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The july 14th, 2000 "Bastille Day" solar event as observed by Voyagers 1 and 2 in the distant heliosphere

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Abstract. One of the most powerful solar events observed over the current cycle occurred at 1024 July 14, 2000 accompanied by an X-5.7 x-ray burst and a full halo coronal mass ejection that initially was traveling at a velocity of > 1700 km/s. At earth the solar energetic particle event was the largest so far in cycle 23. Some 177 days later (2001.02) at V-2 (63 AU, 24°S) there began a step decrease in the cosmic ray intensity (15% for 265 MeV/n GCR He) and a complex enhancement with multiple structure in the magnitude of the interplanetary magnetic field. For low-energy 2.3 MeV protons there was a 10-fold increase in intensity that tracks the increase in the solar wind velocity which reached a peak value of ~450 km/s. This event is discussed in the context of the increases in intensity of MeV ions and the modulation events for galactic and anomalous cosmic rays that have been observed in the distant heliosphere for solar cycle 23 through 2001.4.

1 Introduction

In the inner solar system the major disturbances observed in the interplanetary medium are shock waves associated with coronal mass ejections (CMEs) and fast co-rotating streams that originate from coronal holes on the sun. CMEs are the major manifestation of solar activity. These massive ejections of plasma from the sun generate interplanetary disturbances that can accelerate solar energetic particles and produce transient Forbush decreases in the cosmic ray intensity. At earth the larger CMEs can trigger strong geomagnetic storms and auroral displays. Near solar maximum they occur at a whole sun rate of about 3.5 events/day which decreases to ~0.1 events/day at solar minimum (Gosling, 1999). High speed co-rotating streams generally form a system of forward and reverse shocks beyond 1 AU that accelerate ions to MeV energies and also produce short term cosmic ray decreases.

In the outer heliosphere there is a superposition of these two solar related phenomena leading to the creation of a large-scale disturbance in the interplanetary medium–a global merged interaction region (GMIR). These long-lived systems form and evolve with increasing heliocentric distance. Through this process multiple individual solar events merge their identity into a collective whole, but one that may still reflect the properties of a single dominant CME.

GMIRs were originally identified in the Voyager magnetic field and plasma data by Burlaga (1984, 1985, 1993) as these spacecraft moved toward the outer heliosphere. GMIRs are a major element in producing the long-term (11 year) cosmic ray modulation (Burlaga, et al. 1991, 1993; le Roux and Potgieter, 1993; McDonald and Burlaga, 1997) and there is now strong evidence that the largest GMIRs continue to modulate cosmic rays for several years after they have crossed the termination shock and moved into the region of the heliosheath (McDonald et al., 2000) where they also produce low frequency 1.8 – 3.6 kHz radio emission (Gurnett and Kurth, 1996). These GMIRs appear to have an effective lifetime that can span a significant portion of a solar activity cycle. GMIRs also accelerate and transport MeV ions which provide a useful diagnostic tool for studying these systems.

For cycle 23 it is now possible to study GMIRs at much greater heliocentric distances (>80AU) at moderate latitudes in both the northern and southern hemisphere.

In this paper we study the increases of low energy ions (2.3 MeV) observed at V-1, V-2 along with the associated changes in the intensity of galactic and anomalous cosmic rays (GCR, ACR) over the period 1998-2001.4. Special attention is focused on the GMIR which is dominated by the large solar disturbance of July 14, 2000 (The Bastille day event) which produced the largest interplanetary disturbance and SEP event observed over the first 4 years of cycle 23. The V-1/2 interplanetary magnetic field data and the V-2 solar wind data are of special value in interpreting this event. The large GMIR of 2000.31 (at V2) is discussed in a companion paper at this conference (Burlaga, Ness and McDonald, 2001).

2 Observations

The 1998-2001.37 time histories of 1.8-2.8 MeV protons (5 day moving averages), 15 MeV/n anomalous cosmic ray helium (ACR He) and 265 MeV/n galactic cosmic ray He (GCR He) (26 day averages) and the daily solar wind velocities, V, (from the V-2 MIT PLS experiment) are shown in Fig. 1. Over this period there are only two increases of 2.3 MeV protons that rise significantly above the ambient counting rate (we have set a threshold for

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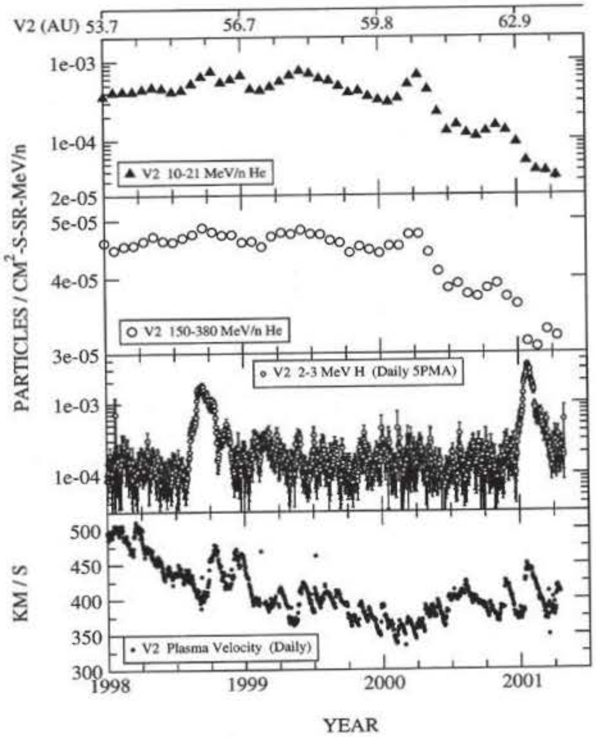

Fig. 1: Time histories of 10-21 MeV/n ACR H, 150-380 MeV/n GCR He (26 DAY AVG) and 2-3 MeV H (5 day moving averages From the Voyager 2 CRS Experiment; E. C. Stone, P.I.). The solar Wind velocities (daily averages) are from the Voyager-2 PLS Experiment; J. D. Richardson, P.I. Voyager 2 is at a heliolatitude of 24°S over this period. The 5 PMA for the 2-3 MeV protons (third paper) are 5 day moving averages

event definition at 6 x 10^{-4} P/cm^2-s-sr-MeV–some 4x the quiet-time level). The first event starts around 1998.6. The second event starting at 2001.00, is associated with the GMIR containing the Bastille-day CME (hereafter referred to as the Bastille-Day GMIR). The 1998 event has no effect on the galactic cosmic ray intensity while the second produces a 15% decrease in the GCR He intensity.

Over this 3.37 year period from solar minimum to close to solar maximum the GCR He at V-2 decreases by some 33% while the ACR He decreases by a factor of ~21. Nevertheless their relative modulation history over this period is very similar. There is one large modulation event beginning around 2000.31 that is the first cycle 23 large step decrease observed in the outer heliosphere. There are no associated solar wind or 2.3 MeV proton increases. However Burlaga, Ness and McDonald (2001) report the passage of a region of enhanced magnetic fields extending over a radial distance of ~15-20 AU with a good correlation between the strongest fields in the GMIR and the changes in the cosmic ray intensity.

At V-1 (Fig. 2) there are six increases in the proton intensity over the 3.37 year period and if the event threshold was decreased by some 25% there would be at least 3 more–suggesting there is an asymmetry in the solar activity between the northern and southern hemisphere. The first

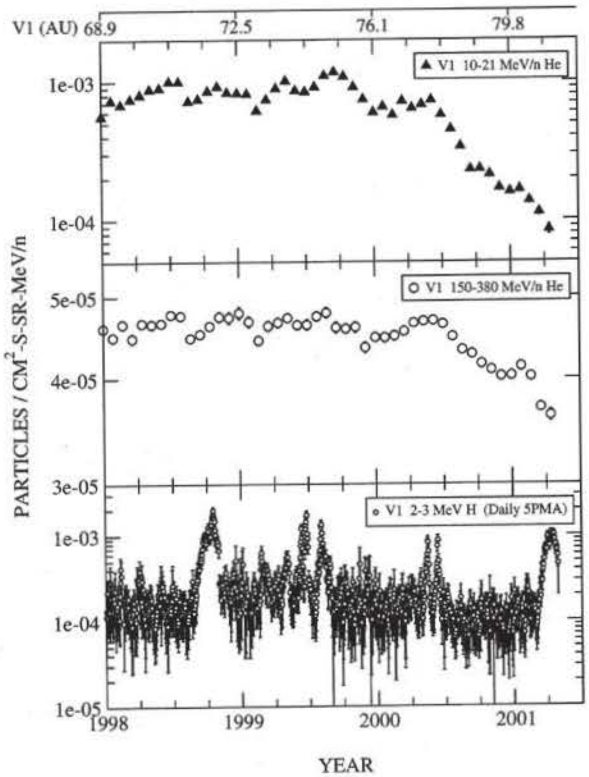

Fig. 2. Energetic particle data – same as for Fig. 1

and last of the V-1 events correspond to the two V-2 events with the expected delay of ~0.2 years. The two increases centered about 1999.53 are associated with small increases in the cosmic ray intensity that occur just prior to a modest step decrease in ACR He but which is barely discernible in the GCR component. The 4th and 5th low energy particle events centered about 2000.32 also occur just before the onset of the major modulation event (Burlaga et al., 2001). Preliminary studies indicate they may be associated with spike-like increases in the interplanetary magnetic field.

2.1 The Saga of the Bastille Day GMIR: The solar activity relating to the Bastille day event began with a flare at N 17 W 65 on 12 July 2000 that produced a sizeable ESP event. There was a second flare at 10:21 on 14 July followed by an X5.7 x-ray flare at N 22 W 07 on the 14th. The SOHO LASCO experiment observed a full halo-CME starting at 10:54 moving with an estimated velocity of 1700 km/s. Over a five day period starting on 13 July the experiments on the ACE spacecraft observed three shocks, four CMEs and three magnetic clouds. Whang et al. (2001) in a simulation of the solar wind structure observed at 1 AU found that by 4 AU this system had evolved into a large merged interaction region bounded by forward and reverse shocks.

To examine the nature and effects of the GMIR associated with the Bastille day GMIR in the distant heliosphere, expanded plots of the data of Figs. 1 and 2 are shown for that period along with the time histories of 4-8 MeV protons and of the magnitude of the interplanetary magnetic field at V-2 (Figs. 3 and 5). The 2-3 MeV and 4-8 MeV proton fluxes are 5 day moving averages. The 26 day averages of GCR and ACR He have been replaced by daily averages of the Pen rate which is the integral rate of ion > 70 MeV/n and electrons > 10 MeV. Also the 2.3 MeV H and solar wind velocity, V, are superimposed in the top panel of Fig. 3.

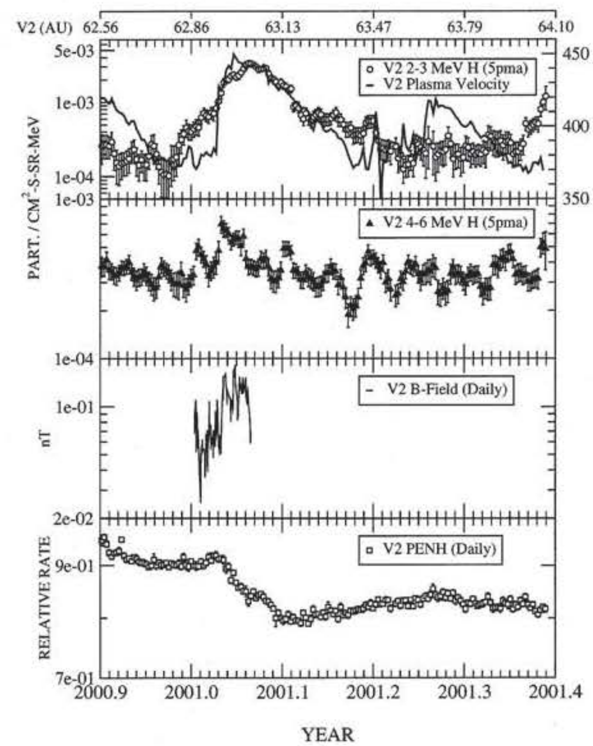

Fig. 3. Expanded time history of V-2 energetic particle, solar wind and magnetic field data. Note that the 2-3 MeV and 4-6 MeV H are 5 day moving averages plotted at the beginning of the averaging period. For relative comparisons, these data need to be shifted .007 years (.7 divisions) to the left.

Wang, Richardson and Burlaga (2001) have interpreted the 63 km/s increase in V on day 2001.032 as the passage of the shock associated with the Bastille day GMIR. The field magnitude jumped from 0.06 to 0.13 nT and they found a density compression ratio of about 1.9. A rapid cosmic ray decrease (Fig. 3) starts some 3.5 days later coincident with the first major spike in the magnetic field strength, B. A gradual increase in 2.3 MeV protons begins some 21 days before 2001.03. There is no significant change in this component at the time of shock passage. The peak intensity occurs some 12 days after day 2001.03. Their subsequent decay in intensity as well as the rate of change in the cosmic ray intensity follows closely the decrease in V.

There is an increase in the flux of 4-6 MeV protons (second panel Fig. 3) near 2001.032 which suggests that the shock is further accelerating the energetic protons trapped in the GMIR. The He increases (not shown), even at the lowest energies, are small (H/He = 78 ± 20 at 1.8–2.8 MeV/n). The changes in ACR H and He at energies > 10 MeV reflect the fact that they are being swept outward by the GMIR in the same manner as the GCRs (Fig. 1).

At this time the V-1 data set for this event is still incomplete. The available data (Fig. 4) shows the initial arrival of 2.3 MeV H at 2001.17 followed by an 8x increase in intensity. There is a second sharp increase that peaks at 2001.355 (with no change in the > 70 MeV integral rate) that may mark the passage of the reverse shock. The changes in the GCR He and integral rate of ions > 70 MeV is essentially the same at V-1 and V-2. The peak intensity of 2.3 MeV protons is ~50% higher at V-2 (63 AU) than at V-1 (80 AU), suggesting the presence of a stronger GMIR at the V-1 heliolatitude since a much larger decrease is expected between 63 and 80 AU.

3 Discussion

The rate of occurrence and time histories of the MeV ions increases in the distant heliosphere in cycle 23 through 2001.4 is very different from that observed earlier for the solar active periods of cycle 21 and 22. From 1978 to 1986 as Pioneer 10 moved from 14 to 32 AU there were continual increases in the flux of 4 MeV protons with this component

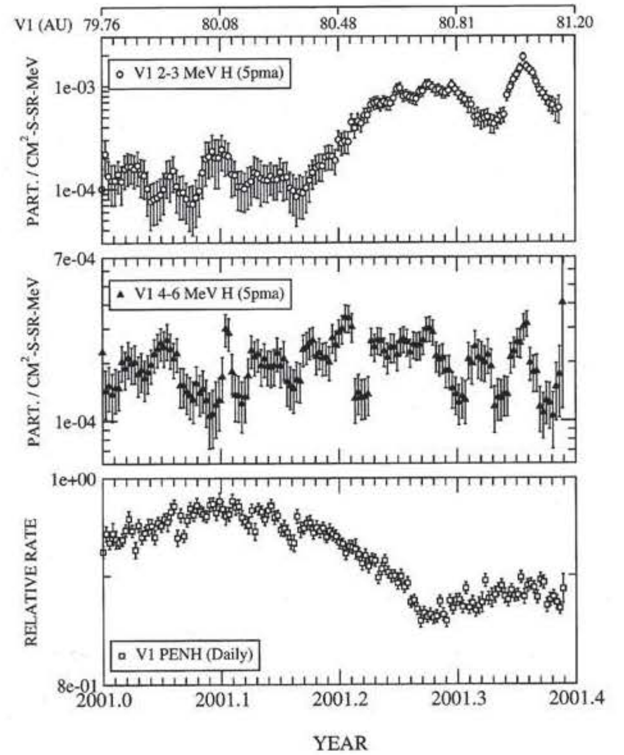

Fig. 4. Expanded time history of the V-1 energetic particle data for the Bastille day GMIR.

almost always being above the quiet time level (McDonald and Selesnick, 1991). At higher energies (15 MeV H) Dröge et al., 1992 interpreted these as super events associated with GMIRs, with local acceleration, trapping and solar energetic particles being key factors in their formation. Because of this combination of factors we will refer to these ions as S/IP (solar/interplanetary) particles.

From 1988-1993 the CRT and CRS experiments on Pioneer 10 and the Voyagers between 28 and 53 AU found that all of the activity of cycle 22 (the 2nd most active cycle on record) had evolved into 5 large systems, each of which were remarkably similar at widely different locations (McDonald et al., 1994). At lower energies (>0.5 MeV) the Voyager LECP (Krimigis et al., 1995) observed six events over this period. There was a steady decrease in the maximum amplitude of individual events with increasing heliocentric distance that was consistent with an average gradient on the order of 10% AU (McDonald and Selesnick, 1991). The large S/IP events in the outer heliosphere generated by the September-October, 1989 and March/June 1991 periods of exceptional solar activity indicate, as would be expected, that the cumulative magnitude of this activity is an important factor. Both the Voyager LECP and CRT, and Pioneer CRT data found an almost total absence of S/IP particles over solar minimum.

The V-1, V-2 S/IP event in 1998 has been extensively studied (Burlaga and Ness, 2000; Lockwood and Webber, 1999; Decker et al., 1999; McDonald et al., 2000). At V-2 (56 AU, 24°S) and V-1 (72 AU, 34°N) there are increases of 2.3 MeV protons starting at 1998.65 and 1998.7 that mark the passage of a large interplanetary disturbance that was most probably associated with the solar activity of April-May, 1998. It produced no durable decrease in the intensity of galactic or anomalous cosmic rays. At V-2 there is a precursor increase in the ACR and S/IP protons just before the arrival of large increases in the interplanetary magnetic field. This "snow plow" event was interpreted as evidence that reacceleration of anomalous cosmic rays can occur in the outer heliiosphere. At V-1 the S/IP event coincides with the increases in B, a much different relationship than that observed at V-2.

At the time of the 14 July event there was a remarkable alignment in heliolongitude with the CME source being close to central meridian and the two Voyagers being within a few degrees of the earth's heliolongitude. The effects of the Bastille day GMIR appears to be what is expected of a moderate sized GMIR in the distant heliosphere. At 1 AU the CME had a flow speed of ~1100 km/s, and maximum value of $B = 60$ nT. At 63 AU almost 6 months later, $V =$ 445 km/s and the peak fields are on the order of 0.18 nT, the peak flux of 2.3 MeV protons is some 300x smaller than that of the March/June 1991 GMIR at 46 AU and the GCR He decrease is 15%. This attenuation of the effects of the GMIR is due to the important role of pick-up ions which dominate the internal energy of the solar wind, decrease V and play an important role in shock propagation in the distant heliosphere (Burlaga et al., 1994; Zank and Pauls, 1997; Whang, 1998; Wang et al., 2001).

For the March/June 1991 GMIR McDonald et al. (2000) observed a strong flow of 30-60 MeV ACR into the heliosphere which they interpreted as marking the crossing of the GMIR into the region of the heliosheath. The timing of this flow relative to the passage of the GMIR gave a value of the location of the termination shock at 85.7 ± 7 AU. Webber et al. 2001 examined the intensity-time profile of an outward moving transient decrease of ACR and GCR. They compared the V-1 observations with the profiles obtained by le Roux and Fichtner who used numerical simulations of the time dependent cosmic ray modulation produced by the passage of large GMIRs out to the termination shock. Webber et al. estimated that the termination shock was located at 83.2 ± 0.6 AU. It will be interesting to observe the cosmic ray response at the Voyagers as the Bastille day GMIR crosses the termination shock.

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