SH3.2.03

Propagation of the Onset of Modulation in Cycle 23 from 1 to 72 AU

R.B. McKibben[1], R.B. Decker[2], S.M. Krimigis[2], C. Lopate[1], J.A. Simpson[1], and M. Zhang[1]

[1]*Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*

[2] *Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, 20723, USA*

Abstract

In late 1997, the modulation of galactic cosmic rays at 1 AU began to increase in response to increasing solar activity. We report observations of the onset of modulation from spacecraft ranging from *IMP-8* and *Ulysses* near the ecliptic at 1 AU and 5 AU respectively out to *Voyager 1* and *2*, in the northern and southern solar hemispheres at radii beyond 55 AU, to test whether specific features of the modulation onset can be identified and traced from *IMP* to *Voyager*. We find that, though the onset of modulation occurs throughout the heliosphere at times consistent with outward propagation between 400 and 800 km/s, specific features are difficult to trace from *IMP* and *Ulysses* to *Voyager*.

1 Introduction:

During the recent solar minimum and the onset of new modulation, the fleet of heliospheric spacecraft composed of *IMP-8*, *Ulysses*, *Voyager 1*, and *Voyager 2* has provided the most extensive network ever available for a study of global modulation throughout the heliosphere. Of particular interest, given the current understanding of the 3-dimensional nature of heliospheric modulation enforced by *Ulysses* observations, is the way in which changes in modulation propagate through the heliosphere.

2 Instrumentation:

Figure 1 shows the locations on January 1, 1999 of the spacecraft used in this study. During the period of this analysis (1997.0 - 1999.3) *Ulysses* remained at a nearly constant radius from the sun near 5 AU and scanned the latitude range 20°N - 23°S. *Voyager 1* stayed at a nearly constant latitude of ~32°N while moving outward from 66 to 75 AU, and *Voyager 2* moved outwards from 52 AU at 18°S latitude to 61 AU at 21°S. The *Voyagers* were oriented roughly in the direction of the sun's motion through the interstellar medium, while *Ulysses* was at about 90° to this motion. *IMP-8*, at earth, scanned the full range of heliospheric longitude once per year.

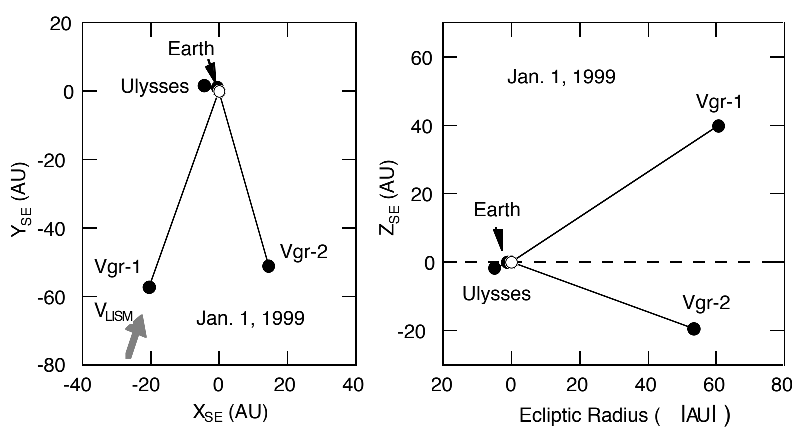

Figure 1: Positions of spacecraft with respect to the ecliptic and the inflowing interstellar medium on January 1, 1999.

For this study we use charged particle observations from the Low Energy Charged Particle (LECP) instruments on *Voyagers 1* and *2*, described by Krimigis et al. (1977), the COSPIN High Energy Telescope on *Ulysses*, described by Simpson et al. (1992), and the University of Chicago

Cosmic Ray Experiment on *IMP-8*, described by Garcia-Munoz et al. (1977).

3 Observations and Discussion:

As shown in Figure 2A, the intensity of galactic cosmic rays in the inner heliosphere reached a maximum and then began a gradual decrease in the fall of 1997. The decrease began somewhat before the onset of the first significant solar activity associated with cycle 23, a series of large solar energetic particle events in November 1997 originating from an active region in the southern hemisphere of the sun. A second series of large events occurred in April/May 1998, again generated from active regions primarily in the southern hemisphere of the sun. In association with the April/May activity, a rapid step-like increase in modulation was observed in the inner heliosphere, similar to the steps reported by McDonald et al., (1981) during onset of modulation following the 1977 solar minimum. After the step decrease, a new modulation level was established that persisted through the end of the observations in early 1999, a period of more than 6 months. Thus, at least in the inner heliosphere, a new long-term level of modulation was established after April/May 1998. Since the step was such a major feature in the inner heliosphere it might be expected to act as an identifiable marker for the propagation of the modulation change outward through the heliosphere.

In the analysis reported in this paper, we focus on observations of low energy (<100 MeV) galactic cosmic ray protons to define the onset of modulation. From the *Voyager 1* and *2* LECP experiments, we obtain measurements of ~22-30 MeV protons drawn from the highest energy well-characterized channel currently available from these instruments. At the large distance of the *Voyager* spacecraft, contamination of the flux in this energy interval with solar energetic particles during the period of our analysis was not observed, as verified by the near constancy of the ratio of the proton flux in the window ~3-16 MeV to that in the 22-30 MeV window. In the inner solar system, however, solar energetic particles appeared frequently in energy windows below 30 MeV. Consequently, we have chosen the window ~70 - 90 MeV from *IMP-8* and *Ulysses* to give a clearer picture of the time dependence of the modulation. While the energies are not

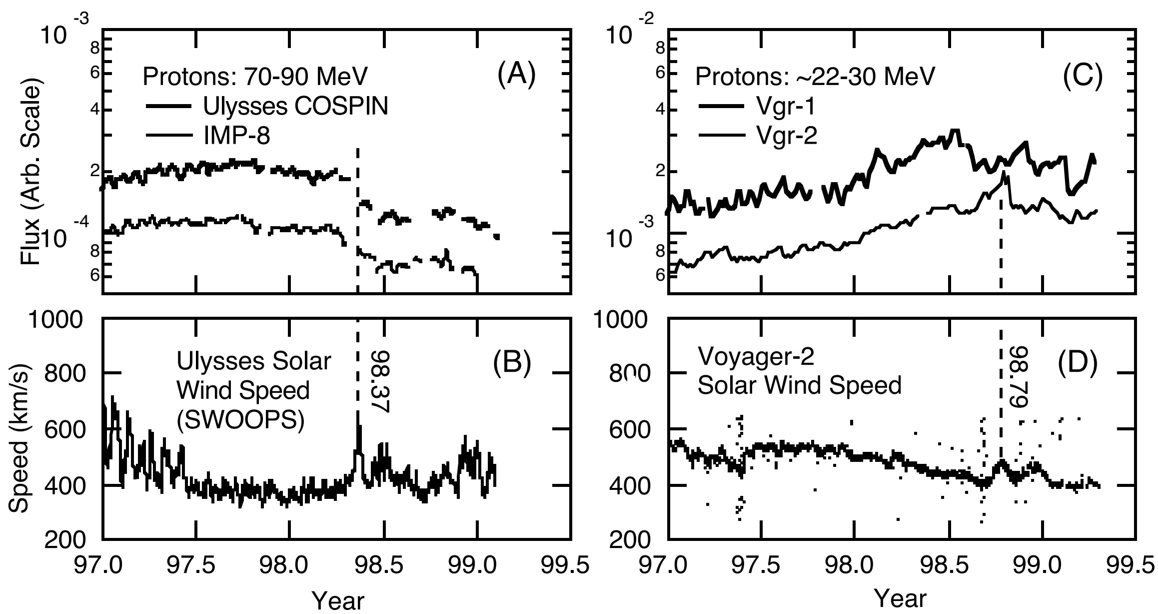

Figure 2: A) 9 day running averages of 70-90 MeV proton fluxes from *Ulysses* and *IMP-8*; B) 6 hour average solar wind speeds from the *Ulysses* SWOOPS instrument (Bame et al. 1992); C) 5 day averages of 22-30 MeV proton fluxes from the *Voyager 1* and *2* LECP instruments; D) 1-hour average solar wind speeds from the *Voyager 2* Plasma Science Instrument (Bridge et al. 1977). Proton fluxes have been multiplied by arbitrary scale factors.

well matched, our objective is to examine the timing of the onset of modulation in the inner and outer heliosphere, which does not show strong energy dependence at any of the spacecraft.

As shown in Figure 2, the profile of intensities at *IMP* and *Ulysses* was rather simple. The major feature was the step decrease in early 1998. At *Voyager 1* and *2*, the profile was more complex, and the decrease in intensity associated with the onset of modulation did not occur until after the middle of 1998. This is qualitatively consistent with outward convection of the modulation level, as has been observed for many years with the *Voyager* and Pioneer spacecraft (e.g. Garcia-Munoz et al. 1981, McDonald et al. 1981).

Also shown in Figure 2 are solar wind speeds measured on *Ulysses* and *Voyager 2*. During the onset of modulation, the only significant feature in the solar wind speed in the inner heliosphere was the broad increase that reached a maximum speed of about 600 km/s around May 15, 1998 (98.37). Otherwise, after mid-1997 *Ulysses* was embedded in the equatorial solar wind zone, and the speed was near 400 km/s. Thus solar wind structures alone do not seem to account for the changes in modulation at *IMP* and *Ulysses*. During this same period, the solar wind velocity at *Voyager 2*, at ~20°S latitude, decreased gradually from ~500 km/s to ~400 km/s, except for two modest increases in late 1998, the first of which peaked about Oct. 15, 1998, and was associated with an unusual increase in the intensity of low energy protons observed at *Voyager 2*. The spectrum of protons in the intensity increase, as measured by the ratio (3-16 MeV)/(22-30 MeV), was consistent with that of the galactic protons measured before and after the increase. The *Voyager* solar wind speed increase is unlikely to be connected with the increase observed at *Ulysses* since the mean propagation speed required would be ~610 km/s, about equal to the maximum speed observed at *Ulysses*.

In studies comparing modulation in the inner and outer heliosphere (e.g. Lopate et al. 1991, Fujii and McDonald 1997) changes in modulation have usually been assumed to propagate outwards at about 400 km/s, consistent with convection by the equatorial solar wind. However *Ulysses* has clearly shown that near solar minimum the 400 km/s solar wind occupies only a narrow region of the heliosphere near the ecliptic, and that at latitudes above 20 or 30 degrees, the solar wind originates from the polar coronal holes with a velocity of about ~800 km/s (e.g., Phillips et al. 1995, Goldstein et al. 1996). For the current sign of the

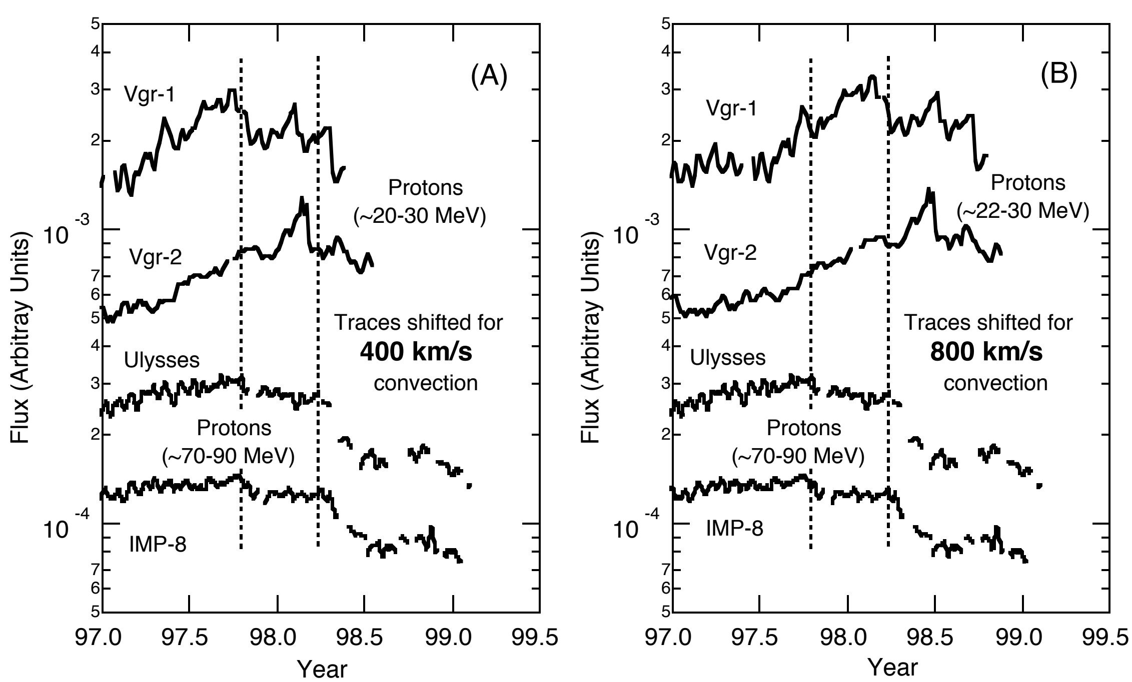

Figure 3: Fluxes shifted with respect to *Ulysses* for outward convection of changes in modulation at speeds of 400 km/s (A) and 800 km/s (B). Fluxes have been multiplied by arbitrary scale factors.

solar magnetic dipole, consideration of the gradient and curvature drifts experienced by positively charged cosmic rays in the heliospheric magnetic field suggests that most of the cosmic rays observed at low latitudes enter the heliosphere at high latitudes and reach the ecliptic by propagation through the fast high latitude solar wind. Thus, the modulation level may be controlled by high latitude effects, and the propagation speed of changes in modulation could be close to the speed of the fast high latitude solar wind.

In Figure 3 A and B, we show the effects of assuming velocities for the outward propagation of modulation changes at 400 and 800 km/s, respectively. In both panels we plot the *Ulysses* time intensity profile as measured, and shift the *IMP* and *Voyager* profiles forward (*IMP-8*) or back (*Voyager 1* and *2*) by the time interval corresponding to the propagation time to or from *Ulysses* at 5 AU. Vertical dashed lines mark the maximum intensities at *Ulysses* before the onsets of the gradual increase in modulation in late 1997 and the sharp step increase in 1998. As can be seen from the figure, plausible associations can be made for either choice of convection velocity. For 400 km/s, the onset of the gradual increase in modulation in the inner heliosphere can be associated with the first decrease in modulated intensity at *Voyager 1*, and with a leveling off of the flux at *Voyager 2*. The step decrease can be approximately associated with the decrease after the unusual increase seen at *Voyager 2*, but the association at *Voyager 1* is unclear. For 800 km/s the step decrease is associated with a similarly significant step decrease at *Voyager 1* and a smaller step at *Voyager* 2 that initiates the leveling off of fluxes. While for 800 km/s the later intensity variations at the *Voyager* spacecraft have no correlates in the inner heliosphere, this choice of velocity produces a somewhat better correlation between the *Voyager*s for these features. In the inner heliosphere, the faster velocity also produces a slightly better correlation between *Ulysses* and *IMP*.

4 Conclusions:

To pursue this analysis further, other particle species and energies must be examined and all available information about the interplanetary medium must be considered. However even at this preliminary stage of analysis it is clear that the first step in the onset of modulation, observed near the beginning of April, 1998 in the inner heliosphere, initiated a change in the global level of modulation observed at all longitudes around the sun and over a range of latitude from ~20°S near 60 AU (*Voyager* 2) across the current sheet to ~30°N near 70 AU (*Voyager 1*) in the outer heliosphere. At present it is not clear what changes in the heliospheric magnetic field and/or solar wind structure are responsible for this global onset of modulation.

Acknowledgments: This work was supported in part by NASA/JPL contract 955432 (*Ulysses*) and NASA Grant NAG5-8032 (*IMP-8*) at the University of Chicago, and by NASA Grant NAG5-4365 (Voyager 1 and 2) at JHU/APL. We are grateful to D. McComas for solar wind observations from Ulysses and to A. J. Lazarus for solar wind data from Voyager 2.

References

Bame et al. 1992, A&A, 92, 237.
Bridge et al. 1977, Sp. Sci. Rev., 21, 259.
Fujii, Z., & McDonald, F.B. 1997, Proc. 25th ICRC (Durban.), 2, 89.
Garcia-Munoz, M., Mason, G.M. & Simpson, J.A. 1975, Ap.J., 217, 859.
Garcia-Munoz, M., Pyle, K.R., & Simpson, J.A. 1981, Proc. 17th ICRC (Paris), 3, 270.
Goldstein, B.E., et al. 1996, A&A, 316, 296.
Krimigis, S.M., et al. 1977, Sp. Sci. Rev., 21, 329.
Lopate, C., et al. 1991, Proc. 22nd ICRC (Dublin), 3, 268.
McDonald, F.B., et al. 1981, Ap.J., 249, L71.
Phillips et al. 1995, Geophys. Res. Letters, 22, 3301.
Simpson, J.A., et al. 1992, A&A., 92, 365.