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# Validating the proton prediction system (PPS)

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**Abstract**

The proton prediction system (PPS) is a program developed at the Air Force Research Laboratory (AFRL) to predict solar energetic ($E > 5$ MeV) proton (SEP) intensities at 1 AU following solar flares. It is based on average observed SEP intensity-time profiles, peak intensities, and event durations. The input parameters are solar flare peak or time-integrated X-ray or radio fluxes and their times of onsets and maxima, and solar flare locations. We do a limited validation of the PPS using 78 GOES solar X-ray flares of peak intensity $\geqslant$M5 with well associated H$\alpha$ flare locations. Predicted peak proton intensities $J(E > 10\,\text{MeV})$ and event onset and rise times are compared with SEP events observed by GOES. We also select all GOES $E > 10$ MeV SEP events above 10 proton flux units (pfu) during the same time period to compare with those predicted by the PPS. With our M5 X-ray flare threshold the PPS yields approximately equal numbers of correct predictions, false predictions, and missed 10-pfu SEP events.


*Keywords:* Energetic particles; Solar flares; Space weather forecasting; Space weather models

## 1. Introduction

Solar energetic ($E > 10$ MeV) protons (SEPs) can have deleterious effects on Air Force and civilian spacecraft (Tylka et al., 1997) and communications systems and can present serious hazards for astronauts on the missions to the Moon and Mars envisioned by the NASA Vision for Space Exploration (VSE). Predicting SEP events at 1 AU is therefore a necessary goal for mitigating the effects of SEPs on those systems and missions. Different approaches have been taken to predict SEP events. On the longer (3–$\geqslant$10 years) climatological scales important for spacecraft design, Gabriel and Feynman (1996) found the differential distribution of SEP event fluences for several SEP integral energies to be well approximated by power laws. The JPL proton fluence model (Feynman et al., 2002) fits observed SEP event fluences of $E > 10$ MeV SEP events to an approximate log-normal distribution of occurrence probability, and Xapsos et al. (1998) have used the maximum entropy principle to derive a truncated power-law distribution for peaks of SEP event intensities $J(E > 10\,\text{MeV})$. Recent SEP models are included in the European Space Agency's SPENVIS system, which provides standardized access for spacecraft engineers to current space environment models (Heynderickx et al., 2005).

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For near real-time astronaut activities, Bayesian prediction methods (Neal and Townsend, 2001) and artificial neural networks (Hoff and Townsend, 2003) have used the radiological dose equivalents measured early in SEP events to predict the dose rate profiles during the remainders of the SEP events. However, for the manned missions of the VSE it will be necessary to use observations of solar eruptive events to make advance predictions of the occurrence of SEP events and their intensity-time profiles. An early criterion for SEP event prediction was the U-shaped solar radio burst, consisting of two spectral peaks, one above and one below ~2.6 GHz. U-shaped bursts appear increasingly frequently in larger microwave bursts and are likely due to gyrosynchrotron emission in the higher cm range and coherent emission, such as plasma emission, in the dm range (Nita et al., 2004). The U-shaped burst criterion was tested by Cliver et al. (1985) and found to produce high rates (~50%) of false alarms and missed predictions of SEP events. They concluded that a type II or type IV burst, not the U-shaped spectrum, was the critical observable. Other potential prediction techniques for SEP events are based on their reported associations with solar soft X-ray flares of relatively low temperatures (Garcia, 2004a) and with spectral hardening for at least 3 min in $E \geqslant 20$ keV X-ray flare bursts (Garcia, 2004b). Extending the predictions to well before event onsets, Gabriel and Patrick (2003) have used neural network techniques to predict SEP events 48 h in advance using 3-h averages of the detrended ratios (0.5–3 Å)/(1–8 Å) of X-ray fluxes observed by the GOES satellites.

The current effort is to predict the SEP profiles at any point in space by combining models of propagating coronal/interplanetary shocks either with databases of observed SEP events (e.g., Lario et al., 1998; Aran et al., 2005) or with models of shock acceleration and propagation of SEPs (e.g., Sokolov et al., 2004; Spence et al., 2004; Manchester et al., 2005).

Two similar empirical systems for prediction of SEP events are employed in the US. Both reflect their heritage of the 1970s, when solar active-region flares were believed to be the sources of SEPs. The Space Environment Center of the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado, uses PROTONS, a program which takes a flare soft X-ray burst "half-power" fluence, Hα flare location, and metric type II/IV radio burst occurrence as inputs to produce the probability of occurrence of an associated $E > 10$ MeV SEP event and its predicted time and peak intensity at maximum (Heckman et al., 1992). PROTONS was validated by Balch (1999) with a database of 88 SEP events of $\geqslant 10$ peak flux (intensity) units (pfu; $1\,\mathrm{p\,cm^{-2}\,s^{-1}\,sr^{-1}} \geqslant 10$ MeV) and associated flares; a second database of 1334 X-ray flares of $\geqslant$M1 peak flux, with which SEP events did not occur, constituted a control set. Significant discrepancies with observations were found for the predicted peak intensities and rise times, which were mitigated by selecting best fits between the predicted and observed values.

## 2. The proton prediction system (PPS)

The subject of this work is the second empirical SEP prediction system, the proton prediction system (PPS), developed by Smart and Shea (1979, 1989, 1992) to use solar flare observations to predict the occurrence, timing, intensities, spectra, and elemental composition of $E >$ 5, 10, and 50 MeV SEP events at 1 AU, and other SEP applications such as terrestrial radiation dose rates and ionospheric absorption. The PPS is based on correlations between the properties of a large number of SEP events observed with the IMP satellites and their associated solar flare signatures. It differs from PROTONS primarily by not using the metric type II/IV radio burst occurrence as an input and in not producing a probability of occurrence of a SEP event. In addition, PROTONS and PPS use different algorithms to calculate the SEP intensities.

In the PPS, SEPs are assumed to be accelerated in solar flares and injected into interplanetary magnetic fields 0.25 h after flare onsets. A time-invariant longitudinal SEP intensity gradient of a factor of ~10 per radian from the flare location is assumed. For observations at 1 AU, the PPS uses the heliographic location of the flare to calculate $T_{\max}$, the rise time of the SEP event to maximum intensity relative to the flare onset time. For $E > 10$ MeV protons the equation is (Smart and Shea, 1979)

$$T_{\max}(\mathrm{h}) = A \times \Theta^2 + 2.7, \quad (1)$$

where $\Theta$ is the longitudinal angular displacement in radians of the flare site from the Earth's magnetic footpoint, which is taken as W57.3° for an assumed solar wind speed of 404 km s$^{-1}$. $A$~6 for flares east of W57.3° and ranges from 6 to 12 for flares west of W57.3°. The convective westward displacement of the symmetric SEP population due to solar rotation results in those asymmetric values of $A$. If $J(E>10\,\text{MeV})$ reaches 10 pfu, then PPS gives that time as the onset time $T_{\text{onset}}$. Both $T_{\text{onset}}$ and $T_{\text{max}}$ are given relative to the X-ray flare onset time.

The maximum of $J(E>10\,\text{MeV})$ in pfu for the assumed optimum flare connection at W57.3° is given by

$$J(E>10\,\text{MeV}) = 30.67 \times (F_{XW} \times \Delta T)^{1.327}, \qquad (2)$$

where $F_{XW}$ is the GOES peak 1–8 Å X-ray flare flux in ergs cm$^{-2}$ s$^{-1}$ and $\Delta T$ is the X-ray flare rise time from onset to peak in min, or by

$$J(E>10\,\text{MeV}) = 347 \times (F_X)^{0.941}, \qquad (3)$$

where $F_X$ is the GOES 1–8 Å X-ray flare half-power fluence in J cm$^{-2}$.

PPS is a part of the AFRL Geospace prediction system (Hilmer et al., 2002) and is used by the Air Force Weather Agency for predictions of SEP events. Despite its importance for space weather, there has not been a systematic validation of the PPS.

## 3. The validation procedure

To validate the PPS, we first listed all $\geqslant$M5 X-ray flares observed by the GOES satellite for the 5-year period 1997–2001. We then selected only those for which an H$\alpha$ flare location was given in Solar-Geophysical Data reports, requiring at least a class 1 H$\alpha$ flare with an onset and/or maximum within the X-ray flare time interval. This resulted in a total of 101 solar flares. For each flare we ran PPS using both options of $F_{XW}$ and $\Delta T$ (Eq. (2)) and of $F_X$ (Eq. (3)) to predict the peak GOES $J(E>10\,\text{MeV})$ intensities. To compare with GOES SEP observations, we distinguish three peak $J(E>10\,\text{MeV})$ SEP classes: no SEP event, $J<0.3$ pfu, which is approximately twice the GOES 0.15 pfu background; small SEP events, $0.3\,\text{pfu}<J<10$ pfu; and NOAA SEP events, $J\geqslant 10$ pfu. Table 1 indicates the importance of the solar flare longitude for the PPS predictions.

Table 1
PPS Predicted $J(E>10\,\text{MeV})$ SEP event class by solar hemisphere for $\geqslant$M5 flares, 1997–2001

| SEP Event class | Peak Flux (J in pfu) | East | West | Total |
|---|---|---|---|---|
| No SEP | <0.3 | 28 | 0 | 28 |
| Small SEP | 0.3–10 | 16 | 13 | 29 |
| NOAA SEP | >10 | 4 | 40 | 44 |
| Total | | 48 | 53 | 101 |

A small or NOAA-class SEP event was predicted for all 53 western hemisphere flares, but for only 20 of the 48 eastern hemisphere flares. This result reflects the strong longitudinal intensity gradient used in the PPS.

### 3.1. PPS predictions of SEP peak intensities

We compared the PPS predictions with GOES $E>10$ MeV proton observations after each flare. The presence of previous or immediately following SEP events limited the useful PPS test cases to 78 of the 101 solar flares. Although they can be serious radiation hazards (Reames, 1999), PPS does not predict the $E>10$ MeV peaks often seen during the 1 AU shock appearances. We therefore used earlier GOES peak intensities and times for some events after subtracting off the shock peak profiles. The shock list of the ACE spacecraft at http://www.bartol.udel.edu/~chuck/ace/ACElists/obs_list.html#shocks was used to determine the times of shocks at 1 AU.

We first compared logs of observed GOES peak SEP intensities, modified for shocks, with those of the 78 PPS predictions using the $F_{XW}$ and the $F_X$ input options. Only 33 observed SEP events were found for the 78 cases; in the remaining cases the GOES background value was used. The correlation coefficient $r = 0.55$ for the $F_{XW}$ predictions shown in Fig. 1, and $r = 0.50$ for the $F_X$ predictions. We therefore continued the analysis of the PPS predictions for $J(E>10\,\text{MeV})$ using only the $F_{XW}$ option. Fig. 1 shows that differences between the PPS and

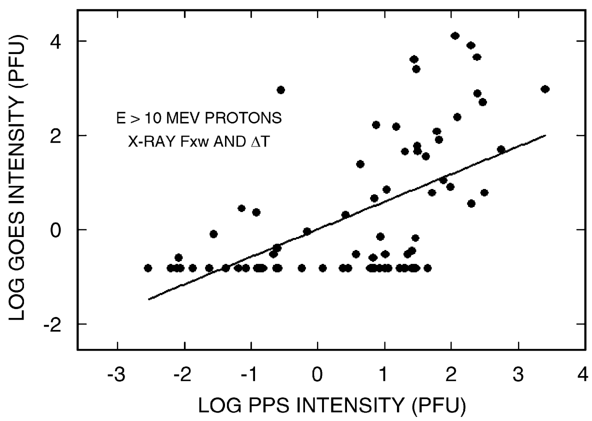


Fig. 1. Comparison of the GOES peak $J(E>10\,\text{MeV})$ SEP intensities with the PPS predictions using 78 flares. The 1–8 Å X-ray peak fluxes $F_{XW}$ and rise times $\Delta T$ were inputs to the PPS. The correlation coefficient $r = 0.55$. The line is the least-squares best fit, and the GOES values at $\log J = -0.82$ correspond to the GOES background at $J = 0.15\,\text{p}\,\text{cm}^{-2}\,\text{sr}^{-1}\,\text{s}^{-1}$.

GOES peak SEP intensities can range over several orders of magnitude.

### 3.2. PPS predictions of SEP $T_{\max}$ and $T_{\text{onset}}$

For each of the 33 observed SEP events we determined the log of the observed $T_{\max}$ and plotted that value against the log of the predicted $T_{\max}$ of the PPS in Fig. 2. We find a correlation of $r = 0.36$ with a significance of 96% (Bevington and Robinson, 2003). If a PPS predicted intensity exceeded 10 pfu, then $T_{\text{onset}}$ at the 10-pfu threshold and the duration of the event above 10 pfu were also predicted. For the 25 cases with predicted NOAA SEP events we compare the predicted and observed $T_{\text{onset}}$ values in the log–log plot of Fig. 3. There is no significant correlation for that plot.

### 3.3. PPS predictions of NOAA SEP events

The NOAA SEP events with peaks of $J \geqslant 10$ pfu, of most concern for space weather effects, are posted at http://umbra.nascom.nasa.gov/SEP/seps.html. There are 50 10-pfu events on the NOAA list during 1997–2001. We added two previously unlisted SEP events that occurred during high ($>10$ pfu) GOES intensities and subtracted seven SEP events for which only the shock peaks exceeded 10 pfu. The resulting 45 SEP events were compared with the PPS predictions. The question here is how well the PPS predicts the occurrence of NOAA SEP events, regardless of peak SEP intensities. We classified the GOES SEP observations and the 78 PPS predictions into the following four groups, where the bold font indicates incorrect PPS predictions:

| | |
|---|---|
| NOAA events predicted: | 18 |
| Null events predicted: | 39 |
| **NOAA events missed**: | **3** |
| **False NOAA events predicted**: | **18** |
| Total PPS predictions: | 78 |

Thus, based only on prediction of NOAA SEP events, the PPS was correct in $\frac{57}{78} = 73\%$ of the time. However, another $45 - 18 - 3 = 24$ NOAA SEP events were not predicted by the PPS because it was not run; for each of those cases no appropriate X-ray and Hα flare was found. The best candidate flare associations for those SEP events were distributed in X-ray intensities as follows:

| | |
|---|---|
| Class $<$M1 flares: | 11 |
| Class M1–M5 flares: | 10 |
| Class $\geqslant$M5 flares: | 3 |

The 3$\geqslant$M5 flares were not run in PPS because suitable Hα flares were not reported. The SEP event and X20 flare on 2001 April 2, during a time of no Hα flare patrol, is the most egregious case of that group. Using various solar flare data sets, we determined that 22 of these 24 flares not run in PPS occurred in the western hemisphere.

### 3.4. PPS predictions and HAFv.2 model flares

As mentioned in Section 2, the PROTONS predictions differ from those of the PPS in using

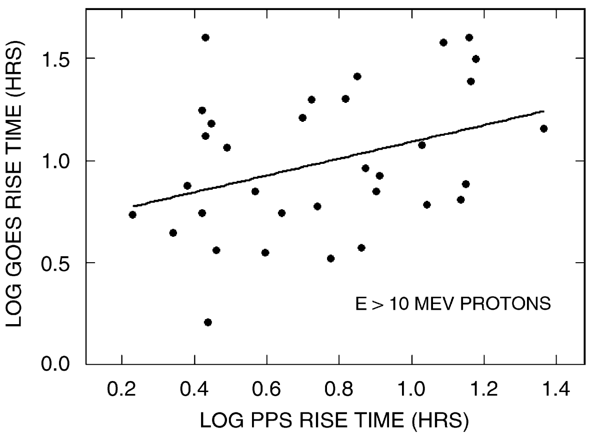


Fig. 2. Comparison of PPS and observed GOES SEP event rise times $T_{\max}$ (times from X-ray flare peaks to SEP peaks) for the 33 cases with observed events. The correlation coefficient $r = 0.36$, with a 96% significance.

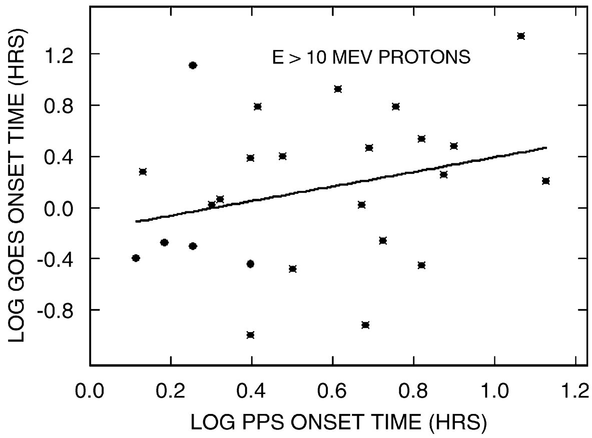


Fig. 3. Comparison of onset times $T_{\text{onset}}$ (from X-ray flare peaks to times when $J$ reaches 10 pfu) for the 25 cases for which PPS predicts a NOAA class SEP event. The least-squares best-fit line is shown, but the PPS predictions are not significantly correlated with the GOES observations.

the occurrence of type II and/or type IV metric radio bursts as one factor to predict the probability of occurrence of a SEP event. Can we use type II metric radio events to improve the PPS accuracy? We examine this possibility by comparing our PPS events with those used in a study of the Hakamada–Akasofu–Fry version 2 (HAFv.2) model of interplanetary shocks (Fry et al., 2003). The model inputs require coronal shock speeds determined from metric type II bursts that occurred when X-ray observations were available in real time. Forty-six of our 78 PPS events coincided with those of the HAFv.2 study, and a correct NOAA event prediction was made in $\frac{31}{46} = 67\%$ of those cases. The remaining PPS events, with no matching HAFv.2 study events, were correct $26/32 = 82\%$ of the time, but this high number was due to the 23 cases in which the null events were correctly predicted. The main effect of adding a requirement for type II bursts to PPS would therefore probably be to eliminate these latter cases.

We can further examine the shock speeds of the 46 HAFv.2 events with PPS predictions. The type II burst median shock speed for the 18 HAFv.2 events with NOAA SEP events was $1300\,\mathrm{km\,s^{-1}}$; for the 28 events without NOAA SEP events it was $907\,\mathrm{km\,s^{-1}}$. However, within each of these groups the median speeds of the two subgroups correctly and incorrectly predicted by the PPS were very similar, suggesting that the PPS predictions would not be improved by considering the type II burst shock speeds.

## 4. Discussion

The logs of peak $J(E > 10\,\mathrm{MeV})$ SEP intensities predicted by the PPS are correlated with those observed by GOES (Fig. 1), but the intensities show several orders of magnitude in scatter. The SEP $T_{\mathrm{max}}$ and $T_{\mathrm{onset}}$ predictions (Figs. 2 and 3) are worse. The peak SEP intensity correlation of $r = 0.55$ for PPS is comparable to that of 0.455 found by Balch (1999) for PROTONS, but his SEP intensity validation test consisted of running PROTONS for 88 known NOAA SEP events while we used for PPS a database of 78 large solar flares, only 21 of which were associated with NOAA SEP events. We find a much lower correlation ($r = 0.36$) for the 33 PPS predicted $T_{\mathrm{max}}$ than did Balch (1999) ($r = 0.71$) for his 88 PROTONS events. Again there are significant differences between the two studies. We used logs of $T_{\mathrm{max}}$ and Balch (1999) used linear $T_{\mathrm{max}}$ (his $t_{\mathrm{rise}}$) in his correlation. For $t_{\mathrm{rise}}$ of his Eq. (20) Balch (1999) finds significant differences from our equivalent Eq. (1), in particular, the earliest $t_{\mathrm{rise}}$ occurs at W78°; PPS takes W56° for that longitude.

A critical aspect of the PPS is the scaling power-law exponents of Eqs. (2) and (3), which take X-ray fluences, either $F_{XW} \times \Delta T$ or $F_X$, respectively, as inputs. Recently, Belov et al. (2005) have compared peak $J(E > 10\,\mathrm{MeV})$ SEP intensities with associated X-ray peak fluxes $F_{XW}$ for well connected SEP events over a 28-year period. They found a best-fit scaling of $J(E > 10\,\mathrm{MeV}) \sim (F_{XW})^{1.14 \pm 0.14}$. To relate their result to Eqs. (2) and (3), we first note that a log–log plot of $\Delta T$ versus $F_{XW}$ for the $101 \geqslant$ M5 X-ray events of this study shows no correlation, i.e., that $\Delta T$does not scale with $F_{XW}$. This suggests that to first order we can directly compare the Belov et al. (2005) $F_{XW}$ exponent of 1.14 to the fluence exponents of Eqs. (2) and (3); their $F_{XW}$ exponent is slightly smaller than the former (1.323), larger than the latter (0.941), and larger than the best-fit (0.82) deduced by Balch (1999) in his Eq. (17). Given the large scatter evident in Fig. 1, the differences in exponents do not appear significant.

The limitations of this PPS validation are considerable. First, we have tested only the $E > 10\,\mathrm{MeV}$ proton option, and not the $E > 5$ and $E > 50\,\mathrm{MeV}$ proton or other options of the PPS. Second, other input flare variables could have been used. We used flare X-ray peak fluxes $F_{XW}$ (Eq. (2)) rather than fluences $F_X$, although the former require the X-ray rise times $\Delta T$ and therefore have dimensions of fluence. We did not test flare microwave bursts. Because flare X-ray and microwave intensities are generally correlated (e.g., Benz and Guedel, 1994), we would not expect a significant difference in the PPS results if microwave parameters had been used in place of the soft X-rays the GOES. Third, we have not considered the durations or fluences of the SEP events although these are also output parameters (Smart and Shea, 1979; Hilmer et al., 2002). Fourth, the PPS SEP energy spectra were not examined. Because of variations of characteristic "knee" energies among SEP event spectra (Tylka, 2001), the quality of the PPS predictions may be very energy dependent.Finally, M5 X-ray flare threshold was an arbitrary choice for the PPS validation. A lower X-ray threshold would obviously increase the number of correct SEP event predictions, but only at the expense of more false predictions. Conversely, a higher X-ray threshold would decrease the number of false predictions at the cost of more missed predictions. We have not attempted to optimize this tradeoff, but M5 may be a fortuitous choice. In comparing long-term monthly occurrences of SEP events and X-ray flares over a range of peak X-ray flux thresholds, Belov et al. (2005) found a maximum correlation for $\geqslant$M5 flares, as we used here.

To summarize this PPS validation for the NOAA $J \geqslant 10$ pfu events, we find roughly equal numbers of correct predictions (18), false predictions (18), and missed predictions (27). We suggest these numbers as a current standard against which results of future SEP event prediction models should be compared. If we include the addition of the correct predictions of null events (39) in a formal success criterion, then the PPS success rate is $(18+39)/(78+24) = 56\%$ (Section 3.3).

The basic PPS assumption of solar flare sources for the SEP events and the fact that the PPS and PROTONS have endured over three decades as our best SEP prediction tool is testimony to the embarrassingly poor progress made in this crucial area of space weather forecasting. We can be encouraged that we have recently gained new insights into particle acceleration, particularly at shocks driven by coronal mass ejections (CMEs) (e.g., Gopalswamy et al., 2004; Cliver et al., 2005). On the horizon are models capable of using solar and CME observations to calculate shock propagation and SEP acceleration and propagation to 1 AU (Sokolov et al., 2004; Kóta et al., 2005). However, we can be optimistic about those models only after successful validation that shows a performance superior to that of the standard PPS and PROTONS. Until that time SEP events will remain a serious concern for the execution of the VSE.

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