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A new model for the 1-10 MeV proton fluxes (part of ONERA GREEN-V3 model)

A. Sicard, S. Bourdarie, D. Lazaro, D. Standarovski, R. Ecoffet, L. J. Lanzerotti, A. J. Gerrard

Abstract—A new version of the ONERA GREEN model (GREEN V3) is in development, with a focus on low-energy proton fluxes (1-10 MeV). Newly available measurements of the magnetosphere population of these particles make a revision of the GREEN model timely. Measurements from the RBSPICE instrument on the dual Van Allen Probes spacecraft and from the SEM2 instrument on the NOAA-POES spacecraft have been used to construct a proton flux model in this energy range. In order to take into account the dependence on the solar cycle of proton fluxes in the radiation belts, the correlation between those fluxes and the F10.7 solar radio noise has been studied. This paper describes the method used to estimate the proton fluxes between $L^*=2$ and $L^*=6$ for GREEN V3. Only the proton energy range 2.5-6.9 MeV is shown here but a larger energy range (1-10 MeV) will be presented in the final paper.

Index Terms—plasma, specification model.

I. INTRODUCTION

It is well known that low-energy protons (1-10 MeV) have a significant effect on the performance of solar cells in space [1][2]. However, these low-energy protons are difficult to measure and so there are not many good quality data available. The reference model to estimate the proton fluxes in this energy range (1-10 MeV) is currently the NASA-AP8 model [3]. In recent years two models have been developed to estimate the proton fluxes. The first is IRENE (or AE9/AP9) [4] and provides proton flux levels different from those in the AP8 model. The second is GREEN, developed at ONERA [5]. But for this 1-10 MeV energy range, the proton fluxes provided by GREEN come from AP8. Thus, the goal of this paper is to develop a new version of the ONERA GREEN model in which the 1-10 MeV proton fluxes are better estimated than using the AP8 model. To this goal, good quality contemporary data have been used: RBSPICE

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A. Sicard is with ONERA/DPHY, Université de Toulouse, Toulouse, France, (phone: +33-5-61-25-28-81; e-mail: angelica.sicard@onera.fr).

S. Bourdarie is with ONERA/DPHY, Université de Toulouse, Toulouse, France, e-mail: sebastien.bourdarie@onera.fr.

D. Lazaro is with ONERA/DPHY, Université de Toulouse, Toulouse, France, didier.lazaro@onera.fr.

D. Standarovski is with CNES, The French Space Agency, Toulouse, France, (email: denis.standarovski@cnes.fr).

R. Ecoffet is with CNES, The French Space Agency, Toulouse, France, (email: robert.ecoffet@cnes.fr).

L. J. Lanzerotti is Center for Solar-Terrestrial Research, New Jersey Institute of Technology, Newark, NJ, USA. (email: louis.j.lanzerotti@njit.edu)

A. Gerrard is Center for Solar-Terrestrial Research, New Jersey Institute of Technology, Newark, NJ, USA. (email: gerrard@njit.edu)

measurements [6] on the dual Van Allen Probes spacecraft and SEM2 data on the NOAA-POES spacecraft on LEO orbit [7].

II. DATA USED

A. Van Allen Probe/RBSPICE

The first data set used in the development of a 1-10 MeV proton model is the data from RBSPICE (Radiation Belt Storm Probes Ion Composition Experiment) instrument on the dual Van Allen Probes spacecraft (VAp-A and VAp-B) [6]. RBSPICE measures protons and electrons from a few keV to several MeV. The data used in this study are unidirectional proton fluxes measured from 2013 to the end of 2018. Fig. 1 represents L-time cartographies of omnidirectional proton flux measured by VAp-A/RBSPICE for several energies: 1.022 MeV (at the bottom), 3.95 MeV (in the middle) and 7.148 MeV (at the top).

To construct a 1-10 MeV proton model as accurate as possible, and to extract as much information as possible from the data, it is essential to use unidirectional fluxes (depending on time, energy, L^* and local pitch angle of the particles) instead of omnidirectional fluxes. Knowing the local pitch angle of particles measured at a given point, the unidirectional data allow the estimation of fluxes along the magnetic field line even at latitudes not reached by the spacecraft. In this study, unidirectional fluxes were sorted according to the equatorial pitch angle of the particles, the L^* , the energy and the year.

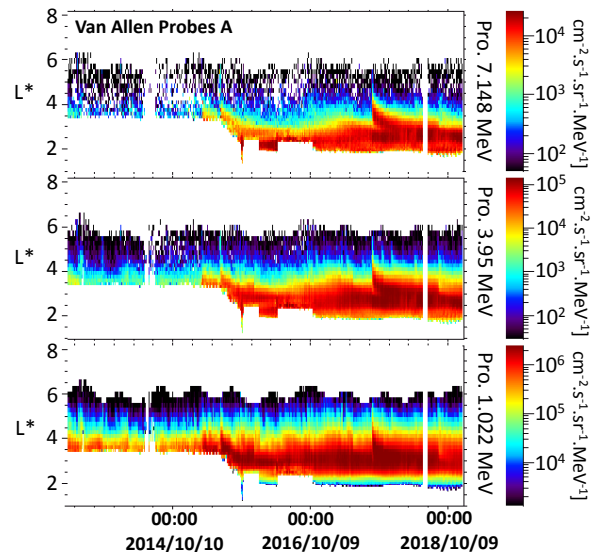


Fig. 1 : L-time cartographies of omnidirectional proton flux measured by VAp-A/RBSPICE for several energies: 1.022 MeV (at the bottom), 3.95 MeV (in the middle) and 7.148 MeV (at the top).

B. NOAA-POES/SEM2

The second data set used to develop the 1-10 MeV proton model are NOAA-POES measurements at LEO orbit. These data have been chosen for two reasons: first, long term data are available since 1998 with the same detectors MEPED, which are part of the SEM2 suite of instrument [7]; secondly these data are rare data for these energies not to be too contaminated and with a high signal-to-noise ratio. In this study, only data from POES-15 have been used. From the POES/SEM2 database, three proton channels from the MEPED instrument were considered: 0.24-0.8 MeV, 0.8-2.5 MeV and 2.5-6.9 MeV. Fig. 2 represents L-time cartographies of unidirectional proton flux measured by NPOES-15/SEM2 for these energies: 0.24-0.8 MeV (at the bottom), 0.8-2.5 MeV (in the middle) and 2.5-6.9 MeV (second panel). A solar cycle dependence can be clearly seen, particularly in the 2.5-6.9 MeV channel. Regarding the F10.7 solar noise parameter (upper panel), the proton fluxes decrease when solar activity increases.

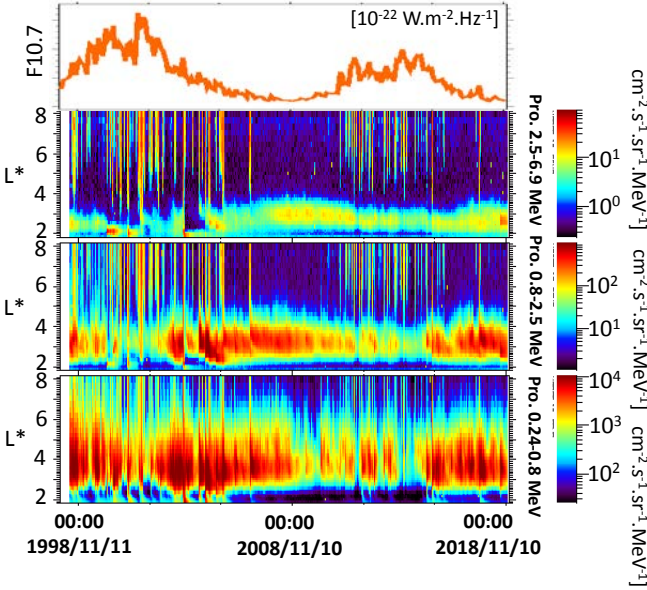


Fig. 2 : L-time cartographies of unidirectional proton flux measured by NPOES-15/SEM2 for several energies: 0.24-0.8 MeV (at the bottom), 0.8-2.5 MeV (in the middle) and 2.5-6.9 MeV (at the top).

III. MODEL DEVELOPMENT

A. Construction of the model based on RBSPICE and SEM2 data

The development of a 1-10 MeV proton model consists of several stages. All the stages described briefly in this abstract will be detailed in the full article and done for the three energy channels of NOAA (0.24-0.8 MeV, 0.8-2.5 MeV and 2.5-6.9 MeV) but in this abstract only the results for the highest channel will be shown. The first step is to compare VAp and POES-15 data sets. To do that, it is essential to integrate in energy proton fluxes from RBSPICE over the same range as SEM2. An example of these comparisons are shown on Fig. 3 with the variation of the normalized year averaged unidirectional flux as a function of the equatorial pitch angle

of the protons from RBSPICE (+) and from SEM2 (\diamond) for $L^* = 3.5$ for the range 2.5-6.9 MeV in 2018. These flux variations in equatorial pitch angle correspond to the flux variations along the magnetic field line from the equator ($\alpha_{eq}=90^\circ$) to the end of the field line.

Several observations can be obtained from this figure. First, we can note that the variation of fluxes from SEM2 is very steep because of strong flux gradients at this altitude (800 km). Then, fluxes from SEM2 reach a plateau at a small equatorial pitch angle corresponding to the background of the instrument. A plateau is also visible for RBSPICE data corresponding to uncertainties in the local pitch angle of particles measured due to the resolution of the instrument (10° in local pitch angle). Thus, a fit representing the variation of the proton flux along the magnetic field line, can be plotted using SEM2 data at small equatorial pitch angle and RBSPICE elsewhere (full line curve on Fig. 3).

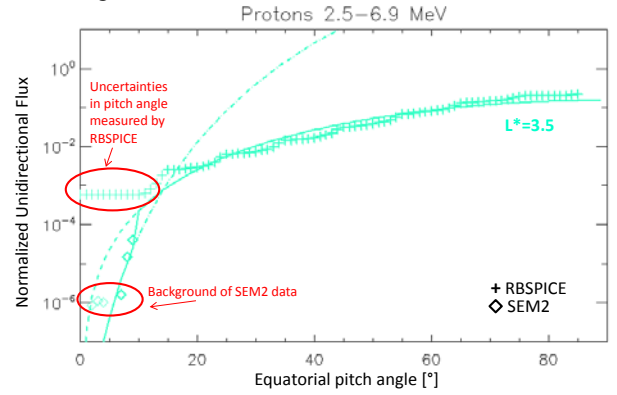


Fig. 3 : Normalized year averaged unidirectional flux (divided by RBSPICE fluxes at $\alpha_{eq} = 80^\circ$ and $L^* = 3$) versus equatorial pitch angle for protons from RBSPICE (+) and from SEM2 (\diamond) for $L^* = 3.5$ for the energy channel 2.5-6.9 MeV in 2018. The dashed curves correspond to the best fit of RBSPICE data, the dash-dotted ones to the best fit of SEM2 data and the full line curves correspond to the best global fit.

The same type of fit has been done for all L^* values between 2 and 6 and for all years from 2013 and 2018. For each year, the ratio between the fluxes obtained with the fit and those measured by the spacecraft has been calculated to estimate the errors on the fit and will be shown in the full paper. Fig. 4 shows an example of results with unidirectional proton fluxes from 2.5-6.9 MeV versus L^* and equatorial pitch angle in 2015 (on the left) and 2018 (on the right).

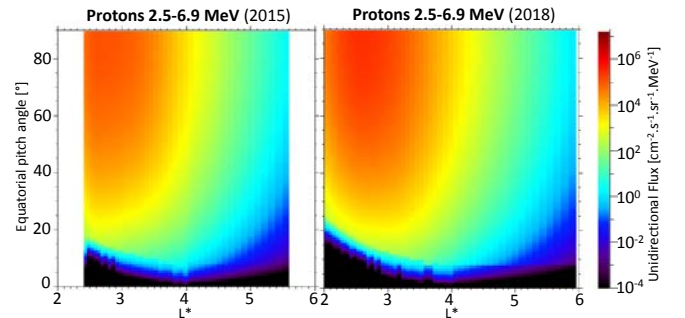


Fig. 4 : Unidirectional proton fluxes for 2.5-6.9 MeV versus L^* and equatorial pitch angle resulting from fit functions in 2015 (on the left) and 2018 (on the right).

The variations of the proton fluxes versus L^* and α_{eq} per year thus obtained for the energy channel 2.5-6.9 MeV have been applied to the energy channels of RBSPICE beyond 2.5 MeV. Consequently the unidirectional differential proton fluxes between 2.5 MeV and 10 MeV can be estimated all along the magnetic field lines (from magnetic equator where $B/B_{Eq}=1$ to the loss cone) for $2 < L^* < 6$. Examples of these results are plotted in Fig. 5 for 4 MeV protons for two years: 2015 (on the left) and 2018 (on the right). We note that, as expected, the fluxes decrease from the equator to the end of the magnetic field line in the loss cone.

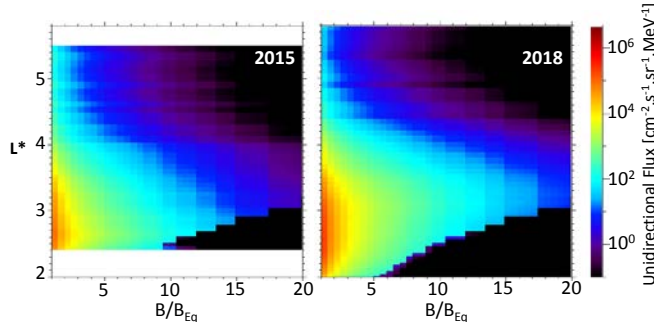


Fig. 5 : Unidirectional proton fluxes versus L^* and B/B_{Eq} resulting from model for 4 MeV protons, for two years: 2015 (on the left) and 2018 (on the right).

B. Variation of the proton flux with solar cycle

As mentioned in the previous paragraph, the dependence of proton fluxes with solar cycle seems to be significant. Thus, it appears that a model depending on the solar cycle is needed. For many years ONERA has been developing several specification models that depend on the solar cycle, as IGE-2006 [8], OZONE [9], Slot model [10] and OPAL [11]. The first three depend on the year of the solar cycle (from -6 to 4 with 0 being the year of the minimum) and the last one (OPAL) depends on the solar F10.7 parameter.

In this paper, we choose to study the dependence of the proton flux with F10.7. To do that we need a long time period of data covering more than one solar cycle. On one hand we have RBSPICE data which covers only 6 years and on the other hand we have almost two solar cycles of data from SEM2 on NPOES-15. Consequently, SEM2 data are used to study the dependence of the proton flux with solar cycle. As for the previous analysis, only the solar cycle dependence of the energy channel 2.5-6.9 MeV will be shown in this paper. The first step is to correlate SEM2 proton fluxes with the F10.7 parameter. An example of this correlation is plotted in Fig. 6 on the left for $L^*=3$. Each point corresponds to a year between 1998 and 2018. The correlation factor of -0.74 is quite good and reflects the decrease of proton fluxes when solar activity increases. However, it is important to verify if this correlation is an instantaneous process or if there is a time lag between the increase of F10.7 and the decrease of proton flux. Thus a correlation factor has been calculated between the F10.7 parameter and the 2.5-6.9 MeV proton fluxes from SEM2 taking into account time shifts from 0 to 30 months. The plot on the right in Fig. 6 shows that the best correlation factor calculated for $L^*=3$ is equal to -0.8 and is obtained with a time shift of +9 months. This correlation is fitted by a power law (a straight line in log-log) as represented in red in Fig. 6.

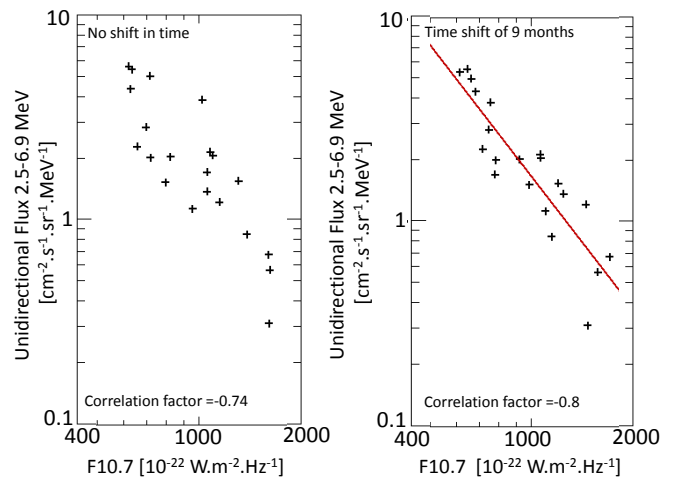


Fig. 6 : Year averaged unidirectional 2.5-6.9 MeV proton fluxes from NPOES-15/SEM2 at $L^*=3$ versus F10.7 parameter. On the left, no shift in time and on the right F10.7 is shifted by 9 months.

The time shift leading to the best correlation factor between F10.7 and proton flux has been calculated for all L^* values between $L^*=2$ and $L^*=6$ as well as the coefficients of the power law.

According to these power laws, 2.5-6.9 MeV protons fluxes can be estimated for any F10.7 values at LEO orbit. Then, we assume that the variation of the proton fluxes with solar activity is the same at the POES orbit (at high latitudes) than at more equatorial latitudes. This hypothesis will be confirmed later. Consequently we applied the F10.7 dependence thus obtained (Fig. 6) to unidirectional fluxes calculated and plotted in Fig. 5.

Finally, it is essential to compare the results obtained from the model thus developed to RBSPICE data. Fig. 7 represents unidirectional proton fluxes obtained from the new model (dashed lines) compared to RBSPICE measurements (full line) at $L^*=3.5$ at the magnetic equator for three energies: 2.5 MeV in black, 4 MeV in blue and 6 MeV in red. This figure shows that there is a good agreement between the fluxes estimated by the model and RBSPICE data. These results prove two things: (1) the method used to construct the model is good, and (2) the assumption that the variation of proton fluxes with solar activity is the same at the NPOES orbit (at high latitudes) than at more equatorial latitudes is valid.

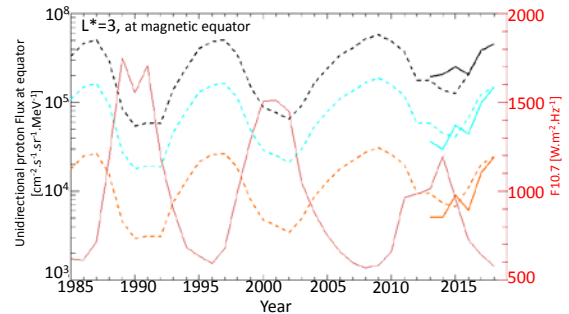


Fig. 7 : Unidirectional proton fluxes obtained from the new model (dashed lines) compared to RBSPICE measurements (full line) versus year at $L^*=3.5$ at magnetic equator for three energies: 2.5 MeV in black, 4 MeV in blue and 6 MeV in red. F10.7 is plotted in red.

IV. COMPARISON WITH AP8 AND AP9-V1.5

Proton fluxes provided by the new version of GREEN can be compared to those resulting from AP8 and AP9-V1.5 model. Fig. 8 presents the omnidirectional proton fluxes for energy > 4 MeV in a meridian plot (X vs Z in GEO coordinates) resulting from GREEN on the top right, from AE8 Min on the top left and AP9-V1.5 (mean model) at the bottom. These mappings highlight several points : (1) the flux at the maximum of the proton belt (xGEO \sim 2.8 near equator) is slightly higher in GREEN than in AP8 which is higher than in AP9; (2) the radial extension of high fluxes in the proton belt is larger in GREEN than in the two others; (3) AP9-v1.5 provides fluxes where GREEN and AP8 do not (for L^* values > 6 , i.e. high ZGEO values) but those fluxes are very low; (4) the GREEN model does not provide proton fluxes for $L^* > 2$ (the white zone for xGEO < 2) because the data used to construct the model are contaminated in this region.

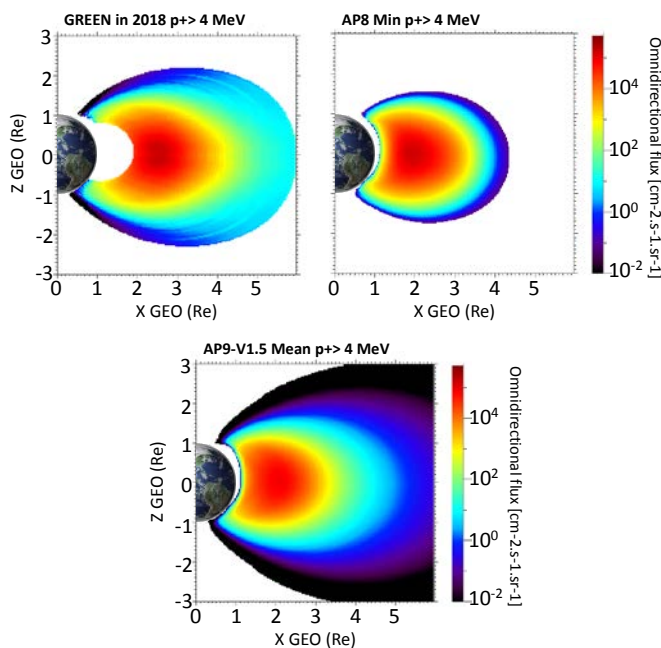


Fig. 8 : Omnidirectional proton fluxes for energy > 4 MeV in a meridian plot (X vs Z in GEO coordinates) resulting from the new model on the top right, from AE8 Min on the top left and AP9-V1.5 (mean model) at the bottom.

In the final paper, results from the GREEN model will be compared to AP8 and AP9-V1.5 for other energies and also with other data, as for example THEMIS/SST data.

V. CONCLUSION

A new version of the ONERA GREEN model (GREEN-V3) is in development, with a focus on low-energy proton fluxes (1-10 MeV). Measurements from RBSPICE on the Van Allen Probes mission and from SEM2 on the NOAA-POES spacecraft have been used. In this paper only the results for the 2.5-6.9 MeV energy range are shown. Proton fluxes can be estimated between $L^*=2$ and $L^*=6$ from the equator to the loss cone and depend on solar activity through the solar F10.7 parameter. The fluxes obtained have been compared to AP8 and AP9 models for protons > 4 MeV. In the final paper, the

energy range will be extended to 1-10 MeV using other energy channels of the RBSPICE and SEM2 instruments.

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