

Hey, can you give a spacecraft a boost?

Evaluation of Planetary "Gravity-Boost" Effects on Various Spacecraft

Emma Harrison^{1,2}, Advisor Dr. Scott Schneider¹ – Lawrence Technological University, CoAS¹, CoE²

Abstract

Spacecraft missions that visit outer (and inner) planets often use gravity assists from other planets (notably the inner planets of Mercury, Venus, Earth, and Mars).

A close planetary flyby can change the speed and trajectory of the spacecraft, and boosts (or "de-boosts") can help minimize fuel consumption.

We selected three spacecraft: Lucy {NASA}, Europa Clipper {ESA}, and BepiColumbo {ESA/JAXA}. To evaluate the gravity assist behavior, the energy and eccentricity of each spacecraft was calculated and plotted to reveal the boost or 'de-boost' nature of the interaction.

This work demonstrates the effects of gravity assists during exploratory missions and showcases the challenges associated with creating mission trajectories among the constantly moving planetary system.

Method

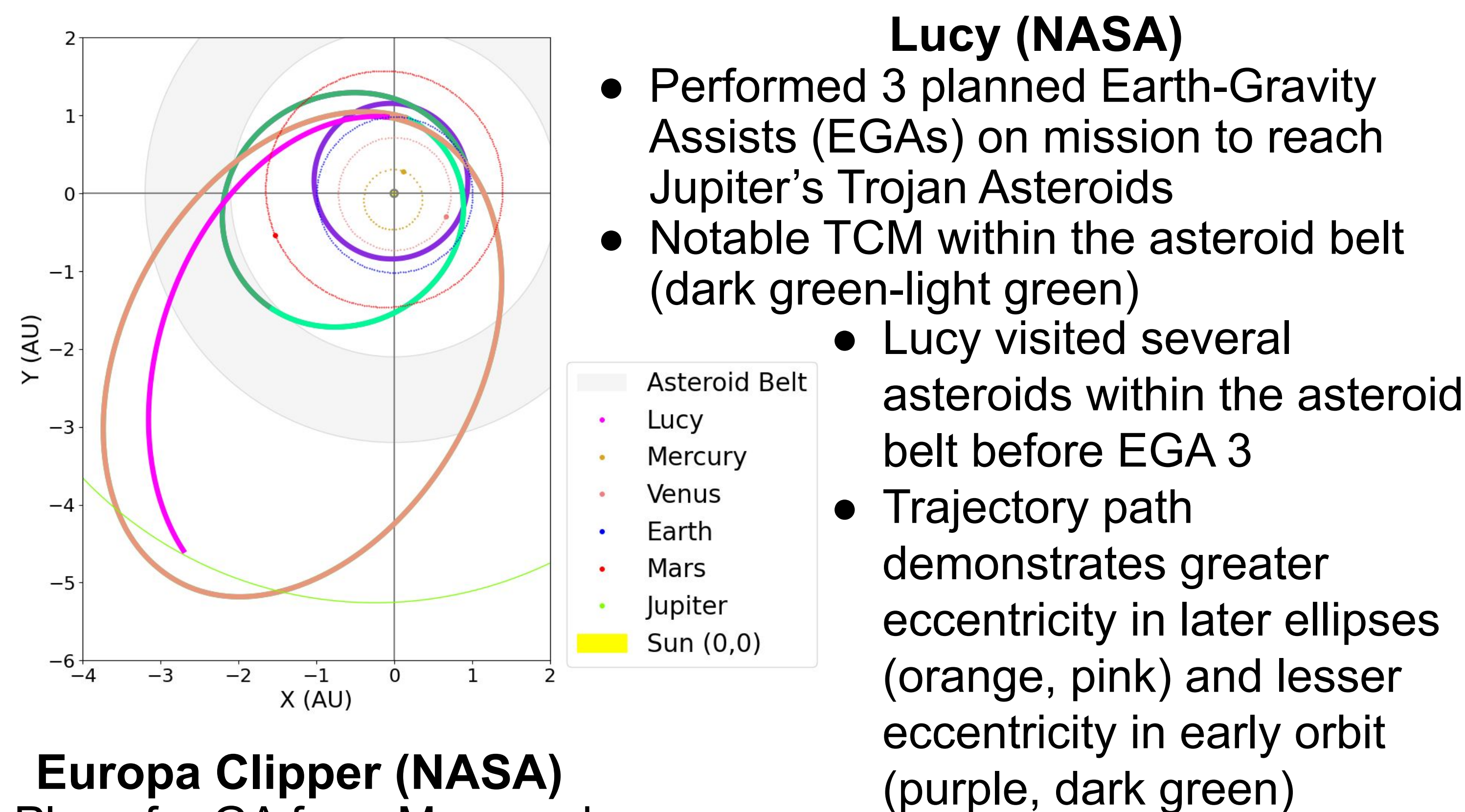
- Spacecraft trajectory data was obtained from the NASA Jet Propulsion Laboratory (JPL) Horizons database
- Spacecraft total energy (E_{total}) and trajectory eccentricity (e) were calculated using the following equations, implemented in Python and plotted:

$$l = |\vec{r} \times \vec{v}| \quad E_{total} = \frac{1}{2}mv^2 - \frac{k}{r} \quad k = GM$$

$$e = \sqrt{1 + \frac{2(E_{total}^*)l^2}{(GM)^2}}$$

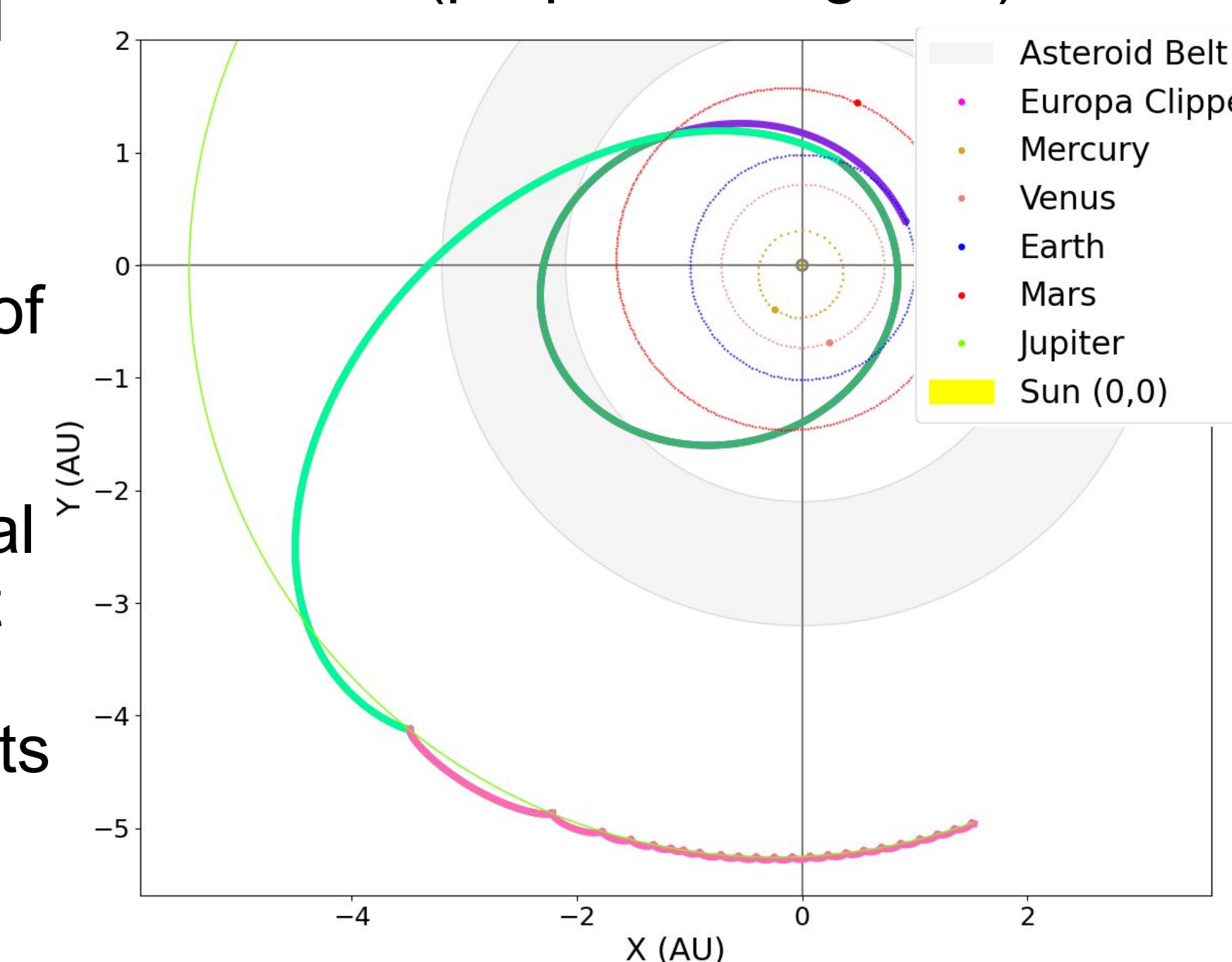
- Notable GA (Gravity Assist) and TCM (Trajectory Correction Maneuver) data was obtained from mission websites and JPL trajectory path observation
 - Listed maneuver dates correspond to noticeable changes in spacecraft eccentricity and total energy
 - To denote significant interactions throughout the mission (GAs or TCMs), the color of the path plot curve varies immediately following an interaction
 - Corresponding color grading is applied to the eccentricity plot depicting the same timeline
- Spacecraft movement toward the outer planets (Jupiter, Saturn, etc.) tends to yield a more-elliptical trajectory path (high eccentricity) with less negative total energy
- Spacecraft moving toward the innermost planets tend to experience a more-circular trajectory path (low eccentricity) and have more negative total energy

Trajectory Paths



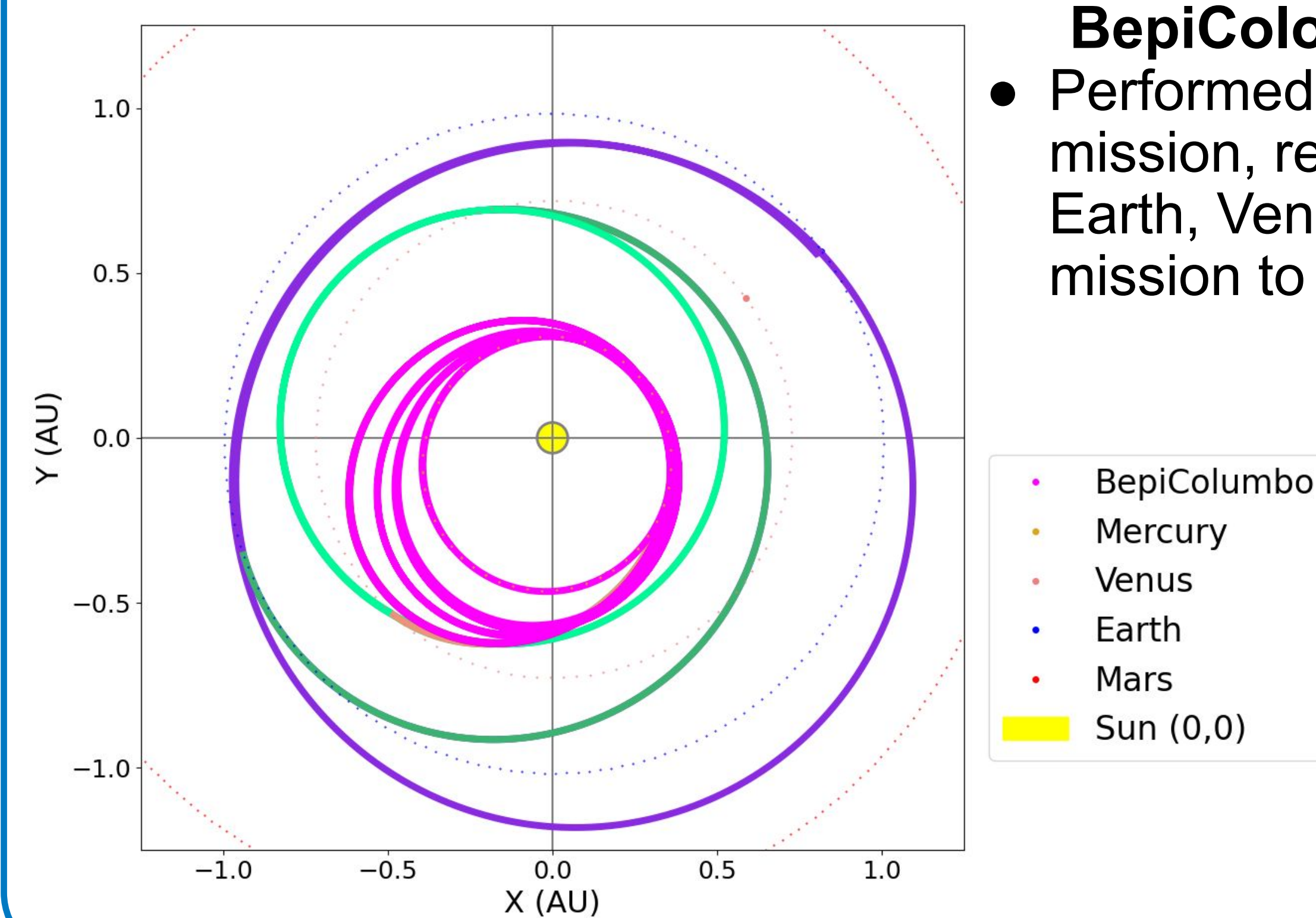
Europa Clipper (NASA)

- Plans for GA from Mars and Earth to receive boosts needed to reach one of Jupiter's moons, Europa
- Notable behavior near end of mission
 - Spacecraft approaches Jupiter from outside orbital path before arcing in past Europa
 - The "oscillations" are orbits of Jupiter/Europa for a planned 49 Europa flybys over 4 years



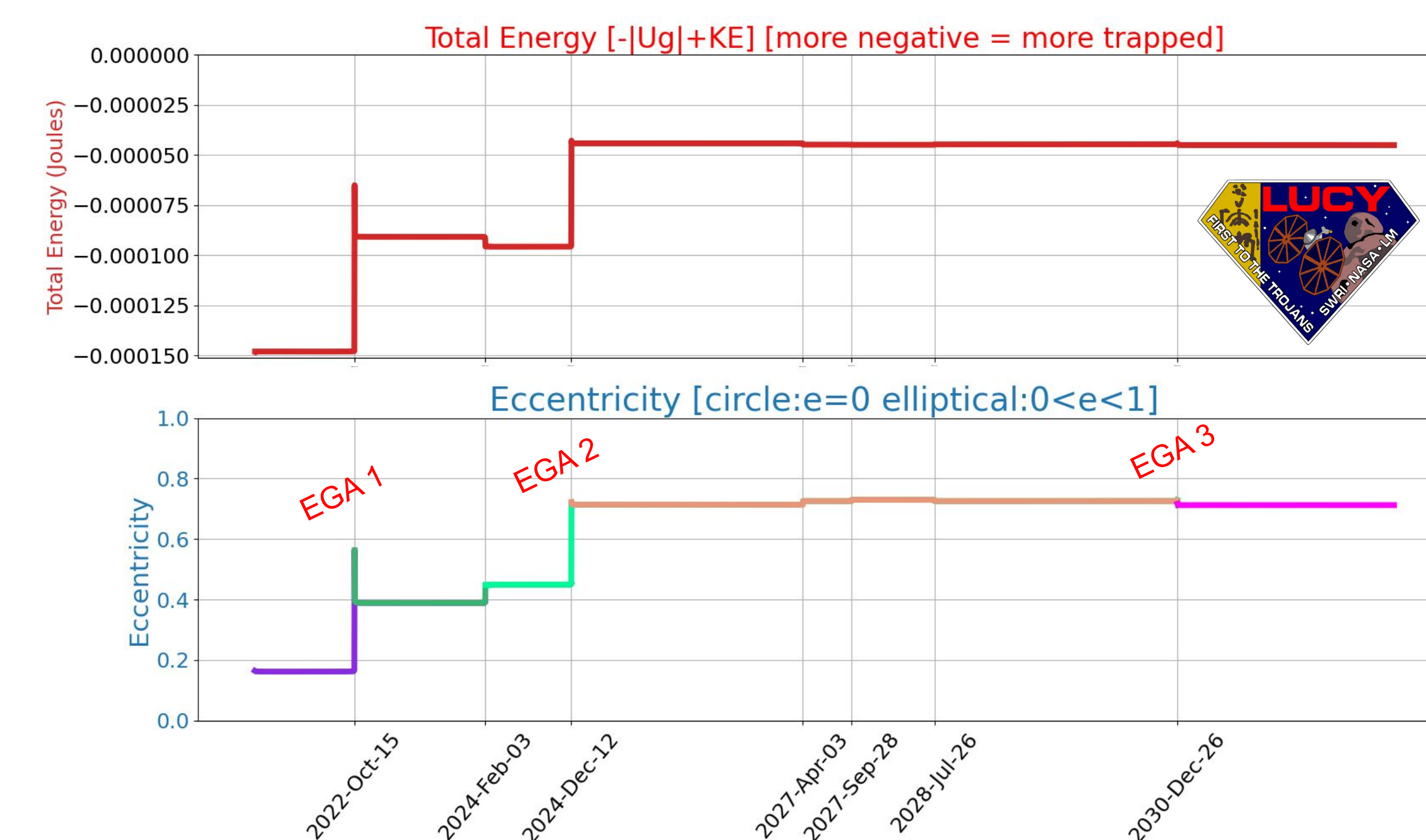
BepiColumbo (ESA/JAXA)

- Performed 9 flybys throughout mission, receiving GAs from Earth, Venus and Mercury on mission to study Mercury
 - Spacecraft received a series of 'de-boosts' to enter Mercury orbit
 - Enters interaction ahead of Mercury, using gravity to reduce speed

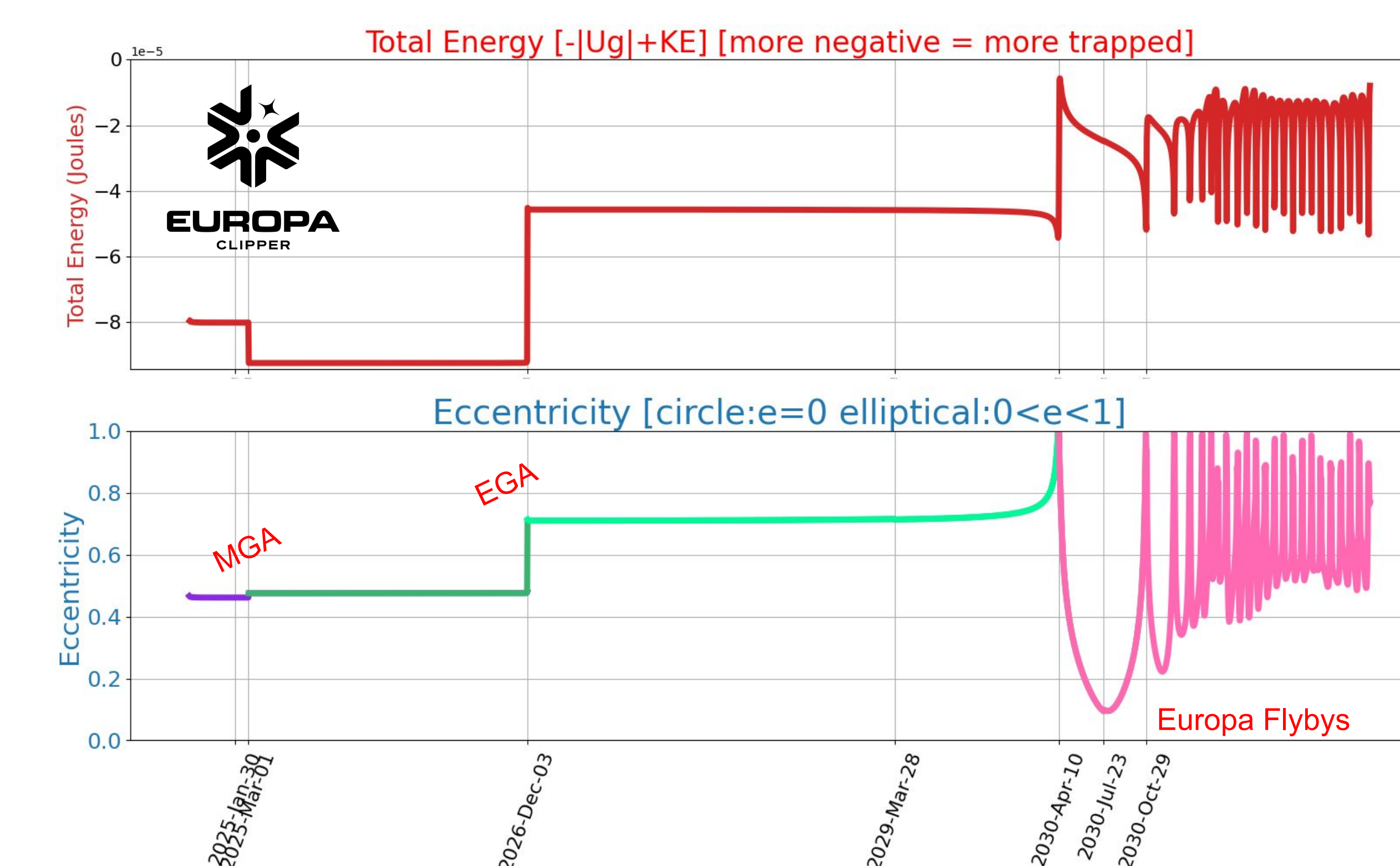


Energy & Eccentricity

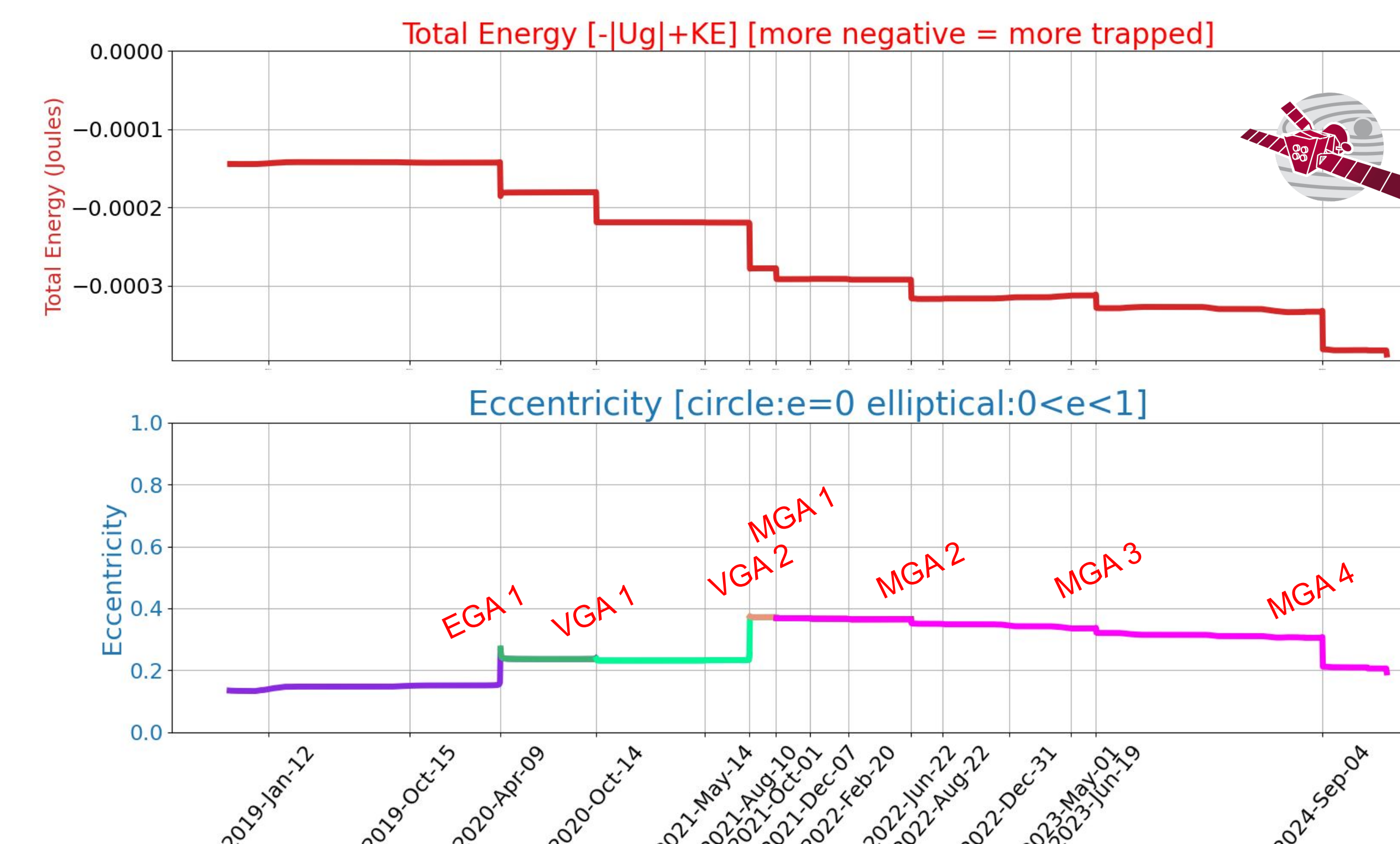
LUCY



EUROPA CLIPPER



BEPICOLOMBO



Conclusions

- Mission trajectory planning must consider many effects, and increases in complexity when using GAs and TCMs
- Notable events in mission timelines can be found through trajectory plotting and energy/eccentricity calculation
- Other events (small TCMs, etc.) are revealed through calculation and plotting that are not explicitly described
- Events of each type provide varying responses as observed in eccentricity plotting

Future Investigations

- Expand evaluation to other missions involving gravity assist maneuvers
- Refine eccentricity calculation model for more-accurate approximation
- Use evaluation findings to design a mission plot utilizing planetary GA
 - Without actual telemetry data, tools would be required to iterate the paths, predict the position of relevant planetary bodies, and determine the effect of each body on the final mission trajectory
- Re-evaluate RK4 approximation method to achieve higher agreement with actual telemetry data

References & Acknowledgements

Jet Propulsion Laboratory. (2026). Horizons system. National Aeronautics and Space Administration.
<https://ssd.jpl.nasa.gov/horizons/>

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