HOT PLASMA ENVIRONMENT MODEL (HPEM): A EMPIRICAL MODEL OF THE JOVIAN ENERGETIC ELECTRON ENVIRONMENT FOR SPACECRAFT CHARGING STUDIES

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ABSTRACT

HPEM is an empirical radiation belt model designed to provide time-series of energetic electron spectra (0.15 - ~50 MeV) for Jupiter's magnetosphere that can be used as an input for internal charging studies for the JUICE mission. It is applicable for all regions of the jovian magnetosphere that JUICE will visit. The novel feature of the model is that it can be used to constrain the time-scales of the particle environment's variability that a spacecraft can encounter at Jupiter. The time variability is obtained through analytical equations and flux probability functions while temporal changes in the electron spectra are constrained by the L-gradients that Galileo's EPD/LEMMS detector has recorded. The model reproduces both the statistical scatter of energetic electron fluxes observed with Galileo/EPD, the lifetimes/time scales and the occurrence probability of flux enhancements that Galileo encountered. An application for the worst-case internal charging electron spectra for the JUICE mission is shown.

1. INTRODUCTION

Jupiter's magnetosphere is the largest in the solar system, powered by a very strong internal magnetic field that has a magnetic moment five orders of magnitude larger than that of Earth's and two orders of magnitude greater than that of Saturn. A variety of acceleration processes, modulated internally by the volcanic moon Io, continuously feed the planet's radiation belts with high energy charged particles, that, thanks to the high trapping efficiency provided by the strong magnetic field, accumulate at flux levels that make the operation of spacecraft and instruments or scientific measurements, very challenging. Indeed, Jupiter's magnetosphere contains the most powerful radiation belts in the solar system, strong enough to emit synchrotron radiation and to be observed remotely from the Earth [1].

A particular challenge for operating spacecraft in the jovian radiation belts is that of the internal charging. In particular, energetic electrons above several hundreds of keV in energy can penetrate spacecraft or instrument structures and deposit their charge on insulating components with the chance of causing discharges (Internal Electrostatic Discharges - IESD), due to the high fluxes of mildly relativistic electrons trapped in Jupiter's magnetosphere. 42 on-board computer resets that occurred during the Voyager-1 flyby of Jupiter in 1972 are actually attributed to IESDs [2].

The possibility for the occurrence of IESD at Jupiter depends on the levels of penetrating electron fluxes encountered by a spacecraft, which determine the source rate for charge accumulation on its internal elements, and the spacecraft material, the properties of which (e.g. conductivity) determine how fast it will distribute (or loose) the accumulated charge. The balance between the source and loss rate of charge on materials needs to be calculated. As a first step an energetic electron environment model for Jupiter is necessary to provide the source function for this calculation.

While several radiation belt models for Jupiter exist [3, 4], none of those can describe all components of the variability of the electron spectra, the time scales of which compared to the charging time constants of materials has to be known. The variability has two main components, the spatial and the dynamic. The spatial component results from the motion of a spacecraft in a spatially varying planetary magnetosphere. The dynamic component derives from magnetospheric dynamics and transients and describes the changes in the charged particle spectra that a spacecraft may encounter even if it remains continuously at the same magnetospheric position.

All available models can describe the spatial variability component (e.g. by flying a virtual spacecraft in a model magnetosphere), but cannot describe dynamics. For instance, the JOSE model [3] can output the L- and latitude dependent profiles of energetic particle spectra (where L is the McIlwain L-parameter) as a function of a confidence level. A high confidence level definition will output extreme spectra that a spacecraft may encounter at any magnetospheric location, without, however, any information for how much time the spacecraft can be exposed to such spectra or whether extreme flux enhancements can occur simultaneously at all magnetospheric locations and electron energies.

The Hot Plasma Environment Model (HPEM) is a new empirical model for Jupiter's energetic electron environment that was designed with the scope to overcome the aforementioned limitations. HPEM returns time-series of energetic electron energy-flux spectra that can be used as input to model the internal charging of the JUICE spacecraft. It is developed as part of the Jupiter Charging Analysis Tools project (JCAT), sponsored by the European Space Agency. In the following sections we provide a description of the HPEM capabilities, development methodology and implementation and show several example applications.

2. HPEM MODEL REQUIREMENTS AND CAPABILITIES

The requirements for an energetic electron environment model for internal charging studies of JUICE at Jupiter are the following:

- Export time series of energetic electron integral flux spectra for the energy range of 500 keV - 30 MeV. The lowest energy is defined at the typical value above which electrons can penetrate a spacecraft structure, while the highest from a limit above which integral electron fluxes low enough to be considered as unimportant for charging.
- Be applicable between the orbit of Europa (~9.5 Rj) up to 30 Rj, which is near Callisto's orbit, and in a latitude range of 40 degrees from the planetary equatorial plane. This requirement is driven by the orbital coverage of JUICE and the distances within which high relativistic electron fluxes may be encountered by the spacecraft.
- Describe the time variability of the system (both spatial and dynamic components).

HPEM satisfies or exceeds all aforementioned requirements. More specifically, it returns time-series of energetic electron (differential or integral) energy-flux spectra. The model describes the electron distribution function above 150 keV and is constrained by data up to 31 MeV, using also input by Pioneer 10 and 11 observations, as previous models have done [3, 4]. Above 31 MeV the energy spectrum can be extended assuming a power-law function. The model is applicable from the orbit of Europa (~9.5 Rj) up to a radial distance 100 R_j within the magnetosphere (1 R_j is a jovian radius equal to 69911 km). High latitudes are covered through empirical extrapolations of the data used to construct the model. The model that describes the time variability of the system is based on the combination of a simplified mean-model for the "average magnetosphere" and a Monte-Carlo approach for magnetospheric dynamics. The concept behind the development of HPEM is described in Section 3.

3. HPEM CONCEPT

Single-point measurements by the spacecraft that have visited Jupiter are not sufficient to separate spatial from temporal variations. Combinations of in-situ measurements with simultaneous aurora observations did not provide a straightforward method to separate the two variability components and in a way required to develop an empirical environment model. Multi-point charged particle measurements from spacecraft have taken place only during the brief Cassini flyby of Jupiter, and this limited dataset was insufficient to contribute to the development of HPEM. For that reason, HPEM development could be based only on the Galileo/EPD dataset [5], the most complete one available until today. The approach chosen for describing magnetospheric dynamics is purely empirical and basically constrains the time variability instead of defining it. The concept chosen for designing HPEM was the following:

- A model for the electron spectra as a function of magnetospheric position (L, latitude, local time and S3-longitude) should describe the average, spatial distribution of energetic electron fluxes in the jovian magnetosphere
- The scatter of electron fluxes as a function of position and energy should also be described. This defines the allowed dynamic range of electron fluxes and the probability that certain electron flux levels as a function of energy and position can occur.
- A spatial or temporal gradient of electron fluxes as a function of position should also be evaluated. This will define the allowed range of flux variations between sequential energy spectra that the HPEM model outputs. In essence, it prevents extreme and unrealistic variations within a single time step.

As it is not practical for HPEM to be parameterized at many individual energy ranges between 150 keV and several ten MeV, HPEM has to use a predefined form for the electron spectrum. The model makes all evaluations for one of the spectrum's coefficients, while the other coefficients can be obtained from correlation functions defined through data analysis. In that way, the whole energy spectrum can be evaluated from a single coefficient. The use of a spectral form ensures that fluxes at different energies cannot vary independently, so extreme fluxes at distant energy ranges cannot occur simultaneously, unless this is allowed by the spectrum's properties. The spectral form chosen is a double power law (indices γ, λ) that includes spectral break energy, at $E=E_c$ (Eq. 1).

$$j_{high} = j_{O,h} E^{\gamma} \left(1 + \frac{E}{E_c}\right)^{\lambda} \frac{1}{E_o^{\gamma}\left(1 + \frac{E_o}{E_c}\right)^{\lambda}} \quad (1)$$

Eq. 1 is used to calculate the differential electron energy spectrum, from which also the integral flux spectrum can be evaluated. All spectral indices are negative. The energies are always in keV and E_o=400.26 keV. The coefficient $j_{o,h}$, is the parameter that the HPEM model is built upon and it was evaluated from time series of Galileo/EPD observations. In some cases, the base-10 logarithm of this parameter, $\log_{10}(j_{o,h})$, is used instead for data analysis or calculations within HPEM. The reason the Eq. 1 form was chosen was to have more flexibility to fit different types of spectra.

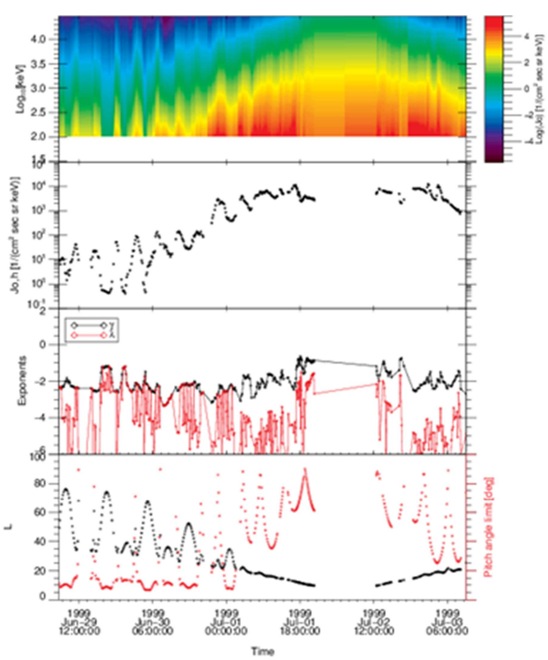

Figure 1: Data from orbit C21 of Galileo (end of June, 1999). From top: synthetic energetic electron energy-differential flux spectrogram, the $j_{o,h}$ parameter, the values of the exponents of Eq. 1 and the L (black) and a pitch angle related parameter (red).

4. DATA ANALYSIS

As mentioned above, the model was developed based on data from Galileo's Energetic Particle Detector (EPD). Galileo/EPD has several detectors, including LEMMS, which provides energetic electron fluxes and pitch angle information between about 15 keV and 1 MeV with differential energy channels and above 1 MeV with integral channels. A total of seven LEMMS channels (4 differential and 3 integral) we used to obtain spectral parameters through fits of Eq. 1 to the data. The data were from LEMMS's real-time mode, i.e. the low time resolution mode of the instrument, which provides measurements with about 11 minutes time resolution and limited angular resolution. Before the fitting procedure, dead-time correction and background subtraction was applied to each channel's count-rates. The fitting procedure for data from the integral LEMMS channels above 1 MeV required for Eq. 1 to be convolved with the channels' response function available through [4].

The spectral coefficients from the successful fittings where organized as a function of magnetospheric coordinates obtained through the *JUPLIB* library that was developed as part of the JOSE radiation belt model [3]. About 20000 spectra where used to construct HPEM. Sample output from the fitting procedure is shown in Fig. 1.

As a first step, a simple analytical model that describes the L and local time dependence of $\log_{10}(j_{o,h})$ was obtained. Pitch angle or S3-longitude effects could not be resolved parly due to the low-time and angular resolution mode of LEMMS. Gaussian fits to the scatter of $\log_{10}(j_{o,h})$ were also used to obtain the probability distribution function of $\log_{10}(j_{o,h})$ as a function of L (Fig. 2).

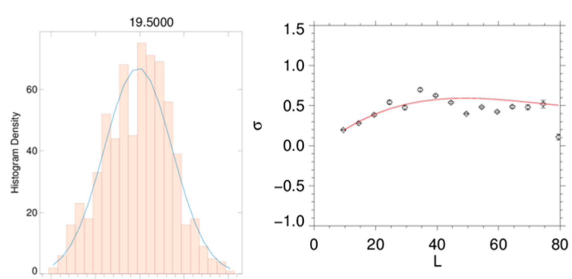

Figure 2: (Left) Histogram of $\log_{10}(j_{o,h})$ at L=19.5, after its average value has been subtracted. A Gaussian fit is also shown in blue (Right) The Gaussian distribution sigma, from fittings to EPD/LEMMS data and a simple polynomial profile (in red) that describes the trend. The red profile is what is used in the HPEM code.

A differential flux gradient was calculated from the time series of LEMMS, as described in Section 3, in order to obtain the allowed range of flux variability between subsequent time steps, as a function of L. The gradient function chosen is that of Eqs. 2 and 3.

$$j_{grad} = Log(\frac{|k|}{j}) \qquad (2)$$

where:

$$k = \frac{dj}{dL} \qquad (3)$$

The $j_{grad}(L)$ product was evaluated at two energies: 400 keV (practically the energy at which $j_{high}=j_{o,h}$) and 10 MeV. In each case $j_{grad}(L)$ is described through a polynomial function, while the magnitude of its scatter, modelled through a Gaussian function, was independent of L. Defining a gradient over time instead of L, gave similar results in the test runs of HPEM, so the choice of gradient function defined is secondary. $j_{grad}(L)$ practically defines the range of flux gradients expected when a spacecraft moves across different L-values due to the combined effects of spatial and dynamical variations. Maximum and minimum fluxes where also defined as a function of L, based on the analysed LEMMS observations. Finally, ratios between $j_{o,h}$ (or $log_{10}(j_{o,h})$) and other spectral coefficients of Eq. 1 were calculated and their L-dependence was described with analytical equations. An example is shown in Fig. 3.

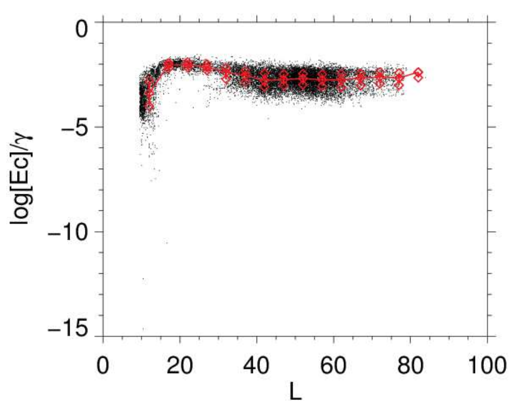

Figure 3: The ratio $log(E_c)/\gamma$ (black) and the binned averages over L (red). The spectral index γ can be obtained from similar profiles of the $log_{10}(j_{o,h})/\gamma$ ratio.

5. HPEM DESIGN

HPEM can work in a variety of modes, but the mode that includes most of its features is described in the diagram of Fig. 4. The user defines a time series of spacecraft positions, which HPEM converts to the appropriate magnetic coordinates. Using these coordinates, the code evaluates the average $log_{10}(j_{o,h})$ at each position. A random number generator returns a pseudorandom number from a normal distribution with a standard deviation (sigma) equal to the value defined by data analysis for the given position. This is added as a deviation to the average $log_{10}(j_{o,h})$, giving the logarithm of differential flux at 400 keV at this location. From this the spectrum is evaluated through the derived correlation functions and the differential electron spectrum is evaluated. If an electron spectrum is available from the previous time step, a flux gradient based on Eqs. 2 and 3 is evaluated at 400 keV and 10 MeV and tested against the acceptable limits derived from data analysis. If the condition is satisfied, absolute differential fluxes at the two energy ranges are tested against minimum and maximum allowed flux levels defined from EPD/LEMMS data. If all conditions are satisfied, the spectrum is stored and HPEM moves to the next time step. If any of the two conditions is not met, the code returns to the "random number generator" step, and the calculations are repeated until an acceptable spectrum is obtained. If calculation is not successful after a user defined, maximum number of iterations, HPEM forces an acceptable solution. Typically, less than 1% of time steps are completed without a successful evaluation of an electron spectrum. A series of test applications of HPEM were used to slightly modify and optimize the data analysis derived analytical functions used to predict the spectral coefficients for Eq. 1.

The code was originally developed in Interactive Data Language (IDL) and can easily be handled by a single computer. A Fortran version for integration with SPENVIS is under preparation. Due to the Monte-Carlo type of calculations done by HPEM, the code has to be run multiple times for any given scenario so that a representative or most-likely solution can be obtained.

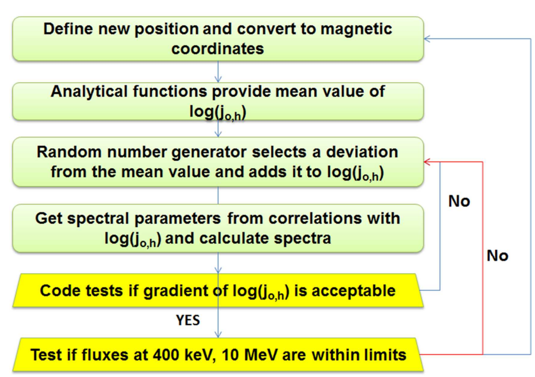

Figure 4: Simple flow diagram of HPEM

6. APPLICATION AND SAMPLE RESULTS

The user can select which features active in every HPEM run. In all examples below, HPEM runs take into account the simplified model for the local time dependent fluxes and all other features outlined in the flow diagram of Figure. In one case (Fig. 5), we show an HPEM run where only the mean model is used. In all cases the time resolution of the output is 30 minutes.

6.1. Example runs and comparison with observations

Below we show an example where time series of differential fluxes at three different energies have been calculated for three JUICE periapsis crossings through the orbit of Europa (Fig. 5). In this example, only the mean (spatial) model is used. Superimposed on each time series is a 24h averaged time series. As it is visible, the variability at the highest time resolution output reveals the ~ 10 h periodic changes due the planetary rotation and the dipole-rotational axis offset as well as the current sheet configuration of the jovian magnetosphere. Besides that, the 24h-averaged time series show smooth flux variations, as expected for a model that does not include dynamical features.

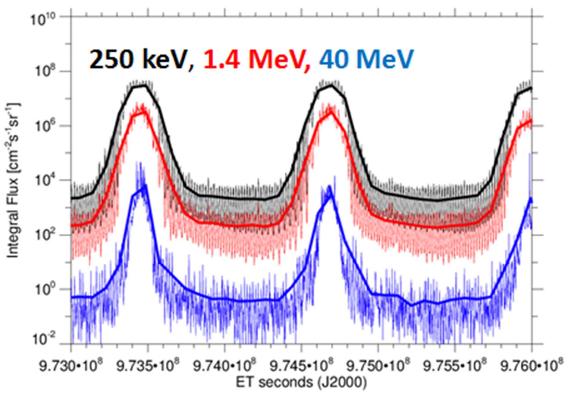

Figure 5: Time series of differential fluxes at three different energies from an HPEM run that outputs only the mean electron fluxes based on the spacecraft position.

When the Monte-Carlo features and gradient control of the code are included in the run (Fig. 4), output for the same time period shows less smooth time variations (Fig. 6). The ~10 h periodicity is still present but superimposed are seen periods of flux enhancements or depressions, most with durations of 0.5-3 days. Sharp changes are prevented from the gradient control of HPEM.

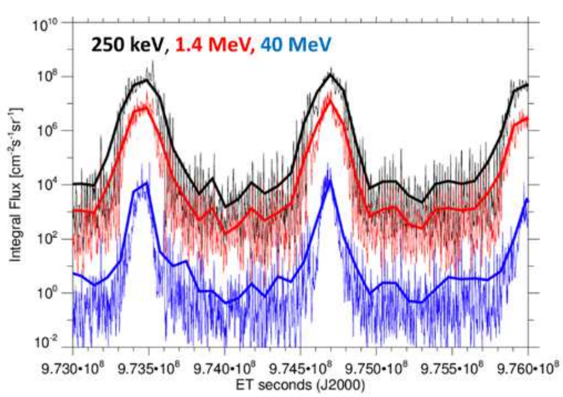

Figure 6: Same as Fig. 5, but with HPEM using the Monte-Carlo and gradient-control functions.

Instantaneous flux enhancements around periapsis (where worst case spectra are expected) can reach flux levels up to a factor 3-5 higher than the corresponding long-term average fluxes for certain energy ranges and depending on the averaging interval. This is confirmed also from the averaging of Galileo EPD data, a sample of which is shown in Fig. 7 from a periapsis pass that Galileo crossed Europa's orbit. Duration, intensity and profiles of enhancements appear similar as in the output of HPEM.

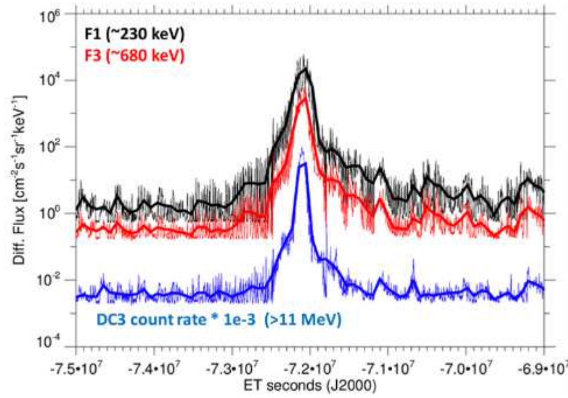

Figure 7: LEMMS observations for a periapsis pass from Europa's orbit. The top profiles are in differential flux units, the DC3 profile is a scaled count-rate.

Finally, we run HPEM for 500 times and for the JUICE trajectory and compared the L-dependent output for the differential or integral fluxes at several energy ranges with measurements by Galileo. A comparison at 1 MeV is shown in Fig. 8, where the black points are from the 500 HPEM runs and the green points are from spectrum fittings to the LEMMS observations. Predictions of HPEM are in good agreement with Galileo observations. Furthermore, since HPEM uses theoretical Gaussian functions to estimate fluxes at a given position, its estimations can be extrapolated above the maximum flux levels measured or below the instrumental background, seeing as a cutoff in the green point distribution in Fig. 8 for *L>30.*

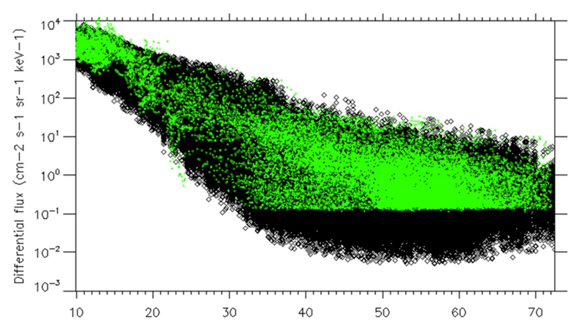

Figure 8: Comparison of the HPEM output for the differential flux at 1 MeV (black) , with Galileo LEMMS observations (green).

6.2. Worst case fluxes

HPEM was used to calculate the worst case internal charging environment for the JUICE spacecraft. We performed 2223 runs of HPEM. The JUICE mission phase that was simulated covers five periapsis passes that include the two Europa flybys and the time period where the worst case charging spectrum is expected to be encountered. For each of the HPEM runs we retrieved the maximum omnidirectional integral flux observed for 1 and 10 MeV as well as the spectral coefficients of each of the corresponding spectra. The spectra at the time of the observed maxima are shown in Fig. 9.

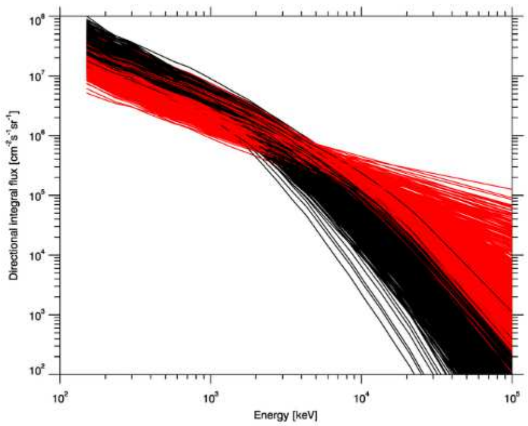

Figure 9: Integral electron flux spectra from HPEM. Each curve corresponds to the worst-case spectrum based on the maximum integral flux per run observed at 1 and 10 MeV (black and red, respectively)

Black spectra are defined based on the maximum flux at 1 MeV, red based on 10 MeV maximum. As we see, because of the restricted spectral shape (Eq. 1), it is not necessary that when the maximum flux at 10 MeV is observed a maximum also occurs at 1 MeV (or the contrary). In reality, the maxima at these two energies are anti-corellated. The distribution of fluxes for a given energy range follows a Gaussian distribution (Fig. 10).

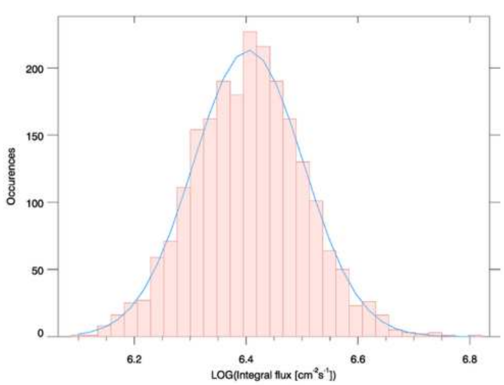

Figure 10: Distribution of Integral electron fluxes at 1 MeV from 2223 HPEM runs. The blue line is a Gaussian profile.

Similar set of spectra were also obtained from a time averaged HPEM output, at the period that the worst case instantaneous electron spectrum was observed. Using all that information we constructed a model for the worst-case electron spectra at 1 and 10 MeV, together with their probability of occurrence (percentile, p) and for different time averaging intervals.

The most likely worst-case charging spectrum (percentile=0.5) based on the 1 and 10 MeV integral fluxes is shown in Figs. 11 and 12. The dashed line marks the worst-case instantaneous electron spectrum used in the latest environment definition for the JUICE project (Issue 5, Revision 4) [6].

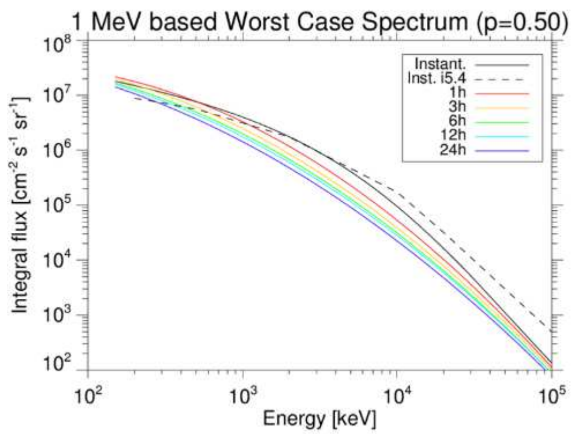

Figure 11: 1-MeV based worst-case integral flux spectra for a percentile of 0.5 (proposed, most likely worst-charging spectrum scenario for JUICE). Profiles for different time averaging are also shown. The dashed line is from [6]

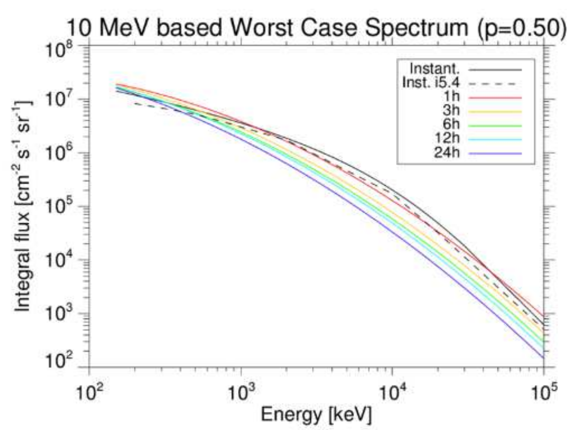

Figure 12: Same as in Fig. 10, but for the 10-MeV based worst-case integral flux spectra

We observe that differences between spectra estimated from HPEM and spectra for latest JUICE environment definition are below 50% for the most critical energy range (1 to several 10 MeV). This is also a validation of HPEM against other environment models, in specific

JOSE which is currently used for relevant studies from the JUICE project.

Differences between the JUICE worst-case spectra from the JOSE model and HPEM may have their origin in the slightly different assumptions used to extract fluxes from LEMMS during data analysis and the different calculation methods of spectra within the two models. For instance, response functions of the LEMMS channels above 1 MeV were used in order to calculate to the electron spectra for the HPEM development. Ideal channel passbands were instead used for JOSE.

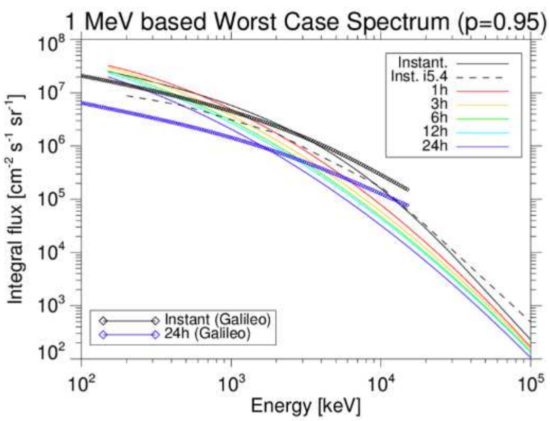

Figure 13: Same as in Fig. 11, for percentile of 0.95 and comparison with Galileo measurements.

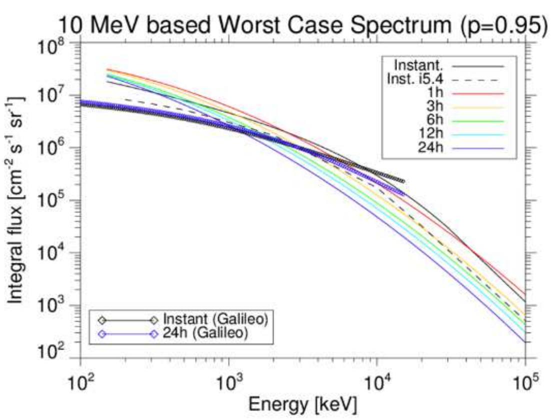

Figure 14: Same as in Fig. 12, for percentile of 0.95 and comparison with Galileo measurements.

A comparison of the worst-case spectra from HPEM with measurements up to 11 MeV, where Galileo observations are directly available, suggests that a percentile of 0.9-0.95 for the analysed HPEM results is probably the best choice to define the worst case spectra for JUICE. The corresponding spectra are shown in Figs. 13 and 14. Note that there is also good agreement between HPEM and Galileo observations regarding the reduction of the flux levels if we average the spectra over long time periods. Results shown in Figs. 11-14 are preliminary and have not yet been adopted by the JUICE project, but are indicative of the capabilities of HPEM.

7. SUMMARY

The HPEM model is a new type of empirical energetic electron environment model for Jupiter that uses a Monte-Carlo approach to describe the electron distribution function above 150 keV and constrain its time variability. The code is primarily designed to support studies of internal charging for the JUICE spacecraft, but can have additional applications, e.g. estimating radiation doses for spacecraft or instrument electronics. HPEM has been tested against Galileo observations and other, validated environment models of Jupiter. The model will be integrated in SPENVIS (https://www.spenvis.oma.be/) and be available to the users within 2016. Future improvements of HPEM are also expected to use the highly anticipated energetic particle measurements by the Juno spacecraft.

8. ACKNOWLEDGMENTS

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