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STREAMING-LIMITED INTENSITIES OF SOLAR ENERGETIC PARTICLES ON THE INTENSITY PLATEAU

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ABSTRACT

We examine the energy spectra of H, He, O, and Fe ions on the temporal intensity plateau region in large solar energetic-particle (SEP) events, where intensities may be "streaming limited." Upstream of shock waves near the Sun, equilibrium may occur when outwardly streaming protons amplify resonant Alfvén waves that then scatter subsequent protons sufficiently to reduce the streaming. In the largest SEP events, the so-called ground-level events (GLEs), we find proton energy spectra that are peaked near ∼10 MeV with the energy of similar peaks decreasing for heavier ions and for smaller events. These spectra contrast sharply with spectra near the time of shock passage which rise monotonically above the plateau spectra with decreasing energy. We suggest that strong suppression of upstream ion intensities near ∼1 MeV amu^{-1} on the plateau occurs when those ions resonate with waves amplified earlier by streaming protons of ∼10 MeV and above. GLEs with much lower intensities of 10–100 MeV protons on the plateau show spectra of ions that rise monotonically toward low energies with no peaking and no suppression of low-energy ions. Wave amplification by streaming protons and the pitch-angle dependence of the resonance condition are essential factors in our understanding of the limiting behavior.

Key words: acceleration of particles – shock waves – Sun: coronal mass ejections (CMEs) – Sun: particle emission

Online-only material: color figures

1. INTRODUCTION

Large solar energetic-particle (SEP) events are produced when fast shock waves are driven out from the Sun by coronal mass ejections (see reviews, Reames 1990a, 1995, 1999, 2002, 2009a, 2009b; Kahler 1992, 1994, 2001; Gosling 1993; Lee 1997, 2005; Tylka 2001; Tylka et al. 2005; Tylka & Lee 2006; Sandroos & Vainio 2009). In some of the largest SEP events, the intensities of GeV protons are sufficient to produce radiation that penetrates Earth's atmosphere to ground level. Seventy of these ground-level events (GLEs) have been identified since 1942 (Cliver et al. 1982; Cliver 2006) and 16 have occurred during the last solar cycle (cycle 23). These energetic events are of practical importance since they also present a serious radiation hazard to astronauts and equipment in space and even to the passengers and crew of commercial aircraft flying polar routes. Any constraint on the intensities of the radiation from these events should be of particular interest in the design of strategies to mitigate the effects of this hazardous radiation.

SEPs streaming outward from the continuing acceleration at a shock source near central meridian on the Sun sometimes reach a plateau of intensity near Earth that can exist over a broad energy range and last for many hours prior to a renewed increase toward the time of arrival of the shock wave itself. These streaming particles generate and amplify Alfvén waves (Stix 1992; Melrose 1980) that scatter the particles coming behind. As long as there are streaming protons, wave growth continues until the increased scattering by the waves throttles the particle flow and the intensity to an equilibrium level now described as the "streaming limit." The basic properties of the streaming limit have been studied both experimentally (Reames 1990b; Reames & Ng 1998; Tylka 2001) and theoretically (Ng & Reames 1994; Ng et al. 2003; Vainio 2003; Lee 2005). The waves that control the streaming limit are generated upstream of the shock source near the Sun, where the SEP intensities are extremely high, *not* near 1 AU; these intensities then decrease with radius, R, out from the Sun (Reames & Ng 1998).

For an intuitive understanding of the streaming limit, consider a thought experiment where we slowly increase the injection of energetic protons from a shock near the Sun. Initially, the protons will be transported to 1 AU through the ambient wave intensity. When the injection increases sufficiently, the protons will begin to amplify resonant waves, beginning near the shock, where the intensity is highest, and continuing outward until increased scattering has reduced the proton streaming and the wave amplification. Further increases in injection cause more wave growth which is large near the shock but decreases with distance as the protons scatter. At a sufficient distance from the shock, the intensity no longer increases when the source injection increases. This intensity has reached the streaming limit.

Outward propagating waves are generated almost entirely by protons while the other ions, such as He, O, and Fe, act as test particles, with varying mass to charge ratios A/Q, that probe the waves as they are scattered by them. The condition for cyclotron resonance of particles and waves is that the wave number $k \approx B/P\mu$, where $P = pc/Qe$ is the magnetic rigidity of a particle of momentum $\boldsymbol{p}$ and μ is the cosine of its pitch angle with respect to the magnetic field $\boldsymbol{B}$. Apart from the factor μ, protons of a given rigidity amplify the waves which scatter other ions of the same rigidity. High-energy protons at small μ can generate waves that scatter low-energy ions at $\mu \approx 1$, and conversely.

Previously, a complete observational description of the energy spectra of multiple particle species at the streaming limit has not been available to test or challenge theoretical predictions. Are the particle intensities truly in time equilibrium and independent of early streaming, for example? To what extent is there coupling where waves generated by high-energy protons affect low-energy ions?

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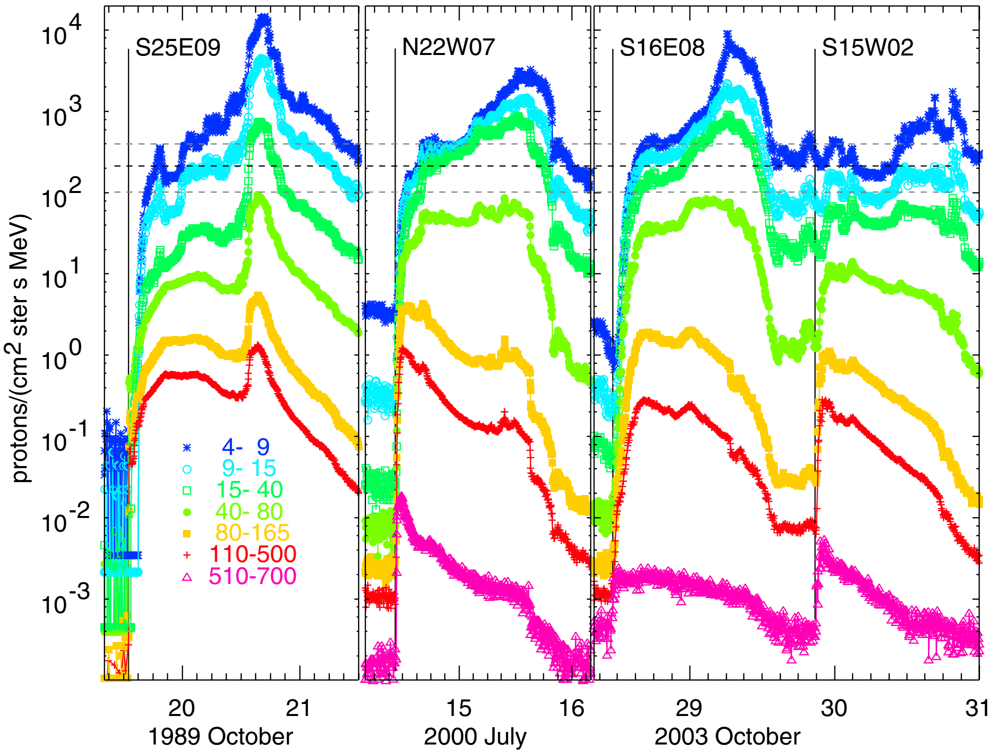

Figure 1. Comparison of time histories of *GOES* proton channels from three recent GLE events in 2000 and 2003 with the historic 1989 October 19 event. All of the events show evidence of a plateau in the intensities after the initial rise. Dashed lines in the figure show the nominal intensity, with x2 errors, of the low-energy streaming limit (Reames & Ng 1998).

(A color version of this figure is available in the online journal.)

If we want to observe the effect of the streaming limit on the energy spectra in SEP events at 1 AU, we must choose a time that is late enough that the low-energy ions have had time to arrive but early enough to avoid times when the shock itself is approaching since the streaming limit does not apply near the shock. Particles at 1 MeV amu^{-1} travel 3 hr AU^{-1}. SEP events from sources near central meridian sometimes have a well-defined intensity plateau during this time which is ideal for such studies. However, we refer to this early time period as the "plateau" region even when the intensities are not perfectly flat at all energies.

In this paper, we present observations of particle intensities and spectra during this plateau phase of several large GLEs during the last solar cycle, especially those from sources near the central meridian on the Sun. While events from other solar longitudes are subject to the streaming limit as well, they have plateaus that are very poorly defined and time varying spectra that are usually more difficult to understand since the streaming-limited peak intensities at different energies may occur at different times. General properties of some of our events have been studied previously (e.g., Tylka et al 2001, 2005; Cohen et al. 2005; Mewaldt et al. 2005), but not from the perspective of defining the physical consequences of the proton streaming.

SEP measurements used in this paper come from the Ultra Low Energy Isotope Spectrometer (ULEIS; Mason et al. 1998) and the Solar Isotope Spectrometer (SIS; Stone et al. 1998) on the *Advanced Composition Explorer* (*ACE*) and available from the *ACE* Web site (http://www.srl.caltech.edu/ACE), from the Low Energy Matrix Telescope (LEMT) in the Energetic Particle Acceleration, Composition, and Transport experiment (von Rosenvinge et al. 1995) on *Wind*, and from the Goddard Medium Energy experiment (McGuire et al. 1986) on the *Interplanetary Monitoring Platform 8* (*IMP 8*). We also use proton data from the Energetic Particle Sensor and the High Energy Proton and Alpha Detector on the NOAA *Geostationary Operational Environment Satellites* (*GOES*) from the Space Physics Interactive Data Resource Web site (http://spidr.ngdc.noaa.gov) where instrument descriptions may also be found.

In this study of GLEs, one may appropriately ask why we omit using the neutron-monitor data that define them. GLEs serve as a well-defined and independently determined sample of large energetic SEP events, but the neutron-monitor measurements themselves are not very helpful for our study. First, in more than half of the GLEs, neutron monitors rise less than 10% above the galactic cosmic-ray background so the data are meager. Second, the time profiles of an event often look much different at different monitors depending on how the asymptotic look directions of each are aligned with the interplanetary magnetic field, and thus how they sample the anisotropic particle distribution—which may also change significantly during an event. Third, each station's measurement is an integral above a different cutoff rigidity. To determine a spectrum, one must fit intensities for different rigidity cutoffs and look directions over the entire Earth. This is only possible in rare large GLEs (e.g., Lovell et al. 1998). Interplanetary spacecraft provide more accurate and complete energy spectra, from ∼0.1 MeV to ∼1 GeV, and are much more suited to the present study.

2. TIME HISTORIES AND THE INTENSITY PLATEAU

The general character of the GLEs in question is shown in Figure 1 which compares *GOES* proton data during three GLE events from solar cycle 23 with the well-known historic GLE of 1989 October 19. Generally the proton intensities in the events are quite comparable. All of the events show some evidence of a plateau in their intensities after an initial rise. The dashed

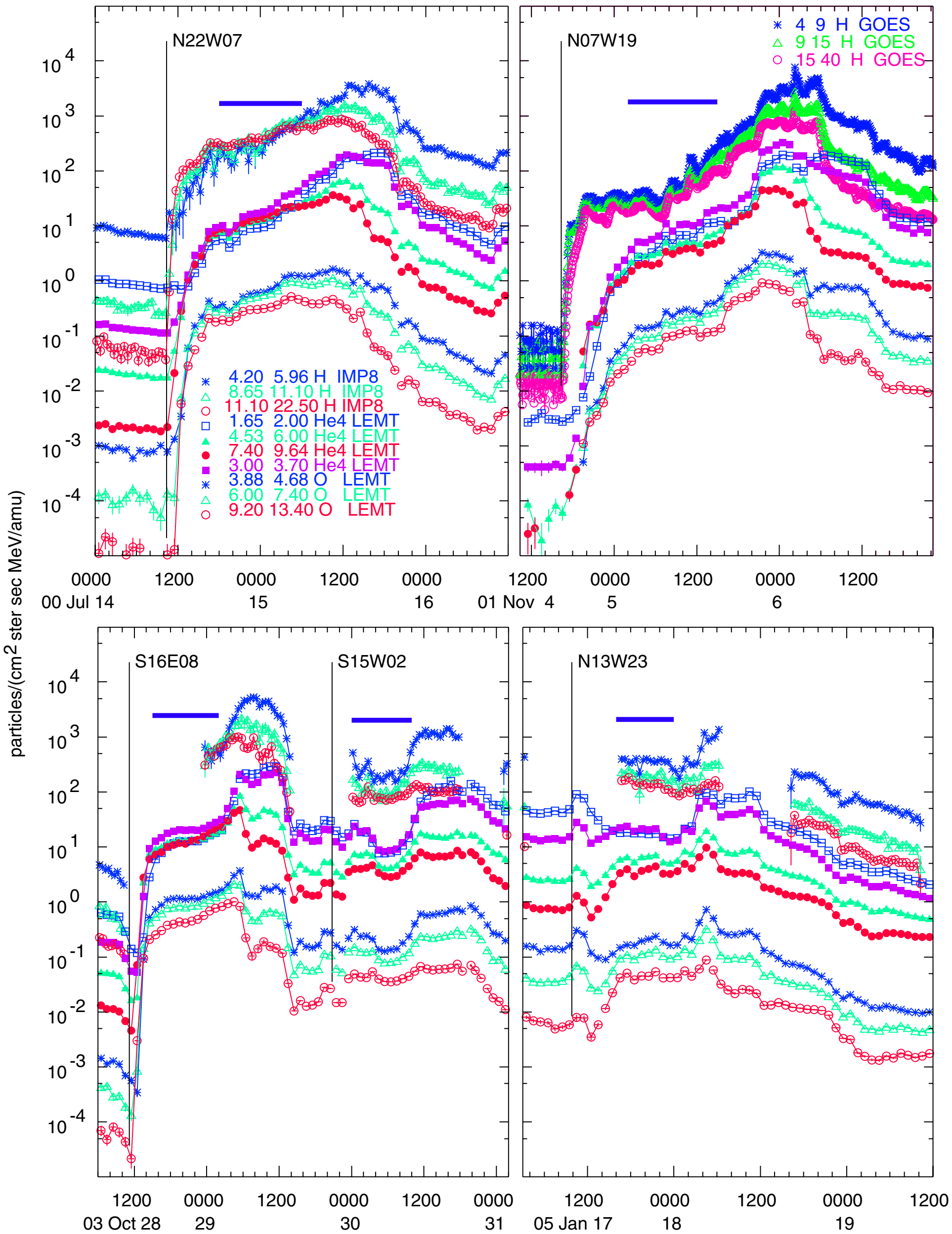

Figure 2. Proton, He, and O intensities at several energies are shown during five GLEs. For each species, the intensities tend to be compressed together in the energy region shown during the nominal plateau regions which are defined by the horizontal bars above the data.

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lines in the figure show the nominal intensity of the low-energy streaming limit identified by Reames & Ng (1998) together with uncertainties of a factor of 2 in either direction. As noted earlier, the streaming limit, being a transport phenomenon, does not apply later in the events when the intensities rise up to a peak near the time of shock passage.

An important feature we have found on the plateau region in these large events begins to appear in the 2000 July 14, "Bastille Day," event in Figure 1, where the three lowest energy channels, spanning the 4–40 MeV region, show the same intensities on the plateau. We expand the study of this effect to include He and O intensities in five GLEs in Figure 2. All species show the flattened time profiles and the intensity compression in the plateau region suggesting a plateau in energy as well as in time.

It is important to realize that the flattening of the lowest energy ion intensities does not arise from classical velocity dispersion, or from an unusually slow rise of lower-energy ions at 1 AU. Comparing the 1.65–2.0 MeV amu^{-1} He (blue open square) with the 7.4–9.64 MeV amu^{-1} He (red solid circle) in Figure 2, especially for the 2000 July 14 and the 2003 October 28 events, we see that, apart from an initial delay, the low-energy He rises just as smartly to the plateau value as does the higher energy He. The rise phase of these events is shown at high time resolution by Reames (2009a). There is no problem of a slower transport or slower rate of rise for these ions early in these events.

3. ENERGY SPECTRA

Energy spectra of H, He, O, and Fe on the plateau region in three of these large events are shown in Figure 3. In the figure, data below ~2 MeV amu^{-1} come from ULEIS, protons above 4 MeV from *IMP 8* and *GOES*, ions from ~2 to ~10 MeV amu^{-1}

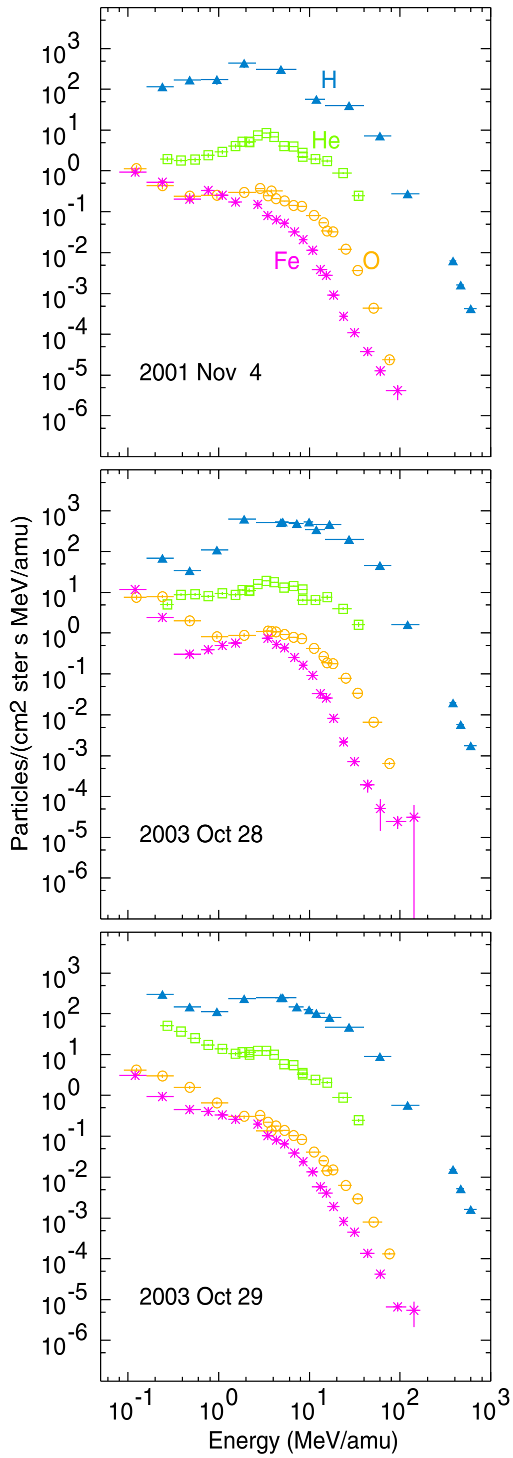

Figure 3. Energy spectra of H, He, O, and Fe are shown in the plateau region for the three largest GLE events of this study. Data below ~2 MeV amu^{-1} come from ULEIS, protons above 4 MeV from *IMP 8* and *GOES*, ions from ~2 to ~10 MeV amu^{-1} are from LEMT and those above ~10 MeV amu^{-1} are from SIS (see the text).

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are from LEMT and those above ~10 MeV amu^{-1} are from SIS. In some cases ULEIS data, especially H and He, have been normalized to the higher energy data in the energy region of overlap to correct for variations in the particle detection efficiency of the ULEIS time-of-flight system. For the events we study, proton data from *IMP 8* and *GOES* agree reasonably well where the instruments overlap as do ion data from LEMT and SIS.

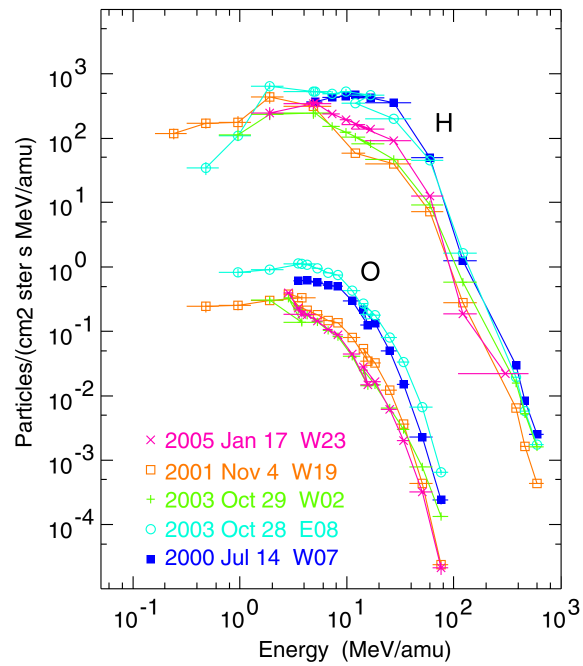

Figure 4. Proton and O energy spectra are compared for the plateau regions of the five GLEs shown in Figure 2.

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For the largest event in Figure 3, the spectra show a clearly defined spectral maximum at ~10 MeV for protons, and the curves for different species are similar in shape but show a decrease in the energy of the peak to 2–3 MeV amu^{-1} for Fe. For Fe and O, for example, this energy shift would cause Fe/O to rise at low energies. The rise in the spectra toward the lowest energies, below about 0.5 MeV amu^{-1}, comes from high residual pre-event background. At energies of ~0.1 MeV amu^{-1} the pre-event background intensities are often comparable with those during the events and may represent the seed population used for subsequent shock acceleration (Mason et al. 1999; Allegrini et al. 2008). For the 2003 October 29 GLE the proton maximum is nearer ~4 MeV and the peak for Fe has degenerated to an inflection down at ~1 MeV amu^{-1}. However, pre-event background from the October 28 event makes a large contribution to the October 29 event plateau spectra at low energies.

Where do the proton spectra for the other large events fall in comparison with the 2003 October 28 event? In Figure 4, we compare the H and O spectra in the five largest events from our study for which time histories were shown in Figure 2. Low-energy points affected by background have been removed. The 2000 July 14 event spectra are quite comparable with those of 2003 October 28 above ~4 MeV for H and ~3 MeV amu^{-1} for O; lower energy data are not available for the former event. The three smaller events in this sample have spectral behavior that is similar to that of the two largest GLEs but less extreme.

4. A SMALL GLE: 1998 MAY 2

In Figure 5 we consider an event that is much smaller, but nevertheless a GLE. Proton time profiles are shown in the upper panel. A plateau region is clearly indicated in the data and the selected plateau time interval is shown in the figure. Note

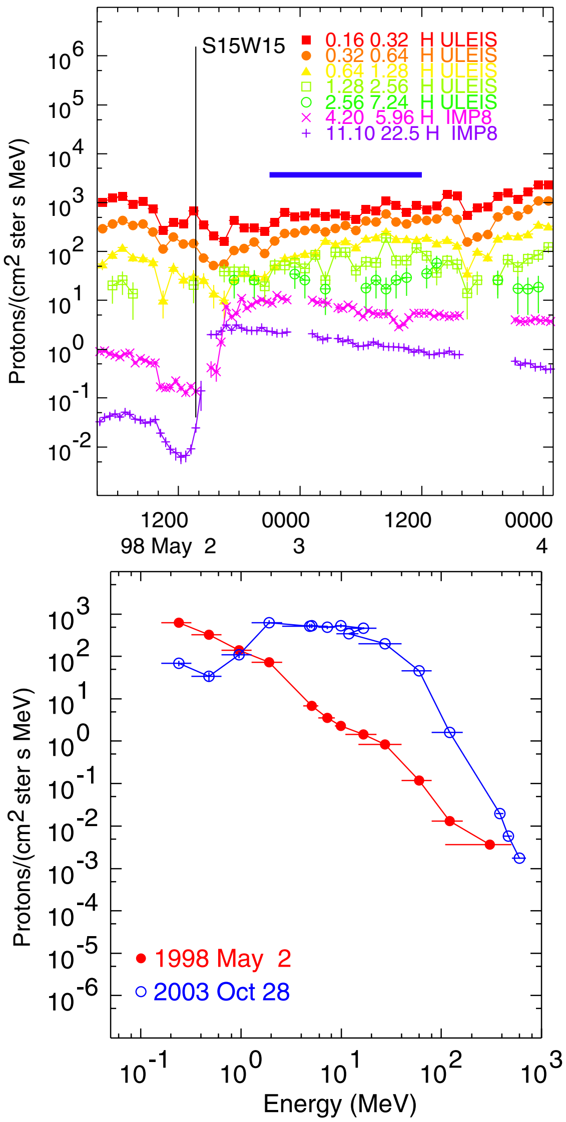

Figure 5. Upper panel shows the time history of protons of various energies in the 1998 May 2 GLE. The plateau region used is shown by the horizontal bar above the data. The lower panel compares the plateau proton spectrum in this event with that from the 2003 October 28 GLE. Intensities in the 1998 May 2 GLE are well below the streaming limit but an order of magnitude larger than the 2003 October 28 event at low energy (<1 MeV).

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that pre-event background does not contribute to the low-energy H channels in this event. The lower panel of Figure 5 compares the proton plateau spectrum in the 1998 May 2 GLE with the corresponding spectrum in the 2003 October 28 GLE.

The 1998 May 2 event proton spectrum shown in Figure 5 decreases monotonically with energy and shows none of the complexity of the spectra of the larger events. At 10–100 MeV the 1998 May 2 spectrum is a factor of ∼100 below that of the 2003 October 28 GLE, but its spectrum continues to rise well above the latter spectrum below about 1 MeV. Evidently, in the large events, wave energy produced by the 10–100 MeV protons can powerfully scatter $< \sim 1$ MeV protons in the inner heliosphere to depress their intensity at 1 AU by orders of magnitude. A 95 MeV proton at $\mu = 0.1$, a 25 MeV proton at $\mu = 0.2$, and a 4 MeV proton at $\mu = 0.5$, all generate waves that resonate with a streaming 1 MeV proton with $\mu = 1$. Note that, in the large events, as 10–100 MeV protons flow out toward

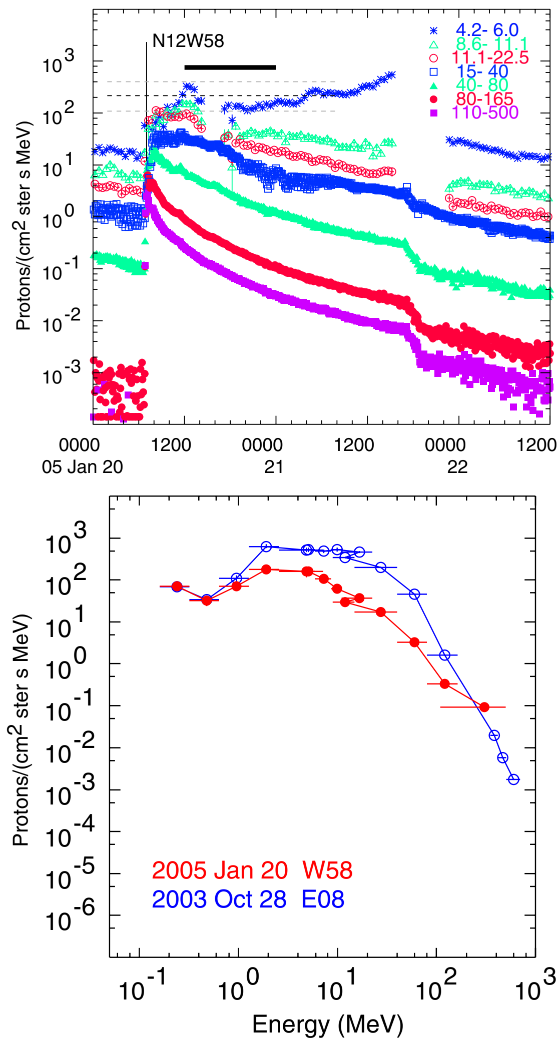

Figure 6. Upper panel shows the time history of protons of various energies in the 2005 January 20 GLE. Dashed lines show the nominal low-energy streaming-limited intensity (see Figure 1). The region chosen for spectral analysis is shown by the horizontal bar above the data, and the lower panel compares the proton spectrum in this region with the plateau spectrum from the 2003 October 28 GLE.

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1 AU they scatter to fill a larger region of pitch-angle space and generate waves long before the 1 MeV protons begin to arrive.

5. A LARGE WESTERN GLE: 2005 JANUARY 20

In the previous sections, we have considered six GLEs from sources near central meridian because they form intensity plateaus with quasi-static energy spectra. Events from source regions at western solar longitudes are more difficult to analyze since their spectra vary much more rapidly with time. An observer is magnetically well connected to the nose of the shock source early in these western events when the shock is strongest. With increasing time, the connection point moves along the shock surface toward weaker regions on the flank of the shock while the shock itself is weakening. Thus, the initially hard energy spectra can soften rapidly with time. In this section, however, we consider the extremely large GLE of 2005 January 20 from a solar longitude of W58. The upper panel in Figure 6 shows proton intensities in the January event. Note that the intensities of protons from ∼4 to ∼20 MeV are consistent with the nominal low-energy streaming limit which is shown, with errors, as the dashed lines in the figure.

Also shown by the horizontal bar in the upper panel of Figure 6 is the period selected for spectral analysis. The time period is selected to be comparable with that in the other GLEs and to allow sufficient time for protons below 1 MeV to contribute. In the lower panel, the proton spectrum from this period is compared with the spectrum of the 2003 October 28 GLE. Protons of ∼4 to ∼40 MeV are not strongly affected by the choice of time period, but protons above 40 MeV are much more intense at earlier times. Thus, our choice of time period emphasizes the spectrum in the ∼0.5 to ∼40 MeV region of greatest interest, but neglects the high-energy region. We will discuss this high-energy region in Section 7.

6. PLATEAU VERSUS SHOCK SPECTRA

In Figure 7, we compare the plateau spectra with those near the time of the subsequent shock passage for the 2003 October GLE events. The intensity–time plot in the figure emphasizes the low-energy proton channels since higher-energy data were shown previously in Figures 1 and 2. It is interesting to follow the relative temporal behavior of the lowest energy channel, 0.16–0.32 MeV (red filled square), in the upper panel of Figure 7. This channel has the highest intensity during most times, including those near the times of shock passage where the intensities are the highest. However, during the two plateau periods the intensity of the 0.16–0.32 MeV channel falls below that of many of the higher-energy channels. These are the only periods when the spectra are suppressed at low energies.

The H, He, and O shock spectra in Figure 7 (filled symbols) show a monotonic decrease with increasing energy for both events. The plateau spectra (open symbols) show a relative suppression that increases with decreasing energy in most cases, although pre-event background does cause a low-energy turn-up in some spectra as previously noted, especially in the October 29 event. Strictly speaking, the region of the shock that accelerated the ions seen on the plateau is not the same as that of the shock seen at the spacecraft. However, the comparison gives some idea of the magnitude of the streaming-limited suppression of ions below ∼10 MeV amu^{-1}, which can be as large as several orders of magnitude. This comparison also illustrates the great limitation in the common practice of studying event-averaged spectra which muddle the effects of several different physical mechanisms. The SEP onset (Reames 2009a, 2009b), the plateau, the shock peak, and the invariant spectral region (Reames et al. 1997; Reames 2010) all involve different physical processes.

7. DISCUSSION

The GLEs of 2000 July 14 and 2003 October 28 have similar spectra of all species above 4 MeV amu^{-1}. These events have the highest intensities of ions in the region from ∼2 to ∼50 MeV amu^{-1} and appear to define the streaming limit in this interval. To our surprise, the intensities below ∼1 MeV also appear to be actually defined by the proton intensities in the ∼2 to ∼50 MeV amu^{-1} region.

The comparison of a typical small event from near central meridian, the 1998 May 2 event in Figure 5, with the larger events has been especially revealing. This comparison shows (1) that temporal plateau formation and the streaming limit need not be the same, (2) that the suppression of the intensities below ∼1 MeV in the largest events is related to the high intensities of streaming protons at energies of ∼10 MeV and above, and (3) that the spectra below 1 MeV are not constrained by other factors

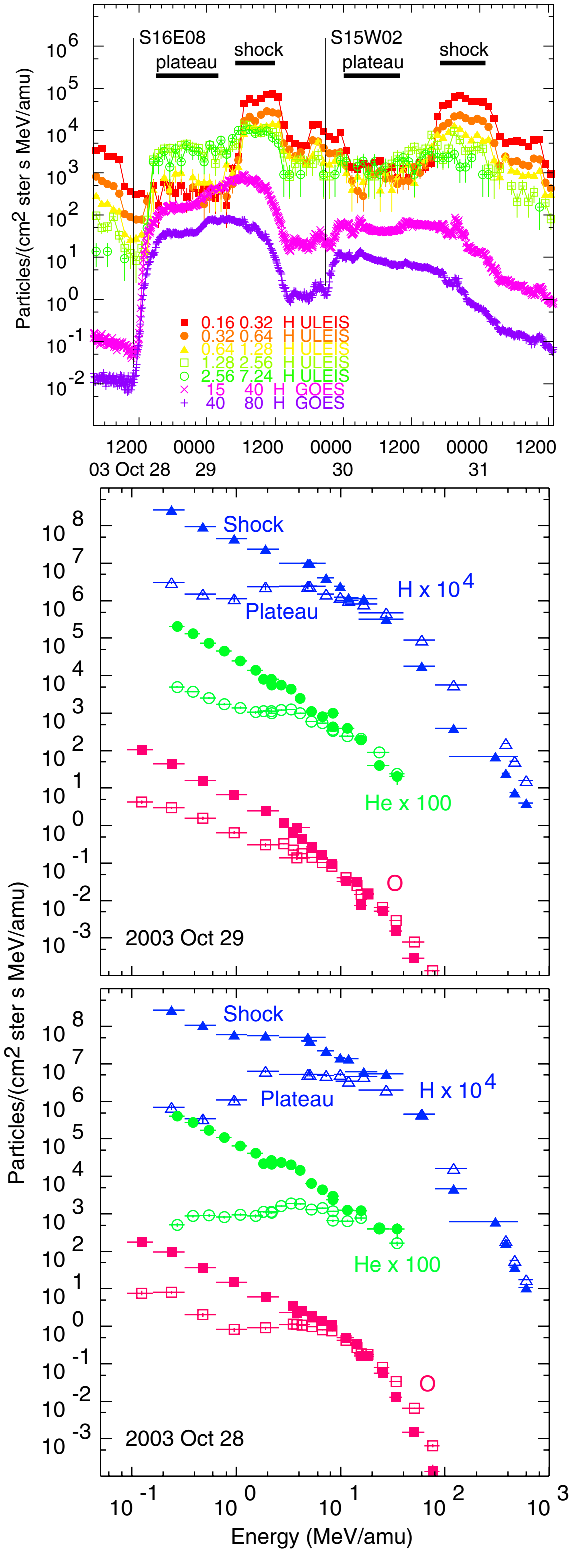

Figure 7. Upper panel emphasizes the time history of low-energy protons during the two GLEs of 2003 October (for higher energies see Figure 1). The lower panels compare the spectra of H, He, and O during the time periods selected for the plateau (open symbols) and the subsequent shock region (filled symbols) in each event. The shock spectra also show that the instruments we use are quite capable of measuring intensities well above those on the event plateaus.

(A color version of this figure is available in the online journal.)

such as scattering on ambient pre-event waves. Observations in small events like that of 1998 May 2 validate the conclusions from the larger events.

The 1998 May 2 event has a reasonably well-defined temporal plateau even though strong streaming effects are absent. Early in a central-meridian event the magnetic field from the observer is connected to the weak western flank of the shock. With increasing time, the connection point moves along the shock from the flank (where the shock is weak) toward the nose (where the shock is strong), while at the same time the strength of the shock may decrease as it moves outward. The end result may be that the observer is connected to a region of shock of approximately constant strength prior to the approach of the shock itself.

When high intensities of higher-energy ($\geqslant$10 MeV) protons are absent, as in the 1998 May 2 event, the plateau energy spectrum rises continuously below $\sim$1 MeV. The low-energy spectrum is not limited by velocity dispersion, nor is it suppressed or delayed by scattering against ambient waves. The strong suppression of low-energy particles does not exist during the rise phase of the largest events (see Reames 2009a); the waves must grow later as the proton intensities rise to the plateau. Also, low-energy protons are not initially limited by streaming of protons of the same low energy in the largest events. This is seen by the order of magnitude higher intensities of the $<$1 MeV protons in the 1998 May 2 event where no limiting is seen. For large events with high intensities of protons of $\sim$10 MeV, before the $\sim$1 MeV protons have any opportunity to stream outward and generate new waves themselves, they are scattered mercilessly as they encounter the waves generated by the protons of $\sim$5, $\sim$10, or even $\sim$100 MeV at smaller μ that have filled the space ahead of them. After their initial rise, few of the $\sim$1 MeV ions are able to diffuse to 1 AU through this newly generated wave field during the plateau period, suppressing the observed intensity.

For protons, peak plateau spectra in the largest events show a broad maximum in intensity from $\sim$5 to $\sim$20 MeV of $\sim$400 (cm^2 s ster MeV)$^{-1}$. However, the value of the streaming limit in any specific SEP event certainly must depend upon the plasma parameters, such as the Alfvén speed or the background wave intensity (Ng & Reames 1994; Lee 2005), in the spatial region where the limit is being determined, thus it must vary from event to event. In this paper, we have chosen to quote the largest values seen in the largest events; Reames & Ng (1998) discussed the average value for several large events of $\sim$200 (cm^2 s ster MeV)$^{-1}$ with an error, or spread, of a factor of 2 in either direction. This latter choice corresponds reasonably well with the average maximum of the events shown in Figure 4, for example. It is difficult to say if the lesser events in Figure 4 have failed to reach the streaming limit or if they simply reached the streaming limit appropriate to a somewhat different region of space. Probably both occur.

The protons below about 40 MeV from the 2005 Jan 20 event conform well to the low-energy streaming-limited conditions established in the other events. However, the intensity of 110–500 MeV protons briefly exceeds the nominal limit established from the GLEs examined by Reames & Ng (1998) by a factor of almost 10. The theory of Vainio (2003) gives a streaming limit only slightly less than the observation using the $\sim p^{-1}$ dependence of that theory. However, we must remember that the resonant wave amplitude depends upon the time integral of the number of streaming protons and upon the initial wave amplitude before the protons arrive. Energetic protons have an unusually fast rise in intensity in the 2005 January 20 event, indicating that the background wave intensity is extremely low, and we must integrate the proton streaming, however large it may be, for a finite time period in order to accumulate enough resonant waves. Thus, this extremely fast rise may mean that the intensities of high-energy protons approach the streaming limit equilibrium *from above* in this event. Thus, the nominal high-energy streaming limit may be exceeded for a sufficiently short time. However, the high-energy streaming limit remains somewhat illusive and requires further study.

The equilibrium theory of Lee (2005) predicts plateau intensity levels in agreement with observations and can predict energy spectra that peak and decrease at low energies, but a typical energy dependence of the plateau spectrum from the theory is $\sim E^{-1}$. Under some assumptions, the theory also predicts that the modulation of the ions by streaming-amplified waves increases as the A/Q power of the proton modulation, contrary to our observation of roughly similar spectral shapes for all species (see also Lee 1983). However, a variety of different forms of abundance variation are possible with this theory. Since the theory does not follow particle pitch-angle distributions in detail, it also does not correctly follow the coupling of high-energy protons at small μ to low-energy ions near $\mu = 1$ via common resonant amplified waves.

Vainio (2003) discusses the time integration required in formation of the streaming limit. He predicts that at $\sim$1 MeV, proton intensities below $\sim$10 (cm^2 s ster MeV)$^{-1}$ will continue to propagate as test particles. That is observationally correct especially if there are no significant intensities in the 5–50 MeV region. Vainio (2003) also assumes $\mu \approx 1$ and he finds that the plateau spectra vary as p^{-1}, or, non-relativistically, as $\sim E^{-0.5}$. The approximation of $\mu \approx 1$ may be more nearly valid at high energies in events like that of 2005 January 20, where the background wave intensities are initially very low and the proton anisotropies are very high.

The work of Ng et al. (2003) numerically calculates particle transport, at all values of μ, from a shock source, with time-dependent wave growth. This model shows well-defined intensity plateaus early in SEP events (see Figures 1 and 8 of Ng et al. 2003). The model shows energy spectra 10–20 hr after event onset (Figures 6 and 9 of Ng et al. 2003) where all species have intensity maxima in the 1–10 MeV amu^{-1} region. While numerical values of the plateau intensity and details of the spectral shape of these representative calculations differ somewhat from the observations, this model has clearly predicted the major features we observe and guides our interpretation of the physical processes involved.

The streaming limit does not depend at all upon the nature of the particle source itself, but only on the intensity and spectra of the accelerated particles. However, different properties of the source can cause the large variations observed in the spectra and the intensities of the protons in the 1–100 MeV region, for example. Change in the source shock geometry (see, e.g., Tylka & Lee 2006) is one possible source of such variations. Quasi-perpendicular shocks (with the shock normal perpendicular to the magnetic field vector) might generate quite hard energy spectra with modest intensities at low energies while quasi-parallel shocks generate higher intensities throughout, but with softer energy spectra. While this shock geometry itself has no direct effect on the streaming limit, resulting intensity variations could explain why some GLEs reach the low-energy streaming limit and some do not, as seen in the events compared in Figure 5, for example.

In addition to the importance of wave generation itself, which causes the streaming limit, we emphasize the importance of the evolving pitch-angle distributions in both acceleration and transport of particles arising from the dependence of the resonance condition on μ, as follows.

1. The first particles to be accelerated to a given "high" energy have $\mu \sim 0$ so that they (1) cross the shock more frequently and (2) scatter against waves produced by more abundant lower-energy protons streaming outward with $\mu \sim 1$ (see Ng & Reames 2008).
2. As these higher-energy particles scatter toward $\mu \sim 1$, their higher velocity allows them to stream out ahead of low-energy ions with $\mu \sim 1$ that are also leaking from the shock.
3. Farther upstream they begin to scatter on self-generated waves and the particle pitch-angle distribution and the wave spectrum broadens.
4. Waves produced upstream by high-energy protons with $\mu < 1$ begin to scatter the slower low-energy ions that are just beginning to arrive on the plateau with $\mu \sim 1$. These low-energy ions are strongly suppressed, and few make it to 1 AU at the time of the plateau, as we observe.

8. CONCLUSIONS

We have studied H, He, O, and Fe ion energy spectra early in large GLEs and found strong evidence of streaming-limited intensities. The two large events, 2000 July 14 and 2003 October 28, have nearly identical spectra of all species above $\sim$4 MeV amu^{-1} and the 2003 October 28 GLE appears to define the maximum streaming-limited spectrum in the energy range 0.5–50 MeV amu^{-1}. For protons, these spectra show a broad maximum in intensity from $\sim$5 to $\sim$20 MeV of $\sim$400 (cm^2 s ster MeV)$^{-1}$ and a suppression by a factor of $\sim$10 from this level by $\sim$0.5 MeV. Spectra of other ions show peaks at energies that decrease with increasing Z. Peak intensities do not occur at the same energy or rigidity for all species.

Somewhat smaller events have lower ion intensities at the peak, and the peak moves toward lower energy. For events where the intensity has decreased significantly at $\sim$10 MeV, the peak disappears and the intensity rises monotonically toward low energy, greatly exceeding intensities in the larger events below $\sim$1 MeV (Figure 5).

Guided by the theory of Ng et al. (2003), we can understand this behavior in terms of the generation and amplification of Alfvén waves by streaming protons in the region upstream of the shock. A rise in proton streaming increases the wave amplitude and increases scattering of the protons that follow; this soon throttles the streaming and limits the proton intensities at 1 AU. He, O, and Fe are test particles limited by the proton-generated waves. Low-energy ($<$10 MeV amu^{-1}) ions are strongly suppressed on the temporal plateau because they can resonate with the intense waves generated by higher-energy protons of varying pitch angle that have preceded them in the upstream region. The pitch-angle dependence of the wave-particle resonance condition is extremely important in understanding our observations.

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