Yale Observing Proposal *Standard proposal* **Semester:** *2018B*
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Jovian Seismology with Dragonfly

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Abstract of Scientific Justification *(will be made publicly available for accepted proposals)***:**

With the exception of one planet with extremely detailed data (Earth), our knowledge of planetary seismology is extraordinarily ill-defined. While global oscillations of Jupiter have previously been detected using odd-degree radial velocity Dopplergrams derived from the SYMPA Fourier tachymeter (Gaulme et al., 2011), so far no comparable study has been completed with photometric data in the optical (as has been traditionally done with helio- and now asteroseismology). In part, this is because Jupiter has low intrinsic luminosity in the optical; consequently, surface pressure perturbations are not expected to produce the same luminosity variations as would be expected of stars. However, variations of the albedo with pressure (particularly for low-degree modes of oscillation, which should have a large penetration depth) should still produce a photometric response in the reflected light. We therefore propose to derive photometric time series of odd-degree Jovian reflectivity variations from Dragonfly imaging, with the intent of characterising the time-domain spectral properties of these reflectivity variations. These observations will detect or constrain the spectral envelope of the Jovial seismological power spectrum in this observing mode, and (should a global oscillation signature be detected) will calibrate a planetary velocity-photometry seismological amplitude relation analogous to that of solar-type oscillations.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Min. Nights	Moon	Optimal months	Accept. months
1	Dragonfly	N/A	1	1	Any	April 2018	April 2018
2							
3							
4							
5							

Scheduling constraints and non-usable dates *(up to four lines).*

Scientific Justification *Be sure to include overall significance to astronomy. Limit text to one page with figures, captions and references on no more than two additional pages.*

The Case for Jovian Seismology Under hydrostatic equilibrium, stars with convectively unstable outer surfaces undergo p-mode oscillations (p for "pressure", as these are pressure perturbations), driven stochastically by convective motion in the envelope. Power spectra of their surface radial velocities and luminosities reveal a comb-like structure (Figure 1) parameterised by the quantities $\Delta\nu$ and $\nu_{\max}$. Together, the individual p-mode frequencies offer strong constraints on internal stellar structure. This technique has previously been applied to great effect in the Sun (permitting inference of compositional, thermal and dynamical structure) as well as, more recently, to stars in the Kepler field (e.g. 16 Cyg A and B, see Bellinger et al., 2017). Giant planets such as Jupiter are thought to exhibit similar phenomenology, although analogous observations of these planets have been considerably scarcer. For Jupiter in particular, detailed seismology may permit constraints on the size and composition of the postulated solid core (Provost et al., 1993), which are otherwise less accessible via other means of probing Jupiter's internal structure (e.g. measuring multipole moments of its gravitational field *a la* Juno; see Gaulme et al., 2014).

The majority of previous attempts at detecting Jovian oscillations have been defeated by either low SNR or other instrumental systematic errors (Gaulme et al., 2014, and references therein). Much of this can be attributed to the use of integrated full-disk velocimetry or IR photometry, which is susceptible to contaminated variability from the solar oscillation and granulation power spectrum. The only successful measurement of Jovian seismology to date originates from the SYMPA Fourier tachymeter (Gaulme et al., 2011), which owes the success of its measurements to its ability to return resolved Dopplergrams of the Jovian disk. This permits decomposition of the disk into projected spherical harmonics (as in Figure 2). The odd-degree spherical harmonics, in particular are less susceptible to solar variability, and it is with respect to these that Jovian global oscillations were detected with little ambiguity (Figure 3). We therefore propose to use Dragonfly's imaging capabilities to produce odd-degree projected spherical harmonic decompositions of Jupiter's brightness.

Detectability of Photometric Seismology Since Jupiter is not a star, it is not expected to evince solar-type luminosity variations in the optical (except for what it reflects), as much of its intrinsic luminosity is in the thermal IR continuum. Rather, any variations in its optical brightness (discounting solar variability, Earth's atmosphere, and zodiacal scattering) must be a result of changes in its albedo over time in response to changes in atmospheric conditions (as discussed in e.g. Donohoe & Battisti, 2011).

While there is a known relationship between the amplitude of solar-type oscillations from velocities vs. from photometry (Kjeldsen & Bedding, 1995), this applies specifically to intrinsic luminosity variations. If seismological pressure perturbations within Jovian planets also lead to albedo variations, any relationship between the pressure and putative albedo amplitude is almost entirely unconstrained (although there is an implicit constraint in that it must be subtle enough to not have been picked up immediately in historical observations or by amateur astronomers).

Therefore, even if we are unable to directly detect an oscillation signature, we will (SNR permitting) be able to place the first formal constraints on the variations of albedo vs. the pressure amplitudes (determined from velocimetry) at these characteristic timescales within the atmospheres of giant (exo)planets. On the other hand, should the Jovian oscillation signature emerge in albedo variations, we will be able to relate its albedo to its velocity and pressure amplitudes (similarly to the solar case). Moreover, a positive detection would justify follow-up investigations, potentially culminating in detailed seismology and structural inversions. Either result would advance our general understanding of giant planet atmospheres.

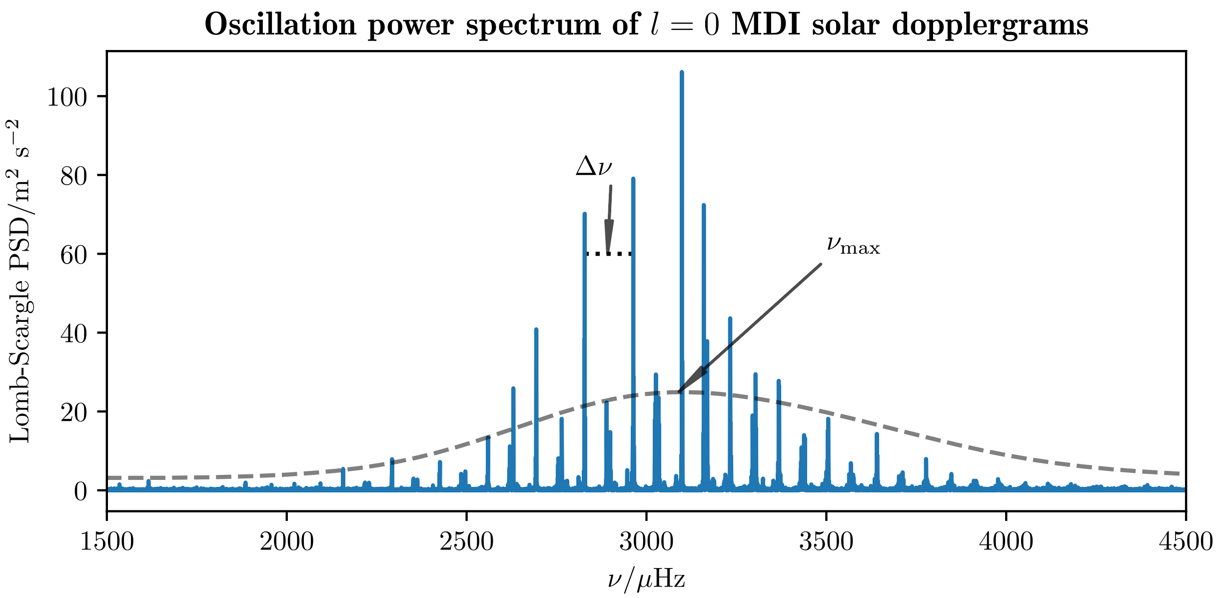

Figure 1: Solar oscillation power spectrum from MDI dopplergrams, showing comb structure modulated by spectra enveloped centered at $\nu_{\max}$ (figure from JO's oral qualifying exam slides). The time resolution of an observing campaign determines the maximum sampled frequency of the time series, which has to be much larger than $\nu_{\max}$, while the overall duration of an observing campaign determines the frequency resolution, which needs to be less than $\Delta\nu$ for detailed seismology. This will not be possible with a single night, but we should still be able to resolve the spectral envelope of the Jovian oscillation signature.

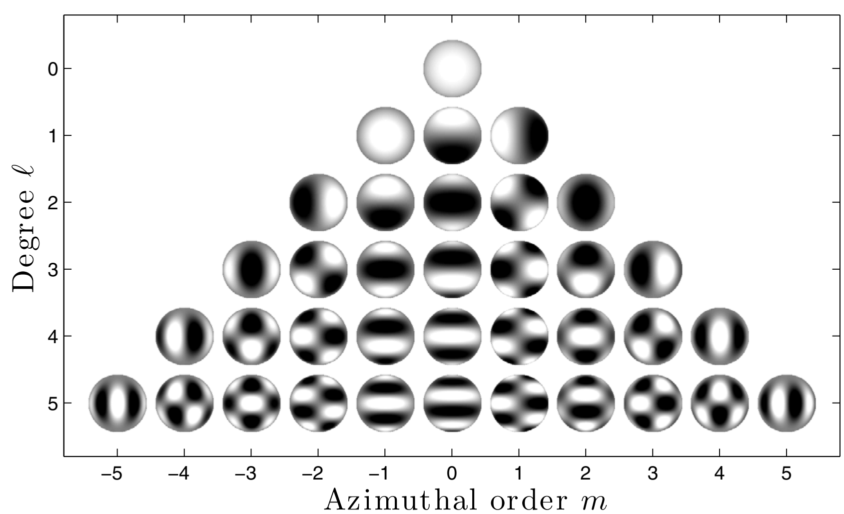

Figure 2: Spherical harmonic mask functions, as a function of the degree l and azimuthal wavenumber m (figure from Gaulme et al., 2011).

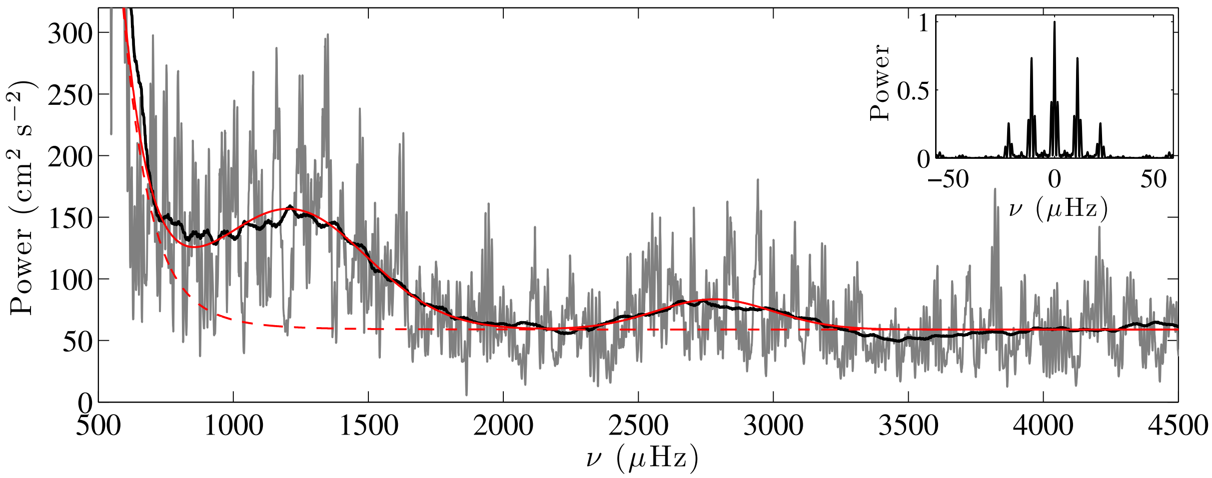

Figure 3: Power spectra of $l = 1$ time series derived from Dopplergrams returned from the SYMPA campaign (figure from Gaulme et al., 2011). Some traces of the solar oscillation power spectrum ($\nu_{\rm max} =$ 3010 μHz) are visible, but there is a distinct separate oscillation envelope, at $\nu_{\rm max} \sim 1200$ μHz, attributed to intrinsic Jovian pulsations. The black line shows the oscillation power spectrum as degraded by a low-pass filter, which is equivalent to the data returned from a shorter observing window. From 5 hours of Dragonfly time, we expect a frequency-domain resolution of 60 μHz, which would allow us to resolve the spectral envelope (about 500 μHz wide).

References

Bellinger, E. P., Basu, S., Hekker, S., & Ball, W. H. 2017, The Astrophysical Journal, 851, 80

Donohoe, A., & Battisti, D. S. 2011, Journal of Climate, 24, 4402

Gaulme, P., Mosser, B., Schmider, F.-X., Guillot, T., & Jackiewicz, J. 2014, arXiv:1411.1740 [astro-ph], arXiv: 1411.1740

Gaulme, P., Schmider, F.-X., Gay, J., Guillot, T., & Jacob, C. 2011, Astronomy and Astrophysics, 531, A104

Kjeldsen, H., & Bedding, T. R. 1995, Astronomy and Astrophysics, 293, 87

Provost, J., Mosser, B., & Berthomieu, G. 1993, Astronomy and Astrophysics, 274

Impact to Yale Astronomy *Describe how this program fits into the Yale astronomy program. Will the data analysis and resulting papers be based at Yale? If the project is led by a faculty member, does the project involve students? What is the role of the PI viz-a-viz other non-Yale co-Is. Are the resources in place to analyze the data and come to a timely publication? (limit text to one page)*

This project is particularly relevant and pertinent to the Yale Astronomy program due to its scientific potential as well as its educational value for Yale Astronomy graduate students. The PI and CoI's of this project are PhD students within the Yale Astronomy Department; in addition, all resulting data analysis and publications from this project will be led and completed entirely by Yale Astronomy graduate students. Tools to bin and reduce obtained data are available such that the relevant power spectra can be readily produced soon after observations are taken, and Co-I JO has an existing pipeline in place for the extraction of seismic parameters from time-series power spectra. As a result, we anticipate that a thorough analysis of the results of this project will be completed in a timely manner (prior to the end of the 2018 spring semester). This independently-run student project will thus provide both a valuable educational experience and a salient opportunity to explore and constrain Jupiter's interior structure, a topic with immediate significance and implications for planetary formation theories in the broader scientific community.

Previous Use of Yale Facilities and Publications *Please list previous use of Yale observing facilities and any publications resulting from these data in the past 3 years. If this is a long term project, please state this here and describe the overall strategy of the project.*

CoI MW has been awarded 12 nights during the 2018A/B year at Palomar for observations of candidate black hole binary systems using DBSP. The first four nights were observed in March. Analysis is underway for this data.

Observing Run Details for Run :

Technical Description *Describe the observations to be made during the requested observing run. Justify the specific telescopes, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section.*

The Dragonfly Telephoto Array is particularly well-equipped to complete the required observations because of its high-cadence capabilities as well as its specialization in observations of low-surface brightness objects. As a result, Dragonfly will be able to effectively capture rapid variations in Jupiter's atmospheric pressure in the form of albedo changes.

Based on existing velocimetry, we estimate that the Jovian oscillation power spectrum occurs at about $\nu_{\mathrm{max}} \sim 1200\ \mu$Hz. Consequently, we would need to take data at a minimum cadence of 4 minutes per exposure. In practice, Jupiter will saturate Dragonfly sensors well before this, and our exposure time will be set by Dragonfly's shutter speed. As such, we intend to take data at a considerably higher cadence (essentially limited by read-out time), and then bin the resulting photometry in time before taking the projected spherical harmonic decomposition, which would have the additional benefit of reducing aliasing and increasing the SNR of the resulting time series.

R.A. range of principal targets (hours): 15.2 to 15.4

Dec. range of principal targets (degrees): -17 to -15

Instrument Configuration

Filters:
Grating/grism:
Order: 1
Cross disperser:

Slit:
Multislit:
λ_{start}:
λ_{end}:

Fiber cable:
Corrector:
Collimator:
Atmos. disp. corr.: