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The JPL proton fluence model: an update

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Abstract

The development of new technologies and the miniaturization of sensors bring new requirements for our ability to predict and forecast hazardous space weather conditions. Of particular importance are protons in the energy range from 10s to 100s of MeV which cause electronic part and solar cell degradation, and pose a hazard to biological systems in space and to personnel in polar orbit. Sporadic high-energy solar particle events are a main contributor to the fluences and fluxes of such protons. A statistical model, JPL 1991 (J. Geophys. Res. 98 (1991) 13,281), was developed to specify fluences for spacecraft design and is now widely used. Several major solar proton events have occurred since that model was developed and one objective of this paper is to see if changes need to be made in the model due to these recent events. Another objective is to review the methods used in JPL 1991 in the light of new understandings and to compare the JPL methods with those used in other models. We conclude that the method used in developing JPL 1991 model is valid and that the solar events occurring since then are completely consistent with the 1991 model. Since no changes are needed we suggest that the name of the model be changed to "the JPL fluence model". © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The sporadic increases in high-energy fluxes and fluences produce environments that are hazardous to spacecraft, instruments and biological systems in space. The most important particles for the interplanetary environment are protons and ions with energies of 10 MeV or more. These particles also effect space systems within the magnetosphere as they propagate through the Earth's magnetic field. For many deleterious effects the relevant parameter is the total fluence of particles accumulated during a mission. For others it is the peak flux. For the design of space systems several models have been developed that allow an estimate of the expected environments to be made. Among these models is the JPL 1991 fluence model (Feynman et al., 1993) that has received wide acceptance. It provides a statistical estimate of the fluences that a spacecraft in the interplanetary medium can be expected to experience.

Here we study the observations of solar particle events that have occurred since the JPL 1991 model developed and find that they fall well within the distribution of fluences found in our earlier studies. No changes in the model are required by them. We also test the validity of underlying assumptions used in the model development in the light of comments that have appeared in the literature.

There are two sources of particles with energies >10 MeV in interplanetary space, galactic cosmic rays and solar energetic particles (SEP). The interplanetary environment caused by the galactic cosmic rays is relatively easy to predict (Adams et al., 1981; Adams, 1986; Mewaldt et al., 1988). The particles are present at all times and the flux is dependent on the solar cycle. We will not discuss them further here. For more information see Smart and Shea (1985).

The prediction of SEP presents more of a challenge. These particles appear in space only intermittently and the

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environments that present major hazards to space technology are due to the occasional very intense SEP events. These very major events drive spacecraft design and occur perhaps 3 or 4 times a solar cycle. Two types of solar events that produce energetic particles have been distinguished (Reames et al., 1994). Sometimes particles are accelerated at the Sun in association with impulsive X-ray flares. These events are rich in electrons but have relatively small proton fluxes. The more hazardous events are associated with gradual, long duration X-ray flares. These flares are usually accompanied by coronal mass ejections (CMEs) which propagate in the solar wind (Sheeley, 1985). If the CME velocities are super-Alfvénic a shock will form in the solar wind. This shock is believed to accelerate particles to the MeV energy range (Kahler et al., 1984). Particles that escape from the shock region propagate to the Earth. The first particle may arrive at the Earth in as little as 25 min after the initiation of the CME (Cliver et al., 1982).

2. The JPL model

The JPL 1991 model used data collected between 1963 and early 1991. Since then several large SEP events have occurred. In this section we review the methods used in JPL 1991 in the light of new understandings and compare the 1991 results with the results obtained with the data extended to 1998.

The JPL 1991 is one of a class of fluence models which follow the lead set by King (1974). The basic method for developing a fluence model contains several steps:

1. Select a data set.
2. Identify solar energetic events and calculate the fluence during each event.
3. Determine the mathematical form of the probability distribution of event fluences.
4. Choose a class of missions of interest (for example, a mission in interplanetary space at I AU for 3 years). Using the function determined in step 3, generate the total fluence for a large random sample of such missions.
5. Using this large sample, calculate the distribution of mission-integrated fluences and express the results as the "confidence level" that the total mission fluence will not exceed a given value. In the JPL case, graphs giving mission-integrated fluences at 1 AU for missions of 1–7 years in duration have been published (Feynman et al., 1993) and can be used directly from that paper.

At each step of this process of model development choices have to be made, and each choice is subject to debate in the community. In this paper we discuss considerations involved in steps 1–4 and the choices that were made in the JPL 1991 model development.

2.1. The data set

In order for a data set to be appropriate for statistical analysis it must satisfy several criteria. First, the data set must be commensurate in that the efficiency of observation of an event must be the same throughout the data set. Second, the events must be defined in such a way that the probability of having an event is independent of whether a previous event has taken place or not. Third, the distribution of fluences must be smooth, i.e. without discontinuities.

Energetic particle events have been observed for almost half a century using ground-based neutron monitors and space-based instruments. The observed fluences and fluxes depend on the energy range measured and on where the instrument is. The Earth's magnetic field provides a rigidity-dependent shield (for a more extensive discussion see Smart and Shea, 1985), so that events detected on the ground and in low Earth orbit will not have the same fluences as the same events detected in high Earth orbit or in interplanetary space. If the fluence in interplanetary space is known, the fluence in lower orbit can be calculated from a knowledge of the Earth's field (Smart and Shea, 1985). It is, however, very difficult to calculate the interplanetary fluences and fluxes from low orbit observations. Thus, the data set used to develop the model should not include data from detectors that are effected by the Earth's shielding. In addition, since instruments differ from one another in sensitivity, the ideal situation would be to use data from a single instrument. Fortunately, a series of closely related instruments (Armstrong et al., 1983) on board IMP 1, 2, and 3 and OGO 1 and IMP 5, 6, 7, and 8 has collected data from 1963 to the present. These data constitute a nearly commensurate set in that the fluences and fluxes measured during an event will be almost independent of the time at which the event took place, whether in 1967 or in 1987. These data were used to generate the JPL 1991 fluence model. IMP 8 data sets have also been used exclusively in Tylka et al. (1997) heavy-ion model and the peak flux model developed by Xapsos et al. (1998). In contrast, the data set used to generate the models developed at Moscow State University (MSU) mixed IMP/OGO data with data from instruments on MIR (Nymmik, personal communication, 1999).

IMP 8 carried several instruments that measured the fluxes of high-energy protons. Data from the Applied Physics Laboratory (APL) instrument were used in the JPL model. Comparison of APL proton data to those obtained by the Goddard and Chicago instruments aboard IMP 8 for the energy range >10 MeV shows excellent agreement (Tylka, personal communication, 1999). The APL proton data for this energy range are used for this update.

2.2. Identification of events and calculation of fluence during each event

The next step in model development is to choose a definition of "an event". The statistical techniques required to gen-

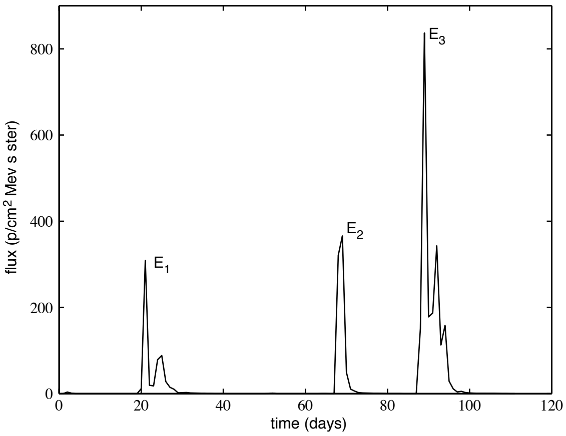

Fig. 1. The definition of "an event". Events, denoted by E_1, also E_2, E_3, are sums of fluences from successive CMEs. The time intervals between events are defined as the difference between the beginning times of two sequential events. For example, τ_1 is the difference between the beginning of event E_1 and event E_2.

erate the mission-integrated fluences from the event fluences are greatly simplified if the "events" are independent of one another. However, the problem is that each super-Alfvénic CME produces energetic particles but the initiation of CMEs is not independent of one another.

The fastest CMEs that cause hazardous environments typically occur in a series from a single activity center as it is carried across the face of the Sun (Malitson and Webber, 1962; Feynman et al., 1993; Feynman, 1997; Ruzmaikin and Feynman, 1998). Thus, if each separate CME was considered to be an event the data set would not have statistical properties that would justify random sampling. To mitigate this problem the "events" used in the JPL model were defined as the total fluence occurring over a series of days during which the fluence exceeded a selected threshold. More precisely, a fluence event was assumed to begin when the daily fluence exceeded background and assumed to end when the fluence fell below threshold for two consecutive days. With this definition a single event will usually encompass all of the CMEs from an individual activity center. The time of an event was defined as the first day the fluence exceeded the threshold value. This definition of "an event" is illustrated in Fig. 1 where we show a typical section of the observed data containing three events. The irregular variation within events E_1 and E_3, for example, is caused by such series of CMEs.

To obtain an event list from the data set we first define a background level which is assumed to be due to galactic cosmic rays at the magnetopause. The selected level must be small compared to the fluxes and fluences considered dangerous. Second, we unify adjacent flux bursts into fluence events. This allows us to reduce the problem to consideration of discrete events, $E_i,\ i = 1, 2, 3, \ldots$ in Fig. 1, separated by random time intervals, τ_i. The event magnitude and time intervals between events are treated as independent random numbers. The result of unifying the clustered fluxes into distinct events is that the distribution of τ_i can be approximated by the Poisson distribution (see Section 2.4 below).

2.3. The distribution of event fluences

In developing a model, random samples are taken of a mathematical function representing the distribution of event fluences. This function is obtained by fitting the observed distribution of the event magnitudes with some function. We discuss two issues, the stability of the observed distribution in time and the selection of the function to represent the distribution.

The question that is addressed first is how the distribution defined from the observations has changed since June of 1991. Ideally the distribution of observed fluences would be an accurate representation of the underlying true distribution. If this is the case the form of the distribution will not change when we add new observations. In early studies of proton events the distribution changed markedly with the addition of new events. For example, King (1974) showed that the events that had been observed at that time could best be described as forming two distinct distributions, a lower-fluence set of events and a single high-fluence event which occurred in August 1972. Subsequent studies using larger data sets (Feynman et al., 1990, 1993) demonstrated that a single distribution with a high-energy tail was the more correct description.

The right panel in Fig. 2 shows the distribution of events during the time studied in JPL 1991, i.e. from day 331 of 1963 to day 126 of 1991. The abscissa is chosen so that the data points will lie on a straight line if the data have a log-normal distribution. The left panel in Fig. 2 shows the same data with the addition of the events that took place between Day 126, 1991 and Day 365, 1998; note for example that large new events have been added between fluence values of 2×10^9 and 6×10^9 particles/cm^2. As demonstrated in the figure, the two lines fitting the data for fluences greater than the average fluence are the same within the accuracy of the fits. No change need be made on this basis to the probability distribution used in the model.

Thus, the events that have taken place since JPL 1991 was developed make no changes whatsoever to the fluences predicted. Apparently, the data set used in JPL 1991 is stable and is a good representation of the underlying true distribution. It is therefore no longer necessary to label the model by the year during which the data set terminated. The model can now be called simply the JPL model. Of course, the stability of the distribution should be checked from time to time but it can be expected to remain stable for the next several solar cycles.

Note that the "confidence level" of an estimate of the fluences is a formal statistical quantity evaluated on the basis of the probability distribution function. The "confidence level" is not changed by increasing the accuracy with which

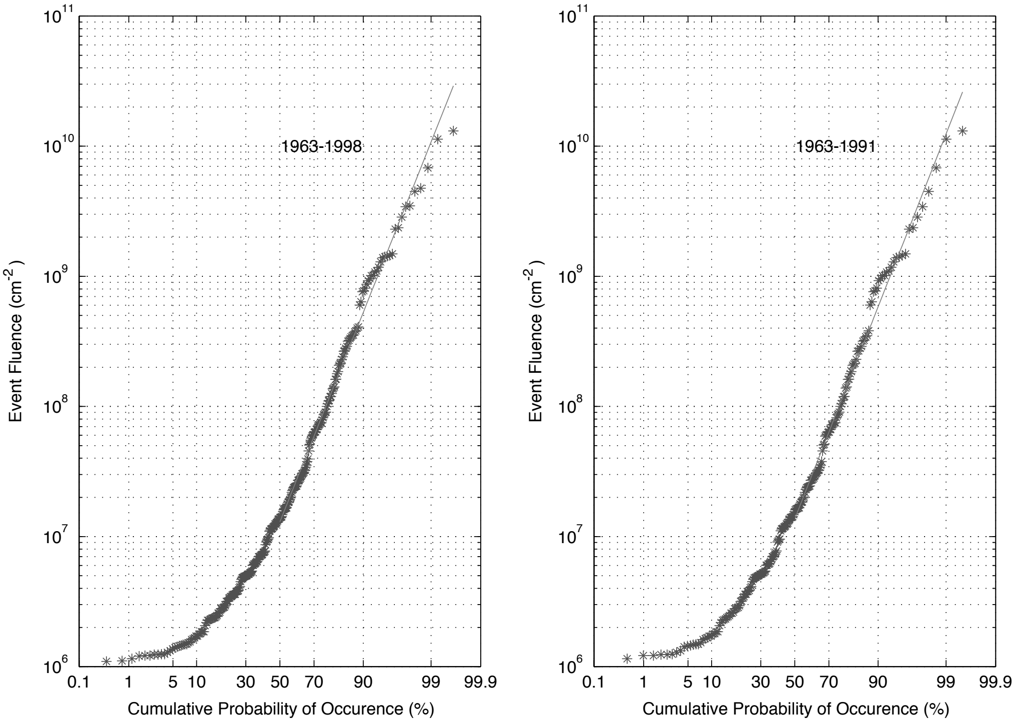

Fig. 2. Comparison of event distributions for two time periods: 1963–1998 (left panel) and 1963–1991 (right panel). Straight lines have been fit to the data for fluences greater than the average (50%) fluence. The slopes (1.25 ± 0.1 and 1.26) and the positions of the intercepts (7.11 and 7.14) are essentially same for both data sets.

the function is determined and hence is not a function of the number of points in the data set. The choice of an appropriate "confidence level" is an engineering decision that must be made on the basis of tradeoffs between radiation risk and other factors in the mission design.

As pointed out in our description of JPL 1991 (Feynman et al., 1993), the data in its entirety are not distributed as a log-normal. This can easily be seen in Fig. 2 from the deviation from a straight line for fluences less than the average (50%). A log-normal distribution should not be expected for the entire range of fluences. Such a distribution would require that the number of events decreased as the fluence both increased and decreased. This is reasonable for the large fluence events but certainly not for the small fluence events. There is no reason to expect only a small number of small events. Nevertheless, as described in Feynman et al. (1993), we chose to represent the distribution by a log-normal distribution.

The problem of choosing a function to represent the underlying true distribution has many interesting features. We note first that the total fluence during a mission is dominated by the number of large events it experiences. The number of small events is not important (except perhaps for the special case of extrapolation of the distribution to events near the Sun). One large event is equivalent to about 500 small events. The cumulative fluence from small solar events at Earth can be estimated as comparable to the effects of the known cosmic ray background. Keeping in mind that the purpose of this model is to specify an environment to use as a design criteria for a future mission, it is much more important to estimate the highest fluence part of the distribution correctly than it is to represent the entire distribution.

For the JPL 1991 model we also studied several other fitting functions including Types II and III extreme value functions and kappa functions (Gabriel et al., 1991), but the fits to the high fluence part of the observed distribution was not improved. These data have also been fit to a power law (Gabriel and Feynman, 1996) and more complex empirical functions (Nymmik, 1999a). We note that there is a very important technical difficulty in using a power law for the underlying distribution to be sampled. In a power law the probability of having an event does not decrease with the size of the event fast enough to prevent extremely large events from being predicted, and the predicted total mission fluence will be effected by these huge events. This appears to be unrealistic. Thus, in order to use a power law a choice must be made as to the largest fluence that can occur. That is the power law must be cut off at some value and, unfortunately, the fluences calculated from the model will depend on the cutoff value. If the assumed cutoff (i.e. worst case event) is simply a guess, this is entirely unsatisfactory. An attempt to find an experimental value for the cutoff by examining the lunar rock isotope data has been unsuccessful (Nymmik, 1999b). The log-normal used in JPL 1991 and other models (Tylka et al., 1999) has the advantage of not requiring an arbitrary cutoff. As a corollary, there is no worst case event in the JPL model. There is a finite probability of getting an event, no matter how large, but the probability that extremely large events occur is extremely small and the estimate of the total fluence at a given confidence level converges to a finite value for all confidence levels.

2.4. Sampling the distribution and dependence on the solar cycle

The next step in model development consists of sampling the distribution of event fluences to obtain a sample of mission-integrated fluences.

Here a decision must be made on how frequently SEP events are expected to occur. There is a strong variation in the high-energy particle environment with the solar cycle. A mission flying near solar minimum will experience many fewer SEPs and a much more benign environment than a mission flying during an active solar period. This solar cycle difference needs to be expressed in the predicted environments. In Feynman et al. (1993) we argued on the basis of the observed values of the total yearly fluence that the solar cycle could be divided into two periods, a quiet period near solar minimum and a 7-year hazardous period during the rest of the cycle. The newly added events follow the same pattern. We suggested that the chances of a truly major event during the quiet period were small enough so that those years could be neglected in comparison with the active years. We also suggested the active years all be treated alike because the observed yearly fluences did not show a preference for solar maximum. A more correct approach would be to compare the annual sunspot number to the number of events per year, rather than the total annual fluences. Fig. 3 compares the observed number of SEP events per year in the JPL data set to the annual sunspot number for sunspot numbers >50, i.e. solar active years. The correlation of these data is only 0.6. These results agree with many other studies that have reported that the yearly sunspot number and the number of events are not strongly correlated during active years (Shea and Smart, 1990; Kurt and Nymmik, 1998; see however Nymmik, 1999a).

The determination of the mission-integrated fluence was made in three steps. First we found the distribution function for single fluence events, $f_0(E)$, see Section 2.3. Then we defined the distribution function $f_k(\Phi)$ for the fluences Φ summing a given number of events k. Mathematically, this is the problem of finding the distribution function for the sum of equally distributed independent random variables (magnitudes of individual events). In the JPL91 model this problem was handled by sampling the (log-normal) approximation to the distribution function of single events.

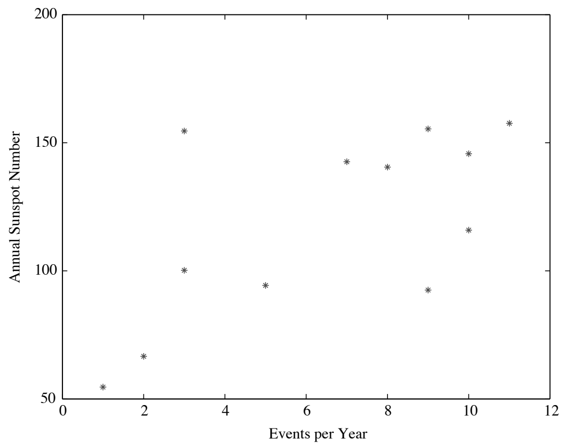

Fig. 3. The annual sunspot number versus the number of solar proton events per year in three solar cycles. The correlation coefficient between these two numbers is 0.6.

To calculate the distribution of mission-integrated fluences $f_t(\Phi)$ we need to know how many events occur during a mission lasting a given time interval t. Because the number of events is random, another probability, a probability $p_k(t)$ that k events occur in time t comes into play. Then

$$f_t(\Phi) = \sum_{k=1}^{\infty} p_k(t) f_k(\Phi), \tag{1}$$

where the sum takes into account the fact that during the time interval t one ($k = 1$), two ($k = 2$), or any number of events can occur.

In the JPL91 model the function $p_k(t)$ was assumed to be Poissonian. Now we show that this assumption is well justified. For this purpose, we evaluate the distribution of time intervals between the events from observations. Because there are no events between any two events this distribution obviously coincides with $p_0(\tau)$. We use again the daily flux for the solar protons with energies exceeding 10 MeV in the period from day 331 in 1963 to day 350 in 1998, total 112,456 days. To take into account the solar cycle modulation discussed above we select the active periods, namely 2 years before solar maximum through 4 years following the maximum (Feynman et al., 1993). This gives us three time series: (1) from day 1, 1966 to day 365, 1972; (2) from day 1, 1977 to day 365, 1983; (3) from day 1, 1987 to day 365, 1993. The time series of the events above the threshold 1.08×10^6 particles/cm^2, the omnidirectional daily equivalent of the threshold 1 particle/(cm^2 s sr), for these periods are shown in Fig. 4. There are 59 events in the first period, 68 events in the second, and 75 in the third period.

The empirical distribution (histogram) of the time intervals between events is shown in Fig. 5. It is fit by an exponential function $p_0(\tau) = e^{-\mu\tau}$ with μ determined by the slope of the line in this figure.

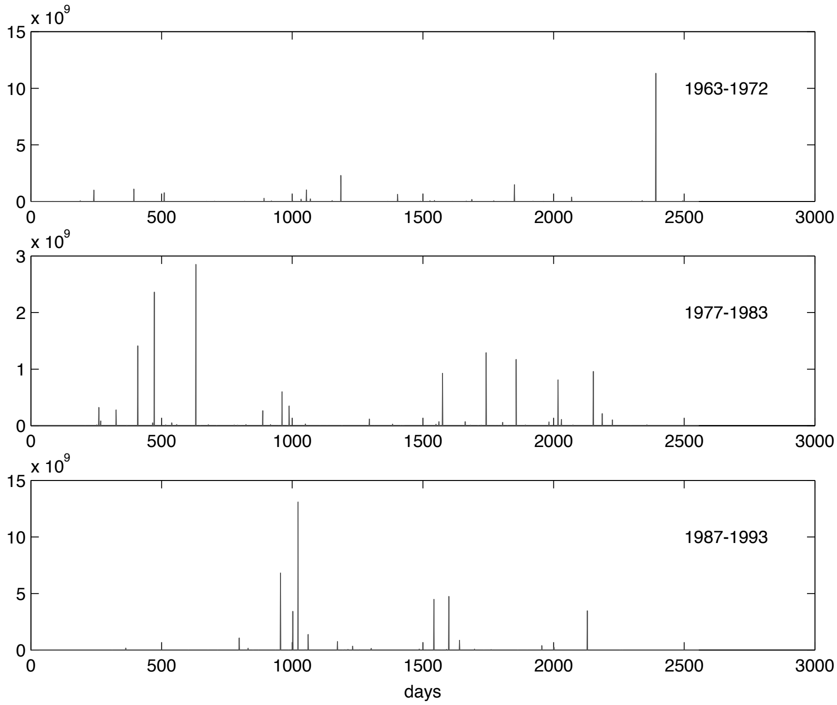

Fig. 4. The solar proton events for active years in three solar cycles. The data are for particles of energy exceeding 10 MeV.

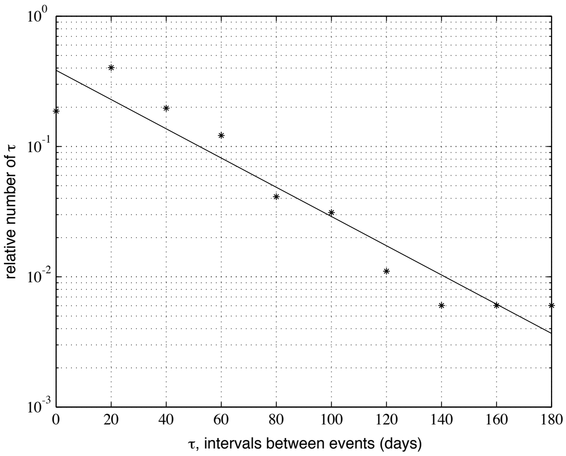

Fig. 5. The empirical distribution of times between the events (stars) corresponding to the distribution shown in Fig. 4. The straight line shown is the least-squares fit to the data. Since the ordinate is in semilog coordinates this line corresponds to an exponential fitted to this empirical distribution.

There are several ways to determine the function $p_k(t)$ from the known $p_0(\tau)$. The simplest one is to proceed iteratively and find $p_1(\tau)$, $p_2(\tau)$, etc. To do this we notice that for a small time interval δt, $e^{-\mu\,\delta t} \approx 1 - \mu\,\delta t$ and hence $\mu\,\delta t$ is the probability of having one event in this small time interval. Consider now the interval $0:t+\delta t$ in which one event occurred. It can occur either in $0:t$ or in $t:t+\delta t$. Then the probability of this occurrence is the sum of two products:

$$p_1(t+\delta t) = p_1(t)(1-\mu\,\delta t) + p_0\mu\,\delta t.$$

The solution of this equation yields $p_1(t) = \mu t \exp(\mu t)$. The iteration of this procedure results in the Poisson distribution:

$$p_k(t) = \frac{(\mu t)^k}{k!}e^{-\mu t}, \quad k = 0, 1, 2, \ldots \,. \tag{2}$$

The figure shows that the Poisson distribution is a reasonably good fit to the distribution of the time between events and justifies the use of the random sampling scheme used in JPL 1991.

3. Discussion

We have confirmed that the choices made in developing the JPL 1991 model are justified. The choice of data and the definition of events have resulted in a data set that is close to that randomly distributed in time. The division of the solar cycle into active and quiet periods expresses the main aspect of the solar cycle variation, i.e. these events are common during the active period and very uncommon during the quiet period. The number of events for active periods (sunspot number >50) has such a large variation for a given sunspot number that it is reasonable to treat every active year the same, without regard to sunspot number. This is very convenient since the purpose of the model is to predict environments for the design of spacecraft. If we had to predict the sunspot number to estimate the number of events per year the procedure would have to begin by a prediction of the sunspot number during the mission. The prediction of the sunspot numbers is almost as uncertain as the prediction of the launch date of the mission. We are fortunate that the sunspot number does not have to be predicted. Most spacecraft should be designed to fly during active solar periods unless there is some really impelling reason to know that the mission will fly during solar minimum.

The distribution chosen to fit the observed event fluences is a good representation of the data for events larger than average. As argued in JPL 1991 the failure of this function to fit the small events is unimportant, except for missions that approach the Sun. The literature contains other suggested functional fits (Gabriel and Feynman, 1996; Nymmik, 1999a), each of which has its own problems. All of these fits are based on fitting the large fluence events as accurately as possible. Each suggested fit implies some physical model underlying the event fluences. At this time we do not have a good enough grasp on what that physics is to justify any of the functions theoretically. The log-normal distribution has a major advantage in that no arbitrary high fluence cutoff is required.

Perhaps our most important result is that the major solar events that occurred since JPL 1991 was developed have not altered the distribution of events. The 35-year long data set now appears to be a reliable representation of the underlying true distribution. It is no longer useful to emphasize that date of mission development and we suggest the JPL 1991 model be renamed the JPL model.

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