Modelling Energy-Dependent Fe/O Ratios Observed Above 12 MeV/nucleon

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Abstract

Iron-to-oxygen abundance ratios measured during solar energetic particle (SEP) events are often found to be strongly energy dependent. We suggest that such behavior can be explained by rigidity-dependent diffusion effects in that the enhancement or depletion of the Fe/O ratio with increasing energy depends on whether lower- or higher-rigidity particles are better confined to the shock region. We apply a simple model to 36 large SEP events and find good results for events in which the measured Fe/O ratios are simply increasing or dereasing with energy but not for the many events that have both behaviors.

1. Introduction

Iron-to-oxygen ratios that decrease with energy are considered to be a result of rigidity-dependent escape from a shock [2] in which the lower rigidity ions are better confined to the shock region. This results in a cutoff of the lower rigidity particles (e.g., oxygen) at a higher energy than that seen for higher rigidity particles (e.g., iron). In an attempt to explain events in which the Fe/O ratio *increases* with increasing energy (e.g., [5,6]), Cohen et al. [1] present a model in which the power-law spectral index, γ, of the wave power spectrum at the shock determines whether higher-rigidity or lower-rigidity particles are better confined. Fig. 1 illustrates this by showing the results of the model (assuming exponential spectra) for wave power spectra of different spectral indices (left panel). As shown in the right panel, the $\gamma = 0$ spectrum produces a decreasing Fe/O ratio with increasing energy, while $\gamma = -5/3$ yields an increasing Fe/O ratio, and $\gamma = -1$ an energy-independent Fe/O ratio.

The model was applied to two solar energetic particle (SEP) events (one with increasing Fe/O ratios and one with decreasing Fe/O ratios) using Solar Isotope Spectrometer (SIS) data above 12 MeV/nucleon and assuming exponential shaped spectra [1]. In this paper we further test this model by applying it to 36 large SEP events observed by the Ultra Low Energy Isotope Spectrometer

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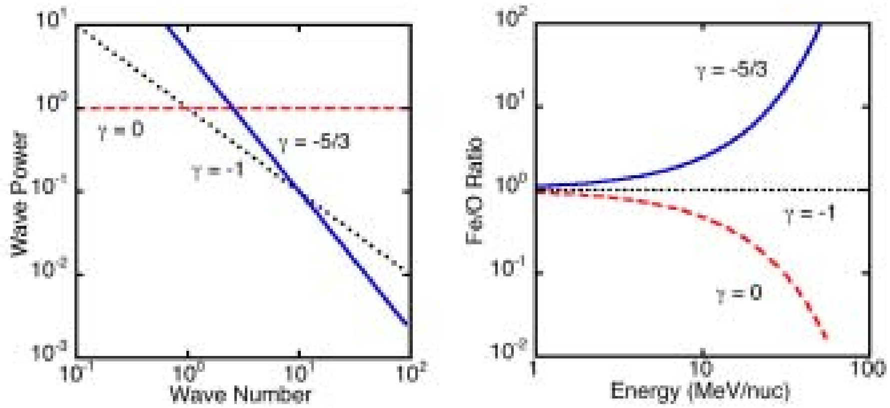

Fig. 1. Wave power spectra (left panel) in arbitrary units of different spectral indices and the energy dependence of the Fe/O ratio (right panel) predicted by the model of [1].

(ULEIS; [3]) and SIS [4] instruments on the ACE spacecraft during the years 1997-2002. We use the observed oxygen spectra from the combined ULEIS and SIS measurements as a template for the Fe energy spectra in the model rather than assuming a spectral shape.

2. Event Selection and Application of Model

Thirty-six SEP events with peak oxygen intensities > 3 x 10^{-4} (cm^2 sec sr MeV/nucleon)$^{-1}$ at 7 MeV/nucleon are identified for which data from SIS and ULEIS are available. Time periods for examination during the decay of the events are determined in the following manner: the start time is when the 0.16 MeV/nucleon oxygen ULEIS rate reaches its maximum value; the stop time is either just prior to the passage of an interplanetary shock or when the counting rates decrease sufficiently that the event is deemed ‘over’, whichever comes first.

During the specified time period, hourly combined ULEIS and SIS spectra for oxygen and iron are used to create Fe/O ratios as a function of energy. The measured ULEIS and SIS oxygen energy intervals overlap, resulting in a well measured spectrum from 0.04 to 90 MeV/nucleon. Unfortunately this is not the case for Fe; there is a gap from 3 to 10.5 MeV/nucleon. For each hour, the Fe spectrum is shifted in energy (equivalent to plotting versus rigidity instead of energy) until the energy dependence in the Fe/O ratio above 1 MeV/nucleon is minimized (this shift in energy can be related to a value of γ by assuming Q/M values for Fe and O). A simulated Fe spectrum is then created by using the observed oxygen spectrum shifted in energy as determined above, and Fe/O ratios as a function of energy are calculated and compared to the observed values. Examples are given in Fig. 2 and discussed below.

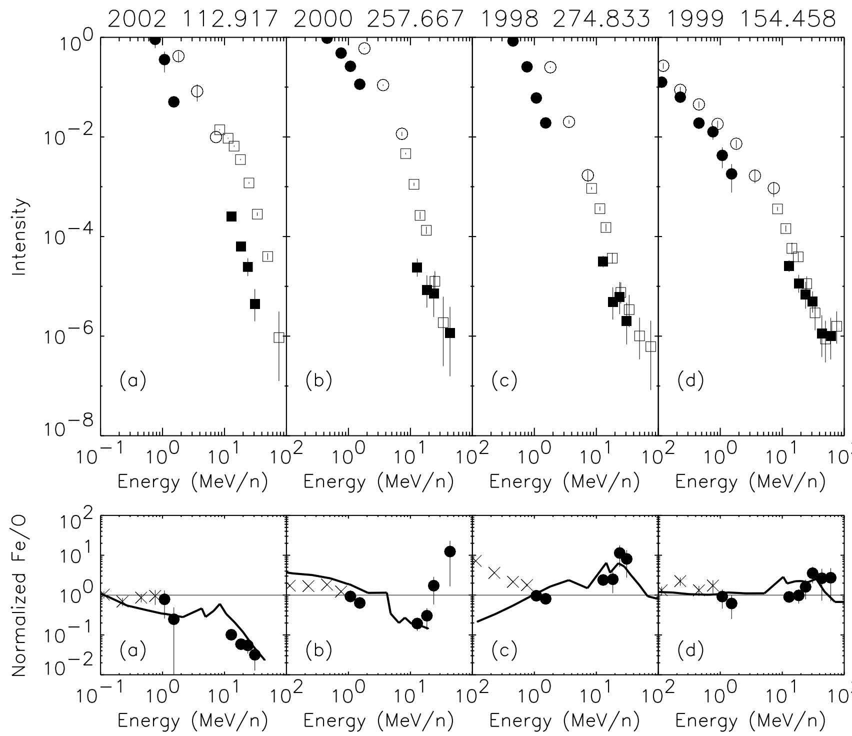

Fig. 2. Combined ULEIS (circles) and SIS (squares) oxygen (open sysmbols) and iron (closed symbols) spectra for 4 events (top panels). In the bottom panels filled circles indicate the Fe/O data used in the fit (normalized to the 1 MeV/nuc value), crosses are the remaining Fe/O values, and the solid lines show the simluated results.

3. Results and Future Work

Of the 36 events examined, 15 have Fe/O ratios that are independent of energy. Of the remaining 21 events, 6 have Fe/O ratios that strongly decrease above 1 MeV/nucleon (e.g., Fig. 2a). These events are well fit by the model (corresponding γ values range from 0 to -0.6 when charge states of 7 and 14 are assumed for O and Fe, respectively). The other 15 events show varying amounts of increase in Fe/O above 1 MeV/nucleon, with 8 having clear increases in the SIS ratios but starting at a value lower than the 1 MeV/nucleon ULEIS value (e.g., Fig. 2b). Of the rest, all but one have Fe/O values that decrease with energy between 0.1 and 1 MeV/nucleon while values above 10 MeV/nucleon are higher than that found at 1 MeV/nucleon and typically show modest increases with energy (e.g., Fig. 2c). Only 1 event (2 June 1999) appears to have an increasing Fe/O ratio above 10 MeV/nucleon and a fairly energy-independent Fe/O ratio below 1 MeV/nucleon. The model does not fit the data well as it predicts an increase in the Fe/O ratio at a lower energy than seen in the data (Fig. 2d).

The resulting 'V' shaped signature apparent in the types of events shown in Figs. 2b and 2c has been reported previously for the 15 April 2001 event [5]. As can be seen in Figs. 2b and 2c, our model cannot simultaneously replicate both the decreasing and increasing Fe/O ratio trends. When fitting data above 1 MeV/nucleon for events like Fig. 2b, the model result fits the decreasing Fe/O portion but not the increasing section at higher energies. For events such as Fig. 2c the model adequately represents the increasing trend above 1 MeV/nucleon but diverges from the data at lower energies. Previously reported fitting successes involved only data above 12 MeV/nucleon [1] so such complications were not present.

In these events it is apparent that the spectral shapes of oxygen and iron are substantially different such that a shift in energy is not sufficient to significantly reduce the energy dependence in the Fe/O ratio over a broad energy range. The 'V' shape is most likely an indication of two processes, one dominant at low energies and one at high energies. In such cases the model, which attempts to describe abundance variations due to leakage from the shock region, is only applicable to the high energy portion. More work is needed to fully explore the application of the model to these events.

Further testing of the model will also involve examining the energy dependence of other elemental ratios. It will be interesting to test the model on energetic storm particle events where the shock is locally accelerating particles and the wave power at the shock can be measured using the magnetometer instrument on ACE and compared to what the model predicts for γ.

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4. References

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