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Forecasting solar proton events by using the ESPERTA model

T. ALBERTI([1]), M. LAURENZA([1]) and E. W. CLIVER([2])

([1]) *INAF, Istituto di Astrofisica e Planetologia Spaziali - Roma, Italy*
([2]) *National Solar Observatory - Boulder, CO, USA*

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Summary. — The ESPERTA (Empirical model for Solar Proton Event Real Time Alert) forecast tool has a Probability of Detection (POD) of 63% for all >10 MeV events with proton peak intensity ≥10 pfu (i.e., ≥S1 events, S1 referring to minor storms on the NOAA Solar Radiation Storms scale), from 1995 to 2014 with a false alarm rate (FAR) of 38% and a median (minimum) warning time (WT) of ∼4.8 (∼0.4) hr. The ESPERTA model modified to predict ≥S2 (i.e., ≥100 pfu) has a POD of 75% and a FAR of 24% for the 1995 - 2014 interval with a median (minimum) WT of ∼1.7 (∼0.2) hr based on predictions made at the time of the S1 threshold crossing. Here, both versions of the ESPERTA model have been applied to forecast recent solar proton events from 2015 to 2017, yielding results consistent with model performance for the 1995 to 2014 interval.

1. – Introduction

Solar proton events (SPEs) are defined as those for which the peak proton flux meets or exceeds the Space Weather Prediction Center (SWPC) threshold of 10 pr cm^{-2} s^{-1} sr^{-1} (or 10 proton flux units (pfu)) at energies >10 MeV. They pose serious hazards in the interplanetary medium and near-Earth environment due to their effects on space operations and radio communications, satellite electronics, and airlines flying over polar regions [1]. Thus, forecasting SPEs is of primary interest for the Space Weather community [1]. Several SPE forecasting models have been proposed during past decades (see, e.g., [2-8]), mostly based on flare- and CME-related phenomena, such as soft X-ray (SXR) and low-frequency radio bursts (see, e.g., [9]). Particularly, the ESPERTA model [4, 9], based on the logistic regression analysis on three solar parameters, viz., the flare location, 1-8 Å SXR and ∼1 MHz Type III time-integrated intensity (i.e., fluence), has been developed to provide a warning within 10 minutes following the SXR peak for ≥M2 flares. Crucial metrics for validating SPE forecasting tools are the Probability of Detection (POD), i.e., the percentage of correctly predicted SPEs, the False Alarm Rate (FAR), i.e., the percentage of erroneous predictions, and the lead warning time (WT). The ESPERTA prediction parameters [9] are fairly typical for such SPE forecast

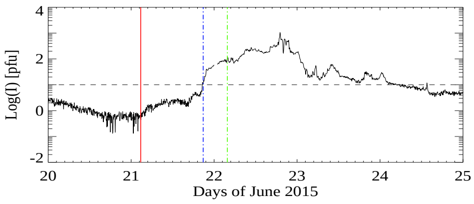

Fig. 1. – Intensity time profile for the 2015 Jun 21 SXR event. The vertical red line gives the time 10 minutes after the peak of the ≥M2 SXR flare, the blue line gives the time that the proton event intensity crossed the S1 level, and the green line gives the crossing time of the S2 event threshold.

methods: POD = 63% (69/110); FAR = 38% (42/111); median (minimum) warning time = ∼4.8 (0.4) hr, during the 20-year interval from 1995 to 2014. SPEs are usually designated according to their peak intensities as "minor" (S1, ≥10 pfu), "moderate" (S2, $\geq 10^2$ pfu), "strong" (S3, $\geq 10^3$ pfu), "severe" (S4, $\geq 10^4$ pfu), and "extreme" (S5, $\geq 10^5$ pfu) events, respectively, on the NOAA Space Weather Prediction Center (SWPC) scale of Solar Radiation Storms (`http://www.swpc.noaa.gov/noaa-scales-explanation`). Recently, the ESPERTA model has been modified to predict only ≥S2 events [10] leading to a POD of 75% (41/55) and a FAR of 24% (13/54) for the 1995-2014 interval with a median (minimum) WT of ∼1.7 (0.2) hr based on predictions made at the time of the S1 threshold crossing. This improved performance is a reflection of the big flare syndrome, which postulates that the measures of the various manifestations of eruptive solar flares increase as one considers increasingly larger events [11]. Here, we used both versions of the ESPERTA model to forecast the most recent SPEs during the time interval from 2015 to 2017.

2. – Database and forecasting method

We used the most recent SPEs events from 2015 to 2017 consisting of a data set of 8 events, as listed at `https://umbra.nascom.nasa.gov/SEP/`. Fig. 1 shows, as an example, the intensity time profiles for the 2015 Jun 21 SXR event.

Table I reports the date of the SXR event, the time of the peak of the SXR event, the SXR class, the location of the flare on the Sun, the SXR and radio fluences, the maximum proton flux as measured by GOES satellite, the warning times and the forecast results of both versions of ESPERTA. Two events (viz., 2015 Jun 18, and 2015 Oct 29) were <M2 SXR events from flares located behind the limb, thus no prediction would be made by ESPERTA. Also, for the event that occurred on 2017 Sep 10 no radio data are available. The SXR fluence is obtained by integrating the X-ray intensity (as measured by GOES satellite, `http://www.ngdc.noaa.gov/stp/satellite/goes/dataaccess.html`) between the one-third-power point before the X-ray peak and the one-third power point after it. An exponential fit, based on the intensity values from 6 to 10 minutes after the SXR peak, is performed to obtain an estimate of the SXR fluence (between the one-third power points) in real time for bursts that did not decay to one-third peak intensity within 10 minutes. The ∼1 MHz radio fluence (from radio intensity measured by WIND/Waves instrument, `ftp://solar-radio.gsfc.nasa.gov/`) is obtained by integration from 10 minutes before the time of the SXR integration (at the one-third intensity point before the SXR peak) to 10 minutes after the X-ray peak [4].

TABLE I. – *SPE list, associated parameters and forecast results.*

SXR Date & Peak Time (yy/mm/dd hh:mm)	SXR Class	Hα Loc.	SXR Fluence (J/m^2)	Radio Fluence (SFU min)	Peak Proton Flux (pfu)	Warning Time ≥S1 [≥S2] (hr)	Forecast (1) Result ≥S1 [≥S2]
15/06/18 01:27	M1	SW limb			16	-	NP
15/06/21 02:36	M2	N13W00	$1.6\ 10^{-1}$	$7.8\ 10^{6}$	1070	18.3 [5.3]	Hit [Hit]
15/06/25 08:16	M7	N12W40	$2.1\ 10^{-1}$	$3.5\ 10^{5}$	22	19.6	Hit [CN]
15/10/29		(farside)			23	-	NP
16/01/02 00:11	M2	S12W73	$8.5\ 10^{-2}$	$4.5\ 10^{3}$	21	4.7	Miss [CN]
17/07/14 02:09	M2	S06W29	$1.8\ 10^{-1}$	$5.4\ 10^{5}$	22	6.7	Hit [CN]
17/09/04 20:33	M5	S11W16	$1.5\ 10^{-1}$	$2.9\ 10^{6}$	844	3.9 [3.5]	Hit [Hit]
17/09/10 16:06	X8	S08W83	$1.9\ 10^{0}$	Data gap	1490	-	NP

(1)NP = No Prediction; CN = Correct Null.

To obtain a yes/no forecast result a logistic regression model is used [4, 9] based on exploring the parametric space with two variables (i.e., the SXR and radio fluences) and by considering the heliographic longitude (i.e., the location of the flare on the solar surface) by separating the ≥M2 flares into three different longitude bands: E 120° - E 41°, E 40° - W 19°, and W 20° - W 120°. Specific values from 0 to 1 for the probability can be assigned in the logistic regression formula with some step that would lead to several contours (see Figs. 2-3 in Ref. [10]). Then, one probability threshold (PT) contour can be selected above which these probabilistic forecasts are translated into a yes or no warning for an SEP event occurrence: given a ≥M2 solar flare, if the related data point is above the selected PT contour level, a warning is given; if it is below, none is issued. For ≥S1 predictions, PT are 28%, 28%, and 23%, for western, central, and eastern events, respectively; for ≥S2, the PT values are 35%, 28%, and 23%, respectively. The ≥S2 alerts are given only for events with S1 crossings that followed ≥M2 SXR peaks within 6/15/30 hr for west/central/eastern flares, respectively.

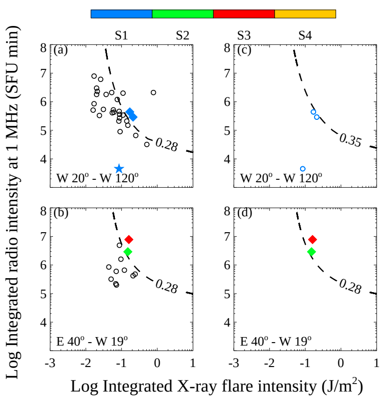

Fig. 2. – ESPERTA probability contours for the prediction of ≥S1 (left panels) and ≥S2 (right panels) SPEs for two solar longitude bands (western events, panels (a)-(c); central events, panels (b)-(d)). Diamonds are correctly predicted SPEs (Hits), stars are not predicted SPEs (Misses), circles inside/outside contours are false alarm/correct null forecasts. Color coding gives the NOAA Radiation Storms scale.

TABLE II. – *Verification measures for the three time intervals.*

(a) $\geq$**S1**(2)	1995-2014	2015-2017	1995-2017
POD	$69/110 = 63\%$	$4/5 = 80\%$	$73/115 = 63\%$
FAR	$42/111 = 38\%$	$2/6 = 33\%$	$44/117 = 38\%$
(b) $\geq$**S2**(3)	1995-2014	2015-2017	1995-2017
POD	$41/55 = 75\%$	$2/2 = 100\%$	$43/57 = 75\%$
FAR	$13/54 = 24\%$	$0/2 = 0\%$	$13/56 = 23\%$

(2)False alarms are 2015-03-03 at 01:35 and 2015-06-25 at 08:16.
(3)For two events (2015-06-21 at 01:42, 2015-06-21 at 09:44) a S1 crossing has been observed (2015-06-21 at 21:35) within 20 and 6 hr. However, the corresponding SXR and radio fluences are below the probability thresholds of 28% and 35%, respectively; for one event (2015-06-22 at 18:23) the proton flux was >100 pfu at the SXR peak time; for one event (2015-06-25 at 08:16) the S1 crossing occurred after the 6 hr threshold (2015-06-26 at 03:50).

3. – Discussion and conclusions

Fig. 2 shows the forecast results for SPEs during the period from 2015 to 2017. From the $\geq$S1 ESPERTA model we obtain four events classified as Hits and only one Missed event. The $\geq$S2 ESPERTA model correctly predicts both $\geq$S2 events, while $\geq$S1 SPEs are classified as correct nulls [10]. However, to correctly predict the 2015 Jun 21 event it was necessary to shift the S1 crossing threshold, for central events, from 15 hr to 20 hr. We verified that this change does not affect previous forecast results for past events [10], obtained by using the 15 hr threshold. The median (minimum) S1 warning time was 6.7 (3.9) hr, higher with respect to the median (minimum) WT obtained from the time interval 1995-2014 (i.e., 4.8 (0.4) hr [9]). Summing the statistics over the entire 1995 to 2017 interval in Table II gives results that are consistent with those obtained for the much larger sample sizes considered in the previous works [4, 9, 10]. ESPERTA is a viable forecast method in terms of both verification measures (at least comparable with competitive techniques) and warning time alert (exceeding some other forecasting models [5]).

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