Energetic Neutral Atoms at Ganymede and Europa : preparation to the JUICE mission

R. Modolo (1), C. Baskevitch (1,2), T. Le Liboux (1,3), F. Leblanc (1), B. Cecconi (2), N. André (3)
(1) LATMOS, (2) LESIA, (3) IRAP

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Abstract
The JUICE (JUpiter ICy moon Explorer) mission, launched by the European Space Agency in April 2023, the first large mission within the Cosmic Vision Program 2015–2025, will arrive in the jovian system in 2031 and it will provide the most comprehensive exploration to date of the Jovian system in all its complexity, with particular emphasis on Ganymede as a planetary body and potential habitat (JUICE Red Book, 2014). The Galilean satellites are known to have thin atmospheres, technically exospheres (McGrath et al., 2004), produced by ion-induced sputtering and sublimation of the surface materials. These moons and tenuous atmosphere are embedded in the flowing plasma of Jupiter. Among the measurements that will be performed by JUICE, the Particle Environmental Package (PEP, Barabash et al, 2024) will be able to monitor the interaction with the ENA imaging technique. We make use of the LatHyS and EGM models to prepare the JUICE observations and to model the energetic neutral atom (ENA) flux generated by charge exchange of magnetospheric ions with Europa's atmosphere.

Introduction
Energetic Neutral Atoms (ENA) are generated during a charge exchange process. An energetic ion from the jovian plasma undergoes to charge exchange with cold neutral atmospheric species of Europa, producing a cold pickup ion and an ENA.

$$O^+ + M \rightarrow M^+ + O^{ENA}$$

The morphology of ENA emissions from a moon's atmosphere can help constraining the structure of the moon-magnetospheric interaction region (Dandouras and Amsif, 1999).

- ENA detectors capture ENA emissions as an image, analogous to how cameras detect photons
- ENA imagers produce a two-dimensional "snapshot" of the ENA flux integrated along the detectors' lines of sight.
- JUIE / PEP / Jovian Neutrals Analyzer (JNA) will measure ENAs in the Jovian environment in the energy range between 10 eV and 3.3 keV, with a field-of-view of 15° in elevation and 150° in azimuth, divided into 11 pixels (Shimoyama et al., 2018).

Simulation models

- The LatHyS model (Modolo et al, 2016) is used to describe the jovian plasma interaction with Europa (Baskevitch et al, 2024, in prep) ⇒ provides a 3D description of the moments (*n, **u**, **T***) of the jovian O+ ions (Figure 2 a,b).
- For the atmosphere description, we've used two different inputs :
  - An analytical model with a spherical symmetry assumption $n_{O_2}(z) = 2{,}5 \times 10^7 \exp\left(-\frac{z}{100}\right)$ Harris et al, 2021, (Figure 2c)
  - A 3D description from the Exospheric Global Model (Oza et al, 2019)
- We compute the ENA production rate $q(\boldsymbol{r}) = n(\boldsymbol{r})u(\boldsymbol{r})n_{O_2}(\boldsymbol{r})\sigma_i$ (Figure 2d)

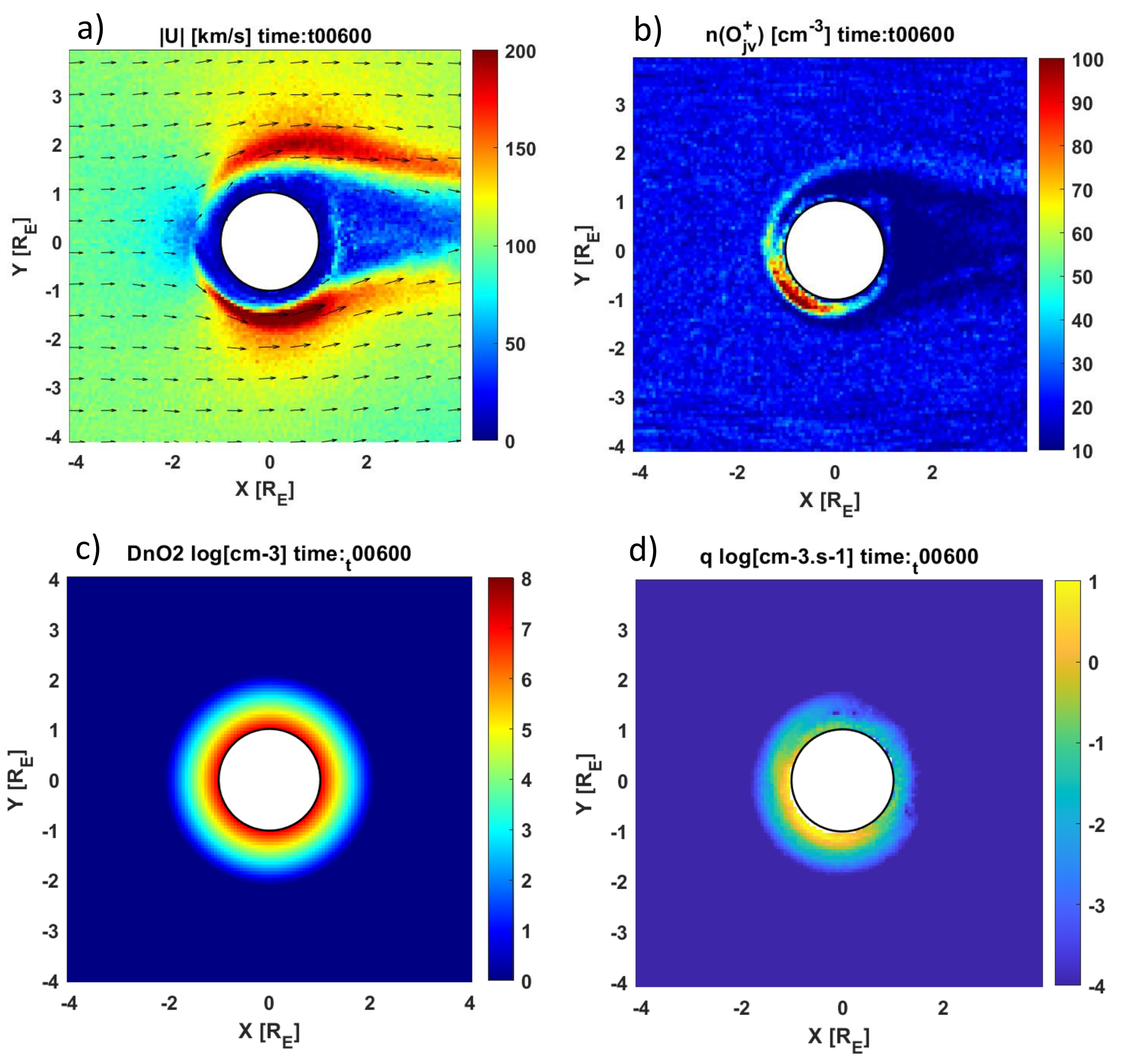

Figure 2 : LatHyS results in the XY (equatorial) plane (coordinate system EphiO) a) Bulk speed of the jovian plasma, b) O+ ion density, c) O2 Europa's atmosphere, d) ENA production rate.

ENA images to detect water plume ?
several remote and in-situ observations have revealed localized, transient plumes of H2O vapor emanating from Europa's surface (Roth et al, 2014; Jia et al, 2018).

- We consider a single water vapor plume with the neutral density profile suggested by Jia et al. (2018) $n_{H2O}(h, \Delta\theta) = n_{0p} exp\left[-\left(\frac{h}{h_p}\right)^2 - \left(\frac{\Delta\theta}{h_\theta}\right)^2\right]$ with h the radial distance from the plume center and $\Delta\theta$ the angular distance from the plume
- For simplicity, the plume is located at the South pole

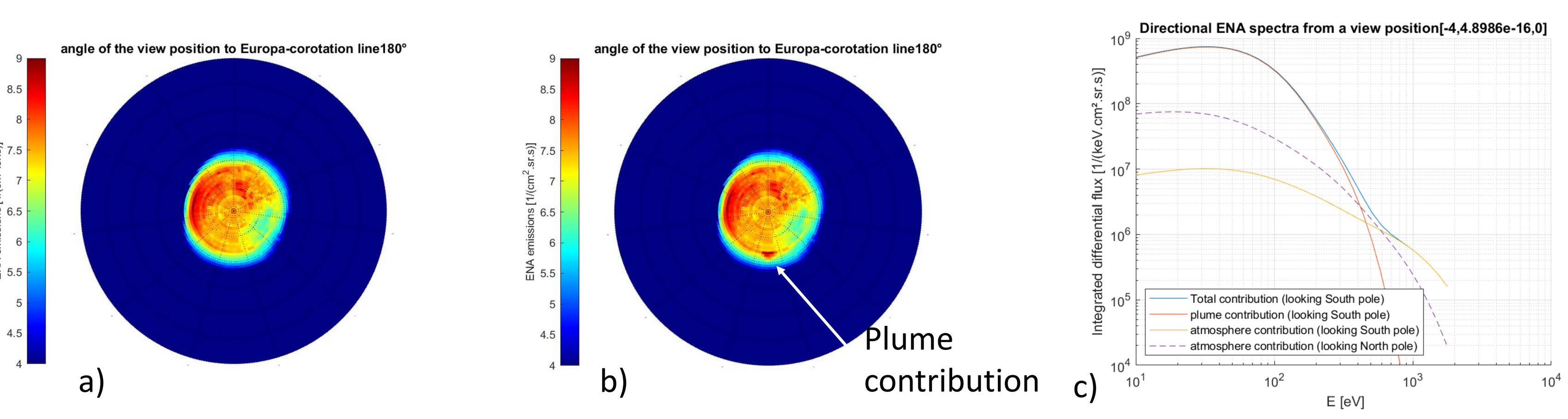

Figure 4 : ENA image from an observer at 4 Re at va=180° (trailing hemisphere) with O2 atmosphere (a) and O2 atmosphere + H2O plume (b).
c) Directional Oxygen ENA spectra with a look direction at South and North pole with the respected contribution from O2 ad H2O

Methodology
We followed the same approach than Holmström et al (2002) developped for Mars.

- An ENA image $w(\boldsymbol{r}, \boldsymbol{d})$ is a 2D map of ENA flux seen by an observer at position $\boldsymbol{r}$ looking in direction $\boldsymbol{d}$.
- We define a look direction $\boldsymbol{d_l}$ and perpendicular directions $\boldsymbol{d_u}$ and $\boldsymbol{d_p}$, and thus two angles θ and φ that define the line of sight direction $\boldsymbol{d}$ (Figure 1).

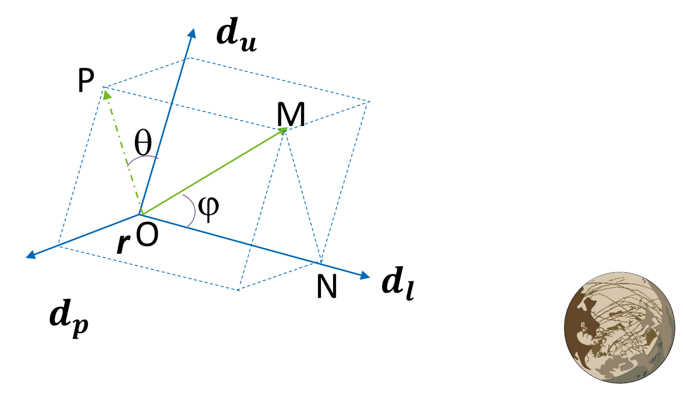

Figure 1 : The view geometry ofor ENA images

$\boldsymbol{d}=\boldsymbol{OM}=\boldsymbol{ON}+\boldsymbol{NM}=\boldsymbol{ON}+\boldsymbol{OP}=$ cosφ $\boldsymbol{d_l}$ +sinφ cosθ $\boldsymbol{d_u}$ +sinφ sinθ $\boldsymbol{d_p}$

- Differential flux $w(\theta, \varphi, E)$ [1/(eV.cm².sr.s)] : incoming ENAs with energy E

$$w(\theta, \varphi, E) = \int_0^\infty g(\boldsymbol{r} + s\boldsymbol{d}, -\boldsymbol{d}, E)ds$$

$\boldsymbol{r} + s\boldsymbol{d}$ is the source location, $-\boldsymbol{d}$ is the emission direction, and E is the emission energy E.

- $g(\boldsymbol{R}, \boldsymbol{D}, E)$ is the differential flux [1/(eV.cm³.sr.s)] of ENAs with energy E emitted from the position $\boldsymbol{R}$ in the direction fo $\boldsymbol{D}$.

$g(\boldsymbol{r}, \boldsymbol{d}, E) = \frac{v}{m} f_{ENA}(\boldsymbol{v}, \boldsymbol{r})$ with the ENA velocity $\boldsymbol{v}(\boldsymbol{d}, E) = \sqrt{\frac{2E}{m}}\boldsymbol{d}$

$$f_{ENA}(\boldsymbol{v}, \boldsymbol{r}) = q(\boldsymbol{r})\left(\frac{m}{2\pi kT}\right)^{3/2} e^{-\frac{m}{2kT}|\boldsymbol{v}-\boldsymbol{u}|^2}$$

m is the ion mass, *T(r)* is the ion temperature, ***u(r)*** is the ion bulk velocity, ***q(r)*** the ENA production rate.

ENA images
ENA images (Figure 3) are generated with an observer located in the equatorial plane (Z=0) at a distance of 4 R_E and for different view angles (va).

- Asymetries are due to the production rate (main contribution in the trailing hemisphere) and the view geometry

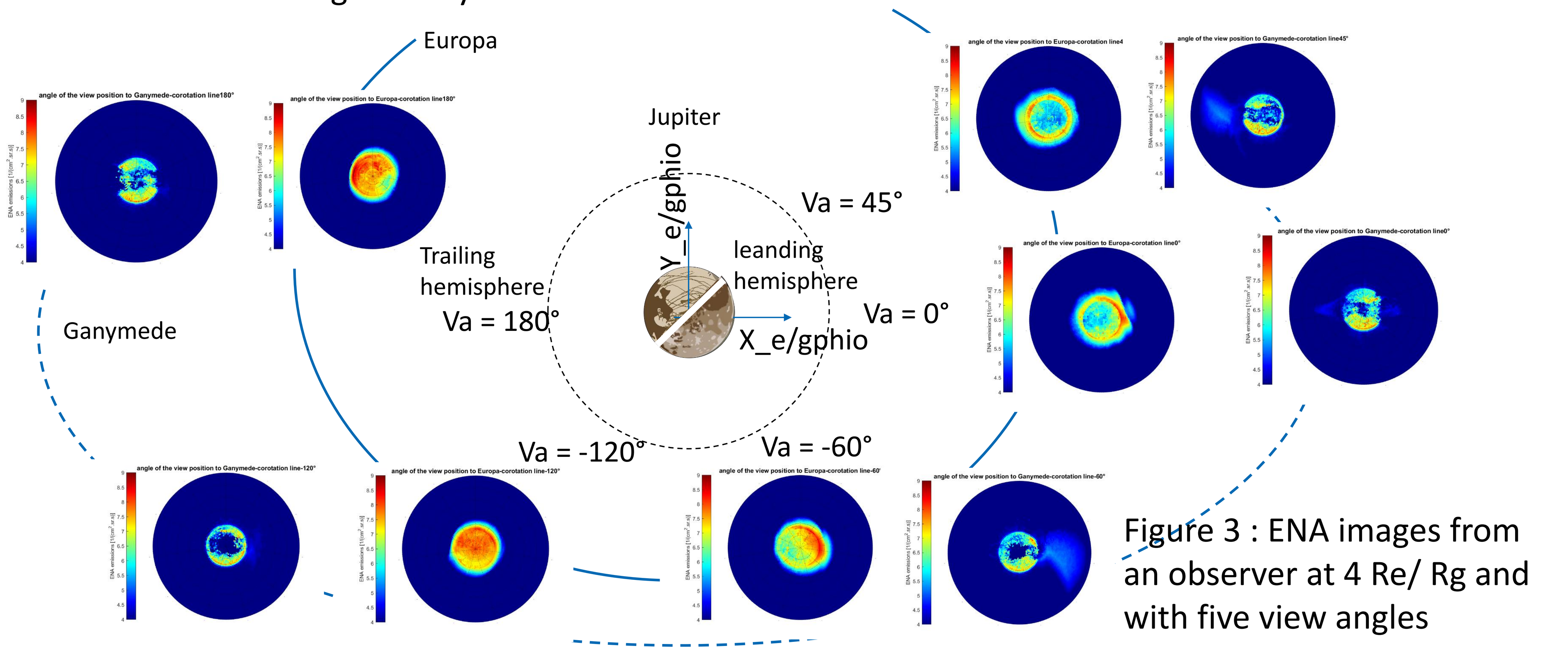

Figure 3 : ENA images from an observer at 4 Re/ Rg and with five view angles

Preliminary conclusions and perspectives

- We model the ENA flux generated by charge exchange of magnetospheric ions with Ganymede's atmosphere and Europa's atmosphere and water vapor plume
- ENAs emissions are mainly coming from the disk surface and an atmospheric halo over few tenths of km, and in Ganymede's polar region
- ENA images are strongly dependent on the view geometry, with an important trailing / leading asymmetry.
- ENA images might be suitable to detect H2O plume
- ENA surface albedos have to be taken into account in the next steps
- 3D EGM (with the temporal variability of the H2O plume) will provide a comprehensive picture of the plume and atmosphere signatures
- To compute diagnostics with PEP-JNA performances