ISSI International Team 2014

Towards a global unified model of Europa's exosphere in view of the JUICE mission

http://www.issibern.ch/teams/exospherejuice/index.html

Final Report

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The physics of the tenuous atmosphere of Jupiter's moon Europa, often referred to as an exosphere, is one of the major interests of the international community of Planetary Sciences. The recent discovery of transient water plumes erupting off the surface of Europa, with their potential implication on the nature of the moon's inner ocean, opened a new chapter in the study of the moon's neutral environment. In this context, the accurate characterization of the moon's tenuous atmosphere is imposed as a mandatory prerequisite.

In a coherent logical frame including **theoretical, observational** and **space activities**, our International Team 2014 "*Towards a global unified model of Europa's exosphere in view of the JUICE mission*" adopted a 'larger view approach' and stipulated the following **main accomplishments**:

Scientific Highlights

- Provided a detailed review of the available observations related to Europa's environment. In particular, we revised the UV and VIS observations of Europa's atmosphere, the plasma and magnetic field observations, and the ENA measurements of Europa's neutral torus. Potential synergies between different datasets and related variability were also assessed;
- Provided for the first time a detailed comparison of the existing plasma and MHD models of Europa's environment as well as of the atmospheric models, pointing out in detailed Tables the exact points of disagreement/agreement in each case;
- Evidenced some debated points on the methods used in modeling, providing ranges of applicability for each one of the current implementations;
- Identified the main improvements required to current plasma and atmospheric models;
- Defined the characteristics for a community unified model of Europa's environment, including the main physical phenomena to be considered and the acceptable assumptions and approximations;
- Identified the future experimental work required to constrain the plasma and atmospheric models, with special emphasis on the experiments of ice sputtering and radiolysis;
- Defined a set of suitable observation strategies for future missions namely JUICE and Europa Clipper (see Figure 1)

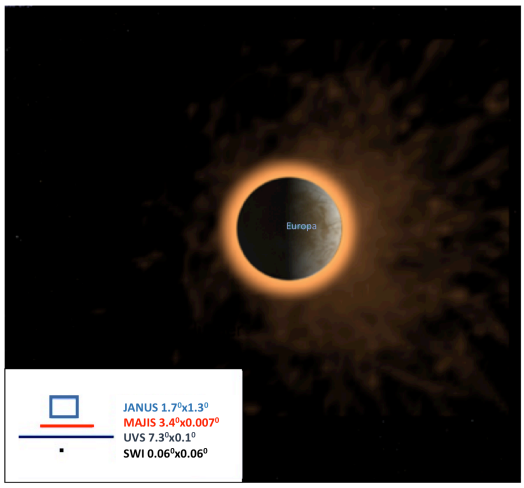

Figure 1: Europa's trailing hemisphere as viewed from the JUICE spacecraft while approaching the moon at a distance of ~ 22,735 km, on 13 Feb 2031 at 1h40m prior to the closest approach. The expected spatial distribution of the O_2 atmospheric density according to the EGEON model (Plainaki et al. 2013) is also shown. This observation will allow to check, through measurement of the diffused high-altitude component of the atmospheric density, if an asymmetry between the illuminated and non-illuminated hemispheres of Europa exists. From Plainaki et al., Space Sci Rev, 2018.

The actual scientific **products of the team's activities** corresponding to these goals are all included in a **review paper**, currently in press in Space Science Reviews journal:

Plainaki, C., T. Cassidy, V. Shematovich, A. Milillo, P. Wurz, A. Vorburger, L. Roth, A. Galli, M. Rubin, A. Bloecker, P. Brandt, F. Crary, I. Dandouras, X. Jia, D. Grassi, P. Hartogh, A. Lucchetti, M. McGrath, V. Mangano, A. Mura, S. Orsini, C. Paranicas, A. Radioti, K., Retherford, J. Saur, B. Teolis, 2018.
Towards a Global Unified Model of Europa's Tenuous Atmosphere
Space Sci Rev, *in press,*
DOI: 10.1007/s11214-018-0469-6

In this article, we pointed out some important issues, derived after the team's discussions in ISSI. In particular, we justified the need of a detailed comparison among the existing models of Europa's tenuous atmosphere, which are based on different scenarios and considerations. Also, in lack of an adequate number of in situ observations of Europa's environment, the existence of such a wide variety of models has resulted in our fragmentary understanding of the interactions of the magnetospheric ion population with both the moon's icy surface and neutral gas envelope. Defining, therefore, a unified model of Europa's tenuous atmosphere becomes an important global goal for the scientific community working on Europa's science.

In this view, and in consistency with our project's science goal, in our Space Sci Rev article we revised the existing models of Europa's tenuous atmosphere and discussed each of their derived characteristics considering the neutral and plasma environment in the vicinity of Europa. We also pointed out clearly the discrepancies among different models and the assumptions considered in each case. Most importantly, in our paper we defined the properties of a global model of the tenuous atmosphere as well as the required future experimental activity in laboratories to improve our understanding on the physical processes, which are active at Europa.
We believe that this effort of our team, summarized in our Space Sci Rev paper, will result in a useful feedback for the international planetary science community which is currently working on the preparation of the two upcoming missions to the Galilean moons, i.e. the ESA's JUpiter ICy moons Explorer (JUICE) mission and the NASA's Europa Clipper mission.

Additionally to the aforementioned goals, our Team performed a number of detailed studies to **expand the return of the collaboration**, assessing several scientific issues related to the thematic of Europa's tenuous atmosphere. These related scientific activities involved also members of the scientific community other than the ones included in the Team, **maximizing** in this way **the diffusion of knowledge** and **facilitating further progress** in numerous related disciplines. In particular, within the period of the team's existence, **important scientific add-on** considering the following topics was obtained:

- Interaction between the particle and photon radiation with Europa's tenuous atmosphere and implications to the atmospheric loss rate;
- Morphology of Europa's FUV oxygen aurora based on HST observations;
- Interactions between particle populations and fields at Europa in the context of planetary space weather, an emerging discipline of significant importance in view of future planetary missions;
- Laboratory measurements of surface charging of thick porous water ice layers relevant for ion sputtering experiments;
- Determination of radiolysis and sputtering yields and suggestion of a new model for Icy Astrophysical bodies

Our team held two one-week meetings in ISSI-Bern, in 1-5 Dec 2014 and in 12-16 Oct 2015. Both times the collaboration within the team was fruitful and efficient. During the meetings in Bern, our team discussed data analysis methods, and compared theories and models of Europa's environment. Many times discussions initiated in ISSI continued through emails and teleconferences also during the months following the meetings. Let us also note that the activities of our team were brought to the attention of several international experts in the field, who effectively contributed to the studies.

Below we provide a detailed list of all the **peer review articles (in total 9)** that were published in the framework of the project. These paper were related to the team's activities either thoroughly, i.e. being a direct output of the project, or partially, i.e. the knowledge obtained within the team's studies

partially contributed to those works. All listed peer review articles contain the **acknowledgement to ISSI** for supporting the related research. For completeness, we include also a list of the contributions to national and international conferences, where ISSI was acknowledged.

At the end of this fruitful period of international collaboration, we would like to thank the ISSI Bodies and the Science Program Manager Dr. Maurizio Falanga, for the opportunity that they gave us to have such an efficient international team. Special thanks also to Dr. Saliba F. Saliba for his support and help in organizing our meetings in Bern.

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List of peer-review papers

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1. Plainaki, C., T. Cassidy, V. Shematovich, A. Milillo, P. Wurz, A. Vorburger, L. Roth, A. Galli, M. Rubin, A. Bloecker, P. Brandt, F. Crary, I. Dandouras, X. Jia, D. Grassi, P. Hartogh, A. Lucchetti, M. McGrath, V. Mangano, A. Mura, S. Orsini, C. Paranicas, A. Radioti, K., Retherford, J. Saur, B. Teolis, (2018). Towards a Global Unified Model of Europa's Tenuous Atmosphere, Space Sci Rev, in press, DOI: 10.1007/s11214-018-0469-6
2. Galli, A. Vorburger, P. Wurz, M. Tulej, (2017). Sputtering of water ice films: A re-assessment with singly and doubly charged oxygen and argon ions, molecular oxygen, and electrons, Icarus 291, 36–45, doi: 10.1016/j.icarus.2017.03.018
3. Teolis, B. D., Plainaki, C., Cassidy, T. A., & Raut, U. (2017). Water ice radiolytic O2, H2, and H2O2 yields for any projectile species, energy, or temperature: A model for icy astrophysical bodies. Journal of Geophysical Research: Planets, 122. https://doi.org/10.1002/ 2017JE005285
4. Blöcker, A., J. Saur, and L. Roth (2016), Europa's plasma interaction with an inhomogeneous atmosphere: Development of Alfvén winglets within the Alfvén wings, J. Geophys. Res. Space Physics, 121, 9794–9828, doi:10.1002/2016JA022479.
5. Galli, A., Vorburger, A., Pommerol, A., Wurz, P., Jost, B., Poch, O., Brouet, Y., Tulej, M., Thomas, N. (2016). Surface charging of thick porous water ice layers relevant for ion sputtering experiments, PSS, 126, 63–71, doi:10.1016/j.pss.2016.03.016.
6. Lucchetti, A., Plainaki, C., Cremonese, G., Milillo, A., Cassidy, T., Jia, X., Shematovich, V., (2016). Loss rates of Europa's exosphere. Planet. Space Sci., 130, 14–23, doi:10.1016/j.pss.2016.01.009.
7. Milillo, A., Plainaki, C., De Angelis, E., Mangano, V., Massetti, M., Mura, A., Orsini, S., Rispoli, R., (2016). Analytical model of Europa's O2 exosphere. Planet. Space Sci., 130, 3-13, doi:10.1016/j.pss.2015.10.011
8. Plainaki, A., Lilensten, J., Radioti, A., Andriopoulou, M., Milillo, A., Nordheim, T.A., Dandouras, I., Coustenis, A., Grassi, D., Mangano, V., Massetti, S., Orsini, S., Lucchetti, A. (2016). Planetary Space Weather: Scientific aspects and future perspectives. Journal of Space Weather and Space Climate 6 (2016) A31, doi:10.1051/swsc/2016024.
9. Roth, L., Saur, J., Retherford, K.D., Strobel, D.F., Feldman, P.D., McGrath, M.A., Spencer, J.R., Bloecker, A., Ivchenko, N., (2016). Europa's far-ultraviolet oxygen aurora from a comprehensive set of HST observations, J. Geophys. Res. - Space Physics, 121, 3, 2143–2170, doi:10.1002/2015JA022073

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National and International Conferences Papers (not refereed)

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- **(invited keynote lecture)** Plainaki, C., (2017). Recent Advances in Planetary Space Weather, ESWW14, Oostende (Belgium) http://www.stce.be/esww14/program/keynotes.php#K27-K2-1
- Plainaki, C., Milillo, A., Massetti, S., Mura, A., Jia, X., Orsini, S., Mangano, V., De Angelis, E., Rispoli, R., (2015). The H2O and O2 exospheres of Jupiter's moon Ganymede, XII Congresso Nazionale di Scienze Planetarie, 2-6 February 2015, Bormio, Italy
- Plainaki, C., Milillo, A., Andriopoulou, M., Dandouras, I., Radioti, A., Lilensten, J., Coustenis, A., Nordheim, T., Orsini, S., Mura, A., Mangano, V., (2015). Bridging Space Weather to Planetary Environments, XII Congresso Nazionale di Scienze Planetarie, 2-6 February 2015, Bormio, Italy

- Lucchetti, A., Cremonese, G., Schneider, N.M., Plainaki, C., Mazzotta Epifani, E., Zusi, M., Palumbo, P., (2015). Simulation of Europa's water plume, XII Congresso Nazionale di Scienze Planetarie, 2-6 February 2015, Bormio, Italy
- Galli, A., Pommerol, A., Vorburger, A., Wurz, P., Tulej, M., Scheer, J.A., Thomas, N., Barabash, S., and Wieser, M., (2015). The first laboratory measurements of sulfur ions sputtering water ice, EGU General Assembly 2015 abstracts, Vol. 17, EGU2015-3752.
- Lucchetti, A., Plainaki, C., Cremonese, G., Milillo, A., Shematovich, V., Jia, X., and Cassidy, T., (2015). Estimation of Europa's exosphere loss rates, EGU General Assembly 2015 abstracts, Vol. 17, EGU2015-4893.
- Milillo, A., Plainaki, C., Orsini, S., De Angelis, E., Mangano, V., Massetti, S., Mura, A., Rispoli, R. and L. Colasanti, (2015). Analytical model of Europa's O2 exosphere, Vol. 17, EGU2015-12575.
- Plainaki, C., Milillo, A., Massetti, S., Mura, A., Jia, X., Orsini, S., De Angelis, E., Mangano, V., Rispoli, R., (2015). Generation of Ganymede's exosphere, EGU General Assembly 2015 abstracts, Vol. 17, EGU2015-3964.
- Plainaki, C., Milillo, A., Andriopoulou, M., Dandouras, I., Radioti, A., Lilensten, J., Coustenis, A., Nordheim, T., Orsini, S., Mura, A., and Mangano, V., (2015). Space weather at different planetary environments, EGU General Assembly 2015 abstracts, Vol. 17, EGU2015-3977.
- **(invited)** Plainaki, C., A. Mura, A. Milillo, X. Jia, S. Massetti, T. Cassidy, J. Saur, S. Orsini, V. Mangano, E. De Angelis, R. Rispoli, (2015). The exospheres of Europa and Ganymede, 12th Annual Meeting Asia Oceania Geosciences Society, session: PS08-06 "Outer Planets and Their Exoplanetary Analogs", 2-7 August, Singapore, 2015
- Lucchetti, A., Plainaki, C., Cremonese, G., Milillo, A., Cassidy, T., Jia, X., Shematovich, V., 2015. Loss rates of Europa's exosphere, EPSC Abstracts Vol. 10, EPSC2015-487
- **(invited)** Roth, L., K. D. Retherford, J. Saur, D. F. Strobel, P. D. Feldman, M. A. McGrath, F. Nimmo, J. R. Spencer, C. Grava, and A. Blöcker, 2015. Europa's neutral and plasma environment investigated through FUV aurora imaging, EPSC abstracts, Vol. 10, EPSC2015-453