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PARTICLES ACCELERATED BY SHOCKS IN THE HELIOSPHERE

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ABSTRACT

The populations of energetic ions accelerated by shocks in the heliosphere are reviewed briefly. Characteristic spectra and representative fluxes are given.

INTRODUCTION

Shocks accelerate energetic ions throughout the heliosphere. Travelling interplanetary shocks, presumably generated by solar flares or coronal transients, produce energetic storm particle (ESP) events. The forward and reverse shocks bounding corotating interaction regions (CIRs) in the solar wind accelerate the corotating ion events. Planetary bow shocks at Earth, Jupiter, and Saturn accelerate the diffuse upstream ion distributions. The seed particles in all cases are either solar wind ions or solar flare ions, with the possible addition of leaked magnetospheric ions at planetary bow shocks. In most cases, however, these shocks are not efficient producers of energetic particles above 1 MeV/nucleon.

The locations of these populations in the heliosphere are indicated schematically in Figure 1. Also shown is the cosmic ray anomalous component, described elsewhere in this volume, which is presumably accelerated at the solar wind termination shock and propagates back into the inner heliosphere with reduced intensity. Solar flare ions are also indicated with possible origin at a coronal shock; they are also described elsewhere in this volume. Finally, for completeness the interstellar and cometary pickup ions are shown. Although they are energetic with respect to the solar wind thermal distribution their energies in the spacecraft frame are comparable with the ~ 1 keV/nucleon energy of the solar wind and are of little interest in this report.

COROTATING ION EVENTS

The forward and reverse shocks bounding CIRs generally form by 3-4 AU during solar minimum conditions when a polar coronal hole extends to mid latitudes and produces a fast solar wind stream there. The shocks presumably extend as identifiable shocks to 10-15 AU where they criss-cross, merge and dissipate. They may extend to 20°-30° latitude. Although these shocks can be long-lived (over several solar rotations), they are weak, quasi-perpendicular (which tends to inhibit injection of solar wind ions into the acceleration process) and their ion acceleration is partially balanced by adiabatic deceleration of the ions in the diverging solar wind. The differential intensity spectrum of accelerated ions beyond ~ 1 MeV/nucleon is proportional to $\exp(-v/v_0)$ where v is speed and $v_0 \sim 0.01 - 0.03c$, and a typical maximum proton flux (i.e., at the shock at $\sim 5-10$ AU) at 1 MeV is $10 \text{ protons cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$. The corotating ion events are described in detail by McDonald et al. (1976), Barnes and Simpson (1976), Marshall and Stone (1977), Pesses, van Allen and Goertz (1978), Van Hollebeke et al. (1978), Gloeckler et al. (1979), Mewaldt et al. (1979), and Fisk and Lee (1980).

Energetic Particles in the Heliosphere

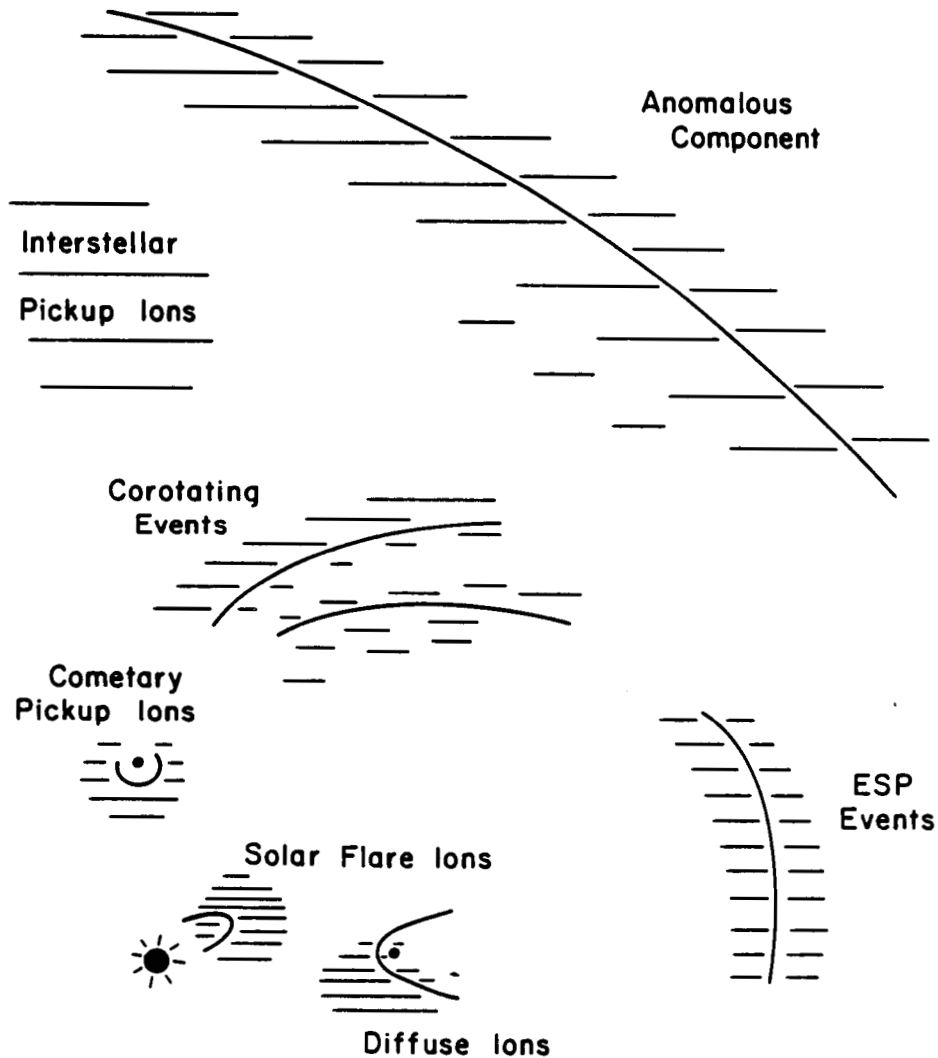


Fig. 1. A schematic diagram of energetic particle populations in the heliosphere.

DIFFUSE ION EVENTS

Planetary bow shocks are strong near their nose but their limited size ($\sim 20 R_E$ at Earth and $\sim 100 R_J$ at Jupiter) limits acceleration efficiency. At Earth beyond ~ 20 keV per charge the distribution function of diffuse upstream ions is proportional to $\exp(-E/E_0)$ where E is energy per charge and $E_0 \sim 15-25$ keV per charge. A typical maximum differential flux at 20 keV at the shock is $4000 \text{ protons cm}^{-2} \text{ s}^{-1} \text{ str}^{-1}$

keV⁻¹. The ion intensity decays with distance from Earth's bow shock with a scalelength of $\sim 10\text{-}20 R_E$ depending on energy. At Jupiter the maximum differential intensity appears to be ~ 20 protons cm⁻² s⁻¹ str⁻¹ keV⁻¹ at 100 keV, with a similarly soft exponential spectrum. Good references on the diffuse ions are Ipavich et al. (1979, 1981), Gosling et al. (1979), Eastman et al. (1981), Lee (1982), Mitchell and Roelof (1983), Wibberenz et al. (1985), Zwickl et al. (1981), Baker et al. (1984), and Smith and Lee (1986).

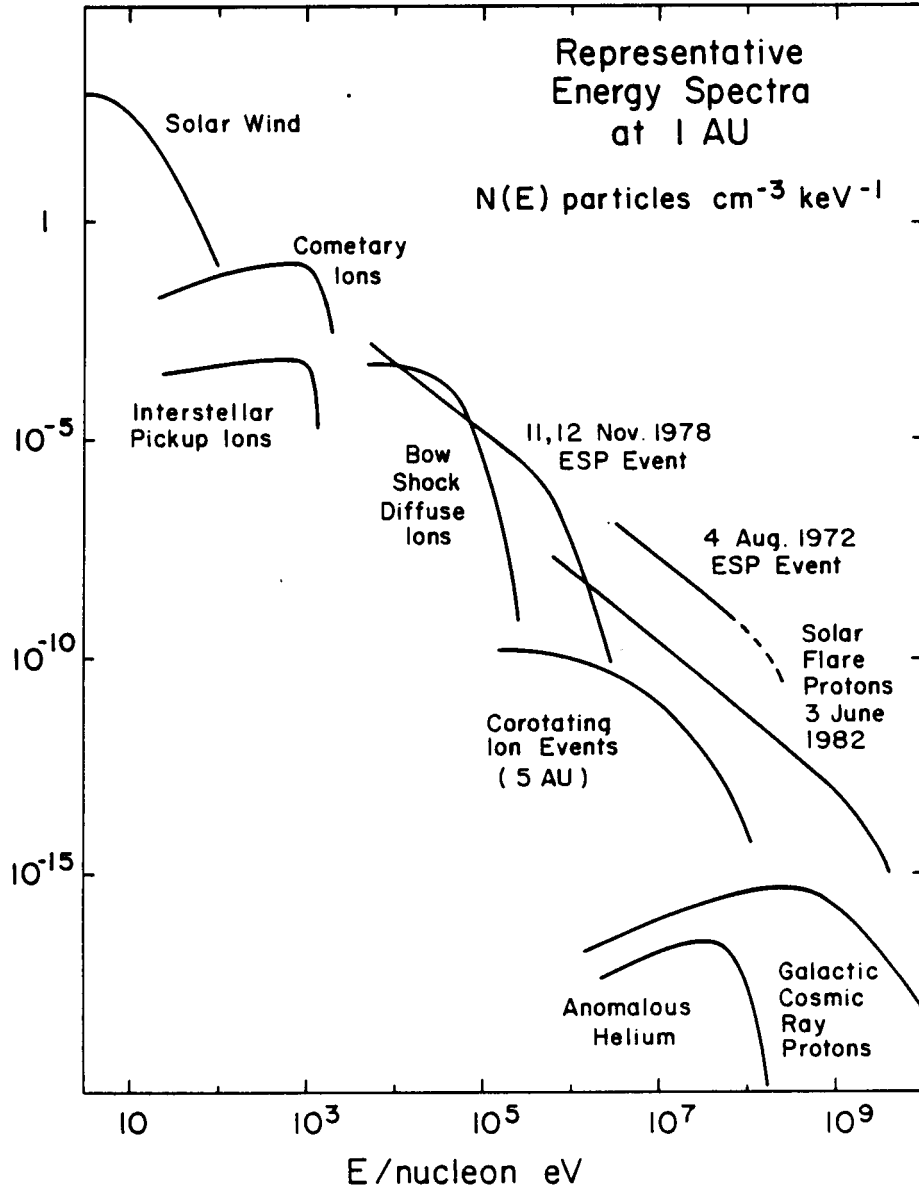


Fig. 2. Representative and particular energy spectra of energetic particle populations at 1 AU (the corotating ion spectrum is at 5AU).

ENERGETIC STORM PARTICLE (ESP) EVENTS

Energetic storm particle events are more variable and difficult to characterize. Interplanetary travelling shocks enhance the background solar flare ion distribution, particularly at quasi-perpendicular shocks, but the enhancement is generally small in comparison with the flare event itself. A few strong quasi-parallel shocks can accelerate solar wind ions (these are so-called "supercritical" shocks), creating very large enhancements at low energies, but finite shock lifetime at ~ 1 AU limits the enhancement to energies $\lesssim 500$ keV/nucleon. For example, the large event of 11,12 November 1978 produced a maximum differential flux of $2000 \text{ cm}^{-2} \text{ s}^{-1} \text{ str}^{-1} \text{ keV}^{-1}$ at 30 keV at 1 AU with a differential flux power law, $\propto E^{-1.1}$, up to energies of about 200 keV. However, occasionally a very strong shock can produce huge enhancements at 1 AU. The shock on 4 August 1972 was such a shock (Yates et al., 1974; Eichler, 1981). This huge variation is apparently caused by nonlinearity in the injection rate as a function of shock strength and in the acceleration timescale (due to excitation of ion-excited waves), and perhaps in the solar flare seed particle population. Useful references on ESP events are Bryant et al. (1962), Rao et al. (1967), Sarris and Van Allen (1974), Scholer et al. (1983), Lee (1983), Van Nes et al. (1984), Sarris et al. (1984), Kennel et al. (1984a,b, 1986), Tsurutani and Lin (1985), and Bavassano-Cattaneo et al. (1986).

REPRESENTATIVE SPECTRA

Representative and particular ion spectra in units of particles $\text{cm}^{-3} \text{ keV}^{-1}$ are shown in Figure 2. It is clear that the energetic particle environment within the heliosphere covers a huge range of energies and differential intensities. All spectra with the exception of that for the corotating ion events are at 1 AU. For purposes of comparison with the shock-associated energetic ion events, the spectra of the solar wind protons, cometary water-group pickup ions, interstellar pickup helium, the large solar flare proton event of 3 June 1982, anomalous cosmic ray helium, and galactic cosmic ray protons are also indicated.

SUMMARY

The heliosphere is rich in its populations of shock-accelerated energetic ions. Nevertheless at energies greater than 1 MeV/nucleon they would appear to be dominated by large solar flare ion events in the inner heliosphere. At ~ 5 AU, however, during solar minimum conditions, the corotating ion events tend to dominate solar flare events. Diffuse ions at planetary bow shocks have negligible intensities at energies $\gtrsim 1$ MeV/nucleon. Interplanetary travelling shocks can enhance the solar flare ion flux as an ESP event, but the enhancements are generally not large at energies $\gtrsim 1$ MeV/nucleon. Occasionally an ESP event can have a substantial intensity at energies $\gtrsim 1$ MeV/nucleon as shown for the 4 August 1972 event in Figure 2.

Acknowledgements

The author wishes to thank Dr. Joan Feynman for her efforts in organizing the Workshop on the Interplanetary Charged Particle

Environment. This work was supported, in part, by NSF Grant ATM-8513363, NASA Grant NAG 5-728, and NASA Solar Terrestrial Theory Program Grant NAGW-76.

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