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A new model for the plasma particles fluxes (part of GREEN model)

A. Sicard, D. Boscher, D. Lazaro, D. Standarovski, R. Ecoffet

Abstract—A new specification model of low energy particles fluxes, included in GREEN model, has been developed at ONERA. This model is based on several data sets, from low altitudes with NOAA-POES measurements to higher altitudes with POLAR, THEMIS and LANL measurements. This model provides mean MLT dependent electron and proton fluxes between L=2 and L=10 for energies between 0.19 keV and few 10s of keV. In this paper, the model is compared to AE9/SPM model and Van Allen Probe measurements.

Index Terms—plasma, specification model.

I. INTRODUCTION

The space environment is composed of charged particles: electrons and ions (mainly protons). These particles have some effects on materials used in space systems like the well-known effects of high energy particles (> 30 keV) on electronic devices. But high-energy particles are not the only population to consider. Indeed lower-energy particles (< 30 keV) can create significant damages on materials used in space systems at their outer surface. The generated effects are cumulative such as the relevant specification for the environment is the total fluence of low-energy particles over the entire mission. Now, the model used to evaluate this low-energy population is part of AE9/AP9 models and is called SPM [1][2]. This empirical model is mainly based on CAMMICE, POLAR and LANL data. However, SPM model, valid from 1 keV to 40 keV for electrons and 1 keV to 164 keV for protons, is not MLT (Magnetic Local Time) dependent.

In this paper, we will show that low-energy protons and electrons (<30 keV) are very MLT dependent in the inner magnetosphere (up to L=10) and that a MLT dependent model is necessary to well reproduce this population. Thus, a new empirical model of low-energy plasma, based on THEMIS, POLAR, NOAA-POES and LANL data, has been developed. In this abstract the model for electrons from 0.1 keV to 8 keV is presented and compared to SPM model and validated with Van Allen Probe data. This low-energy plasma model will be integrated in the GREEN (Global Radiation Earth ENVironement) model.

II. DATA USED

A. Low Earth Orbit Data

At LEO orbit, NOAA-POES spacecraft (POES-15, POES-16, POES-17, POES-18 and POES-19) measurements have been used for two reasons. First, thanks to the POES spacecraft time continuity data are available since 1998 with the same detectors TED, which is a part of SEM [3]. Then, quality of measurements is good and detectors seem to be well calibrated. On these POES spacecraft, we have used 4 energy channels for electrons from TED instrument: 0.19 keV, 0.84 keV, 2.6 keV and 8 keV.

Electrons data have been analysed and filtered in order to remove false measurements. Data from 1998 to 2018 have been sorted according to magnetic local time (MLT) and L (McIlwain Parameter) as represented on Fig. 1 for two energies: 0.19 keV (on the left) and 8 keV (on the right). A MLT-dependent flux can be clearly observed, particularly at 8 keV with higher fluxes in the night side. As data seem to be contaminated for L<2, this very near-Earth region will not be covered by the model.

![Fig. 1 : Cartographies MLT-L of electrons flux measured by NPOES/TED from 1998 to 2017 for 2 energies: 0.19 keV and 8 keV.](image)

Table 1 resumes the characteristics of data used at LEO.

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Time coverage</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOAA-13/TED</td>
<td>07/1998→now</td>
<td>0.19 keV</td>
</tr>
<tr>
<td>NOAA-16/TED</td>
<td>10/2000→06/2014</td>
<td>0.84 keV</td>
</tr>
<tr>
<td>NOAA-17/TED</td>
<td>07/2002→04/2013</td>
<td>2.6 keV</td>
</tr>
<tr>
<td>NOAA-18/TED</td>
<td>06/2005→now</td>
<td>8 keV</td>
</tr>
<tr>
<td>NOAA-19/TED</td>
<td>02/2009→now</td>
<td>8 keV</td>
</tr>
</tbody>
</table>

Table 1: Characteristics of electron data used at LEO

B. Data in the magnetosphere

In order to obtain a global model at low energy up to L=10, data at other orbits than LEO have been taken into account. In
this study, data from four other fleets of spacecraft have been used: THEMIS, LANL-GEO spacecraft, Van Allen Probes and POLAR. While the first three fleets have orbits near the equator, POLAR has an elliptical orbit and covers a wider part of the magnetosphere in term of L and B/B\text{eq}. In this study, THEMIS and POLAR data are used to develop the model due to their wide coverage in L and MLT. POES data are used to calibrate all the data sets between each other while the validation of the model is done with Van Alen Probes data. THEMIS is a fleet of four spacecraft launched in 2007 but only data from THEMIS-A and THEMIS-D are used in our model. Even if several detectors are on board these spacecraft, only data from ESA [4], covering energies between 7 eV and 26 keV for electrons and 6 eV and 21 keV for protons, were investigated. Electron data from 2008 to 2015 have been sorted according to MLT and L as represented on Fig. 2 for two energies: 0.19 keV (on the left) and 8 keV (on the right). On the 0.19keV cartography, the magnetosheath at L>|8| on the day side can be clearly observed. As for POES data, THEMIS data seem to be contaminated at L<2.

POLAR was launched in 1996 on an elliptical orbit with several on-board instruments including HYDRA [5], a detector measuring electrons and protons from 12 eV to 18 keV. Due to its orbit and contrary to the two previous fleets of spacecraft presented in this paper, POLAR data cover not only the equator as THEMIS, or only the highest latitudes as POES. POLAR data have been sorted in three classes according to the equatorial pitch angle $\alpha_{eq}$ ($\alpha_{eq}=\arcsin(\sqrt{B_{eq}/B})$, with $B_{eq}$ the equatorial magnetic field and $B$ the local magnetic field) deduced from the spacecraft position along the field line: $\alpha_{eq}<30^\circ$, $30^\circ<\alpha_{eq}<60^\circ$ and $\alpha_{eq}>60^\circ$. Moreover, POLAR data have been analyzed in details and some periods of suspicious measurements have been removed. Fig. 3 represents MLT-L cartographies of fluxes measured by POLAR/HYDRA from 1998 to 2008 for 8 keV electrons near the equator ($\alpha_{eq}>60^\circ$) on the left and at high latitudes ($\alpha_{eq}<30^\circ$) on the right. These plots show that there is a dependence of electron fluxes with latitude. Moreover, comparing cartographies from POLAR near equator (on the right) to those from THEMIS (Fig. 2) for the same energy, electron fluxes from POLAR seem to be lower than those from THEMIS. Calibration of data will be described in the next section of this paper.

Fig. 2 : Cartographies MLT-L of electrons flux measured by THEMIS/ESA from 2008 to 2015 for 2 energies: 0.19 keV and 8 keV.

Las Alamos National Laboratory (LANL) has a fleet of many spacecraft in geostationary orbit since 1976 with several particle detectors including MPA (Magnatospheric Plasma Analyser) [6] measuring electrons and protons from 100 eV to 34 keV. Taking into account the very good quality of these data but the narrow coverage in L, they have only been used to calibrate the data sets of this study between them (see section III-A). Only data from LANL-1994-084 has been investigated. Van Allen Probes A and B have been launched in 2012 on an equatorial orbit between 500 km and 30600 km with the plasma instrument HOPE [7] measuring electrons from 15 eV to 50 keV and protons from 1 eV to 50 keV. The spatial coverage of these data, from L=1 to L=6, does not cover the entire L-range of this study (up to L=10). Moreover, a detailed analysis of these data seems to highlight contamination below L=4. For these reasons, Van Alen probes data have not been used to develop the new model but only to validate it.

Table 2 resumes the characteristics of the entire electron data used in this study at other orbits than LEO.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Time coverage</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>POLAR/HYDRA</td>
<td>03/1996→03/2008</td>
<td>39 channels between 12 eV and 18 keV</td>
</tr>
<tr>
<td>THEMIS/ESA</td>
<td>03/2007→now</td>
<td>21 channels between 7 eV and 26 keV</td>
</tr>
<tr>
<td>LANL/MPA</td>
<td>09/1989→11/2005</td>
<td>23 channels between 100 eV and 34 keV</td>
</tr>
<tr>
<td>VAP/HOPE</td>
<td>12/2012→now</td>
<td>72 channels between 15 eV and 50 keV</td>
</tr>
</tbody>
</table>

Table 2: Characteristics of electron data used at other orbits

III. MODEL DEVELOPMENT

A. How to correlate the available data?

In order to have coherent data sets to develop the model, their cross calibration are essential. The cross calibration is based on POES data (high latitude) and LANL-GEO data (near equator) which are well-known to be of good quality. First, all the data sets have been interpolated in order to have the same four energy channels than POES data. (0.19, 0.84, 2.6 and 8 keV). Then, ratio between LANL-1994-084 data and POES data is calculated at geostationary orbit for each energy channel and for the common time period between the two data sets. This ratio corresponds to the dynamics of flux between high latitude and equator along a single magnetic field line. This ratio should be the same than the one between THEMIS and POES data or POLAR and POES data (when POLAR is near the equator). If it is not the case, a correction factor will
be apply to POLAR and THEMIS data in order to be consistent with POES and LANL data. Table 3 presents LANL, THEMIS and POLAR ratios calculated for the four energy channels. Results show that the variation of the flux along the magnetic field lines depend on energy. For the highest energies, electron fluxes are higher at equator than at high latitude at geostationary orbit, while it is the contrary for the lowest energies (for middle energies channels, it depends on the spacecraft). Moreover, as mentioned in the previous section, electron fluxes measured by POLAR seem to be lower than those measured by LANL or THEMIS near geostationary orbit as the ratio associated to POLAR are lower than the others.

### TABLE III

<table>
<thead>
<tr>
<th>Ratio</th>
<th>$0.19 \text{ keV}$</th>
<th>$0.84 \text{ keV}$</th>
<th>$2.6 \text{ keV}$</th>
<th>$8 \text{ keV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio LANL/POES</td>
<td>0.43</td>
<td>0.734</td>
<td>1.44</td>
<td>2.54</td>
</tr>
<tr>
<td>Ratio THEMIS/POES</td>
<td>0.97</td>
<td>1.71</td>
<td>2.2</td>
<td>3.51</td>
</tr>
<tr>
<td>Ratio POLAR/POES</td>
<td>0.159</td>
<td>0.298</td>
<td>0.548</td>
<td>1.58</td>
</tr>
</tbody>
</table>

Table 3: Ratio between equatorial data (LANL, THEMIS and POLAR) and POES data near geostationary orbit.

Correction factors are deduced from the ratios presented in Table 3 and are applied to POLAR and THEMIS in the entire region studied here ($L=2$ to $L=10$).

**B. How to take into account the time period of the data sets?**

It is essential to take into account the different time periods of the data sets used in this study. Indeed, POES data cover two solar cycles while THEMIS and POLAR cover only one solar cycle. Moreover, THEMIS measured fluxes during the last solar cycle, a cycle very calm compared to the previous one. Thus, in addition to the cross calibration described in the previous paragraph, another correction has to be applied to THEMIS and POLAR data to take into account the difference of time period. To do so, ratios between the mean POES flux over all time period (1998–2018) and the mean POES flux over THEMIS time period on one side and POLAR time period on the other side, shall be calculated for a given energy, a given $L$ and a given MLT. These ratios correspond to the different of dynamics of electron fluxes during the different time periods. The factor applied to THEMIS and POLAR is then defined as follow:

$$
\text{Corr. factor (E,
\text{L, MLT})} = \frac{\text{Mean POES flux (E, L, MLT) between 1998 and 2018}}{\text{Mean POES flux (E, L, MLT) during s/c period}}
$$

This correction factor is applied to electron fluxes from THEMIS and POLAR, for all energies, $L$ and MLT in order to obtain equivalent electron fluxes for these two spacecraft, corresponding to the entire period of POES data (1998–2018).

**C. Variation of electron flux along magnetic field lines**

The third step in the development of the model is to find a general equation, for each $L$ bin (from $L=2$ to $L=10$), MLT and energy, allowing to calculate mean electron fluxes along the magnetic field line. Fig. 4 represents examples of electron fluxes versus equatorial pitch angle for each $L$ bin (40 bins from $2.0<L<2.2$ in black to $9.8<L<10.0$ in red). The color lines (40 $L$-bins from $2.0<L<2.2$ in black to $9.8<L<10.0$ in red), whose equation is of the form $Y=\exp(A \sin(B \alpha))$, correspond to the best fits for each $L$ interval for a given energy and a given MLT.

These graphs show that at the bottom, electron fluxes increase along the field line, whatever the $L$ value. However, the variation between equator and high latitudes is clearly higher for low $L$ values (black curve) than for high $L$ values (red curve). On the top, it is quite different because, as seen on Fig. 4, at high $L$ values electron flux is lower at equator compared to high latitudes. This difference is due to the energy but also to the different MLT plotted here. The behaviour of electron flux is really MLT dependent.

**D. Mean electron model with MLT dependence**

Using the fits determined for each of the 4 energies studied, each $L$ interval (40 linear intervals from $L=2$ to 10) and each MLT interval (24 linear intervals), electron fluxes from 0.19 keV to 8 keV can be calculated anywhere in the inner magnetosphere, taking into account the MLT dependency. Fig. 5 shows an example of results with two MLT $L$-cartographies of flux obtained with the new model near equator for 1 keV electrons on the left and for 8 keV on the right. As already mentioned, the new model is valid from $L=2$ up to $L=10$ and clearly depends on the MLT.
A. Comparison with AE9/SPM

The standard model used to estimate low-energy plasma fluxes is currently SPM model that is part of the AE9/AP9 models [1]. This empirical model is mainly based on CAMMICE/MICS [2] and LANL/MPA [6] data and is valid from 1 keV to 40 keV. Fig. 6 shows two cartographies MLT-r of flux obtained with SPM model at equator for 1 keV electrons on the left and for 8 keV on the right. It is important to note that cartographies from SPM are plotted in terms of the radial distance while those from our new model are plotted in terms of L McIlwain parameter. However the difference is not significant at the equator. Comparing these cartographies with those deduced from our new empirical model (Fig. 5), we can clearly see than there is no MLT dependence in SPM model, however maximum fluxes (for 0h<MLT<6h) have the same order of magnitude. In the final version of the paper, cartographies of electron fluxes out of the equator will be presented to complete the comparison.

B. Comparison with Van Allen Probes data

As mentioned in the section II, due to limited spatial coverage (up to L=6) and likely contamination of electron data below L=4, Van Allen Probes plasma data are not used to develop the model but used to validate it. Comparisons between fluxes measured by Van Allen Probes data and those calculated with our model have been done with an example of electron fluxes at 8 keV versus MLT at 5.8< L<6.0 plotted on Fig. 7. Fluxes measured by THEMIS and POLAR and those calculated with SPM are also represented. These graphs show that fluxes from our model are clearly coherent with Van Allen probes measurements. The MLT dependency and flux values are well consistent. As already mentioned fluxes from POLAR are lower than those from the other data sets and have been corrected to be used to develop the new model.

IV. COMPARISON WITH SPM/AE9 MODEL AND VAP DATA

A new low-energy plasma model has been developed for surface damages calculation. This empirical model is valid for electrons between 0.1 keV to 8 keV from L=2 up to L=10 and is based on NOAA-POES, THEMIS, POLAR and LANL data. This MLT dependent model has been compared with SPM results and validated with Van Allen Probes data. In the final paper, the electron model will be extended up to few tens of keV and a proton version will be presented. In the near future this low-energy plasma model will be integrated in GREEN (Global Radiation Earth Environment model).

REFERENCES


