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Cosmic Rays in the Heliosphere: Requirements for Future Observations

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Abstract Since the publication of *Cosmic Rays in the Heliosphere* in 1998 there has been great progress in understanding how and why cosmic rays vary in space and time. This paper discusses measurements that are needed to continue advances in relating cosmic ray variations to changes in solar and interplanetary activity and variations in the local interstellar environment. Cosmic ray acceleration and transport is an important discipline in space physics and astrophysics, but it also plays a critical role in defining the radiation environment for humans and hardware in space, and is critical to efforts to unravel the history of solar activity. Cosmic rays are measured directly by balloon-borne and space instruments, and indirectly by ground-based neutron, muon and neutrino detectors, and by measurements of cosmogenic isotopes in ice cores, tree-rings, sediments, and meteorites. The topics covered here include: what we can learn from the deep 2008–2009 solar minimum, when cosmic rays reached the highest intensities of the space era; the implications of ^{10}Be and ^{14}C isotope archives for past and future solar activity; the effects of variations in the size of the heliosphere; opportunities provided by the Voyagers for discovering the origin of anomalous cosmic rays and measuring cosmic-ray spectra in interstellar space; and future space missions that can continue the exciting exploration of the heliosphere that has occurred over the past 50 years.

Keywords Cosmic rays · Cosmogenic nuclides · Solar activity · Solar wind · Interplanetary magnetic field · Heliosphere · Heliopause · Interstellar medium

1 Introduction

At the ∼15-year reunion of the two very successful ISSI workshops on "Cosmic Rays in the Heliosphere" held in 1995 and 1996 it is appropriate to also look forward to the next 15 years

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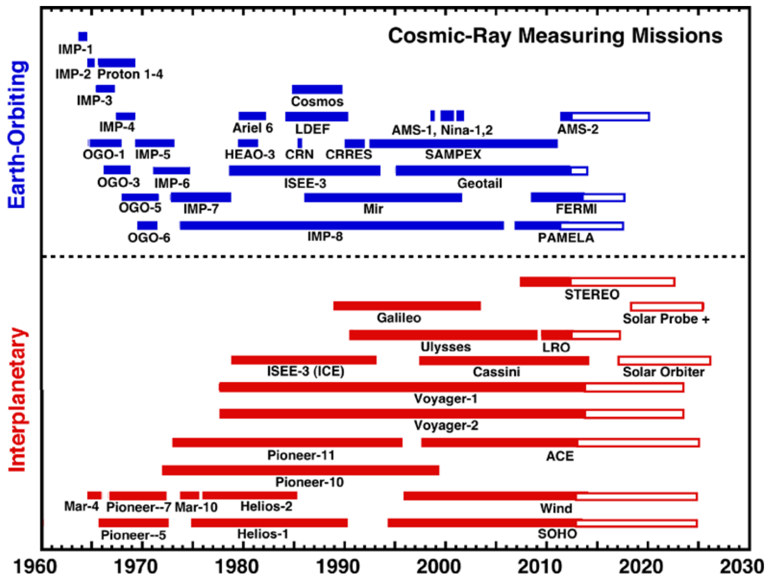

Fig. 1 Plot of selected Earth-orbiting (*top panel*) and interplanetary (*bottom panel*) space missions that have carried instrumentation to measure galactic and/or anomalous cosmic rays. For missions that are currently active an indication is made of their potential for continuation (the length of these extensions should not be taken seriously; continuation depends on periodic approval processes). For Solar Orbiter and Solar Probe Plus only the prime missions are shown. With the launch of AMS-2 there is a remarkable opportunity to cross-correlate high-energy cosmic-ray spectra from three large spectrometers (including PAMELA and Fermi), while at the same time continuing lower-energy measurements from Voyager and ACE, SOHO, STEREO, Wind, and LRO. This plot is reasonably complete for missions in which the US has been involved, but does not include all European and Japanese missions that measured cosmic rays. Of the on-going or planned missions, Voyager, PAMELA, FERMI, and AMS-2 measure cosmic ray electrons >50 MeV

and consider the new measurements that will be needed to continue making progress. Figure 1 includes a summary of space missions that have, are presently, and will be measuring cosmic rays near Earth and beyond. We are very fortunate that there is presently a remarkable constellation of active spacecraft, including the Voyagers, launched in 1977; Wind, SOHO, and ACE, launched in the mid-1990s and all circling the inner Lagrangian point; the twin STEREO spacecraft, presently $\sim$120° ahead and $\sim$120° behind Earth in $\sim$1-AU orbits; and three relatively new high-energy spectrometers (PAMELA, Fermi, and AMS). These spacecraft are augmented by balloon-borne instruments that include AESOP, BESS, and CREAM. In addition, IBEX and Cassini are providing fascinating and challenging new images of the outer heliosphere, including the region that the Voyagers are exploring. Although there is presently more limited radial and latitudinal coverage than during the 1996–1997 meetings of this workshop when the Pioneers, Voyagers, and Ulysses were exploring the 3-dimensional heliosphere for the first time, there is now remarkable coverage in energy, composition, and rare species like antiprotons, positrons, and radioactive isotopes, and we have two spacecraft poised to enter the interstellar medium.

This paper discusses what is needed in the future to continue making advances in understanding cosmic rays in the heliosphere.

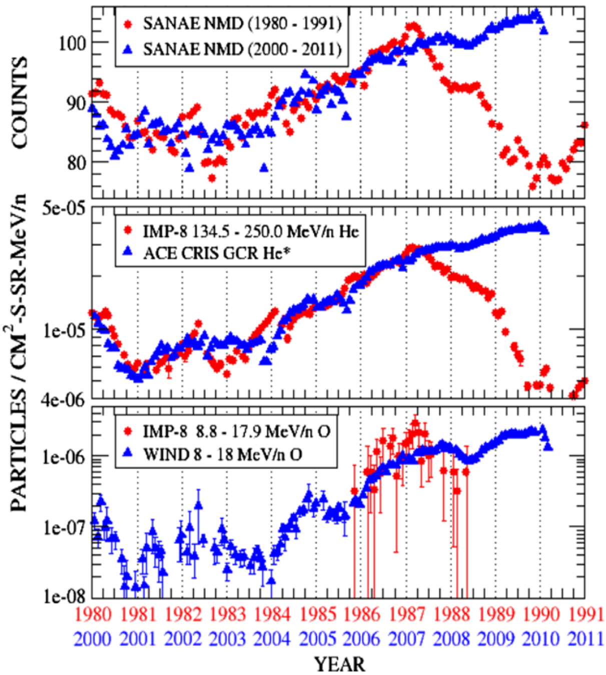

Fig. 2 Comparison of galactic cosmic ray He, neutron monitor, and ACR oxygen intensities during the 1987 and 2009 solar minima (from McDonald et al. 2010). The 1980s spacecraft data are from IMP-8; the data after 2000 are from ACE and Wind. The neutron monitor data are from the Sanae Neutron Moderated Detector (SA NMD) in South Africa

2 Understanding the 2009 Solar Minimum

The deep 2008–2009 solar minimum continues to be important to cosmic ray studies for several reasons. First of all, it provided an opportunity to measure the highest galactic cosmic-ray intensities of the space age with high-precision instrumentation while at the same time the Voyagers were traversing the heliosheath, the region where most cosmic-ray modulation takes place (e.g. Webber and Higbie 2010a). Record-breaking cosmic ray intensities were measured on spacecraft (McDonald et al. 2010, Mewaldt et al. 2010), by balloon-borne instruments (Stozhkov et al. 2011), and by ground-based neutron monitors (Moraal and Stoker 2010; McDonald et al. 2010). Figure 2 compares the galactic cosmic ray (GCR) and anomalous cosmic ray (ACR) intensities from the 1987 and 2009 solar minima. The He intensities near the peak in the cosmic ray spectrum are elevated by ∼25 % over those in 1987 (and also exceeded intensities in previous minima) while the Sanae Neutron Moderated Detector (NMD) intensities in 2009 rose 3.7 % above the neutron-monitor intensities in 1987. In contrast, the 2009 anomalous cosmic ray (ACR) oxygen intensities were not at record levels—they were comparable to those in 1987 (Fig. 2), but ∼30 % lower than in 1997–1998 (Leske et al. 2011).

Data from 12 neutron monitors with vertical cutoff rigidities ranging from 0.8 to 9.2 GV is shown in Fig. 3. While 11 of the 12 are equal to or greater than the March 1987 intensities (previously the highest), the spread in the 2009/1987 ratios at cutoffs of <1 and ~ 2 GV suggests that there could be long-term stability issues that should be investigated. Thus, the 2009 solar minimum offers the opportunity and stimulus to intercalibrate neutron monitors around the world.

There is broad interest from many communities in developing the means to extend the neutron monitor record both forward and backward back in time. Figure 4 shows a reconstruction of the Climax, Colorado neutron monitor count rate (geomagnetic cutoff

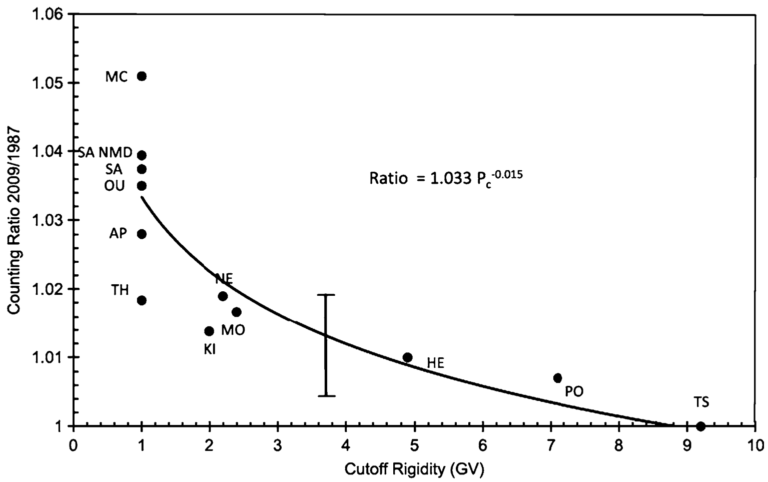

Fig. 3 Counting rates of 12 neutron monitors in 2009 relative to March 1987. The form of a best-fit power-law to these data is indicated. The ±0.7 % error bar on the curve is based on the estimated uncertainties in the individual neutron monitor rates (see Moraal and Stoker 2010). Neutron monitors shown include McMurdo (MC), Sanae NMD (SA NMD), Sanae (SA), Oulu (OU), Apatity (AP), Thule (TH), Kiel (KI), Newark (NE), Moscow (MO), Hermanus (HE), Potchefstroom (PO), and Tsumeb (TS)

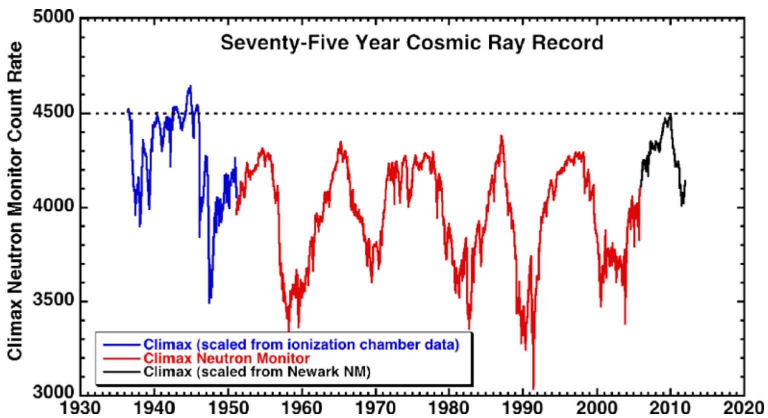

Fig. 4 Reconstructed Climax Neutron Monitor count rate for the period from June 1936 to December 2011. The red trace is 27-day Bartels-rotation averages of Climax Neutron Monitor data from the Climax website. The blue trace extending from June 1936 to February 1951 was derived by McCracken and Beer (2007; see their Table 1) from balloon-borne and ground-based ionization chamber data measured by Forbush (1958) and Neher (1971). It was normalized during the 1-year period centered on August 1, 1954. The black trace was scaled from Newark Neutron Monitor data by the author after normalizing the Climax and Newark count rates using overlapping data from cycles 19 and 21. Note that the late 2009 count rates are the highest of the space age, but this indirect comparison implies that the cosmic ray intensity was somewhat greater in late 1944 and possibly in the 1930s

3.0 GV), including Climax data from early 1951 to late 2005 (see http://ulysses.sr.unh.edu/NeutronMonitor/neutron_mon.html); and pseudo-Climax count rates from mid-1936 to early 1951 and late 2005 to late 2011. The earlier data are based on cosmic-ray measurements with ionization chambers on the ground (Forbush 1958) and carried high in the atmosphere by balloons (Neher 1971 and references therein). McCracken and Beer (2007) have done a comprehensive job of translating and renormalizing the ionization chamber measurements to monthly averages equivalent to those of Climax. The late 2005 to late 2011 data are scaled from Newark neutron-monitor data (2.2 GV cutoff) and represent an estimate of what Climax would have measured if still operating. We see in Fig. 4 that 2009 GCR intensities are comparable to (but not greater than) intensities in the 1930s and 1940s.

Cosmic ray intensities were not the only unusual aspect of the near-Earth environment during the recent solar minimum. The average sunspot number during the cycle 23–24 minimum was the lowest since the 1914 solar minimum (e.g., Schrijver et al. 2011). The strength of the Sun's polar fields after the 2000–2001 solar maximum was only about one half of that in the previous three solar cycles (Svalgaard et al. 2005). The unusual 2009 conditions were also reflected in the lowest interplanetary magnetic field (IMF) strength of the space age (Smith and Balogh 2008; Balogh and Erdös 2011; see also Cliver et al. 2011). The solar wind dynamic pressure was the lowest it has been in the last 3 minima, due mainly to a reduction in the solar wind density (McComas et al. 2008). In addition, the average mass, and kinetic energy of coronal mass ejections (CMEs) were about a factor of $\sim$5 lower than in the previous minimum (Vourlidas et al. 2010).

All of these extreme conditions affected the ability of cosmic rays to enter the inner heliosphere. For example, it is well known that the cosmic-ray intensity is inversely correlated with the interplanetary magnetic field strength (e.g., Burlaga and Ness 1998). In particular, a reduced IMF results in higher drift velocities (Jokipii et al. 1977). The strong magnetic fields associated with CMEs are effective in causing Forbush decreases—the significant decrease in the number of CMEs in 2007–2009 (Vourlidas et al. 2010) minimized one potential source of barriers to cosmic ray entry into the inner heliosphere. There was also evidence for an increase in the parallel diffusion coefficient (Mewaldt et al. 2010).

It is interesting that while galactic cosmic rays with rigidities up to at least 7 GV reached their maximum intensity of the space era (Fig. 3), anomalous cosmic ray (ACR) oxygen, with a rigidity of $\sim$2.2 GV at 10 MeV nuc^{-1}, did not (McDonald et al. 2010; Leske et al. 2011). The reduced ACR intensity could be because the heliospheric current sheet (HCS) had a larger average tilt in 2009 than in other recent solar minima (McDonald et al. 2010; Leske et al. 2011), or it could be because a larger diffusion coefficient in 2009 led to a lower acceleration rate (Moraal and Stoker 2010), assuming ACRs are accelerated somewhere on the termination shock. Detailed modeling of the time-intensity profiles at the Voyagers, 1-AU, and possibly at an intermediate distance like Cassini may answer this question (see also Strauss et al. 2012).

Study of the solar cycle 23 minimum therefore may provide an opportunity to understand conditions that led to higher intensities in the past (see also Cliver et al. 2011), and it may help us determine if the Sun is now evolving into a state similar to those during grand minima of the recent past (see Sect. 4).

2.1 Additional Opportunities

During solar cycle 23 several studies investigated changes in the abundances of isotopes such as ^{49}V and ^{51}Cr that decay to ^{49}Ti and ^{51}V by electron capture (e.g., Niebur et al. 2003; Mewaldt et al. 2004; Caballero-Lopez et al. 2007). As a result of the energy-dependent probability of capturing an electron, the ^{49}Ti/^{49}V and ^{51}V/^{51}Cr ratios in local interstellar space are expected to have very strong energy dependence (e.g., Caballero-Lopez et al. 2007). Measurements of these isotope ratios by ACE varied significantly during solar cycle 23, which was used to: estimate the increase in adiabatic energy-loss that cosmic rays suffer as the cycle proceeded from solar minimum to solar maximum; place limits on the local interstellar spectra of cosmic ray nuclei; and to place limits on the amount of re-acceleration that occurs as cosmic rays cross the termination shock. Electron-capture isotope studies should be revisited using 2009 data—it should be possible to refine estimates of the significantly smaller amount of energy loss inferred for 2009 relative to that in 1998 by comparing peak intensities and energy spectra with cosmic ray transport models. It is important to interpret these studies using models that treat separately cosmic-ray transport in the interplanetary medium (where energy loss is important) and in the heliosheath, where it is thought not to be important.

2.2 Other Secondary to Primary Ratios

In addition, it is important to examine other cosmic-ray secondary/primary ratios such as ^{2}H/^{4}He, ^{3}He/^{4}He, B/C, and (Sc + Ti + V)/Fe from 2009. The "secondary" species that are rare in cosmic ray source material have steeper spectra in interstellar space because of energy-dependent escape from the Galaxy (e.g., George et al. 2009). Thus, measurements of these ratios over the solar cycle 23/24 minimum should test models of interstellar and heliospheric transport during a period when cosmic rays had much greater access to 1 AU than during earlier solar minima of the space age.

2.3 Charge-Sign-Dependent Modulation

Once the effects of gradient and curvature drifts were fully incorporated into cosmic ray modulation models it became clear that positive and negative particles would be modulated differently in $A > 0$ and $A < 0$ portions of the solar cycle because they drift in opposite directions in the interplanetary magnetic field (IMF). Early evidence for charge-sign-dependent modulation came from comparisons of the electron/He ratio at similar magnetic rigidities (Garcia-Munoz et al. 1986; Evenson 1998). Ulysses made it possible to compare the electron/proton ratio at high rigidities (e.g., Heber et al. 2009; Heber 2011).

Until the launch of PAMELA, tests of charge-sign-dependent modulation models using antiparticles were limited to roughly once-a-year balloon-flight opportunities carrying instruments such as AESOP and BESS (see, e.g., Clem and Evenson 2009; Asaoka et al. 2002). The PAMELA spectrometer (Adriani et al. 2009) and now AMS make it possible to measure the antiproton/proton and the e^+/e^- ratios continuously over the solar cycle to compare in much greater detail with models that depend on the solar magnetic dipole, IMF strength, tilt of the current sheet, solar wind turbulence, and other interplanetary conditions. Of course, for studies such as these it is important to measure the e^+/e^- and antiproton/proton ratios during both orientations of the solar magnetic field and during both solar minimum and solar maximum conditions. This is just one of many important reasons to keep these high-resolution magnetic spectrometers operating over this coming decade.

3 Cross-Calibration of Neutron Monitor and In Situ Measurements

Beginning in June of 2006, with the launch of the PAMELA magnetic spectrometer, it became possible to cross-calibrate the cosmic ray record measured by the world-wide neutron monitor network with a single *in situ* instrument that can measure H, He, and heavier ion spectra from ∼0.5 to ∼1000 GV, including essentially all cosmic rays that contribute to the response of neutron monitors around the world (see e.g., Adriani et al. 2011). Comparisons of neutron monitor count rates with, e.g., 27-day and yearly spectra from PAMELA (and now also with AMS-2) can test and improve neutron-monitor yield functions with much greater precision than was ever possible before. Up to now, it has been necessary to combine data from many instruments at different times to obtain complete spectral information over an extended time period. This effort should improve our ability to interpret and inter-calibrate the long-term records of neutron monitors in operation since 2006, and also improve the interpretation of earlier data.

3.1 Extending the Neutron Monitor Record

It is now more than 60 years since neutron monitors began recording the time variations of >1 GV galactic cosmic rays as well as Ground-Level Events (GLEs) due to large solar energetic particle events. This record of more than five solar cycles also connects the era of ground-based and balloon-borne ionization chambers (1930s–1960s) with the space era (see, e.g., McCracken and Beer 2007), and it continues to provide a means of interrelating cosmic-ray modulation conditions that applied to cosmic-ray balloon flights and to space missions that flew at different times. More recently, neutron monitors are used to estimate radiation doses for astronauts (e.g., O'Neill 2006) and commercial air crews (e.g., Lantos et al. 2003). One key element of this network is that it includes locations with geomagnetic cutoffs ranging from $\sim$0 GV to $\sim$16 GV.

There are presently $\sim$60 neutron monitors in operation around the world. Of special interest are those with long data records that span several solar cycles. Unfortunately, during the last decade the US National Science Foundation stopped funding most of the neutron monitor work in the USA that they had been supporting for many years. As a result, data from Climax are no longer available.

It is essential that this record be continued, especially in light of the record-setting cosmic ray intensities in 2009, and because of recent projections, based on solar data, that we could be heading into another period like the Dalton Minimum (McCracken et al. 2011), or possibly even the Maunder Minimum (see, e.g., http://www.boulder.swri.edu/~deforest/SPD-sunspot-release/).

3.2 New Opportunities for Balloon-Borne Studies

In 2012 we celebrate the 100th anniversary of the discovery of cosmic rays, made on a balloon flight by Viktor Hess. Ever since that time balloon-borne instruments have played a major role in measuring cosmic-ray composition, energy spectra, and solar cycle variations. Balloons have the advantage that they can carry very large payloads to the brink of space for much lower cost than space missions, and they can be developed much more quickly. As a result they are excellent vehicles for testing new detector technology and for training students and engineers.

Beginning $\sim$20 years ago it became possible to achieve balloon flights ranging from $\sim$10 to $\sim$40 days by taking advantage of the continuous Sunlight in Antarctica during austral summer. Many of these investigations are made by international teams. In 2009 NASA made a breakthrough with a successful flight of a super-pressure balloon that may ultimately carry 1000 kg payloads at an altitude of 38 km on flights of 100 days or more, including flights at mid-latitudes (see Israel et al. 2009). In an era when there may be budget cuts to many space programs it is essential that programs are continued that offer frequent, low-cost access to space, like the balloon program, and NASA's Explorer Program.

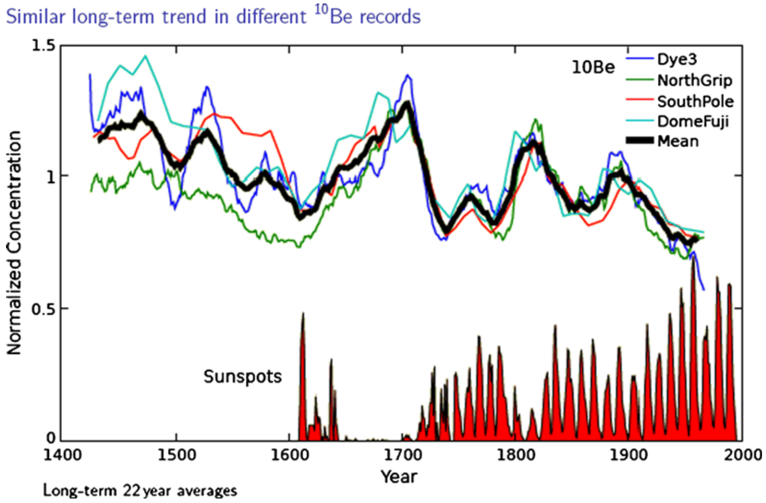

Fig. 5 The long-term ^{10}Be record from ∼1420 to ∼1960 measured at four different polar sites is shown as 22-year averages along with the mean value (*thick black trace*) and the smoothed sunspot number (from Steinhilber et al. (this workshop); McCracken et al. 2011). All four ^{10}Be records show similar trends. The ^{10}Be maxima in ∼1700, 1810, and 1900 represent the Maunder, Gleissberg, and Dalton minima, respectively. Note that at the beginning of the space age ^{10}Be was at its lowest level in the last 550 years

4 The Intensity and Implications of Cosmic Rays in the Past

One of the highlights of this third workshop on cosmic rays in the heliosphere was the excellent series of talks on progress in deriving the history of cosmic rays and solar activity over the last ∼10 000 years and more using the cosmogenic radionuclides ^{10}Be and ^{14}C (see, e.g., Beer et al. 2011; McCracken et al. 2011; and Heikkilä et al. 2011). There has been tremendous progress in reconstructing this record, using ^{10}Be concentration data such as that illustrated in Fig. 5, which was derived from four separate polar ice cores. Note the very clear anticorrelation of the ^{10}Be record and the Sunspot record. All four ^{10}Be records show very similar patterns, including evidence for ^{10}Be maxima that coincide with the Maunder, Gleissberg, and Dalton solar activity minima centered at ∼1700, ∼1810, and ∼1900 AD. It is also apparent that the space age began at a time when the cosmic ray intensity was apparently at it's lowest level in the last ∼600 years.

Recent studies (e.g., Muscheler et al. 2007; Beer et al. 2007, 2011) have shown the value of combining the ^{10}Be ice core and ^{14}C tree-ring records, which are produced by cosmic rays in the atmosphere in essentially the same manner, but are then transported through the atmosphere and stored in their respective archives by different mechanisms. Using the combination of these archives it is possible to extract the common production signal and improve the signal-to-noise ratio in resolving the cosmic ray production history of these isotopes. Figure 7 shows the production rates over the past 9300 years. An analysis of these data, which must also take into account variations in the geomagnetic field over this interval, leads to the identification of ∼22 solar activity minima that are coincident in both records, including four within the past 1000 years.

4.1 Variations in the Interplanetary Magnetic Field

It is well known that cosmic ray intensity is anti-correlated with solar activity and this enables the use of ^{10}Be data to infer solar activity over the past 9300 years. Cosmic ray diffusion into the inner heliosphere can be modeled using a cosmic ray diffusion coefficient, $K(R, r, t)$, which depends on particle rigidity, R, distance from the Sun, r, and time, t (see e.g., Gleeson and Axford 1968). The rigidity and spatial dependence of K are usually taken to be separable and in this discussion we ignore the rigidity dependence since we are dealing with the very high-energy portion of the cosmic-ray spectrum responsible for most ^{10}Be production.

In interplanetary space the cosmic-ray intensity is found to be inversely correlated with the interplanetary magnetic field strength (B; e.g., Burlaga and Ness 1998). This has led to various descriptions of the interplanetary diffusion coefficient as a function of B (see, e.g., Caballero-Lopez et al. 2004). Cosmic ray modulation is often described by the modulation potential ϕ (see Gleeson and Axford 1968), which can be formulated as

$$\phi(t) \propto \int_{1\ \mathrm{AU}}^{r_b} \left(\frac{V_{\mathrm{sw}}(t, r')}{3\kappa(t, r')} \right) \mathrm{d}r' \tag{1}$$

$$\kappa \propto B^{-\alpha} \tag{2}$$

Then

$$B_{\mathrm{imf}}(t) = B_{\mathrm{imf},0} \times \left(\frac{\phi(t) V_{\mathrm{sw},o}}{\phi_0 V_{\mathrm{sw}}} \right)^{1/\alpha}. \tag{3}$$

Applying this approach using ^{10}Be data to define ϕ and with α ranging from 1.6–2, Steinhilber et al. (2008, 2010) reconstructed the IMF over a 9300-year period as shown in the top panel of Fig. 6. The constants were obtained by fitting data from the space era. Also shown in the top panel is the 4.6 nT "floor" in the IMF derived from measurements of the open magnetic field by Svalgaard and Cliver (2007; later reduced to 2.8 nT following the 2009 solar minimum; see Cliver and Ling 2010). Steinhilber et al. (2010) conclude from Fig. 6 that there is no "floor" in the IMF. The middle panel shows the results of filtering the inferred field strength through a $1/1000$ year^{-1} low-pass filter and a 2250 year^{-1} boxcar filter.

Note that the average field strength during the space era was at a relatively high level (>6 nT); during most of the last 10 000 years the field was weaker, indicating a lower level of solar activity. Using this description of the IMF history the 26 cosmic ray maxima in Fig. 7 provide evidence for 26 grand minima, when the IMF was substantially weaker than at present and cosmic ray intensities were substantially greater. The best known of these is the Maunder minimum (∼1645–1715), which was followed by the Dalton and Gleissberg minima (Fig. 5).

It is interesting that Fig. 6 includes several periods when the inferred field was negative as a result of negative ϕ values. While these occurrences might cast doubt on the accuracy of the approach taken to reconstruct the long-term IMF, Steinhilber et al. (2010) attribute the negative ϕ values to their choice of the local interstellar (LIS) proton spectrum, which they take from Castagnoli and Lal (1980; first proposed by Garcia-Munoz et al. 1975). Use of a higher-intensity LIS could avoid these unphysical ϕ values (Steinhilber et al. 2008; Herbst et al. 2009). Possible LIS choices are discussed further in Sect. 7.

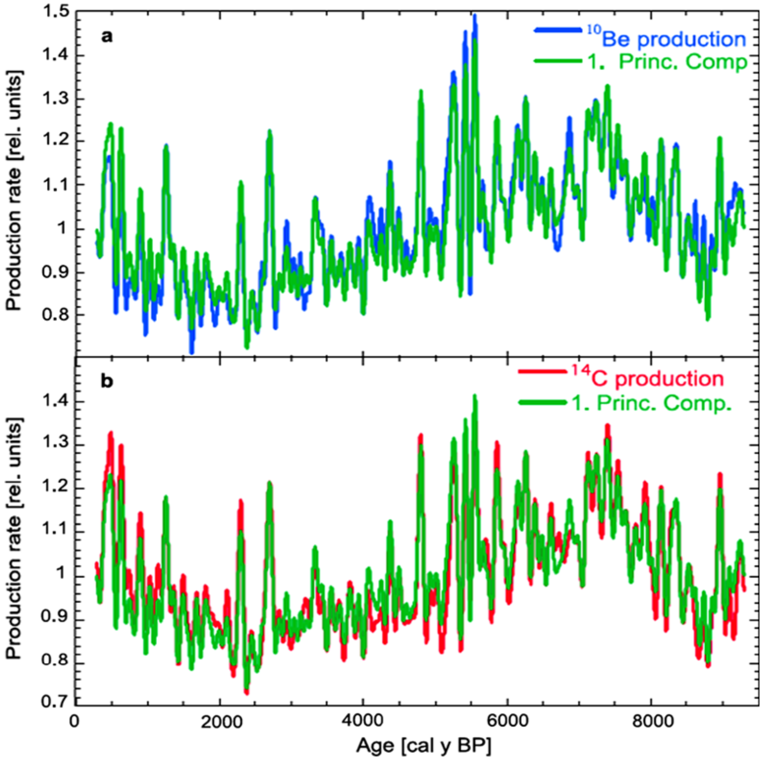

Fig. 6 Relative production rates of ^{10}Be (Panel **a**) and ^{14}C (Panel **b**) over the last 9300 years (Beer et al. 2007, 2011). Also shown in green is the "Principal Component" derived from a combination of the ^{10}Be and ^{14}C rates (see Beer et al. 2011). There are 22 intervals in common identified as "Grand Minima" during which cosmic rays had the greatest access to 1 AU

How might the reconstructions of ϕ and the IMF described above be improved? One of the sources of noise in this approach is the fact that there are differences in the ^{10}Be production rates derived from individual ice cores (see, e.g., the period before 1600 in Fig. 5 and Webber and Higbie 2010b). Beer et al. (2011) estimate that the statistical precision of annual ^{10}Be data is ∼19 %, while that for 22-year averages (e.g., Fig. 4) is ∼5 %. Heikkilä et al. (2011) identify several other sources of "noise". Latitude differences in production rates due to geomagnetic variations are washed out because of thorough mixing in the stratosphere, so it is expected that all regions sample the global mean production rate of ^{10}Be. However, local variations can also occur due to differences in precipitation, ice flow, uncertainties in dating, and analytics. Heikkilä et al. conclude that it is important to combine as many records as possible (e.g., Muscheler et al. 2007), extract the common ^{10}Be production signal from several records, including comparison with ^{14}C, and work with statistical distributions of data and statistical modeling to filter out noise.

From the above discussion it is clear that one way to improve the accuracy of the ^{10}Be record and the reconstruction of solar activity is to collect and analyze more ice-core samples. In particular, it is important to analyze more samples that overlap with the space era, when we have accurate measurements of cosmic ray intensity and energy spectra and also direct measurements of the solar wind and interplanetary magnetic field. Improvements in

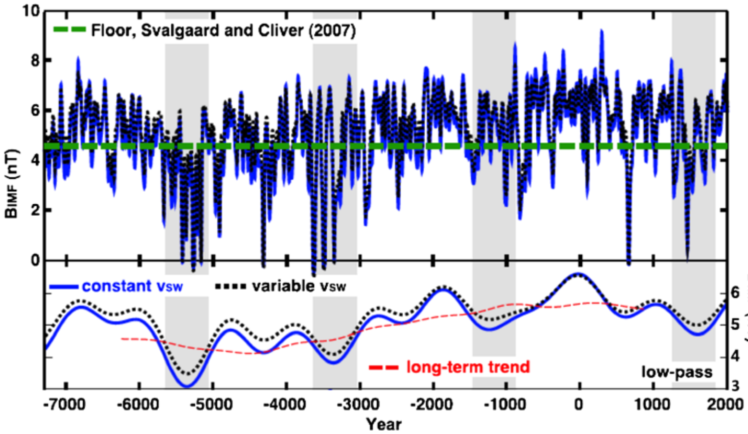

Fig. 7 (*Top*): Forty-year running averages of the interplanetary magnetic field (B_{IMF}) over the last 9300 years as derived from the modulation parameter (ϕ) determined from ^{10}Be data by Steinhilber et al. (2010). The *blue curve* is for a constant solar wind speed of 446 km s^{-1} and the *black curve* is for a variable solar wind speed [$V_{\mathrm{SW}} = 0.23\phi + 0.33$ km s^{-1}, with ϕ in units of MV]. Also shown is the 4.6 nT IMF "floor" derived by Svalgaard and Cliver (2007). (*Bottom*): The IMF blue and black IMF traces in the top panel are filtered through a 1/1000 year^{-1} low-pass filter. Also shown (*red curve*) is a 2250 year^{-1} boxcar filter of the constant V_{SW} data

the resolution of atmospheric general circulation models (GCMs) can also help with interpreting effects of climate and variations in production rates (Heikkilä et al. 2011).

Cliver et al. (2011) report that there is improved agreement between space-based direct measurements of the interplanetary magnetic field strength (B) and the more indirect determination of interplanetary B using the InterDiurnal Variability (IDV) index based on geomagnetic data. They also report improved agreement with other recent determinations based on cosmogenic isotopes (e.g., Steinhilber et al. 2010). Further improvements in this index can improve our knowledge of the IMF history back to the early part of the 19th century.

During large solar energetic particle (SEP) events the intensity of >100 MeV protons hitting the upper atmosphere can be >1000 times that of GCR protons. Averaged over a solar cycle it has been estimated that SEP protons typically contribute only 1 %–2 % of the production of ^{10}Be by galactic cosmic rays, but in unusually active years such as 1956, 1972, 1989 and 2005 SEPs may contribute 5 %–10 % of the global average production by GCRs. (These estimates assume complete atmospheric mixing before ^{10}Be becomes entrained in polar ice cores; see Usoskin et al. (2006) and Webber et al. (2007).)

The production of ^{10}Be by in large SEP events is mostly due to >100 MeV protons, for which there have not always been accurate spectral measurements in historical SEP events. As an example, Usoskin et al. (2006) represent SEP energy spectra by an exponential in rigidity, but measurements during solar cycle 23 show that proton spectra in large SEP events are better represented by double power-law energy spectra (Mewaldt et al. 2005, 2012; Tylka et al. 2006). In addition, there are now much more precise estimates of SEP fluences >500 MeV based on neutron monitor data during ground-level events (Tykla and Dietrich 2009).

Finally, it is not unusual to have geomagnetic storms during large SEP events. During these storms the size of the polar cap that is accessible to SEPs can grow by a factor of ∼2 in area (correlated with the geomagnetic Kp and Dst indices) enabling ^{10}Be production by SEPs down to much lower latitudes than during quiet time (e.g., Leske et al. 2001).

It is therefore worth re-examining the SEP contribution to ^{10}Be production during solar maximum years in hopes of improving the precision of year-to-year GCR contributions to ^{10}Be in polar ice-cores. Models of ^{10}Be and ^{14}C production can also benefit from improved cross sections for reactions initiated by neutrons.

4.2 Total Solar Irradiance Variations

Measurements of Total Solar Irradiance (TSI) have been made since 1978 by a series of space instruments, as discussed in Fröhlich (2011). Although all of these instruments have agreed that the TSI is, on average, higher by $\sim$0.12 % during solar maximum than during solar minimum, they have not agreed well on the absolute value of TSI, and there has been evidence for calibration uncertainties, instrumental drift and/or other sources of background. In order to overcome these limitations several composite TSI records have been constructed from the individual TSI records, relying on periods of overlap to correct for offsets between the individual records (e.g., Willson and Mordvinov 2003; Dewitte et al. 2004; Fröhlich 2006). The last of these three, known as the PMOD composite, has attracted interest because it shows a gradual decrease in the solar minimum value of TSI from the cycle 21/22 minimum to the cycle 23/24 minimum that apparently correlates with a decrease in the radial component of the IMF (Br) at solar minimum (Fröhlich 2009, 2011). Steinhilber et al. (2010) capitalized on this correlation, and used the correlation of ^{10}Be deposition with Br, to estimate TSI variations over the past 10 000 years.

To have confidence in the long-term TSI record it is clearly important to understand the cause of offsets between instruments and the origin of instrumental drifts. Building on a 2005 workshop sponsored by NASA and the National Institute of Instruments and Technology (NIST), several recommendations were made (Butler et al. 2008) to resolve these differences by comparing ground-based versions of the instruments with NIST reference sources to validate their calibration, by validating aperture areas with calibrations of flight-spare apertures, and by applying diffraction corrections. The result of this effort is an improved TSI composite averaged over three separate composites (Kopp and Lean 2011) that is normalized to the SORCE/TIM scale, the instrument that was shown to have the best accuracy and stability. The 2008 solar minimum value of the new composite is $1360.8 \pm 0.5\ \mathrm{W\,m^{-2}}$; compared to the canonical value of $1365.4 \pm 1.3\ \mathrm{W\,m^{-2}}$.

Clearly, it will be necessary to revisit the possible connection between solar activity, the IMF, and TSI. One important lesson is the need for spacecraft instruments to be as well calibrated as possible before launch (rather than post launch). Hopefully, ground-based accelerators will continue to provide a means of carrying out such calibrations for new cosmic ray instruments.

5 Low-Energy Heliosheath Particles, ENAs, and the Size of the Heliosphere

5.1 Effects of a Record Breaking Solar Minimum

As the solar wind blows radially outward it blows a bubble in the interstellar medium called the heliosphere, as illustrated in Fig. 8. At some point the solar wind and interstellar medium pressure balance, and a termination shock (TS) forms. The actual interface between solar and interstellar plasma and magnetic fields is called the heliopause (HP). Because of the relative motion of the Sun through the interstellar medium this bubble is distorted into a comet-like shape.

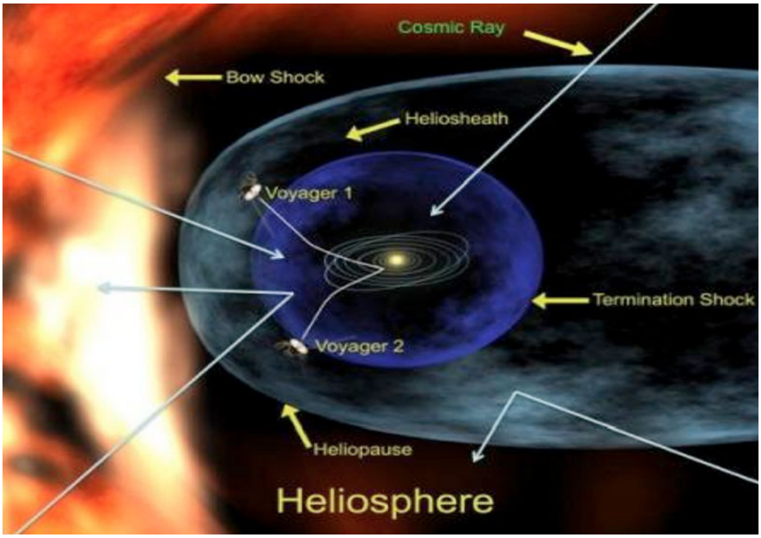

Fig. 8 Illustration of the structure of the heliosphere, including the termination shock, the heliopause (the interface between solar and interstellar plasma), and a possible bowshock. Voyager 1 & 2 are currently exploring the region between the termination shock and heliopause known as the heliosheath. Upon crossing the heliopause it is hoped that one or both Voyagers will measure the local interstellar spectra of cosmic rays from H to Fe as well as electrons, an objective sometimes regarded as the *Holy Grail of Cosmic Ray Physics*

In late 2009 the galactic cosmic ray intensity at 1-AU reached the maximum intensity of the space age, while at the same time the solar-wind dynamic pressure was also reaching record lows. As a result of the decreased dynamic pressure models predict that the termination shock (TS) and heliopause (HP) have recently been receding (see Fig. 9). Unfortunately, the two Voyagers are not presently in a position to directly monitor the motions of these boundaries. As the distance between the TS and HP shrinks this might be reflected (with a significant time delay) by changes in the ENA intensity measured by IBEX (McComas et al. 2010a) and by INCA (Krimigis et al. 2009) on Cassini, and, indeed, there was a decrease between the first and second year ENA intensities measured by IBEX.

In addition, the suprathermal ion intensity in the heliosheath has also begun to decrease recently after several years of being very constant (Krimigis et al. 2011). This suggests a possible means of remote-sensing the distance to the heliospheric boundaries. A recent White Paper submitted to the US Solar and Space Physics Decadal Survey proposes a future ENA mission that would have 100 times the sensitivity of IBEX and 10 times the angular resolution (McComas et al. 2010b). With improved angular resolution, ENA parallax measurements might also sense changes in the size of the heliosphere (E.R. Christian, private communication, 2011).

It is especially important that there be IBEX, Cassini, or future ENA measurements of the outer heliosphere overlapping the possible crossing of the heliopause by one or both Voyagers, since this crossing would provide the first *in situ* measurement of the size of the region of space under the control of the Sun.

It has also been recognized that a decrease in the size of the heliosphere as a result of the recent reduction in the solar wind dynamic pressure (McComas et al. 2008) should lead to an increase in the GCR intensity at Earth (Mewaldt et al. 2010; Schwadron et al. 2011). We can make a simple estimate of this effect by comparing the estimated decrease in the TS distance

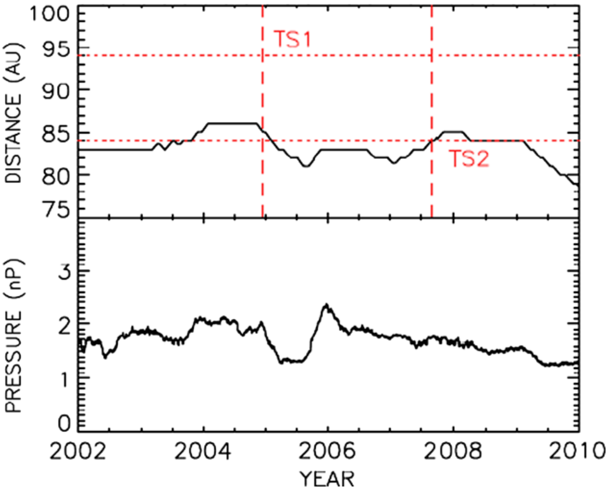

Fig. 9 The *bottom panel* shows the solar wind dynamic pressure measured at 1 AU. The *top panel* shows the inferred distance to the termination shock based on a MHD model that is driven by the solar wind pressure and normalized to the two Voyager termination shock crossings (labeled TS1 and TS2). As a result of the decrease in the dynamic pressure starting in 2006 the termination shock is estimated to have receded from 84 AU to ∼79 AU from 2008 to late 2009. From Richardson (2010)

with measurements of the cosmic ray intensity gradient in the outer heliosphere for cycles with $A < 0$. Using 150–380 MeV nuc^{-1} He data from ∼5 to ∼40 AU, Fujii and McDonald (2005) find a radial gradient of ∼0.9 %/AU. This gradient should decrease between 40 AU and the TS, and McDonald and Fujii (1998) estimate a gradient of ∼0.5 %/AU at 80 AU in 1987 (22 years earlier than 2009). The distance to the TS decreased by ∼4.5 AU from 2008.5 to 2010.0 (see Fig. 9). Combining these, the effect of a closer TS accounts for about one tenth of the ∼25 % increase in ∼200 MeV nuc^{-1} cosmic-ray intensities observed in late 2009 (Mewaldt et al. 2010; McDonald et al. 2010).

It is important that such comparisons continue as the solar cycle evolves. According to McDonald and Fujii (1998) the GCR gradient in the outer heliosphere should be significantly greater at solar maximum. Measuring the effect of the distance to the termination shock on 1-AU GCR intensities is important for forecasting radiation effects on astronauts as well as for interpreting production rates of cosmogenic isotopes. The above back-of-the-envelope estimate should be replaced by a study of inner/outer heliosphere solar-wind, cosmic-ray, and ENA measurements from solar cycles 23 and 24, combined with time-dependent models of cosmic-ray transport and the radial evolution of the heliospheric boundaries.

Of course, it is possible that during the long period over which there are ^{10}Be and ^{14}C measurements the boundaries of the heliopause may have changed by much greater amounts due to encounters with interstellar clouds, as discussed by Frisch and Mueller (2011). Florinski et al. (2003) considered the passage through a cloud with a density of 8.5 H cm^{-3} and estimated an increase of 1.5–3 in the intensity of <1 GeV protons at Earth. In addition, they found an order of magnitude increase in ACR protons (but their energy spectrum is probably not sufficient to significantly affect ^{10}Be production). Over even longer periods, measurements of radionuclides in meteorites indicate that the average GCR intensity has remained constant over time scales of hundreds of thousands to millions of years (Wieler et al. 2011).

5.2 Tracking Cosmic Rays and Transients into the Outer Heliosphere

In the mid-1990s when the first two of these workshops took place, Pioneer 10/11 and Voyager 1/2 were exploring the outer heliosphere, Ulysses was exploring high latitudes between 1 and 5 AU and there were several 1-AU spacecraft measuring cosmic rays (see Fig. 1). During 2006–2007 Ulysses was still going, Cassini was at ∼10 AU, and Voyager-2 was inside the TS with Voyager-1 in the heliosheath. Unfortunately, there are presently no cosmic-ray instruments between Cassini and the heliosheath, making it difficult to measure large-scale cosmic-ray spatial and temporal variations during a time when cosmic-ray modulation is less than in earlier cycles. It is also more difficult to track (in situ) large transients that lead to MIRs and GMIRs, and to forecast if and when they may reach the Voyagers. Such transients can become barriers to cosmic ray entry to the inner heliosphere (Burlaga 1995) and cause "Forbush decreases" in the cosmic-ray intensity as far away as in the heliosheath (e.g., Burlaga et al. 2011; Richardson and Burlaga 2011).

On the plus side, measurements of CME properties from STEREO and SOHO have greatly improved because of stereo imaging techniques. Thus, we now have a continuous 360° view of the CME output of the Sun. In addition, we have continuous 3-point in situ measurements of near-ecliptic solar wind and transient input to the outer heliosphere.

One possibility for adding in situ data from the outer heliosphere is New Horizons (http://www.nasa.gov/mission_pages/newhorizons/main/index.html), approaching 24 AU in mid-2012 and moving at 3.2 AU yr^{-1} toward the nose of the heliosphere and a 2015 Pluto encounter. Although New Horizons has gotten limited telemetry coverage the past few years, an effort should be made to improve this, a side-benefit of which would be an intermediate measurement of transient activity headed toward the Voyagers. In addition, the memory on New Horizons records a steady rate of single-event upsets (SEUs) apparently due to cosmic rays. If this SEU rate could be calibrated with 1-AU cosmic-ray intensities during 2006, it might provide an intermediate GCR record. (There is an excellent correlation of the SOHO SEU rate with GCR Fe measurements from ACE). With a solar magnetic field reversal expected soon we should expect a change in interplanetary GCR and ACR gradients (McDonald and Fujii 1998; Strauss and Potgieter 2010).

Delory et al. (2012) have recently shown that microchannel plates in the Electron Reflectometer on Mars Global Surveyor could monitor galactic cosmic ray intensities at Mars during 1999 to 2006. It was also shown that large solar energetic particle events could be measured. Perhaps there are instruments on Cassini, or other planetary spacecraft, that have a useful response to GCR intensity variations (Cassini does measure anomalous cosmic rays).

6 The Voyagers' Race to the Heliopause and Entry into the Nearby ISM

Although volcanic activity prevented Voyager Project Scientist Ed Stone from attending this workshop, I later asked him what the community could do over the next few years to support the Voyager race to the heliopause, and anticipated entry into the LISM. He said that the most important contributions would be to provide comprehensive measurements of the solar input into the heliosphere and measurements of the time history and spectra of anomalous and galactic cosmic rays at 1 AU (and possibly intermediate points). The solar input, in combination with models, can be used to forecast the changing distance to the boundaries of the heliosphere and the arrival of transients for comparison with ongoing Voyager measurements in the heliosphere. An accurate record of cosmic rays at 1 AU is needed to properly interpret the evolving effects of solar modulation between 1 AU and the Voyagers, especially if and when one of the Voyagers crosses the heliopause.

One advantage of the present array of spacecraft is that there is *in situ* coverage over ∼360° provided by the STEREOs and 1 AU spacecraft, as well as accurate 2 and 3-point measurements of the properties of all CMEs that could form long-lived MIRs and GMIRs, whose effects might be experienced beyond the termination shock. It is important to keep these assets operating at least as long as the Voyagers continue.

6.1 The Acceleration of Anomalous Cosmic Rays

One of the major surprises when the Voyager-1 crossed the solar wind termination shock (TS) in 2004 was that the intensity of anomalous cosmic rays did not reach a peak intensity at the shock for energies more than a few MeV nuc^{-1} (Stone et al. 2005). Indeed, the high energy ACR intensity kept increasing long into the heliosheath (Stone et al. 2008). This indicates that the highest-energy ACRs are accelerated somewhere other than where the Voyagers crossed the TS, possibly by some mechanism other than shock acceleration. Leading candidates include the (1) acceleration at the flanks or tail of the termination shock, where the ions may be able to stay in contact with the shock for much longer times (McComas and Schwadron 2006; Kota and Jokipii 2008); (2) random "hotspots" of ACR acceleration on the termination shock due to large scale turbulence (Jokipii and Kota 2008); (3) particle acceleration due to the contraction of magnetic islands resulting from magnetic reconnection (Lazarian and Opher 2009; Drake et al. 2010); and (4) acceleration in the heliosheath as particles move within random compressions in the plasma (Fisk and Gloeckler 2009).

Continued observations from the Voyagers (aided by 1-AU in situ data and/or by ENA data) offer the best possibility for deciding between these possibilities—it will be a long time before another spacecraft explores the termination shock and heliosheath (see Sect. 8), so it is essential that the Voyager data are continued and that modelers make clear predictions that can be tested by these and other data. For example, the last two of the above models predict that the main acceleration occurs near the heliopause. Richardson and Burlaga (2011) report that, "despite predictions to the contrary, magnetic reconnection is not an important process in the inner heliosheath, with only one occurrence observed to date". However, they also say that magnetic reconnection could become an important process as the Voyagers approach the heliopause, so this will remain an active field of investigation.

A comparison of the energy requirements of each ACR model may also be revealing. For example, in solar events the flare energy is limited by the free magnetic energy in the active region (e.g., Falconer et al. 2012) and the energy in CME shock-accelerated particles apparently is limited by the CME kinetic energy (e.g., Emslie et al. 2012, and references therein). Can all of the ACR models produce and maintain the observed ACR energy density?

6.2 Local Interstellar Cosmic Ray Spectra

If Voyager is able to cross the heliopause and pass into the local interstellar medium it is widely anticipated that it will finally measure the local interstellar spectra (LIS) of cosmic rays—sometimes referred to as the Holy Grail of cosmic-ray physics. It is anticipated that these spectra will reveal, for the first time, the shape of the low-energy GCR spectrum that should be used as the input to models of the solar modulation of cosmic rays in the heliosphere—an unmodulated spectrum that reflects the combined effects of acceleration, transport, energy-loss, re-acceleration in the ISM, and escape from the Galaxy. Once we have measured the LIS of key species we will know the absolute maximum production rate of ^{10}Be and ^{14}C in the past and (assuming we have concurrent measurements at Earth) we will know how much the effects of solar modulation modify this spectrum. We will learn even more if we can compare LIS and 1-AU spectra at both solar minimum and solar maximum. In addition, we will learn the maximum radiation dose that future astronauts could experience.

In addition, the composition of low-energy interstellar cosmic rays is expected to provide measurements of beta-decay and electron-capture isotopes such as ^{7}Be that can reveal information about the lifetime of cosmic rays in the Galaxy, and may reflect the density

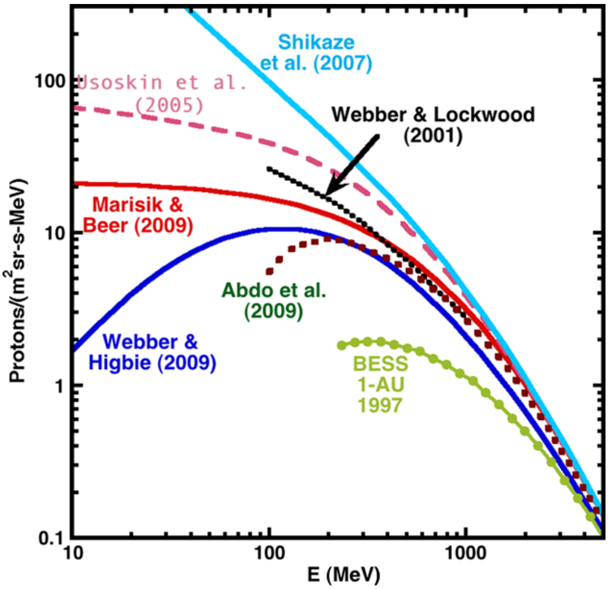

Fig. 10 A variety of local interstellar (LIS) proton spectra have been proposed, some of which are shown above. Some of these were derived from models of cosmic-ray transport in the Galaxy (Webber and Higbie 2009; Abdo et al. 2009), which generally roll over at low energy due to ionization energy-loss. Other proposed spectra represent analytical functions derived to fit available data (Webber and Lockwood 2001; Usoskin et al. 2005; Shikaze 2007). The Masarik and Beer (2009) spectrum was first proposed by Garcia-Munoz et al. (1975). Also shown for comparison is the proton spectrum measured by the BESS balloon-borne spectrometer during the 1997 solar minimum. It is hoped that Voyager 1 and/or 2 will cross the heliopause and distinguish between these and other possibilities

distribution of interstellar matter traversed by cosmic rays (Raisbeck et al. 1973). For a comprehensive review of what is known about the shape of interstellar cosmic-ray electron, proton, and heavier ion spectra see Wiedenbeck (2011). Here we restrict our attention to examples of interstellar H and He spectra commonly used in studies of solar modulation, including the production of ^{10}Be and ^{14}C.

Although there is presently no consensus on the spectral shape of the LIS, a sample of proposed proton LIS candidates is shown in Fig. 10. It is interesting that at ∼100 MeV these spectra differ in intensity by more than a factor of 25. Some of the spectra are based on cosmic-ray acceleration and/or transport models (e.g., Webber and Higbie 2009; Abdo et al. 2009), while others are simply parameterized spectra that can be made consistent with the observations by adjusting the modulation level and thus the amount of energy-loss that cosmic rays suffer in reaching the inner heliosphere. One distinguishing feature is whether or not the interstellar spectra roll over and decrease below ∼100 MeV. In so-called steady-state models of cosmic-ray transport in the Galaxy the spectra typically roll over at low energy because of $\mathrm{d}E/\mathrm{d}x$ losses (e.g., Meyer 1974; George et al. 2009; Webber and Higbie 2009; Abdo et al. 2009), unless there is a recent, or continuous, nearby cosmic-ray source (e.g., Moskalenko et al. 2003).

There are also differences between these spectra at higher energies. Note that at 500 MeV there is a spread of a factor of ∼2.5 in the intensities and at 3 GeV there is still a spread of ∼1.8. In addition, the recent Webber and Higbie (2009) spectrum is systematically lower than the others between 3 and 10 GeV. This suggests the possibility of testing these spectra

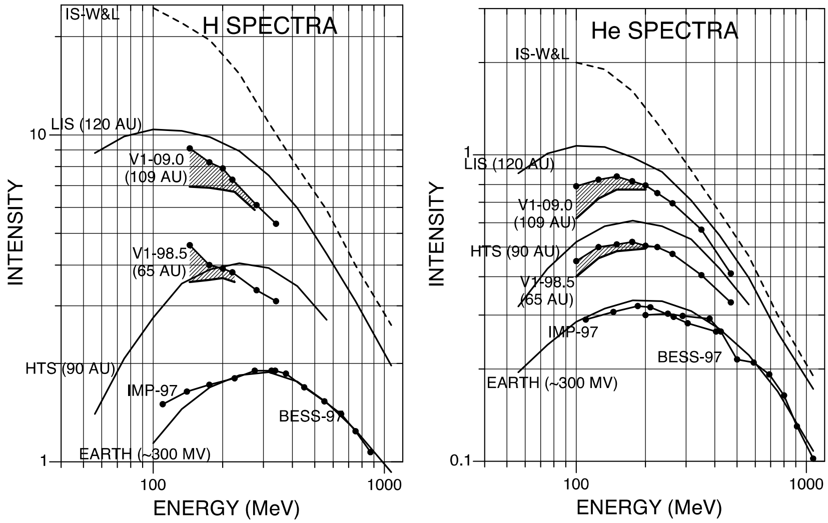

Fig. 11 A comparison of cosmic ray proton (*left*) and He (*right*) energy spectra from 1997 at 1 AU, 1998.5 at 65 AU, and 2009.0 at 109 AU (from Webber and Higbie 2010a). Also shown are LIS proton and He spectra from Webber and Lockwood (2001) and Webber and Higbie (2010a) and modulated spectra based on the LIS spectra of Webber and Higbie (2009). The shaded areas in the Voyager spectra represent the estimated contribution of anomalous cosmic ray H and He

using Voyager measurements of the integral cosmic ray spectrum. The Voyager >70 MeV integral intensity is not presented much lately, probably because it is partially contaminated by ACR protons (see Fig. 11). By correcting for ACR protons, or choosing a higher threshold (e.g., >200 MeV as in McDonald et al. 2006), a comparison with both the differential and integral Voyager proton spectra may limit the proposed LIS spectra in Fig. 10 to a smaller subset.

Recently, Webber and Higbie (2009) derived new LIS for H, He and heavier elements based on models for cosmic-ray transport in the Galaxy and the heliosphere, and assessed whether these LIS were compatible with recent Voyager data. Figure 11 illustrates how their proton LIS compared to Voyager-1 data centered on 2009.0. In a following paper, Webber and Higbie (2010a) evaluated the ^{10}Be production from their new proton LIS and concluded that it fell short of accounting for the ^{10}Be production rate during the Maunder and Spoerer Minima by 9 % to 27 %. An evaluation (not shown) of ^{10}Be production rates by the (unmodulated) LIS spectra in Fig. 10 suggests that they have a spread of a factor of ∼1.8. As a result, the capacity of the various LIS to account for the large variations in ^{10}Be that are observed in Figs. 5 and 7 differ considerably (see also Herbst et al. 2009).

From 2009.0 to 2011.0 the 130-day average intensity of ∼200 MeV nuc^{-1} GCR H at Voyager 1 (see Webber et al. 2011) increased to within ∼2 % of the Webber and Higbie (2009) LIS intensity. One possibility for explaining this is that Voyager-1 was already measuring the LIS at ∼113 AU. Florinski et al. (2011) point out that near the nose of the heliopause, where the distance between magnetic sectors decreases, "a particle is able to travel across a stack of sectors without impediment", so that "the nose of the heliopause could be quite permeable to GCRs". However, a second possibility is that the model of Webber and Higbie (2009) has somehow underestimated the actual LIS, and there was still significant solar modulation at Voyager-1 at the beginning of 2011.

Until one of the Voyagers crosses the heliopause and observes an interstellar GCR intensity that no longer responds to solar-cycle variations, the actual intensity and shape of the LIS, and their capacity to produce cosmogenic isotopes will remain uncertain. However, in the meantime, it is possible to evaluate and test whether proposed LIS spectra can account for recent observations at 1 AU (such as the 2009 proton H and He spectra from PAMELA) and at Voyager, as well as for the ^{10}Be record.

7 Exploring Beyond Ulysses and Voyager

During the coming decade NASA and ESA will begin exploring the inner heliosphere with Solar Orbiter and Solar Probe Plus (presently scheduled for launch in 2017 and 2018, respectively). Solar Orbiter will penetrate to 0.28 AU and eventually reach ∼30° latitude after multiple encounters with Venus. From this vantage point it will be possible to measure the photospheric magnetic field strength to higher latitude than ever before. Solar Probe Plus is being designed to penetrate to 9.5 solar radii (∼0.044 AU) where it will make *in situ* measurements of the corona for the first time, with the goal of discovering how the corona is heated and the solar wind accelerated. While Solar Probe Plus and Solar Orbiter are not designed to make new discoveries in cosmic ray physics, they will undoubtedly make significant breakthroughs in the related areas of solar energetic particle acceleration and transport. In particular, Solar Orbiter will eventually reach latitudes of ∼30°, from where it can provide the best measurements yet of the polar magnetic field, and investigate the latitude variations of cosmic rays, CIRs, and solar energetic particles over an extended time period.

The Alpha Magnetic Spectrometer was installed on the International Space Station in 2011, with the goal of searching for antimatter and signatures of dark matter. At the same time it should provide statistically accurate measurements of cosmic-ray rigidity spectra up to TV rigidities, extending the excellent work of the PAMELA mission.

7.1 Maintaining Comprehensive Solar Wind, Solar Energetic Particle, and Cosmic Ray Measurements at 1 AU

Since the mid 1990s the solar-heliospheric community has had the good fortune to have comprehensive measurements of solar wind properties, solar energetic particle (SEP) events, solar radio bursts, and ACR and GCR elemental/isotopic and spectral measurements from the inner Lagrangian point (L1). While the L1 point is best known for providing real-time and other space weather measurements upstream of the magnetosphere, it is also the ideal location for measuring GCR, ACR, and SEP intensity variations, composition and energy spectra, free from the influence of Earth's magnetosphere.

Beginning in 2014 it is planned that the DSCOVR satellite will take over real-time solar wind measurements for the US NOAA Space Weather Prediction Center (SWPC). DSCOVR presently will include solar wind and magnetic field measurements (which meet NOAA's requirements for real-time space weather data), but it does not make either cosmic ray or SEP measurements. There is also an interest within NOAA and NASA to put a spacecraft near the L5 (or possibly L4) Lagrangian points (±60° away from Earth in longitude). This mission would make helioseismology, vector magnetic field, CME, and particle/fields measurements from a vantage point that is advantageous for space weather forecasting (Gopalswamy et al. 2011). L5 is also a location where important measurements of solar energetic particles and cosmic rays could be made with limited resources.

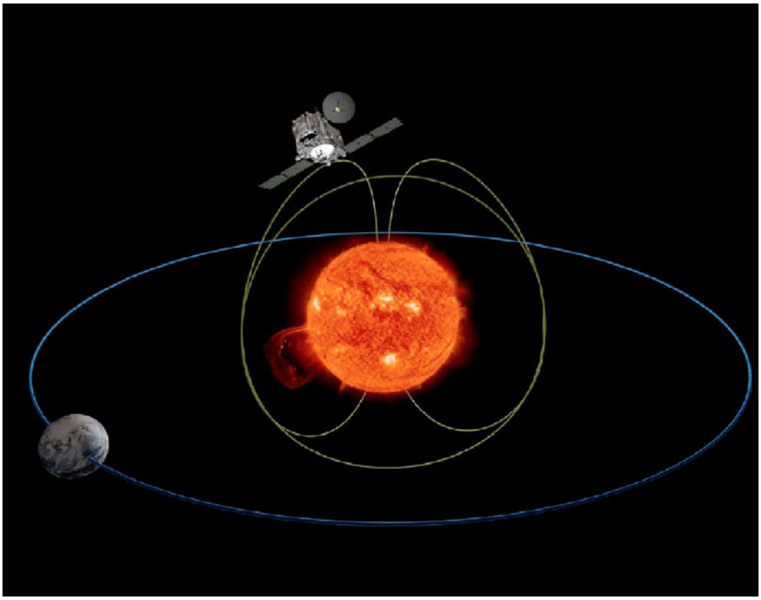

Fig. 12 The proposed orbit for the Solar Polar Imager (SPI; aka Polaris) mission is an inclined circular orbit at 0.48 AU in a 3:1 resonance with Earth. In this orbit SPI could provide a global perspective on solar and hemispheric activity and make six fast latitude scans per year. SPI would address key solar and heliospheric objectives from a new 3-D perspective with a payload of imaging and *in situ* instrumentation. For more information see Liewer and Ayon (2008) and Appourchaux et al. (2009)

7.2 Solar Polar Imager/Polaris

It is time to make longer range plans for investigating cosmic rays in the Heliosphere. Missions that combine imaging and in situ measurements have the advantage that they can address a broader range of objectives; in addition they serve a broader constituency and therefore gather more support. The solar community is very interested in making helioseismology and solar magnetic field measurements from high heliographic latitudes. The Solar Polar Imager Mission has been extensively studied in the US (Liewer and Ayon 2008) and in Europe (where it was known as POLARIS; Appourchaux et al. 2009). These essentially identical mission concepts would make a combination of remote-sensing and *in situ* measurements from a circular orbit at 0.48 AU with a 4-month period (see Fig. 12). The strawman payload includes a Doppler magnetograph, coronagraph, EUV imager, TSI monitor, UV spectrograph, solar wind composition and electron spectrometer, energetic particle spectrometer (20 keV nuc^{-1} to 100 MeV nuc^{-1}), and a magnetometer. It is important that such missions carry adequate cosmic ray and low-energy energetic particle instrumentation if they are to extend the high-latitude studies of Ulysses (see Heber 2011).

One of the advantages of studying cosmic rays from this orbit is that SPI would make six complete Ulysses-type “fast latitude scans” a year, all at the same radius. To achieve this orbit the best option appears to be solar sail propulsion. There has recently been remarkable progress in solar sail propulsion, led by Japan’s very successful IKAROS satellite that passed Venus propelled by a 14 m × 14 m sail (http://www.jspec.jaxa.jp/e/activity/ikaros.html) and by NASA’s NanoSail-D mission (www.nasa.gov/mission_pages/smallsats/nanosaild.html). However, it is not yet possible to consider launching a sail of the size needed for Solar Polar

Imager (∼150 m to 180 m on a side; Liewer and Ayon 2008) without a test flight of a sail that is a significant fraction of this size. In addition, a joint NASA-NOAA mission known as "Sunjammer" with a sail ∼38 m on a side, (∼7 times the area of IKAROS) is presently in development for a 2014 demonstration flight (http://www.nasa.gov/mission_pages/tdm/solarsail/solarsail_overview.html).

A related mission concept is Telemachus (the son of Ulysses), that would use a Jupiter flyby to achieve a 0.2 AU by 2.5 AU orbit passing over the poles of the Sun twice every 1.5 years (Roelof et al. 2004). Telemachus would also carry a combined imaging and *in situ* payload that would include a Doppler magnetograph. An advantage of Telemachus is that it does not require new technology to be carried out.

7.3 Interstellar Probe

Beginning in ∼1990 there has been growing interest in launching an Interstellar Probe, a mission that would be designed to explore the boundaries of the outer heliosphere and carry out *in situ* exploration of the local interstellar medium (LISM) with state of the art instrumentation. Among the new cosmic ray measurements that could be considered for such a mission (not available from the Voyagers) are higher-resolution cosmic-ray isotope measurements that can measure cosmic-ray clocks (e.g., ^{10}Be, ^{26}Al, ^{36}Cl, ^{54}Mn; Yanasak et al. 2001) free from solar modulation effects, the spectra of electron-capture nuclei that can serve as "densitometers" of the cosmic-ray storage region (e.g., ^{7}Be, ^{37}Ar, ^{49}V, ^{51}Cr and ^{55}Fe; Raisbeck et al. 1973), and low-energy cosmic-ray positron and antiproton measurements (Strong et al. 2007; Wells et al. 1999). In addition, it will be important to measure the elemental/isotopic, and ionic-charge-state composition of the interstellar medium as a template for comparing with the composition of solar wind, SEP, ACR, and GCR abundance measurements.

One of the design goals under discussion for such a mission is that it travel at least ∼2 times faster than the Voyagers in order to reach the LISM in a reasonable time. This requires either advanced propulsion or a very innovative orbit, such as following a Solar Probe trajectory and performing a large delta-V maneuver near the Sun (e.g., Mewaldt et al. 1995). While a Solar Probe trajectory for Interstellar Probe will await the successful visit of Solar Probe Plus to the solar corona, other advanced propulsion ideas have also been proposed, including solar sails (Liewer et al. 2001).

Given the widespread interest in the scientific objectives of an Interstellar Probe it seems reasonable that a costly, long-lasting mission of this type should be an international effort and in 2009 Wimmer-Schweingruber et al. (2009a, 2009b) proposed a Interstellar Heliopause Probe: Heliospheric Boundary Explorer Mission (IHP/HEX) as an ESA L-class mission. IHP/HEX would be powered by a solar sail that maneuvers the spacecraft into 0.25 AU, where it can then be accelerated to ∼10 AU year^{-1}. Figure 13 shows two views of the IHP/HEX concept, before and after the solar sail is jettisoned at 5 AU. The strawman payload is composed of 13 instruments requiring 26 kg and 24 W, including a dust analyzer, Ly-α photometer, and energetic neutral atom imager in addition to a suite of particles and fields instruments. The time to reach 200 AU was estimated to be 25 years. As mentioned above, demonstration flights of much larger sails are required to enable a mission of this type.

Other proposed propulsion technologies for an ISP mission include Solar-Electric propulsion and RTG-powered ion propulsion, that could also be coupled with planetary flybys (McNutt et al. 2011a). McNutt et al. (2011b) have studied a design that would use an Ares V launch vehicle, Centaur I upper stage, Jupiter gravity assist, followed by a final

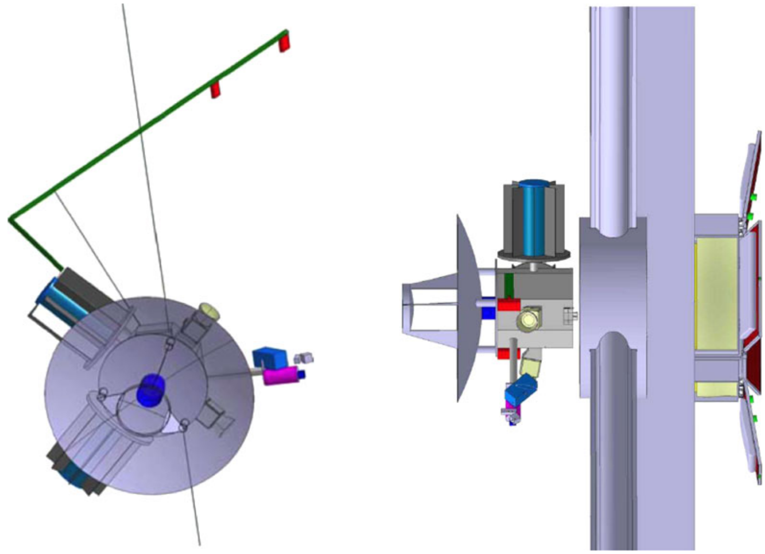

Fig. 13 The Interstellar Heliosphere Probe (IHP) concept is shown with the sail deployed (*right side*), and in science mode (*left side*) after the sail has been jettisoned (from Wimmer-Schweingruber et al. 2009a). Visible on the left are the magnetometer boom, plasma wave antennae, a science boom, the high-gain antenna, and two radioisotope power system (RPS) units

stage powered by radioisotope electric propulsion (REP). The terminal velocity is impressive (9.7 AU year^{-1} at 200 AU), which it would reach after 23 years. Nuclear-powered interstellar missions have also been considered (Zurbuchen et al. 2008), but in this case the very high mass and cost, and the background radiation from the reactor are not a good match for the payload.

For additional information on possible instrumentation and objectives for an interstellar probe mission see McNutt et al. (2011a, 2011b), Wimmer-Schweingruber et al. (2009a, 2009b), Mewaldt and Liewer (2001), and Möbius et al. (2000).

8 Summary

The extended solar cycle 23/24 minimum provides an opportunity to investigate conditions that produced galactic cosmic ray intensities and spectra similar to those in the first half of the 20th century. The difference is that this time there are much more precise cosmic ray measurements, including detailed spectral and composition data, and multipoint measurements of solar wind conditions that are also, in many cases, outside our earlier experience during the space age.

Although attention has so far focused on the higher GCR intensities in 2009, there are additional studies that can be carried out with data from this period (including measurements of electron-capture isotopes, the positron/electron ratio, and the antiproton/proton ratio) that will provide independent information on key processes the modulate cosmic-ray intensities at 1 AU. Finally, there are Voyager data from the heliosheath, where solar minimum arrived 1–2 years later and where solar minimum intensities at ∼200 MeV nuc^{-1} reached ∼2 times those at Earth.

As discussed in Sect. 2, the time is ripe for cosmic ray transport models to pin down how and why GCR spectra in 2009 were significantly greater than any observed before in the space age. This period also provides both the opportunity and motivation to cross-calibrate the large number of ground-based and space-based instruments that witnessed the remarkable cycle 23/24 minimum.

The reduced solar wind dynamic pressure in 2007–2009 are estimated to have caused the boundaries of the heliosphere to move in by $\sim$5 AU by the end of 2009. It will be interesting if either in situ cosmic ray measurements or ENA images can see evidence for changes of this magnitude. Infrequent passages of the Earth through interstellar clouds could have produced much larger changes.

During the past 15 years there has been remarkable progress in analyzing and interpreting the ^{10}Be and ^{14}C produced by cosmic rays in the atmosphere, which are now beginning to reveal much more than the history of their production rates. Using our understanding of solar modulation processes the long-term cosmogenic isotope record is providing information on how the interplanetary magnetic field strength has varied in the past. Fortunately, there has been progress in extracting the field strength from early geomagnetic data, making it possible to extend comparisons between independent records of solar activity further back in the past.

Experience shows that the fidelity of ^{10}Be measurements is improved if data from multiple ice cores is included, indicating a need for additional ice core samples. Although not always possible, it is especially useful to have ice core samples that overlap with the space age, when there are independent measurements of solar wind properties and cosmic-ray intensities. Models of cosmogenic isotope production and transport in the atmosphere can also benefit from higher-resolution atmospheric general circulation models and from improved cross section data.

The Voyager spacecraft began exploring the heliosheath in late 2004 and we were immediately faced with the need to consider additional sites and mechanisms for the acceleration of anomalous cosmic rays. There are several candidates, two of which predict that the acceleration occurs near the heliopause. As the Voyagers penetrate deeper into the heliosheath there is growing evidence that Voyager-1 may be approaching the heliopause, beyond which it may be possible to measure local interstellar cosmic-ray spectra for the first time, along with other interstellar properties. Measurements of the LIS would bound cosmogenic isotope production rates as well as test cosmic-ray acceleration and transport models and nail down needed boundary conditions. In the meantime it may be possible to test proposed LIS spectra with recent solar minimum data from Voyager and 1 AU.

There is broad international interest in possible successors to the exploratory Ulysses and Voyager missions that would carry new, state-of-the-art instruments to a high-inclination near-Sun orbit, and to the interstellar medium. Both missions have challenging propulsion requirements that can possibly be met by solar sail technology if recent progress can be sustained.

There are presently a dozen spacecraft measuring anomalous and galactic cosmic rays in situ over energies from $<$1 MeV to $\sim$1 TeV and from 1 to $>$110 AU (see Fig. 1). These space missions are supplemented by ground-based detectors such as neutron monitors, and by balloon-flight instruments. We now have by far the most impressive array of cosmic-ray instrumentation in history and later this decade Solar Orbiter and Solar Probe Plus will begin their journeys close to the Sun. The challenge during the next decade will be to maintain enough of these missions and facilities to support the Voyagers' approach and (hopefully) passage through the heliopause into interstellar space, and to record in detail the evolving story of how cosmic rays in the heliosphere respond to the Sun's new direction in solar activity.

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