Detailed Project Explanation & Exoplanet Research Correlations
Project Title:
"Modeling Jupiter's Galilean Moons: A Gateway to Exoplanet Detection Techniques"
Objective:
To observe, analyze, and model the orbital dynamics of Jupiter's four largest moons Io, Europa, Ganymede, and Callisto using astrophotography and Keplerian mechanics, ultimately deriving Jupiter's mass—and exploring how these methods apply to exoplanet research.

Methods & Observations

1 Data Collection:
- Used a Celestron NexStar 8SE along with an iPhone to capture images of Jupiter and its four Galilean moons over 3+ weeks, covering at least one full orbital period of Callisto at approximately 17 days while scaling it down to a consistent size for accurate measurements.
- Tracked the positions of each moon relative to Jupiter's center in every image while keeping the scaling at a consistent size using Jupiter's diameter, ensuring precise angular measurements.

2 Measurements & Analysis:
- Orbital Distance: Measured the apparent separation in millimeters of each moon from Jupiter's center, converting to physical distances using Jupiter's known equatorial diameter approximately 143,000 km.
- Orbital Periods: Plotted each moon's position vs. time to confirm their published orbital periods (Io: 1.8 days; Europa: 3.6 days).
- Kepler's Third Law: Applied the formula: $T^2=4\pi^2/GM\ \ a^3$.
- where T = orbital period, a = semi-major axis,and M = Jupiter's mass. Solved for M which is Jupiter's mass and compared to the accepted value of 1.9×10^{27} kg.

3. Scaling: Measured the relative scale of the distances of the moons from the middle of Jupiter using markup and measured the diameter of Jupiter using the measuring ruler in the Photos app on my iPhone. The units used to measure it were in millimeters.

Results & Key Findings

- Successfully derived Jupiter's mass within ~10% error of the accepted value, validating the methodology.
- Observed the orbital resonances of each of these four moons, mirroring dynamics seen in exoplanet systems.
- Demonstrated that amateur astrophotography + computational analysis can yield robust dynamical models.

Correlations to Exoplanet Research

1. Transit Photometry & TTVs (Transit Timing Variations)
   - Jupiter's moons passing in front/behind Jupiter → analogous to exoplanets transiting their host stars.
   - Measuring moon positions → similar to detecting exoplanet transit depth/duration (TESS, Kepler).
   - Small deviations in moon transit times → comparable to TTVs, used to infer unseen planets of exomoons or multi-planet systems.
2. Orbital Dynamics & Mass Determination
   - Fitting moon orbits to derive Jupiter's mass → identical to calculating exoplanet host-star masses via radial velocity with an assumed orbital inclination value in degrees for the planet by measurements or even astrometry.
   - Resonant interactions Io-Europa-Ganymede → directly observed in exoplanet systems (e.g., TRAPPIST-1's 2:3:4 chain).
3. Direct Imaging & High-Contrast Photometry
   - Resolving moons against Jupiter's glare → similar to challenges in direct imaging exoplanets similar to JWST's coronagraph.
   - Precision photometry of moon brightness → scalable to studying exoplanet phase curves dayside/nightside temperature maps.
4. Exomoon Detection
   - The Galilean moons are a proxy for exomoons; our methods could be adapted and applied to even larger methods to search for moons around exoplanets like Kepler-1625b's candidate exomoon using space telescopes with a larger mirror diameter than the combined mirrors of JWST, Hubble, or perhaps even interferometry from more large telescopes on Earth than is currently available for more light gathering power to carefully observe the dip in the exoplanet's brightness in an extended period of careful observing time. Comparable to the much easier ways of detecting exoplanets usually similar in size to Jupiter or even Neptune by using the Transit Method, spectroscopy, or even direct imagining with a telescope capable of blocking out the bright star light to show the exoplanet. With these factors of consideration applied to the current telescopic telenology, it may be plausible to detect these faint exomoons around their host planet quite easily if they are done correctly.

Future Work & Exoplanet Applications

- Adapt methods to analyze real exoplanet data (e.g., Kepler/K2/TESS light curves).
- Simulate how moon-like bodies would appear in exoplanet transit surveys.
- Explore machine learning to identify TTV signals in archival datasets.

Why This Matters

This project demonstrates that fundamental orbital mechanics—practiced in our solar system—are the bedrock of exoplanet science. By mastering these techniques with Jupiter's moons, I've built skills directly transferable to:

- Transit surveys (PLATO, future Habitable Worlds Observatory).
- Dynamical modeling of multi-planet systems.
- Exomoon searches, a cutting-edge frontier in astrobiology

Although most of my observations primarily relied on detecting the Galilean moons themselves through a series of photographs around Jupiter, it would be otherwise very difficult to do so for exoplanets because their parent star they orbit would block out their light being seen from Earth by the star's powerful glare.

For this reason, there are alternative methods that can be applied to this such as measuring the radial velocities with due to respect of their inclination around Jupiter in degrees and/or observing the dip in Jupiter's brightness through one of them transiting in front of Jupiter like how exoplanets are typically detected through transits done by observing a dip in brightness of their host star.

So, while it may not be possible to detect the exoplanets directly around their host star through direct imagining like how I did for Jupiter's moons, there are other indirect methods that can be used to detect them such as the Transit Method and measuring their radial velocities with their orbital inclinations.

References:

https://youtu.be/G9iXdqo_wL4?si=6V9B2Um-Fhoqv_L_

https://psuttonblog.wordpress.com/2021/06/11/how-to-calculate-jupiters-mass-with-a-telescope-and-the-galilean-moons/