Fire Under Fire: Proton Probabilities at Perihelion

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Abstract

This paper computes the probabilities that the near-Sun flyby mission, Fire, might be bombarded by high energy protons from solar-activity related proton acceleration lying beneath Fire's perihelion altitude of three solar radii. Although the very largest interplanetary proton events are commonly believed to be caused by interplanetary shocks, this paper assumes the working hypothesis that there is a second proton acceleration process associated with progressively spectral hardening hard X-ray flares studied by Kiplinger (1 995), Those studies found that progressively hardening spectral behavior was highly associated with interplanetary protons seen near Earth. Progressive hardening is easily distinguished from the spectral evolutionary behavior of common "impulsive flares" that generally have no associated interplanetary protons. This paper develops an equation to assess the probability that such an event might occur while the spacecraft orbits directly above the source and it analyzes two moderate proton events in order to estimate the proton dosages that may be received. It is concluded that, potentially, some events could pose a serious risk to Fire, but that the probability of a direct hit is only one in every few thousand missions.

1. Introduction

For decades, solar physicists have generally considered solar flares as the primary drivers of many types of gee-effective phenomena. One such phenomenon has been the occurrences of high energy interplanetary protons, More recently, a new paradigm has emerged which stipulates that coronal mass ejections may be more important than flares in driving many such gee-effective phenomena (cf. Gosling, 1993; Cliver, 1995; Reames, 1995). Indeed, an extremely important type of acceleration of interplanetary protons is attributable to interplanetary shocks that are associated with coronal mass ejections and prominence eruptions (cf. Kahler, 1992).

Recently, however, in a series of studies of hard X-ray spectral evolution in solar flares and interplanetary proton events, Kiplinger (1 995) found strong associations between

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a particular signature seen in hard x-rays and interplanetary protons. The signature is found in the temporal evolutions of hard X-ray spectra (with energies of -40-200 keV) during X-ray flux peaks and final X-ray decay stages of flares. Most solar flares are classified as impulsive solar flares and most solar flares do not produce proton events at Earth, Impulsive solar flares have hard X-ray spectra that harden (i.e.,become relatively more energetic) as fluxes increase and soften as fluxes decline. In contrast, the hard X-ray signature associated with energetic interplanetary protons is that the hard X-ray spectra progressively harden as fluxes decline, Therefore, a flux peak from an impulsive flare undergoes a soft-hard-soft evolution, while a progressively hardening flux peak evolves as soft-hard-harder. Kiplinger proposed that the progressively hardening spectra are the signatures of an electron acceleration process that is simultaneous with the acceleration of high energy interplanetary protons.

This paper addresses the probabilities that the near-Sun flyby mission, Fire, might be bombarded by high energy protons from a progressively hardening flare-associated proton event as the spacecraft passes perihelion, We assume here that there is more than one acceleration source of interplanetary protons (implying that the new paradigm is incomplete). Thus, we are making the *working hypothesis* that the interplanetary protons associated with the periods of hard X-ray spectral hardening (as reported by Kiplinger; 1995) are produced relatively close to the Sun's surface (e.g. within -0.1 $r_{\odot}$). In this scenario, proton production from such events may pose direct threats to spacecraft near the Sun. The purpose of this paper is to assess the probability that such an event might occur while the spacecraft orbits directly over the source and to estimate the proton dosages that may be received, To attempt to further justify the working hypothesis is beyond the scope of this paper. Moreover, it is generally believed that coronal pressure waves must proceed past - $5r_0$-15r0 (cf. Kahler; 1992) before they become supermagnetosonic, resulting in collisionless shock waves that are sufficiently strong to accelerate energetic protons. Fire will have a perihelion over active latitudes inside the regions where this type of shock acceleration of protons can occur. On both the inbound and outbound trajectories, it will be at higher latitudes, above the active latitude zone which is the focus of this study, Accordingly, we will not consider interplanetary shock accelerated protons in this paper.

II. Probabilities of Encountering Protons at Perihelion

After a long and circuitous journey from the Earth to the Sun, the Fire mission is slated to pass by the Sun in an over-the-poles trajectory passing through the ecliptic plane near perihelion, The calculation of interest here is to estimate the probability that the spacecraft will pass directly over a proton acceleration site (in this context, a proton event associated with a progressively hardening event) *at the time that the acceleration is occurring.* Although the pole to pole passage takes approximately 10 hours, the crossing of the spacecraft over the active latitude zone, assumed here to lie between N30 and S30, is only three hours, Thus, the spacecraft has an angular velocity, V = 20 deg/hr. We also assume that the proton acceleration site has a source size with equal angular extent, O, in both latitude and longitude. The goal is to compute P_H which is the probability that Fire will be "hit" by any of the protons released during the duration, τ, of the event. The hit probability, P_H, may now be represented as the combined (multiplicative) probability of three factors: (1) a temporal probability, P_T, reflecting the chance that the event actually occurs while the spacecraft is in the active latitude zone, (2) a latitude factor, P_{Lat} that accounts for the probability that any portion of the spacecraft's flyby arc, while the event is in progress, may be over any portion of the source, and (3) a longitude factor, $P_{Lon} = 0/360$, representing the probability that the spacecraft is at the longitude spanned by the source,

The temporal probability is simply, $P_T = \tau R_E$, where R_E is the rate at which proton associated events occur. During the Solar Maximum Mission (1 980- 1989) the highest number of SESC proton-associated, progressively hardening events observed was 10 in 1988. Since SMM, in low Earth orbit, had a duty cycle of 50% and observed only the Earth-facing side of the Sun, $R_E = 40/\text{yr} = 0{,}00456/\text{h}$. With regard to calculating P_{LAT}, one can see that the probability of Fire *not* being hit, $1 - P_{LAT}$, is proportional to the angular extent of the active zone less the angular extent of the source and less the length of the flyby arc, 20τ, during the course of the event. Thus, we have

$$1 - P_{Lat} = \frac{60 - \theta - 20\tau}{60}, \qquad (1)$$

or

$$P_{Lat} = \frac{\tau}{3} + \frac{\theta}{60} \qquad (2)$$

where τ is in hours and θ is in degrees. Therefore the combined hit probability, P_H is

$$P_H = P_T \, P_{LON} \, P_{LAT} = \frac{R_E}{1080}\left(\theta\tau^2 + \frac{\tau\theta^2}{20}\right), \qquad (3)$$

or, substituting for R_E

$$P_H = 4.\ 23 \times 10^{-m}\left(\theta\tau^2 + \frac{\tau\theta^2}{20}\right). \qquad (4)$$

To illustrate the magnitude of this probability for various values of θ and τ, we have computed safety factor percentages rather than P_H directly. The safety factor is equal to: $100(1 - P_H)$ which is the percentage probability that Fire will not fly over a near-

Sun proton event during perihelion passage. Figure 1 shows safety factors for sources up to *20* degrees in extent and for event durations of 1 and 2 hours. Fire does appear to be relatively safe from such episodes of proton production, For an event lasting 1 hour and with a source size of 10 degrees, Fire would only encounter protons once in more than 15,000 missions. The lowest safety factor computed, for θ = 20 and τ = 2 h, results in a proton encounter only once every 2000 missions and these values refer to solar maximum. Flybys at solar minimum would reduce these probabilities by more than an order of magnitude.

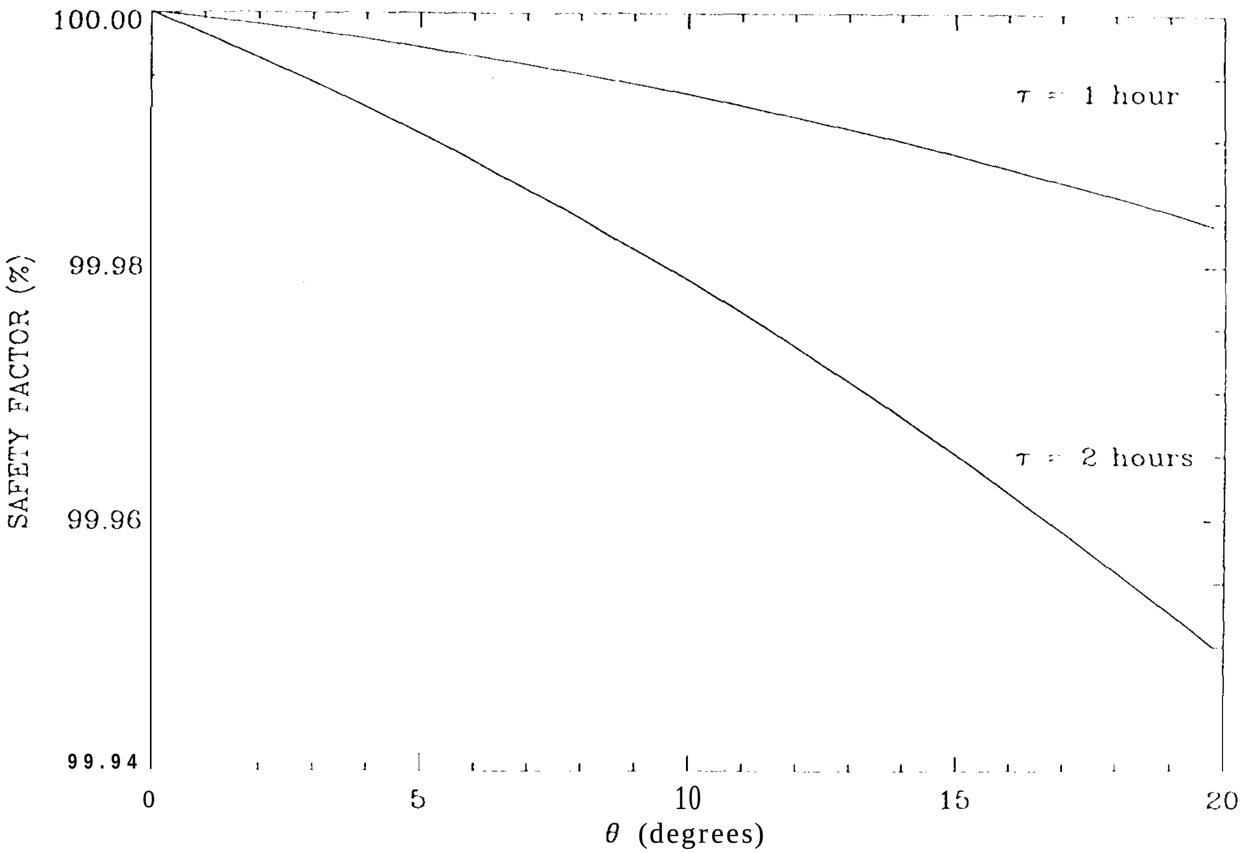

Figure 1, Safety factors for the Fire spacecraft to safely avoid a flare-associated proton event during its perihelion passage over active latitudes. The two solid curves give safety factors, $100(1 - P_H)$, for two values of τ, the duration of the proton acceleration process at the Sun. The parameter θ represents the angular extent in latitude and longitude of the acceleration site,

III. Expected Proton Fluences

Although it is unlikely that Fire will encounter high energy protons near the Sun, for completeness we provide an estimate of the proton fluences that would be encountered if such an event did occur, We consider Iwo proton events observed by the IMP-8 satellite in its proton channel which detects protons with energies greater than 10 MeV (cf. T. P. Armstrong, 1991). Rather than taking the most extreme cases of large proton events (which are more likely to be produced by interplanetary shocks) we examine two moderately-sized, but significant, proton events with somewhat different time profiles as seen in proton fluxes. By significant, we mean that these events have just enough flux to be classified as a Space Environment Services Center (SESC) qualified event. To qualify as an SESC event, a peak flux of 10 protons cm^{-2} S-l sr^{-1} (with energies >10 MeV) must be maintained for at least 15 minutes.

The quantitative approach used is to integrate the >10 MeV proton fluxes from IMP-8 over time and to calculate total fluences expected at $3r_{\odot}$. The first event occurred on 01 April 1981 and was associated with an X2,3 soft X-ray flare that occurred at S43W52 (cf. Kiplinger, 1995). The time profile as seen by IMP-8 is characterized by an 8-hour rise to - 70% of peak flux, followed by a 9-hour rise to peak flux and finally by a 76-hour exponential decay. Note that the actual decay was interrupted by a second event when fluxes had declined to .-50% of background, Thus, the final 38 hours of continued exponential decay was assumed. Nevertheless, any errors incurred by making this assumption should be small since the assumed final decay contributes less than 7% to the total integral. The total fluence seen at Earth for this event is 8.4 x 105 protons sr^{-1} cm^{-2}.

The question here is to determine what fluences would be experienced by the spacecraft flying at $3r_{\odot}$ over the source. To compute this, we will make the further assumptions that the injected proton distribution is isotropic and that the magnetic field lines followed by the protons uniformly diverge from the source. Isotropic injection increases the total fluence by a factor of 2π since fluxes are normalized to 1 steradian. The uniform divergence increases the fluence by a factor equal to the square of the ratio of distances involved, i.e.,the Earth's orbital radius, $R_{\oplus}$ versus $3r_{\odot}$. Substituting, we find that $R_{\oplus}^2 / 3r_{\odot}^2 = 5.16$ x 103. Combining these factors with the fluence of the event derived above yields a total fluence of 2.7 x 1010 protons cm-z at the spacecraft's altitude. However, one must also consider how long the spacecraft is actually over the source and the time period over which protons are being accelerated. If one assumes that the source size, θ = 20°, then the spacecraft could intercept the beam for only one hour. With regard to acceleration times, one should note that the spacecraft is so close to the Sun that a 10 MeV proton can travel from the source to the spacecraft in only 7 seconds, Therefore, the long duration decays and propagation effects seen at Earth do not occur so close to the Sun, Accordingly, it seems appropriate to correct for the time intervals of proton injection or acceleration when calculating proton fluences near the Sun. For this event, one may estimate that the protons were being accelerated primarily during the initial 8-hour rise to 70% of peak flux, If all of the protons are accelerated over an interval of 8 hours and the spacecraft is in the beam for 1 hour, then the total absorbed fluence of protons is 2,7 x 1010 ÷ 8 = 3.4 x 109 protons cm^{-2} (with energies > 10 MeV).

For comparison, a second event with a much more impulsive time profile also was measured. This proton event occurred on March 6, 1986 and is associated with an X-ray class C4 flare (1 F optically) occurring at N02E01, Like the event above, it minimally reached SESC event levels. The proton flux time profile of this event can be characterized as three exponential curves: (1) a fast 4-hour rise to peak flux, (2) a rapid 18-hour decay to 5% of peak flux and, (3) a 30-hour final decay to background flux levels. Performing the same calculations as in the previous example, we find a total fluence of 8.3 x 10^9 protons cm^{-2} at $3r_\odot$. If the acceleration interval is roughly the duration of the flare, ~ 1 hour, then the maximum incurred fluence experienced by the spacecraft would be 8.3 x 10* protons cm^{-2} for $\theta = 20°$. If the acceleration interval equals the proton flux rise time, then absorbed fluences would be reduced by a factor of four. One should note that all of the estimated absorbed fluences by Fire lie within an order of magnitude of one another. It also should be noted that the largest proton events seen at Earth (probably more likely to have been produced by interplanetary shocks) can maintain fluxes > 103cm-2 S-l sr^{-1} above 10 MeV for two or more days and can maintain fluxes > 104 cm^{-2} S-l sr^{-1} for several hours. This implies that the fluences derived above for $3r_\odot$ for these modest events are comparable to the fluences received from the very largest proton events as observed from Earth.

IV. Discussion

The computations described above indicate that the probability of the Fire spacecraft encountering protons from a proton event associated with a progressively hardening hard X-ray event are quite low. The lowest safety factor computed is for an acceleration source size of 20° and an event duration of 2 hours. The results indicate a proton encounter only once every 2000 missions during solar maximum. However, in addition to the two proton acceleration sources implied by the working hypothesis presented in the introduction, one should recognize that there is a third source of accelerated high energy particles in the interplanetary medium. Specifically, these are the particles associated with *impulsive* solar flares such as reported by Reames et al. (1 994). These particle events tend to be rich in ‘He, Fe and electrons and relatively deficient in energetic protons, Reames (1 995) also estimates that 1000 such particle events occur per year over the entire Sun out of an estimated 4,000- 10,000 hard X-ray, Hα and type III bursts per year at solar maximum. Since this particle acceleration is associated with impulsive flares close to the Sun, Eq. 3 should still be valid for these events. The event rate for such impulsive flare associated particle events is 25 times greater than the progressively hardening events studied in this paper. Therefore, in the same worst case scenario described above, one would expect Fire to encounter a ^{3}He rich particle event every 80 missions during solar maxima with much better chances during solar minimum conditions. A mitigating factor is that most of these events show a persistent steepening of the particle flux spectra above 10 MeV (Reames et al, 1992). Conversely, the two proton events studied in this paper reveal proton fluxes at energies >30 MeV that are a full 10% of the proton fluxes for proton energies > 10 MeV. Simple calculations show that 30 MeV protons can affect spacecraft components far more readily than 10 MeV protons (T. Jordan, private communication), but quantitative results on spacecraft damage require sophisticated modeling that are beyond the scope of this paper.

Finally, one should recognize that the events used for calculating the proton fluences that may be encountered by Fire are the smallest events that can be counted as SESC qualified events (i.e., having peak fluxes of 10 protons cm^{-2} S-l sr^{-1}). While proton fluxes associated with progressively hardening hard X-ray events may not reach flux values in the tens of thousands that arc produced by interplanetary shocks, they arc likely to carry flux values of hundreds and probably thousands of protons cm^{-2} S-l sr^{-1}. Therefore, in an absolute worst-case scenario, it is possible, but highly unlikely, that Fire could experience a proton event that is hundreds of times more intense that any proton event that ever occurs at Earth,

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