar for the two groups. The difference between RL and RQ events seems to be erased as the CMEs propagate into the interplanetary medium because of the momentum exchange between the CMEs and the ambient solar wind. Another significant difference was that the RQ CMEs accelerated on the average, while the RL CMEs decelerated near the Sun (within the coronagraphic field of view). In general, the RL CMEs drove shocks near the Sun, which weakened as they propagated into the IP medium. Among the RL CMEs, some were radio loud only near the Sun, some only near Earth, and others throughout the IP medium. The heliocentric distance range over which the radio emission occurred essentially depended on the CME speed.

Pulupa *et al.* (2010) attempted to identify shock parameters that favor production of upstream Langmuir waves, and hence type II radio bursts. Among the 178 interplanetary shocks observed by the Wind spacecraft, only 43 (or 24%) were found to produce upstream Langmuir waves, as measured by the enhancements in wave power near the plasma frequency. They found that the de Hoffmann-Teller speed is the best indicator of the Langmuir wave production, consistent with the fast Fermi model of electron acceleration. Several other parameters, including the magnetic field strength and the level of solar activity (but not the Mach number) were also found to be correlated with Langmuir wave production. They suggest that additional parameters may be associated with an increased level of shock front curvature or upstream structure, leading to the formation of upstream foreshock regions, or with the generation of an upstream electron population favorable for shock reflection.

Langmuir waves require electron acceleration in the shock, but the energetic storm particle (ESP) events indicate ion acceleration at the shock front. Looking at the properties of the driving CMEs near the Sun, Mäkelä *et al.* (2011) found that CMEs with an ESP-producing shock are faster than those driving shocks without an ESP event and have a larger fraction of halo CMEs (67% versus 38%). The fraction of halo CMEs in a population is indicative of how energetic the population is. It was also found that the Alfvénic Mach numbers of shocks with an ESP event are on average 1.6 times higher than those of shocks without. The ESP events occur more often in radio-loud shocks (RL, shocks producing type II bursts) than in radio-quiet shocks: 52% of RL shocks and only ∼33% of RQ shocks produced an ESP event at proton energies above 1.8 MeV; in the keV energy range the ESP frequencies are 80% and 65%, respectively. The interplanetary shocks seem to be organized into a decreasing sequence by the energy content of the CMEs: radio-loud (RL) shocks with an ESP, followed by RL shocks without an ESP event, then radio-quiet (RQ) shocks with and without an ESP event.

4.7. *Large-scale CME Deflections*

CMEs can interact with other CMEs leading to deflection and/or merging. CMEs can also interact with neighboring streamers and coronal holes. Different processes dominate during different phases of the solar cycle. For example, deflection towards the equator in the solar minimum phase is expected because of the strong global solar field. During the solar maximum phase, CME-CME interaction is expected to be common. During the declining phase, the equatorial coronal holes appear in great abundance, so CME-coronal hole interaction is most common (Gopalswamy *et al.* 2009b). The CME deflection by coronal holes has also important consequences for space weather: a CME originating close to the disk center may not arrive at 1 AU. For example, shocks are observed at 1 AU without any discernible driver at 1 AU, although the associated CME is clearly observed near the Sun. These “driverless shocks” represent extreme deflection by coronal holes (Gopalswamy *et al.* 2009b, 2010). The CME deflection essentially makes disk center CMEs behave like limb CMEs. The amount of CME deflection needed for driverless shocks has been estimated to be in the range $20-60$ degrees, depending on the orientation of the CME axis with respect to the ecliptic plane. For example, a high-inclination flux rope needs to be deflected less in the longitudinal direction compared to a low inclination one because of the smaller east-west extent of the CME. Gui *et al.* (2011) reported on the change in propagation directions for a set of eight CMEs. They interpreted the deflections as a consequence of the gradient of the magnetic energy density of the background medium. Lugaz *et al.* (2011) performed numerical simulations to understand the CME propagation in the heliosphere. In addition to the coronal hole deflection discussed above, they also suggested additional deflection caused by a second faster CME.

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5. Coronal Mass Ejections and Their Heliospheric Aspects

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5.1. *Recent Reviews of CMEs*

Coronal mass ejections (CMEs) consist of large structures containing plasma and magnetic fields that are expelled from the Sun into the heliosphere. They are of interest for both scientific and technological reasons. Scientifically they are of interest because they are responsible for the removal of built-up magnetic energy and plasma from the solar corona, and technologically they are of interest because they are responsible for major space weather effects at Earth (Baker *et al.* 2009). Most of the ejected material comes from the low corona, although cooler, denser material probably of chromospheric or photospheric origin can be involved. The CME plasma is entrained on an expanding magnetic field, commonly of the form of helical field lines with changing pitch angles, i.e., a flux rope. Observations of Earth-directed CMEs, often observed as halos surrounding occulting coronagraphs, are important for space weather studies. In this section we emphasize results on the heliospheric aspects of CMEs, especially their imaging, during the last triennium.

Until the last decade, images of CMEs had been made near the Sun primarily by coronagraphs on board spacecraft. Coronagraphs view the flow of density structures outward from the Sun in broadband white light by observing Thomson-scattered sunlight from the free electrons in coronal and heliospheric plasma. This emission has an angular dependence which must be accounted for in the measured brightness (e.g., Vourlidas & Howard 2006; Howard & Tappin 2009). CMEs are faint relative to the background corona, but more transient, so some form of background subtraction is typically needed to identify them. The first spacecraft coronagraph observations of CMEs were made by the OSO-7 coronagraph in the early 1970s, followed by better quality and longer periods of CME observations using Skylab (1973 – 1974), P78-1 (Solwind; 1979 – 1985), and SMM (1980, 1984 – 1989). In late 1995, SOHO was launched and two of its three LASCO coronagraphs still operate today (Brueckner *et al.* 1995; Gopalswamy *et al.* 2009, 2010). Finally late in 2006, LASCO was joined by observations from the STEREO CORs (Howard *et al.* 2008; Russell, ed. 2008). These satellite observations have been complemented by white light data from the ground-based Mauna Loa Solar Observatory (MLSO) K-coronameters, currently the MK4 version viewing from $1.2 - 2.9\, R_\odot$ (Fisher *et al.* 1981).

There were several excellent reviews of solar eruptive phenomena and CMEs published just before this triennium, including Gopalswamy *et al.* (2006), Kahler (2006), Aschwanden (2006). In addition, there are several *Living Reviews of Solar Physics* articles (http://solarphysics.livingreviews.org/), including "Space Weather: The Solar Perspective" (Schwenn 2006), and two, "Solar Eruptive Phenomena" (Webb & Howard 2011), and "Coronal Mass Ejections: Models and Their Observational Basis" (Chen 2011), published very recently. In addition, other published or planned *LRSP* articles include on prominences, flares, space weather and other related phenomena. An introductory text on CMEs (Howard 2011) has also recently been published. Finally, analyses of the CMEs observed during the Whole Heliosphere Interval (WHI) international campaign in 2008 were recently published: Cremades *et al.* (2011) and Webb *et al.* (2011).

5.2. *Heliospheric Aspects of CMEs*

Several decades ago, interplanetary transients were observed at larger distances from the Sun than viewed by coronagraphs using interplanetary radio scintillation (1964 – present; Hewish *et al.* 1964; Vlasov 1981) and from the zodiacal light photometers on the twin Helios spacecraft (1975 – 1983; Jackson 1985). The Helios photometers observed regions in the inner heliosphere from 0.3 – 1.0 AU but with a very limited field of view (FoV). The new millennium saw the arrival of a new class of detector, the heliospheric imager, with the Solar Mass Ejection Imager (SMEI) launched on board the Coriolis spacecraft early in 2003 and the Heliospheric Imagers (HIs) launched on the twin STEREO spacecraft in late 2006. LASCO has detected well over 10^4 CMEs during its lifetime (Gopalswamy *et al.* 2009; http://cdaw.gsfc.nasa.gov/CME_list/), SMEI has observed over 360 transients (Webb *et al.* 2006; Howard & Simnett 2008), and the number of "events" reported using the HIs is well over 500 (http://www.sstd.rl.ac.uk/stereo/Events Page.html), despite their operation during the least active Sun during the space age.

CMEs carry into the heliosphere large amounts of coronal magnetic fields and plasma, which can be detected by remote sensing and in-situ spacecraft observations. Here they have been called interplanetary CMEs or ICMEs. The term ICME was originally devised as a means to separate the phenomena observed far from the Sun (e.g., by in-situ spacecraft) and those near the Sun (e.g., by coronagraphs). However, in the STEREO era, where CMEs can now be tracked continuously from the Sun to 1 AU and beyond, the term has become largely redundant. Consequently, in a recent workshop on remote sensing of the heliosphere in Wales (http://heliosphere2011.dph.aber.ac.uk/) it was decided to no longer use the term ICME.

The passage of CME material past a single spacecraft is marked by distinctive signatures, but with a great degree of variation from event to event (e.g., Zurbuchen & Richardson 2006). These signatures include transient interplanetary shocks, depressed proton temperatures, cosmic ray depressions, flows with enhanced helium abundances, and unusual compositions of ions and elements. Often observed in in-situ data are highly structured magnetic field configurations corresponding to the arrival of a CME. The field assumes the structure of a helix and is accompanied by strong magnetic fields with low field variance, low plasma beta and low temperature. Such structures were called magnetic clouds by Burlaga *et al.* (1981). Such a structure is often modeled as a flux rope, having a series of helical field lines like the coils of a spring with pitch angles increasing toward the outer edge. Since many if not all CMEs are now considered to contain flux ropes, it is logical to expect magnetic clouds to form the core of CMEs. Models have been developed for the force free and non-force free states, the latter also known as the Grad–Shafranov technique. See recent Living Reviews of Solar Physics articles by Chen (2011) and Webb & Howard (2011) for detailed discussions of CME models. Around 30% to 50% of CMEs observed in-situ show a clear signature of a magnetic cloud. It remains unknown whether the remainder does not show the signature because the imbedded flux rope is less structured, is absent, or whether the spacecraft did not pass through the flux rope component (i.e., skirted its flank; e.g., Möstl 2010). The in-situ signatures of CMEs are well described in several recent reviews (Schwenn 2006; Zurbuchen & Richardson 2006; Richardson & Cane 2010).

Several techniques have been developed to remotely detect and track disturbances related to CMEs in the interplanetary medium (Jackson 1992; Jackson *et al.* 2011) and see http://heliosphere2011.dph.aber.ac.uk/. These have utilized radio and white light wavelengths to detect and image these structures. The techniques are kilometric radio observations from space and interplanetary scintillation (IPS) observations from the ground. The kilometric observations can track the emission typically from strong shocks traveling ahead of fast CMEs. Such instruments have been flown on the ISEE-3 and Ulysses spacecraft and are currently on board Wind and STEREO (Bougeret *et al.* 2008).

The IPS technique relies on measurements of the fluctuating intensity level of a large number of point-like distant meter-wavelength radio sources. They are observed with one or more ground arrays operating in the MHz range. IPS arrays detect changes to density in the (local) interplanetary medium moving across the line of sight to the source. Disturbances are detected by either an enhancement of the scintillation level and/or an increase in velocity. When built up over a large number of radio sources a map of the density enhancement across the sky can be produced. The technique suffers from relatively poor temporal (24 hour) resolution and has a spatial resolution limited to the field of view of the radio telescope. For example, high-latitude arrays such as the long-deactivated 3.5 ha array near Cambridge in the UK could not observe sources in the mid-high-latitude southern hemisphere. Scattering efficiency also poses a limitation on IPS measurements as increasing the frequency at which to measure the sources allows an observer to detect disturbances closer to the Sun. Higher frequencies means fewer sources, however, so the spatial resolution is effectively decreased. Finally ionospheric noise limits viewing near the Sun and near the horizon, and a model-dependence for interpreting the signal as density or mass. Workers have, however, been working with these difficulties for almost 50 years and a number of techniques have evolved to extract reliable CME measurements using IPS. Recent papers involving such measurements include Bisi *et al.* (2008), Jackson *et al.* (2011), Tappin & Howard (2010) and Manoharan (2010).

Today's heliospheric imagers are the successors to the zodiacal-light photometers (Leinert *et al.* 1975) on the twin Helios spacecraft flown in solar orbits in the 1970s and early 1980s. SMEI, in particular, was designed to exploit the heliospheric remote sensing capability demonstrated by that instrument (Jackson 1985; Webb & Jackson 1990). Unlike Helios, which could only observe a few narrow strips across the sky, this new generation of imager could observe large areas simultaneously. SMEI was the first, developed as a proof-of-concept U.S. Air Force experiment for operational forecasting. Launched in January 2003 on the Coriolis spacecraft, SMEI images nearly the entire sky in white light once per 102 minute spacecraft orbit, using three baffled camera systems with CCD detectors. Individual frames are mapped into ecliptic coordinates to produce a nearly complete sky map. SMEI has observed over 360 CMEs, many of which were Earth-directed allowing the comparison with in-situ spacecraft and prediction of arrival times and speeds. Unlike with in-situ spacecraft, however, SMEI enables the comparison with coronagraph events in any direction, enabling large-scale tracking and 3D reconstruction.

SMEI has been used for CME tracking, (e.g., Howard *et al.* 2007), space weather forecasting (Webb *et al.* 2009; Howard & Tappin 2010) and 3D reconstruction (Jackson *et al.* 2011; Tappin & Howard 2009). SMEI observations have been compared with coronagraph and in-situ spacecraft measurements (Howard *et al.* 2007; Howard & Simnett 2008; Webb *et al.* 2009) and with IPS observations (Jackson *et al.* 2008; Bisi *et al.* 2008). While it observes the entire sky beyond 20° elongation, its field of view is often obscured by energetic particle saturation during its passage through the magnetospheric polar caps and the South Atlantic Anomaly, and by hot pixel degradation.

In late 2006 the twin STEREO spacecraft were launched (Russell, ed. 2008) carrying the Heliospheric Imagers (HIs) (Howard *et al.* 2008; Eyles *et al.* 2009). The HIs view the inner heliosphere starting at an elongation of 4° from the Sun. HI-1 has a FoV of 20°, from 4–24° elongation ($\sim 12-85\,R_{\odot}$), and HI-2 of 70°, from $\sim$ 19–89° elongation ($\sim 68-216\,R_{\odot}$). There is a 5.3° overlap between the outer HI-1 and inner HI-2 FoVs. The HIs do not cover the entire position angle (PA) range around the Sun, but observe up to a 90° range in PA, usually centered on the ecliptic and viewing either east (HI-A) or west (HI-B) of the Sun. They do not suffer the same problems with particle saturation as SMEI, but are constrained by their fields of view about the ecliptic plane. Combined with the coronagraphs, the HIs do provide for the first time a continuous view from the Sun to around 1 AU and the stereoscopic viewpoints enable the possibility for 3D reconstruction using the coronagraphs and HI-1.

The STEREO spacecraft share similar $\sim$ 1 AU orbits about the Sun as the Earth but separate from the Sun-Earth line by 22.5° per year. STEREO-A (Ahead) leads the Earth in its orbit, while STEREO-B (Behind) lags. Most of the work involving the STEREO-HIs and CMEs to date have focused on their detection and tracking, and comparison with in-situ spacecraft. Publications include Harrison *et al.* (2008), Davies *et al.* (2009), Mierla *et al.* (2010), Möstl (2010), Davis *et al.* (2011), Kilpua *et al.* (2011), Liewer *et al.* (2011) and DeForest *et al.* (2011).

The important difference between heliospheric imagers and coronagraphs is that 3D information is available in heliospheric imagers that is not available in coronagraphs. This is because the assumptions imposed on coronagraphs (Thomson scattering assumptions, low angles) break down at large elongations and across large distances. This increases the difficulty of the analysis, but makes available additional information on the structure and kinematics of the CME. This thereby removes the need for auxiliary data to provide this information. The theory describing this ability is developed by Howard & Tappin

(2009). Recently papers have been published that consider the 3D structure of the CME, including Wood & Howard (2009), Lugaz *et al.* (2009, 2010) and Howard & Tappin (2009, 2010). Techniques involving the extraction of 3D properties from heliospheric image data are reviewed by Howard (2011).

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6. Interplanetary Scintillation and 3-D Heliosphere

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6.1. *Solar Wind Structures at Peculiar Solar Minimum*

During the period 2009 – 2011, at the end of solar cycle 23 and the beginning of cycle 24, the Sun remained at a quiet level. Several studies have been made based on interplanetary scintillation (IPS) measurements taken from radio telescopes, located at Ooty, India (327 MHz), STELab, Japan (327 MHz), and Pushchino, Russia (111 MHz). During the deep minimum of activity, the distribution of low-speed solar wind occupied a wider latitude range of ±60°, whereas the high-speed regions were confined close to the poles. The above latitudinal structures were however different from that of the corresponding phase of the previous cycle 22, in which the low-speed wind was distributed within the equatorial latitude range of ±30° (Manoharan 2010a; Tokumaru *et al.* 2010; Janardhan *et al.* 2011).

As the solar activity declined, the density turbulence around the Sun decreased rapidly and suggested an excessive reduction in solar wind mass flux of ∼30 – 40% in comparison with previous minima. Moreover, the radial dependence of IPS during 2006 – 07 was weaker than that of an expected spherically symmetric solar wind model. It was consistent with the quiet levels of IPS and ionospheric scintillation as well as unusual weak radial dependence of scintillation index during 2008, at the deep solar minimum phase. Such a weak dependence can only be explained by the considerable concentration of absolute solar wind turbulence confined to the solar equatorial plane that was connected to the strong influence of pronounced heliospheric current sheet (Glubokova *et al.* 2010; Manoharan 2011; Shishov *et al.* 2010).

A co-ordinated study of solar wind structure in the inner heliosphere, combining IPS measurements from EISCAT, imaging of heliospheric structures from STEREO HI and in-situ measurements from the ASPERA instrument on Venus Express displayed well-defined dominant co-rotating structures throughout the declining phase of solar cycle 23 (Bisi *et al.* 2010a). In a multi-wavelength study, in-situ data and IPS measurements identified that the high-speed magnetic clouds associated with a magnetically complex solar source caused the severe geomagnetic storm of the cycle 23 (Dst = -457) (Schmieder *et al.* 2011).

6.2. *IPS Measurements and 3-D Reconstruction of Heliospheric Structure*

Several studies have been made using the time-dependent computer-assisted tomography technique (CAT) developed at the University of California, San Diego, by B. V. Jackson and his team to reconstruct the solar wind density and velocity in the inner heliosphere (see, e.g., Jackson *et al.* 2010, 2011a and references there in). The basic data sets required for the 3-D reconstruction are the time series of velocity and g-value for a number of lines of sight of the heliosphere. Particularly, when a large number of scintillators were employed, the 3-D reconstruction provided a better understanding of the evolution of coronal mass ejections (CMEs) and showed that the CMEs associated with flux-rope systems were magnetically driven. Such a magnetically energetic CME caused an intense geomagnetic storm, even if the trailing part of the CME passed through the Earth's magnetosphere (Manoharan 2010b).

The solar wind reconstructed structures have been compared with in-situ measurements from the Wind spacecraft orbiting the Sun-Earth L1-Point and the high correlation validated the 3-D tomographic reconstruction results of transients and quiet solar wind (Bisi *et al.* 2009b).

Regular IPS observations at 327 MHz using the four-station system of the Solar-Terrestrial Environment Laboratory (STEL) revealed that solar origin, dynamical behavior and 3-D feature of the solar wind are crucial to develop the space weather prediction model. The accuracy of prediction also critically depends on the number of IPS lines of sight (Fujiki *et al.* 2010).

6.3. *Coronal Mass Ejection Studies Using IPS Technique*

The CME study using the IPS picket-fence method provided evidence that the density turbulence (also density) embedded within the CME was large at small solar offsets and decreased at large solar distances. In the case of a fast CME, the shock was formed within $\sim 100\ R_\odot$ and the compression ahead of the shock increased with distance from the Sun (Manoharan 2010b).

The link between the travel time of the CME and the effective acceleration in the Sun-Earth distance (85 out of 91 events) showed the effects of aero-dynamical drag between the CME and the solar wind. In consequence, the speed of the CME equalized to that of the background solar wind. However, for a large fraction of CMEs (for $\sim 50\%$ of the events), the inferred effective acceleration in the Sun-Earth line prevailed over the above drag force, suggesting an average dissipation of energy $\sim 10^{31}$ ergs per event, which was likely provided by the Lorentz force associated with the internal magnetic energy carried by the CME (Manoharan & Mujiber Rahman 2011).

In a multi-instrument, multi-technique, coordinated study of the solar eruptive event of 13 May 2005, it became evident that the 3-D structure of the CME event was complex, which was determined by asymmetries in the initial eruption as well as by interaction between the ICME/MC and the background solar wind during the interplanetary transit. The 3-D structure of the ICME also played an important role in governing the way in which it coupled into the magnetosphere and ionosphere of the Earth (Bisi *et al.* 2010b).

The UCSD time-dependent 3-D reconstruction of SMEI and IPS have been compared with measurements at the SOHO, Wind, ACE, and STEREO spacecraft. The analyses of these shocks from hour-averaged in-situ data showed that the enhanced density column associated with the shock response varied considerably between different instruments, even for in-situ instruments located at L1 near Earth. The relatively-low-resolution SMEI 3-D reconstructions generally showed density enhancements, and within errors, the column excesses match those observed in situ. In these SMEI 3-D reconstructions from remotely-sensed data, the shock density enhancements appeared not as continuous broad fronts, but as segmented structures. This may provide part of the explanation for the observed discrepancies between the various in-situ measurements at Earth and STEREO, but not between individual instruments near L1 (Jackson *et al.* 2011b).

6.4. *The Whole Heliosphere Interval*

The Whole Heliosphere Interval (WHI), an international campaign to study the 3D solar-heliospheric-planetary connected system near solar minimum. The data and models correspond to solar Carrington Rotation 2068 (20 March – 16 April 2008) extending from below the solar photosphere, through interplanetary space, and down to Earth's mesosphere. Nearly 200 people participated in aspects of WHI studies, analyzing and interpreting data from nearly 100 instruments and models in order to elucidate the physics of fundamental heliophysical processes. The solar and inner heliospheric data showed structure consistent with the declining phase of the solar cycle. A closely spaced cluster of low-latitude active regions was responsible for an increased level of magnetic activity, while a highly warped current sheet dominated heliospheric structure. The geospace data revealed an unusually high level of activity, driven primarily by the periodic impingement of high-speed streams. The WHI studies traced the solar activity and structure into the heliosphere and geospace, and provided new insight into the nature of the interconnected heliophysical system near solar minimum (Thompson *et al.* 2011).

In another study, the low-resolution 3-D reconstructed heliosphere with STELab IPS velocity data, from a central part of the WHI period (around 4 April 2008), showed what appears to be a co-rotating region passing across the Sun-Earth L1 point (and crossing STEREO-B first and STEREO-A later). The global reconstructed density and radial velocity compared well with multi-point in situ spacecraft measurements in the ecliptic, namely STEREO and Wind data, as the interplanetary medium passes over the spacecraft locations (Bisi *et al.* 2009a).

6.5. *Turbulence in the Fast/Slow Solar Wind Flows*

Measurements of the magnetic field are necessary to validate competing theories and models of solar wind dynamics. In the Potential Field Source Surface (PFSS) model, the photospheric magnetic field is mapped out to a boundary condition, such as a radial configuration set to a few solar radii and then associated with observed structure in the corona. The coronal field analysis of the 1983 Alfven wave event, based on Faraday rotation measurements, was utilized to estimate the background magnetic field strength, which was nicely predicated by the PFSS model (Jensen & Russell 2009).

Turbulence studies of the solar wind showed that MHD wave efflux energy contributes to heating. Alfven waves theoretically carry 10^{22} W in the chromosphere, 10^{20} W in the corona, and are measured to carry 3×10^{17} W at 1 AU. Analysis of the magnetic field perturbation of the 1983 Alfven perturbations inferred that the efflux energy at 4 solar radii was at least 6×10^{19} W. It approximately accounts for 20% of the wave energy required to accelerate the solar wind (Jensen & Russell 2009). Further, the Faraday rotation observations of CME/ICMEs have demonstrated the usefulness of determining the critical parameters, such as the orientation and radius of a flux cylinder in the interplanetary space (Jensen *et al.* 2010).

The radio sounding studies of pulsars at 111 MHz by the Large Phased Array of the Lebedev Physical Institute, during 2005 and 2007 indicated that the acceleration of fast, high-latitude solar wind continued to heliocentric distances of 5 − 10 $R_\odot$. The mean plasma density at about 5 $R_\odot$ was $1.4{\times}10^4 \mathrm{cm}^3$, which was substantially lower than that of the solar maximum period. A comparison of these results with Stanford coronal magnetic field data, STEREO/SECCHI, and SOHO/EIT synoptic maps showed that the solar wind from the polar coronal holes was associated with the above reduced density. Further, the estimated Faraday rotation at heliocentric distances of 6 − 7 R⊙ showed a modest deviation of magnetic field from the spherically symmetric distribution (Chashei *et al.* 2010).

A study on the turbulence spectrum of the solar wind in the near-Sun region $R{<}50$ $R_\odot$, obtained from IPS measurements with the Ooty Radio Telescope at 327 MHz showed that the scintillation was dominated by density irregularities of size about 100 − 500 km. The scintillation at the small-scale side of the spectrum, although significantly less in magnitude, has a flatter spectrum than the larger-scale dominant part. Furthermore, the spectral power contained in the flatter portion rapidly increased closer to the Sun. These results on the turbulence spectrum for $R < 50$ $R_\odot$ quantified the evidence for radial evolution of the small-scale fluctuations ($\leqslant$50 km) generated by Alfven waves (Manoharan 2010c).

6.6. *New IPS Facilities*

The Murchison Widefield Array (MWA) is a new radio interferometer, currently under construction in the radio-quiet Western Australian outback, which exploits the recent advances in digital signal processing to rise to this challenge. The MWA expected to play a very useful role in improving our understanding of both the quiet and the dynamic Sun, and of space weather phenomena (Oberoi *et al.* 2010, 2011b). The first spectroscopic images of solar radio transients from the prototype of MWA, observed on March 27, 2010, over a frequency band of 170.9 − 201.6 MHz, showed broadband emission features and numerous short-lived, narrowband, non-thermal emission (Oberoi *et al.* 2011a).

A new antenna, Solar Wind Imaging Facility (SWIFT), dedicated for IPS observations, has been developed at the STELab, Japan. The SWIFT has an aperture size of 108m (N-S) by 38m (E-W), and allows IPS observation on more number of sources fainter than those observed in the existing system. The IPS systems at Fuji and Kiso observatories have also been updated in 2010. These updated systems enable to make cross correlation measurements at the solar wind speed between Fuji, Kiso, and Toyokawa (Tokumaru *et al.* 2011).

A new IPS observing system has been established at Urumqi Astronomical Observatory (UAO), China, and a series of experimental observations have been successfully carried out from May to December 2008, at bands of 327/611 MHz and 2.3/8.4 GHz (Liu *et al.* 2010).

The Ooty Radio Telescope (one of the radio observing facilities of TIFR, India) front-end is being upgraded. It involves installation of digital acquisition system at each output of 4-dipole combiner (∼2m section of the telescope). The new system allows wider bandwidth and will also provide a flexible system to correlate signals between pair of above 2-m-section outputs. The daily IPS observation is expected to increase from ∼1000 − 1400 radio sources to ∼3 to 4 times (Prasad & Subrahmanya 2011).

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7. Solar Energetic Particles and Galactic Cosmic Rays

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With the exception of a few solar energetic particle (SEP) events that marked the beginning of solar cycle 24 in mid-August 2010, in early March, June, August 2011 and September 2011, the main characteristic of the period between September 2009 and September 2011 was the absence of large SEP events to analyze. Therefore, most of the research efforts in this time interval were focused on the study of the energetic particle enhancements associated with corotating interaction regions (CIRs), small ^{3}He-rich events observed by multiple spacecraft spread through the interplanetary medium, the record-setting intensity of galactic cosmic rays (GCRs) and long-term recompilations of SEP events observed during the last solar cycle.

Because CIR-associated particles are very prominent during solar minimum, the unusually long solar minimum period provided the opportunity to examine the overall organization of CIR energetic particles for a much longer period than ever before. Recurrent low-energy (<1 MeV) proton enhancements associated with CIRs were observed near 1 AU for many solar rotations (up to 30) due to several persistent high-speed solar wind streams (Lee *et al.* 2010). The multipoint observations (by near-Earth space observatories and the twin STEREO spacecraft) of CIR events provided evidence that CIR-associated energetic ions frequently show significant differences from spacecraft to spacecraft, particularly at sub-MeV energies. Discrepancies in the observed structures are due to the latitudinal separation between spacecraft, changes in the coronal hole generating the high-speed solar wind streams, and/or the presence of interplanetary coronal mass ejections (ICMEs) or small-scale interplanetary (IP) transients in the vicinity of or embedded within the CIRs (Gomez-Herrero *et al.* 2011). Temporal variations in the CIR-associated ion increases may also be due to concomitant SEP events that produce a mixing of SEP and CIR particle populations (Lee *et al.* 2010).

Energetic particles observed in association with CIRs are thought to be accelerated by distant shocks formed by the compression between fast and slow solar wind streams. However, unshocked compression regions associated with CIRs near 1 AU have been hypothesized as candidate to energize particles (Giacalone *et al.* 2002). Bucik *et al.* (2009) compared the predictions of compression acceleration with measurements of ∼0.1 to ∼1 MeV/n ion intensities. Observations show that the ion intensity in CIR events with in-situ reverse shocks is well organized by the parameters that characterize the compression region itself, like compression width, solar wind speed gradients and total pressure. In turn, for CIR events with the absence of shocks the model predictions are not fulfilled.

During this protracted solar minimum, small ^{3}He-rich SEP events were observed by both the ACE spacecraft and by the two STEREO spacecraft as they separated in longitude from ACE at a rate of ∼22 deg per year. In a widely-held view of impulsive solar energetic particle (ISEP) events, electrons and ions are accelerated at the site of a solar flare when magnetic energy is released by reconnection. When the reconnection involves some open field lines, those field lines provide a path for particles to escape into the heliosphere, leading to the observation of ISEP events. The very limited spatial and temporal extent of the acceleration and release was thought to imply that these particles should have a relatively narrow spread in heliolongitude. However, STEREO and ACE observations have shown that ISEP events may be simultaneously detected from well-separated longitudes (Wiedenbeck *et al.* 2010). To understand the spreading of particles in longitude from a flare site Wiedenbeck *et al.* (2010) studied the magnetic field configuration around active regions (ARs) via the potential field source surface (PFSS) model. Such model calculations frequently indicate that open field lines originating near an AR may spread by more than several 10's of degrees before reaching the source surface. Shocks driven by coronal mass ejections (CMEs) have also been suggested as responsible for the acceleration of SEPs as observed from distant longitudes. The presence of ubiquitous suprathermal tails with a solar cycle dependent composition (Dayeh *et al.* 2009) may also serve as seed population for the mechanisms of particle acceleration at traveling shocks.

Efforts to extract the properties of the CME-driven shocks from white-light coronagraph observations were performed (Ontiveros & Vourlidas 2009, see section 4.5 for more details). Extreme-ultraviolet observations from the Solar Dynamics Observatory (SDO) and Type II radio bursts observations were also used to characterize shocks forming low in the corona (Kozarev *et al.* 2011). By modeling the configuration of the overlying coronal magnetic fields (via PFSS) and considering the orientation of the shock fronts, it is possible to estimate the efficiency of the shocks in accelerating particles (Kozarev *et al.* 2011). The multipoint coronagraph observations from SOHO and the two STEREO allow the reconstruction of the 3D envelope of the shock. The spatial extent, radial coordinates and speed of the shocks can be used as input to numerically simulate the CME propagation. Comparison of both the SEP onset times as observed by three spacecraft separated in longitude with the times when the magnetic connection between each spacecraft and the shock is established, together with the evolution of the shock parameters at the region of the shock front connecting to each spacecraft, allowed Rouillard *et al.* (2011) to confirm the description of gradual SEP events established a decade earlier using combined simulations of shock and SEP transport (i.e., Lario *et al.* 1998).

Among the works recompiling properties of SEP events observed during the last solar cycle, Cane *et al.* (2010) examined the properties and associations of 280 proton events that extended above 25 MeV. The events were divided into five representative types based on the relative abundances and particle profiles to illustrate how particle characteristics vary with their associated solar parameters (i.e., CMEs, flares and radio emissions). A continuum of event properties with no indication of specific parameters that clearly separate the groups of events was found. There was, however, a reasonable separation of events based on the timing of the associated type III emissions relative to the Hα flare. Type III bursts indicate the presence of flare particles that escape to the IP medium. The least intense, relatively short-lived, proton events that are electron-rich have associated type III bursts that occur at the start of the flare, indicating rapid acceleration and escape of particles. In the largest events the type III emissions occur after the impulsive phase. Cane *et al.* (2010) suggested that this late acceleration and/or release of particles results in a composition different from that of impulsive acceleration and release; proposing a scenario in which concomitant flare processes contribute particles in the majority of SEP events. On the other hand, Gopalswamy & Mäkelä (2010) showed that the occurrence of a long-duration and low-frequency (<14 MHz) type III burst is not a good indicator for the occurrence of an SEP event, and neither the type III burst duration nor the burst intensity can distinguish between SEP and non-SEP events. The lack of solar energetic protons in association with a large complex type III burst that reached local plasma frequencies was explained by Gopalswamy & Mäkelä (2011) as a signature that the acceleration of low-energy electrons responsible for the type III burst at the flare site does not imply the acceleration of protons, which most likely occurs in the CME-driven shock.

Solar cycle 23 also showed a few SEP events that exceeded the previously determined streaming limit, even in their prompt component (Lario *et al.* 2009). The mechanisms leading to the exceeding of the streaming limit include, apart from an intense source of particles, the inhibition of amplification of waves by the streaming particles and/or the existence of large-scale IP structures able to modify the nominal conditions for SEP transport. Ng *et al.* (2010) presented new theoretical results on how the streaming limit depends on ion species and energy, ambient wave intensity spectrum, Alfvén speed, solar-wind speed, shock speed, and the presence of IP shocks and interaction regions. The potential relevance of the latitude of the observer in the SEP intensity-time profiles was investigated by Rodriguez-Gasen *et al.* (2011). The influence of IP structures on the SEP transport was also proven by using both SEP observations (Tan *et al.* 2009) and SEP transport simulations (Agueda *et al.* 2010).

During solar cycle 23 sixteen ground-level events (GLEs) were detected by neutron monitors. A study of their spectra in the energy range ~0.1 to 700 MeV/n showed that the proton fluence for all 16 GLEs were well fit by the double power-law. Minimizing the difference between the spectral indices above and below the "break" energy minimizes also the energy requirements for accelerating enough 500 MeV protons for a detectable GLE (Mewaldt *et al.* 2009a).

STEREO observations were also used to discover the possible presence of energetic neutral hydrogen atoms (ENAs) emitted during the X9 solar flare event on 2006 December 5. Mewaldt *et al.* (2009b) concluded that the observed ENAs were most likely produced in the high corona and that charge-transfer reactions between accelerated protons and partially stripped coronal ions are, in general, an important source of ENAs in solar events. Taking into account ENA losses, the observed ENAs in the event were produced in the high corona at heliocentric distances $\geqslant 2$ solar radii.

During this extended solar minimum, galactic cosmic rays (GCRs) achieved the highest intensities observed in the space age. In the energy interval from ~70 to ~450 MeV/n, the measured intensities of major species from C to Fe were each 20%-26% greater in late 2009 than in the 1997-1998 minimum and previous solar minima of the space age (1957-1997) (Mewaldt *et al.* 2010). The elevated intensities (also observed at neutron monitor energies; Ahluwalia & Ygbuhay 2010) were due to several unusual aspects of the solar cycle 23/24 minimum, including record-low interplanetary magnetic field (IMF) intensities, an extended period of reduced IMF turbulence, reduced solar-wind dynamic pressure, and extremely low solar activity. GCR intensity variations at 1 AU were found to lag IMF variations by 2-3 solar rotations, indicating that significant modulation occurs inside ~20 AU. In 2010, the intensities suddenly decreased to 1997 levels following increases in solar activity and in the inclination of the heliospheric current sheet.

Hard X-ray and gamma-ray observations by RHESSI allowed the identification of the properties of the accelerated ions and electrons that interact in the solar atmosphere and photosphere during flares and relate them to the SEPs observed in space. These properties provide information on the acceleration processes and particle transport of particles in solar flares (e.g. Zharkova *et al.* 2011). It is generally agreed that magnetic reconnection is the energizing mechanism of solar flares and CMEs but the connection between these processes and observations involves intermediate processes of acceleration and heating of plasma particles, transport of particles and their radiative signatures that are still not fully understood. In most of the intense flares observed by RHESSI (and previously by SMM) the heavy interacting particles at the Sun have composition that is similar to gradual SEP events (i.e. coronal), but that in at least one flare it was found a composition close to that observed in impulsive SEP events (Murphy *et al.* 2011). On the other hand, comparison of the number of flare-accelerated 30 MeV protons that interact in the solar atmosphere (estimated using gamma-ray RHESSI data) with the deduced number of SEPs reaching 1 AU shows that the latter to be typically ~10-100 times larger than those interacting in the solar atmosphere. This implies that the vast majority of the protons observed in situ are accelerated by a CME-driven shock or other coronal or interplanetary processes rather than by the flare; although flare-accelerated ions may still contribute to some SEP events, possibly for heavy elements (Mewaldt *et al.* 2008).

Studies of SEPs at 1 AU over the last few years have made very significant progress, but they also reveal that many key questions will remain unanswered until it is possible to fly fully instrumented spacecraft closer to the Sun where the bulk of SEP acceleration takes place. Solar cycle 24 will provide us with the opportunity to analyze SEP events from multiple points of view by using STEREO, near-Earth spacecraft and the MESSENGER spacecraft in orbit around Mercury. However, issues like the composition of seed particle populations, the nature of wave-particle interactions, the separation between the roles of SEP acceleration and transport processes, and the timing relation between SEP acceleration and solar eruptive events are best studied from distances close to the Sun. In this recent years, multiple efforts have been focused on the development of the future exciting new missions such as the ESA Solar Orbiter and the NASA Solar Probe Plus that will explore the inner heliosphere between 0.04 and 0.7 AU.

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8. The Outer Heliosphere

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8.1. *Introduction*

Progress in understanding the outer heliosphere and its interaction with the local interstellar medium (LISM) continues its rapid advance. The previous two reports showcased the Voyager 1 (V1) and 2 (V2) crossings of the termination shock and first observations of the heliosheath. Highlights of the current report are the Interstellar Boundary Explorer (IBEX) observations of the the global heliosphere observed with energetic neutral atoms (ENAs) and the Voyager observations of the heliosheath, particularly recent results which suggest that Voyager 1 is close to the heliopause and the LISM. Theorists and modellers have been active in trying to explain these new observations.

8.2. *IBEX*

IBEX observes neutrals from 10 eV to 6 keV with the goal of mapping the 3D structure of the outer heliosphere. The first results were published in a series of Science papers in October 2009. The key result was a detection of ribbon of ENAs forming a 300° arc on the sky (Funsten *et al.* 2009) and passing between the Voyager spacecraft (McComas *et al.* 2009). The ribbon is observed at all energies above 200 eV with an average width of about 20° and has the largest intensities at about 1 keV (Fuselier *et al.* 2009), roughly the average solar wind energy. Fine-scale variations are observed within the ribbon, most notably one bright "knot" region and several weaker knots (McComas *et al.* 2009; Livadiotis *et al.* 2011). A similar but wider feature was observed at higher energies ($6-16$ keV) by the Cassini MIMI experiment (Krimigis *et al.* 2009). The ribbon seems to emanate from regions where the local interstellar magnetic field is perpendicular to the direction of Earth (Schwadron *et al.* 2009). These results suggest that the LISM magnetic and gas dynamic pressure both have a major influence on the LISM interaction with the heliosphere (McComas *et al.* 2009; Krimigis *et al.* 2009), placing the actual interaction between the two limiting cases discussed by Parker (1961).

The second IBEX map (a complete ENA map of the heliosphere is obtained every six months) showed the same basic ribbon structure, but some changes were observed (McComas *et al.* 2010). The bright knot spread out and became $25-35\%$ less intense in the second map and the intensities from the polar regions decreased by $10-15\%$. Suggestions for the causes range from solar cycle variation to the smaller-scale solar wind variation driving waves which propagate back and forth through the heliosheath (Washimi *et al.* 2011).

Numerous possible explanations for the origin of the ribbon have been suggested with source regions ranging from the termination shock to the boundary of the local interstellar cloud (McComas *et al.* 2009, 2011; Grzedzielski *et al.* 2010; Heerikhuisen *et al.* 2010). One of the more developed hypotheses is that the ribbon is formed by secondary ENAs (McComas *et al.* 2009; Heerikhuisen *et al.* 2010). Solar wind protons charge exchange with LISM neutrals inside the heliosphere and move outward of the solar wind speed. These fast neutrals are re-ionized via charge exchange with interstellar ions outside the heliopause, then become secondary ENAs when they charge exchange with interstellar neutrals. These neutrals, which have undergone three charge exchange reactions, would then be observed by IBEX with energies near 1 keV. If the ions formed in the LISM charge exchange to form secondary ENAs before they scatter in pitch angle, then only neutrals from regions where the LISM magnetic field is perpendicular to Earth would be observed. If the pitch angle scattering time is assumed small, this mechanism matches the observations quite well (Heerikhuisen *et al.* 2010), although the validity of this assumption is still under discussion (Florinski *et al.* 2010; Gamayunov *et al.* 2010).

IBEX was recently shifted into a more stable orbit and should continue studying the variability of the heliosphere for many years.

8.3. *Heliosheath*

The Voyager spacecraft continue to explore the heliosheath on their way to the LISM. An exciting result suggests that V1 is approaching the heliopause (HP) and has entered a previously unknown heliopause boundary layer more than 4 AU thick where flow is parallel to the HP (Krimigis *et al.* 2011). The radial flow speed in the heliosheath at V1 derived from the LECP instrument using the Compton-Getting effect (the V1 plasma instrument does not work) show a monotonic decrease from mid-2005 to early 2010, when the radial speed reached zero. The radial speed has remained near zero through mid-2011. The flows in the T plane (parallel to the solar equator) oscillated about a mean of 40 km/s before late 2010, when they slowed to about 10 km/s (meridional flows are not measured by LECP). These very slow flows were a surprise - models show a flared HP with an outward radial flow component even at the HP. The observed flows are of the same magnitude as the LISM speed of 26.3 km/s Witte (2004). Krimigis *et al.* (2011) suggest that a boundary layer with flow roughly parallel to the HP boundary is present with a width of at least 4 AU. Such a boundary layer was proposed by Suess (1990), although the current paradigm had envisioned a relatively quick transition from heliosphere to LISM.

The V2 plasma experiment observes very different flow vectors from those at V1. The V2 flow magnitude remains roughly constant, but the flow direction has shifted as the flow turns toward the heliotail (Richardson & Wang 2011; Richardson 2011). Flow angles are larger in the RT than RN planes, with the average flow in the RT plane 55° from radial in 2011 and turning about 10°/year. The density in the heliosheath decreased by a factor of 2 from the termination shock (TS) crossing thru the end of 2010, then started to increase. The temperature has fallen by a factor of 3 across the heliosheath, much more than the expected adiabatic decrease. The magnetic field increases across the heliosheath if the change in the source field (as measured at 1 AU) is taken into account (Burlaga *et al.* 2009), consistent with model predictions (Burlaga & Ness 2010). The heliosheath field and plasma are highly variable. As solar minimum conditions with lower dipole tilts reached V2, fewer heliospheric current sheet (HCS) crossings were observed and V2 remained mostly in the same solar wind sector (Burlaga & Ness 2011). V1, although at higher heliolatitudes, continues to spend comparable amount of time in each sector although the HCS crossings are far apart. These observations are consistent with northward flow in the heliosheath carrying the HCS northward past the V1 heliolatitude (Borovikov *et al.* 2011). The large amount of time spent in each sector results from the very slow radial speeds observed at V1 convecting the sectors past V1 very slowly. Plasma parameters are fit well by Gaussian distributions (Richardson 2011) while the magnetic field distributions are sometimes Gaussians and sometimes power laws (Burlaga & Ness 2010, 2011).

The Voyager spacecraft will continue measuring heliosheath and hopefully LISM properties through 2025.

8.4. *Energetic Particles*

Energetic particles observed in the heliosheath can be divided into three main classes: termination shock particles at low energies, from a few keV/nuc to several MeV/nuc, anomalous cosmic rays, which are pickup ions accelerated to energies from a few to hundreds of MeV/nuc, and galactic cosmic rays (GCRs), which are accelerated elsewhere in the galaxy and which dominate the energy spectra above typically 50 to 100 MeV/nuc. The termination shock particle intensity peaks at the TS, indicating they are accelerated at the TS. A recent model suggests they are formed from the core population of pickup ions which are accelerated to the observed energies at the TS by a process similar to shock drift acceleration (Giacalone & Decker 2010). The source of the ACRs was also thought to be the TS before the Voyagers found no evidence of ACR acceleration at the TS crossings (Stone *et al.* 2005; Stone *et al.* 2008). The ACR source location and acceleration mechanism are now puzzles. The spectra of ACRs have continued to unfold as the two Voyager spacecraft penetrate further into the heliosheath (Cummings *et al.* 2011).

Suggestions for the ACR source include acceleration in the flanks or tail of the heliosphere (McComas & Schwadron 2006; Kota 2008), reconnection in the outer heliosphere (Lazarian & Opher 2009; Drake *et al.* 2010; Opher *et al.* 2011), or a stochastic pumping mechanism (Fisk & Gloeckler 2009). The galactic cosmic rays modulation boundary had been expected to occur at the HP, with relatively undisturbed GCR intensities in the LISM. However, Scherer *et al.* (2011) suggest that the GCR modulation boundary is beyond the heliopause , due both to modified diffusion in the outer heliosheath and confinement and cooling of these particles in the heliosphere. Caballero-Lopez *et al.* (2010) show that there is a large intensity difference in GCR electrons at V1 and V2, suggesting large hemispherical asymmetries.

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9. Closing Remarks

There have been enormous progress in the study of the Sun, the interplanetary plasma, and the heliosphere over the past three years largely because of the new instruments that provided unprecedented views from new vantage vantage points away from the Sun-Earth line. A large number of publications have been added to the scientific literature, but all of them could not be included in the report due to space limitations. The cited work is therefore a biased sample of what is available in the literature. More results are expected to be presented during the IAU general assembly in Beijing. These activities demonstrate that Commission 49 is a vital component of Division II and will continue to add new knowledge.

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