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# Resonant moons of Neptune

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## Abstract

We used integrated orbits to fit astrometric data of the regular moons of Neptune. We found a 73:69 inclination resonance between Naiad and Thalassa, the two innermost moons. Their resonant argument librates around 180° with an average amplitude of ~66° and a period of ~1.9 years. This is the first fourth-order resonance discovered between the moons of the outer planets. The resonance enabled an estimate of the *GMs* for Naiad and Thalassa, $GM_N$= 0.0080±0.0043 km$^3$ s$^{-2}$ and $GM_T$=0.0236±0.0064 km$^3$ s$^{-2}$. More high-precision astrometry of Naiad and Thalassa will help better constrain their masses. The *GM*s of Despina, Galatea, and Larissa are more difficult to measure because they are not in any direct resonance and their masses are small. We also found that the newly discovered moon Hippocamp is in a 13:11 near-resonance with Proteus. Future observations of Hippocamp could reveal the mass of the largest regular moon Proteus.

## 1. Introduction

The Neptune system has seven regular moons that orbit close to the planet in nearly-circular orbits. Naiad, Thalassa, Despina, Larissa, Galatea, and Proteus were discovered by the Voyager 2 spacecraft during the 1989 flyby of Neptune [1, 2]. [3] reported on the HST discovery of the seventh regular moon – Hippocamp. This tiny moon, ~17 km in radius, orbits between Larissa and Proteus. All regular moons have their semi-major axes span 48,000-118,000 km. The semi-major axis of the farthest moon, Proteus, is less than five Neptune radii from the planet's center. The entire closely-packed system would fit within one third of the Earth-Moon distance.

The regular moons are strongly perturbed by massive Triton. The Neptunian system has the invariable plane defined by both the rotational angular momentum of the planet and by the orbital angular momentum of Triton.

## 2. Methods

### 2.1 Observations

The astrometric data cover the period from 1981–2016, with the most significant amount of data originating from the Voyager 2 spacecraft and HST. Voyager 2 imaged all regular satellites except Hippocamp between 1989 June 7 and 1989 August 24. The follow-up observations originated from several Earth-based telescopes, but the majority were still obtained by HST. [4] published the latest set of the HST astrometry including the discovery and follow up observations of Hippocamp. These measurements were obtained during 2004–2016.

### 2.2 Orbital model

Our orbital fit is based on numerical integration of the satellites of the outer planets [5]. The equations of motion are defined in Cartesian coordinates with the Neptune system barycenter at the origin and referenced to the International Celestial Reference Frame (ICRF). The equations include the gravitational effects of Neptune, the $J_2$ and $J_4$ zonal harmonics of its gravity field, and perturbations by Triton, Jupiter, Saturn, Uranus, and the Sun. The mass of the Sun is augmented with the masses of the terrestrial planets and the Moon.

We used precessing ellipses to summarize the results of integration in terms of the mean orbital elements and rates. The elements were defined with respect to each moon's Laplace plane.

## 3. Results

The fitting process revealed the data sensitivity to the masses of Naiad and Thalassa, but not to the masses of other moons. The fitted *GMs* for Naiad and Thalassa are $GM_N$= 0.0080 ± 0043 km$^3$ s$^{-2}$ and $GM_T$=

$0.0236 \pm 0.0064$ km$^3$ s$^{-2}$. All satellites have short orbital periods, ranging from ~0.3 days for Naiad to just over a day for Proteus. The orbits are also characterized by relatively short nodal and apsidal precession periods ranging from ~0.3 years for Naiad to ~13 years for Proteus. The satellites have fairly circular orbits with the highest eccentricity being ~0.0012 for Larissa. The Naiad and Thalassa rates revealed a resonant argument of the form: $73\, d\lambda_T/dt - 69\, d\lambda_N/dt - 4\, d\Omega_N/dt \approx 0$. Figure 1 shows the resonant angle calculated from osculating elements based on integrated orbits. A Fourier fit revealed an average amplitude of ~66° and a period of ~1.9 years. The latest addition to Neptune's system, Hippocamp, has the smallest eccentricity, $e=1\times10^{-5}$, and the smallest free inclination, $i_{free}=0.0019°$, among all inner moons of Neptune. Hippocamp appears to be very close to the 13:11 mean motion resonance with Proteus. As Proteus is migrating outward due to tidal interactions with Neptune, growth in its semimajor axis of only several tens of km will bring it into resonance with Hippocamp. This is only the third second-order resonance among outer planet moons after the 4:2 Mimas-Tethys [6] and the 77:75 Anthe-Methone [7].

# 4. Figures

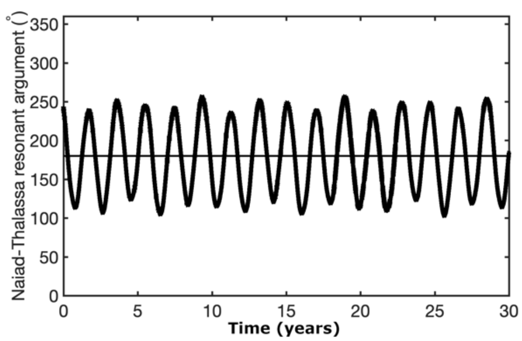


Figure 1: The resonant angle $\varphi = 73\, \lambda_T - 69\, \lambda_N - 4\, \Omega_N$ calculated based on osculating elements from integrated orbits. The starting epoch is 1950 Jan 01 UTC.

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