JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. A10, PAGES 20,979-20,983, OCTOBER 1, 2001

Forecasting the arrival of shock-accelerated solar energetic particles at Earth

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Abstract. Energetic particles accelerated at interplanetary shocks can result in an increased radiation dose for astronauts as well as an increased risk to satellite hardware. These shocks are known to occasionally accelerate protons to energies greater than 100 MeV and can result in very high fluxes. Advanced warning of the arrival of strong interplanetary shocks can enable steps to be taken to minimize the potential risks. In an effort to monitor and assess the radiation risk to astronauts, two real-time count rate monitors were implemented in the Solar Isotope Spectrometer (SIS) on the ACE spacecraft. These rates measure protons with energies >10 and >30 MeV. Since ACE is located at the L1 Lagrangian point, these rates provide information and warning up to 1 hour before an interplanetary shock reaches Earth. Using ACE and GOES, data we have examined examples of shocks and associated energetic particles that have been detected at ACE and were later observed near Earth in an effort to develop more fully the forecasting capability of ACE. Because of the limited amount of solar activity during 1997-1999, this current work is primarily a proof of concept.

1. Introduction

Recently, the Committee on Solar and Space Physics (CSSP) and the Committee on Solar-Terrestrial Relations (CSTR) examined the risk of increased radiation hazards to astronauts working on the International Space Station (ISS). The results of the study were published in the report "Radiation and the International Space Station: Recommendations to Reduce Risk" and indicated that there is a significant probability that several construction flights of the ISS could be impacted by penetrating particle radiation events. Of primary concern to the astronauts are events with significant fluxes of >10 MeV/nucleon particles. During these events, astronauts could experience a significantly increased radiation dose (especially if they are performing extravehicular activity), possibly affecting their future health and flight schedules. Additionally, increased exposure could require more frequent rotation of the crews, thereby impacting space station schedules and costs.

The radiation hazard can be especially high when a suppression of the geomagnetic cutoff is coincident with high fluxes of energetic particles [*Leske et al.*, this issue]. The geomagnetic cutoff is suppressed during geomagnetic storms when a favorable orientation of the interplanetary magnetic field is combined with increased solar wind pressure on the magnetosphere [*Shea et al*, 1999]. The same shocks which compress the magnetosphere in these geomagnetic storms may accelerate substantial numbers of protons (and heavier ions) to energies greater than 100 MeV. Such local acceleration (as well as turbulence near the shock, which can confine the particles to the shock region) can result in intensities at the shock which temporarily dominate an ongoing solar energetic particle (SEP) event, as was the case during the October 19, 1989, SEP event. During the decline of this event, the passage of the associated shock resulted in a greater than fivefold increase in >100 MeV protons as measured by the GOES 7 spacecraft (Figure 1). Since the time profile of particle intensities in a typical SEP event decays relatively smoothly (especially at $E > 100$ MeV), such an increase during the decay phase is unexpected and therefore would not be predicted without information about the arriving shock. Forehand knowledge of such a situation would allow astronauts to move to more protected areas of the ISS or to reschedule planned extravehicular activities.

A large effort was made in the 1980s to understand shocks and their acceleration of particles to MeV energies. It was found that shocks can be divided into two broad categories, parallel (where the angle between the shock normal and the magnetic field, ϑ_B, is 0°-45°) and perpendicular (where ϑ_B is 45°-90°). At parallel shocks, ions gain energy through Fermi acceleration, a process where the ions are reflected by waves upstream and downstream of the shock. Since the wave fields are converging, the particles are being reflected by moving barriers and thus gain energy. The more times an ion is

Paper number 2000JA000216.
0148-0227/01/2000JA000216$09.00

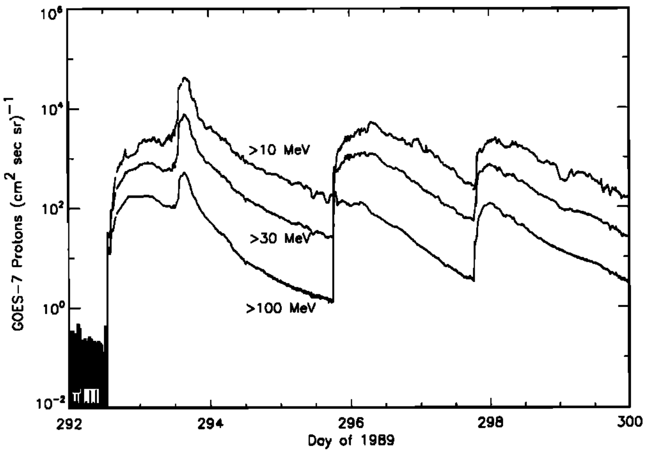

Figure 1. GOES 7 fluxes of >10, >30, and >100 MeV protons during the events of October 1989

reflected, the more energy it gains. At perpendicular shocks, shock drift acceleration is the primary process involved. In this case the particles drift according to **v** x **B** forces in the direction of the induced electric field at the shock and are accelerated. The more time the particle spends near the shock (under the influence of the electric field), the more energy it gains. In both cases the amount of energy a particle gains depends on ϑ_B and the speed of the shock. In shock drift acceleration the energy gain also depends on the pitch angle of the ion. Comprehensive overviews of both types of shock acceleration have been presented by *Armstrong et al.* [1985] and *Scholer* [1985].

Unfortunately, although the general acceleration processes have been established, the details of shock acceleration of energetic particles and their subsequent transport involve a number of interplanetary parameters, and it is hard for particle acceleration events such as that of October 19, 1989, to be accurately forecast from observations of the coronal mass ejections (CMEs) typically driving the shocks [*Feynman and Gabriel* 2000]. It is also difficult to predict from observations of erupting CMEs whether a shock will develop that will still be capable of accelerating significant numbers of particles when it arrives at Earth. *Kahler et al.* [1984] found a significant correlation between the speed of CMEs observed with the Solwind coronagraph and the associated proton fluxes measured by the IMP 8 and ISEE 3 spacecraft. However, for a given CME speed the observed proton fluxes varied from event to event by as much as 4 orders of magnitude [see *Kahler et al.*, 1984; Figure 5].

The Advanced Composition Explorer (ACE) [*Stone et al.*, 1998a], at the L1 Lagrangian point, is far enough upstream of the Earth that it can provide advanced warnings (~1 hour) of incoming shocks. Since few shocks are strong enough to accelerate particles to high energies, it is not adequate to merely observe the shock at L1. A measure of the energetic particles locally accelerated by the shock when it passes ACE is needed for a reasonable indication of what will occur when the shock reaches Earth. The Real-Time Solar Wind monitoring system [*Zwickl et al.*, 1998], which is a compilation of ACE measurements telemetered in near real time, provides the necessary information for monitoring shock events.

2. Instrumentation and Data Selection

The Solar Isotope Spectrometer (SIS) on ACE measures energetic ions from ~10 to 100 MeV/nucleon [*Stone et al*, 1998b]. A stack of large-area silicon detectors is used to determine the kinetic energy, nuclear charge, and mass of incoming particles. The large geometry factor of SIS allows measurements of low fluxes of heavy ions to be made with good temporal resolution. These measurements require trajectory information which is obtained from the top two detectors, which are position sensitive. While energetic protons typically do not deposit enough energy in these detectors to exceed the set thresholds (which are optimized for higher-Z particles), the energy thresholds of single detectors deeper in the stack are low enough that the associated single-detector rates are dominated by protons.

Shortly before launch, provisions were made to include two such rates from SIS among those telemetered continuously as part of the Real Time Solar Wind monitoring system on ACE [*Zwickl et al.*, 1998]. These two rates are the counting rates of the single T4 detector and the coincidence between the T6 and T7 detectors (Figure 2). The T4 and T6•T7 rates respond primarily to >10 and >30 MeV protons, respectively, similar to the I3 and I4 rates on the GOES spacecraft. Increases in these SIS rates due to a passing shock should be followed by corresponding increases in the GOES rates when the shock reaches GOES.

In an effort to study this correlation and develop the capability for near-real-time utilization of the SIS rates in a warning system, we have examined the data obtained since launch in August 1997 through December 1999 for shock-related increases in the T4 rate. An indication that the increases are a result of local shock acceleration is that both

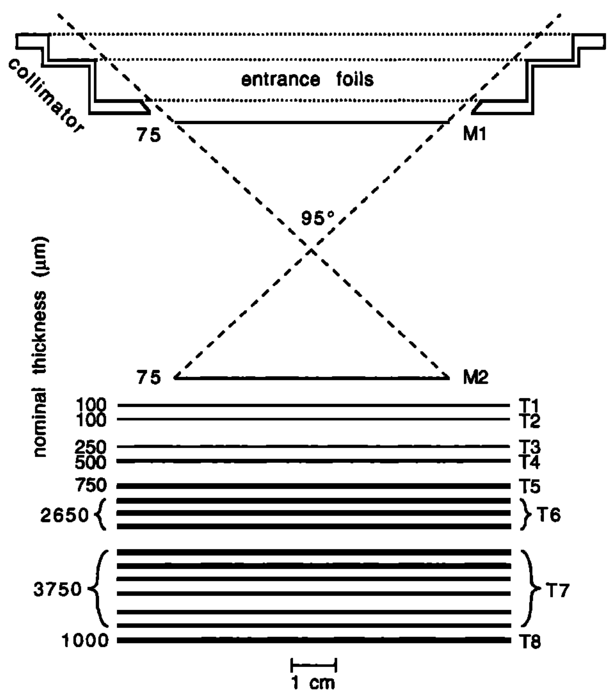

Figure 2. Schematic of the Solar Isotope Spectrometer (SIS; one of two telescopes). Two real-time rates are derived from the single T4 detector and the coincidence of the T6 and T7 detectors.

the T4 and T6•T7 rates rise together with negligible energy dispersion. Energy dispersion is typical of SEP events with acceleration occurring near the Sun, since the higher-energy particles travel at a greater velocity and thus arrive first. In addition, we have examined the solar wind proton speed profiles from the Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) level 2 data (see *McComas et al.* [1998] for the instrument description) for abrupt increases typical of a shock. An increase in the I3 rate of GOES was then searched for, and if found, taken as an indication that the shock reached Earth and was still accelerating particles.

Five time periods were identified in the SIS data, but solar wind plasma and magnetic field data were only available for three of them. The SIS T4, GOES I3, SWEPAM proton velocity and density, and magnetic field strength profiles from the Magnetometer (MAG) (see *Smith et al* [1998] for the instrument description) for the three selected time periods are plotted in Figure 3. Shocks identified by the MAG and SWEPAM teams (C. Smith, private communication, 2000) are indicated by vertical lines.

3. Observations

As can be seen from Figure 3, the time profiles of the rate increases observed by SIS and GOES can be remarkably similar. During the 1998 day 267 event, many of the small variations in the rates are apparent in both data sets. This is an indication of how little the properties of the shock had changed during the propagation from L1 to the Earth's magnetosphere. Although GOES is rarely outside the magnetosphere, the bow shock and magnetopause have little effect on the shock particles at these energies.

The time delays between the particle increases seen at ACE and GOES were determined by temporally shifting the two

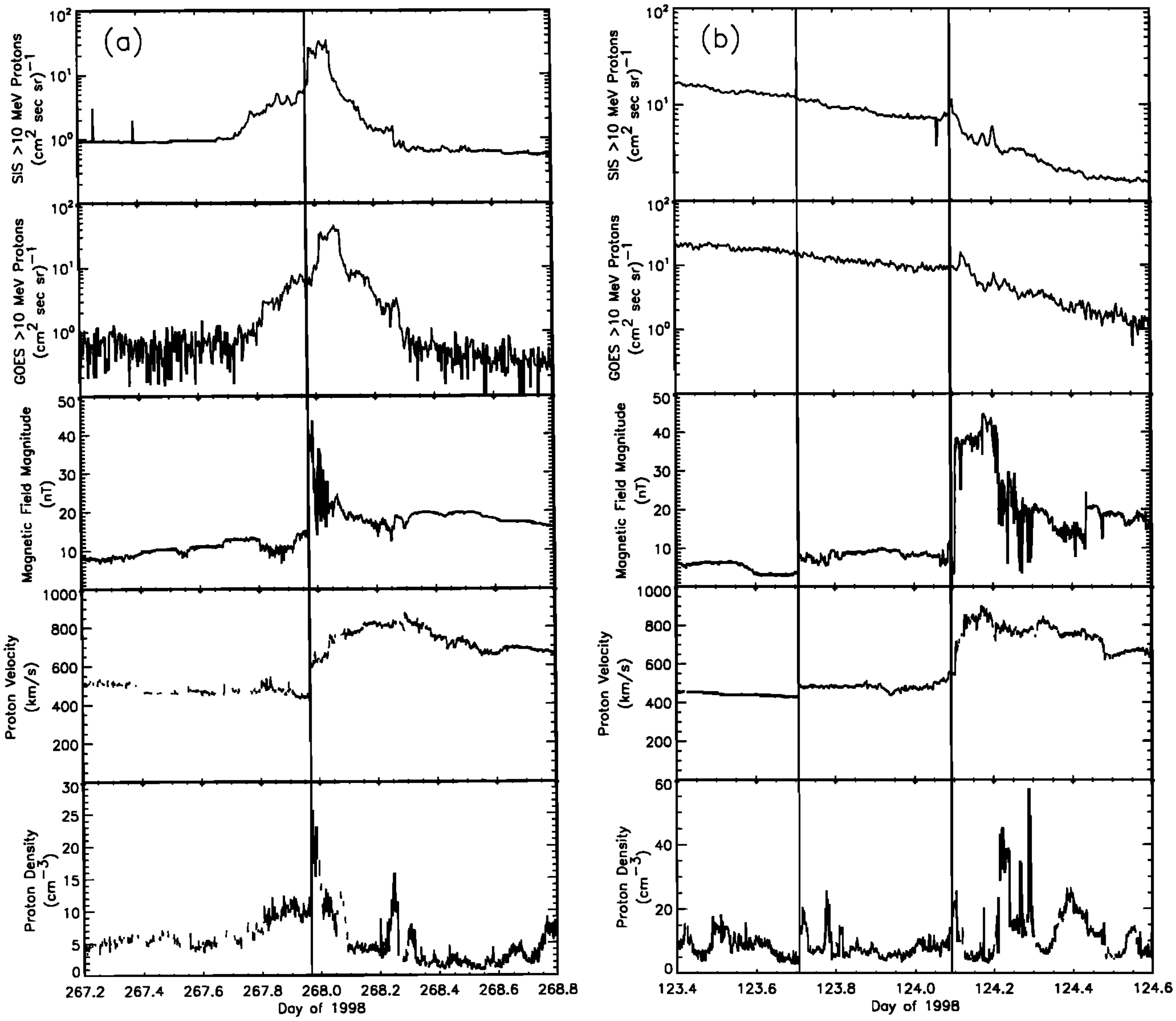

Figure 3. (a-c) Three selected time periods where shock-accelerated >10 MeV protons were observed first by SIS (first panel) and then later by GOES (second panel). The third through fifth panels present the solar wind magnetic field magnitude, proton velocity, and density as measured by the MAG and SWEPAM sensors on ACE during the events. Shocks identified by the MAG and SWEPAM teams are indicated by the vertical lines. The list of shocks did not include 1999 data, so none are indicated in Figure 3c.

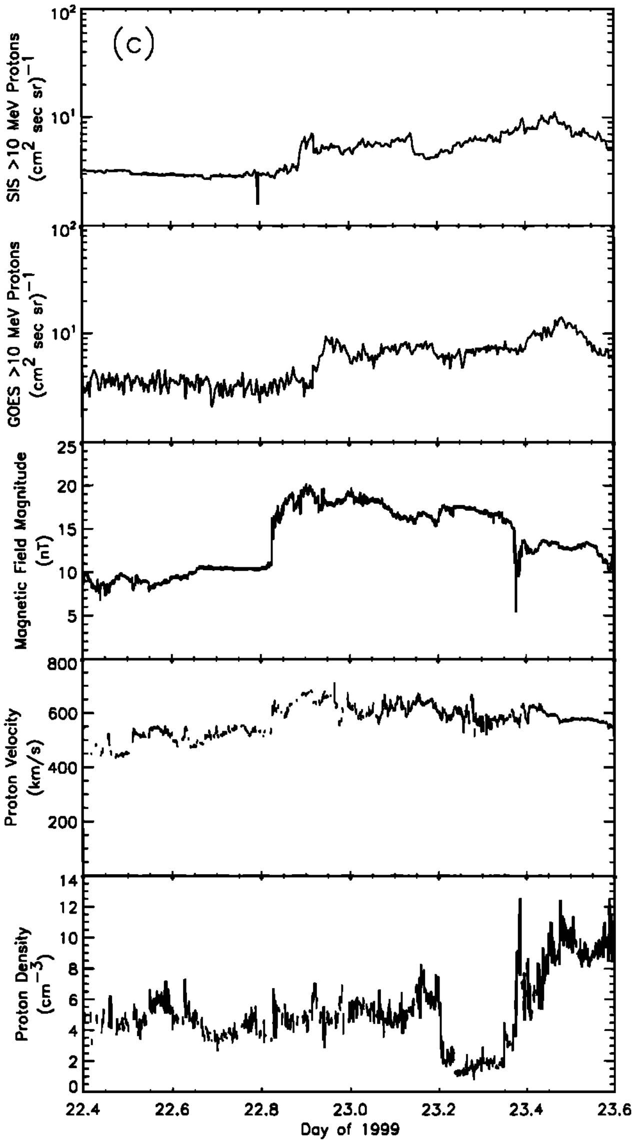

Figure 3. (continued)

profiles relative to each other until distinguishing features were best matched by eye. These time delays are given in Table 1 along with uncertainties which reflect the variation of the determined time delays from the different features of the rate profiles.

Using the proton velocity components and densities from the SWEPAM data and the magnetic field components from the MAG data, the shock speed and normal were calculated using the equations given by *Abraham-Shrauner and Yun* [1976]. The normal plane is defined as the plane that contains the magnetic field vectors (ahead of and behind the shock) and the vector difference of the flow velocities on both sides of the shock. Equations involving five different combinations of these vectors can be used to define this plane, and a consistency check between the different expressions provides an indication of the reliability of the normal vector determination. The shock speed is then calculated using the reduced Rankine-Hugoniot conservation equations (which combine Maxwell's equations with the assumption of mass flux and momentum flux conservation). The time required for the shock to traverse the distance between L1 and Earth at the calculated radial speed is given in Table 1 for time periods 1998 day 267 and 1999 day 022. It was not possible to obtain a shock speed for time period 1998 day 124 since the simplified equations used here were not applicable to the conditions at that shock. The given uncertainties indicate the variation in the calculated shock normal vector from the different equations given by *Abraham-Shrauner and Yun.*

Although there are only two examples, and the uncertainty is large on the calculated time delay for the 1999 day 022 shock, it appears that the time delays observed between the SIS and GOES rates are consistent with the calculated radial shock speeds. This indicates that shock-related particle fluxes observed by SIS are a reasonable indication of what GOES will measure 30-60 min later and that the time delay can be determined from the shock speed as calculated from the measured plasma parameters.

4. Summary

With the construction of the International Space Station (ISS), the radiation environment to which astronauts are exposed is of particular concern. The assembly of the ISS will require numerous extravehicular activities during which astronauts are more susceptible to the increased radiation possible from high intensities of solar energetic particles. The ability to provide advanced warning of such conditions can greatly help to mitigate this risk.

In examining time periods in which shock-related particle increases were observed initially by SIS on ACE and subsequently by GOES, we have shown that warnings of 30-60 min are possible. Since the vast majority of shocks passing ACE are not strong enough to accelerate energetic particles to >10 MeV and cause a significant increase in their intensities, it is not sufficient to merely identify the occurrence of a shock at ACE. Measurements of energetic particles in real time are also required. SIS provides two real-time count-rate monitors which respond to protons at energies of >10 and >30 MeV. These data are available via the Internet at http://sec.noaa.gov/ace/SIS_3d.html and http://www srl caltech.edu/ACE/ASC.

The work presented here is primarily a "proof of concept." Additional examples are needed to evaluate the usefulness and accuracy of this technique. It is also important to determine how many shock-accelerated increases are observed by SIS but not by GOES; how many increases are measured by GOES and not identified with the proposed technique; as well as how many incidents are forecast correctly.

Table 1. Shock Time Delays[a]

Time Period			SIS-GOES ΔT, min	Shock Derived ΔT, min
Year	Day	Time, UT		
1998	267	2330	43 ± 7	38 ± 3
1998	124	0209	36 ± 10	
1999	022	2120	66 ± 5	69 ± 30

[a] SIS, Solar Isotope Spectrometer

Acknowledgments. We thank the SWEPAM and MAG teams and the ACE Science Center for providing level 2 data for shock analysis. We thank Adam Szabo for helpful discussions regarding the shock calculations. The GOES data were contributed by the U.S. Department of Commerce, NOAA, Space Environment Center. This work was supported by NASA at the California Institute of Technology (under grant NAG5-6912), the Jet Propulsion Laboratory, and the Goddard Space Flight Center.

Janet G. Luhmann thanks Stephen W Kahler and Ronald D. Zwickl for their assistance in evaluating this paper.

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(Received June 30, 2000; revised October 25, 2000; accepted November 17, 2000.)