

Io's loss of neutral material: Numerical simulations

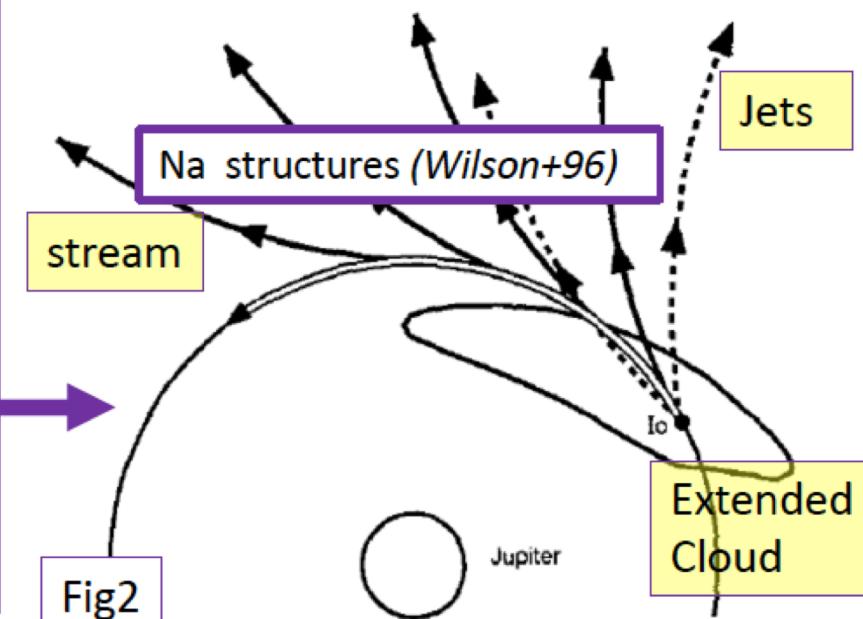
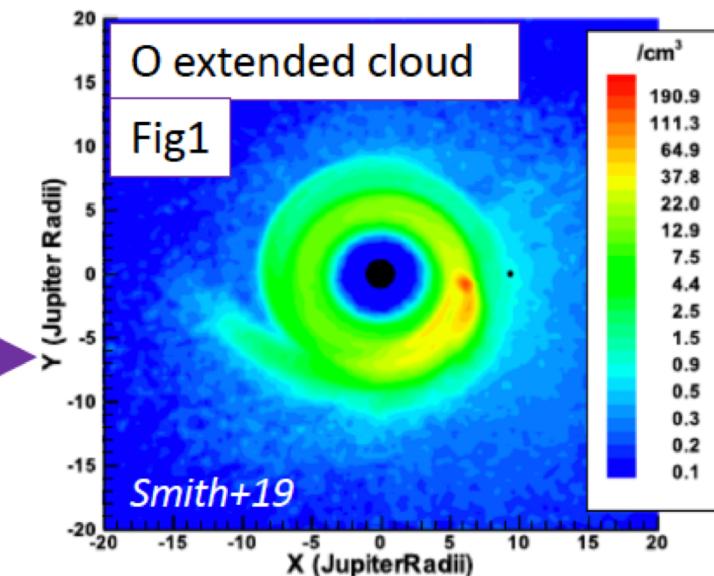
V. Dols, F.J. Crary, F. Bagenal LASP/Colorado University

Email: dols@lasp.Colorado.edu

1) GOAL: Model neutral sources from Io's atmosphere/corona

2) MOTIVATION

- Source of extended clouds in S, O, SO_2 as input for neutral cloud models (Smyth+92; Smith+19; Koga+18)
- S and O ions detected in Jupiter's equatorial atmosphere by Juno in Jupiter's equatorial regions (Valek+19)
- Voyager detection of SO_2^+ in the cold torus (Bagenal85)
- Galileo detection, far from Io, of EMIC waves at SO_2^+ gyrofrequencies (Russell+03)
- Motivate observations of neutral structures similar to Na
- O and S jets? (C. Schmidt+AGU15)
- SO_2 extended cloud? (ALMA ?)
- SO_2 , S&O Mendillo-discs? (Krimigis+02)



3) METHOD to compute rates around Io (Dols2008,2012 ; Bagenal&Dols2020)

3.1) Multi-species physical chemistry (O, S , SO₂ , SO)

Cross-sections:

- Electron-impact ionization of: SO₂ (*Shemansky priv. com.*), S and O
- SO₂ resonant charge-exchange (*Saur+1999*)
- Asymmetric charge-exchange of atomic torus ions on SO₂ at 60 km/s (*McGrath&Johnson1989*)
- Electron cooling (*Strobel priv.com. as in Saur+1999*)

3.2) Atmosphere description

- Prescribed SO₂ atmospheric profile (Fig 4&5)
H=500 km and H= 30 km for N_{col}= 5.6e16 cm⁻² (dense !)
equatorial band: at latitude < 35 deg
- Prescribed spherical S and O corona : *Wolven+2001*

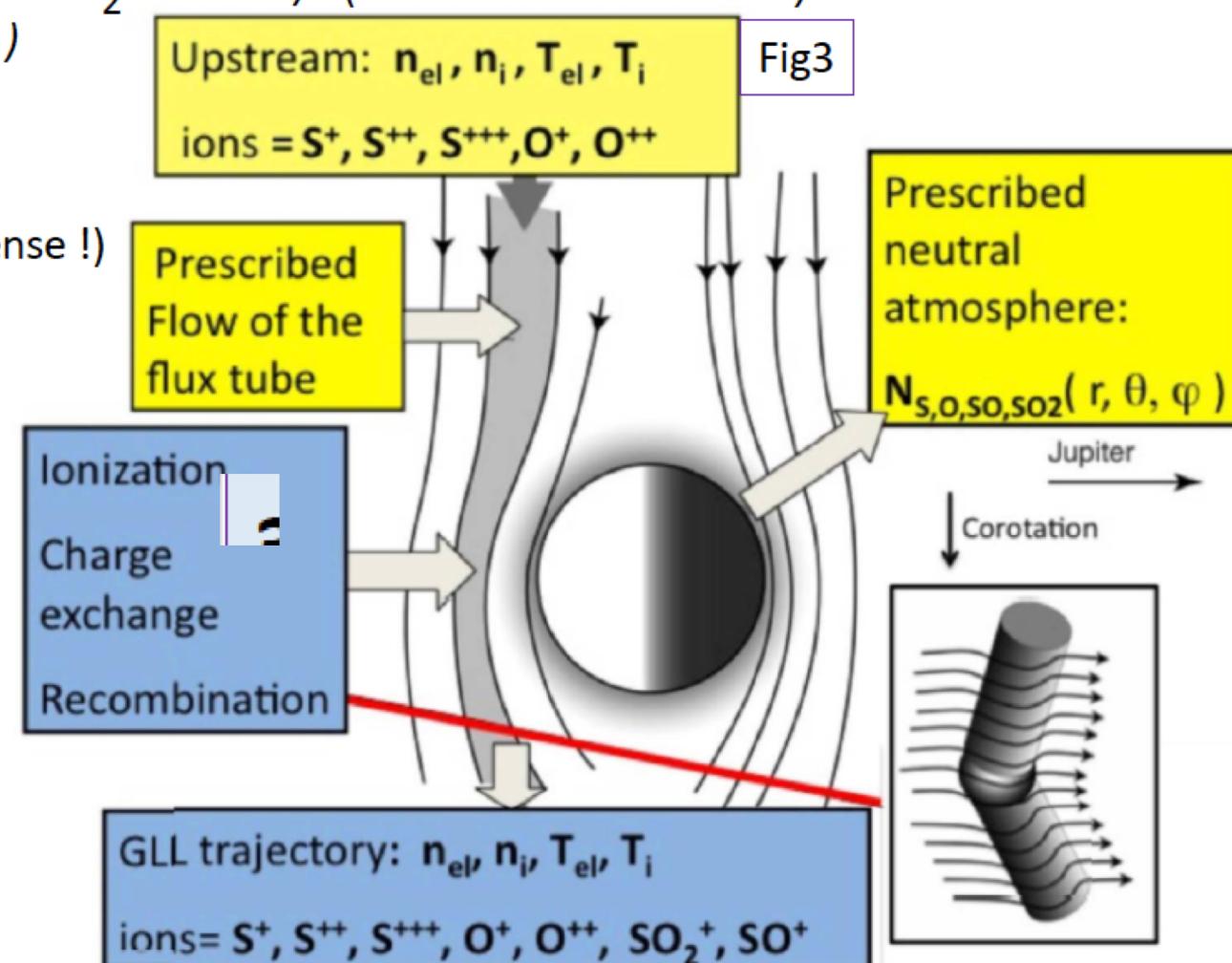
3.3) upstream plasma condition (Galileo J0 flyby)

N_{el} ~ 4,000 cm⁻³
T_{el} = 5 eV
T_i ~ 100 eV

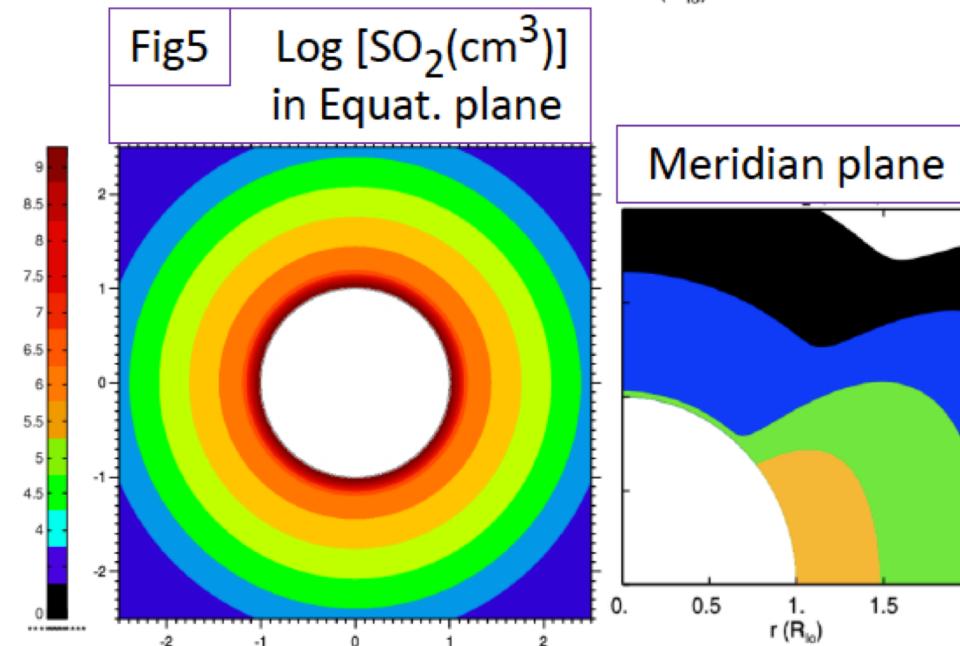
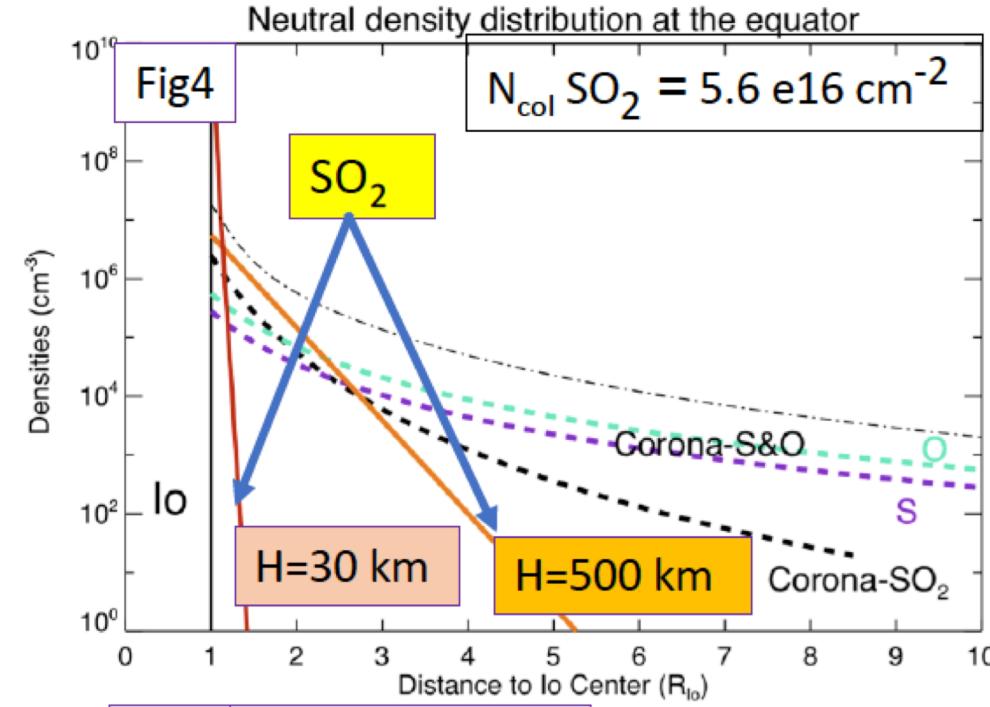
3.4) plasma flow around Io: MHD (Fig 6&7)

3.5) Reaction rate calculation along flow lines (Fig 3) :

- Iteration of chemistry and MHD flow
- some lack of self-consistency



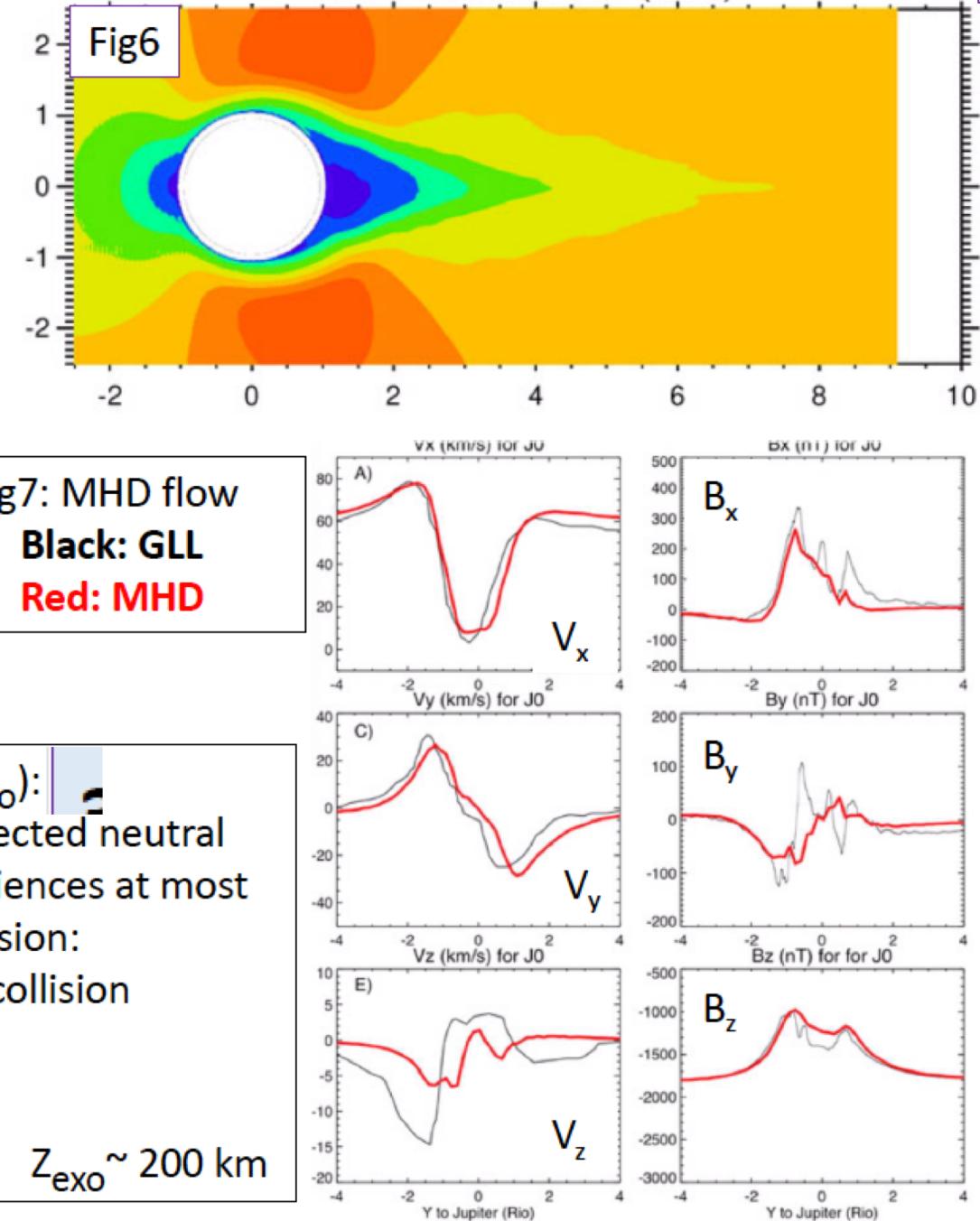
3.6) SO₂ atmosphere/Corona



Exobase altitude(Z_{exo}):
altitude where an ejected neutral experiences at most 1 collision:
 $N_{\text{col}}(z>z_{\text{exo}}) * XS = 1$ collision
 $XS \sim 30 \text{ A}^2$ (typical)

For this atmosphere: $Z_{\text{exo}} \sim 200 \text{ km}$

3.7) MHD flow



3.8) Reaction rates around Io (the wake is not yet included ! See next slide)

- Fig 8&9: SO₂ electron-impact dissociation/ionization is mainly upstream as electrons cool
- Fig10: SO₂ resonant charge-exchange wraps around the flanks of Io

Fig8: SO₂ electron-impact dissociation

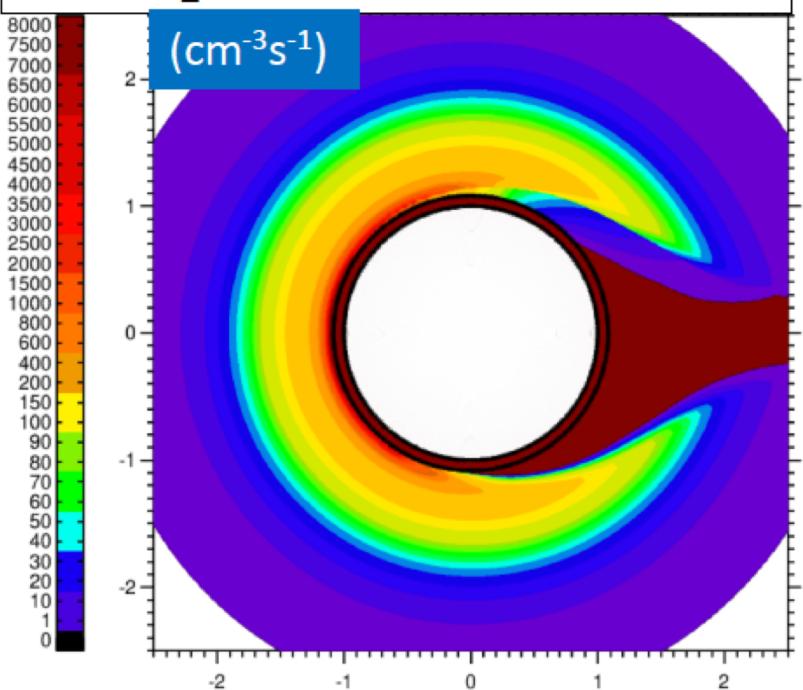


Fig9: SO₂ electron-impact ionization

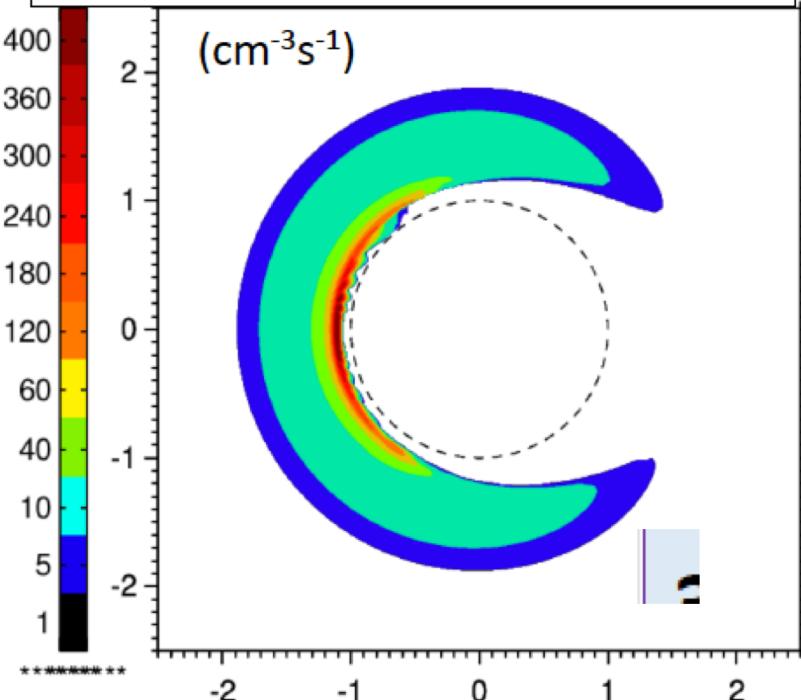
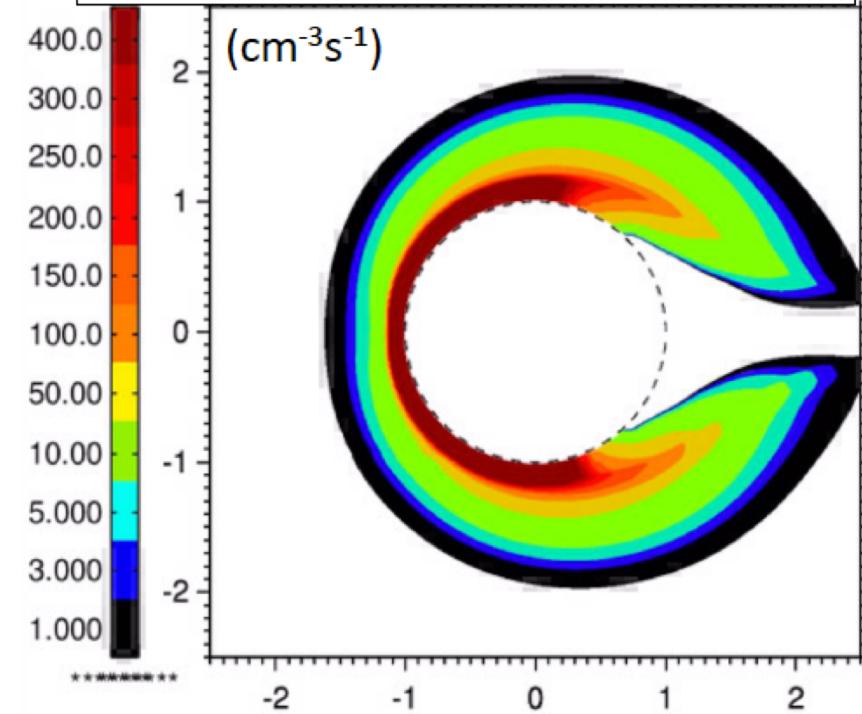


Fig10: SO₂ resonant charge-exchange



Integrated SO₂ reaction rates above exobase (not including the wake)

$\sim 1,500$ kg/s

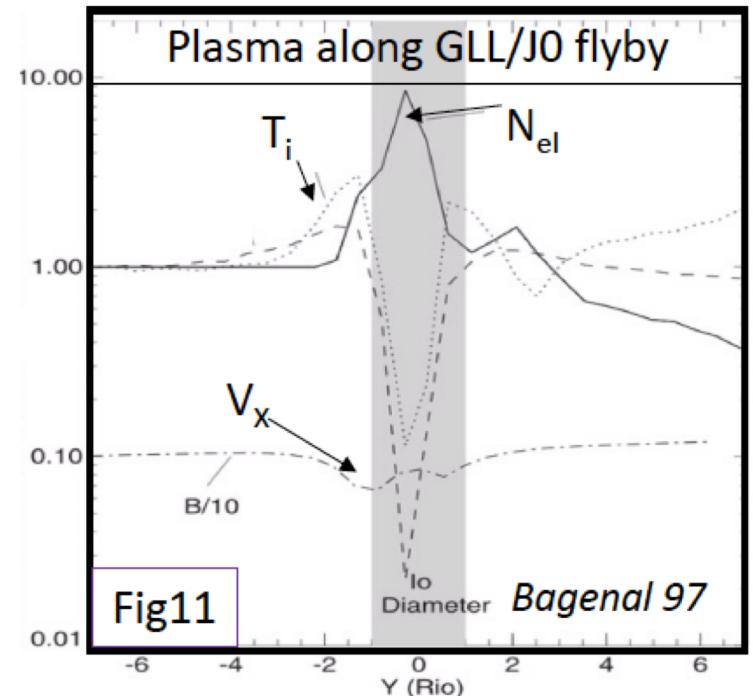
~ 100 kg/s

~ 700 kg/s

4) METHOD to compute reaction rates in the wake

4.1) Galileo flybys in the wake (GLL/J0)

- High plasma density in the wake: $N_{el} \sim 30,000 \text{ cm}^{-3}$ (Fig 11: EPD)
- Bi-directional field-aligned electron beams: 100 eV-100 keV (Fig 12)

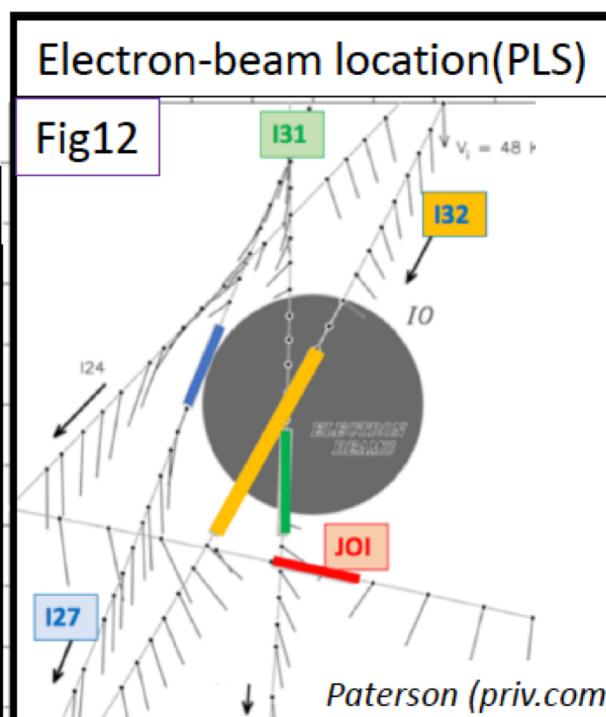
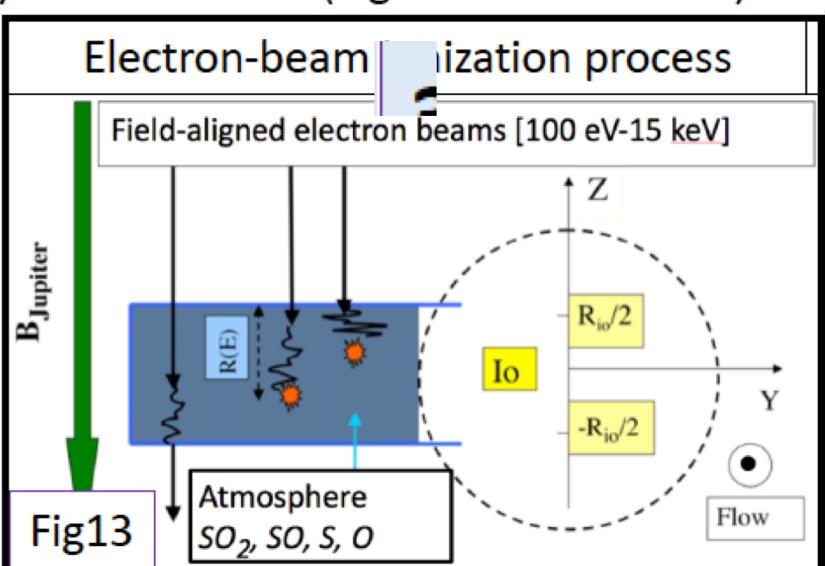


4.2) Hypotheses

- Ionization by electron beams in wake \Leftrightarrow Dense wake (Saur+2002; Dols+2008)
- Dense wake= secondary electrons: $T_{el}=0.5 \text{ eV}$
- Assume that downstream SO_2 atmosphere in daylight \Rightarrow fully developed
- Wake composition: only SO_2^+

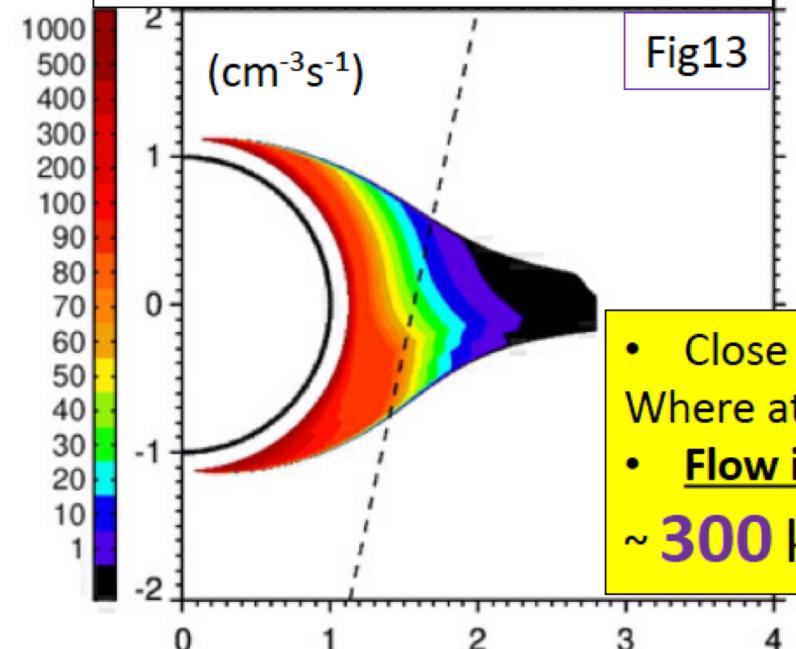
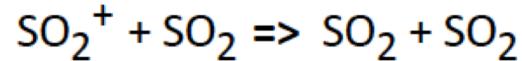
4.3) Method

- We do not compute the process of ionization by electron beam (Fig 13:Dols+MOP2018)
- We prescribe high plasma density along GLL/J0
- Compute SO_2^+ recombination along MHD flow lines down and up the wake
- Compute also SO_2 resonant charge-exchange

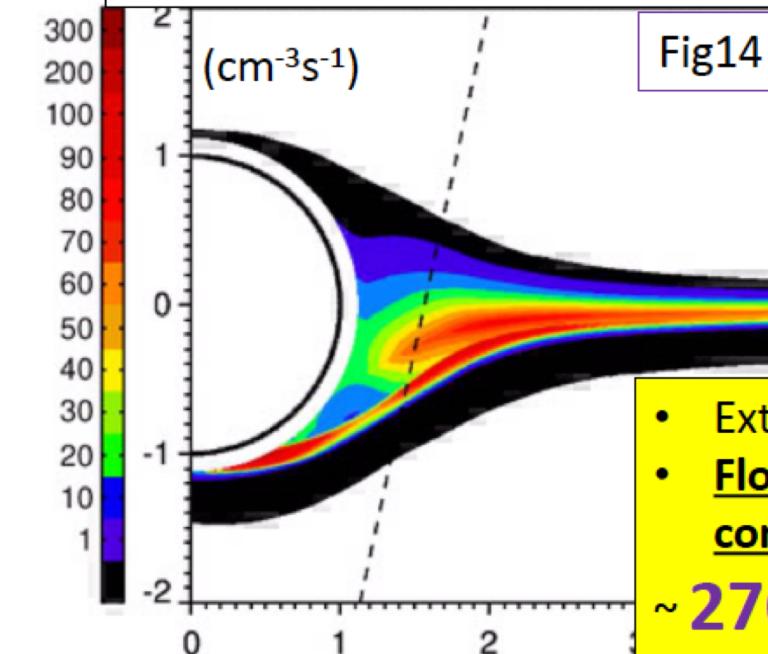
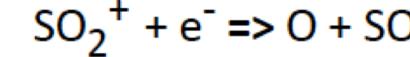


4.4) Reaction rates in the wake

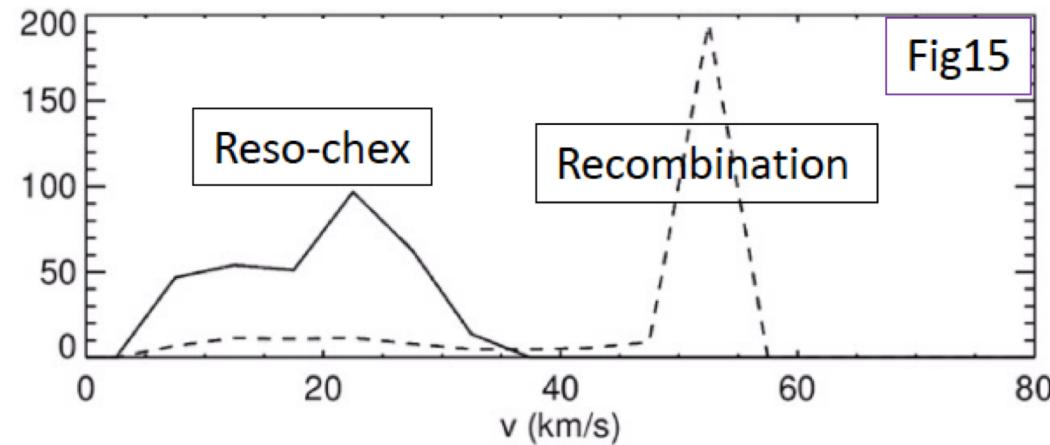
SO_2 resonant charge-exchange



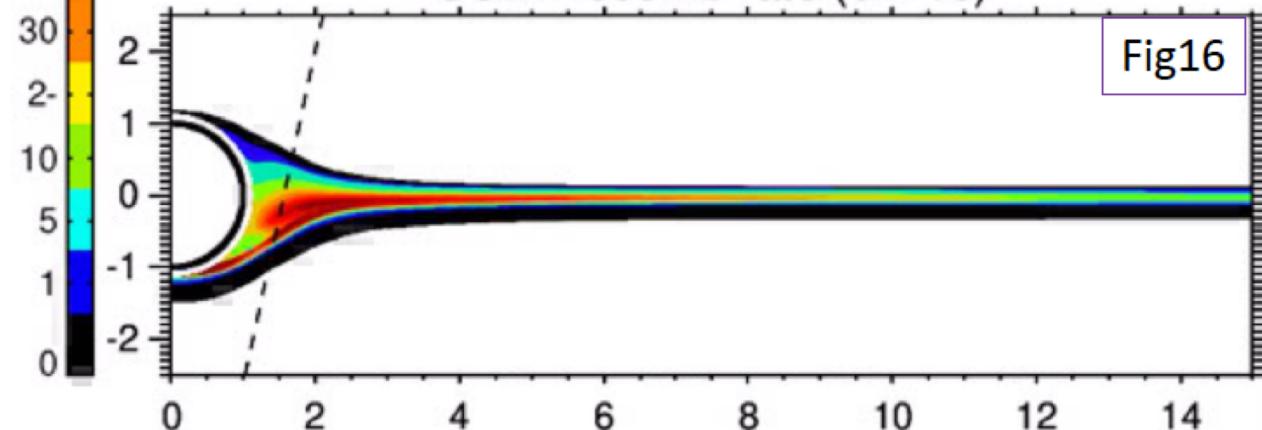
SO_2^+ recombinative-dissociation



Velocity distribution of the rates (kg s⁻¹)



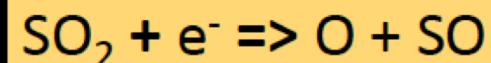
SO_2^+ recomb rate (cm^{-3}/s)



RESULTS: Some rates are very large

Future Work: Where do the ejected neutrals go?

e-impact SO_2 dissociation



~ 1,500 kg/s

Slow S&O neutrals

Source of: S&O corona

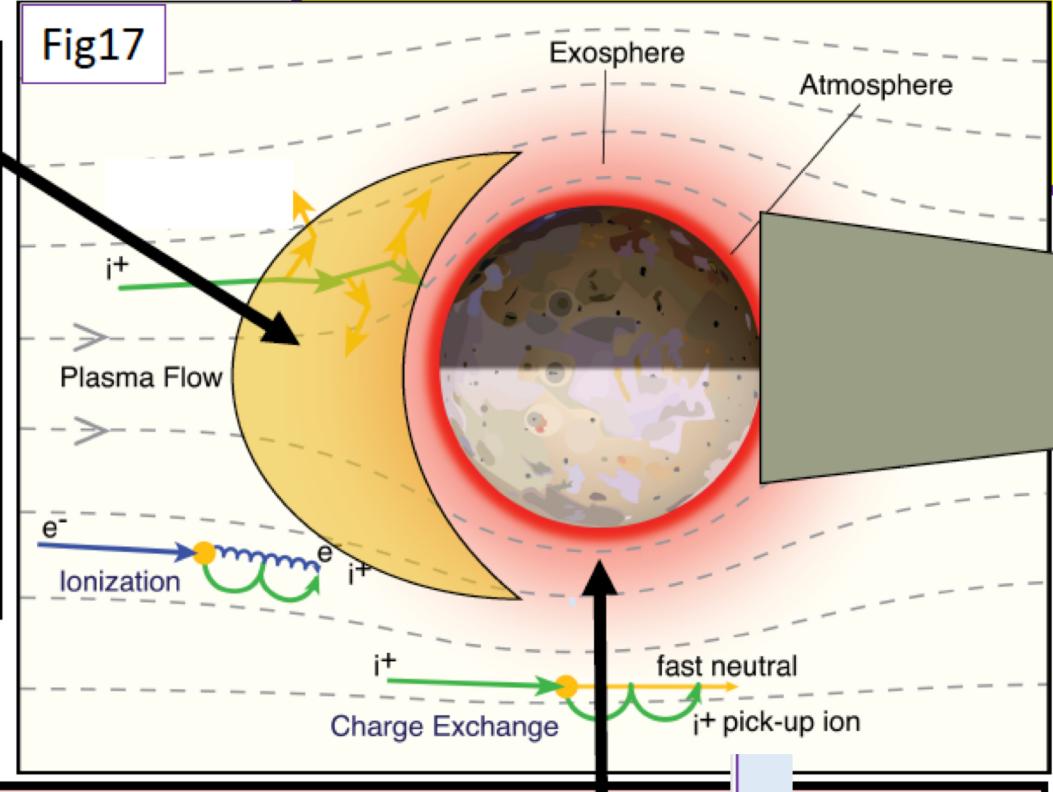
S&O extended clouds?

Asy-chex with SO_2

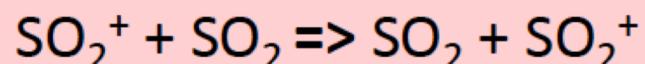


small amount

Fig17



SO_2 resonant charge-exchange



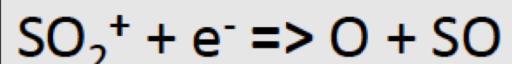
~ 1,000 kg/s

Fast to slow ejected SO_2 , depending on local flow

Source of: Jets? Mendillo-disc? Banana cloud?

=> Implement these sources in Neutral Cloud Models as in *H. Smith+2019*

Recombinative-dissociation of SO_2^+



~ 270 kg/s

Fast S&O

Source of: S and O jets?