Corotating Interaction Regions in the Outer Heliosphere

Article *in* Space Science Reviews · July 1999

DOI: 10.1007/978-94-017-1179-1_14

COROTATING INTERACTION REGIONS IN THE OUTER HELIOSPHERE

Report of Working Group 4

P. R. GAZIS[1] AND F. B. MCDONALD[2]
CO-CHAIRS

R. A. BURGER[3], S. CHALOV[4], R. B. DECKER[5], J. DWYER[2], D. S. INTRILIGATOR[6], J. R. JOKIPII[7], A. J. LAZARUS[8], G. M. MASON[2], V. J. PIZZO[9], M. S. POTGIETER[3], AND I. G. RICHARDSON[10]
PARTICIPANTS

L. J. LANZEROTTI[11]
CONTRIBUTING AUTHOR NOT PARTICIPATING IN THE WORKSHOP

[1]*SJSU Foundation, NASA Ames Research Center, Moffett Field, California, USA*
[2]*Dept. of Physics and IPST, University of Maryland, College Park, Maryland, USA*
[3]*Potchefstroom University for CHE, Potchefstroom, South Africa*
[4]*Institute for Problems in Mechanics, Russian Academy of Science, Moscow, Russia*
[5]*Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland, USA*
[6]*Carmel Research Center, Santa Monica, California, USA*
[7]*Depts. of Planetary Sciences and Astronomy, University of Arizona, Tucson, Arizona, USA*
[8]*Center for Space Research, Massachusetts Institute of Technology, Cambridge, Mass., USA*
[9]*NOAA/SEC, Boulder, Colorado, USA*
[10]*NASA/Goddard Space Flight Center, Greenbelt, Maryland, USA (also at Dept. of Astronomy and IPST, University of Maryland, College Park)*
[11]*AT&T Bell Laboratories, Murray Hill, New Jersey, USA*

Received: 7 January 1999; Accepted: 16 June 1999

Abstract. We discuss the structure and evolution of CIRs and their successors in the outer heliosphere. These structures undergo significant evolution as they are convected to greater heliocentric distances. A progression of different types of structure are observed at increasing distance from the Sun. Similar structures are observed at similar heliocentric distance at different portions of the solar cycle. CIRs and their successors are associated with many important physical processes in the outer heliosphere. We discuss the relationship between these structures and recurrent phenomena such as cosmic ray variations, and review some of the associated theoretical models on the role of corotating structures and global merged interaction regions (GMIRs) in global cosmic ray modulation. We also discuss some outstanding questions related to the origin of non-dispersive quasi-periodic particle enhancements associated with CIRs and their successors in the outer heliosphere.

1. Introduction

P. R. GAZIS and R. B. DECKER

Corotating interaction regions (CIRs) and their successors play an important role in the dynamics and evolution of the solar wind in the outer heliosphere. They are a dominant structure at timescales on the order of a solar revolution throughout much

Space Science Reviews **89:** 269–305, 1999.

of the solar cycle. They convert bulk kinetic energy into thermal energy, and may be responsible for much of the observed radial profile of solar wind temperature at large distances from the Sun. They are also associated with important physical processes such as particle acceleration and cosmic ray modulation.

This chapter describes the structure, evolution, and effects of CIRs in the outer heliosphere. Section 2 discusses the structure and evolution of CIRs and their successors, Section 3 the effects of these structures on energetic particles and cosmic rays, and Section 4 will discuss questions related to the energetic particle enhancements associated with CIRs and their successors in the outer heliosphere.

Much of our knowledge of the outer heliosphere comes from in-situ observations from Pioneer 10, Pioneer 11, Voyager 1, and Voyager 2. These spacecraft constitute a rich source of information about the behavior of CIRs, their successors, and related phenomena. Figure 1 shows the trajectories of these four spacecraft from launch through 1999. Heliographic latitude (degrees north/south) in the upper panel and radial distance from the Sun in the lower. Pioneer 11, Voyager 1, and Voyager 2 are headed upstream with respect to the local interstellar medium (LISM) while Pioneer 10 is headed downstream. Normal reception of data from Pioneer 11 ended in late 1995, while that from Pioneer 10 was discontinued in mid 1998. Voyager 1 and Voyager 2 should continue to return scientifically useful data for another 20 years. The trajectories of these four spacecraft have made them uniquely suited to investigate the radial evolution, latitudinal variation, and solar cycle variation of a wide range of phenomena in the outer heliosphere.

2. Structure and Evolution of CIRs and Their Successors

P. R. GAZIS and A. J. LAZARUS

CIRs are dominant physical entities at heliocentric distances between 2 and 10 AU (Burlaga *et al.*, 1985a; Goldstein and Jokipii, 1977; Gosling *et al.*, 1976; 1978; Schwenn *et al.*, 1978). Between 8 and 12 AU, CIRs begin to spread, merge, and interact, to produce merged interaction regions (MIRs). (Because MIRs are corotating structures like their parent CIRs, they are also referred to as corotating merged interaction regions or CMIRs.) This process has been studied for individual events observed during spacecraft alignments out to heliocentric distances of approximately 15 AU (Burlaga, 1988; Burlaga *et al.*, 1983; 1985b).

CIRs and their successors undergo considerable evolution as they are convected into the outer heliosphere, and many questions remain regarding the nature of these structures at large heliocentric distances. While the detailed dynamics of the solar wind has been the subject of numerous models (Gosling *et al.*, 1976; Goldstein and Jokipii, 1977; Pizzo, 1991; 1994a; 1994b), many of these models suffer from limitations related to the way in which shocks are represented or the assumption of periodic initial boundary conditions. Most studies of interplanetary shocks have been limited to larger events or heliocentric distances < 30 AU (Smith *et al.*, 1985;

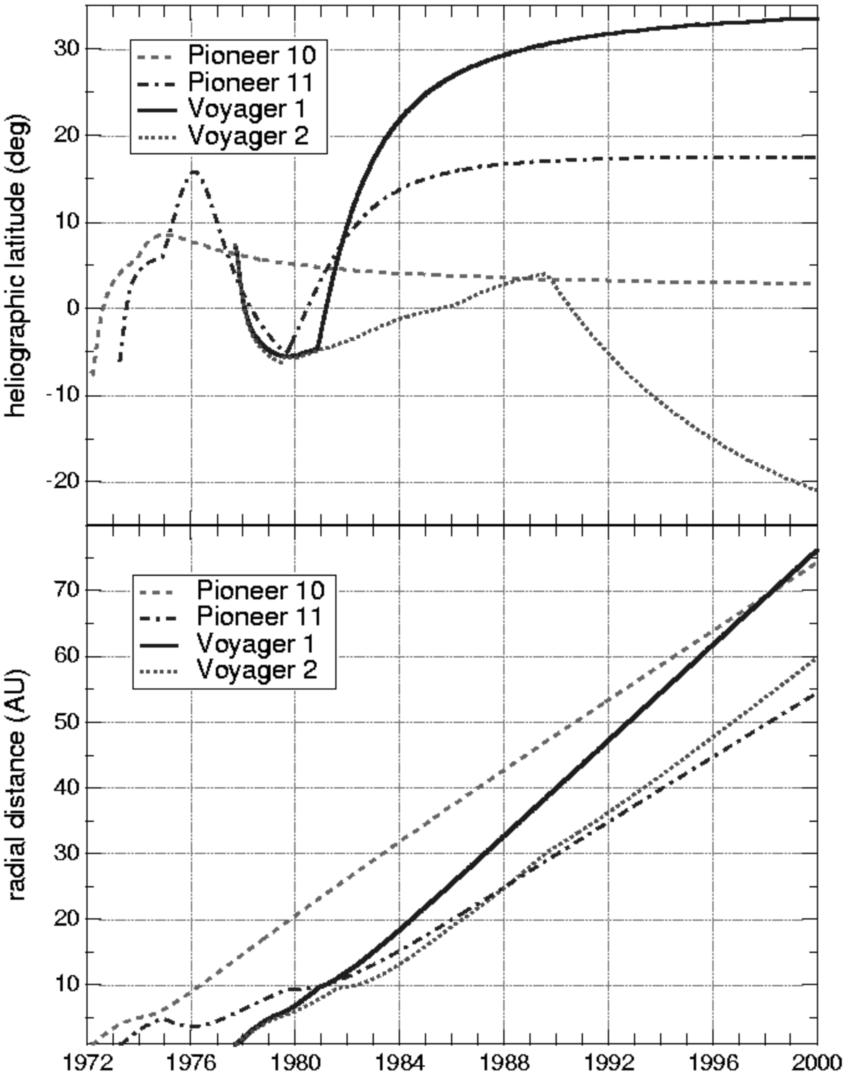

Figure 1. Trajectories of Pioneer 10 and 11 and Voyager 1 and 2. *Top panel:* Heliographic latitude. *Bottom panel:* Heliocentric distance.

Burlaga, 1994). Recently, Burlaga *et al.* (1997) compared observations from Voyager 2 at 14 and 43 AU during comparable periods of the solar cycle to conclude that the structure of solar wind streams at large heliocentric distances was qualitatively different from the structure observed closer to the Sun, but these observations were limited to a single spacecraft during the years 1983 and 1994 (Lazarus *et al.*, 1999).

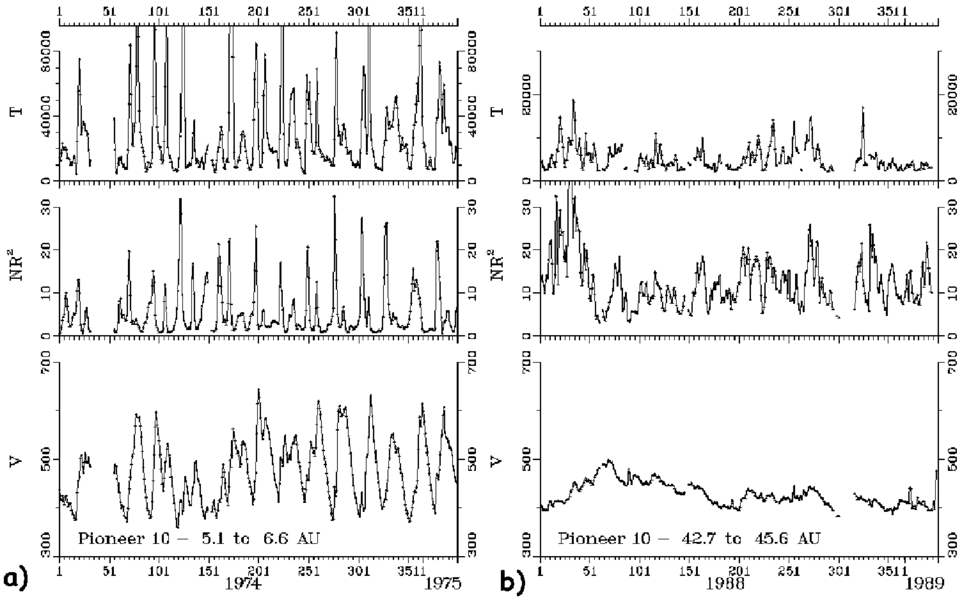

Figure 2. a) From the top, panels show temperature, density, and speed of the solar wind at Pioneer 10 between days 1 of 1974 and 35 of 1975. Density has been multiplied by R^2 to account for presumed radial expansion. b) Solar wind parameters at Pioneer 10 between days 1 of 1991 and 35 of 1992.

Figure 2a shows a time series of solar wind parameters observed at Pioneer 10 for a 400-day interval beginning in 1974 as the spacecraft traveled between heliocentric distances of 5.1 and 6.6 AU. At these heliocentric distances, the solar wind was dominated by a regular and periodic succession of CIRs. Each CIR was characterized by a significant enhancement (typically by a factor of 10–20) in solar wind density and temperature, most of which were associated with a well-defined forward and reverse shock pair. These enhancements were on the order of 3–5 days in duration.

Figure 2b shows a time series of solar wind parameters observed at Pioneer 10 for a 400-day interval beginning in 1991 as the spacecraft traveled between heliocentric distances of 50.7 and 53.6 AU. At these heliocentric distances, the structure of the solar wind was significantly different from that observed closer to the Sun. Small-scale structure is at best only quasi-periodic. Variations in solar wind parameters were comparatively small and there was little evidence for well-defined CIRs of the type seen closer to the Sun. Instead, the solar wind was dominated by variations over timescales of approximately 1–1.3 years of the type reported by Richardson *et al.* (1994) and Gazis (1996).

Many different methods can be used to characterize the evolution of CIRs and their successors as they propagate outward from the Sun. The discussion that follows will be based on the results of a physical survey of the entire Pioneer 10 and Voyager 2 data sets. Peaks in solar wind density (or if density was constant, peaks in solar wind speed) were used to identify individual events. These events were then classified based on duration, the magnitude of variations in solar wind and IMF parameters, and the presence or absence of shocks, stream interfaces, and periodicity.

The advantages of this method are that it is simple, well-defined, and the identification of different types of structures is not affected by details of the data reduction. The biggest disadvantage of this method is its inability to resolve fine distinctions between different types of structure. The need to avoid subjective judgments, particularly at heliocentric distances greater than 15–25 AU, where events can be irregular and poorly defined, can make it necessary to lump a wide range of roughly similar events into a single class. But in spite of this limitation, this method gives consistent results, and it can serve as a basis for and source of comparison with more elaborate techniques.

2.1. STRUCTURES

Two physical processes occur as CIRs are convected outward from the Sun. First, CIRs spread, merge, and combine to form more complex structures. Second, shocks decline in strength to the point where they are difficult to detect, and presumably have little effect on the dynamics of the solar wind. There do not appear to be signs of any other processes, except for effects associated with the low inclination of the heliospheric current sheet (HCS) in the vicinity of solar minimum, when CIRs may disappear over a wide range of heliographic latitudes (Gazis *et al.*, 1988; 1989; Mihalov *et al.*, 1990; Pizzo, 1991; 1994b; Gazis, 1997; Gosling and Pizzo, 1999). In particular, there is no evidence for the formation of new shocks or of any appreciable strength at heliocentric distances greater than 10 AU.

There appears to be a regular succession of different types of structure at increasing heliocentric distances. Similar structures appear at similar heliocentric distances throughout most of the solar cycle. Structure at large heliocentric distances appears to vary with heliographic latitude. Voyager 2 observed different types of structure when it left the vicinity of the solar equator and began to head south after its encounter with Neptune in 1989. (There were also solar cycle effects associated with low inclination of the HCS in 1986, but these are beyond the scope of this discussion.)

Figure 3a shows a time series of solar wind and IMF parameters observed at Pioneer 10 between days 100 and 150 of 1974 when that spacecraft was in the vicinity of 5.2 AU. Three CIRs were observed during this time period: between days 106 and 109, days 121 and 127, and days 134 and 137. These events are typical of CIRs observed between heliocentric distances of 2 and 8 AU. At these heliocentric distances, the duration of CIRs is comparatively short: on the order of 3–6 days. Most CIRs are associated with a forward and reverse shock pair and a stream interface (shown in figure). In most cases, the region prior the stream interface is characterized by high density and moderate temperature while the

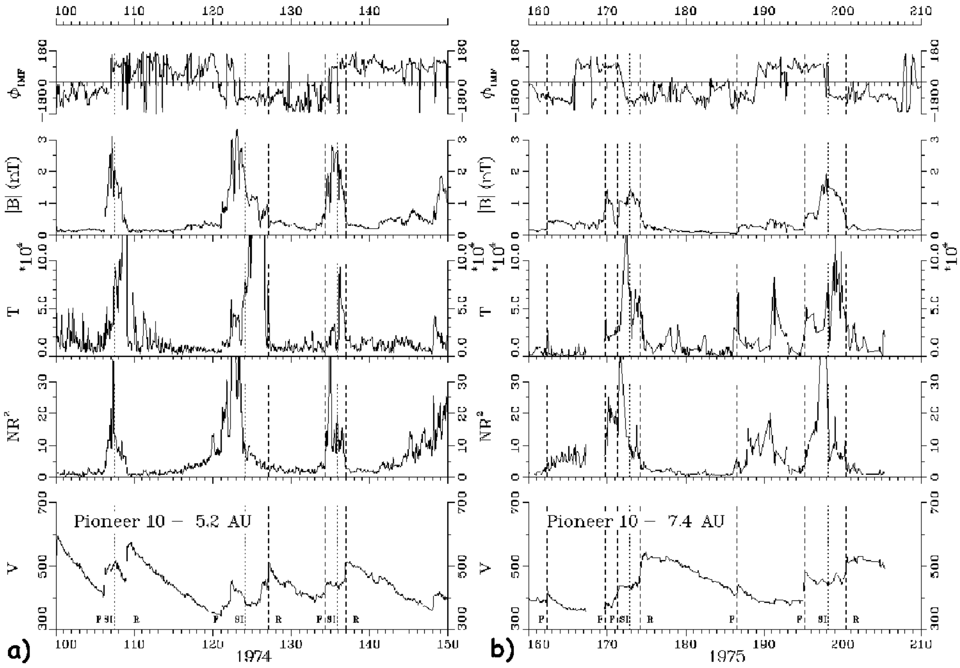

Figure 3. a) From the top, panels show azimuthal angle and magnitude of the IMF, and temperature, density, and speed of the solar wind at Pioneer 10 between days 100 and 150 of 1974. Density has been multiplied by R^2 to account for presumed radial expansion. Forward and reverse shocks and stream interactions are indicated by vertical dashed lines and stream interfaces by vertical dotted lines. b) IMF and solar wind parameters at Pioneer 10 between days 160 and 210 of 1975.

region after the stream interface is characterized by moderate density and higher temperatures.

At larger heliocentric distances, CIRs begin to interpenetrate and merge. Figure 3b shows solar wind parameters observed at Pioneer 10 between days 160 and 210 of 1975 at a heliocentric distance of 7.4 AU. Two merged interaction regions were observed during this time period: between days 162 and 174 and between days 186 and 200. These are typical of the structures observed between heliocentric distances of 8 and 12 AU. These merged interaction regions (MIRs) are wider than the CIRs observed closer to the Sun: on the order of 10–15 days as opposed to 3–6 days. Each event may contain multiple shocks and stream interfaces, but they often retain the general pattern of high density and moderate temperature followed by moderate density and higher temperatures.

At larger heliocentric distances, shocks decay to the point where they are difficult to detect. The resulting structures have been described by Burlaga (1983) as ‘corotating pressure waves without streams’, but this terminology is suggestive of smaller-scale effects such as MHD waves, so for the purposes of this survey, these events will be referred to as corotating pressure enhancements. Figure 4a shows solar wind and IMF parameters measured at Voyager 2 between days 150 and 200

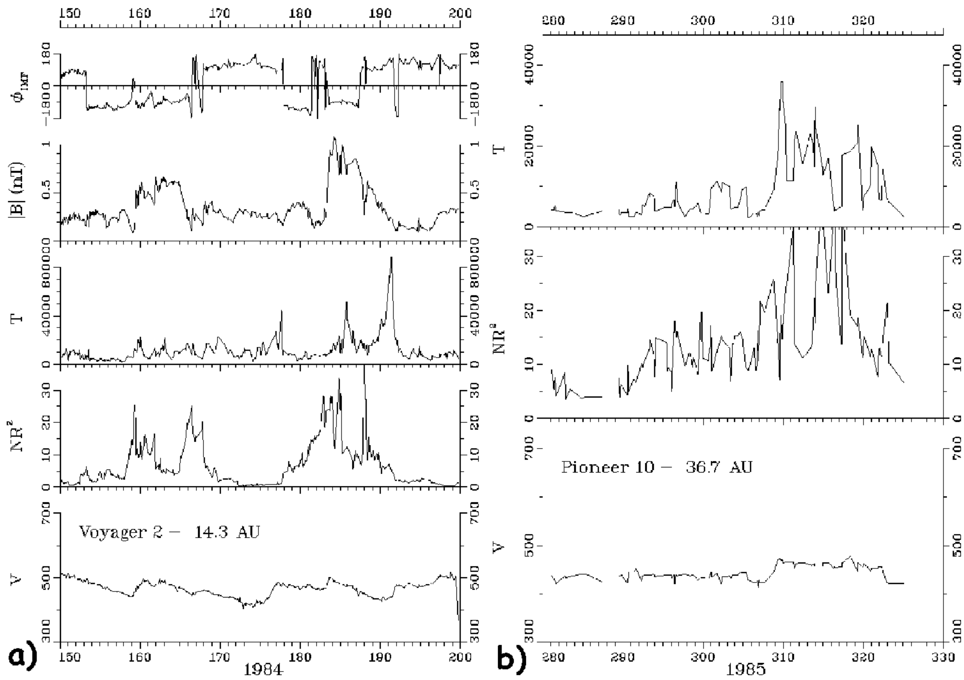

Figure 4. a) From the top, panels show azimuthal angle and magnitude of the IMF, and temperature, density, and speed of the solar wind at Voyager 2 between days 150 and 200 of 1984. Density has been multiplied by R^2 to account for presumed radial expansion. b) Solar wind parameters at Pioneer 10 between days 280 and 330 of 1985.

of 1984, during which Voyager 2 observed two of these events: between days 159 and 170 and between days 186 and 192. These corotating pressure enhancements are even wider (10–25 days) than merged interaction regions and in most cases they are not associated with any shocks. But they still tend to be quasi-periodic and they often retain the pattern of high density and moderate temperature followed by moderate density and high temperature that was characteristic of CIRs and MIRs closer to the Sun.

At even larger heliocentric distances, this organization disappears. Figure 4b shows observations from Pioneer 10 between days 280 and 330 of 1985 when the spacecraft was in the vicinity of 36.7 AU. This is typical of structure observed at heliocentric distances greater than 15 AU in the vicinity of the solar equator. At these heliocentric distances, the spacecraft observed broad but irregular enhancements in density and temperature. These events can be extremely wide ($\gg$15 days). They are not associated with any significant shocks, but they do involve correlated enhancements in density and temperature, sometimes preceded by a slight enhancement in speed. The variation in solar wind speed can be extremely small. These events do not appear to be periodic. This makes it difficult to determine if they are associated

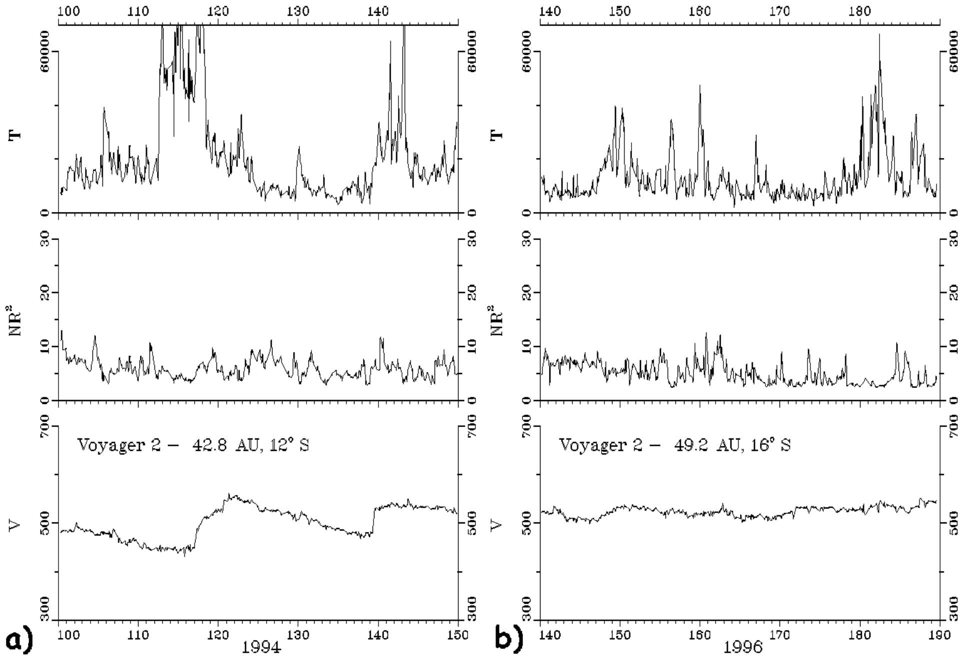

Figure 5. a) From the top, panels the temperature, density, and speed of the solar wind at Voyager 2 between days 100 and 150 of 1994. Density has been multiplied by R^2 to account for presumed radial expansion. b) Solar wind parameters at Pioneer 10 between days 140 and 190 of 1996.

with temporal variations in the solar wind source region or remnants of MIRs that have spread to extremely large size.

Different types of structure are observed at higher latitudes. Figure 5a shows data from Voyager 2 between days 100 and 150 of 1994 when the spacecraft was at comparable a heliocentric distance (42.8 AU) during a comparable phase of solar activity but significantly farther from the plane of the solar equator (12°S versus 3°N). At these heliocentric distances and heliographic latitudes, Voyager 2 observed quasi-periodic enhancements in solar wind speed and temperature of the sort reported by Burlaga *et al.* (1997). The width of these structures varied between 15–25 days. These structures involved correlated enhancements in solar wind speed and temperature while the variation in density was extremely small.

These events were described in detail by Burlaga *et al.* (1997), who also compared them to the 1983 (14 AU) Voyager 2 observations at a similar phase of cycle 21, during which Voyager 2 observed corotating pressure enhancements of the type shown in Fig. 4a. Burlaga and co-workers suggested that these qualitative differences between Voyager 2 observations at 14 and 43 AU represent a change in the state of the solar wind marking a transition from a quasi periodic (ordered) state in B and N near 14 AU to a disordered state in the more distant heliosphere with just the opposite happening with V and T as they approach an ordered state in the outer heliosphere. But comparison with observations from Pioneer 10 and Voyager 2 in

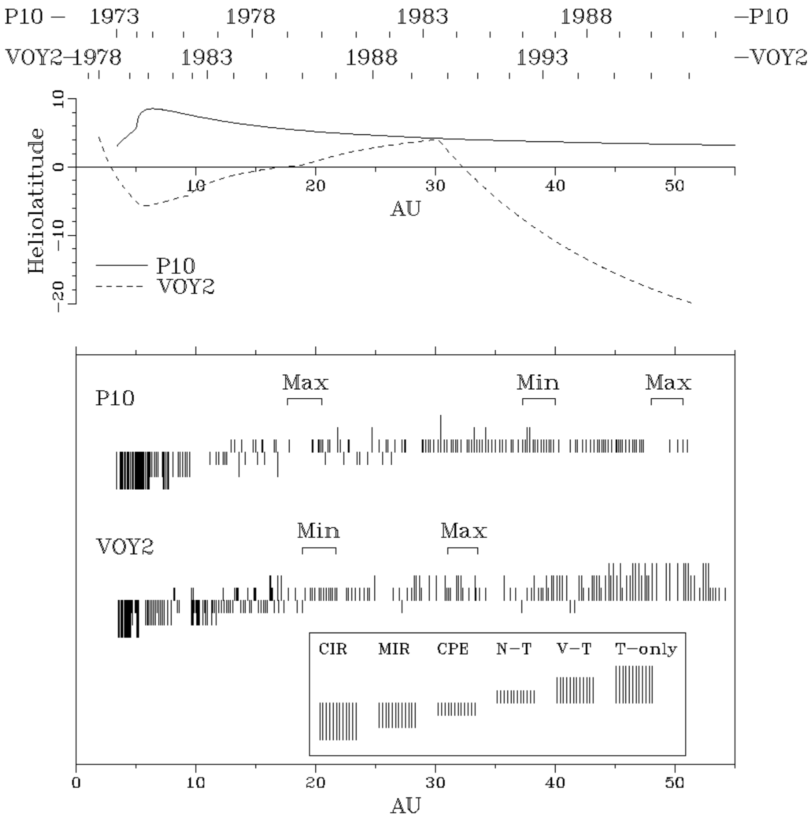

Figure 6. Top panel: Heliographic latitude of Pioneer 10 and Voyager 2 plotted versus heliocentric distance. *Bottom panel:* Different types of structure observed at Pioneer 10 and Voyager 2 plotted *vs.* heliocentric distance. Solar minimum and maximum are indicated for each spacecraft and times at each spacecraft are shown at top of page. See text for abbreviations.

the vicinity of the solar equator suggests that the speed-temperature enhancements were generally restricted to latitudes $>10°$.

At larger heliocentric distances, the variation in speed decreases until these quasi-periodic velocity and temperature variations are replaced by structures that only involve a variation in temperature. A structure of this type is shown in Fig. 5b. These structures involve quasi-periodic variations in solar wind temperature with width on the order of 15–25 days, but the associated variations in speed and density are extremely small.

2.2. Radial Evolution

Figure 6 summarizes the radial evolution of solar wind structure observed by Pioneer 10 and Voyager 2. A succession of different types of structure was observed at increasing distance from the Sun. These types of structure can be distinguished by qualitative differences, such as the presence or absence of shocks. Similar structures were observed at comparable heliocentric distances at different spacecraft during different portions of the solar cycle. At heliocentric distances between 2–8 AU, CIRs were the most common structures. Between 5–8 AU, MIRs began to replace CIRs, until MIRs became the most common structure between 8–12 AU. At even larger heliocentric distances, between 10–12 AU, shocks declined in frequency and strength and MIRs were replaced by corotating pressure enhancements. These corotating pressure enhancements were a common structure between 12 AU and 15–20 AU.

There was some suggestion that different types of structure persisted to larger heliocentric distances during the declining phase of the solar cycle. MIRs persisted to 12 AU at Voyager 2 during 1984 versus 9 AU at Pioneer 10 during 1977. Corotating pressure enhancements were significantly more common between 14–20 AU at Voyager 2 during 1984–1987 than they were at Pioneer 10 during 1978–1980.

At heliocentric distances greater than 15–20 AU, two different types of structure were observed. When Pioneer 10 and Voyager 2 were in the vicinity of the solar equator, they observed non-periodic enhancements in density and temperature. As Voyager 2 ascended to higher heliographic latitudes after 1989, it began to observe periodic enhancements in temperature and speed. As Voyager 2 is headed upstream with respect to the LISM while Pioneer 10 is headed downstream, it remains to be determined to what extent the difference between Voyager 2 and Pioneer 10 is due to latitudinal gradients, solar cycle variation, or the effect of interstellar pickup ions.

3. Behavior of Energetic Particles and Cosmic Rays

R. B. DECKER, F. B. MCDONALD, and M. S. POTGIETER

We now discuss observations of energetic particles and cosmic rays measured in the distant heliosphere. We first define a few terms. By ‘distant heliosphere’ we mean the volume between 10–30 AU and the termination shock. Beyond 10–30 AU, pickup ions play a major role in determining the global structure of the heliosphere (*e.g.*, Gloeckler *et al.*, 1993; Burlaga *et al.*, 1994; Zank and Pauls, 1997; Whang, 1998), including how disturbances such as CIRs and their successors evolve, which in turn affects the ability of such structures to accelerate energetic particles and modulate cosmic rays.

By ‘energetic particles’ we mean suprathermal charged particles, mainly ions, with kinetic energies in the range a few keV to a few MeV/amu that, as implied in the previous sentence, are accelerated at CIR and MIR shocks or within the turbulent interaction region plasma, or both, and therefore exhibit CIR- or MIR-associated intensity increases. The term ‘cosmic rays’ includes galactic cosmic ray (GCR) ions as well as anomalous cosmic rays (ACR), pickup ions convected to and accelerated at the termination shock, with both populations expected to undergo recurrent modulation in the enhanced, turbulent magnetic fields within CIRs and MIRs.

3.1. OVERVIEW

Figure 7 shows time histories of 26-day averaged GCR helium, He, (top panel), hydrogen, H, (middle panel), and 10–22 MeV/amu ACR He (bottom panel) from IMP 6, 7, and 8 at 1 AU, and at Voyager 2 and Pioneer 10 at larger heliocentric distances (helioradii of Pioneer 10 and Voyager 2 are listed at the top of Fig. 7). Time periods with significant fluxes of solar energetic particles ($>$20 MeV) have been eliminated from these data sets. After 1993.0 the Pioneer 10 fluxes are 3-period (78-day) moving averages to remove data gaps produced by the on-board power sharing plan. The anomalous He in the lower panel has not been corrected for the presence of galactic He (which is important only near solar maximum).

Time histories of energetic protons observed at Pioneer 10, Voyager 1, Voyager 2, and IMP 8 are shown in Fig. 8. The traces are 10-day averaged intensities for protons 3.51–5.16 MeV from the Cosmic Ray Telescope (CRT) on Pioneer 10 (*e.g.*, Trainor *et al.*, 1974), protons 0.57–1.78 MeV from the Low Energy Charged Particle (LECP) instrument on Voyager 1 (Krimigis *et al.*, 1977), protons 0.52–1.45 MeV from the LECP instrument on Voyager 2, and protons 0.50–0.96 MeV from the Charged Particle Measurement Experiment (CPME) on IMP 8 (*e.g.*, Sarris *et al.*, 1978). Helioradii and heliographic latitudes of Pioneer 10, Voyager 1, and Voyager 2 are listed atop the respective panels. Times covered by Solar Cycles 20–23 are listed above the IMP 8 panel. Intensity increases of protons by about a few MeV are due mainly to solar energetic particles (SEPs), injected at the Sun and convected to spacecraft in the distant heliosphere, and to protons accelerated at traveling shocks (those associated with MIRs and GMIRs) and recurrent shocks (those associated with CIRs and MIRs).

It is instructive to compare general features in Figs. 7 and 8. Periods of minimal solar activity (*i.e.*, 1976–1977, 1986–1987, 1996–1997) are associated with cosmic ray intensity maxima and energetic particle intensity minima out to $\simeq$70 AU within $\simeq 30^\circ$ of the heliographic equator. (The CPME trace in Fig. 8 does not reach as low a minimum in 1996–1997 as compared with 1976–1977 and 1986–1987 due to partial failure of an anti-coincidence detector.) During periods of maximal solar activity (*i.e.*, 1979–1981, 1989–1991) there are sustained injections of SEPs that elevate intensities of protons near 1 AU and in the distant heliosphere; indeed, several of the broad structures seen in the IMP 8 data in Fig. 8 during 1989–1991 survive intact after convecting for several months to Voyager 2, Voyager 1, and Pioneer 10. As is evident in Fig. 7, enhanced modulation associated with high levels of solar activity produces minima in the galactic and anomalous cosmic ray intensities. Note that peak SEP intensities during solar active periods decrease radially outward, as spacecraft recede from the source (the Sun), whereas ACR and

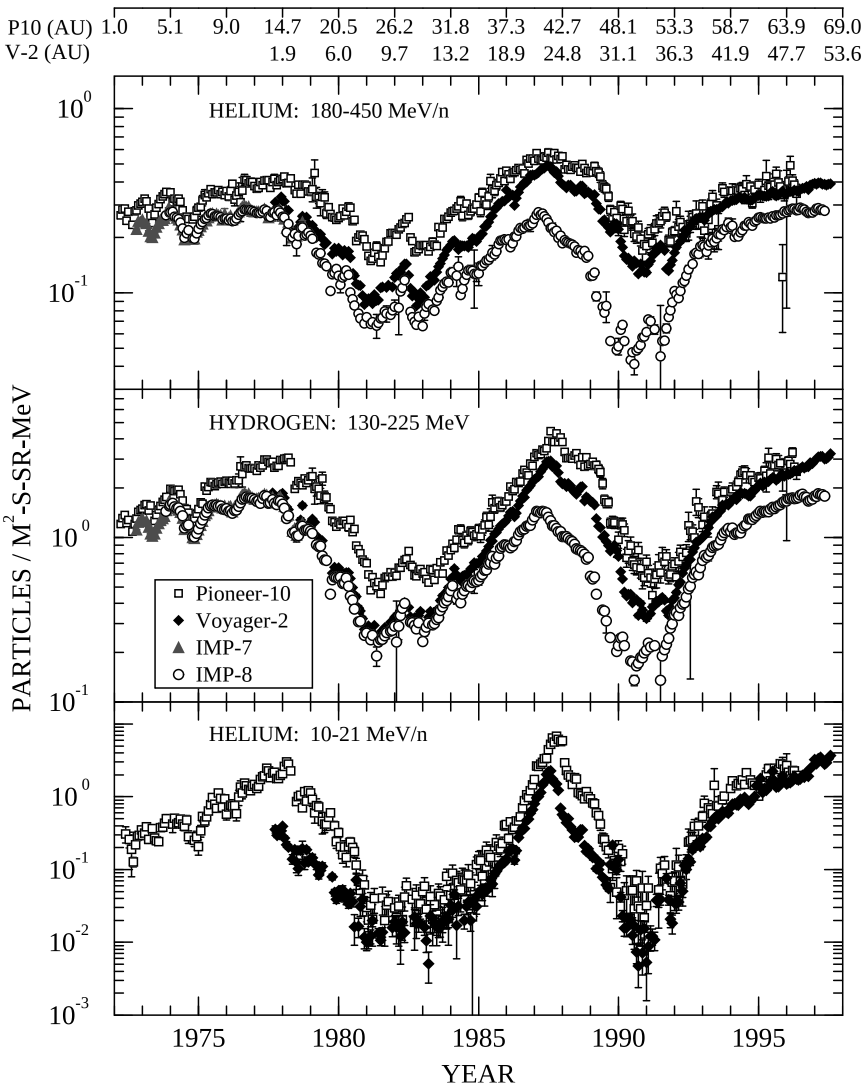

Figure 7. From top to bottom, time histories of the galactic cosmic ray (26-day averages) He, H and 10–22 MeV/amu anomalous helium from IMPs 6, 7, and 8 at 1 AU and Voyager 2 (Voyager 2) and Pioneer 10 (Pioneer 10) at larger heliocentric distances. Time periods with significant fluxes of solar energetic particles (>20 MeV) have been eliminated from these data sets. After 1993.0 the Pioneer 10 fluxes are 3 period (78 day) moving averages to remove data gaps produced by the on-board power sharing plan. The anomalous He in the lower panel has not been corrected for the presence of galactic He (which is important only near solar maximum).

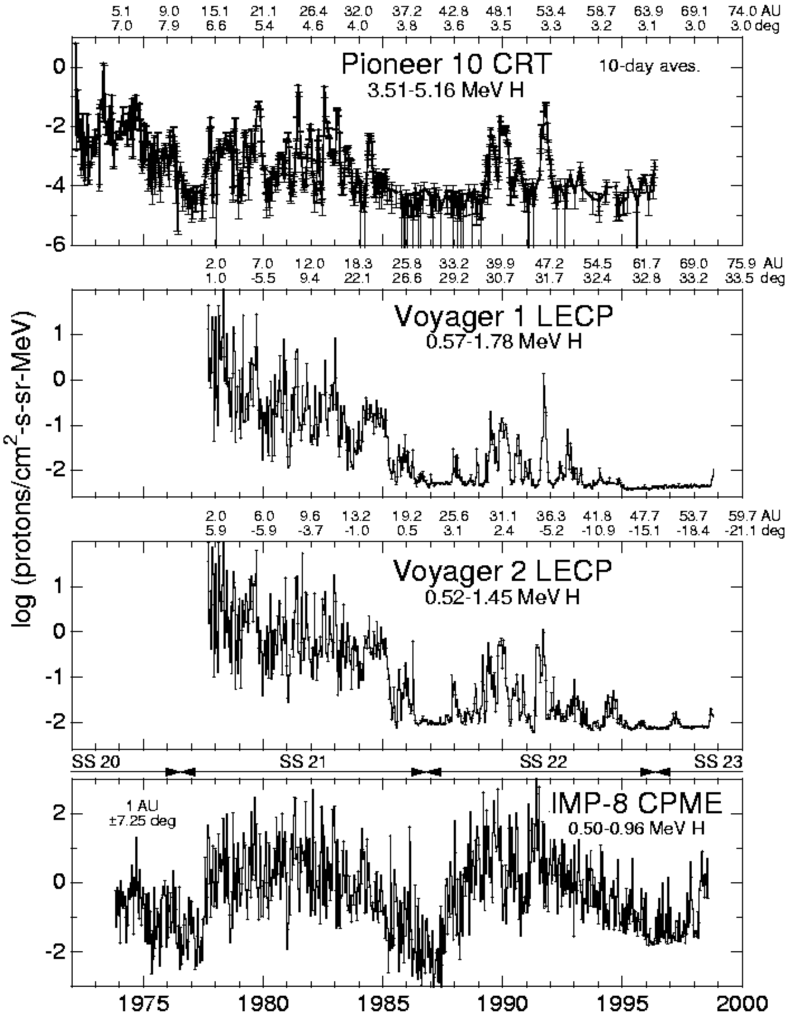

Figure 8. From top to bottom, time histories of energetic protons (H) observed at Pioneer 10, Voyagers 1 and 2, and Earth-orbiting IMP 8. Data are 10-day averaged intensities for protons 3.51–5.16 MeV from the Cosmic Ray Telescope (CRT) on Pioneer 10, protons 0.57–1.78 MeV from the Low Energy Charged Particle (LECP) instrument on Voyager 1, protons 0.52–1.45 MeV from the LECP instrument on Voyager 2, and protons 0.50–0.96 MeV from the Charged Particle Measurement Experiment (CPME) on IMP 8.

GCR peak intensities increase radially outward, as spacecraft approach the sources (the termination shock and interstellar medium, respectively).

Our focus here is to describe effects on energetic particles and cosmic rays that are associated with MIRs. For the most part, these effects are not evident in Figs. 7 and 8, both because of the rather long time averages used (26- and 10-days), and because of the predominant role played by 11- and 22-year processes.

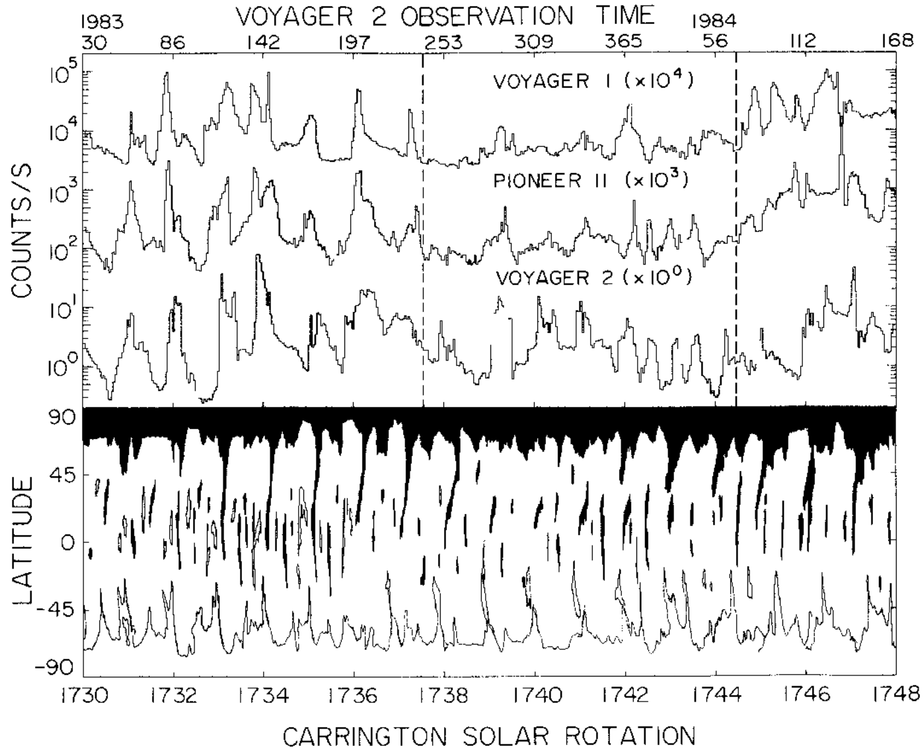

Figure 9. Top panel: From top to bottom, daily averages of protons $\simeq$0.5 MeV at Voyager 1, Pioneer 11, and Voyager 2 during 1983-84. *Bottom panel:* solar latitude of estimated coronal hole boundaries as a function of Carrington solar rotation.

This is particularly relevant for cosmic rays, where intensity variations mediated by MIRs are essentially of second-order compared to those driven by solar-cycle processes. Consequently, to properly elucidate MIR-associated effects it is necessary to examine data at higher time resolution for shorter time periods when it is either clear from supporting data (such as plasma and magnetic field) that MIRs are present, or else their presence is strongly suspected based on indirect evidence, *e.g.*, characteristic signatures in either the energetic particle data, the cosmic ray data, or both. In Sects. 3.2 and 3.3 we discuss MIRs in the distant heliosphere during two-year stretches in the decline-to-minimum activity phases of Solar Cycles 21 (1983–1984) and 22 (1993–1994). It is during this phase of the solar activity cycle that CIRs and MIRs are most prominent in the heliosphere. In Sects. 3.4 and 3.5 we describe some aspects of MIR-associated particle data during the near-minimal activity periods of Cycles 21 (1986–1987) and 22 (1996–1997), and in Sect. 3.6 models on the role of CIRs, GMIRs, and other structures in global cosmic ray modulation are reviewed.

3.2. Recurrent Phemona in the Outer Heliosphere During Decline to Solar Minimum: Period 1983–1984

At low-latitudes, CIRs, MIRs, shocks at their leading and/or trailing edges, and energetic ions accelerated at these shocks, should show time variations correlated with those of equatorward extensions of polar coronal holes. Christon and Stone (1985) compared recurrent energetic proton ($\simeq$0.5 MeV) events observed over 450 days during 1983–1984 at Voyager 2 (11–14 AU, 2.4°–0.8° S), Pioneer 11 (13–16 AU, 12°–14° N), and Voyager 1 (15–20 AU, 17°–23° N). The top panel in Fig. 9 shows 1-day averaged proton count rates from the Voyager 1 CRS (0.6–17.5 MeV), Pioneer 11 CRT (0.8–1.6 MeV), and Voyager 2 CRS (0.4–15.5 MeV). For ease of data intercomparison, observation times have been time-shifted back to the Sun using spacecraft helioradius and a convection speed of 500 km/s; the Voyager 2 time is indicated for reference. This procedure removes, for the most part, convective time delays among the three spacecraft, so that a convecting structure will then appear at nearly the same time in the time-shifted intensity profiles. The bottom panel shows the solar latitude of estimated coronal hole boundaries (based on He 10830 line) versus Carrington solar rotation (synodic period about 27.28 days), with the shaded (unshaded) regions having the same magnetic polarity as the predominant high-latitude northern (southern) coronal hole.

The dashed vertical lines in Fig. 9 separate the 18 rotations into three periods of interest, based upon comparison of relative intensities and passage times of recurrent protons events as observed at Voyager 2, Pioneer 11, and Voyager 1. Observed differences among the three spacecraft are nicely ordered, at least on a qualitative level, by evolution of the finger-like extensions of the coronal hole boundaries and their associated fast flows to low latitudes. For example, during the first interval (rotations 1730–1738), the dominant source of fast solar wind is the equatorial extension of the northern polar hole, consistent with six or so $\simeq$26-day recurrent proton events observed with similar intensities and in near time coincidence at all three spacecraft. During the second interval (1738–1744), the north polar hole recedes to high latitude while the south polar hole extends toward the equator, consistent with observed decreases in recurrent proton intensities at Voyager 1 and Pioneer 11 and with the maintenance of those at Voyager 2. Finally, during the third interval the north polar hole extends again toward the equator, and the intensities at Voyager 1 and Pioneer 11 increase, as expected.

Gold *et al.* (1988) investigated spatial variations in MIR-associated $Z = 1$ ion intensities, 30 keV to 4 MeV, using Voyager 1 and Voyager 2 LECP data in 1984–1986. All of 1984 showed large recurrent ion intensity peaks at both spacecraft, with these peaks superposed on an enhanced, plateau-like background of shock-accelerated ions (this $\simeq$14-month wide "square-wave" structure is evident in Fig. 8 in the two middle panels during 1984 to early 1985). On average during 1984, Voyager 1 saw one peak per solar rotation, while Voyager 2 saw two. (Figure 9 shows data from Voyager 1 and Voyager 2 for over 6 solar rotations in 1984; the difference in proton event recurrence rates at Voyager 2 and Voyager 1 is evident during the first two rotations in 1984). The shock-accelerated ion energy spectra extended from at least 30 keV to 4 MeV at both Voyager 1 and Voyager 2 (Mason, von Steiger *et al.*, 1999). Early in 1985 both Voyagers saw a dramatic decrease in the elevated background intensity, with the aforementioned plateau essentially disappearing with $\simeq$90 days, corresponding to a factor $\simeq$50 drop in the intensity of $\simeq$1 MeV protons. This background decrease was also observed earlier at IMP 8 (*e.g.*, bottom panel in Fig. 8), and based on delay times, was consistent with a heliosphere-wide depletion in the background level of MIR shock-accelerated ions that swept outward from the Sun at about 570 km/s (Gold *et al.*, 1988).

3.3. Recurrent Phenomena in the Outer Heliosphere During Decline to Solar Minimum: Period 1993–1994

Implications for Evolution of MIRs. In 1994 during the recovery phase of cycle 22 there was reasonable stability in the coronal hole structure of the sun and well defined solar wind streams in the inner heliosphere. However there were strong coronal mass ejections occurring in late February, March and June 1994. At this time in the distant heliosphere the Voyager 2 (43 AU, 12°S) plasma experiment observed a gradual increase in the solar wind velocity, V, from $\simeq$450 km/s to a peak velocity of 630 km/s in 1994.55 (Fig. 10). Superimposed on this velocity peak were large, quasi-periodic variations that extended from 1994.2–1995.2. There were accompanying increases in the intensity of 0.043–3.5 MeV ions (Decker *et al.*, 1981a; Krimigis *et al.*, 1995), that were in phase with the individual increases in the solar wind velocity. Also shown in Fig. 10 is the integral rate of galactic cosmic rays with energies $>$70 MeV/amu and the intensity of 6–10 MeV/amu anomalous He. In the lower panel is shown the available magnetic field data from the Voyager 2 magnetometer experiment (Burlaga *et al.*, 1997). The dashed lines mark the times of rapid increases in V for the individual peaks.

There is a striking correspondence between the time history of V and that of the low energy protons and between the modulation of galactic cosmic rays and the low energy anomalous He. However in contrast to the observations in the inner heliosphere, there does not appear to be a well-defined phase relation between V and low energy proton increases and the short-term cosmic ray decreases. In fact, the limited set of magnetic field data suggest this modulation may be due to increases in the interplanetary magnetic field as Burlaga *et al.* (1985a) have proposed from previous Voyager observations.

On 20 February 1994 there began the largest solar energetic particle increase observed since the intense series of events in March/June 1991. This increase was associated with a solar event at N09/WO2 and with a particularly strong CME. At the same time in the inner heliosphere Bothmer *et al.* (1995) noted in the Ulysses data that a transient such as this one results in a higher intensity in the next recurrent low energy proton peak that decreases over subsequent recurrent

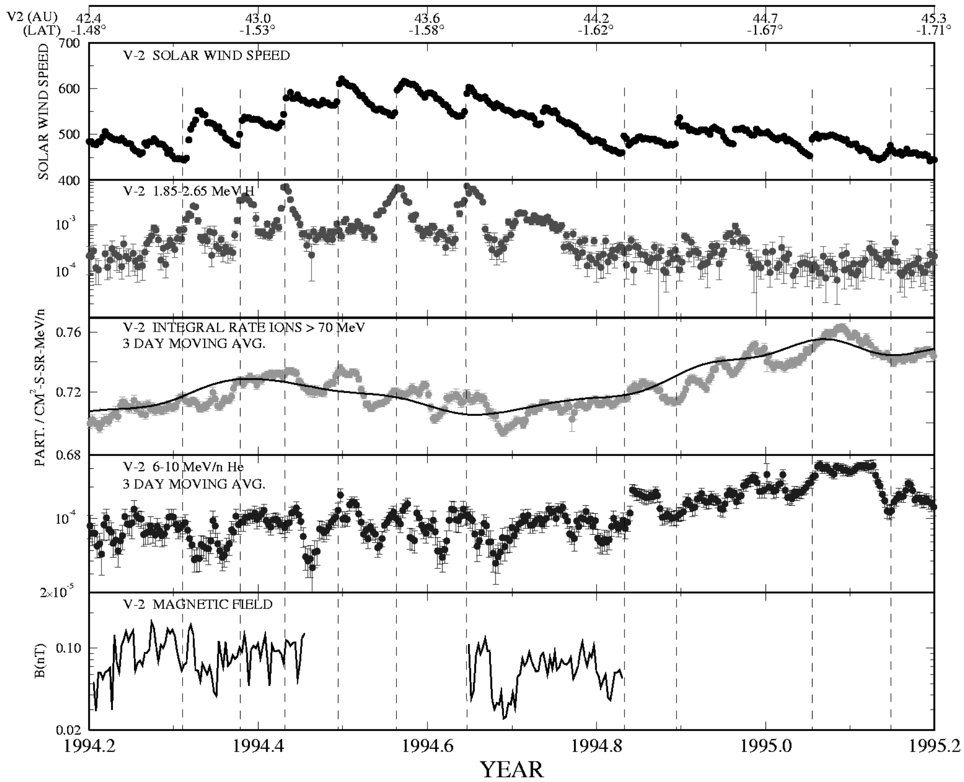

Figure 10. Top to bottom, time histories of the solar wind speed (24-hr averages) from the MIT Voyager 2 solar wind experiment; 1.85–2.65 MeV H, galactic cosmic ray rate for ions >70 MeV/amu; anomalous cosmic ray He, from the CRS Voyager 2 experiment; and daily averages of the Voyager 2 magnetic field experiment. The data gaps in the magnetic field measurements are periods dominated by spacecraft generated interference. The vertical dashed lines mark the time when there was a rapid increase in the solar wind velocity. The solid line through the integral rates shown in the center panel is a smoothed fit to the 26-day averages of this data.

events. This behavior was interpreted as possible evidence that these solar energetic particles might provide a portion of the seed population for the recurrent CIRs to accelerate. If there were no deceleration of the shock from this event on its passage from the Sun to 43 AU then it should arrive at Voyager 2 around 1994.46 which is close to the time of the peak value of V. A smooth fit (3-day running averages) to the galactic cosmic ray day (center panel of Fig. 10) clearly shows a small decrease starting near 1994.4 and extending over some 5–6 months. It appears very probable that the CME associated with the solar event of 20 February is shaping the time histories shown in Fig. 10. During this time period at Voyager 1 (56 AU, 34°N), cosmic ray intensities showed no recurrent patterns, and $\simeq$1 MeV proton intensities displayed a few sporadic, narrow increases, but, compared to those at Voyager 2, were relatively flat during most of 1994 (*e.g.*, compare the top two left-hand panels in Fig. 12).

As described in Sect. 2, CIRs and their successors appear to undergo a significant transition as they move into the distant heliosphere. Also, Burlaga *et al.* (1997) have suggested their studies of the magnetic turbulence suggest a shock-dominated spectrum at 14 AU that evolves to a preponderance of Kolmogorov turbulence at 43 AU.

In fact, the Voyager 1 energetic particle observations beyond 60 AU (beyond mid-1995) suggest that the low energy proton increases, if present, are below the level of detectability of the energetic particle experiments. Furthermore the absence of periodic variations in the cosmic ray intensity over the 1993–1994 time period is an additional argument that MIRs are not an important factor in the more distant heliosphere during the time of declining solar activity. However as shown in Sect. 3.5, this changes dramatically over solar minimum at the Voyager 1 location in the Northern hemisphere but not at Voyager 2 in the Southern Hemisphere.

The apparent absence of interplanetary shocks at 43 AU in 1994 raises the question as to the nature of the acceleration process for the MeV protons. The composition data at these relatively low intensities is not adequate to provide any information. There remains the possibility that the CIRs and CMEs at lesser heliocentric distances may have played an important role. The fact that the short-term modulation of galactic and low energy anomalous cosmic rays is identical does not rule out the possibility that significant pre-acceleration of the anomalous cosmic rays at low energies (*e.g.* 10–100 keV/amu) is occurring in this region prior to their encounter with the termination shock (*e.g.* Gloeckler *et al.*, 1994).

H/He Ratio in Recurrent Structures. The above discussion and that of Lazarus *et al.* (1999) in this volume regarding the observations of plasma, magnetic field, energetic particle, and cosmic rays at Voyager 2 during 1994 emphasize that mature MIRs that have evolved and merged during their transit to several tens of AU from the sun are physically distinct from, and have different effects upon ambient particles, than their youthful counterparts at $\simeq$5–10 AU. Burlaga *et al.* (1997) question whether these structures at $\simeq$45 AU can properly be classified as MIRs. In any case, as MIRs or their remnants propagate radially outward, they are still often observed in association with increased energetic ion intensities, yet the temporal association between ion intensity peaks and the passage of a shock, if indeed a shock is even identifiable, becomes ambiguous further from the Sun. Perhaps the energetic particle distributions are themselves remnants, accelerated earlier before the MIR shocks dissipated, and left to convect outward with the solar wind, cooling adiabatically and diffusing spatially as they do so. Or perhaps the adiabatic cooling is offset partially by wave-particle acceleration that continues to draw energy from turbulence in the remnant MIR. This issue remains unresolved.

An effective diagnostic tool, which may help shed light on questions of seed particles and acceleration/transport processes, and which takes advantage of comparable data from CIR-associated ion events observed over a range of latitudes near 5 AU, is to examine the radial evolution of MIR-associated ion composition data. Figure 11 (adapted from Krimigis *et al.*, 1997) contains Voyager 2 data, again

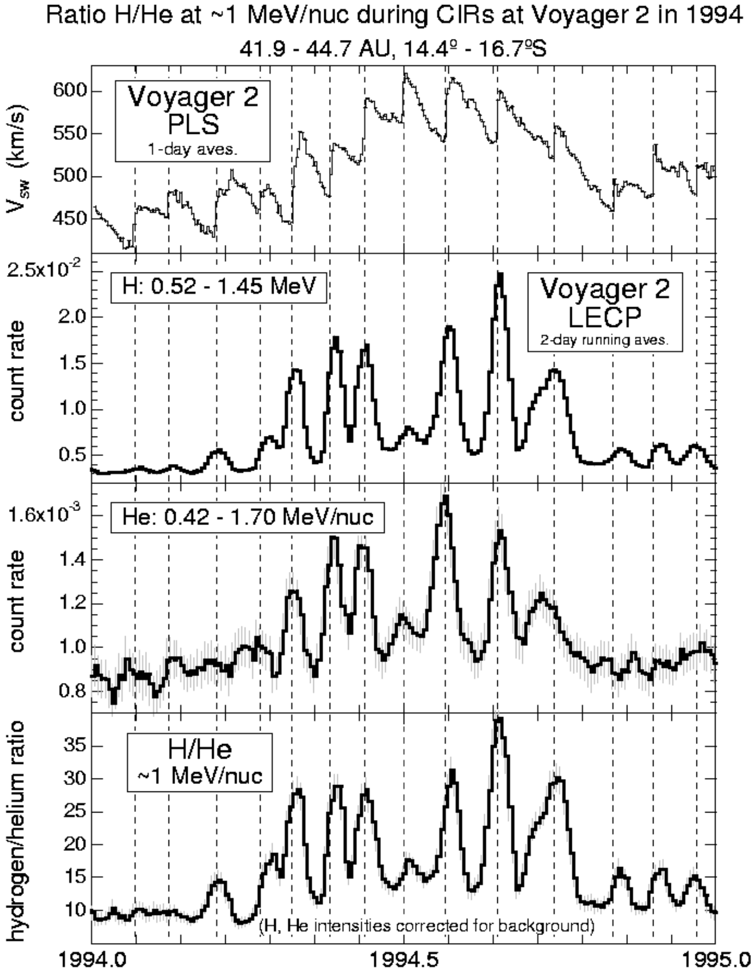

Figure 11. Voyager 2 data during 1994. Top to bottom: daily averages of solar wind speed from the PLS instrument; count rate of protons (H) 0.52–1.45 MeV from LECP instrument; count rate of helium nuclei (He) 0.42–1.70 MeV/amu from LECP instrument; ratio H/He of background-corrected intensities of H and He in middle two panels.

during 1994. From top to bottom, we see solar wind speed (1-day averages) from the PLS instrument, count rate of protons (H) 0.52–1.45 MeV, count rate of helium nuclei (He) 0.42–1.70 MeV/amu, and ratio H/He. Energetic particle data are 2-day moving averages from the LECP instrument, and the ratio H/He was computed from the H and He rates after these data were first corrected for background and then converted to intensities.

Two aspects of Fig. 11 are of interest. First, peaks in the H and He rates are nearly coincident, and occur near, but not necessarily at, times of rapid rise in solar wind speed (dashed vertical lines, reproduced from Fig. 2, Lazarus *et al.*, 1999). Second, the intensities between the peaks during mid-1994 remain elevated, yielding a statistically significant inter-peak ratio H/He. On average, during mid-1994 at 43 AU, H/He$\simeq$30 during peaks and $\simeq$15 between peaks. Ratios H/He $\simeq$15–30 at $\simeq$1 MeV/amu are comparable to those reported, at similar energy per amu (nucleon), for in-situ, low-latitude observations at reverse CIR shocks near 5 AU, while at forward shocks the ratio is typically some 5–10 times larger than at reverse shocks (*e.g.*, Barnes and Simpson, 1976; Decker *et al.*, 1981b). At first sight this may seem curious, since the plasma data show that during 1994 at Voyager 2 the $\simeq$26-day recurrent structures bear signatures of forward shocks (Burlaga *et al.*, 1997; Lazarus *et al.*, 1999). However, the reverse-shock-like H/He ratio may have "frozen-in" much earlier, when particle intensities were dominated by acceleration at reverse shocks (as is generally the case at $\simeq$5–10 AU), before these reverse shocks were destroyed by MIR evolution. Or, maybe the small ratio He/H $\simeq$15–30 reflects a "preference" at MIR forward shocks in the distant heliosphere for injection and acceleration to $\simeq$1 MeV/amu of pickup helium over protons. More work needs to done to clarify these issues.

Finally, as pointed out above during the discussion of Fig. 10, the 6–10 MeV/amu ACR He and $>$70 MeV GCR have similar time histories, indicating that, like the GCR, ACR He at this energy is being modulated. It is interesting that at only a factor $\simeq$10 lower in energy, the time history of 0.42–1.70 MeV/amu He in Fig. 11 is similar to those of the 0.52–1.45 MeV protons in same figure and the 1.85–2.65 MeV protons in Fig. 10, indicating that intensities of He and H at $\simeq$1 MeV/amu are dominated by MIR-associated acceleration processes, whether such processes occurred at the time of observation or earlier, *e.g.*, when the shocks still present or were perhaps more effective at accelerating particles.

Voyager 2 – Ulysses Comparisons. Multi-spacecraft studies are also valuable tools for gaining insight into processes that are inherently of a global nature. The left-hand panel of Fig. 12 shows daily averages of $\simeq$1 MeV proton intensities from (top to bottom) Voyager 1 LECP (Krimigis *et al.*, 1977), Voyager 2 LECP, Ulysses HI-SCALE (Lanzerotti *et al.*, 1992), and IMP 8 CPME (Sarris *et al.*, 1978), from 1992 to 1995.5. Note the striking difference between the intensity variations at Voyager 1 (32°N) and Voyager 2 (5°–15°S), showing the presence of large spatial variations over latitude separations $\simeq$40°. Our focus here is a comparison of the Voyager 2 and Ulysses proton data during 1992.5–1993.5. The right-hand side of Fig. 12 shows (top to bottom) solar wind speed, Voyager 2 LECP protons, and Ulysses HI-SCALE protons. Simnett *et al.* (1997) compared the $\simeq$40 keV electron fluxes and $\simeq$1 MeV proton fluxes, *i.e.*, those in Fig. 12, from recurrent CIRs at Ulysses and quasi-recurrent MIRs (or MIR remnants) at Voyager 2 during the period corresponding to the 1992 Ulysses passage through the southern heliosphere. During late 1992 to early 1993 Ulysses ($\simeq$5 AU, $\simeq$13°S–20°S) and Voyager 2 ($\simeq$38 AU, $\simeq$8°S–10°S) were at comparable southern latitudes and were sampling energetic particles evidently associated with the same (albeit, radially convected) recurrent structures. The $\simeq$1 MeV proton fluxes during the maxima of the recur-

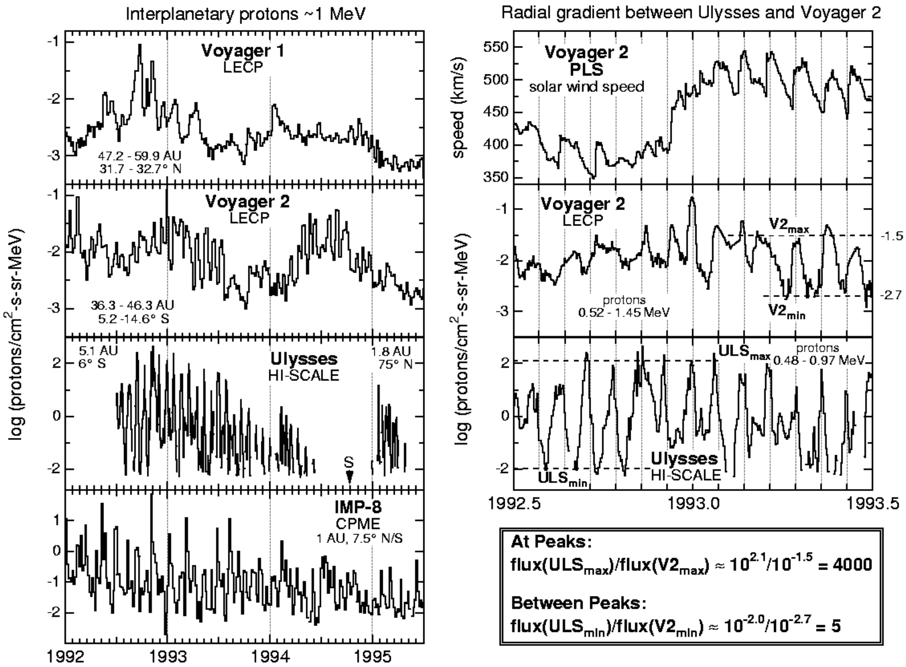

Figure 12. Left-hand side: From top to bottom daily-averaged intensities, 1992.0–1995.5, of protons with energies: 0.57–1.78 MeV from Voyager 1 LECP; 0.52–1.45 MeV from Voyager 2 LECP; 0.48–0.97 MeV from Ulysses HI-SCALE; and, 0.50–0.96 MeV from IMP 8 CPME. *Right-hand side:* From top to bottom daily-averages, 1992.5-1993.5, of: solar wind speed from Voyager 2 PLS; protons intensity 0.52-1.45 MeV from Voyager 2 LECP; protons intensity 0.48–0.97 MeV from Ulysses HI-SCALE; and, estimates of Ulysses/Voyager 2 intensity ratios of $\simeq$1 MeV protons during maxima and minima of recurrent proton events, indicted by dashed horizontal lines in panels showing Voyager 2 and Ulysses proton data.

rent events were $\simeq$4000 times higher at Ulysses, while those during the minima (still well above background) were only $\simeq$5 times higher at Ulysses (box in lower right-hand side of Fig. 12).

The factor $\simeq$4000 is well above the factor $\simeq$60 expected if the peak flux of recurrent ions decreases inversely as the square helioradius, as demonstrated by Decker *et al.* (1981a). However, as Simnett *et al.* (1997) emphasize, this is likely because during late 1992 to early 1993, Voyager 2 sampled only the transition zone to the polar high speed stream, while Ulysses was already measuring the highest $\simeq$1 MeV proton fluxes that is would encounter en route to its southern polar pass. The most interesting result, however, is the small radial gradient in the between-peak, minimum fluxes. The authors conclude the relatively low flux of protons associated with acceleration at recurrent shocks is very effectively confined throughout the heliosphere. Simnett *et al.* (1997) were also able to establish an upper limit at Voyager 2 on the intensity of recurrent electron events, which were routinely observed at Ulysses in 1992–1994. As stated above, at low latitudes (within $\simeq 20^\circ$S) the peak flux of $\simeq$1 MeV protons is lower at Voyager 2 by a factor $\simeq$4000: the upper limit on the $\simeq$40 keV electron flux at Voyager 2 is consistent with this factor.

3.4. Recurrent Phenomena in the Outer Heliosphere at Solar Minimum: Period 1986–1987

At solar minimum, the heliospheric neutral current sheet (HCS) reaches its lowest inclination and the CIRs with their energetic ion enhancements become much smaller. However in the outer heliosphere at moderate latitudes, recurrent (26 day) phenomena are observed in the solar wind velocity, interplanetary magnetic field, and in the intensity changes of galactic and anomalous cosmic rays but there is a striking absence of low energy MeV ion increases.

These solar cycle related changes in the intensity of low energy ions can be seen in Fig. 8 which shows the time history of 0.5–1.5 and 3.3–4.8 MeV protons over a 26 year period during which Pioneer 10 and the Voyagers move out to heliocentric distances beyond 70 AU. With the approach of each of the 3 solar minimum periods there is a rapid decrease in the intensity of these MeV ions down to the background level of the detector systems that persist over a period of several years (Gold *et al.*, 1988; McDonald and Selesnick, 1991).

The variations in the integral counting rate of cosmic rays $>$70 MeV from energetic particle experiments on IMP 8, Voyager 1 (31 AU, 31.4°N), Pioneer 11 (23.7 AU, 16.5°N) and Pioneer 10 (41.4 AU, 3.1°N) are shown in Fig. 13 for 1986.5–1987.5 along with the Pioneer 11 solar wind velocity, V, and Pioneer 11 and Voyager 1 magnetic field data, B. The Pioneer 11 and Voyager 1 observations display a well-defined 26-day periodicity that is anti-correlated with the B and V data. At 1 AU the amplitude of the cosmic ray variations are smaller and at Voyager 2 (20 AU, 1.2°S, not shown) they appear to be almost totally absent. At Pioneer 10 there are small amplitude variations that suggest a quasi-periodicity on the order of 13 days.

From 1986.6–1987.5 the Voyager 1 galactic cosmic ray data exhibits a periodicity of 25.7$\pm$0.06 days with an average peak to peak variation of 3.4$\pm$1.4%. Assuming that the galactic and anomalous cosmic rays have the same phase it is possible to sum over the 10 cycles and determine the amplitude of the variations of representative galactic and anomalous cosmic ray components. Within the errors it is found that the ratio of the amplitude of this variation to the latitudinal gradient, G_λ, of cosmic ray intensity is as consistent as had been previously found by Zhang (1997) using Ulysses data in the inner heliosphere.

Cummings and Stone (1988) had noted the large recurrent variations in the Voyager 1 integral rate of nuclei $>$70 MeV and in the intensity of 6–17 MeV/amu anomalous oxygen that were not present at Voyager 2. This study was extended by Webber and Lockwood (1997) who determined the variations of the modulation

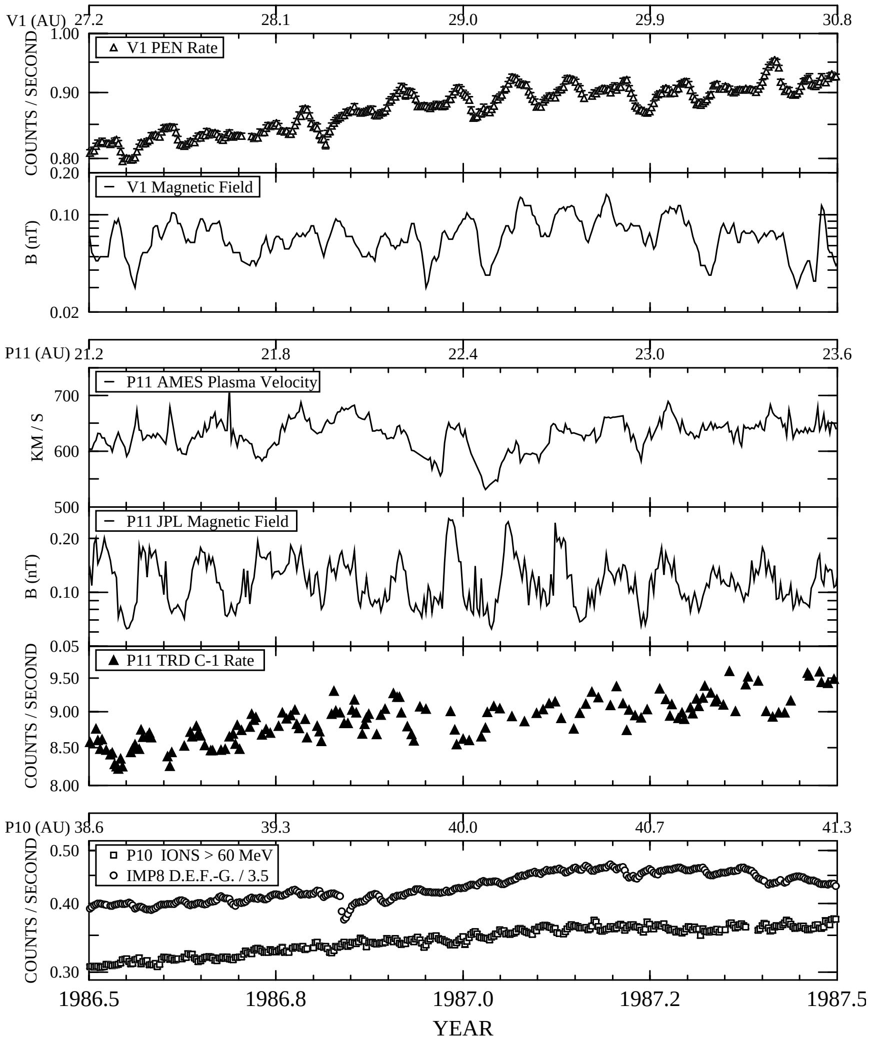

Figure 13. Integral counting rate of cosmic rays >70 MeV from energetic particle experiments on IMP 8 (bottom panel), Voyager 1 (31 AU, 31.4°N, top panel), Pioneer 11 (23.7 AU, 16.5°N, 5^{th} panel from top) and Pioneer 10 (41.4 AU, 3.1°N, bottom panel) for 1986.5–1987.5. Also plotted are Pioneer 11 solar wind velocity, V, (3^{rd} panel from top) and Pioneer 11 and Voyager 1 magnetic field data, B (4^{th} and 2^{nd} panels from top, respectively).

amplitude and the latitudinal gradient, G_λ, combined with a variation in magnetic heliolatitude produced by the wavy neutral current sheet so that $\Delta J/J \simeq G_\lambda \Delta\theta$ where $\Delta J/J$ is the amplitude of the intensity variation and $\Delta\theta = 2\theta_{\rm HCS}$ (where $\theta_{\rm HCS}$ is the current sheet inclination.

However for the Ulysses data in the inner heliosphere, Zhang *et al.* (1995) found no correlated phase relationship between the phase of the tilted HCS and the 26-day recurrent modulation of the cosmic ray intensity. It was also found that the amplitude of the modulation at $\theta_{HCS} \simeq 15^\circ$ and 30° was independent of the value of θ_{HCS} (Simpson, 1998). In fact, Webber and Lockwood (1997) observed that the modulation amplitude for the 1986–1987 Voyager 1 data had its largest value when the current sheet inclination is near its minimum value, and the value of $G_\lambda\, 2\theta_{HCS}$ was $\simeq$0.25 of the predicted value. Furthermore the form of the measured and predicted curves over the $\simeq$0.25 year interval were not in good agreement.

However, Perko (1993) was able to reproduce the Voyager 1 and Voyager 2 time history profiles of the integral rate of ions $>$70 MeV, and hence the observed negative latitudinal gradients, over the 1986–1988 time period using a one-dimensional diffusion coefficient based on the in-situ magnetic field observations and the large increase in solar wind speed seen at the higher heliographic latitude.

It must also be noted over the 1995–1997 solar minimum, when the drift imposed flow of ions into and out of the heliosphere has been reversed from the pattern of 11 years earlier, the latitudinal gradients are positive but much smaller in magnitude than the large negative values observed in 1986–1987 (Cummings *et al.*, 1995; Webber and Lockwood, 1997; McDonald *et al.*, 1998). These observations over two successive solar minima suggest that both diffusion and drift-related effects are important in the outer heliosphere at this time and a proper interpretation of the intensity changes and latitudinal gradients must take both into account. These effects will be discussed in Sect. 3.6.

3.5. Recurrent Phenomena in the Outer Heliosphere at Solar Minimum: Period 1996–1997

Energetic Particles. The Voyager 1 and Voyager 2 traces in Fig. 8 show that during 1995 to late 1998 intensities of $\simeq$1 MeV protons remain, for the most part, near instrumental background levels. Intensity rises in late 1998 at both Voyager 1 and Voyager 2 are apparently signatures in the outer heliosphere of new solar activity starting in late 1997 (note the intensity increases at IMP 8 in 1997–1998). However, there are modest increases during 1995 and 1997 at Voyager 2 that are of a quasi-recurrent nature.

Figure 14 shows an expanded view of Voyager 2 LECP and PLS observations during 1996.8–1997.5, when Voyager 2 was at $\simeq$51 AU, 21°S latitude (time tics are at 26-day intervals). From top to bottom, we see: intensities of four $Z \geq 1$ ion channels, covering 43-540 keV (5-day averages); intensity of protons 0.52–1.45 MeV (1-day averages); and, solar wind speed from PLS instrument (1-hour averages). The five dashed vertical lines mark rapid ($\simeq$1–2 hour) rises in solar wind speed, all of which occur either at the peaks (*i.e.*, the 1^{st}, 2^{nd} and 4^{th} cases) or at the onsets (3^{rd} and 5^{th} cases) of $\simeq$1 MeV proton intensity increases. The Voyager 2 1997 plasma data are discussed in greater detail by Lazarus *et al.* (1999).

The five peaks evident in the $\simeq$1 MeV protons are seen as well in the four $Z \geq 1$ ion intensities in the top panel. As during 1994 at Voyager 2, these non-dispersive, quasi-recurrent energetic ion increases are associated with modest but

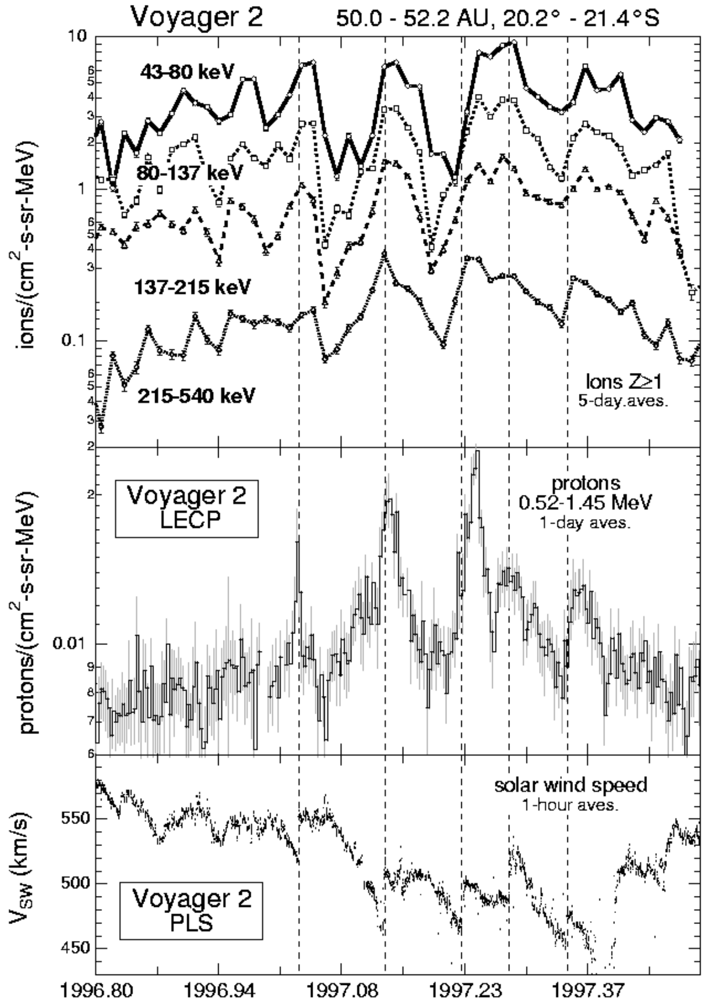

Figure 14. Voyager 2 data during 1996.8–1997.5. *Top panel:* From top to bottom 5-day averages of $Z \geq 1$ ion intensities, 43–540 keV, from LECP. *Middle panel:* 1-day averages of protons, 0.52–1.45 MeV, from LECP; shaded error bars are two standard deviations. *Bottom panel:* 1-hour averages of solar wind speed, from PLS.

impulsive, albeit not necessarily MIR shock-associated, jumps in solar wind bulk flow. Again, it is not clear from these data alone whether (a) the energetic ions are being accelerated locally by shocks, or (b) whether the MIR shocks have long since decayed and what we are observing is the remnant energetic ion population tied to the convecting azimuthal IMF. However, the survey results discussed in Sect. 2 and summarized in Fig. 6 provide strong observational support for scenario (b). In this case the ions will undergo CIR shock acceleration out to 15–20 AU, and thereafter their transport into the outer heliosphere will involve convection, adiabatic deceleration, and spatial diffusion mediated by magnetic fluctuations that may well contribute to further acceleration by, *e.g.*, the second-order Fermi process.

However the situation is quite different for the cosmic ray components. The 3-day moving averages of 6–10 MeV/amu He^+ clearly show the continuous presence of $\simeq$26 day periodic variations in the Voyager 1 data over this 3.4 interval year and their apparent absence in the Voyager 2 observations. The Voyager 1 periodicities also occur in the other galactic and anomalous cosmic ray components but are strongest near 6 MeV/amu in the region of the peak of the He^+ energy spectrum. There does not appear to be a consistent relation between the variations in cosmic ray intensity (Fig. 15) and the variations in solar wind speed at Voyager 2 (Fig. 14), but two of the five rapid rises in solar wind speed observed at Voyager 2 (1997.22 and 1977.30) are in reasonable close association with short term modulation events.

The difference between the Voyager 1 and Voyager 2 observations may reflect the actual heliomagnetic latitude of the two spacecraft with respect to the heliospheric current sheet. In 1997.0, Voyager 1 is at a nominal heliolatitude of 34°N and Voyager 2 is at 17°S. However the 1994–1995 Ulysses cosmic ray studies during the fast latitude scan indicated a displacement of the surface of symmetry of the modulation by about 10°S of the heliographic equation (Simpson *et al.*, 1996; Heber *et al.*, 1996). If this shift was present in the outer heliosphere and persisted through 1998.4, then Voyager 2 would be appreciably closer to the heliographic equator.

Studies of the long-term modulation of galactic and anomalous cosmic rays over this period (McDonald *et al.*, 1998) indicate that the recovery rate observed at Voyager 1 and Voyager 2 are remarkably similar. This would argue that the 26-day variations observed at Voyager 1 do not have any significant effect on the long-term modulation of cosmic rays.

3.6. ROLE OF CIRS, GMIRS, AND OTHER STRUCTURES IN GLOBAL COSMIC RAY MODULATION: A MODELING PERSPECTIVE

The development and utilization of comprehensive models, especially time-dependent models within the framework of the standard transport theory, have been responsible for much progress in understanding the relative importance of the various mechanisms involved in cosmic ray modulation at different time scales. An important step in the modeling of *long-term modulation* was achieved when Le Roux and Potgieter (1990) illustrated that the general observed modulation features from 1985 to 1987 could be reproduced well by using the wavy heliospheric current sheet (HCS) as the *only* time-dependent parameter in a drift model that accounts for drift-related as well as diffusion and convective effects. Before and after this period the model was less successful, so that they concluded that drifts were of primary importance as long as the waviness of the HCS was moderate *i.e.* with 'tilt angles' $\alpha \leq (35 \pm 5)^\circ$. Because α is a good indicator of solar activity, this indicates that for several years around solar maximum the modulation is not drift 'dominated'.

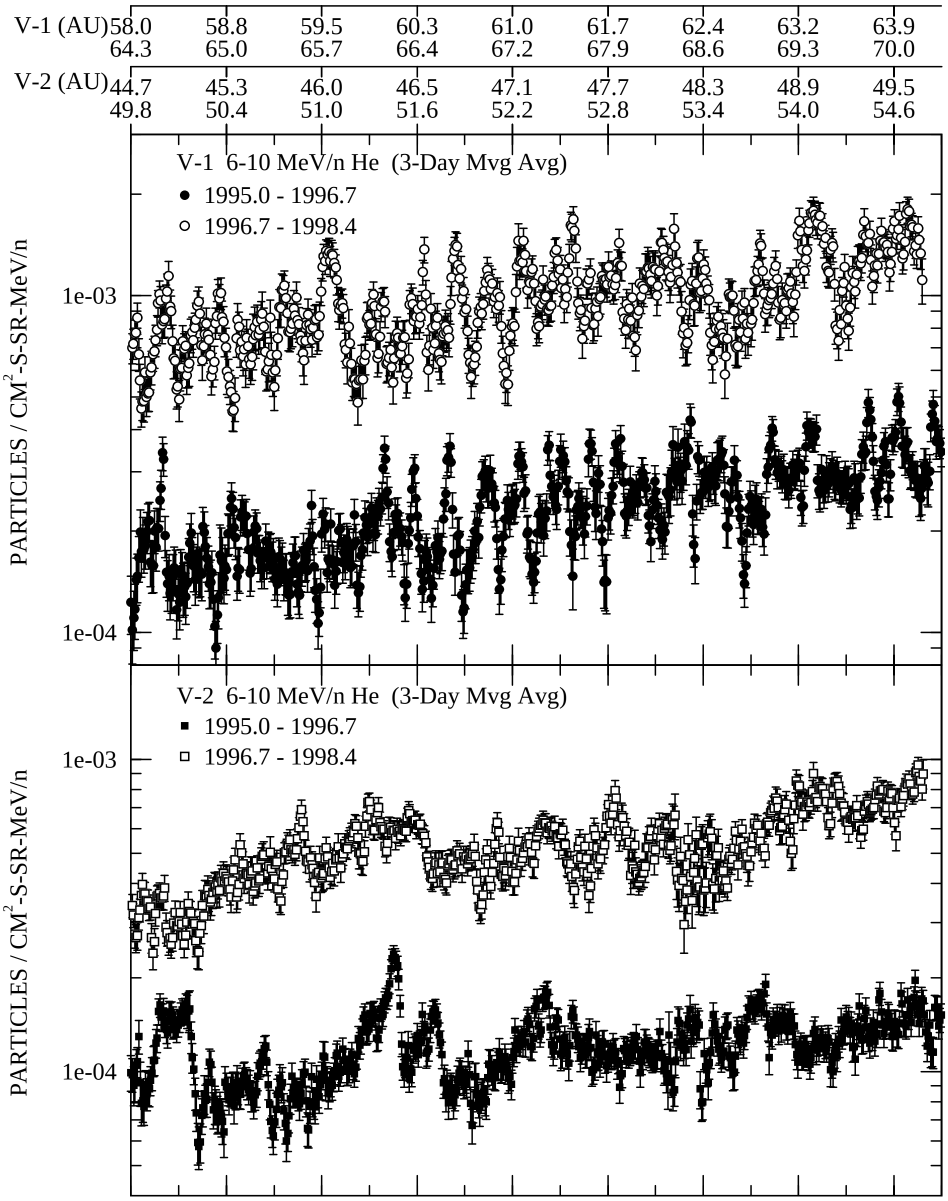

Figure 15. Time history (3-day moving average) of 6–10 MeV/amu anomalous cosmic ray helium as observed at Voyager 1 and Voyager 2 from 1995.0–1998.4.

The transition may happen either gradually (between 1984 and 1987.3, increasing drift effects) or rapidly (after 1987, decreasing drift effects), depending on the rate of change in global solar activity and therefore on global modulation conditions (Potgieter and Le Roux, 1992a; 1992b). A reason why the mentioned model was less successful after the 1987 solar minimum was that the deformation, together with the spatial evolution, of the wavy neutral current sheet were ignored. Once these effects were simulated it became evident that the net result was to produce less drift effects (Le Roux and Potgieter, 1992). It also clearly showed that more than just the changes in the HCS was necessary in the models to understand what happened to modulation during moderate to large solar activity periods.

From an observational point of view, the large and discrete steps in modulation, especially during periods of moderate to high solar activity, have been known since the 1960s (Lockwood, 1960). However, it was only in the 1980s that McDonald *et al.* (1981) had put new perspective on these phenomena and their role in long-term modulation. This stepwise modulation has clearly been detected by spacecraft out to beyond ~ 50 AU (*e.g.*, McDonald *et al.*, 1993; Van Allen, 1993). These steps are very prominent in the outer heliosphere, especially when solar activity exceeds moderate levels. Furthermore, these steps had occurred episodically during both magnetic cycles, whereas drift models predict an insensitivity to changes in the HCS during so-called $A > 0$ cycles. HCS drifts still occur, of course, but due to the direction of the drift velocity field, the wavy HCS 'surrenders' its dominance as an important modulating parameter. But, depending on the level of solar activity, global drifts together with the other main, and well-known, modulating mechanisms of diffusion, convection and adiabatic cooling still have a long-term effect, causing what may be considered the base-line of 11 and 22 year modulation cycles on which recurrent events of whatever size are superimposed.

Burlaga *et al.* (1985a; 1991; 1993) illustrated that one could attribute the modulation steps detected by the Voyager spacecraft to the passage of relatively long-lived shells with intense and disturbed magnetic fields, which emphasized the importance of these large-scale phenomena and that they ought to be taken into account in modulation studies. The concept of MIRs corresponds to the so-called propagating 'barriers' that were used in a time-dependent numerical model first by Perko and Fisk (1983), see also Perko (1993). The concepts of both a 'semi-steady-state barrier' (beyond the termination shock) and propagating 'time-dependent barriers' (inside the shock) as large-scale diffusive modulation features have been advanced by several authors, although with emphasis on different aspects (*e.g.*, Quenby *et al.*, 1990). The MIR concept for time-dependent, propagating 'barriers' seems to be the most plausible so far. It is clear that a new paradigm of CR modulation developed that incorporated both the effects of long-lived, large-scale transients moving through the outer heliosphere and that of gradient, curvature and HCS drifts. There had been three key elements in the evolution of this concept (see McDonald *et al.*, 1993; Potgieter *et al.*, 1993; Potgieter, 1994):

(i) The study of the temporal and spatial variations of galactic and anomalous

cosmic rays at multiple locations throughout the heliosphere.
(ii) The observations of large-scale transients in the interplanetary medium formed beyond 15 AU during periods of enhanced solar activity.
(iii) The development of global, time-dependent simulations (models) of the modulation process that allow detailed exploration of the effects of drifts with the changing inclination of the HCS, of the effects of large-scale disturbances moving out in the solar wind and of the consequences of combining both drifts and GMIRs.

The incorporation of GMIRs in global models gives a very natural and convincing explanation for the observed large step decreases in long-term modulation (Potgieter *et al.*, 1993; Potgieter and Le Roux, 1994). The simulation of two GMIRs, together with a decreasing 'tilt angle' for the HCS for both $A > 0$ and $A < 0$ epochs, illustrated that the effects of the 2 GMIRs could be completely different, but very significant, during the recovery phases of these polarity epochs. Le Roux and Potgieter (1995) showed, to the first order, that the main features of the complete 1977 to 1987 proton modulation cycle can be reproduced with a HCS-drift model combined with 4 major GMIRs which was the number observed during that cycle. Each simulated GMIR was assumed to affect the CR intensity for a maximum of two years, so that long-term modulation for the first and last 2–3 years of the 1977→1987 simulated cycle was totally controlled by the changing HCS. The peaked profile for the $A < 0$ polarity epoch, in contrast to the plateau-like profile of the $A > 0$ epoch, is a characteristic feature of drift models. From this it became evident that an *extended* CR intensity-time plateau region, as observed from 1972→1978, does not necessarily have to occur again during the present $A > 0$ epoch, which seems to be the case. A plateau-like region should, however, be seen when solar activity approaches minimum values and drift effects become important. For more detail, see the review by Potgieter (1995). The parameters that are important to GMIRs were discussed in detail by Potgieter and Le Roux (1994) and Haasbroek *et al.* (1995).

Potgieter and Le Roux (1994) emphasize that the simulated GMIRs give a very natural and convincing explanation for the observed large step decreases in CR modulation and that without drifts, and without GMIRs, the simulation of long-term modulation becomes inadequate, implying that the combination of drifts and GMIRs is essential in explaining long-term modulation over 11- and 22-year cycles. The combination of drifts and GMIRs in one comprehensive model provides the best theoretical simulation of complete 11 year and 22 year CR modulation cycles so far.

Other types of MIRs were found to be of secondary importance in long-term modulation modeling but cannot be neglected (Le Roux and Potgieter, 1995). A series of these effects, and for that matter also CIRs with a relatively large spatial extent, can influence modulation on a time-scale of a year or even more. They can moderate the recovery (or enhance the long-term decrease rate) of cosmic rays as apparently happened in 1993–94. For this to be effective, the modeling indicates that a whole series of CIRs has to occur, and they should be relatively large recurrent structures; a few small structures will have no effect, at least not on what can be considered long-term modulation.

4. The Origin of Recurrent Non-Dispersive Particle Enhancements in the Outer Heliosphere

J. R. JOKIPII, R. B. DECKER, and P. R. GAZIS

The Voyager 1 and Voyager 2 spacecraft both observed non-dispersive quasi-recurrent energetic ion increases at low to moderate heliographic latitudes ($\leq 35°$) at large distances from the Sun. These energetic particle enhancements were observed at heliocentric distances as great as 45 AU. As discussed in Sect. 3 in the discussion for Figs. 9, 10, 11, 12, and 14, these events were correlated with increases in solar wind speed. They resemble the energetic particle enhancements associated with shock acceleration closer to the Sun ($\leq$ 15 AU). But there is little evidence for corotating interplanetary shocks at these large heliocentric distances and the origin of these events has yet to be explained. This constitutes an important unsolved problem in the outer heliosphere.

Observational studies of the evolution of interplanetary shocks at heliocentric distances less than $\simeq$15 AU (Smith and Wolfe, 1976; Mihalov and Wolfe, 1979; Gazis, 1984; Gazis *et al.*, 1985; Dryer, 1987; Mihalov, 1987). These studies suggest while some transient events can persist to large distances from the Sun, shocks associated with CIRs and their successors decline in frequency and strength at heliocentric distances greater than $\simeq$4–5 AU.

There are very few reports of direct observations of corotating shocks at heliocentric distances greater than $\simeq$15 AU. Smith *et al.* (1985) conducted a survey of interplanetary events at heliocentric distances up to 30 AU, but most of the shocks they observed were associated with transient events. Burlaga (1994) conducted a survey of shocks observed at Voyager 2 between 1986 and 1989 as that spacecraft traveled between 18.9 and 30.2 AU. Only 5 shocks were observed at Voyager 2 during this time period. Three of these shocks were very weak ($M_A < 1.5$) while one of the remaining events occurred in association with a global merged interaction region and may have been associated with a transient event. Lazarus *et al.* (1999) reported that many events observed at Voyager 2 near 45 AU that resemble shocks do not appear to be shocks upon closer examination.

Observations such as these suggest that corotating shocks are rare at large heliocentric distances, and should not be a significant source of particle acceleration. This suggests two possibilities: 1) Some particles may accelerated in the outer heliosphere in the absence of shocks. 2) The energetic particle enhancements observed in the outer heliosphere are remnants of shock acceleration events that occurred closer to the Sun.

We consider the conditions under which diffusive shock acceleration may occur. The point is that a shock in nature is not really discontinuous, but has a characteristic scale $L_{\rm sh}$ over which the fluid velocity changes. Clearly, if $L_{\rm sh}$ is small enough, the shock can be regarded as discontinuous, and particles will be efficiently accelerated, whereas if $L_{\rm sh}$ is too large, the particles will simply see a slow change in velocity and not be much accelerated.

Clearly, then, for acceleration to occur in this shock, the shock scale $L_{\rm sh}$ must be smaller than a characteristic scale of the diffusive motion of the particle. There are three length scales which might be relevant. These are the particle gyro-radius in the average local magnetic field, $r_{\rm g}$, the diffusive scattering mean free path, λ and the diffusion length, $L_{\rm diff} = \kappa_{xx}/U_{x,1}$, where we take x to be the direction normal to the shock front and $U_{x,1}$ is the upstream flow speed normal to the shock. The question to be answered is which scale determines the effect of the shock on the particles?

To answer this, first note that in diffusive shock acceleration is described well by the Parker (Parker, 1965) transport equation for the pitch-angle-averaged distribution function $f(\mathbf{r}, p, t)$ as a function of position $\mathbf{r}$, particle momentum p, and time t, in a fluid moving with velocity $\mathbf{U}(\mathbf{r}, t)$. The equation may be written as

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}^{(S)} \frac{\partial f}{\partial x_j}\right] - \mathbf{U} \cdot \nabla f - \mathbf{V_d} \cdot \nabla f + \frac{1}{3}\nabla \cdot \mathbf{U}\left[\frac{\partial f}{\partial \ln(p)}\right] + Q \tag{1}$$

where the successive terms on the right-hand side correspond to diffusion, convection, particle drift, adiabatic cooling or heating and any local source Q. Here, for particles of speed w, momentum p and charge q, and scattering time somewhat greater than the gyroperiod, the drift velocity is

$$\mathbf{V_d} = \frac{pcw}{3q}\,\nabla \times \left[\frac{\mathbf{B}}{B^2}\right] \tag{2}$$

where c is the speed of light and $\kappa_{ij}^{(S)}$ is the symmetric part of the diffusion tensor, corresponding to the diffusive random walk of the particles. In general, we may write $\kappa_{ij}^{(S)}$ in terms of the magnetic field components B_i and $\kappa_{\|}$ and $\kappa_{\perp}$, the diffusion coefficients parallel and perpendicular to it, as

$$\kappa_{ij}^{(S)} = \kappa_{\perp}\delta_{ij} - \frac{\left(\kappa_{\perp} - \kappa_{\|}\right) B_i B_j}{B^2}\ . \tag{3}$$

Because of the general nature of the transport equation, it may be applied equally well to perpendicular and parallel shocks. Notice that the gyroradius r_g and mean free path λ do not appear in this equation and hence are not relevant. Indeed, it may be shown that the solutions to this equation for a velocity profile corresponding to a planar shock with velocity scale $L_{\rm sh}$ approach the standard diffusive shock acceleration solutions for the case

$$L_{\rm diff} \ll L_{\rm sh} \tag{4}$$

whereas in the opposite limit, the particles are simply compressed adiabatically as the gas is compressed in the decreasing flow.

If the diffusion limit is inapplicable (*e.g.*, for example, if the particle speeds are small compared with $U_{x,1}$) then one of the other scales, the gyroradius or scattering mean free path must be considered. It remains to be determined which of these distance scales is appropriate. A detailed survey of shock-like structures in the outer heliosphere will be required to determine if these structures could be associated with particle acceleration.

If the energetic particle enhancements observed in the outer heliosphere are not generated locally, but are remnants of shock acceleration events that occurred closer to the Sun ($\leq$15–20 AU), their transport into the outer heliosphere will involve convection and adiabatic deceleration, and spatial diffusion mediated by magnetic fluctuations. Magnetic fluctuations may also contribute to further acceleration by the 2nd-order Fermi process. It is clear that we need to take a fresh look at the available energetic ion data from the perspective that shock acceleration may well have ceased beyond 10–15 AU, take a careful look at intensity and energy spectral variations as a function of radial distance, and compare these results against theoretical expectations.

5. Conclusions

P. R. GAZIS and R. B. DECKER

CIRs and their successors continue to evolve as they are convected to greater heliocentric distances. A succession of different types of structure are observed at increasing distance from the Sun. Most of the structures observed at heliocentric distances less than 15–20 AU appear to be corotating. CIRs are a dominant structure between 2–8 AU. Between 8–12 AU, CIRs are replaced by MIRs. Between distances of $\simeq$12 AU and 15–20 AU, shocks decline in frequency and strength and MIRs are replaced by corotating pressure enhancements.

At heliocentric distances greater than approximately 15–20 AU, two different types of structure are observed. In the vicinity of the solar equator, both Pioneer 10 and Voyager 2 observed broad and non-periodic enhancements in solar wind density and temperature during which solar wind speed remains constant. These may be remnants of the corotating structures that are observed close to the Sun, but the lack of periodicity also suggests that they might be related to temporal variations at the solar wind source region. At higher heliographic latitudes, Voyager 2 observed periodic enhancements in solar wind temperature and speed during which solar wind density remained constant. The cause of these differences is also an unsolved question. It may be related to latitudinal gradients, solar cycle variations, or the effect of pickup ions at Voyager 2.

Energetic particle enhancements, similar to those that are associated with shocks, are observed at heliocentric distances as great as 45 AU during the decline phases of solar cycles 21 and 22. These energetic particle enhancements were associated with enhancements in the H/He ratio of 15–30, which is similar to the enhancement in H/He associated with reverse shocks at smaller heliocentric distances. The origin of these particle enhancements remains to be determined, as there is little evidence for corotating shocks at these heliocentric distances. Such jumps in solar wind and IMF parameters as occurred were not always correlated or discontinuous. It may be that these events were still sufficiently narrow that some particle acceleration occurred. Another possibility might be that the particle enhancements observed at large heliocentric distances are associated with events that occurred closer to the Sun.

Near the 1986 and 1997 solar minima, energetic particle enhancements disappear, but periodic cosmic ray modulations were observed with periods in the vicinity of 26 days. These events were often anti-correlated with B. These events appear to be associated with the low inclination of the HCS.

References

Barnes, C. W., and Simpson, J. A.: 1976, 'Evidence for Interplanetary Acceleration of Nucleons in Corotating Interaction Regions', *Astrophys. J.* **210**, L91–L96.

Bothmer, V., Marsden, R. G., Sanderson, T. R., Trattner, K. J., Wentzel, K.-P., Balogh, A., Forsyth, R. J., and Goldstein, B. E.: 1995, 'The Ulysses South Polar Pass: Transient Fluxes of Energetic Ions', *Geophys. Res. Lett.* **22**, 3369–3372.

Burlaga, L. F.: 1983, 'Corotating Pressure Waves without Fast Streams in the Solar Wind', *J. Geophys. Res.* **88**, 6,085–6,094.

Burlaga, L. F.: 1988, 'Interaction Regions in the Distant Solar Wind', *in* V. J. Pizzo, T. E. Holzer, and D. G. Sime (eds.), *Proc. Sixth Intern. Solar Wind Conf.*, Tech Note NCARR/TN-306, Natl. Cent. for Atmos. Res., Estes Park, Colo., pp. 547–562.

Burlaga, L. F.: 1994, 'Shocks in the Outer Heliosphere: Voyager 2 Observations from 18.9 AU to 30.2 AU (1986–1989)', *J. Geophys. Res.* **99**, 4,161–4,171.

Burlaga, L. F., Schwenn, R., and Rosenbauer, H.: 1983, 'Dynamical Evolution of Interplanetary Magnetic Fields and Flows between 0.3 and 8.5 AU: Entrainment', *Geophys. Res. Lett.* **10**, 413–416.

Burlaga, L. F., McDonald, F. B., Goldstein, M. L., and Lazarus, A. J.: 1985a, 'Cosmic Ray Modulation and Turbulent Interaction Regions near 11 AU', *J. Geophys. Res.* **90**, 12,027–12,039.

Burlaga, L. F., Pizzo, V. J., Lazarus, A. J., and Gazis, P. R.: 1985b, 'Stream Dynamics between 1 AU and 2 AU: A Comparison of Observations and Theory', *J. Geophys. Res.* **90**, 7,377–7,388.

Burlaga, L. F., McDonald, F. B., Ness, N. F., and Lazarus, A. J.: 1991, 'Cosmic Ray Modulation: Voyager 2 Observations, 1987–88', *J. Geophys. Res.* **96**, 3,789–3,799.

Burlaga, L. F., McDonald, F. B., and Ness, N. F.: 1993, 'Cosmic Ray Modulation and the Distant Heliospheric Magnetic Field: Voyager 1 and 2 Observations from 1986 through 1989', *J. Geophys. Res.* **98**, 1–11.

Burlaga, L. F., Ness, N. F., Belcher, J. W., Szabo, A., Isenberg, P. A., and Lee, M. A: 1994, 'Pickup Protons and Pressure-Balanced Structures: Voyager 2 Observations in Merged Interaction Regions near 35 AU', *J. Geophys. Res.* **99**, 21,511–21,524.

Burlaga, L. F., Ness, N. F., and Belcher, J. W.: 1997, 'Radial Evolution of Corotating Merged Interaction Regions and Flows between 14 AU and 43 AU', *J. Geophys. Res.* **102**, 4,661–4,671.

Christon, S. P., and Stone, E. C.: 1985, 'Latitude Variation of Recurrent MeV-Energy Proton Flux Enhancements in the Radial Range 11 to 20 AU and Possible Correlation with Solar Coronal Hole Dynamics', *Geophys. Res. Lett.* **12**, 109–112.

Cummings, A. C., and Stone, E. C.: 1988, 'Composition Gradients and Temporal Variations of the Anomalous Cosmic Ray Component', *in* V. J. Pizzo, T. E. Holzer, and D. G. Sime (eds.), *Proc. Sixth Intern. Solar Wind Conf.*, Tech Note NCARR/TN-306, Natl. Cent. for Atmos. Res., Estes Park, Colo., pp. 599–614.

Cummings, A. C., Blake, J. B., Cummings, J. R., Fränz, M., Hovestadt, D., Klecker, B., Mason, G. M., Mazur, J. E., Mewaldt, R. A., Stone, E. C., and Webber, W. R.: 1995, 'Radial and Latitudinal Gradients of Anomalous Cosmic Ray Oxygen throughout the Heliosphere', *Proc. 24th Intern. Cosmic Ray Conf.* **4**, 800.

Decker, R. B., Pesses, M. E., and Krimigis, S. M.: 1981a, 'Shock-Associated Low Energy Ion Enhancements Observed by Voyagers 1 and 2', *J. Geophys. Res.* **86**, 8,819–8,831.

Decker, R. B., Krimigis, S. M., and Kane, M.: 1981b, 'Spatial Gradients, Energy Spectra, and Anisotropies of 330 keV Ions at CIR Shocks from 1 to 50 AU', *Proc. 24th Intern. Cosmic Ray Conf.*, **4**, 421.

Dryer, M.: 1987, 'Study of Travelling Interplanetary Phenomena Report', *Sol. Phys.* **114**, 407.

Gazis, P. R.: 1984, 'Observations of Plasma Bulk Parameters and the Energy Balance of the Solar Wind between 1 and 10 AU', *J. Geophys. Res.* **89**, 775–785.

Gazis, P. R.: 1987, 'Solar Wind Stream Structure at Large Heliocentric Distances: Pioneer Observations', *J. Geophys. Res.* **92**, 2,231–2,242.

Gazis, P. R.: 1996, 'Long-Term Enhancements in Solar Wind Speed', *J. Geophys. Res.* **101**, 415–424.

Gazis, P. R.: 1997, 'The Latitudinal Structure of the Solar Wind in the Vicinity of the Solar Equator near Solar Minimum: 1986 and Predictions for 1997', *Geophys. Res. Lett.* **24**, 627–630.

Gazis, P. R., Lazarus, A. J., and Hester, K.: 1985, 'Shock Evolution in the Outer Heliosphere: Voyager and Pioneer Observation', *J. Geophys. Res.* **90**, 9,454–9,460.

Gazis, P. R., Barnes, A., and Lazarus, A. J.: 1988, 'Intercomparison of Voyager and Pioneer Observations', *in* V. J. Pizzo (ed.), *Proc. Sixth Intern. Solar Wind Conf.*, Tech. Note NCAR/TN-306, Natl. Cent. for Atmos. Res. Boulder, Colo., pp. 533–576.

Gazis, P. R., Mihalov, J. D., Barnes, A., Lazarus, A. J., and Smith, E. J.: 1989, 'Pioneer and Voyager Observations of the Solar Wind at Large Heliocentric Distances and Latitudes', *Geophys. Res. Lett.* **3**, 223.

Gloeckler, G., Geiss, J., Balsiger, H., Fisk, L. A., Galvin, A. B., Ipavich, F. M., Ogilvie, K. W., von Steiger, R., and Wilken, B.: 1993, 'Detection of Interstellar Pick-up Hydrogen in the Solar System', *Science* **261**, 70–73.

Gloeckler, G., Geiss, J., Roelof, E. C., Fisk, L. A., Ipavich, F. M., Ogilvie, K. W., Lanzerotti, L. J., von Steiger, R., and Wilken, B.: 1994, 'Acceleration of Interstellar Pickup Ions in the Disturbed Solar Wind Observed on Ulysses', *J. Geophys. Res.* **99**, 17,637–17,643.

Gold, R. E., Decker, R. B., Krimigis, S. M., Lanzerotti, L. J., and Maclennan, C. G.: 1988, 'The Latitude and Radial Dependence of Shock Acceleration in the Heliosphere', *J. Geophys. Res.* **93**, 991–996.

Goldstein, B. E., and Jokipi, J. R.: 1977, 'Effects of Stream-Associated Fluctuations upon the Radial Evolution of Average Solar Wind Parameters', *J. Geophys. Res.* **82**, 1,095–1,105.

Gosling, J. T., Hundhausen, A. J., and Bame, S. J.: 1976, 'Solar Wind Stream Evolution at Large Heliocentric Distances: Experimental Demonstration and the Test of a Model', *J. Geophys. Res.* **81**, 2,111–2,122.

Gosling, J. T., Asbridge, J. R., Bame, S. J., and Feldman, W. C.: 1978, 'Solar Wind Stream Interfaces', *J. Geophys. Res.* **83**, 1,401–1,412.

Gosling, J. T., and Pizzo, V. J.: 1999, 'Formation and Evolution of CIRs and Their 3-D Structure', *Space Sci. Rev.*, this volume, 21–52.

Haasbroek, L. J., Potgieter, M. S., and Le Roux, J. A.: 1995, 'A Computer Simulation of Large Cosmic Ray Decreases and Their Effects on the Declining Modualtion Cycle', *Adv. Space Res.* **9**, 209–212.

Heber, B., Dröge, W., Kunow, H., Müller-Mellin, R., Wibberenz, G., Ferrando, P., Raviart, A., and Paizis, C.: 1996, 'Spatial Variation of $>$106 MeV Proton Fluxes Observed during the Ulysses Rapid Latitude Scan: Ulysses COSPIN/KET Results', *Geophys. Res. Lett.* **23**, 1513–1516.
Krimigis, S. M., Armstrong, T. P., Axford, W. I., Bostrom, C. O., Fan, C. Y., Gloeckler, G., and Lanzerotti, L. J.: 1977, 'The Low Energy Charged Particle (LECP) Experiment on the Voyager Spacecraft', *Space Sci. Rev.* **21**, 329–354.
Krimigis, S. M., Decker, R. B., McNutt, R. L., Venkatesan, D., Hamilton, D. H., and Collier, M.: 1995, 'Energetic Particle Activity in the Heliosphere, 1991–1995', *Proc. 24th Intern. Cosmic Ray Conf.* **4**, 401.
Krimigis, S. M., Decker, R. B., Hamilton, D. H., and Hill, M. E.: 1997, 'Energetic Ions in the Outer Heliosphere, 1992–1997', *Proc. of the 25th Intern. Cosmic Ray Conf.* **1**, 393.
Lanzerotti, L. J., Gold, R. E., Anderson, K. A., Armstrong, T. P., Lin, R. P., Krimigis, S. M., Pick, M., Roelof, E. C., Sarris, E. T., Simnett, G. M., and Frain, W. E.: 1992, 'Heliosphere Instrument for Spectra, Composition, and Anisotropy at Low Energies', *Astron. Astrophys.* **92**, 349–363.
Lazarus, A., Richardson, J. D., Decker, R. B., and McDonald, F. B.: 1999, 'Voyager 2 Observations of Corotating Interaction Regions (CIRs) in the Outer Heliosphere', *Space Sci. Rev.*, this volume, 53–59.
Le Roux, J. A., and Potgieter, M. S.: 1990, 'A Time-dependent Drift Model for the Long-term Modulation of Cosmic Rays with Special Reference to Asymmetries with Respect to the Solar Minimum of 1987', *Astrophys. J.* **361**, 275–282.
Le Roux, J. A., and Potgieter, M. S.: 1992, 'The Simulated Features of Heliospheric Cosmic-Ray Modulation with a Time-Dependent Drift Model - IV. The Role of Heliospheric Neutral Sheet Deformation', *Astrophys. J.* **397**, 686–693.
Le Roux, J. A., and Potgieter, M. S.: 1995, 'The Simulation of Complete 11 and 22 Year Modulation Cycles for Cosmic Rays in the Heliopshere Using a Drift Model with Global Merged Interaction Regions', *Astrophys. J.* **442**, 847–851.
Lockwood, J. A.: 1960, 'An Investigation of the Forbush Decreases in Cosmic Radiation', *J. Geophys. Res.* **65**, 19.
Mason, G. M., von Steiger, R., Dwyer, J. R., Fisk, L. A., Gloeckler, G., Gosling, J. T., Hilchenbach, M., Kallenbach, R., Keppler, E., Klecker, B., Kunow, H., Mann, G., Richardson, I. G., Sanderson, T. R., Simnett, G. M., Wang, Y.-M., Wimmer-Schweingruber, R. F., Fränz, M., Mazur, J. E., and Richardson, I. G.: 1999, 'Origin, Injection, and Acceleration of CIR Particles: Observations', *Space Sci. Rev.*, this volume, 327–367.
McDonald, F. B., Lal, N., Trainor, J. H., van Hollebeke, M.R.I, Webber, W. R.: 1981, 'The Solar Modulation of Galactic Cosmic Rays in the Outer Heliosphere', *Astrophys. J.* **249**, L71–L75.
McDonald, F. B., and Selesnick, R. S.: 1991, 'Solar/Interplanetary Energetic Particles in the Outer Heliosphere', *Proc. 22nd Intern. Cosmic Ray Conf.* **3**, 193.
McDonald, F. B., Lal, N., and McGuire, R. E.: 1993, 'The Role of Drifts and Global Merged Interaction Regions in the Long-Term Modulation of Cosmic Rays', *J. Geophys. Res.* **98**, 1,243–1,256.
McDonald, F. B., Lal, N., and McGuire, R. E.: 1998, 'Cosmic Ray Recovery and Solar Minimum Phase of Solar Cycle 22: An Interim Report', *J. Geophys. Res.* **103**, 373–379.
Mihalov, J. D.: 1987, 'Heliospheric Shocks (Excluding Planetary Bow Shocks)', *Rev. Geophys.* **25**, 697–710.
Mihalov, J. D., and Wolfe, J. H.: 1979, 'Pioneer 10 Studies of Interplanetary Shocks at Large Heliocentric Distances', *Geophys. Res. Lett.* **6**, 491–494.
Mihalov, J. D., Barnes, A., Hundhausen, A. J., and Smith, E. J.: 1990, 'Solar Wind and Coronal Structure Near Sunspot Minimum: Pioneer and SMM Observations from 1985-1987', *J. Geophys. Res.* **95**, 8,231–8,242.
Parker, E. N.: 1965, 'The Passage of Energetic Charged Particles Through Interplanetary Space', *Planet. Space Sci.* **13**, 9.

Perko, J. S.: 1993, 'Solar Cycle Modulation of Galactic Cosmic Rays at High Heliographic Latitudes - A One-Dimensional Simulation', *J. Geophys. Res.* **98**, 1,235–1,241.

Perko, J. S., and Fisk, L. A.: 1983, 'Solar Modulation of Galactic Cosmic Rays - V. Time-Dependent Modulation', *J. Geophys. Res.* **88**, 9,033–9,036.

Potgieter, M. S.: 1993, 'Time-dependent Cosmic-Ray Modulation - Role of Drifts and Interaction Regions', *Adv. Space Res.* **13**, 239–249.

Potgieter, M. S.: 1994, *in* D. A. Leahy, R. B. Hicks and D. Venkatesan (eds.), *Modulation of Cosmic Rays in the Heliosphere*, World Scientific, Singapore.

Potgieter, M. S.: 1995, 'The Long-term Modulation of Galactic Cosmic Rays in the Heliopshere', *Adv. Space Res.* **16**, 191–203.

Potgieter, M. S., and Le Roux, J. A.: 1992a, 'The Simulated Features of Heliospheric Cosmic-ray Modulation with a Time-Dependent Drift Model - I. General Effects of the Changing Neutral Sheet over the Period 1985–1990', *Astrophys. J.* **386**, 336–346.

Potgieter, M. S., and Le Roux, J. A.: 1992b, 'The Simulated Features of Heliospheric Cosmic-Ray Modulation with a Time-Dependent Drift Model - III. General Energy Dependence', *Astrophys. J.* **392**, 300–309.

Potgieter, M. S., and Le Roux, J. A.: 1994, 'The Long-Term Heliospheric Modulation of Galactic Cosmic Rays According to a Time-Dependent Drift Model with Merged Interaction Regions', *Astrophys. J.* **423**, 817–827.

Potgieter, M. S., Le Roux, J. A., Burlaga, L. F. and McDonald, F. B.: 1993, 'The Role of Merged Interatcion Regions and Drifts in the Heliospheric Modualtion of Cosmic Rays beyond 20 AU; A Computer Simulation', *Astrophys. J.* **403**, 760–768.

Pizzo, V. J.: 1991, 'The Evolution of Corotating Stream Fronts near the Ecliptic Plane in the Inner Solar System - II. Three-Dimensional Tilted Dipole Fronts', *J. Geophys. Res.* **96**, 5,405–5,420.

Pizzo, V. J.: 1994a, 'Global Quasi-steady Dynamics of the Distant Solar Wind - I. Origins of North-South Flows in the Outer Heliosphere', *J. Geophys. Res.* **99**, 4,173–4,183.

Pizzo, V. J.: 1994b, 'Global Quasi-steady Dynamics of the Distant Solar Wind - II. Deformation of the Heliospheric Current Sheet', *J. Geophys. Res.* **99**, 4,185–4,191.

Quenby, J. J., Lockwood J. A., and Webber, W. R.: 1990, 'Cosmic-Ray Gradient Measurements and Modulation beyond the Inner Solar Wind Termination Shock', *Astrophys. J.* **365**, 365–371.

Richardson, J. D., Paularena, K. I., Belcher, J. W., and Lazarus, A. J.: 1994, 'Solar Wind Oscillations with a 1.3-Year Period', *Geophys. Res. Lett.* **21**, 1559–1560.

Sarris, E. T., Krimigis, S. M., Bostrom, C. O., and Armstrong, T. P.: 1978, 'Simultaneous Multi-spacecraft Observations of Energetic Proton Bursts Inside and Outside the Magnetosphere', *J. Geophys. Res.* **83**, 4,289–4,305.

Schwenn, R., Montgomery, M. D., Rosenbauer, H., Miggenrieder, H., Mühlhäuser, K.-H., Bame, S. J., Feldman, W. C., and Hansen, R. T.: 1978, 'Direct Observation of the Latitudinal Extent of a High-Speed System in the Solar Wind', *J. Geophys. Res.* **83**, 1,011–1,017.

Smith, E. J., and Wolfe, J. H.: 1976, 'Observations of Interaction Regions and Corotating Shocks between one and five AU: Pioneer 10 and 11', *Geophys. Res. Lett.* **3**, 137–140.

Smith, Z. K., Dryer, M., and Steinolfsen, R. S.: 1985, 'A Study of the Formation, Evolution, and Decay of Shocks in the Heliosphere between 0.5 and 30.0 AU', *J. Geophys. Res.* **90**, 217–220.

Simnett, G. M., Decker, R. B., and Roelof, E. C.: 1997, 'Confinement of Electrons Accelerated at Distant, High-Latitude Corotating Interaction Regions in the Inner Heliosphere', *Proc. 25th Intern. Cosmic Ray Conf.* **1**, 361.

Simpson, J. A.: 1998, 'Recurrent Solar Modulation of the Galactic and the Anomalous Nuclear Components in Three Dimensions of the Heliosphere', *Space Sci. Rev.* **83**, 7–19.

Simpson, J. A., Zhang, M., and Bame, S. J.: 1996, 'A Solar Polar North-South Asymmetry for Cosmic Ray Propagation in the Heliosphere: The Ulysses Pole-to-pole Rapid Transit', *Astrophys. J.* **465**, L69–L72.

Trainor, J. H., McDonald, F. B., Teegarden, B. J., Webber, W. R., and Roelof, E. C.: 1974, 'Energetic Particles in the Jovian Magnetosphere', *J. Geophys. Res.* **79**, 3,600–3,612.

Van Allen, J. A.: 1993, 'Recovery of Interplanetary Cosmic Ray Intensity Following the Great Forbush Decrase of Mid-1991', *Geophys. Res. Lett.* **20,** 2797–2800.

Webber, W. R., and Lockwood, J. A.: 1997, 'Intensities of Anomalous and Galactic Cosmic Rays in the Outer Heliosphere near the Heliospheric Equator in 1987 and during the Period from 1994 to 1996', *J. Geophys. Res.* **102**, 9,773–9,779.

Whang, Y. C.: 1998, 'Solar Wind in the Distant Heliosphere', *J. Geophys. Res.* **103**, 17,419–17,428.

Zhang , M. A.: 1997, 'Linear Relationship between the Latitude Gradient and 26-day Recurrent Variations in Fluxes of Galactic Cosmic Rays and Anomalous Nuclear Component: Observations', *Astrophys. J.* **488**, 841–853.

Zhang, M., Simpson, J. A., McKibben, R. B., Johns, T. S., Smith, E. J., and Phillips, J. L.: 1995, 'Ulysses Observations of 26-day Intensity Variation of Cosmic Rays and Anomalous Helium over the South Pole', *Proc. 24th Intern. Cosmic Ray Conf.* **4**, 956.

Zank, G. P., and Pauls, H. L.: 1997, 'Shock Propagation in the Outer Heliosphere - I. Pickup Ions and Gasdynamics', *J. Geophys. Res.* **102**, 7,037–7,049.

Address for Offprints: P. R. Gazis, MS 245-3, NASA Ames Research Center, Moffett Field, CA, 94035, USA