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Comparing observations and expectations of SEP composition in the two December 2006 events

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Abstract: In early December 2006, a large active region (number 10930) rotated over the eastern limb of the Sun. As it crossed the disk, it produced 4 X-class flares and at least 3 halo coronal mass ejections. Two large SEP events were generated when the region was at ~E70 and ~W25 and were observed by several spacecraft, including ACE and STEREO. We have combined observations from the Solar Isotope Spectrometer (SIS) and the Ultra-Low Energy Isotope Spectrometer (ULEIS) on ACE and the Low Energy Telescope (LET) on STEREO for both SEP events. By integrating the SEP data over the duration of each event, the energy spectra for many heavy ion species (including Mg, Si, and Ca) can be analyzed in detail and the elemental SEP composition can be compared for the two events. We find significant differences in the composition of the two events, with the second event having a high Fe/O ratio, similar to that of impulsive SEP events. Both events are examined in terms of expectations from two prevailing models, but neither model completely predicts the observations.

Introduction

The Sun was very quiet in November 2006. The last half of the month yielded only one C-class x-ray flare and 3 consecutive days of sunspot numbers equal to 0. At the start of December, active region 10930 began to rotate over the Sun's east limb, bringing with it numerous x-ray flares (Figure 1). Over the next 15 days, this region produced 59 flares (C+M+X-class), including 4 X-class. At least 3 coronal mass ejections were also observed during this period (although LASCO data were continuously available only after Dec. 6 [day 340]; E. Robbrecht private communication). When the region was at longitudes of ~E70 and ~W25, two large solar energetic particle (SEP) events were generated and subsequently observed by instruments on ACE and STEREO. Measurements of heavy ion intensities as a function of energy and time were obtained using the Ultra-Low Energy Isotope Spectrometer (ULEIS) and the Solar Isotope Spectrometer (SIS) on ACE and

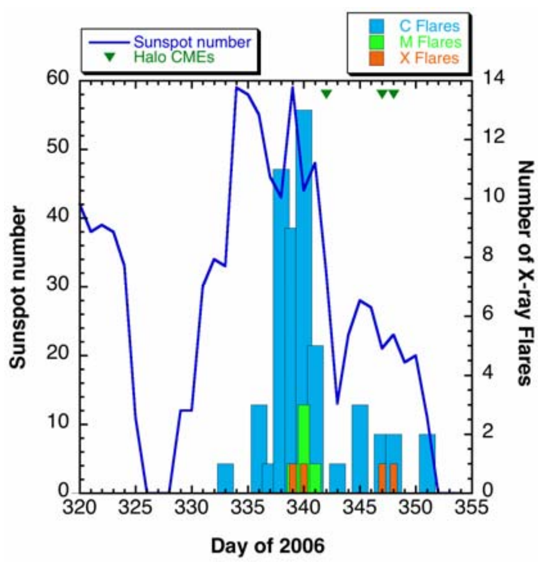

Figure 1: Flare and sunspot number for November 16 (day 320) - December 21 (day 355) 2006. Halo CME times are marked by triangles.

the Low Energy Telescope (LET) on the Behind STEREO spacecraft.

Observations

The temporal evolution of the oxygen intensity for the two SEP events is shown in Figure 2. Hourly intensities from ULEIS, LET, and SIS are given for energies between 0.1 and 50 MeV/nucleon. The solid vertical lines indicate the passages of two interplanetary shocks (as observed by the magnetometer on ACE). The effect of these shocks is clearly energy dependent with intensities peaking at the shock passages for particles with energies below a few MeV/nucleon. At the highest energies (>30 MeV/nucleon) the local effects of the shocks are minimal and the oxygen intensities peak well before the shock in both events.

The heavy ion fluence spectra were obtained by integrating over the duration of the events as indicated by the two yellow-shaded regions in Figure 2 and given in Figure 3 for He, C, O, and Fe. The agreement between the three instruments is very good and yields fairly smooth spectra over more than three decades in energy.

The spectral shapes of the two events are quite different; above 10 MeV/nucleon the spectra of the second event are significantly harder. The

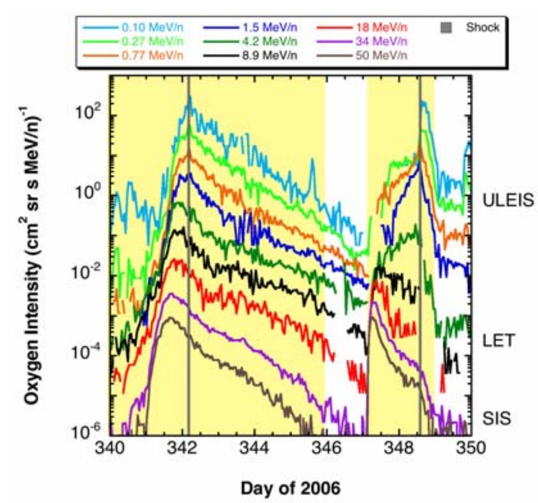

Figure 2: Oxygen intensities at different energies as measured by ULEIS and SIS on ACE and LET on STEREO. Shaded areas denote integration times for composition determination.

inflections in the second event spectra near 7 MeV/nucleon are partly due to the change in the influence of the shock. At lower energies the event-integrated spectra are dominated by the intensities very close to the shock passage, whereas at the higher energies the event-integrated spectra are dominated by intensities well upstream of the shock (>24 hours). Such an effect is not seen in the first event where the intensities, even at 50 MeV/nucleon, peak within 12 hours of the shock passage .

The elemental composition of the two events was calculated by integrating the spectra in Figure 3 from 12 to 60 MeV/nucleon. The abundances

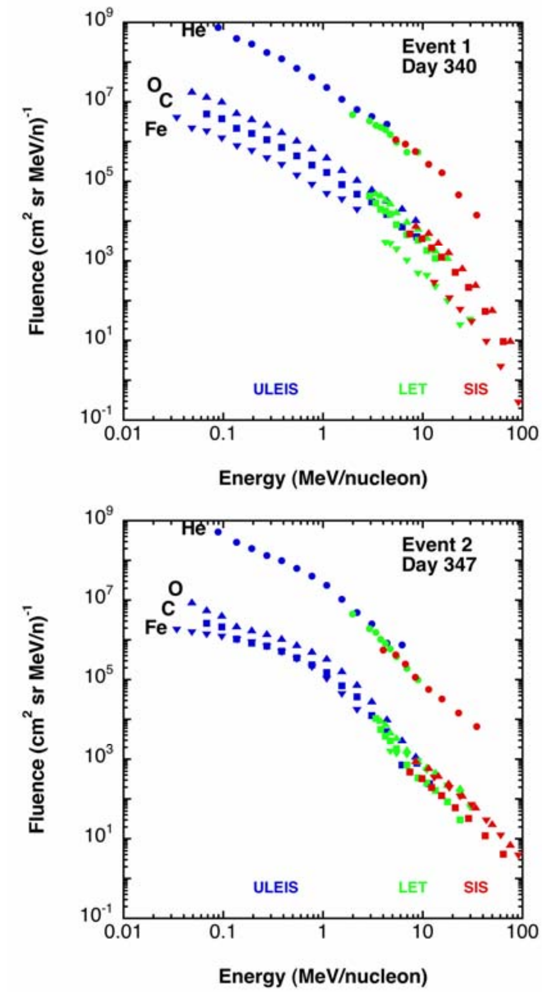

Figure 3: Event integrated spectra for the two events using observations from ULEIS and SIS on ACE and LET on STEREO.

relative to O are shown in Figure 4 along with the abundances (at 5-12 MeV/nucleon) for two types of SEP events, gradual and impulsive, as given by Reames [1]. Put simply, impulsive events are expected to reflect flare composition while gradual events exhibit composition more typical of the solar corona or solar wind. The differences in composition between the two December SEP events are dramatic in the 12-60 MeV/nucleon energy range with the first event having abundances fairly typical of gradual SEP events and the second event having abundances closely resembling that of impulsive SEP events. Similar (although less dramatic) differences are seen at lower energies (~1 MeV/nucleon) as well.

Another distinction between gradual and impulsive SEP events is the ^{3}He/^{4}He abundance. Impulsive SEP events according to [1] exhibit large enhancements while gradual events have values similar to that of the solar wind (however, this differentiation is becoming less clear as numerous large, and presumably gradual, SEP events have exhibited values of ^{3}He/^{4}He significantly enhanced over the solar wind value [e.g., 2, 3]. Measurements from ULEIS in the two December events show little difference in the ^{3}He/^{4}He ratios with values near or below 0.1% (Figure 5).

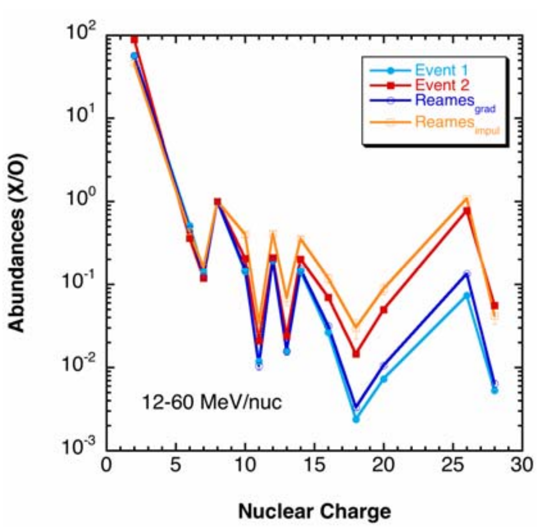

Figure 4: Event integrated abundances (relative to oxygen) obtained over 12-60 MeV/nucleon for the two events. The gradual and impulsive SEP composition (at 5-12 MeV/nucleon) reported by Reames [1] is also plotted for comparison.

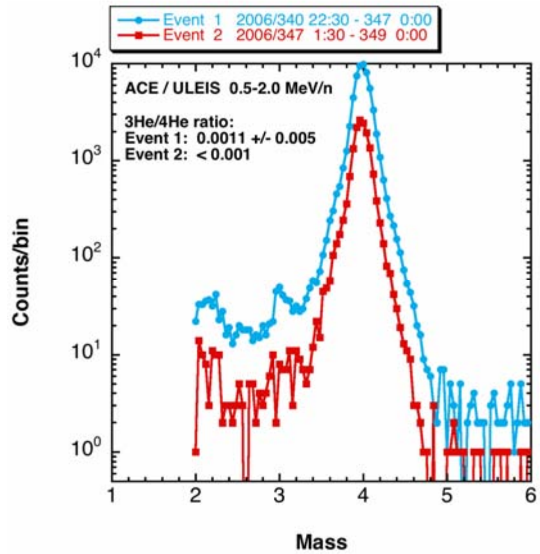

Figure 5: Helium mass histograms for the two events as measured by ULEIS. ^{3}He/^{4}He ratios are given in the top left corner of the plot.

Models

Over the last several years, several scenarios have been put forth to explain observations of large SEP events with ^{3}He/^{4}He and Fe/O ratios significantly enhanced over the gradual SEP values. The process advocated by Tylka et al. [4] is a reacceleration of remnant flare suprathermals by quasi-perpendicular shocks close to the Sun. The scenario of Cane et al. [5] involves the direct observation of flare-accelerated SEP material in addition to the shock-accelerated material of gradual events.

As both models were motivated by ACE SEP heavy ion composition observations, it is difficult to test these models, or favor one over the other, using SEP composition measured at 1 AU. Perhaps the primary, testable distinction between the two scenarios is the longitude dependence of the composition. Cane et al. suggest that the flare-related component is more likely to be detected when the observer is magnetically well connected to the flare site. The proposal of Tylka et al. does not rely on magnetic connection and thus the observed composition should be independent of an observer's longitude relative to the flare site.

Unfortunately, until the twin STEREO spacecraft are sufficiently separated in longitude, heavy ion composition as a function of longitude within a given SEP event is unavailable. However, one could argue that two SEP events originating from the same active region at two different solar longitudes, such as the December 2006 events, might be a reasonable proxy.

Discussion

The expected SEP composition under the Tylka et al. scenario is dependent on the presence of flare suprathermals and the orientation of the shock near the Sun. With 20 C-class x-ray flares in the 2 days prior to the first December SEP event, it seems appropriate to assume the availability of flare suprathermals. This is less clear for the second event where there were only 5 C-class flares in the prior 2 days. Unfortunately, the orientation of the shock is currently unmeasurable but in the Tylka et al. scenario it would need to be quasi-parallel in the first event and quasi-perpendicular in the second to be consistent with the observed SEP composition. The Fe/O ratio as a function of energy in the second event (Figure 6) is similar to calculations made by Tylka and Lee [6] where flare material is preferentially accelerated by a quasi-perpendicular shock.

According to Cane et al., the eastern and western locations of the active region for each of the SEP events predicts typical gradual event composition for the first December event and an Fe-enriched composition for the second. This is consistent with the results presented in the previous section. Cane et al. also suggest that the composition in the second event should become more Fe-rich with increasing energy as the flare-accelerated component becomes more dominant. This is supported by the data in Figure 6. However, Cane et al. point out that the flare-related component can be overwhelmed by the shock-accelerated component when the associated shock transit speed is >1000 km/s. Given a 1200 km/s shock transit speed in this event, it is surprising that the shock-accelerated component is not dominant at ~10 MeV/nucleon.

Lastly, the $^3He/^4He$ in both December SEP events is quite low (~0.1%). Both models discussed here would predict larger $^3He/^4He$ ratios for an event containing flare-related material. Given the very large Fe/O ratio in the second event, it is surprising to find only an upper limit for the $^3He/^4He$ abundance (Figure 5). Many large SEP events with substantial enhancements of Fe/O have also exhibited $^3He/^4He \geq 0.5\%$ [e.g. 2, 7].

Thus it appears that neither model completely predicts the characteristics of the two December 2006 SEP events. Future measurements of SEP composition and spectra obtained simultaneously at different observational longitudes, as will be possible with the instruments on STEREO, should provide a more conclusive test of the Cane et al. and Tylka et al. scenarios as well as vetting other suggested paradigms.

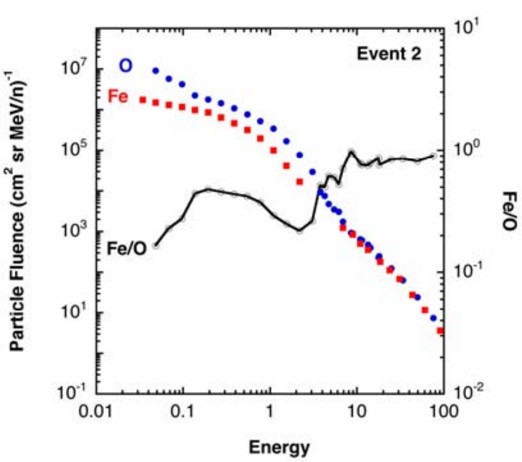

Figure 6: Event integrated O and Fe fluences (left scale) and the Fe/O abundance ratio (right scale) versus energy for the second December event.

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