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Time and space variability of the electron environment at the orbit of Ganymede as observed by Juno

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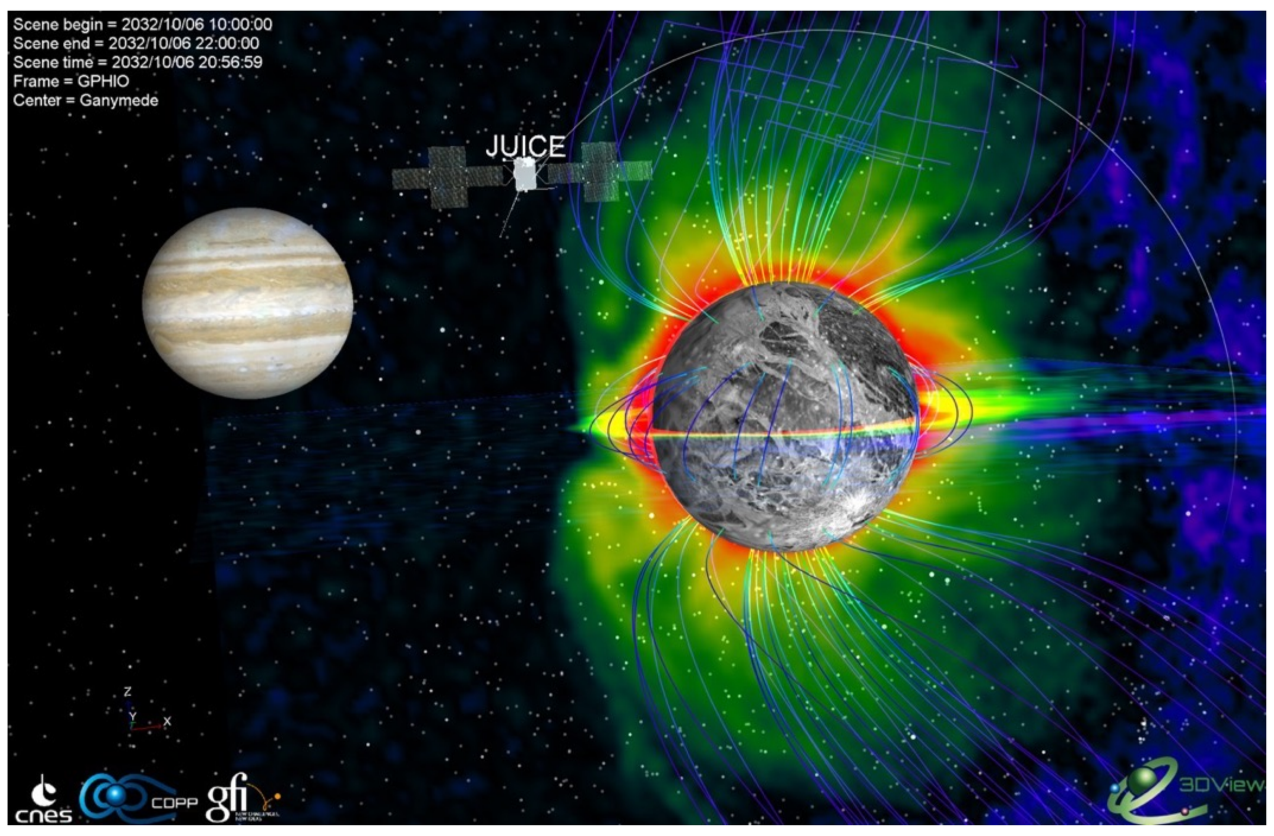
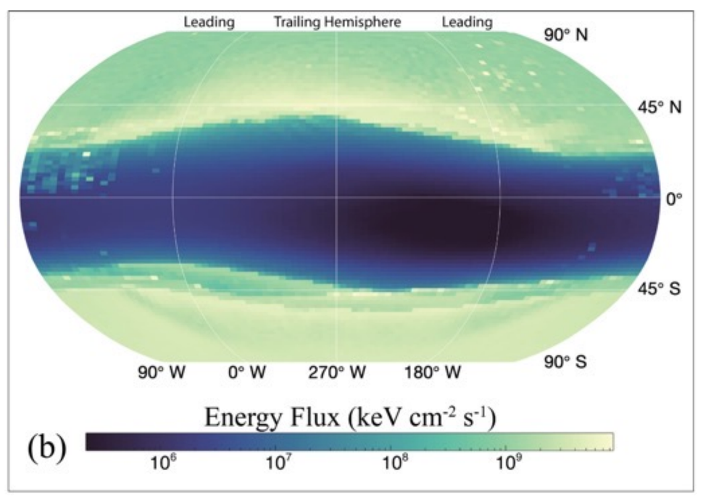
Abstract

The thermal and energetic electrons along Ganymede's orbit not only weather the surface of the icy moon, but also represent a major threat to spacecraft. In this article, we rely on Juno plasma measurements to characterize the temporal and spatial variability of the electron environment upstream of Ganymede. In particular, we find that electron spectra observed by Juno have fluxes larger by a factor of 2 to 9 at energies above 10 keV than what was measured two decades earlier by Galileo. This result will advance our understanding of the surface weathering and may be a concern for the radiation safety of the JUICE mission. Furthermore, the June 2021 close fly-by of Ganymede reveals that the open field line regions of its magnetosphere attenuate electron fluxes at all energies by a factor of 1.6 to 5, thereby offering a natural shelter to visiting spacecraft.



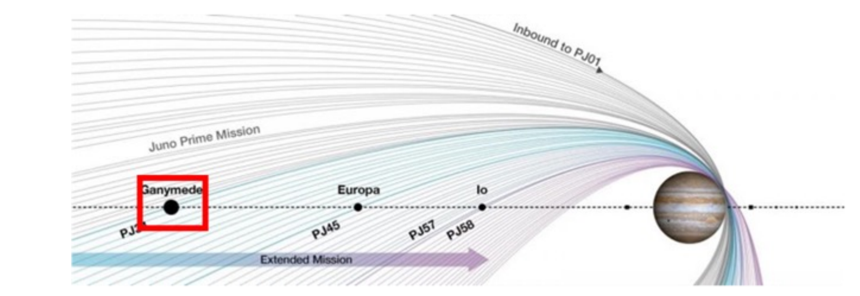
Context

The upstream electron distribution informs on the state of the Jovian magnetosphere and governs the Ganymede-magnetosphere interaction (Fatemi et al., 2016; Plainaki et al., 2015; Poppe et al., 2018; Liuzzo et al., 2020), electron precipitation to the surface (e.g. Liuzzo et al., 2020), and ionization of the moon exosphere (e.g. Vorburger et al., 2022; Leblanc et al., 2017; 2023). Whereas both short- and long-term dynamics as well as latitudinal, longitudinal, and local time variability of the Jovian magnetic field and plasma at the orbit of Ganymede have been previously reported (Krupp et al., 2004; Mauk et al., 1999; Mauk et al., 2020; Jun et al., 2005; Bagenal et al., 2016; Vogt et al., 2022), the impact of this variability has however not been fully explored in those previous studies. Paranicas et al. (2021) recently reported electron differential fluxes measured by Juno (Bolton et al., 2017) near Ganymede's orbital distance significantly higher than previously considered, although they acknowledged that their study only provided a single snapshot of the prevailing plasma and energetic particle conditions there at the time of their measurements.



Method & Results

Searching for the time periods when Juno crossed the environment where Ganymede orbits



Combining observations from the JADE and JEDI instruments

Intercalibration of the JADE and JEDI omnidirectional electron fluxes

Modelling of the observed electron populations with bi-kappa distribution functions

$$j_e = j_1\left(\frac{E}{E_1}\right)^{\gamma_1}\left(1+\frac{E}{E_1}\right)^{-\gamma_1-\kappa_1} + j_2\left(\frac{E}{E_2}\right)^{\gamma_2}\left(1+\frac{E}{E_2}\right)^{-\gamma_2-\kappa_2}$$

Determination of the position of Juno relative to the Jovian magnetodisk

Derivation of the electron density and pressure

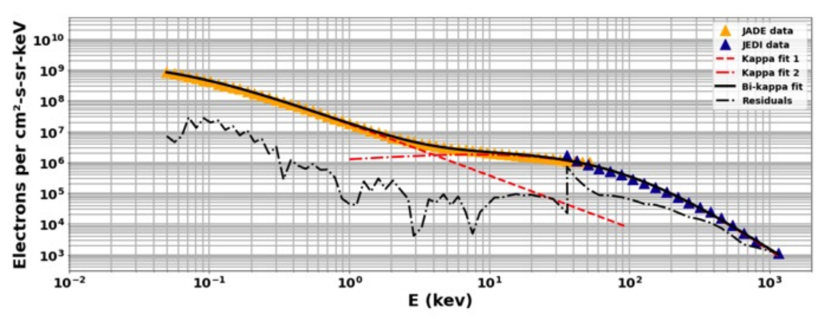


Figure 1. Composite electron energy spectrum for one of the time interval in our catalog (15 September 2020, 09:55-11:05 UT). The JADE and JEDI omnidirectional fluxes are displayed using orange and blue triangles, respectively. The red dashed and dash-dotted lines correspond to the first and second term of the bi-kappa distribution covering JADE and JEDI energies, respectively. The black solid line corresponds to the bi-kappa distribution given by equation (2) when the two terms are summed. The black dash-dotted line represents the absolute value of the difference between the observations and the bi-kappa fit.

A catalogue of 35 events (above/below, inside)

Time interval (UT)	PJ #	Latitude (°)	Longitude (°)	Local Time (hour)	M-shell
16/12/2017 03:55-04:35	10	17.8/18.3	31.2/7.0	3.3/3.3	16.7/15.3
31/03/2018 17:25-17:55	12	14.0/14.3	295.0/276.9	2.8/2.8	17.0/17.6
31/03/2018 18:00-18:05	12	14.4/14.4	270.9/273.8	2.8/2.8	17.8/18.0
23/05/2018 13:35-16:15	13	13.2/15.3	15.6/278.6	2.5/2.5	16.5/15.4
15/07/2018 12:55-14:55	14	12.1/13.6	341.3/268.6	2.2/2.2	16.2/16.3
06/09/2018 08:55-09:05	15	11.3/11.4	68.1/62.0	1.9/1.9	19.1/18.3
06/09/2018 09:10-11:45	15	11.5/13.5	59.0/325.0	1.9/1.9	17.9/14.2
29/10/2018 07:25-07:35	16	12.4/12.5	63.8/57.8	1.7/1.7	16.1/15.6
29/10/2018 07:40-07:45	16	12.6/12.7	54.7/51.7	1.7/1.7	15.4/15.2
21/12/2018 00:35-00:45	17	9.8/9.9	253.7/247.6	1.4/1.4	17.8/18.3
12/02/2019 03:55-04:05	18	10.7/10.8	74.2/71.2	1.1/1.1	16.1/15.8

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Table A1. Start/Stop time values for the orbital parameters (IAU latitude in degree, IAU longitude in degree, Local Time in hour, M-shell) corresponding to particular PJ for each of the time intervals included in our catalog. The time intervals when Juno is within the magnetodisk are indicated in red, whereas the ones when Juno is above or below it are indicated in black and gray, respectively. M-shells are estimated using the JRM33+CON2020 magnetic field model of Connerney et al. (2022).

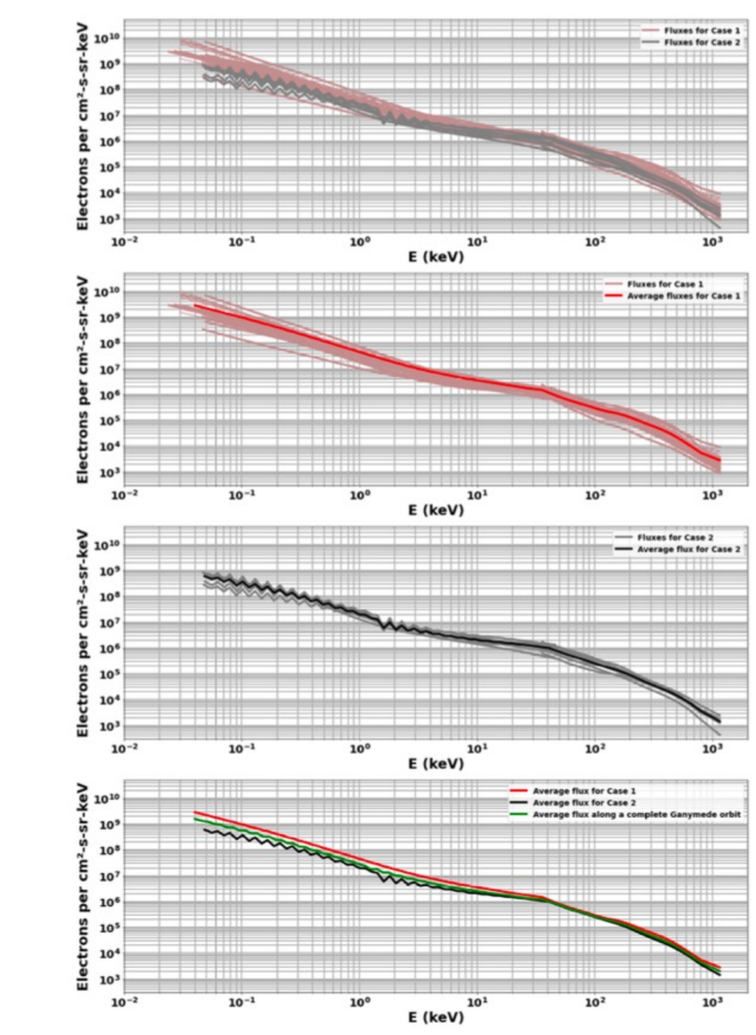


Figure 2. First panel: Electron omnidirectional fluxes sorted according to their origin (in pink, those measured inside the magnetodisk corresponding to Case 1; in gray, those measured above it corresponding to Case 2). Second panel: Electron omnidirectional fluxes for Case 1 together with their average (in red). Third panel: Electron omnidirectional fluxes for Case 2 together with their average (in black). Fourth panel: Red represents the average flux measured inside the magnetodisk, black the average flux measured above the magnetodisk, and green the average flux along one complete orbit of Ganymede around Jupiter.

In a nutshell

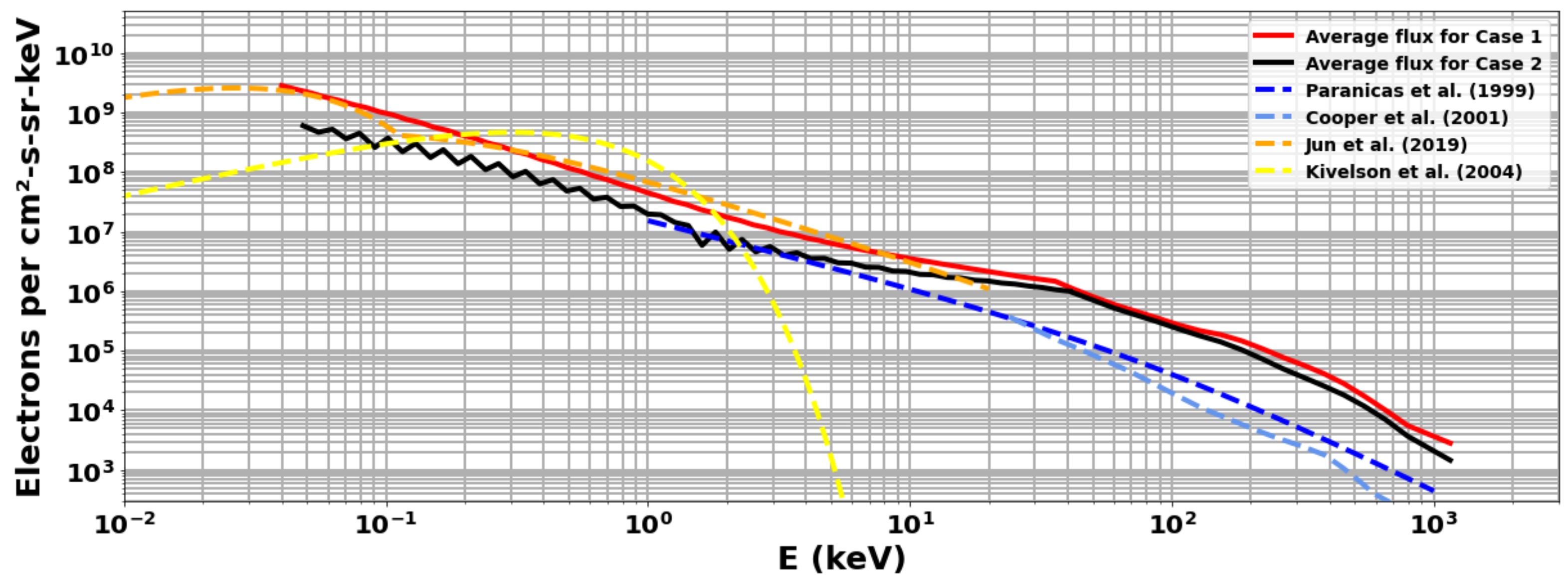
- We present composite electron energy spectra combining all Juno particle data from 07/2017 to 08/2022 at Ganymede's orbit.
- We study the variability of electron fluxes inside and outside the Jovian magnetodisk as well as within Ganymede's magnetosphere.
- Galileo-based models underestimate the electron fluxes observed by Juno in particular at high energies.

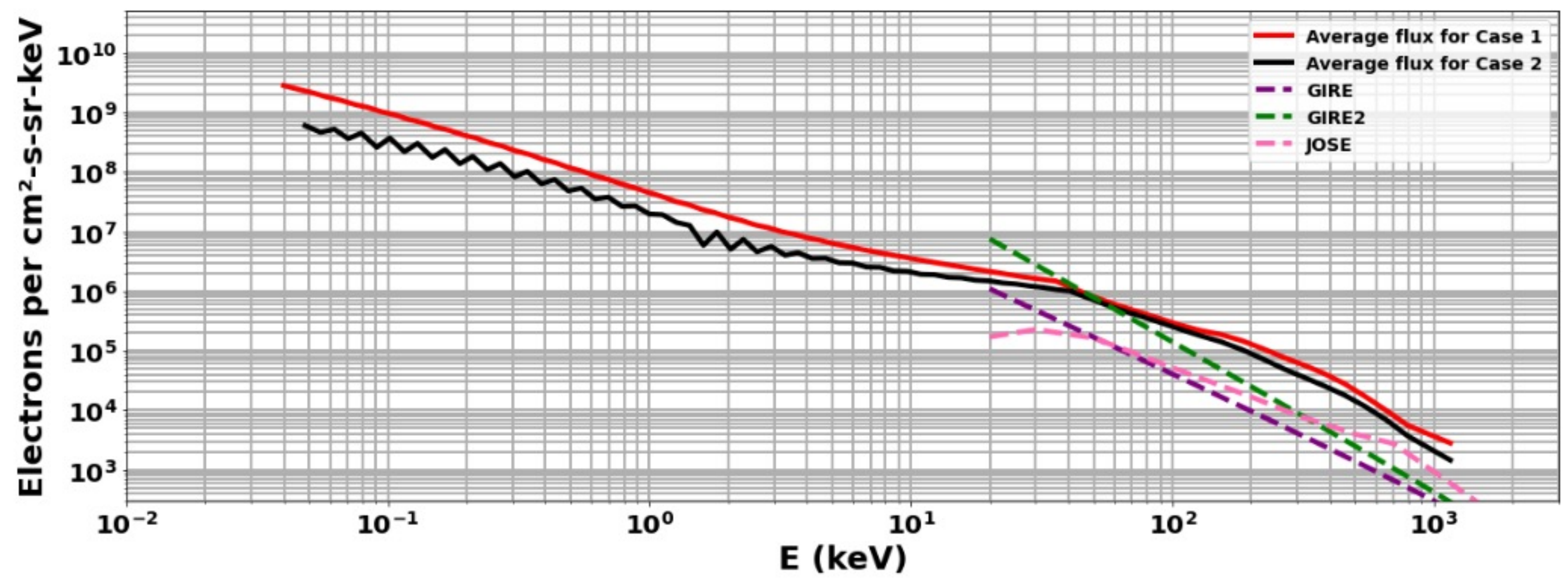
Case	j_1/j_2	E_1/E_2	γ_1/γ_2	κ_1/κ_2
Within the magnetodisk	8e9/6e6	0.03/90	0/0.4	1.45/3.2
Above the magnetodisk	2.7e9/4e6	0.048/85	0.6/0.3	1.6/3
Along a complete Ganymede orbit	4e9/4e6	0.038/85	0 /0.3	1.5/3
Open field line magnetosphere of Ganymede	2.7e9/1e6	0.043/75	0.4/0.5	1.5/2.6

Table C1. Values for the parameters of the bi-kappa distributions presented in equation 2 for the average electron omnidirectional fluxes in the key regions of our study. All the omnidirectional fluxes j are in electrons per cm²-s-sr-keV and all the energies E_1 and E_2 are in keV.

Comparison with models

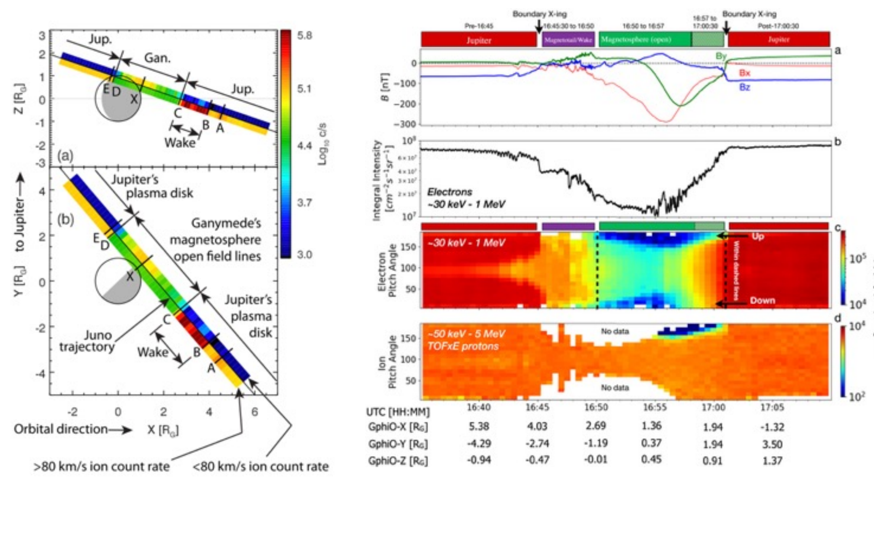
Statistical analysis and comparison with Galileo-based observations and models

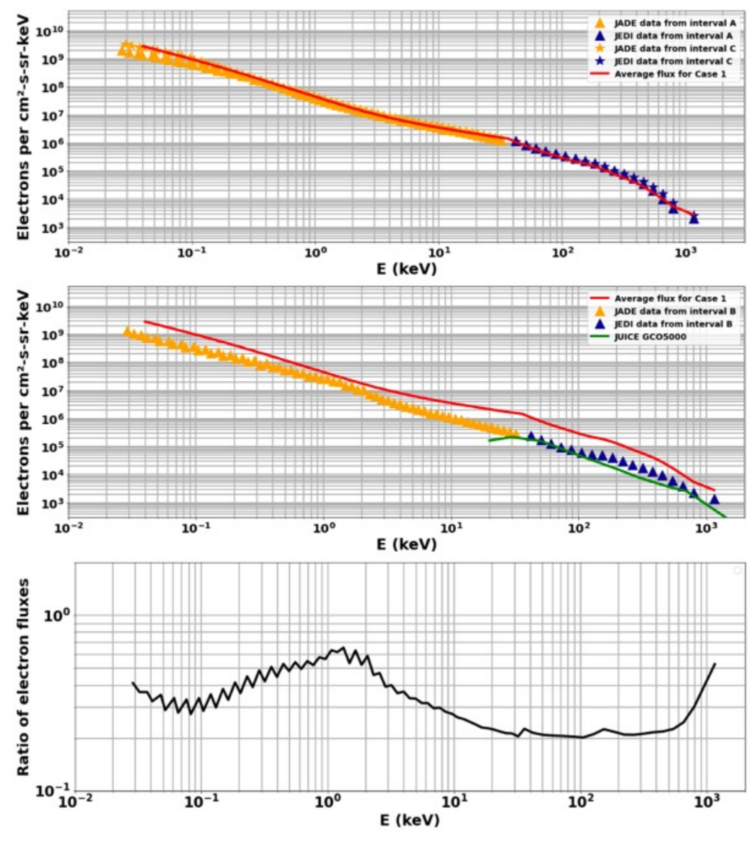




The Juno Ganymede flyby 07/06/2021 (CA = 1049 km altitude)

Almost 20 years after the end of the Galileo mission, the flyby of Ganymede by Juno on June 07, 2021 offers a unique opportunity to compare the electron omnidirectional fluxes observed inside its mini-magnetosphere to closest approach (1,049 km from the surface) with those observed outside of it. This flyby is included in one time interval in our catalog that corresponds to the case when Juno lies within the magnetodisk. Since Juno crossed different plasma regions during the flyby (Allegrini et al., 2022), we further subdivided this particular time interval into three time sub-intervals: two of them, from 15:25 to 16:50 (interval A) and from 17:05 to 18:15 (interval C), when Juno is outside the magnetosphere of Ganymede, in the ambient, undisturbed Jovian plasma near Ganymede, and a third one from 16:50 to 17:00 (interval B) when Juno is embedded into the open field line regions of the magnetosphere of Ganymede, with an altitude relatively to the surface confined between 1,049 km and 3,890 km. Allegrini et al. (2022), Valek et al. (2022) and Ebert et al. (2022) reported the JADE measurements during the Ganymede fly-by, while Clark et al. (2022) and Kollmann et al. (2022) documented JEDI observations. However, previous authors did not investigate the amplitude of the reduction of electron omnidirectional flux offered by the mini-magnetosphere of Ganymede.





Conclusions

1 Electron omnidirectional fluxes experience strong energy-dependent temporal variations. The flux of thermal electrons varies by a factor of 24, while that of suprathermal electrons varies by a factor of 10;

2 Electron omnidirectional fluxes experience strong energy-dependent spatial variations whether they are measured within the Jovian magnetodisk, or above, or below it. Within the magnetodisk the flux of thermal and suprathermal electrons are enhanced by a factor 3 and 1.5, respectively;

3 The June 2021 close flyby of Ganymede by Juno reveals that the electron omnidirectional fluxes observed outside of Ganymede's magnetosphere closely match the average fluxes determined for the case when the moon is embedded within the Jovian magnetodisk. The observed fluxes are however strongly reduced at all energies within the open field line regions of Ganymede's magnetosphere. Whereas the suprathermal electron fluxes are attenuated by a factor of 2.5 to 5, the thermal electron fluxes are attenuated by a factor of 1.6 to 3;

4 The total electron density is dominated by the thermal electron population measured by JADE (up to 93%) and ranges from 1 to 12 electrons per cm^{-3}. The total electron pressure is dominated by the suprathermal electron population measured by JEDI (up to 75%) and ranges from 0.6 to 2.9 nPa;

5 The comparison of the electron omnidirectional fluxes observed during the Juno mission with Galileo-based observations and models shows a closer agreement at low energies than at high energies where Galileo observations are on average 11 times less intense than the fluxes observed by Juno as also noticed by Paranicas et al. (2022) in their very limited sample;

6 The comparison of the electron omnidirectional fluxes observed at the time of Juno with the empirical radiation model JOSE used by the European Space Agency for the design of its JUICE mission shows that the latter underestimates by a factor of 2 to 9 on average the suprathermal electron fluxes between 20 keV and 2 MeV.