SOLAR ENERGETIC-PARTICLE SPECTRA AND THE STRUCTURE OF CORONAL MASS EJECTIONS

D. V. Reames[1], S. W. Kahler[2], and C. K. Ng[3]

[1]*NASA/Goddard Space Flight Center, Code661, Greenbelt, MD 20771, USA*
[2]*Phillips Laboratory/GPSG, 29 Randolph Road, Hanscom AFB, MA, 01731-3010, USA*
[3]*Dept. of Mathematics, RMIT, G. P. O. Box 2476V, Melbourne 3001, Australia*

ABSTRACT

Using multiple spacecraft, we examine the spatial and temporal distribution of energetic particles in large gradual solar energetic particle (SEP) events relative to shock waves driven out from the Sun by coronal mass ejections (CMEs). Nearly identical intensities and spectra are found over a large spatial region magnetically connected to the quasi-parallel eastern flank of the shock. Intensities in this region decrease with time as the shock expands. On its western flank, the shock is quasi-perpendicular and spectra vary dramatically in space and time. A shock speed of >500 km/s is required for any particle acceleration and SEPs always occur for speeds >750 km/s.

SEP OBSERVATIONS

In recent years it has become clear that in the large gradual SEP events, acceleration of the particles we see occurs at the CME-driven shock waves and *not* in solar flares (see e.g. Reames 1990, 1993, 1995; Kahler 1992; Gosling 1993). Recent compelling evidence for SEP origin comes from measurements of Fe ions at 200-600 MeV/amu that have a mean charge of 14.1 ± 1.4 (Tylka et al. 1995). These ions could not come from the hot plasma in a flare and they would be stripped of electrons in seconds by material at densities of the low corona, so they are neither accelerated nor stored in the corona. Particles of GeV energies are evidently accelerated several solar radii out from the Sun (Kahler 1994).

Multi-spacecraft observations have helped us distinguish the spatial and temporal evolution of SEP events and their relationship to the evolving shock (Reames et al., 1996). Even 25 years ago, when the origin of the particles was not correctly known, it was clear that sometimes intensities and spectral shapes varied dramatically and at other times they were highly invariant (McKibben 1972).

The upper panel in Figure 1 shows time profiles at 3 spacecraft for an event studied by Reames et al. (1996). The inset shows the distribution of the spacecraft relative to the event which is moving downward. Spacecraft magnetically connected far around the western flank of the event, like

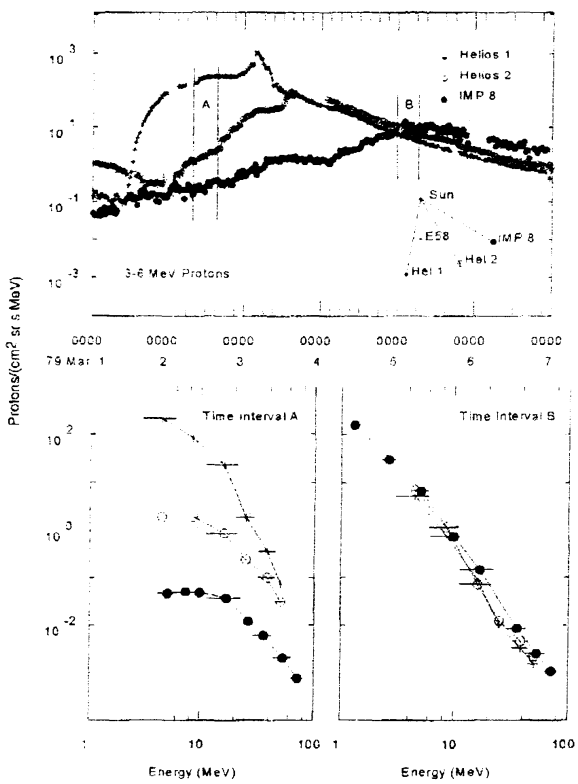

Fig 1. Time profiles in the 1979 March event observed by 3 spacecraft are shown in the upper panel. The lower panels show full energy spectra at the 3 spacecraft during time periods A and B.

IMP 8, have much lower intensities that rise slowly. Yet, long after shock passage all intensities join and track each other, within a factor of ~2, as the overall intensity decreases with time. Energy spectra taken during time period B show the spatial invariance that occurs late in the event when the shock is at about 2 AU. The excellent agreement of the spectra at time B contrasts sharply with the spatial differences seen at time A, prior to the arrival of the shock.

A second example is shown in Figure 2. Despite the wide separation of the spacecraft, nearly 160°, and the presence of large data gaps, it is clear that the intensities join late in the event and that the complete spectra are spatially independent at time B. In the upper panel of this figure we have normalized the Helios 1 time-intensity profiles for different energies at time B to show how closely they track each other late in the event. The onset of the invariant region can be seen to begin rather abruptly a few hours after shock passage at this spacecraft and continues at least 3 days.

In a recent paper, Reames et al. (1997), reported spectral invariance during a 3-day period during the 1995 October 20 event observed by the WIND/EPACT experiment. Energy spectra for elements H, He, C, O and Fe were shown to have nearly power-law spectra from 20 keV/amu to 100 MeV/amu during the invariant period. The invariant period began abruptly almost a day *before* shock arrival in this event from W55° on the Sun. Unfortunately, the WIND spacecraft was launched during solar minimum so we have not yet been able to study other events over this huge dynamic range of particle energies. However, invariance beginning ahead of the shock is also seen for IMP 8 and Helios events at longitudes that are west of the spacecraft.

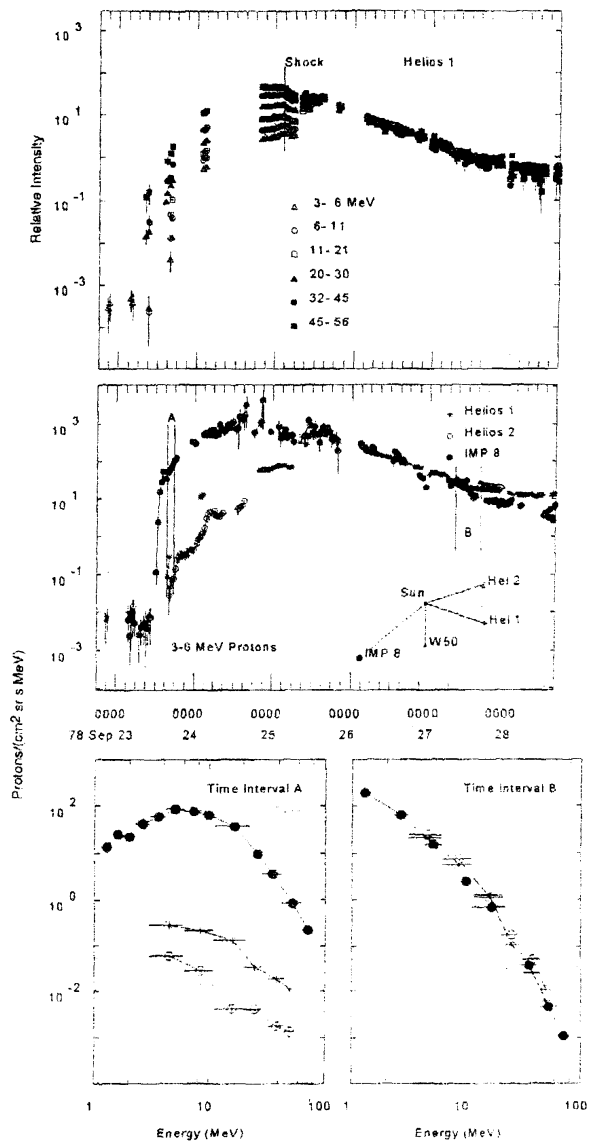

Fig. 2. Time profiles for 3 spacecraft are shown in the center panel for the 1978 September 23 event. Spectra at times A and B are in the lower panel while the upper panel shows normalized time profiles at several energies at Helios 1.

A final example of spectral invariance is shown in Figure 3, where the upper panel shows the normalized time-intensity profiles at Helios 1 and the lower panel shows spectra at 3 times during the event. Spectral invariance begins just after shock passage in this event that strikes the spacecraft nearly head on. Maximum intensity at all energies occurs within one time interval (30 min) of the shock passage in this event. Clearly the spacecraft has passed near the "nose" of the shock where particle acceleration is most intense. In most events the spacecraft passes to the east (west) of the nose so maximum intensity occurs before (after) shock passage when the spacecraft is magnetically connected to shock nose.

If we examine the location of the spacecraft, relative to the CME, during periods of invariant spectra, a pattern emerges like that shown in Figure 4. For a western event, when the spacecraft is on the eastern flank of the shock, invariance begins well before shock passage. For central and eastern events, invariance begins several hours after the spacecraft has crossed the shock, but often when it is inside the region associated with the CME itself. Thus the region of invariant spectra seems to be magnetically connected to the eastern flank of the event where the shock moves in a direction that is quasi-parallel to the magnetic field. Here the local shock is weaker and changes only gradually with time; the highest intensity of particles was injected early when the nose of the shock was connected to this region. As the volume expands, the particle population in this region decays mainly by adiabatic deceleration which preserves the spectral shape. The fact that the invariant region seems to include the CME suggests that magnetic reconnection allows particles to enter the CME.

On its western flank, the shock is nearly quasi-perpendicular and is more dynamic since its angle with the field changes with time along a flux tube and the connection of that flux tube sweeps across the face of the shock toward the nose.

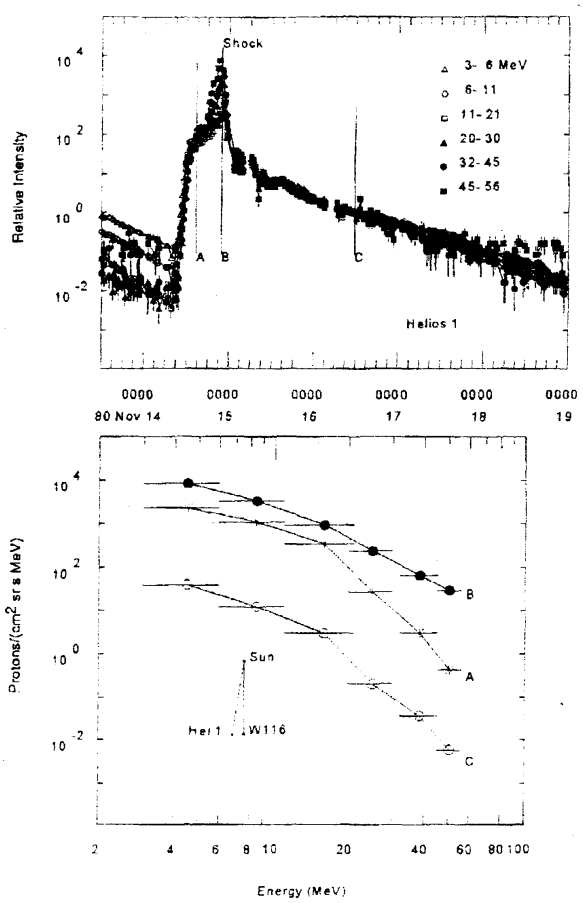

Fig. 3. Normalized time profiles for the1980 November 14 event are shown in the upper panel. Spectra at times A, B and C show maximum intensity and hardness at the shock.

EVENT STATISTICS

To explore the conditions that lead to particle acceleration we began by examining the CME/shock list of Sheeley et al. (1985) where shocks observed by Helios 1 above the solar limbs are correlated with CMEs observed by the SOLWIND coronagraph in Earth orbit. Of the 29 events on this list where we can examine Helios data for accelerated particles, 21 events had associated SEP events and 8 did not. All of the 14 events with shock transit speeds >750 km/s had associated SEP events, while none of the events with shock transit speeds <500 km/s had evidence of particle acceleration. The SEP intensities show a broad correlation with shock speed similar to that found for CME speeds by Kahler et al. (1984) for events observed on IMP 8. For 19 of the 21 Helios SEP events we were able to

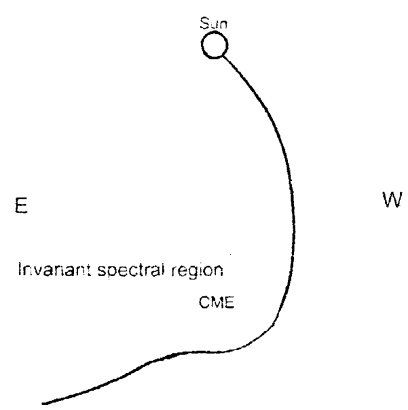

Fig. 4. The location of invariant spectra connected to the quasi-parallel eastern flank of the shock.

observe periods of invariant spectra and to measure e-folding decay times ranging from 6-18 hours. Of the remaining 2 events, one was too small and the other was obscured by a new onset. Therefore, we conclude that essentially all CME/shock-associated SEP events have regions of spectral invariance.

The Sheeley et al (1985) list is especially interesting since it was generated without regard to the presence or absence of energetic particles. However, the same relationship between CMEs, shocks and energetic particles is found in many other events as shown originally by Kahler et al (1984), and the prevalence of spectral invariance has been known since McKibben (1972). In the large sample of proton events studied by Cane et al. (1988), for example, shock speeds can be determined for 119 events; all of these shocks have speeds >500 km/s and particle intensities that are correlated with the shock speed.

CONCLUSIONS

In large SEP events particle acceleration occurs at CME-driven shocks and the time-intensity profiles of the particles can be understood in terms of an observers magnetic connection to that structure as it evolves in space and time. For 25 years we have known of a highly invariant region in SEP events where particle spectra are uniform in space and intensities decline slowly in time. In this paper we have associated this invariance with a large spatial region magnetically connected to the quasi-parallel shock on the eastern flank of the event. Most particles in this region were accelerated early and their intensities in this expanding volume now decline from adiabatic deceleration which preserves spectral shape. Essentially, the invariant region has been processed and "left behind" by the powerful nose of the expanding shock. On the western quasi-perpendicular flank the region of the shock that intercepts a given field line can change rapidly leading to variable spectra and intensities.

REFERENCES

Cane, H. V.. Reames, D. V., & von Rosenvinge, T. T. , JGR, 93, 9555 (1988).
Gosling, J. T., JGR, 98, 18949 (1993).
Kahler, S. W., Ann. Revs. Astr. & Ap., 30, 113 (1992).
Kahler, S. W., ApJ, 428, 837 (1994).
Kahler, S. W., Sheeley, N. R., Jr., Howard, et al., JGR, 89, 9683 (1984).
McKibben, R. B., JGR, 77, 3959 (1972).
Reames, D. V., ApJ Suppl., 73, 235 (1990).
Reames, D. V. , Adv. Space Res., 13 (No. 9), 331 (1993).
Reames, D. V. , Revs. Geophys. (Suppl.) 33, 585 (1995).
Reames, D. V., Barbier, L. M., & Ng, C. K., ApJ, 466, 473, (1996).
Reames, D. V., Barbier, L. M., von Rosenvinge, T. T., Mason, et al., ApJ, 483, 515 (July 1, 1997).
Sheeley, N. R., Jr., Howard, R. A., Koomen, et al., JGR, 90, 163 (1985).
Tylka, A. J., Boberg, P. R., Adams, J. H., Jr. , ApJ (Letters), 444, L109, (1995).