The Juno PJ57 & PJ58 flybys of Io: Multi-species chemistry simulations

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1. Summary & Goal

1.1) Juno: two close flybys downstream of Io (Fig.1)

- PJ57 at CA ~ 1,500 km **above** wake, **inside** Alfven Wing (Dec 23)
- PJ58 at CA ~ 1,500 km, **under** wake, **outside** Alfven Wing (Feb 24)

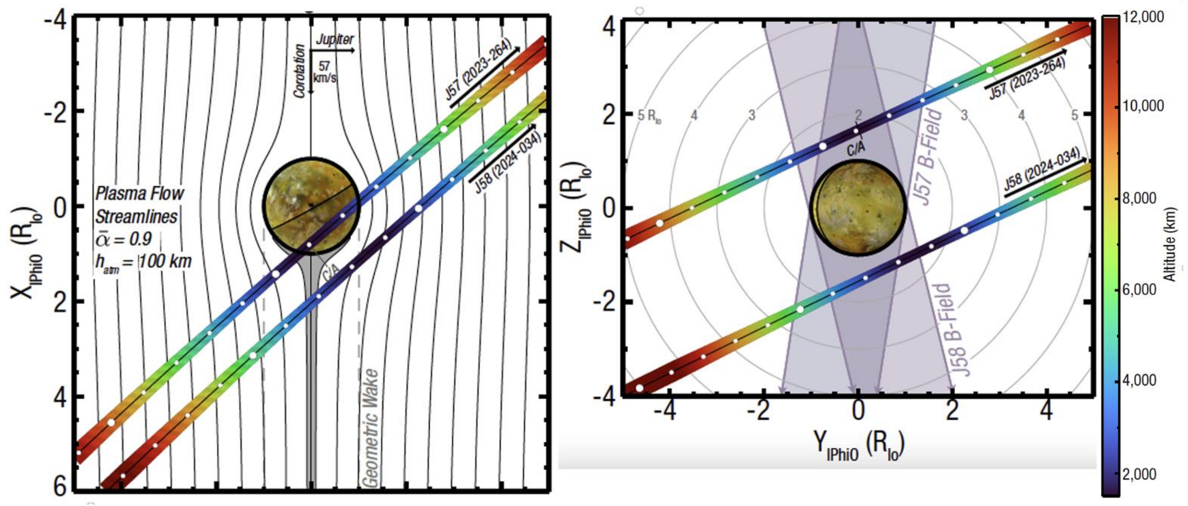


Fig 1: PJ57 & PJ58 trajectories in I-PhiO coordinate system (*Szalay*)

1.2) Goal: Explain electron densities observed along PJ57 & PJ58

1.3) Method of numerical simulations

- Prescribed atmosphere distribution in S, O, SO, SO_2
- MHD simulation of plasma flow into Io's atmosphere
- Physical chemistry code run along flow lines of MHD code
- Ionization by field-aligned electron beams <=> like auroral electron at earth

2. Juno observations

WAVES : electron density along PJ57 and PJ58 (*Sulaiman+24*)
JADE-E: bi-directional Field-aligned electron beams [30 eV-30 keV] (*Ebert+25*)
FGM : EMIC waves at gyrofrequency of SO_2^+, SO^+, and S^+ => pickup (*Cao+25*)
JADE-I: main ion data analysis still in process SO_2^+, SO^+, S^{n+}, O^{n+}
Field-aligned proton beams (*Szalay+24*)

2.1) PJ57 observations : through Alfven Wing

- Juno/Waves: n_{el} ~28,000 cm^{-3} (Fig 2) VERY LARGE
- ~ above the pole at I-PhiO (0.97, -0.24, 1.55)
- Radio-occultation: $<n_{el}>$ ~ 20,000 cm^{-3} (*Buccino+25*) VERY LARGE
- JADE-E: Field-aligned electron beams [2-15 mW/m^2] (Fig 3) LARGER than GALILEO

2.2) PJ58 observations: Behind the Alfven Wing

- Juno/Waves : n_{el} ~2,000 cm^{-3} (Fig 2) TYPICAL Bkg Torus
- at I-PhiO (0.71, 1.50, -0.84) ~ Sub-Jovian wake flank
- Radio-occultation: $<n_{el}>$ ~ 20,000 cm^{-3} (*Buccino+25*) VERY LARGE
- JADE-E: Field-aligned electron beams [2-20 mW/m^2] (Fig 3) larger than Galileo's

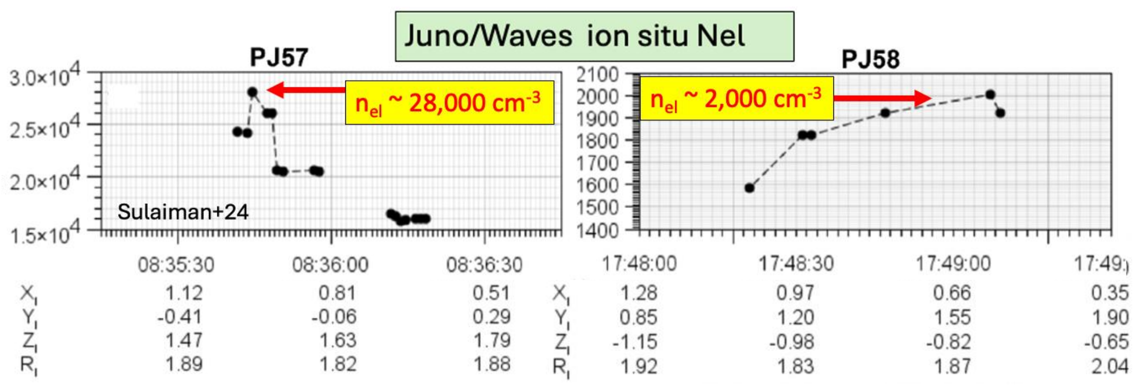


Fig 2: n_{el} from Juno/Waves (*Sulaiman+24*)

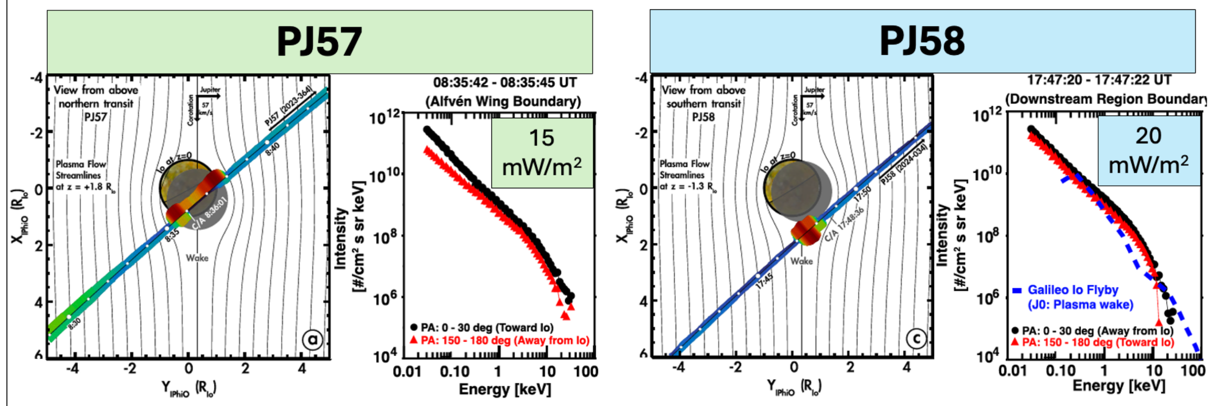


Fig 3: Field-aligned bi-directional electron beams (*Ebert+25*)

2.3) Upstream plasma conditions => Not yet determined

=> use plasma parameters and plasma flow from similar Galileo flybys

	PJ57 as Galileo I27	PJ58 as Galileo I31
Jovian magnetic field (B_{Jup})	1,980 nT	2,080 nT
Ion density (n_i)	1,331 cm^{-3}	1,350 cm^{-3}
Electron density (n_{el})	1,950 cm^{-3}	2,019 cm^{-3}
Average ion charge (Zi)	~ 1.5	~ 1.5
Ion temperature ,Ti>	~ 90 eV	~ 80 eV
Alfven Velocity (V_{Alf})	~ 265 km/s	~ 262 km/s
Alfven Mach Number (M_{Alf})	~ 0.22	~ 0.25
Angle Alfven wing (Theta)	~ 12°	~ 14°

3. Method: 2D simulation of Io's interaction

3.1) Atmosphere (Fig 4) (*Dols+12*)

- atmosphere of S, O, SO_2 and SO (10% SO_2)
- At equator: exobase = 200 km & $N_{col\ SO2}$ = 5.6 x 10^{16} cm$^-$
- O &S corona = Wolven+01 (Fig 4, 7, 8)

3.2) Plasma flow around Io: MHD (*Dols+12*) (Fig 5 for PJ57)

3.3) Multi-species physical chemistry (*Dols+25*)

- Reactions: dissociation, ionization, charge exchange, recombination
- Species: electrons, O^+, O^{++}, S^+, S^{++}, S^{+++}, SO_2^+, SO^+

3.4) Field-aligned electron beams (*Dols+24; 25*)

- Uniformly distributed above Io and in the Wake
  => not consistent with recent JADE-E observations (Ebert+24) => Future Work
- Ionization as auroral electron at Earth (Rees, 1989) (Fig 6)

$$Q_E^{\mathrm{Tot}}(z) = \frac{1}{\Delta \mathrm{E}} * (F * E) * \Lambda\left(\frac{s(z)}{R(E)}\right) * \frac{\rho(z)}{R(E)}$$

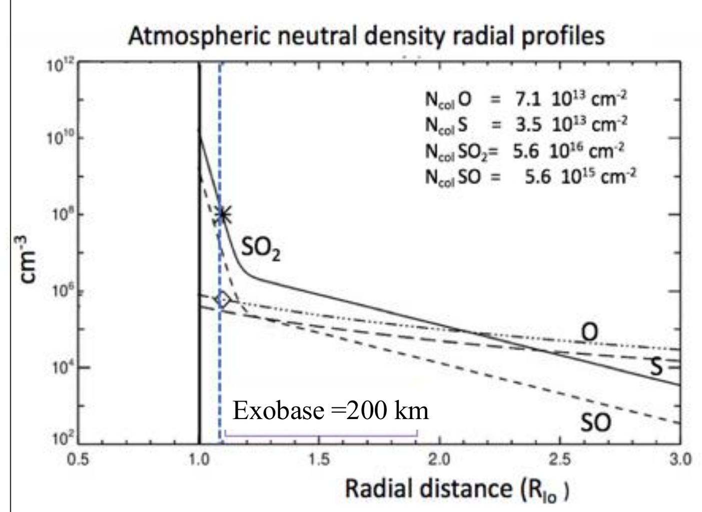


Fig 4: Radial profiles of in equatorial plane of neutrals in Io's atmosphere

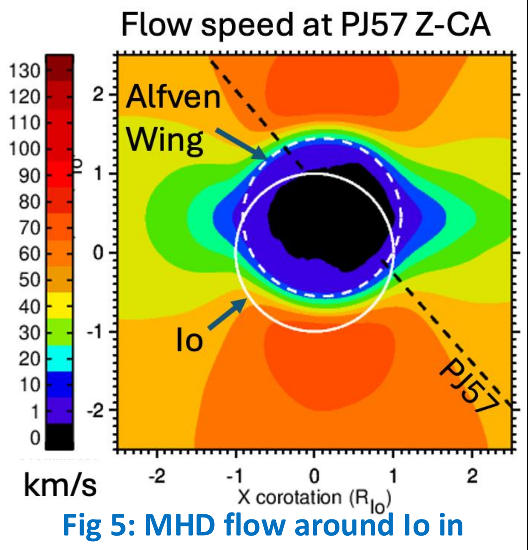


Fig 5: MHD flow around Io in equatorial plane(X,Y)

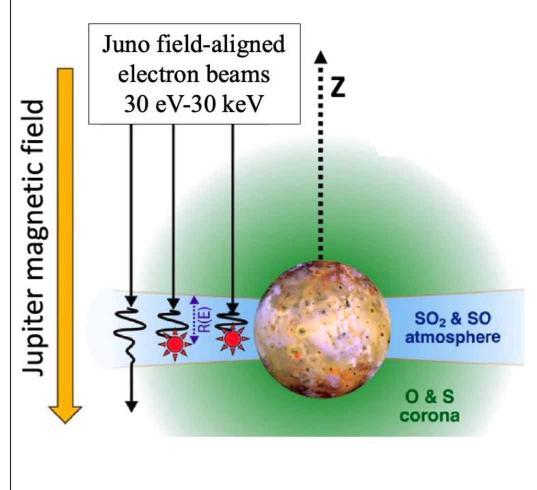


Fig 6: Ionization by field-aligned electron beams

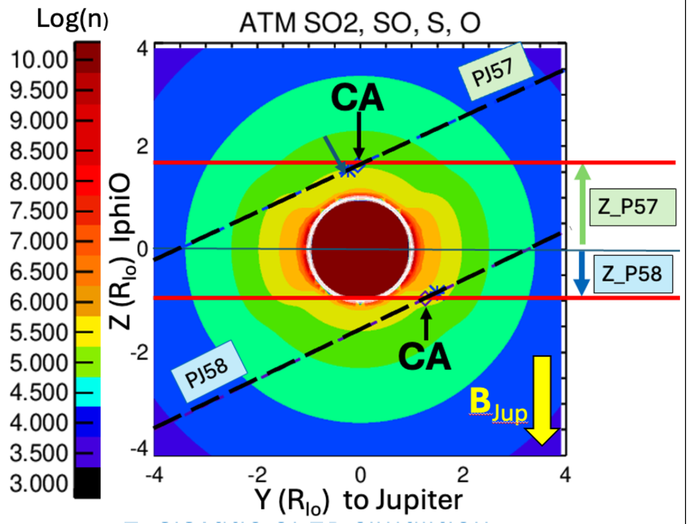


Fig 7: 2D plane of simulation for each flyby at Z-elevation = peak of electron density observed by Juno/WAVE. Also shows latitudinal distribution of atmosphere

3.5) 2D simulation

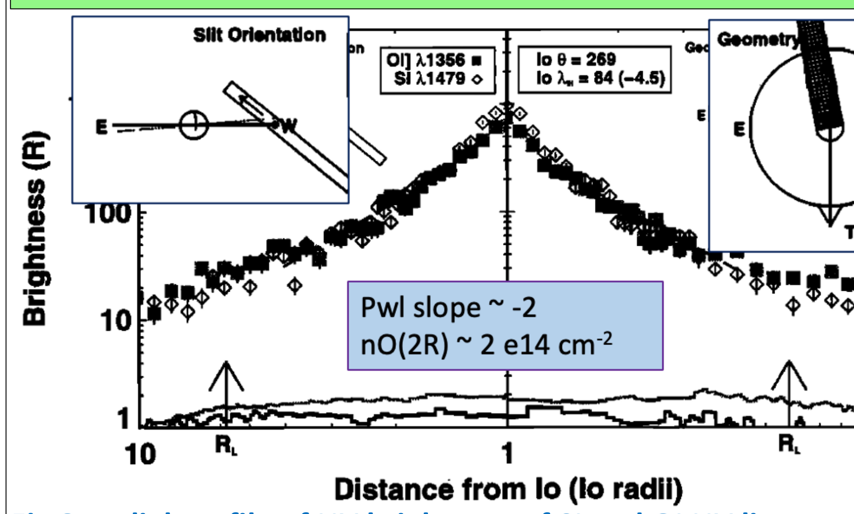
in XY plane at Z-elevation of peak n_{el} in Juno/Waves (Fig 7)

- PJ57 : Z_CA= 1.65 RIo =>Nel_obs = 28,000 cm^{-3}
- PJ58: Z_polar = -1.02 => Not CA
  BUT better look at polar atmosphere => Nel ~ 2,000 cm^{-3}

4. A Denser Atomic Coronae

4.1) Standard Coronae (1 x Wolven+01)

- **At polar latitude**: atmosphere composition dominated by S & O coronae
- **Atomic Coronae radial profile**: HST UV observations of Wolven+01 (Fig 8)
  - Same brightness profiles for S and O extending from 1 to ~ 10 R_{Io}
  - But density and spatial distribution unknown
  => Assume spherical symmetry based on aperture tilt
  => density inferred assuming T_{el}= 5eV and n_{el} ~ 2,000 cm^{-3} => questionable



Standard corona (Wolven+01)

Ncol O =7.3 × 10^{13} cm^{-2}
Ncol S = 3.6 × 10^{13} cm^{-2}

Fig 8: radial profile of UV brightness of SI and OI UV lines

4.2) Denser Coronae : (2 x WOLVEN+01) =======➔

Denser corona
= 2 x Wolven+01

Ncol O =15 × 10^{13} cm^{-2}
Ncol S = 7. × 10^{13} cm^{-2}

5. PJ58 RESULTS in 2D for Denser Corona

5.1) Density contours (n_{el} , S^+, O^+ , other ions not shown) (Fig 9)

5.1.1) at ~ CA ~ Sub-Jovian wake flank Y ~ 1.50 (diamond in Fig 9)

- n_{el} ~ 2,300 cm^{-3} => OK with Juno/Waves
- n_{S+} ~ n_{O+} ~ n_{SO2+} ~ 700 cm^{-3}
  => plasma typical of torus, slightly enriched in S^+ and SO_2^+

5.1.2) In central wake

- n_{el} ~90,000 cm^{-3} caused by electron beams
- Artifact of 2D projection: projected PJ58 goes through wake while real PJ58 skims under Wake (Fig. 1)

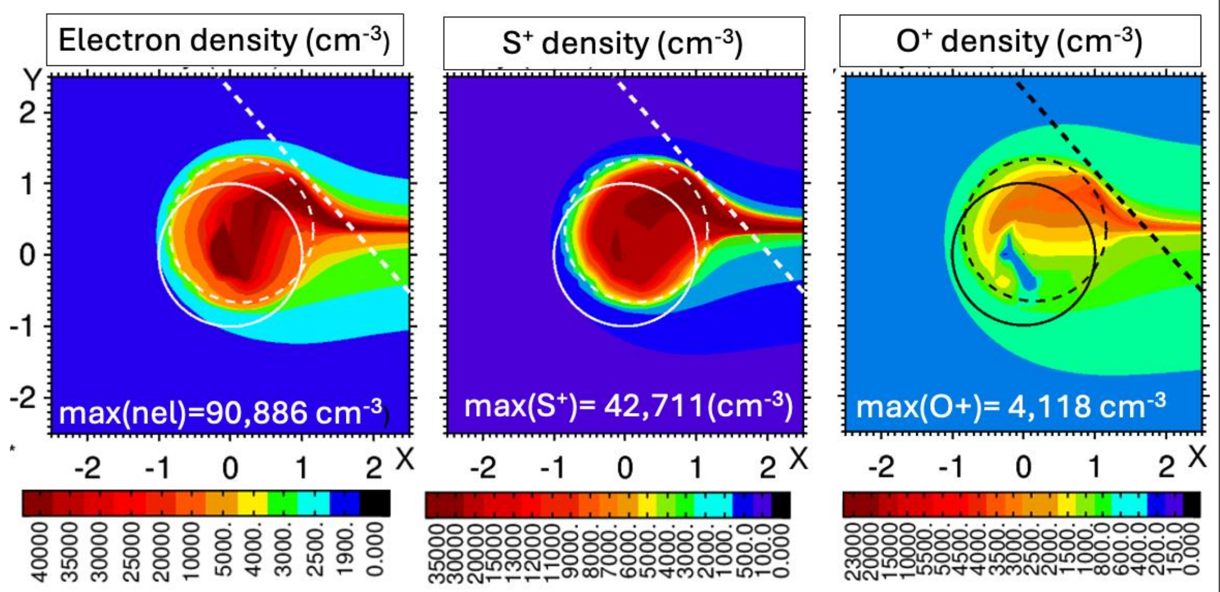


Fig 9: Densities for PJ58 simulation using Denser Corona (2 x Wolven+01)

5.2) Multi-charged ions and ion temperature (Fig 10, 11)

5.2.1) at CA

- (S^{++}, S^{+++}, O^{++}) multi-charged ions drop slightly at ~ Y-CA (Fig 10) because of Charge exchange in polar atmosphere
- $<T_i>$ at ~ Y-CA is quite high ~ 190 eV (Fig 11)

5.2.2) in the Wake

- (S^{++}, S^{+++}, O^{++}) multi-charged ions drop significantly (Fig 10)
- $<T_i>$ is low < 5 eV because Pickup in slow flow (Fig 11)
  => NO EMIC IN WAKE (*Cao+25*)

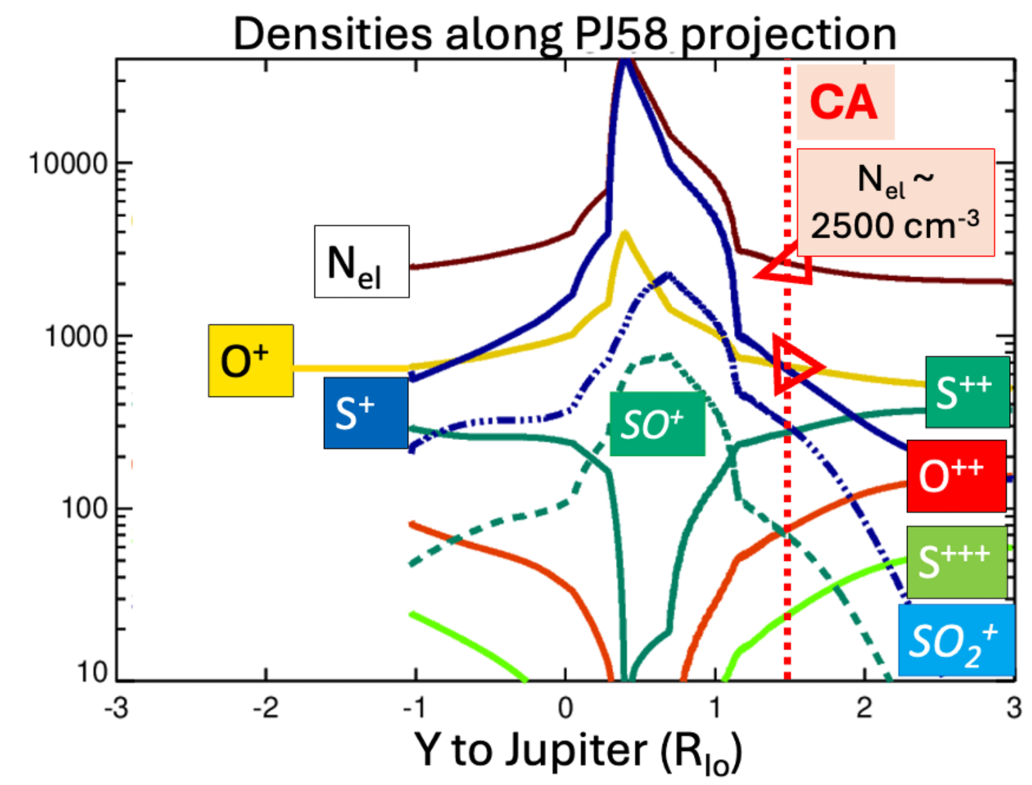


Fig 10: Densities along PJ58 trajectory projected in 2D plane of simulation. The red triangles highlight the calculated densities where Juno/Wave observed the maximum electron density

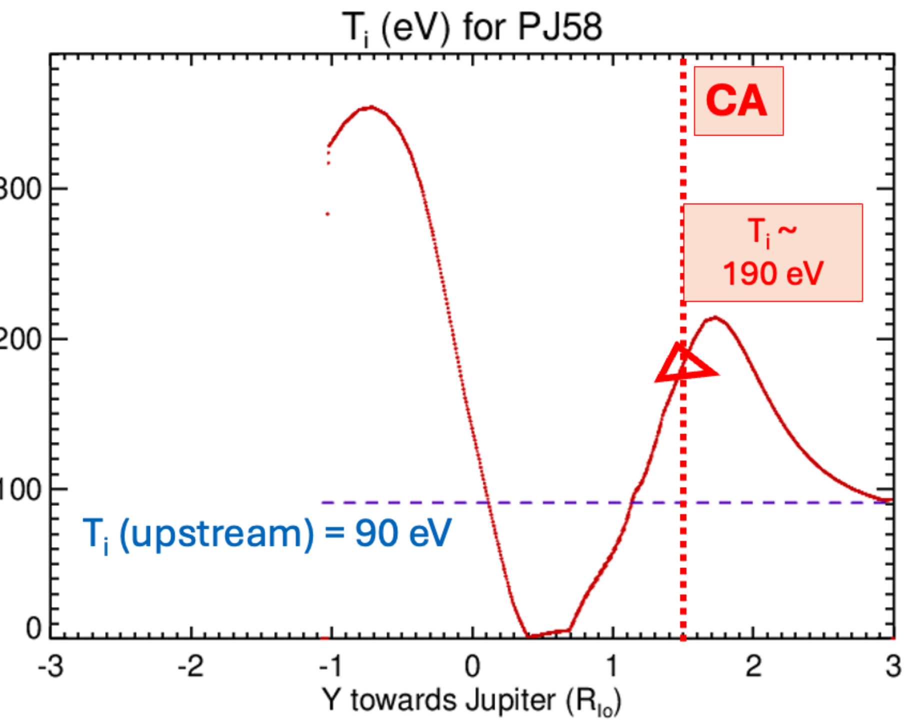


Fig 11: $<T_i>$ =Average ion temperature along PJ58 trajectory projected in 2D plane of simulation.

- Red triangle highlight $<T_i>$ where Juno/Wave observed maximum electron density
- $<T_i>$ is large (190 eV) as PU in fast flow
  => Strong EMIC at CA of SO_2^+ and SO+ but not at S^+ ?? on PJ58 (*Cao+25*)

6. PJ57 RESULTS in 2D for Denser Corona

6.1) Density contours at CA (n_{el} , S^+, O^+ , other ions not shown) (Fig 12)

- Densities peak at back of Alfven wing, not at the pole
- Max(n_{el}) ~ 40,000 cm^{-3} => OK with Juno/Waves along PJ57 ~28,000 cm^{-3}
- Plasma dominated by S^+ : Max (n_{S+}) ~ 33,000 cm^{-3}

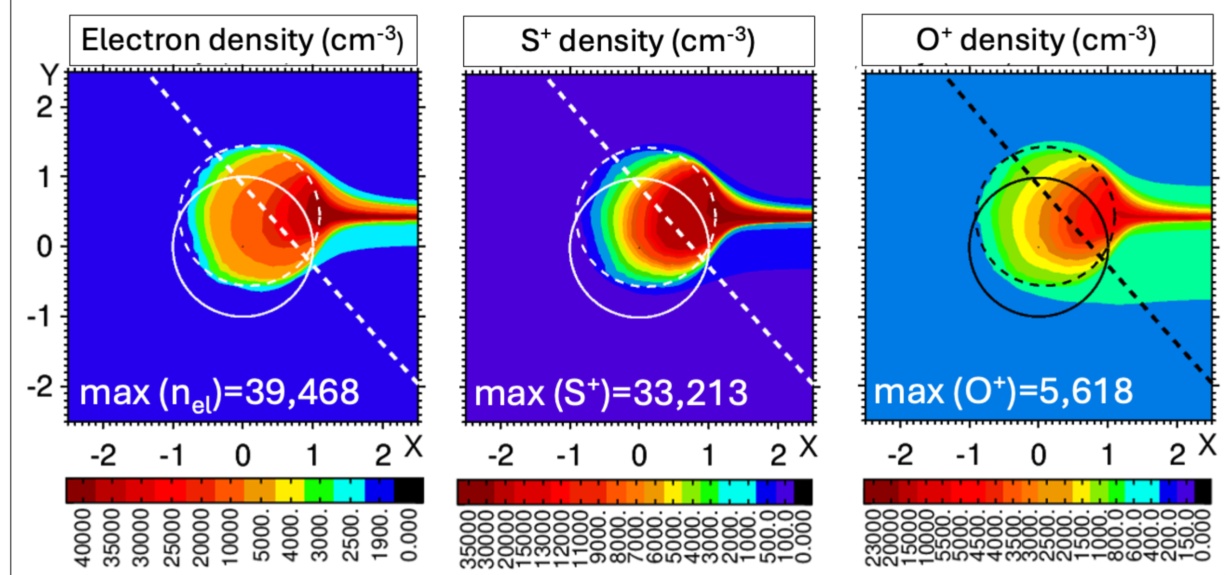


Fig 12: Densities for PJ57 simulation using DENSER Corona (2 x Wolven+01)

6.2) Multi-charged ions and ion temperature (Fig 13)

- (S^{++}, S^{+++}, O^{++}) multi-charged ions drop inside Alfven WIng because of Charge exchange on polar atmosphere
- $<T_i>$ = Ion temperature: (not shown) very low <5 eV because Pickup in very slow flow
  => NO EMIC waves IN ALFEN WING (*Cao+25*)

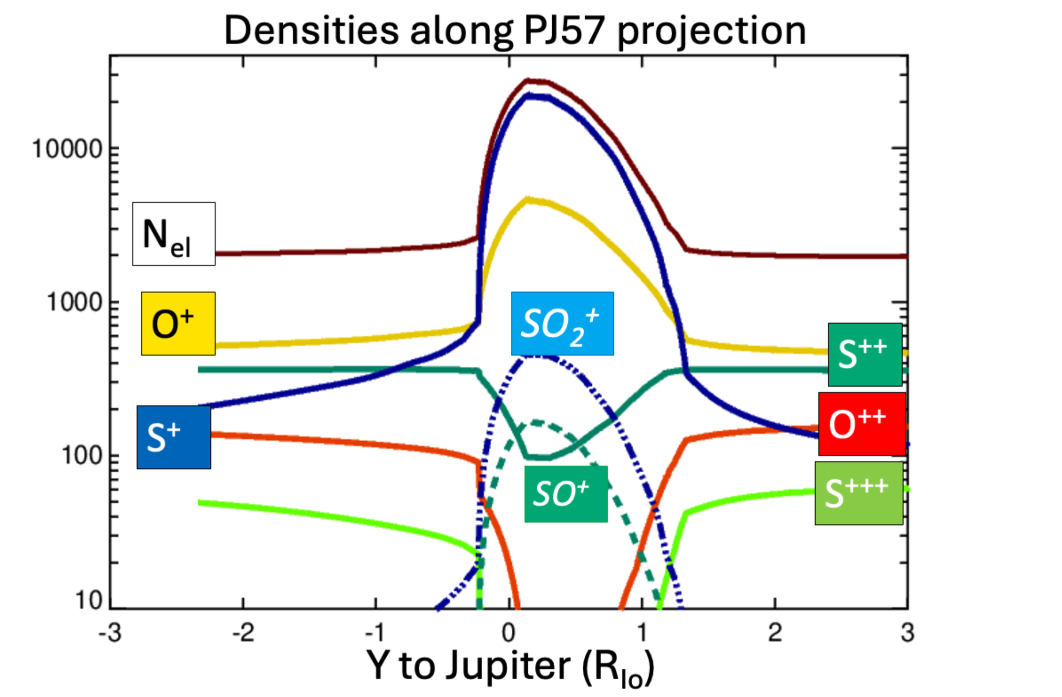


Fig 13: Densities along PJ57 trajectory projected in 2D plane of simulation.

7. CONCLUSIONS

Modeling Io's interaction critically needs multi-species chemistry to address the multi-species ion observation made by Juno.

1) ATMOSPHERE

- PJ57 requires a denser Corona (2 x *Wolven+01*)
- PJ58 is insensitive to a denser corona as skim behind Alfven Wing
  ⇒ **hypothesis of spherically symmetrical corona may be too simplistic ??**

2) PLASMA

Caveat : Results very sensitive to flow speed inside Alfven Wing ~(1-3 km/s)

2.1) PJ57: through Alfven Wing ⇔ **Using denser Corona (2 x Wolven+01)**

- Peak densities inside & at the back of Alfven Wing
- Max (n_{el}) ~ 40,000 cm^{-3} => Ok with Juno/WAVES and Radio-occultation
- Plasma dominated by S^+
- (S^{++} , S^{+++}, O^{++}) multi-charged ions drop drastically inside Alfven Wing
- ion temperature very low => no EMIC in Alfven Wing (Cao+2025)

2.2) PJ58: behind the Alfven Wing ⇔ **Using Denser Corona (2 x Wolven+01)**

2.2.1) close to CA

- Electron density OK with Juno/WAVES: n_{el} ~ 2,300 cm^{-3}
- Similar densities for S^+, O^+, SO_2^+ ~ 700 cm^{-3}
  => torus plasma modified because of interaction with atmosphere of Io
- Ion temperature quite high even after CA => **EMIC ?** (*Cao+25*)

2.2.2) In Wake

- Very large n_{el} ~ 90,000 cm^{-3} caused by field-aligned electron beams
- Artifact of 2D projection: projected PJ58 goes through wake but not real PJ58
- Plasma extremely dominated by S^+
- $<T_i>$ very low => no EMIC in Wake (*Cao+25*)

3) NEED MORE DATA ANALYSIS FROM JUNO

- **Juno is only in situ new observation for next ~20 years**
- **In situ plasma properties needed to understand remote observations (Clipper, JUICE, JWST, HST, Ground) . Juno/JADE-I observations very promising for**
  - ➢ Background plasma Ni
  - ➢ Plasma Velocity n Alfven Wing
  - ➢ Plasma composition along both flybys
  - ➢ ion densities and temperature s