Supporting Information for "The Infrared Footprint Tracks of Io, Europa and Ganymede at Jupiter Observed by *Juno*-JIRAM"

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Introduction

This supporting information Text S1 explains how the infrared altitude of the footprints is estimated and how the uncertainty of its position are evaluated.

The Data Sets S1-S6 contains the fit to the Main Alfvén Wing spot position of Io, Europa and Ganymede as they are shown in Figure 1 of the main text. The coordinates of the Ganymede footprint as function of the satellite longitude (Table S5 and S6) exhibit oscillations that are due to the intrinsic variability of the footprint position. The Europa footprint (Table S3 and S4) also exhibits a similar behaviour, although to a much lesser extent. We did not filter this oscillations out to not introduce an additional layer of data processing, which is left to the reader's needs. The Data Sets S7-S12 contain the fit to the footprint tail position of the three moons.

The Data Sets S13-S18 contain the position of the Main Alfvén Wing spot of Io, Europa and Ganymede derived from the JIRAM images, and the Data Sets S19-S24 the respective footprint-tail position.

Text S1.

To properly determine the coordinates of the peak of the emission, we need to estimate its expected altitude. JIRAM observed the IFP during PJ 4 and 7 between 90° and 120° in the northern hemisphere with two different emission angles of ∼75° and ∼35° respectively (this is the angle between the normal to the planetary surface and the instrument line of sight). By stereoscopy, it is possible to determine the altitude of the emission, which is estimated to peak at 600±100 km. According to chemistry models (Tao et al., 2011), the IR emission peaks between 500 and 1000 km for precipitating electrons with energy between 0.1 and 100 keV. The *Juno*-JADE-E particle detector measured the energy of the precipitating electrons associated with Io (Sulaiman et al., 2020; Szalay et al., 2020b), Europa (Allegrini et al., 2020) and Ganymede (Szalay et al., 2020a). The energy distribution associated with each moon shows remarkable similarity with each other, with a broadband spectrum and the bulk of electrons at energy < 1 keV. Because of this and the weak dependency of the peak altitude with the precipitating electron energy, we conclude that the IR emission of both the MAW spots and the footprint tails of all three satellite is expected to occur at an altitude of 600±100 km. The associated Δ_h in Eq.2 of the main text is then computed by projecting the ±100 km uncertainty along the line of sight of JIRAM.

The uncertainty associated with the JIRAM observations takes into account three contributions, namely: 1) the uncertainty on the altitude of the emission, 2) the physical size of the MAW spot and 3) the resolution of the image. The uncertainty Δ_k (k being an xyz

coordinate) on the position of the MAW spots is then computed as

$$\Delta_k = \sqrt{\Delta^2_{h(k)} + \Delta^2_{size(k)} + \Delta^2_{res(k)}} \tag{1}$$

where the three term on the rhs are the above-mentioned source of uncertainty.

The uncertainty $\Delta_{h(k)}$ is computed by using the instrument pointing provided by the Navigation and Ancillary Information Facility (NAIF, C. H. Acton (1996); C. Acton, Bachman, Semenov, and Wright (2018)) and by referencing the images at surfaces at the different altitudes of 600±100 km.

The longitudinal and transversal size of the MAW spots (Δ_{size}) is estimated from images captured at an emission angles <15°, while we selected images at emission angles >70° for the vertical extension. Unluckily, no images of the GFP at high emission angle are available. Nevertheless, the energy distribution of the precipitating electrons associated with the GFP is similar to the distribution of the EFP and IFP, thus we can assume that the vertical extension of the GFP is also similar to the other two. The longitudinal-transversal-vertical size of the IFP is (438±156)-(154±16)-(382±76) km, while for the EFP we obtain (538±206)-(202±24)-(502±360). The GFP longitudinal and transversal sizes are (958±120) and (200±42) respectively, and we assumed that its vertical extension is 400 km. The higher longitudinal size of the GFP is due to the presence of two lobes in the MAW spot, which are potentially caused by the geometry of the intrinsic magnetic field of Ganymede.

The weight in Eq. 1 of the main text are computed as

$$w_i = \frac{1}{\Delta^2_x + \Delta^2_y + \Delta^2_z} \tag{2}$$

and then they are normalized as

$$W_i = \frac{w_i}{\sum_i w_i} \tag{3}$$

Table S1.

System III spherical coordinates of the Main Alfvén Wing spot of Io in the northern hemisphere, corresponding to the continuous grey line in Figure 1 in the main text. The first column is the satellite longitude in degrees, the second the radial distance in km from Jupiter's center, the third and fourth the footprint longitude and planetocentric latitude in degrees respectively.

Table S2.

System III spherical coordinates of the Main Alfvén Wing spot of Io in the southern hemisphere, corresponding to the continuous grey line in Figure 1 in the main text. The first column is the satellite longitude in degrees, the second the radial distance in km from Jupiter's center, the third and fourth the footprint longitude and planetocentric latitude in degrees respectively.

Table S3.

System III spherical coordinates of the Main Alfvén Wing spot of Europa in the northern hemisphere, corresponding to the continuous grey line in Figure 1 in the main text. The first column is the satellite longitude in degrees, the second the radial distance in km from Jupiter's center, the third and fourth the footprint longitude and planetocentric latitude in degrees respectively.

Table S4.

System III spherical coordinates of the Main Alfvén Wing spot of Europa in the southern hemisphere, corresponding to the continuous grey line in Figure 1 in the main text. The first column is the satellite longitude in degrees, the second the radial distance in km from Jupiter's center, the third and fourth the footprint longitude and planetocentric latitude in degrees respectively.

Table S5.

System III spherical coordinates of the Main Alfvén Wing spot of Ganymede in the northern hemisphere, corresponding to the continuous grey line in Figure 1 in the main text. The first column is the satellite longitude in degrees, the second the radial distance in km from Jupiter's center, the third and fourth the footprint longitude and planetocentric latitude in degrees respectively.

Table S6.

System III spherical coordinates of the Main Alfvén Wing spot of Ganymede in the southern hemisphere, corresponding to the continuous grey line in Figure 1 in the main text. The first column is the satellite longitude in degrees, the second the radial distance in km from Jupiter's center, the third and fourth the footprint longitude and planetocentric latitude in degrees respectively.

Table S7.

System III spherical coordinates of the Io footprint tail in the northern hemisphere, corresponding to the continuous grey line in panel *(b)* and the continuous black line in panel *(c)* of Figure 1 in the main text. The first column the radial distance in km from Jupiter's center, the second and third the footprint tail longitude and planetocentric latitude in degrees respectively.

Table S8.

System III spherical coordinates of the Io footprint tail in the southern hemisphere, corresponding to the continuous grey line in panel *(b)* and the continuous black line in panel *(c)* of Figure 1 in the main text. The first column the radial distance in km from Jupiter's center, the second and third the footprint tail longitude and planetocentric latitude in degrees respectively.

Table S9.

System III spherical coordinates of the Europa footprint tail in the northern hemisphere, corresponding to the continuous grey line in panel *(b)* and the continuous black line in panel *(c)* of Figure 1 in the main text. The first column the radial distance in km from Jupiter's center, the second and third the footprint tail longitude and planetocentric latitude in degrees respectively.

Table S10.

System III spherical coordinates of the Europa footprint tail in the southern hemisphere, corresponding to the continuous grey line in panel *(b)* and the continuous black line in panel *(c)* of Figure 1 in the main text. The first column the radial distance in km from Jupiter's center, the second and third the footprint tail longitude and planetocentric latitude in degrees respectively.

Table S11.

System III spherical coordinates of the Ganymede footprint tail in the northern hemisphere, corresponding to the continuous grey line in panel *(b)* and the continuous black line in panel *(c)* of Figure 1 in the main text. The first column the radial distance in km from Jupiter's center, the second and third the footprint tail longitude and planetocentric latitude in degrees respectively.

Table S12.

System III spherical coordinates of the Ganymede footprint tail in the southern hemisphere, corresponding to the continuous grey line in panel *(b)* and the continuous black line in panel *(c)* of Figure 1 in the main text. The first column the radial distance in km from Jupiter's center, the second and third the footprint tail longitude and planetocentric latitude in degrees respectively.

Table S13.

Cartesian coordinates in km of the Io footprint in the northern hemisphere, corresponding to the data points in Figure 1 of the main text. The first column contains the perijove (PJ) number, the second the hemisphere observed. The third, fourth and fifth columns contain the date of the observation, while the sixth and seventh columns are the starting and ending time of the observation, respectively (they coincide for the Main Alfvén Wing spot observations). The X, Y and Z System-III coordinates of the spot are reported in column 8, 9 and 10. The last six columns contain the upper (up) and lower (dw) error on the spot position.

Table S14.

Cartesian coordinates in km of the Io footprint in the southern hemisphere, corresponding to the data points in Figure 1 of the main text. The first column contains the perijove (PJ) number, the second the hemisphere observed. The third, fourth and fifth columns contain the date of the observation, while the sixth and seventh columns are the starting and ending time of the observation, respectively (they coincide for the Main Alfvén Wing spot observations). The X, Y and Z System-III coordinates of the spot are reported in column 8, 9 and 10. The last six columns contain the upper (up) and lower (dw) error on the spot position.

Table S15.

Cartesian coordinates in km of the Europa footprint in the northern hemisphere, corresponding to the data points in Figure 1 of the main text. The first column contains the perijove (PJ) number, the second the hemisphere observed. The third, fourth and fifth columns contain the date of the observation, while the sixth and seventh columns are the starting and ending time of the observation, respectively (they coincide for the Main Alfvén Wing spot observations). The X, Y and Z System-III coordinates of the spot are reported in column 8, 9 and 10. The last six columns contain the upper (up) and lower (dw) error on the spot position.

Table S16.

Cartesian coordinates in km of the Europa footprint in the southern hemisphere, corresponding to the data points in Figure 1 of the main text. The first column contains the perijove (PJ) number, the second the hemisphere observed. The third, fourth and fifth columns contain the date of the observation, while the sixth and seventh columns are the starting and ending time of the observation, respectively (they coincide for the Main Alfvén Wing spot observations). The X, Y and Z System-III coordinates of the spot are reported in column 8, 9 and 10. The last six columns contain the upper (up) and lower (dw) error on the spot position.

Table S17.

Cartesian coordinates in km of the Ganymede footprint in the northern hemisphere, corresponding to the data points in Figure 1 of the main text. The first column contains the perijove (PJ) number, the second the hemisphere observed. The third, fourth and fifth columns contain the date of the observation, while the sixth and seventh columns are the starting and ending time of the observation, respectively (they coincide for the Main Alfvén Wing spot observations). The X, Y and Z System-III coordinates of the spot are reported in column 8, 9 and 10. The last six columns contain the upper (up) and lower (dw) error on the spot position.

Table S18.

Cartesian coordinates in km of the Ganymede footprint in the southern hemisphere, corresponding to the data points in Figure 1 of the main text. The first column contains the perijove (PJ) number, the second the hemisphere observed. The third, fourth and fifth columns contain the date of the observation, while the sixth and seventh columns are the starting and ending time of the observation, respectively (they coincide for the Main Alfvén Wing spot observations). The X, Y and Z System-III coordinates of the spot are reported in column 8, 9 and 10. The last six columns contain the upper (up) and lower (dw) error on the spot position.

Table S19.

Cartesian coordinates in km of the Io footprint tail in the northern hemisphere, corresponding to the data points in Figure 1 of the main text. The first column contains the perijove (PJ) number, the second the hemisphere observed. The third, fourth and fifth columns contain the date of the observation, while the sixth and seventh columns are the starting and ending time of the observation, respectively. The X, Y and Z System-III coordinates of the tail are reported in column 8, 9 and 10. The last six columns contain the upper (up) and lower (dw) error on the tail position.

Table S20.

Cartesian coordinates in km of the Io footprint tail in the southern hemisphere, corresponding to the data points in Figure 1 of the main text. The first column contains the perijove (PJ) number, the second the hemisphere observed. The third, fourth and fifth columns contain the date of the observation, while the sixth and seventh columns are the starting and ending time of the observation, respectively. The X, Y and Z System-III coordinates of the tail are reported in column 8, 9 and 10. The last six columns contain the upper (up) and lower (dw) error on the tail position.

Table S21.

Cartesian coordinates in km of the Europa footprint tail in the northern hemisphere, corresponding to the data points in Figure 1 of the main text. The first column contains the perijove (PJ) number, the second the hemisphere observed. The third, fourth and fifth columns contain the date of the observation, while the sixth and seventh columns are the starting and ending time of the observation, respectively. The X, Y and Z System-III coordinates of the tail are reported in column 8, 9 and 10. The last six columns contain the upper (up) and lower (dw) error on the tail position.

Table S22.

Cartesian coordinates in km of the Europa footprint tail in the southern hemisphere, corresponding to the data points in Figure 1 of the main text. The first column contains the perijove (PJ) number, the second the hemisphere observed. The third, fourth and fifth columns contain the date of the observation, while the sixth and seventh columns are the starting and ending time of the observation, respectively. The X, Y and Z System-III coordinates of the tail are reported in column 8, 9 and 10. The last six columns contain the upper (up) and lower (dw) error on the tail position.

Table S23.

Cartesian coordinates in km of the Ganymede footprint tail in the northern hemisphere, corresponding to the data points in Figure 1 of the main text. The first column contains the perijove (PJ) number, the second the hemisphere observed. The third, fourth and fifth columns contain the date of the observation, while the sixth and seventh columns are the starting and ending time of the observation, respectively. The X, Y and Z System-III coordinates of the tail are reported in column 8, 9 and 10. The last six columns contain the upper (up) and lower (dw) error on the tail position.

Table S24.

Cartesian coordinates in km of the Ganymede footprint tail in the southern hemisphere, corresponding to the data points in Figure 1 of the main text. The first column contains the perijove (PJ) number, the second the hemisphere observed. The third, fourth and fifth columns contain the date of the observation, while the sixth and seventh columns are the starting and ending time of the observation, respectively. The X, Y and Z System-III coordinates of the tail are reported in column 8, 9 and 10. The last six columns contain the upper (up) and lower (dw) error on the tail position.

References

Acton, C., Bachman, N., Semenov, B., & Wright, E. (2018, January). A look towards the future in the handling of space science mission geometry. *Planetary and Space Science*, *150*, 9–12. doi: 10.1016/j.pss.2017.02.013

Acton, C. H. (1996, January). Ancillary data services of NASA's Navigation and Ancillary Information Facility. *Planetary and Space Science*, *44*(1), 65–70. doi: 10.1016/0032-0633(95)00107-7

Allegrini, F., Gladstone, G. R., Hue, V., Clark, G., Szalay, J. R., Kurth, W. S., ... Wilson, R. J. (2020, September). First Report of Electron Measurements During a Europa Footprint Tail Crossing by Juno. *Geophys. Res. Lett.*, *47*(18). doi: 10.1029/2020GL089732

Sulaiman, A. H., Hospodarsky, G. B., Elliott, S. S., Kurth, W. S., Gurnett, D. A., Imai, M., ... Bolton, S. J. (2020, August). Wave-particle interactions associated with Io's auroral footprint: Evidence of Alfvén, ion cyclotron, and whistler modes. *Geophys. Res. Lett.*. doi: 10.1029/2020GL088432

Szalay, J. R., Allegrini, F., Bagenal, F., Bolton, S. J., Bonfond, B., Clark, G., ... Wilson, R. J. (2020a, February). Alfvénic Acceleration Sustains Ganymede's Footprint Tail Aurora. *Geophys. Res. Lett.*, *47*(3). doi: 10.1029/2019GL086527

Szalay, J. R., Allegrini, F., Bagenal, F., Bolton, S. J., Bonfond, B., Clark, G., ... Wilson, R. J. (2020b, September). A New Framework to Explain Changes in Io's Footprint Tail Electron Fluxes. *Geophys. Res. Lett.*, *47*(18). doi: 10.1029/2020GL089267

Tao, C., Badman, S. V., & Fujimoto, M. (2011, June). UV and IR auroral emission model for the outer planets: Jupiter and Saturn comparison. *Icarus*, *213*(2), 581–592. doi: 10.1016/j.icarus.2011.04.001