A Cover

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4. Project Title: Jovian Interiors from Velocimetry Experiment in New Mexico (JIVE in NM)
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8. Recipient Organization: New Mexico State University, 1050 Stewart St. STE E1200, Las Cruces, NM 88003
9. Full Project Period: 07/17/2014 - 07/16/2018 (extended)
10. Annual Report, Year 3
11. Reporting Period: 05/17/2016 - 05/16/2017
12. Signature of jurisdiction director: Patricia Hynes Digitally signed by Patricia Hynes Date: 2017.05.15 07:50:31 -06'00'

B Progress Summary

This project has 5 goals and associated objectives that are restated and bulleted below, followed by this period's accomplishments and plans for the upcoming year's efforts.

(Goal 1) Instrumentation: *Build an imaging spectrograph capable of measuring Jovian oscillations within the three-year award period.* Specific objectives related to this goal are:

- Adapt an instrument design that has an expected order of magnitude more sensitivity than previous instruments;
- Mount the instrument on a suitable telescope to carry out monitoring of giant planets;
- Develop the software needed to control the instrument and perform data acquisition and reduction;
- Assemble a team of experts who regularly meet and review construction progress.

***Summary of previous period:** Our French colleagues received a grant to build a second identical instrument to JIVE (called JOVIAL) to help allow for more continuous observations of Jupiter in a "network-like" sense. We altered our plans to develop the instrumentation for the Dunn Solar Telescope (DST) where JIVE will be deployed.

***Accomplishments this period:** We were awarded about 3 weeks of observing time by the National Solar Observatory (NSO) at the DST this period. Much of our efforts involved instrumentation acquisition and development, including hardware, software, and optical studies. An all-new custom optical interface to the DST was designed, assembled, and implemented/tested at the telescope in February 2017. This will serve as the link between the output light of the telescope and the input light needed for JIVE. We have developed a very robust and efficient coupling to this quite peculiar telescope. In addition, the guiding system and software that we have developed to track Jupiter (or any non-solar object) is working well. All of the major hardware components are now in our lab at NMSU (chilling system, vacuum pump, cameras), being tested and calibrated by faculty and students. A SPIE paper was published detailing some of the novel developments of JIVE.

***Plans for next period:** This next period is major, since in June 2017 we will be doing observations with the prototype instrument, using the full capabilities of the vacuum chamber and tip-tilt assembly. Then in the spring of 2018 the final instrument will be mounted at the telescope for scientific observations of Jupiter at opposition. These will likely be simultaneous observations with the NASA Juno mission.

(Goal 2) Science: *Determine the interior structures of Jupiter and Saturn to a precision better than ever achieved, enabling the resolution of competing theories about the formation of our giant planets.* Specific objectives related to this goal are:

- Measure Jupiter and Saturn's core mass to within several Earth masses;
- Measure the total mass of heavy elements to within several Earth masses;
- Identify structural discontinuities of the interior density and sound-speed profiles;
- Validate and compare Jive sub-surface inferences with those from the NASA Juno mission.

***Accomplishments this period:** Regarding oscillations of outer planets, we have published 3 papers in this period. The first concerns possible excitation mechanisms relevant to gas giant planets. The second was an effort to use NASA Kepler to obsever Neptune to detect oscillations (none were found, unfortunately). The third was a study of how oscillations in Jupiter could affect the NASA Juno satellite.

Additional work is underway to exploit the groundbreaking measurements of Saturnian surface-gravity waves. New models of Saturn's interior have been generated for forward calculations of mode frequencies. A significant amount of theoretical work has been done by student Dederick to derive what are known as seismic "sensitivity kernels" (detailed more in Section C).

***Plans for next period:** Final work on Saturn oscillation seismic inversions (using computed kernels) will be carried out and published within months. This upcoming period will see us capturing the first science-level data from the JIVE instrument. Detailed analysis to unequivocally demonstate Jovian oscillations will be carried out.

(Goal 3) Science: *Uncover new details of the dynamic atmospheres and climatology of the Jovian planets.* Specific objectives related to this goal are:

- Determine wind speeds directly from Jive maps and compare to cloud-tracking results;
- Measure the momentum cycle driving zonal jets by calculating eddy momentum fluxes;
- Directly characterize the planetary-scale waves in the wind signatures in the Jovian atmosphere;
- Indirectly probe the deep convective region of the planet to advance our understanding of tropospheric-stratospheric coupling.

***Accomplishments this period:** While most of this science goal will be executed in the near future, much work has been done regarding Jupiter's challenging atmosphere. A paper has been recently submitted by our collaborators at New Mexico Tech. and NASA Goddard using Hubble Space Telescope observations of Jupiter's atmosphere, where the zonal wind speeds have been measured. New variability has been observed along the equator in particular. We have additionally been anlayzing data taken with the JIVE prototype instrument. While these data are unsatisfactory for oscillation studies, they are quite suitable for atmospheric analysis. We have found unusual profiles of the wind speeds near the equator that do not agree with past work.

***Plans for next period:** We will be finalizing and publishing the atmospheric wind results. Most of the appropriate data for this study will be collected in the upcoming year with the finalized instrument, which will have the highest sensitivity yet. Modeling efforts will also be carried out in trying to understand the energy budget in the Jovian atmosphere.

(Goal 4) Education: *Train students in technical areas of astronomical instrumentation and modern planetary science to prepare them for careers in related fields.* Specific objectives related to this goal are:

- Hire three graduate students in engineering and astronomy whose work in Jive will form the bulk of their graduate degrees;
- Involve up to six undergraduate students in all aspects of the project;
- Provide effective mentoring and advising practices to help form pathways for future student participation in Jive .

***Accomplishments this period:** Four graduate students have been involved in JIVE work spread over 3 institutions in the past year. One of the students is developing most of the software for JIVE that controls the guiding system and the optical interface with the telescope. Two undergraduates have also participated in both instrumentation and Jupiter atmospheric analysis. These students have furthermore been involved in several publications. One of the undergraduates has been admitted to several graduate schools for astronomy. We engage in regular telecons and report writing with all students.

***Plans for next period:** Students will be available to carry out our first scientific observations at the DST in the coming year as well as contributing to any publications. We also anticipate 4 PhD defenses in the next reporting period from student participants.

(Goal 5) Collaboration: *Develop long-lasting and diverse research partnerships within New Mexico and beyond*. Specific objectives related to this goal are:

- Engage researchers in New Mexico's universities and national laboratories whose interests overlap with JIVE ;
- Utilize existing collaborations with key NASA partners to strengthen the relevance of the project to NASA's scientific priorities;
- Leverage existing international collaborations with critical expertise in this area, and build the case for a future global network of similar instruments.

***Accomplishments this period:** We have been involved in strengthening ties to a group of Japanese colleagues who are interested in building a third JIVE instrument to use in Japan to complete a northern-hemispheric network of observatories. A few of our team members visited Japan to help determine a suitable site and (existing) telescope for this kind of science. The prospects are very promising for this to be realized in the coming year.

For our test observations in Feb. 2017 four members of the French team visiting New Mexico and the DST for 1-2 weeks to help install our optical interface. This was very useful as it brought the whole team together to discuss the plans for the coming year.

***Plans for next period:** The next year will be a time to strongly engage with the NASA Juno team to explore any oscillation data we obtain in concordance with Juno's gravity data.

In the summer of 2017 we will host our NASA EPSCoR Technical Monitor for a review of the project. This is a good opportunity to re-establish all of the collaborations we have been carrying out in New Mexico and with our NASA center points of contact.

C The Research

Here we describe, in some detail, two major foci this period: (1) the instrumentation development of a telescope interface system and its installation; and (2) the analytic derivation, for the first time, of sensitivity kernels for Saturn from a rapidly rotation model.

1 Instrumentation development

Taking the light of Jupiter seen through a solar telescope and making it suitable to feed into the JIVE imaging spectrograph is a non-trivial effort that resulted in a novel interface design.

We first have modified the analog system that guides the telescope to the Sun to a digital system that can track a given nighttime object, such as a star, or Jupiter. A few views of the internal components of our guider system are shown in Figure 1. The DST has a pickoff tube that is fed light from a mirror suspended in the main primary tube. That light comes down to a table on the optical platform, where we have developed some simple optics that focus the light at a high-speed CCD digital camera. As Jupiter drifts through the sky because of Earth's rotation, successive images from the camera are cross correlated to determine the offsets needed to point the telescope to keep Jupiter within the field-of-view. Those offsets are converted from digital signals to analog voltages and then sent to the telescope control system. The guiding software closes the loop and drives the telescope to succesfully track Jupiter over the course of a night.

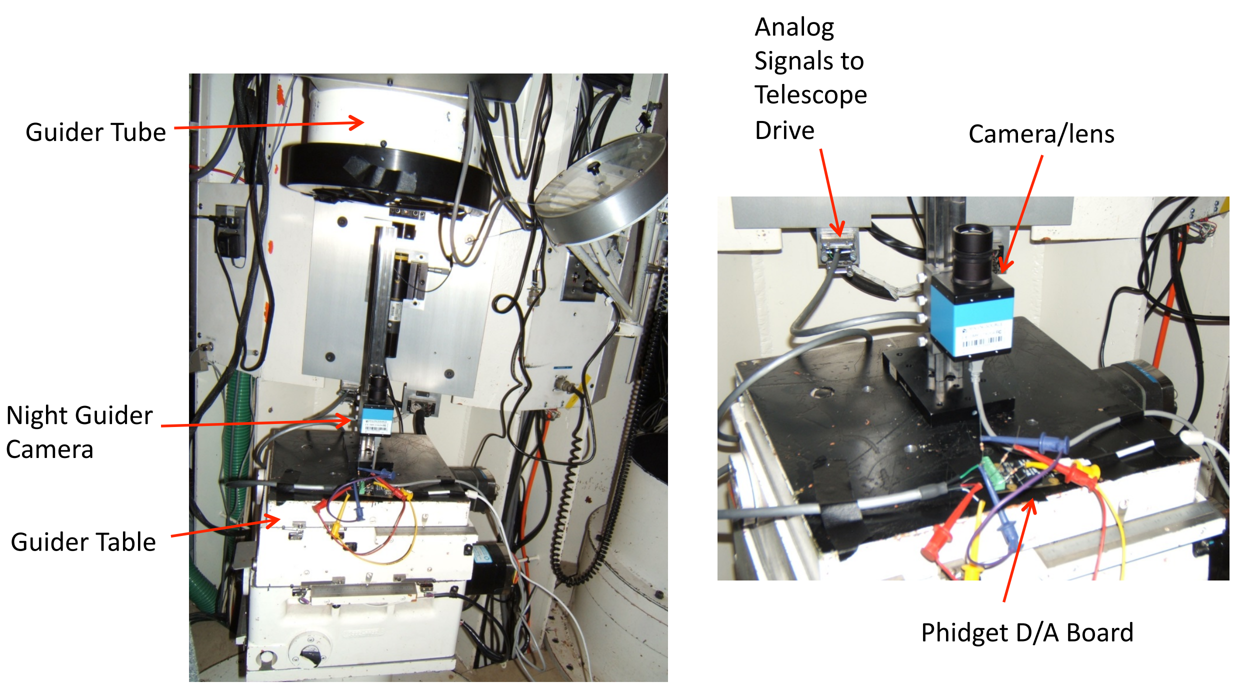
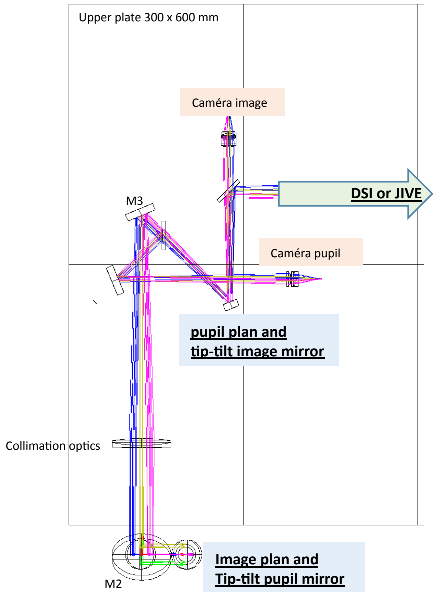


Figure 1: The location and major components of the nighttime guider system at the DST.

Once the tracking system and software were working adequately, the interface optics system was ready to be installed and tested. A schematic optical design is shown in Figure 2. The first component includes a 2-stage pupil control system that stabilizes the pupil with a fast-steering mirror and pupil camera. The pupil image drifts because of some issues with the telescope turret at the level of about 6 pixels, and this corrects for it. There is also an image camera that is rotated at 90 degrees with respect to the pupil camera. We decided to use 2 Prosilica GE680 CCDs for



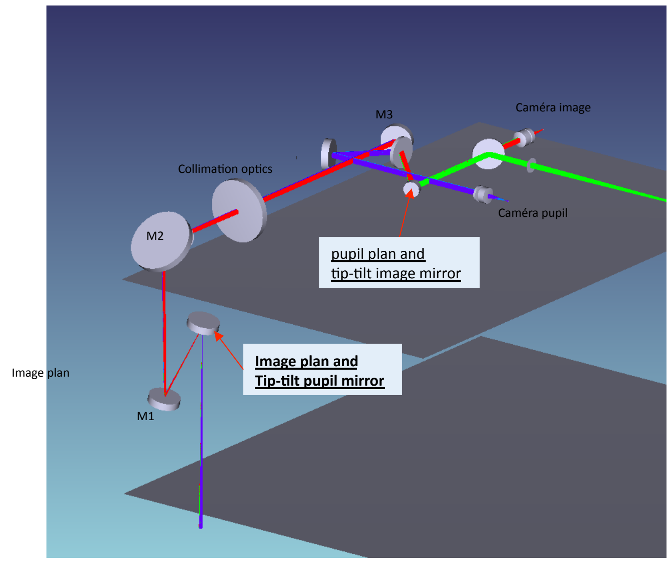


Figure 2: Simple schematic of the optical interface. A top view (left) and side view (right).

this system, as they are very dependable and easy to control.

This interface system was installed at the Dunn Solar Telescope in February 2017. A photograph of the fully assembled interface at the telescope and its graphical interface is shown in Figure 3. Real-time images of Venus are visible on the computer monitor (Jupiter had not risen yet).

2 Theoretical seismic functions for giant-planet oscillation studies

Here we present an abridged derivation of the sensitivity kernels that will be used for inversions of Saturn's mode frequencies. The notation follows that of Fuller (2014). We begin with the eigenequation

$$\mathcal{L}_l(\xi_{n,l}) = \omega_{n,l}^2 \xi_{n,l} \tag{1}$$

where $xi_{n,l}$ is the eigenfunction of a particular mode with radial order n and angular degree l, $\omega_{n,l}$ is the corresponding frequency of that mode and $\mathcal{L}_l$ is the operator acting on the eigenfunction. Solving for the frequency we obtain

$$\omega_{n,l}^2 = \frac{\langle \xi_{n,l} \cdot \mathcal{L}_l(\xi_{n,l}) \rangle}{\langle \xi_{n,l} \cdot \xi_{n,l} \rangle} \tag{2}$$

where the denominator is the inner product of the eigenfunction with itself given by

$$\langle \xi_{n,l} \cdot \xi_{n,l} \rangle = \int dV \rho(r) \xi_{n,l} \cdot \xi_{n,l}^* \tag{3}$$

where the asterisk represents the complex conjugate. Finally, we want to adopt the notation used by Fuller (2014) such that

$$\xi_{n,l} = \vec{\xi}(\vec{r}, t) = \xi_r \hat{r} + \xi_\theta \hat{\theta} + \xi_\phi \hat{\phi} = \xi_r(r) + \xi_h(r, \theta, \phi) \tag{4}$$

$$\xi_r = U(r) Y_{l,m}(\theta, \phi) \tag{5}$$

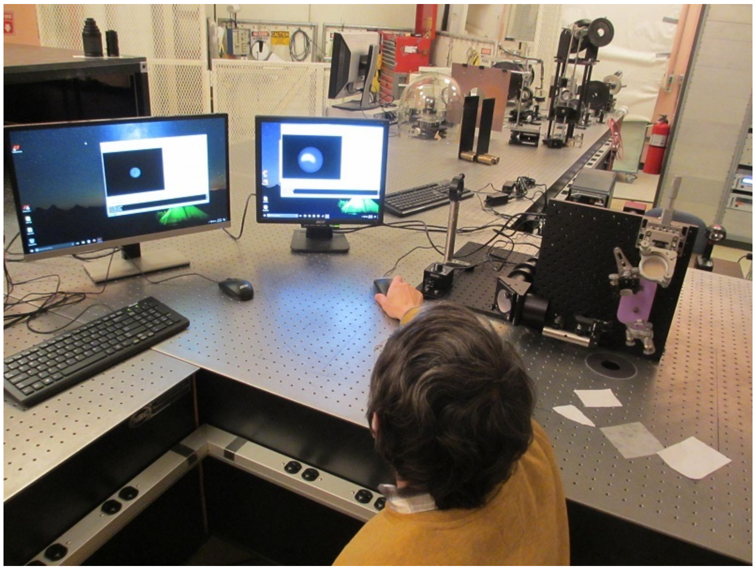


Figure 3: Interface system with black breadboards on the right. This is a side view hiding most of the optics and cameras. The real-time images on the screen are of Venus. The light from the primary mirror on the telescope comes up through the optical table into the optical system shown here.

$$\xi_\theta = V(r)\frac{\partial}{\partial\theta}Y_{l,m}(\theta,\phi) + iW(r)\frac{1}{\sin\theta}\frac{\partial}{\partial\phi}Y_{l+1,m}(\theta,\phi) \tag{6}$$

$$\xi_\phi = V(r)\frac{1}{\sin\theta}\frac{\partial}{\partial\phi}Y_{l,m}(\theta,\phi) - iW(r)\frac{\partial}{\partial\theta}Y_{l+1,m}(\theta,\phi) \tag{7}$$

where $Y_{l,m}(\theta,\phi)$ are the spherical harmonic functions for a given angular degree, l, and azimuthal number, m. $U(r)$, $V(r)$, and $W(r)$ are amplitude functions.

(a) Inner product

First we wish to find the inner product utilizing the above notation. (Let $\rho = \rho(r)$ and $\vec{\xi} = \xi_{n,l}$) Thus we have:

$$\langle \xi_{n,l} \cdot \xi_{n,l} \rangle = \int dV \rho(r) \xi_{n,l} \cdot \xi^*_{n,l}$$

$$= \int_0^R dr \int_{-1}^1 d\cos\theta \int_0^{2\pi} d\phi \rho r^2 \vec{\xi} \cdot \vec{\xi}^*$$

$$= \int_0^R dr \rho r^2 |U(r)|^2 + \int_0^R dr \rho r^2 \int_0^1 d\cos\theta \int_0^{2\pi} d\phi \left(\left| V(r)\frac{\partial Y_{lm}}{\partial\theta} + iW(r)\frac{1}{\sin\theta}\frac{\partial Y_{l+1,m}}{\partial\phi} \right|^2 + \left| V(r)\frac{1}{\sin\theta}\frac{\partial Y_{lm}}{\partial\theta} - iW(r)\frac{\partial Y_{l+1,m}}{\partial\phi} \right|^2 \right)$$

$$= \int_0^R dr \rho r^2 |U(r)|^2 + \int_0^R dr \rho r^2 \int_0^1 d\cos\theta \int_0^{2\pi} d\phi \left(\left| V(r)\frac{\partial Y_{lm}}{\partial\theta} \right|^2 - \left| W(r)\frac{1}{\sin\theta}\frac{\partial Y_{l+1,m}}{\partial\phi} \right|^2 + 2iV(r)W(r)\frac{1}{\sin\theta}\frac{\partial Y_{lm}}{\partial\theta}\frac{\partial Y_{l+1,m}}{\partial\phi} \right.$$
$$\left. + \left| V(r)\frac{1}{\sin\theta}\frac{\partial Y_{lm}}{\partial\phi} \right|^2 - \left| W(r)\frac{\partial Y_{l+1,m}}{\partial\theta} \right|^2 - 2iW(r)V(r)\frac{1}{\sin\theta}\frac{\partial Y_{lm}}{\partial\phi}\frac{\partial Y_{l+1,m}}{\partial\theta} \right)$$

$$= \int_0^R dr\rho r^2 |U(r)|^2 + \int_0^R dr\rho r^2 \int_0^1 d\cos\theta \int_0^{2\pi} d\phi \Bigg(\Big|V(r)\Big|^2 \Big|\frac{\partial Y_{lm}}{\partial\theta}\Big|^2 + \Big|V(r)\Big|^2 \Big|\frac{1}{\sin\theta}\frac{\partial Y_{lm}}{\partial\phi}\Big|^2 - \Big|W(r)\Big|^2 \Big|\frac{\partial Y_{l+1,m}}{\partial\theta}\Big|^2 - \Big|W(r)\Big|^2 \Big|\frac{1}{\sin\theta}\frac{\partial Y_{l+1,m}}{\partial\phi}\Big|^2 \Bigg)$$

$$= \int_0^R dr\rho r^2 |U(r)|^2 + \int_0^R dr\rho r^2 \int_0^1 d\cos\theta \int_0^{2\pi} d\phi \Bigg(\Big|V(r)\Big|^2 \Bigg[\Big|\frac{\partial Y_{lm}}{\partial\theta}\Big|^2 + \Big|\frac{1}{\sin\theta}\frac{\partial Y_{lm}}{\partial\phi}\Big|^2 \Bigg] - \Big|W(r)\Big|^2 \Bigg[\Big|\frac{\partial Y_{l+1,m}}{\partial\theta}\Big|^2 + \Big|\frac{1}{\sin\theta}\frac{\partial Y_{l+1,m}}{\partial\phi}\Big|^2 \Bigg] \Bigg)$$

$$= \int_0^R dr\rho r^2 \Big[|U(r)|^2 + l(l+1)|V(r)|^2 - (l+1)(l+2)|W(r)|^2 \Big]$$

which we define as

$$E_{nl} \equiv \int_0^R dr\rho r^2 \Big[|U(r)|^2 + l(l+1)|V(r)|^2 - (l+1)(l+2)|W(r)|^2 \Big] \quad (8)$$

Several other inner-product calculations are computed that are not shown here.

(b) Kernel Expressions

Once first-order pertubation theory is applied to the structure equations, general kernel expressions for sound speed and density can be expressed in the following form:

$$\frac{\delta\omega_{nl}}{\omega_{nl}} = \int_0^R \left[K_{nl}^{c_s,\rho}(r)\frac{\delta c_s}{c_s}(r) + K_{nl}^{\rho,c_s}(r)\frac{\delta\rho}{\rho}(r) \right] dr. \quad (9)$$

Here, we see how small changes in mode frequencies ($\delta\omega$) are related to small perturbations in sound speed (δc) or density ($\delta\rho$). This relationship is governed by the sensitivity kernels K_{nl}^i, where n and l are radial order and azimuthal degree, respectively.

Our goal now is to plug in the previous derivations to be able to identify the correct expressions for the sensitivity kernels. Combining many of the previous terms, we can show that

$$
\begin{aligned}
2\omega^2 E_{nl}\frac{\delta\omega}{\omega} - 4i\omega\Omega_s\frac{\delta\omega}{\omega}\int_0^R Z_s\rho r^2 dr = &-\omega^2\int_0^R \rho r^2\frac{\delta\rho}{\rho}\left(\tilde{\xi_r}^2 + l(l+1)\tilde{\xi_h}^2\right)dr + \int_0^R \rho r^2\left(2c_s^2 D_1^2\frac{\delta c_s}{c_s} + c_s^2 D_1^2\frac{\delta\rho}{\rho}\right)dr \\
&-\int_0^R \frac{\delta\rho}{\rho}G\rho\tilde{\xi_r}\int_0^r 4\pi r'^2\rho dr'\left[2D_1 + \tilde{\xi_r}\frac{\partial\ln\rho}{\partial r}\right]dr - \int_0^R \frac{\delta\rho}{\rho}4\pi G\rho r^2\left(\int_r^R \rho\tilde{\xi_r}\left[2D_1 + \tilde{\xi_r}\frac{\partial\ln\rho}{\partial r}\right]dr \\
&+\int_0^R \frac{\delta\rho}{\rho}\left(2G\tilde{\xi_r}\rho\frac{\partial\tilde{\xi_r}}{\partial r}\int_0^r 4\pi r'^2\rho dr' + G\tilde{\xi_r}^2\frac{\partial\rho}{\partial r}\int_0^r 4\pi r'^2\rho dr' + 4\pi G\tilde{\xi_r}^2\rho^2 r^2\right)dr \\
&-\frac{4\pi G}{2l+1}\int_0^R \frac{\delta\rho}{\rho}\left((l+1)\rho r^{-l}\left(\tilde{\xi_r} - l\tilde{\xi_h}\right)\int_0^r D_2(r')r'^{l+2}dr'\right)dr \\
&+\frac{4\pi G}{2l+1}\int_0^R \frac{\delta\rho}{\rho}\left(l\rho r^{l+1}\left(\tilde{\xi_r} + (l+1)\tilde{\xi_h}\right)\int_r^R D_2(r')r'^{-l+1}dr'\right)dr \\
&-\frac{16\pi^2 G}{2l+1}\tilde{\xi_r}(R)\rho(R)R^{-l+1}\int_0^R \frac{\delta\rho}{\rho}l\rho r^{l+1}\left(\tilde{\xi_r} + (l+1)\tilde{\xi_h}\right)dr + 4i\omega\Omega_s\int_0^R Z_s\rho\frac{\delta\rho}{\rho}r^2 dr \\
&+\left(4 - 32\pi R^{-2l-1}\right)\left(\pi G\frac{l+1}{(2l+1)^2}\right)\left[\int_0^R \delta D_2(r)r^{l+2}dr\right]\left[\int_0^R D_2(r)r^{l+2}dr\right]
\end{aligned}
$$

Getting a more familiar left-hand-side results in

$$
\begin{aligned}
\frac{\delta\omega}{\omega} = &\left(\omega^2 E_{nl} - 2i\omega\Omega_s\int_0^R Z_s\rho r^2 dr\right)^{-1}\left[-\frac{\omega^2}{2}\int_0^R \rho r^2\frac{\delta\rho}{\rho}\left(\tilde{\xi_r}^2 + l(l+1)\tilde{\xi_h}^2\right)dr + \int_0^R \rho r^2\left(c_s^2 D_1^2\frac{\delta c_s}{c_s} + \frac{1}{2}c_s^2 D_1^2\frac{\delta\rho}{\rho}\right)dr\right. \\
&-\int_0^R \frac{\delta\rho}{\rho}G\rho\tilde{\xi_r}\int_0^r 4\pi r'^2\rho dr'\left[D_1 + \frac{1}{2}\tilde{\xi_r}\frac{\partial\ln\rho}{\partial r}\right]dr - \int_0^R \frac{\delta\rho}{\rho}4\pi G\rho r^2\left(\int_r^R \rho\tilde{\xi_r}\left[D_1 + \frac{1}{2}\tilde{\xi_r}\frac{\partial\ln\rho}{\partial r}\right]dr'\right)dr \\
&+\int_0^R \frac{\delta\rho}{\rho}\left(G\tilde{\xi_r}\rho\frac{\partial\tilde{\xi_r}}{\partial r}\int_0^r 4\pi r'^2\rho dr' + \frac{1}{2}G\tilde{\xi_r}^2\frac{\partial\rho}{\partial r}\int_0^r 4\pi r'^2\rho dr' + 2\pi G\tilde{\xi_r}^2\rho^2 r^2\right)dr \\
&-\frac{2\pi G}{2l+1}\int_0^R \frac{\delta\rho}{\rho}\left((l+1)\rho r^{-l}\left(\tilde{\xi_r} - l\tilde{\xi_h}\right)\int_0^r D_2(r')r'^{l+2}dr'\right)dr \\
&+\frac{2\pi G}{2l+1}\int_0^R \frac{\delta\rho}{\rho}\left(l\rho r^{l+1}\left(\tilde{\xi_r} + (l+1)\tilde{\xi_h}\right)\int_r^R D_2(r')r'^{-l+1}dr'\right)dr \\
&-\frac{8\pi^2 G}{2l+1}\tilde{\xi_r}(R)\rho(R)R^{-l+1}\int_0^R \frac{\delta\rho}{\rho}l\rho r^{l+1}\left(\tilde{\xi_r} + (l+1)\tilde{\xi_h}\right)dr + 2i\omega\Omega_s\int_0^R Z_s\rho\frac{\delta\rho}{\rho}r^2 dr \\
&\left.+\left(2 - 16\pi R^{-2l-1}\right)\left(\pi G\frac{l+1}{(2l+1)^2}\right)\left[\int_0^R \delta D_2(r)r^{l+2}dr\right]\left[\int_0^R D_2(r)r^{l+2}dr\right]\right]
\end{aligned}
$$

After much burdensome but mostly trivial rearrangement and substitution, we can arrive at a final perturbation equation in the desired form from which it is straightforward to identify the form of the kernels. The one for sound speed is:

$$K_{nl}^{c_s,\rho}(r) = \left(\omega^2 E_{nl} - 2i\omega\Omega_s \int_0^R Z_s \rho r^2 dr\right)^{-1} \rho r^2 c_s^2 D_1^2 \tag{10}$$

and the kernel for density is:

$$\begin{aligned}
K_{nl}^{\rho,c_s}(r) = \left(\omega^2 E_{nl} - 2i\omega\Omega_s \int_0^R Z_s \rho r^2 dr\right)^{-1} \rho r^2 \Bigg[&-\frac{\omega^2}{2}\left(\tilde{\xi_r}^2 + l(l+1)\tilde{\xi_h}^2\right) + \frac{1}{2}c_s^2 D_1^2 \\
&+ \frac{2Gm}{r^3}\tilde{\xi_r}\left[\tilde{\xi_r}\left(\frac{\pi\rho r^3}{m} - 1\right) + \frac{1}{2}l(l+1)\tilde{\xi_h}\right] \\
&- 4\pi G \int_r^R \rho\tilde{\xi_r}\left[D_1 + \frac{1}{2}\tilde{\xi_r}\frac{\partial \ln\rho}{\partial r}\right] dr' \\
&- \frac{2\pi G}{2l+1}(l+1)r^{-l-2}\left(\tilde{\xi_r} - l\tilde{\xi_h}\right)\left(\int_0^r D_2(r') r'^{l+2} dr'\right) \\
&+ \frac{2\pi G}{2l+1} l r^{l-1}\left(\tilde{\xi_r} + (l+1)\tilde{\xi_h}\right)\left(\int_r^R D_2(r') r'^{-l+1} dr'\right) \\
&- \frac{8\pi^2 G}{2l+1}\rho(R)\tilde{\xi_r}(R)\left(\frac{r}{R}\right)^{l-1} l\left(\tilde{\xi_r} + (l+1)\tilde{\xi_h}\right) + 2i\omega\Omega_s Z_s \Bigg]
\end{aligned}$$

where the Z_s term is

$$Z_s \equiv \int_0^1 d\cos\theta \int_0^{2\pi} d\phi \left(\sin\theta\left|\xi_r\right|^2 - \cos\theta\left|\xi_\theta\right|^2 + (\cos\theta - \sin\theta)\left|\xi_\phi\right|^2\right). \tag{11}$$

This is the first time such a derivation has been carried out for rapidly rotating giant planets. Such functions will be applied in seismic inversions to Saturn and then, once JIVE data are available, Jupiter.

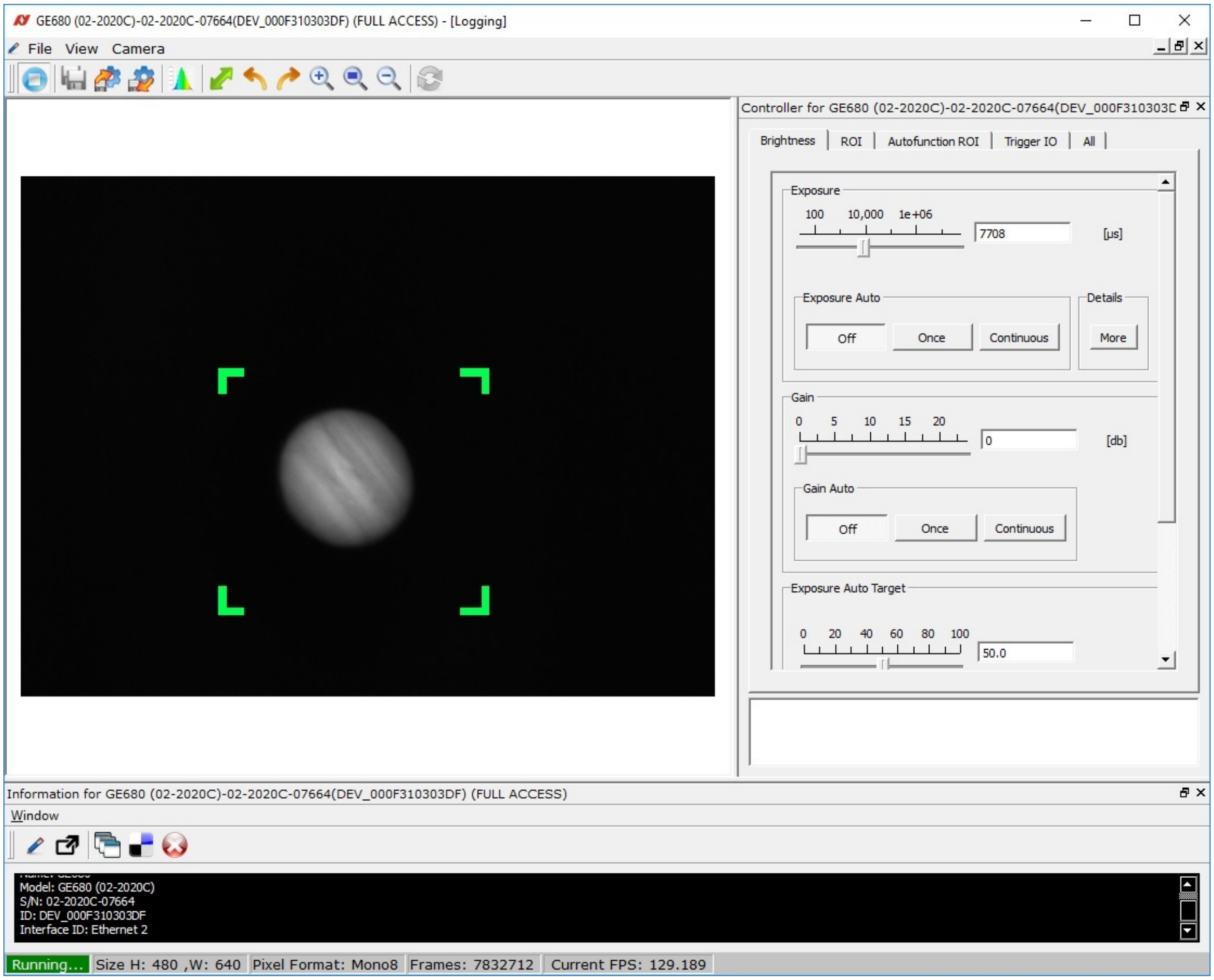


Figure 4: A unique snapshot of Jupiter captured by a solar telescope. A large collection of such images will be used in this project to measure Jupiter's pulsations for the first time.

D NASA EPSCoR Stimulus Article

Measurements of oscillations of Jupiter have eluded astronomers for over 40 years. While they are routinely observed on the Sun, this giant planet requires sensitive, optimized instrumentation. New Mexico State University is leading an international team of researchers in the Jovian Interiors from Velocimetry Experiment (JIVE) in New Mexico, a ground-based instrument and part of a global network that will decisively measure oscillations on Jupiter for the first time. Its results will allow for us to peer inside the planet understand its interior structure and composition.

Initial instrument development and installation is complete at the Dunn Solar Telescope in Sunspot, NM, operated by the National Solar Observatory. The photo shows a real-time snapshot of Jupiter captured by a CCD camera connected to a novel optical interface at the solar telescope. One sees a centered, rather clear image of the planet, with atmospheric clouds and features very prominent. A large collection of images such as these will be obtained and analyzed in the coming year to find those all-important oscillations.

E Education Office Supporting Information

See accompanying spreadsheet.

1 List of Participants

- Patricia Hynes - New Mexico State University (director) - PI
- Jason Jackiewicz - New Mexico State University (faculty) - Science PI, management, seismic inversions
- David Voelz - New Mexico State University (faculty) - Instrument PI, optics
- Patrick Gaulme - New Mexico State University (researcher) - data reduction, seismology
- Bob Hull - New Mexico State University (researcher) - lab technician, software
- Thomas Underwood - New Mexico State University (graduate student) - software
- Ethan Dederick - New Mexico State University (graduate student) - oscillation theory, modeling
- Christopher Trujillo - New Mexico State University (undergraduate student) - instrument testing and documentation
- Raul Morales-Juberias - New Mexico Tech (faculty) - atmospheric winds
- Richard Cosentino - New Mexico Tech (researcher) - atmospheric winds
- Perianne Johnson - New Mexico Tech (undergradute student) - atmospheric winds
- Jim Fuller - Cal Tech (postdoc) - mode physics, internal rotation
- Didier Saumon - Los Alamos National Lab (researcher) - internal structure
- Mark Marley - NASA Ames (researcher) - internal structure, seismology
- Amy Simon - NASA Goddard Space Flight Center (researcher) - atmosphere
- Neil Murphy - NASA Jet Propulsion Lab (researcher) - instrumentation, observations
- Francois Xavier-Schmider - Nice Observatory (researcher) - PI of JOVIAL, data analysis
- Yves Bresson - Nice Observatory (engineer) - Optical design
- Julien Delonghe - Nice Observatory (engineer) - Mechanical design
- Tristan Guillot - Nice Observatory (researcher) - Science PI of JOVIAL, internal structure, planet formation theory
- Ivan Goncalvez - University of Nice (PhD student) - data reduction, atmospheric dynamics

2 Systemic Jurisdiction Improvements

Nothing to report.

3 List of Products, Publications, & Recognitions

(a) Publications

- "A Possible Mechanism for Driving Oscillations in Hot Giant Planets," Ethan Dederick and Jason Jackiewicz. *The Astrophysical Journal*, Volume 837, Issue 2, article id. 148, 7 pp.

(2017).
http://adsabs.harvard.edu/abs/2017ApJ...837..148D

- “The effect of Jupiter oscillations on Juno gravity measurements,” Durante, Daniele; Guillot, Tristan; Iess, Luciano. *Icarus*, Volume 282, p. 174-182 (2017).
http://adsabs.harvard.edu/abs/2017Icar..282..174D
- “A Distant Mirror: Solar Oscillations Observed on Neptune by the Kepler K2 Mission,” Gaulme, P.; Rowe, J. F.; Bedding, T. R.; Benomar, O.; Corsaro, E.; Davies, G. R.; Hale, S. J.; Howe, R.; Garcia, R. A.; Huber, D.; Jimnez, A.; Mathur, S.; Mosser, B.; Appourchaux, T.; Boumier, P.; Jackiewicz, J.; Leibacher, J.; Schmider, F.-X.; Hammel, H. B.; Lissauer, J. J.; Marley, M. S.; Simon, A. A.; Chaplin, W. J.; Elsworth, Y.; Guzik, J. A.; Murphy, N.; Silva Aguirre, V. *The Astrophysical Journal Letters*, Volume 833, Issue 1, article id. L13, 7 pp. (2016).
http://adsabs.harvard.edu/abs/2016ApJ...833L..13G
- “Advances in the development of a Mach-Zehnder interferometric Doppler imager for seismology of giant planets,” Gonalves, Ivan; Schmider, Franois-Xavier; Bresson, Yves; Dejonghe, Julien; Preis, Olivier; Robbe-Dubois, Sylvie; Appourchaux, Thierry; Boumier, Patrick; Leclec’h, Jean-Christophe; Morinaud, Gilles; Gaulme, Patrick; Jackiewicz, Jason. *Proceedings of the SPIE*, Volume 9908, id. 99083M 10 pp. (2016).
http://adsabs.harvard.edu/abs/2016SPIE.9908E..3MG
- “Longitudinal Variability in Jupiter’s Zonal Winds Derived from Multi-Wavelength HST Observations,” Perianne Johnson, Raul Morales-Juberias, Amy Simon, Patrick Gaulme, Michael H. Wong, Richard Cosentino. Submitted to *Planetary and Space Science*, (2017).
- Manuscript (to be submitted): “Jupiter atmospheric dynamics with visible imaging spectroscopy,” Ivan Goncalvez, Patrick Gaulme, F.X. Schmider.
- Manuscript (to be submitted): “Moist Convection Resonance with Jovian Oscillations,” Ethan Dederick, Jason Jackiewicz, Tristan Guillot.

(b) Conferences

- (Talk): “K2 observations of Neptune,” Patrick Gaulme. Joint TASC2 & KASC9 Workshop SPACEINN & HELAS8 Conference, (2016). http://www.iastro.pt/research/conferences/spacetk16/abstractDetails.html?abs=24

(c) Recognition/awards

Nothing to report.

(d) Websites

- http://astronomy.nmsu.edu/JIVE/ - JIVE homepage
- https://www-n.oca.eu/jovial2016/Kick-off_Avril2016/index.html - Information on the JOVIAL project