Probing Neptune with *Kepler*

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Introduction

This white paper suggests a potentially high-reward secondary science target that may be appropriate to include during a revised Kepler planet search. If *Kepler* is to be repurposed to observe a field on or near the ecliptic plane we suggest that Neptune be included in the field of view. Assuming an appropriate field is chosen there should be few additional resources required to observe this planet. A longterm (three months or longer) photometric series taken of Neptune could potentially detect internal oscillation modes of the planet and open a new window to probing the interior structure of an ice giant. *Kepler* has demonstrated both that ice giants are common in the galaxy and the exceptional value of continuous photometric monitoring for detecting and interpreting stellar oscillations. A *Kepler* observation of Neptune would appropriately combine these two successes to perhaps similarly dissect the interior structure of one of our own ice giants.

Scientific Background

There are two classes of solar system giant planets: the gas giants and the ice giants. Uranus and Neptune, with masses around 16 Earth masses comprise a distinct class from Jupiter and Saturn, with masses greater than about 100 Earth masses. The primary constituents of Uranus and Neptune are likely ices surrounding a rocky core with a relatively thin atmospheric veneer of hydrogen rich gas. *Kepler* has ably demonstrated that such Neptune mass planets are common—much more common than gas giants in fact—outside of the solar system (Batalha et al. 2013). It is thus important to understand the interior structure of these worlds in order to better model their formation and evolution. Unfortunately our best data on the interior structure of these worlds comes from the gravitational harmonics measured during the single flybys of *Voyager* 2 about 25 years ago. Given the uncertainties in those harmonics, a number of possible interior structures and compositions are possible (Guillot 2005).

Guillot (2005) outlines a number of important questions surrounding the ice giants, including the size of their cores and the composition of their deep envelopes. Marley et al. (1995) employed a Monte Carlo method for the construction of interior models and demonstrated that the uncertainties in interior structure were sufficiently great that both distinctly layered structures (e.g., envelope-mantle-core) as well as continuously varying models (a deep envelope with varying composition overlying a core) were possible. Without new constraints on the interior structure, little more can be gleaned from the available data.

Seismology is "by far" (Lissauer & Stevenson 2007) the most promising technique for constraining the core mass of a giant planet, independent of the uncertainties that plague interior model inversion. In principle, for a fixed spherical harmonic degree, acoustic oscillation modes of sequentially higher order n penetrate progressively less deeply into the interior. Some oscillation modes thus "see" the core while others do not. The progression of mode frequencies—if observed—uniquely delineates the size of the planet's core as well as the structure of the envelope. The basic theory for computing giant planet oscillations has been discussed as far back as Vorontsov et al. (1976) and includes work by Mosser (1990) for Jupiter and Marley (1991) for Saturn.

There have been a number of searches for giant planet oscillations, primarily for Jupiter.

Gaulme et al. (2011) reported the Doppler detection of jovian modes with peak amplitudes near frequencies of 1.2 mhz, a period of about 14 minutes. While their data window function precluded precise mode identification, they were able to measure the frequency spacing between modes, which they found to be consistent with models. At Saturn, Marley (1990) and Marley & Porco (1993) suggested that density perturbations arising from internal oscillation modes could alter ring particle orbits at resonances between orbital and mode frequencies, thereby launching waves in the rings. Recently Hedmann & Nicholson (2013) confirmed this prediction, which suggests that at very low frequencies at least (periods of hundreds of minutes) Saturn is indeed oscillating. Several years ago the authors of this white paper were awarded time on the Canadian MOST satellite to search for oscillations of Neptune in reflected light. While a data series was obtained, the pointing stability was not sufficient to permit a search for oscillations.

Oscillations of Uranus and Neptune would presumably be excited by turbulence from convection that pumps energy into random sound waves. The production of velocities comparable to the local sound speed is the assumed driving mechanism. Thus, as waves are damped, the appearance of new sources allows the oscillations to be treated as standing waves. Leibacher & Stein (1981) present an intuitive discussion. Deming et al. (1989) estimated the velocity amplitude of Jovian oscillations range could lie in the range of 1 to 10 cm/sec whereas the modes observed by Gaulme et al. had peak amplitudes closer to 50 cm/sec.

Numerous authors (including a series of six papers by Vorontsov and coauthors (see Marley 1991 for a summary)) have studied the expected frequency spectrum for Saturn as well as Jupiter. One of us (MM) carried out an exploratory computation of ice giant mode frequencies some years ago but did not publish the results, but as with Jupiter and Saturn expected periods are in the range of tens to hundreds of minutes. To the best of our knowledge there is no other published calculation for Uranus or Neptune. Such an analysis is eminently possible as the speed of sound in the planets' can be computed for any particular model given the constituent relations for a specified mixture of rock, ice, and gas. Certainly the range of possible frequencies is larger than for Jupiter or Saturn since the interior structures are so much more uncertain. But this of course is part of the reason that any seismological detection of the oscillations of Uranus and Neptune would be so interesting.

Observing Oscillations with *Kepler*

Oscillations of a giant planet change the size of the observable disk, thus altering the total reflected solar flux. From simple geometry alone a velocity of 50 cm/s with a frequencies of 1 mHz changes the reflected flux at the several ppm level. If the frequency of oscillation is 4 mHz the amplitude drops below 1 ppm. The complication of searching for modes in reflected light is variability due to clouds (Lederer et al. 1995) that change the reflectivity of the planet on time scales similar to the rotation period of the planet: hours compared to minutes for oscillations (below 0.7 mHz (Lederer et al. 1995)). However, the presence of clouds can also aid in detection. Gaulme & Mosser (2005) considered propagation of acoustic waves in the Jovian troposphere and its effects on the planetary albedo. Considering the highest cloud layers where ammonia ice at Jupiter is present, acoustic waves become trapped and phase changes occur. Thermodynamic perturbations can have variations as large as 70 ppm for a 3 mHz wave. Depending on how particle size varies with height and where the reflected light originates, clouds may accentuate trapped oscillations. Most of the light in the *Kepler* bandpass scattered from Neptune will be reflected from the cloudtops (red light will be mostly absorbed in the atmosphere) so such a mechanism may also be relevant to Neptune.

The expected performance of *Kepler* using two reaction wheel is maximized if the observed FOV is in *Kepler*'s orbital plane, which is nearly coincident with the orbital planes of the Sun's giant planets, giving *Kepler* the potential to perform planetary seismology within our Solar System.

Neptune's brightness at quadratures is comparable to that of the brightest stars that Kepler has monitored in its exoplanet search. Neptune is also a slightly extended source, so it could be observed as part of an exoplanet search program if an appropriate star field is observed; Neptune currently lies in Aquarius, not too close to the galactic plane. Neptune would move slowly across Kepler's focal plane as a result of parallax, so the aperture assigned would need to either be large or moving. Also, Neptune would move more significantly between the two quarters that it could be observed, so there would be significantly more restrictions on the placement of the FOV to observe Neptune for 2 quarters per year than for just 1 quarter per year. However a time series of several months or more should be sufficient to detect and measure oscillations if they are detectable. A long time series would also allow the lightcurves of the satellites to be identified and removed. Uranus offers an alternative target for this type of program, with more photons and a more extended source, but it is somewhat brighter than the brightest stars for which Kepler has demonstrated excellent photometric performance and it also has larger parallax motions.

Jupiter and Saturn

We briefly note that the optimal *Kepler* targets for planetary seismology might in fact be Jupiter and Saturn, which are both very bright and quite extended on the sky, implying that their images extend over many *Kepler* pixels. A dedicated *Kepler* jovian seismology campaign might focus solely one each planet for several weeks using *Kepler*'s shortest exposure time to avoid oversaturation. Scaling to the bright point source targets that have been searched for planets by Kepler suggests that these observations are viable for Saturn; the potential of doing them for Jupiter, which is significantly brighter, would require additional tests. Such a dedicated program could be highly rewarding but would be much higher risk since the short exposure times required would preclude a simultaneous exoplanet survey. Note that as there would only be a single target for such a program, the pointing of the spacecraft could be moved to account for parallax, so a fixed aperture large enough to include the planet and its scattered light would suffice.

Summary

Observations of Neptune (or any giant planet) with *Kepler* have the potential to answer many long-standing questions regarding the interior structure of ice giants from detecting a core to understanding the compositional structure of the envelope. The clear detection of oscillation modes will of course energize a new generation of theorists to compute model frequencies for comparison with data. We thus urge that the inclusion of Neptune in any appropriate near-ecliptic star field observed by *Kepler* be seriously considered.

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