CAUSTIC.IO (Characterize Activity and Understand Seismic, Tidal and Internal Constitution of IO) – Planetary Mission Concept. M. M. Achkar[1], [1]École Polytechnique Fédérale de Lausanne (EPFL), EPFL-ENT-R ESC, PPH 335 Station 13, CH-1015 Lausanne, Switzerland (mickael.achkar@epfl.ch).

Introduction: Io is one of the most peculiar objects of our Solar System that has not yet been directly explored by a specialized space mission. Only a few mission concepts were proposed [1-3]. As the smallest of the four Galilean moons orbiting Jupiter and the innermost satellite of the Jovian system, Io is also the most geologically active object in the Solar System. The motivation for such a mission arises from needing key answers to the formation and evolution of planetary bodies in our Solar System and beyond. In fact, the Keck Institute for Space Studies (KISS) has expressed that Io is "the best laboratory for understanding the fundamental processes of tidal heating" [4]. This understanding can be inferred from tidally heated bodies such as the ones in the Jovian system (Europa, Io, Ganymede, Callisto).

This abstract will motivate and outline a multiple flyby mission to Io, named *CAUSTIC.IO* (Characterize Activity and Understand Seismic, Tidal and Internal Constitution of IO), as a reference to the moon's scorching environment and its innovative venture. Via these flybys, the mission will focus on capturing fast evolving datapoints on the main geological features of Io, such as *paterae* (volcanic crater, e.g. Loki, Tvashtar, Pillan), volcanoes (e.g. Pele, Zamama, Thor), *vallis* (lava valley, e.g. Tawhaki), and *fluctus* (lava flow, e.g. Kanehekili).

The mission will also introduce in-situ data collection via *planetary penetrators*: low-cost, lightweight, and robust devices that will descend and impact the surface of Io to study the composition and interior structure [5].

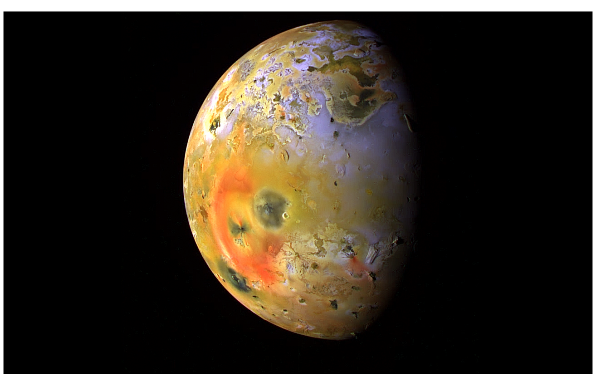

Figure 1: Io and its prominent red ring surrounding volcano Pele (Source: Galileo Mission – NASA/JPL/University of Arizona)

Mission Concept:

A. Science Objectives. The proposed mission seeks to tackle the following scientific objectives:

1. Characterize the current geology of Io:
   - Derive a model of Io's internal structure and composition: lithosphere, asthenosphere, mesosphere.
   - Understand Io's active volcanism and the implications on its atmosphere.
2. Witness the evolution of Io:
   - How and how fast is Io evolving?
3. Identify the mutual influence of Jupiter and other Jovian moons on Io:
   - Portray Io's tidal dynamics and heating.
   - Describe Io's magnetospheric interactions with its neighbors.
   - Provide data for future missions to assess habitability regions in the Jovian system.

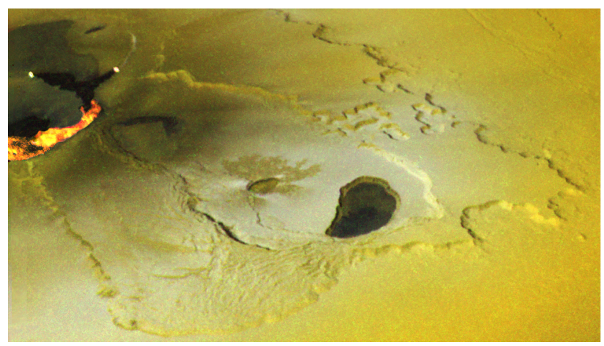

Figure 2: A lava eruption on Io's surface at Tvashtar Paterae (Source: Galileo Mission – NASA/JPL/University of Arizona)

B. Instrument Payload. The spacecraft payload will include several instruments to support the predefined objectives: a thermal mapper, an ion and neutral mass spectrometer, a fluxgate magnetometer, a laser altimeter, a wide-angle high-resolution camera, a dust analyzer, and two planetary penetrators which will each include a seismometer, a spectrometer, a patch antenna, and a small data storage unit. The main spacecraft will also include an antenna and a data storage unit. The close proximity to massive Jupiter constrains the spacecraft to tolerate a high radiation dose. To remediate for this, heritage will be drawn from past successful missions such as Juno, to design robust radiation shielding to protect sensitive equipment [6], for a planned total reduced dose of 150 krad.

C. Mission Strategy. The mission will make use of each instrument to answer the science objectives. The thermal mapper will allow to map temperature and heat flow over time to monitor volcanism over the specific geological features, as well as to portray the tidal heating mechanism. The ion and neutral mass spectrometer will determine the composition of freshly deposited lava and the atmosphere. The fluxgate magnetometer will measure magnetic signatures to characterize the magnetospheric and ionospheric interactions with both the surface and Io's neighbors, and derive a model of the internal structure via measured magnetic induction of the magma ocean. The laser altimeter will be used for high resolution topography. The wide-angle camera will capture high resolution images of areas of interest, to create time-lapses of eruptions, lava flows, and plumes over each coverage. The dust analyzer will examine the composition of dust grains in Io's atmosphere and volcanic plumes.

Two state-of-the-art penetrators will be deployed to probe the surface of the moon in different areas. With a seismometer in two different stations, the tidal flexing of Io can then be studied in detail. Each penetrator will have a spectrometer for in-situ composition, and atmospheric entry analysis. Data collected from the devices will be relayed to the spacecraft via their patch antennas and back to the ground station via an X-band antenna.

Despite being a cheaper alternative to landers, the added complexity with the development of penetrators would restrict the planned budget for the mission. To remediate to this, a solar power source with 30 m^2 of panel surface area will be used, similar to planned mission Europa Clipper [7]. This trade-off will provide significant savings compared to scarce radioisotope power sources.

To perform the flybys, an orbital insertion maneuver will be first executed when the spacecraft arrives in the vicinity of Jupiter. 30 flybys will then be performed, one every 30 days. Multiple high inclination flybys would allow a reduced radiation dose, higher resolution mapping, effective data collection, and in result will facilitate an evolution sweep of Io, witnessing changes on its surface through multiple eclipses, with a slightly different coverage each time.

The mission will end by impact after flying through a volcanic plume, which is allowed since Io is a Category I body/destination as per the COSPAR Planetary Protection Policy [8].

Interplanetary Trajectory:

A. Launch. The designed spacecraft will be launched in 2026 and will have a total lifetime of 10 years. This timeline is adequate to perform the desired trajectory to the planet which minimizes total ΔV and the overall mission cost.

B. Trajectory. After launch from Earth, the spacecraft will follow a trajectory that will avoid the use of large ΔV, with multiple gravity assists (swingbys) along the way. To do that, it undertakes a Venus-Earth-Earth Gravity Assist (VEEGA) trajectory. The specific dates to perform such a path were obtained with Adam Harden's Trajectory Optimization Tool v2.1.1 (see Figure 3).

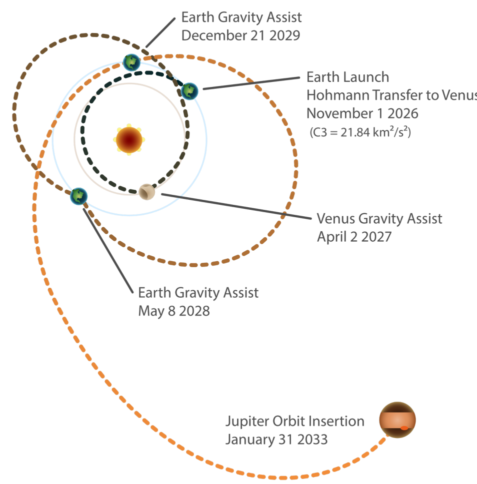

Figure 3: CAUSTIC.IO trajectory and operations

Mission Budget: NASA's Discovery Program funds mid class spacecraft missions destined to explore bodies in our Solar System to achieve scientific understanding. The proposed mission will hence be medium-class and capped at US$500 M to be funded by this program.

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