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STREAMING-LIMITED INTENSITIES OF SOLAR ENERGETIC PARTICLES

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ABSTRACT

Energetic particles streaming outward from an intense source near the Sun reach a maximum-intensity plateau when scattering by self-generated waves restricts the streaming. We compare calculated theoretical values of the streaming-limited intensities with observations from the *Helios 1* and *2* and the NOAA Geostationary Operational Environmental Satellites (*GOES*) spacecraft and examine the energy dependence and radial gradient of the intensities.

Subject headings: acceleration of particles — shock waves — Sun: corona — Sun: particle emission

1. INTRODUCTION

The generation and amplification of Alfvén waves by energetic particles streaming along the magnetic field in a plasma is a well-known phenomenon (e.g., Stix 1962; Melrose 1980). When the intensities of streaming particles are high, waves grow rapidly and soon reach intensities where the wave-particle interactions restrict the streaming to a quasi-equilibrium value, effectively confining subsequent particles to the neigborhood of the source. In the large solar energetic particle (SEP) events, the theory of self-generated waves has been employed to understand both the acceleration of the particles at interplanetary shock waves (Lee 1982, 1983) and the transport of particles outward from the source (Ng & Reames 1994). These papers recognize that the scattering of particles by hydromagnetic waves is a time-dependent nonlinear process in which particles can amplify or damp waves in such a way that the particle transport is drastically modified.

In recent years it has become clear that the particles in the large "gradual" SEP events are actually accelerated at shock waves driven out from the Sun by fast coronal mass ejections (CMEs) and *not* in solar flares (Kahler 1992, 1994; Gosling 1993; Reames 1993, 1995, 1997; Cliver 1996; Reames, Barbier, & Ng 1996). Measurements of ionization states of Fe suggest (Boberg, Tylka, & Adams 1996) that ambient (unheated) coronal material provides the seed population, even for particles that are shock-accelerated to the highest energies (Tylka et al. 1995).

In 1990 it was noted (Reames 1990) that the 3–6 MeV protons accelerated in these large shock events often had flat intensity-time profiles. These profiles would be expected (e.g., Reames 1997) to result from continuous shock acceleration when both the accelerated protons and their source seed population had the same radial divergence. However, the intensity level of this intensity plateau seemed to have a maximum value above $\sim$100 protons (cm^2 sr s MeV)$^{-1}$ that was observed, within a factor of $\sim$2, in many events. Figure 1 shows superposed plots of intensities in several events as reported by Reames (1990). Later in the events, near the time of shock passage, the intensities can suddenly increase by 1 order of magnitude or more. Historically, these peaks near shock passage have been called "energetic storm particle" (ESP) events or shock spikes.

Subsequently, Ng & Reames (1994) performed numerical calculations that followed the spatial and temporal evolution of the spectra of both waves and particles as the particles diverged outward from a source near the Sun. They found that the growth of waves induced by the distribution of streaming particles did indeed increase the scattering of the particles so as to limit their intensity to a value near that suggested by the observations. As the source intensity was increased, the intensity at a given radial distance, R, eventually reached the "streaming limit" and then even declined slightly. Additional particles were effectively "diffusively trapped" near the source by self-generated waves. These diffusively trapped particles form the ESP event (Reames et al. 1996; Reames 1997).

In this paper we examine the available observations of the proton intensities in large events during the last two solar cycles in order to explore the streaming limit and its variation with radial distance and proton energy. For this purpose it is essential that we use data from instruments that do not saturate at high proton intensities. Accordingly, we have used proton data from the Goddard Space Flight Center instruments on the *Helios 1* and *2* spacecraft in solar orbit between 0.3 and 1.0 AU and from the NOAA *Geostationary Operational Environment Satellites* (*GOES*). The latter data have recently become available from NOAA on CD-ROM. Particle intensities from the simple detectors on *GOES* have been corrected for encroachment of higher energy particles into each energy interval, as described in literature accompanying the CD-ROM. We have compared these corrected intensities with corresponding data from the Goddard experiment on the *IMP 8* spacecraft. We found the two instruments to be in good agreement except during times of rapid spectral change early in events, when the *GOES* correction algorithm fails, and during intensity peaks at shock passage, where the *IMP 8* instrument saturates.

2. THE STREAMING-LIMITED INTENSITY DISTRIBUTION AND ITS RADIAL DEPENDENCE

We have scanned data from the *GOES* spacecraft for the period 1986 January 1 to 1997 September 1. We selected all events with intensities of 4.2–8.7 MeV protons greater than 10 (cm^2 sr s MeV)$^{-1}$ during the early peak or plateau period prior to arrival of the shock. A histogram of the

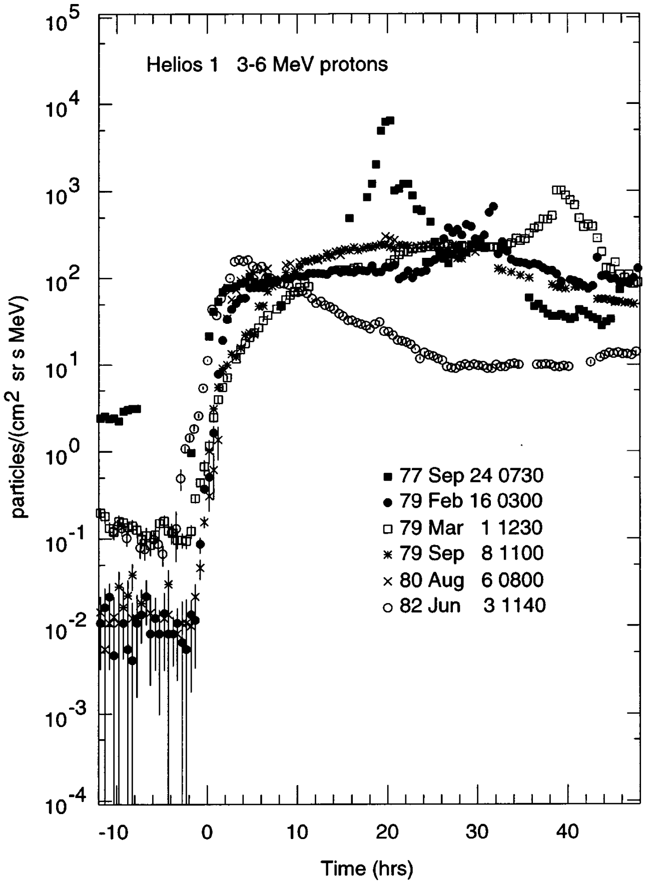

FIG. 1.—Superposed intensity-time profiles of 3–6 MeV protons observed by *Helios 1* are shown for six large events. Streaming-limited flat profiles are seen early in the events. Shock peaks are seen to arrive later in several of the events with intensities increasing by factors up to ~100 near the shock (Reames 1990).

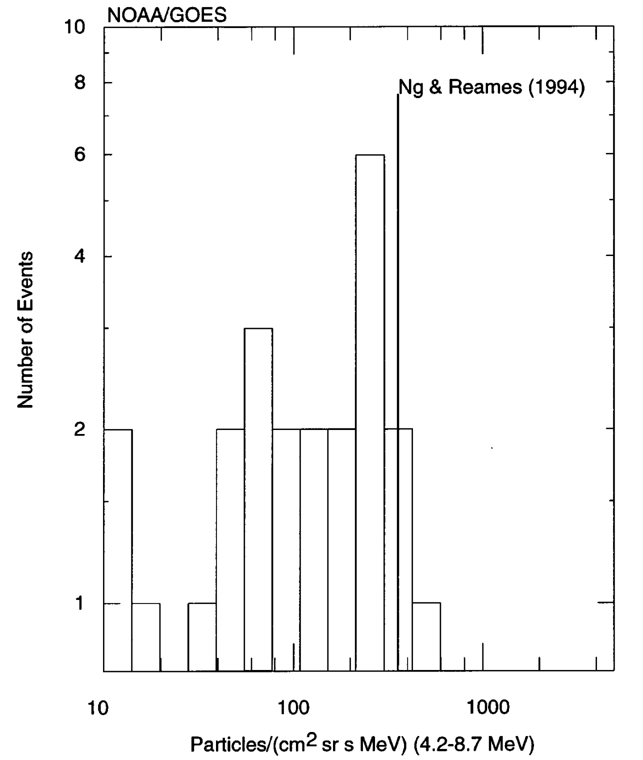

FIG. 2.—A histogram of streaming-limited plateau intensities of 4.2–8.7 MeV protons from the *GOES* spacecraft is compared with the calculated (Ng & Reames 1994) maximum plateau intensity at 1.0 AU.

distribution of these intensities is shown in Figure 2. The distribution shows a peak in the intensity above 200 (cm^2 sr s MeV)$^{-1}$ and a dearth of events with intensities greater than 400 (cm^2 sr s MeV)$^{-1}$. This is in reasonable agreement with the streaming limit of ~300 (cm^2 sr s MeV)$^{-1}$ at 1.0 AU found by Ng & Reames (1994) in the ~1 MeV region.

In order to examine the radial gradient of the streaming limit, we have scanned the 3–6 MeV proton data from *Helios 1* (1974 December 14 to 1982 January 1) and *Helios 2* (1976 January 18 to 1979 December 23) for early peak and plateau intensities exceeding 10 (cm^2 sr s MeV)$^{-1}$. The radial distribution of these intensities is shown together with the *GOES* data in Figure 3. While there are not enough events to establish the radial gradient in the region of 0.3–0.4 AU, beyond 0.5 AU the distribution shown in Figure 3 is consistent with the $\sim R^{-3}$ dependence found in the numerical simulation of Ng & Reames (1994). A particle source associated with a traveling shock is expected to produce a gradient that is more gentle than R^{-3} because particles are newly accelerated as the shock moves outward.

In general, attempts to use multiple spacecraft to measure the radial gradient in individual events are complicated by the differing connection longitudes of the spacecraft. However, these measurements are generally consistent with the R^{-3} dependence (Zwickl & Webber 1977; Mason, Reames, & Ng 1991; Reames et al. 1996) of the nonshock peak intensities that is rigorously predicted by diffusion theory. Since the streaming limits are imposed relatively

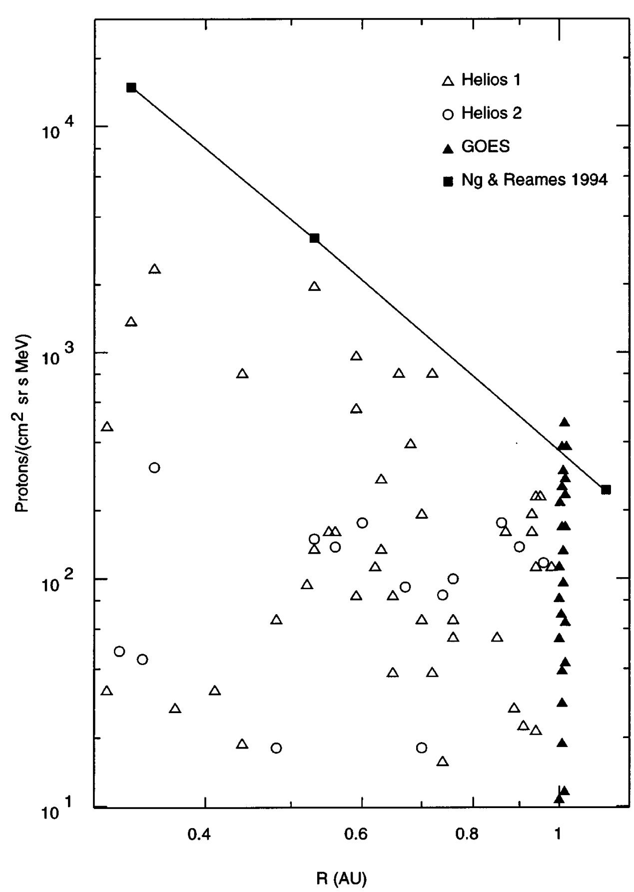

FIG. 3.—Radial gradient of the streaming-limited plateau intensities of 3–6 MeV protons from *Helios 1* and *2* and 4.2–8.7 MeV protons from the *GOES* spacecraft are compared with the calculated (Ng & Reames 1994) intensity gradient.

near the Sun, it is not surprising that an overall R^{-3} dependence controls the subsequent radial evolution.

3. THE STREAMING LIMIT AT HIGH ENERGIES

At energies of a few MeV we can find a dozen or more events per solar cycle that reach the streaming limit. It is much more difficult to examine the streaming limit at higher energies since only the largest few events of the solar cycle appear to be capable of reaching this limit. In Figure 4 we show intensity-time profiles at three different energies in six of the largest event of the last solar cycle. Dashed horizontal lines are drawn at the probable streaming limit for each energy interval. Intensities early in these events peak at or near the nominal limits for the 8.7–14.5 and the 39–82 MeV intervals. For the 110–500 MeV interval, the limiting intensity is only attained for the first four of the six events.

The 1989 October 19 event in Figure 4 is interesting in that it shows characteristic flat profiles followed by ESP-event peak at very high energies. This event originates near longitude 10°E on the Sun and has a shock transit speed of $\sim$1900 km s^{-1} (Bavassano et al. 1994). In this large event, the protons greater than 100 MeV have time profiles similar to those of the 3 MeV protons shown in Figure 1. Only the absolute intensities differ.

4. CONCLUDING REMARKS

The physical process of wave generation by particles streaming outward early in a large SEP event provides a mechanism for self-regulation of the particle intensity. This streaming-limited maximum intensity is consistent with a dependence on the radial distance of the observer from the Sun, R, of approximately R^{-3}. The limit applies only to the intensities of streaming particles and *not* to those accelerated locally or convected out from the source.

Once the source intensity rises above that required to reach the streaming limit, additional particles are diffusively trapped near the expanding shock source. Thus, added acceleration only serves to increase the intensity at the ESP peak, *not* that on the early plateau. Of course, the visibility of the plateau and ESP region is modulated by the geometric effect of the connection longitude of the observer relative to the source, as has been discussed at length in previous papers (e.g., Reames et al. 1996; Reames 1997).

The streaming-limited intensities have an interesting application to the protection of astronauts on deep-space missions to the Moon or Mars from the severe radiation hazard presented by rare large SEP events. Since the streaming-limited intensities pose a minimal radiation hazard, the time between onset of the event and arrival of the shock is available to characterize the amount of risk and to warn the astronauts to take shelter. It is not necessary to attempt to predict the event before its onset at the Sun, a feat that is presently far beyond our capabilities.

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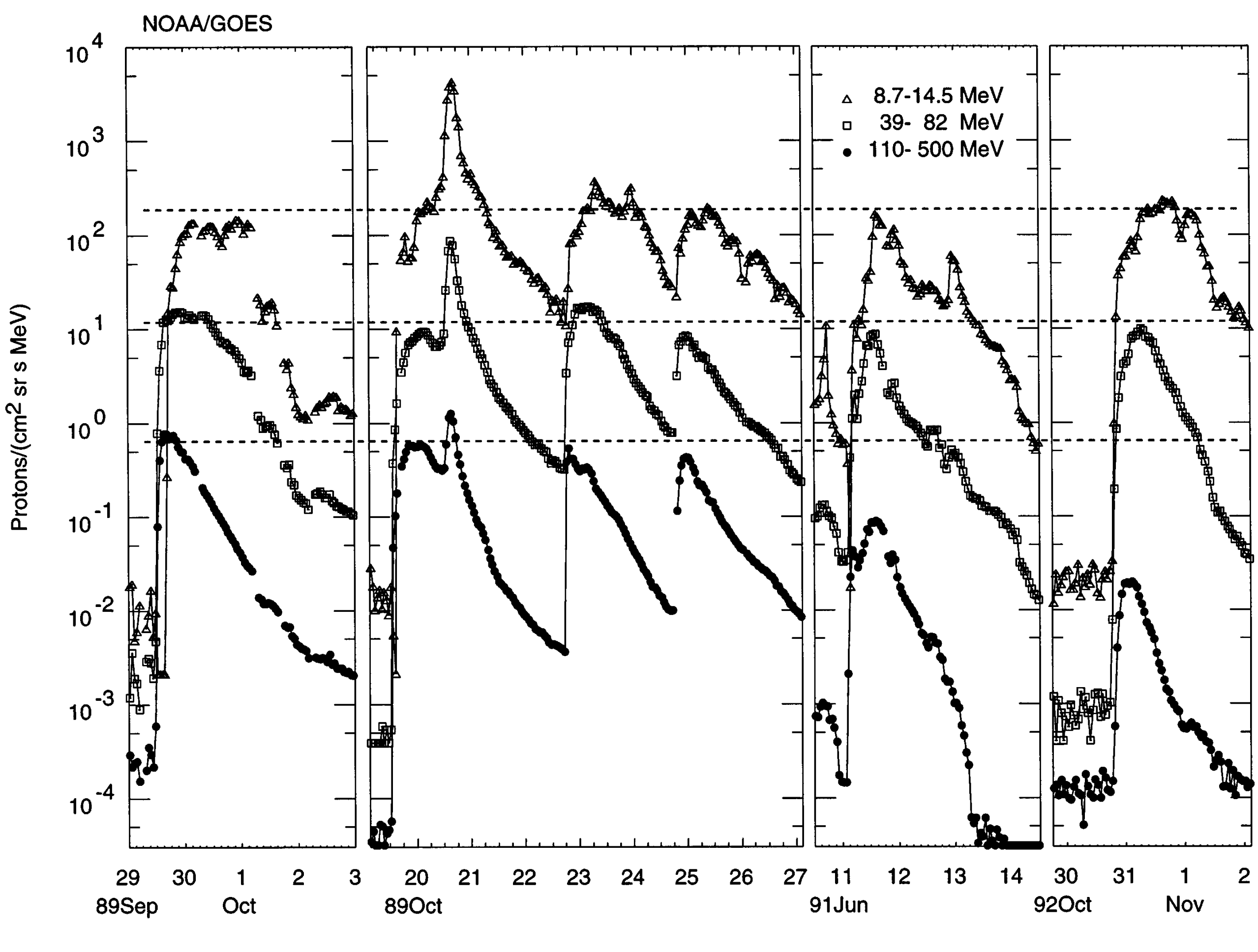

FIG. 4.—Intensity-time profiles of protons in three energy channels are shown for six large SEP events during the last solar cycle as measured on the *GOES* spacecraft. Streaming-limited intensity values for each energy channel are shown as dashed lines. Note the similarity of the high-energy profiles in the 1989 October event with the low-energy profiles in Fig. 1.

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