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Research on Medium- and Short-Term Forecasting Models for Solar Proton Events (Postprint)

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Abstract

The prediction of solar proton event flux is of paramount importance for the radiation hardening design of spacecraft and the extravehicular activities of astronauts. For space missions with durations of less than one year, we employed empirical statistical methods to confirm that during both solar active and quiet years, the integrated flux of solar proton events exceeding 10 MeV, 30 MeV, and 60 MeV within various time intervals of 1-365 days conforms to a log-normal distribution, with the standard deviation and expected value of the logarithmic flux varying as logarithmic functions of mission duration. Based on this foundation, we constructed a short-to-medium-term forecasting model for solar proton flux. This model is capable of providing, for both solar active and quiet years, the distribution of proton event flux exceeding 10 MeV, 30 MeV, and 60 MeV within various time intervals of 1-365 days at a specified confidence level, thereby furnishing predictions of solar proton event flux for short-to-medium-term space missions to mitigate unnecessary risks.

Full Text

Study on the Short-to-Medium Term Forecast Model of Solar Proton Events

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Abstract

The prediction of solar proton event fluences is of critical importance for the radiation hardening design of spacecraft and the extravehicular activities of astronauts. For space missions with durations of less than one year, we have

employed empirical statistical methods to demonstrate that the integrated fluences of solar proton events greater than 10 MeV, 30 MeV, and 60 MeV conform to log-normal distributions across various time periods from 1 to 365 days during both solar active and quiet years. Furthermore, the standard deviation and expectation value of the logarithmic fluence vary with mission duration according to logarithmic functions. Based on these findings, we have constructed a short-to-medium term forecast model for solar proton fluences. This model can provide, for both solar active and quiet years, the distribution of proton event fluences greater than 10 MeV, 30 MeV, and 60 MeV over 1-365 days at specified confidence levels, thereby offering predictions of solar proton event fluences for short-to-medium term space missions to mitigate unnecessary risks.

Keywords: Solar proton events; Solar proton fluences; Short-to-medium term forecast model; Space missions

1. Introduction

Solar proton events represent a manifestation of violent energy release during solar eruptions. When solar eruptive activities (flares or coronal mass ejections) occur, large quantities of high-energy particles are ejected. Through various acceleration mechanisms, these particles are typically accelerated to high energies across extensive spatial scales ranging from the Sun's lower atmosphere to interplanetary space, eventually being observed by space detectors near Earth and ground-based particle monitors. Since the vast majority of ejected high-energy particles are protons—accounting for over 90% of the total high-energy particle population, with alpha particles being the second most abundant and particles with charge numbers greater than three being rare—these events are commonly referred to as solar proton events. The acceleration of high-energy particles in these events involves various radiation mechanisms, particle transport, and specific magnetic field configurations, constituting a rather complex problem. Corresponding to different solar activities and acceleration processes, solar proton events can be broadly classified into two categories: impulsive events and gradual events [1-2]. In actual solar proton events, however, impulsive and gradual proton events cannot be clearly separated; instead, mixed-type proton events typically occur with both flares and CMEs present simultaneously, where acceleration processes from both phenomena coexist [3].

Solar proton events are also among the most destructive space weather phenomena, posing threats to the safety of spacecraft and astronauts outside Earth's magnetosphere and atmosphere, and severely impacting human space activities. Consequently, predicting the occurrence of solar proton events in advance is essential during spacecraft design phases and human space missions to implement appropriate measures for risk mitigation. Depending on the required lead time for proton event forecasts, prediction efforts primarily include long-term forecasting, medium-term forecasting, short-term forecasting or alerts with 1-3 days lead time, and nowcasting.

Long-term forecasting predicts the integrated fluence or energy spectrum of proton events over extended periods (typically more than one year), applicable to spacecraft flight planning, orbit design, attitude control formulation, and the design of space-sensitive instruments and detectors. Internationally prevalent long-term proton event forecast models include the King model [4], JPL model [5-6], ESP model [7-12], and MSU model [13]. In China, Li Tingting et al. [14] evaluated proton fluences under different solar activity levels using data from four solar cycles and established a new model. Short-term forecasting primarily predicts the occurrence and magnitude of proton events, providing risk mitigation basis for astronaut extravehicular activities, spacewalks, and operation of scientific equipment sensitive to high-energy radiation. Major space environment forecasting institutions both domestically and internationally provide 1-3 day short-term forecasts or alerts for proton events. The Space Environment Prediction Center of the National Space Science Center, Chinese Academy of Sciences, and the NOAA Space Weather Prediction Center both provide daily probability forecasts for proton events for the next 1-3 days. Numerous studies on short-term forecasting of solar proton events have been conducted, with forecast factors including 10 cm radio flux, active region configuration parameters, magnetic field parameters, and other related factors. In addition to traditional statistical analysis methods, artificial intelligence techniques have also been incorporated [15-19]. Proton event alerts provide forecasts with lead times of minutes to hours. Two typical operationally running models are the PROTONS model from NOAA's Space Weather Prediction Center [20-22] and the Proton Prediction System (PPS) from the Air Force Research Laboratory [23-26], which primarily forecast the likelihood and timing of proton event occurrence. Xiong Senlin et al. [27] demonstrated that using real-time flux data greater than 10 MeV from the ACE satellite for solar proton event alerts is feasible in practical applications.

Medium-term forecasting typically refers to predictions of proton event fluence and temporal distribution with lead times of several weeks to months. Medium-term forecasting of solar proton events is still in its infancy, with no highly effective methods or mature and practical models yet available. Space engineering has substantial demand for medium-term event forecasting, yet when considering solar proton events, analyses typically reference the most severe historical events or a typical proton event without statistical justification. Article [28] utilized solar energetic particle observation data from 1967-2014 to preliminarily calculate the distribution of greater than 10 MeV proton event fluences for mission durations of less than one year at specified confidence levels. This paper continues to employ the statistical methodology from article [28] to conduct statistical analysis of proton event fluences greater than 30 MeV and 60 MeV, confirming the distribution forms of solar proton fluences at these two energy channels. On this basis, we establish a unified short-to-medium term forecast model for solar proton event fluences greater than 10 MeV, 30 MeV, and 60 MeV, providing predictions of solar proton event fluences for the execution of short-to-medium term space missions.

2. Data Processing

The solar proton data employed in this study are identical to those used in article [28], primarily obtained from the OMNI website (<http://omniweb.gsfc.nasa.gov/>). The selected data span the period from 1967 to 2014, including energy channels greater than 10 MeV, greater than 30 MeV, and greater than 60 MeV. Missing data were supplemented using interpolation methods. For the second half of 2001, and for 2002 and 2003, where large data gaps existed, we supplemented the dataset using observations from GOES satellites.

A proton event was considered to have occurred when the daily average flux of protons greater than 10 MeV exceeded 1 PFU; periods not meeting this condition were considered event-free, with solar proton fluence recorded as zero. We separately considered solar active years and solar quiet years. Solar active years are defined as the period from 2.5 years before to 4.5 years after the solar cycle maximum, with the remaining four years of the activity cycle classified as solar quiet years. In our statistical sample, the considered solar active years include 1967-1972, 1977-1983, 1987-1993, 1998-2004, and 2010-2014, totaling 32 years; the remaining 16 years are solar quiet years.

3. Distribution of Solar Proton Fluences

Article [28] has confirmed that the distribution of solar proton event fluences greater than 10 MeV follows a log-normal distribution. This section employs the same statistical methodology to confirm the distribution forms of solar proton fluences greater than 30 MeV and greater than 60 MeV. Corresponding to different time periods from 1 to 365 days, we calculate the cumulative solar proton integrated fluence for greater than 30 MeV and greater than 60 MeV through a sliding time window approach. The specific method is as follows: assuming the total sample comprises N consecutive days, when the assumed mission duration is n days (where $n = 1, 2, 3, 4, \dots, 365$), we perform daily sliding of the time window to obtain $N-n+1$ sample sets of n -day duration. By accumulating the daily integrated fluence of solar protons greater than 30 MeV and greater than 60 MeV across these $N-n+1$ sample sets, we obtain the solar proton fluence values for the corresponding energy channels over the n -day period.

For assumed mission durations of n days, we compared the relationship between solar proton fluence distributions and log-normal distributions in both solar active and quiet years. By establishing a series of solar proton fluence thresholds, we calculated the proportion of samples with fluence below a given threshold within n days, i.e., the value of $(i \times 100)/(M+1)$, where i represents the number of samples with fluence below the given threshold and M represents the total number of samples. When plotted on normal distribution coordinates, the relationship between solar proton fluence and proportion values revealed that, in both solar active and quiet years and across different time periods from 1 to 365 days, the solar proton fluences greater than 30 MeV and greater than 60 MeV essentially conform to log-normal distributions. Figure 1 [FIGURE:1] displays

the distributions of solar proton fluences greater than 10 MeV, greater than 30 MeV, and greater than 60 MeV for time periods of 5 days and 50 days during solar active and quiet years. The vertical axis represents proton fluence on a logarithmic scale, while the horizontal axis represents the proportion of samples with fluence below a given threshold on normal distribution coordinates. The figure demonstrates that most solar proton fluence data for greater than 30 MeV and greater than 60 MeV are distributed along a straight line, indicating that the solar proton fluence distributions essentially follow log-normal distributions. From this, we can derive the probability density function for solar proton fluence distributions:

$$f(F) = \frac{1}{F\sigma\sqrt{2\pi}} \exp \left[-\frac{(\ln F - \mu)^2}{2\sigma^2} \right]$$

where F represents the solar proton fluence over the assumed mission duration, σ is the standard deviation of the logarithmic fluence, and μ is the expectation value of the logarithmic fluence.

Based on the distribution plots of solar proton event fluences, the values of σ and μ in the probability density function can be obtained through linear fitting. In space missions, large solar proton fluences are of greater concern; therefore, we performed linear fitting only on data points above the 50% probability level. This yields different fitted values of σ and μ for various time periods from 1 to 365 days and for different energy channels greater than 10 MeV, greater than 30 MeV, and greater than 60 MeV. When plotting time on the horizontal axis and the fitted values of σ and μ on the vertical axes, we find that the values of σ and μ can be described by logarithmic functions of time, as shown in Figure 2 [FIGURE:2]. The specific logarithmic function formulas are:

$$\mu(d) = a_0 + a_1 \ln(d) + a_2 (\ln(d))^2$$

$$\sigma(d) = a_0 + a_1 \ln(d) + a_2 (\ln(d))^2$$

where d is the time variable (in days) and a_0 , a_1 , and a_2 are function parameters. The fitting results for these parameters corresponding to solar active and quiet years and to solar proton fluences greater than 10 MeV, greater than 30 MeV, and greater than 60 MeV are presented in Table 1 .

4. Model Establishment and Validation

In actual space mission assessments, it is typically required to provide the proton fluence for the mission duration at a specified confidence level. The confidence level is a statistical quantity based on the probability distribution function. A 95% confidence level indicates a 95% probability that the given proton fluence

will not be exceeded, meaning there is only a 5% chance of exceeding the specified fluence. Using the parameters obtained from the fitting described in the previous section, we can determine the probability density of solar proton fluences, enabling us to calculate the proton fluences greater than 10 MeV, greater than 30 MeV, and greater than 60 MeV for different space mission durations at specified confidence levels. Figure 3 [FIGURE:3] presents the probability distributions of proton fluences greater than 10 MeV, greater than 30 MeV, and greater than 60 MeV for assumed mission durations of 5 days and 50 days during solar active and quiet years. By locating the horizontal coordinate corresponding to a point on the curve at a given vertical coordinate, we can obtain the proton fluence at a particular confidence level. For example, during solar active years with a mission duration of 50 days, to determine the proton fluences greater than 10 MeV, greater than 30 MeV, and greater than 60 MeV at a 95% confidence level, we examine the proton fluence probability curves for the 50-day mission duration in Figure 3 and find the horizontal coordinates corresponding to the vertical coordinate value of 1-95% for the three energy channel curves to be $2.96 \times 10^9 \text{ p} \cdot \text{cm}^{-2}$, $9.80 \times 10^8 \text{ p} \cdot \text{cm}^{-2}$, and $3.98 \times 10^8 \text{ p} \cdot \text{cm}^{-2}$, respectively, which satisfy the required proton fluences.

To validate the model's predictive performance, we compared model predictions with actual observations of solar proton fluences for different time periods from 1 to 365 days at various confidence levels. Figure 4 [FIGURE:4] presents the comparisons between model predictions and observed results for proton fluences greater than 10 MeV, greater than 30 MeV, and greater than 60 MeV during solar active and quiet years. The figure shows that overall, the model predictions agree well with observations, though during solar quiet years at a 99% confidence level, significant deviations occur for mission durations longer than approximately 30 days (varying somewhat across energy channels). Additionally, the model's predictive performance is strongly related to mission duration and confidence level. Model predictions at lower confidence levels show better agreement with observations than those at higher confidence levels, and predictions for shorter mission durations agree better with observations than those for longer mission durations.

Furthermore, we compared our model predictions with those of the JPL model for greater than 10 MeV proton fluences during solar active years with a mission duration of 1 year (365 days), as shown in Figure 5 [FIGURE:5]. In the figure, the red line represents the JPL model predictions, while the black line represents our model's predictions. Overall, the difference between our model predictions and the JPL model predictions is not substantial. At the same confidence level, our model predicts slightly higher greater than 10 MeV solar proton fluences than the JPL model, with this difference decreasing as confidence level increases (i.e., as the probability on the vertical axis decreases). For instance, at a 99% confidence level, our model predicts a greater than 10 MeV solar proton fluence of $6.12 \times 10^{10} \text{ p} \cdot \text{cm}^{-2}$, while the JPL model predicts $5.88 \times 10^{10} \text{ p} \cdot \text{cm}^{-2}$, a difference that is essentially negligible.

5. Summary

Using solar energetic particle observation data spanning 48 years from 1967 to 2014 and employing empirical statistical methods, we have confirmed that the distributions of proton fluences greater than 10 MeV, greater than 30 MeV, and greater than 60 MeV over time periods from 1 to 365 days essentially follow log-normal distributions during both solar active and quiet years, with the standard deviation σ and expectation value μ of the logarithmic fluence satisfying logarithmic functions of time. Based on these findings, we have constructed a unified short-to-medium term forecast model for solar proton fluences. This model can provide solar proton fluences greater than 10 MeV, greater than 30 MeV, and greater than 60 MeV for space mission durations from 1 to 365 days at confidence levels above 50%, thereby offering predictions of likely encountered solar proton event fluence levels for spacecraft executing short-to-medium term missions and providing important support for spacecraft radiation hardening design and astronaut extravehicular activity protection.

Additionally, we compared model predictions with actual observations of solar proton fluences. The model predictions agree well with observations overall. Specifically, predictions at lower confidence levels show better agreement with observations than those at higher confidence levels, and predictions for shorter mission durations agree better with observations than those for longer mission durations. We also compared our model with the JPL model, finding only slight differences between the two. These results provide a foundation for the application of short-to-medium term forecasting models for solar proton events.

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Figures

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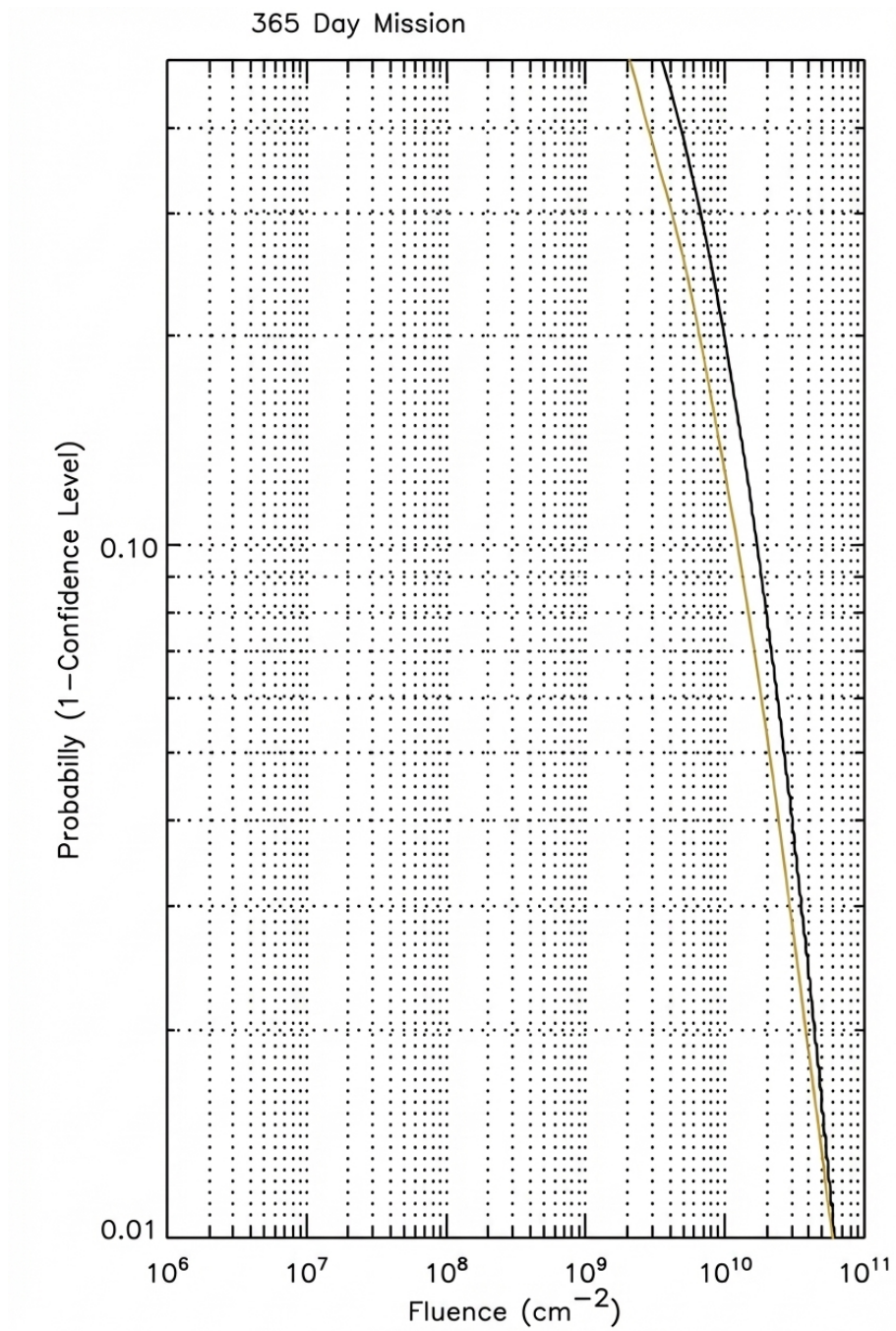


Figure 1: Figure 13