An Observational Test of Doppler's Theory Using Solar-System Objects

John "Jack" D. Wilenchik
Phoenix, Arizona, USA. E-mail: wilenchik1@me.com

The scientific community widely accepted Christian Doppler's theory that light Doppler-shifts, even though it was proposed without empirical evidence and never tested on objects with well-known velocities like solar-system planets and moons. I conducted a test of Doppler's theory on a handful of planets and moons (Venus, Ganymede, Europa, and Ceres) using high-resolution data from the Keck Observatory's High Resolution Echelle Spectrometer (HIRES). In doing so, I was careful not to apply the automatic Doppler (heliocentric) corrections for movement of the earth that are normally applied when reducing such data. After comparing the observed shifts to actual velocities given by the NASA/JPL Horizons ephemeris system, I found both observations that agreed and disagreed with their Doppler-predicted values, which is an indication for more expansive tests. I also identified a significant problem with the Doppler explanation for "inclined" spectral lines, which can be found in the spectra of Jupiter and Saturn.

1 Introduction

This year is the 180th anniversary of Christian Doppler's hypothesis that colors of light shift due to movement by the source or observer [4]. Doppler's original paper describing his hypothesis was purely theoretical, and it reached conclusions that were quickly recognized as erroneous in their own time. For example, Doppler suggested that the actual color of every star was white or yellow, and that the stars' apparent colors (red, blue, etc.) were due solely to their radial velocities with respect to the earth [4, §5].* Nevertheless, the last sentence of his original paper proved to be prophetic: in "[t]he distant future," he wrote, his theory would "offer astronomers a welcome means of determining the motions and distances" of distant stars and other objects whose velocities are otherwise "immeasurable." [4, §11].

The instruments of the 19th Century lacked the resolution needed to test Doppler's theory on celestial objects with known velocities, like solar-system planets and moons [8]. As astronomer William Huggins wrote in 1868: "[t]he great relative velocity of light to the known planetary velocities, and to the probable motions of the few stars of which the parallax is known, showed that any alternations of position which might be expected from [Doppler shift] in the lines of the stellar spectra would not exceed a fraction of the interval between the double line D [sodium doublet line D], for that part of the spectrum." [8, p. 530]. "I have devoted much time," Huggins continued, "[and] I hope to accomplish the detection of so small an amount of change... [but] [t]he difficulties of this investigation I have found to be very great..." [*Id.*]. The first astronomer(s) to apply Doppler's theory therefore focused on targets whose velocities could not be rigorously and independently measured, like distant stars and nebulae or gases on the solar surface [7, 8].

But a modern spectrometer like the Keck Observatory's "High Resolution Echelle Spectrometer" (HIRES) is more than capable of performing the "William Huggins Test". I report the results of a test of Doppler's theory on solar-system planets and moons using the shift in their D lines, much like William Huggins intended.

2 Methodology

I searched the Keck Observatory Archive (KOA)† for solar-system data from the HIRES, particularly planets and moons with low axial rotation [11] ‡. The HIRES has a precision on the order of meters per second and has been heavily used in searches for exoplanets; accordingly, its archives contain comparatively few observations of solar-system objects [2,3]. A handful of observations were used: two observations of Venus in 2007 and 2009, one of Ganymede in 2009, one of Europa in 2009, and one of the dwarf planet Ceres in 2005. The data for various observations of Mercury were also considered, but the signal-to-noise ratio was deemed to be too low (and airmass too high) to be included in this exploratory

*In 1868, astronomer William Huggins described Doppler's error as "obvious": "Doppler endeavored...to account for the remarkable differences of colour which some of the binary stars present, and for some other phenomena of heavenly bodies. That Doppler was not correct in making this application of his theory is obvious from the consideration that even if a star could be conceived to be moving with a velocity sufficient to alter its colour sensibly to the eye, still no change of colour would be perceived, for the reason that beyond the visible spectrum, at both extremities, there exists a store of invisible waves which would be at the same time exalted or degraded into visibility, to take the place of the waves which had been raised or lowered in refrangibility by the star's motion. No change of colour, therefore, could take place until the whole of those invisible waves of force had been expended, which would only be the case when the relative motion of the source of light and the observer was several times greater than that of light." [8, p. 530-31].

†The Keck archive can be accessed from //koa.ipac.caltech.edu/cgi-bin/KOA/nph-KOAlogin . The particular datasets used herein are identified in Appendix "A."

‡Rates of rotation were calculated from [1]; or in the case of Venus, also from [6] (indicating that Venus' atmosphere rotates sixty times faster than its surface).

study.

The KOA offers data that has already been reduced and extracted by the Keck Observatory "MAKEE" pipeline ("M-Auna Kea Echelle Ex-traction"). However, that pipeline normally applies a "heliocentric correction" of up to around ±30 km/s, which is designed to account for the putative Doppler effect of movement of the earth at the time of observation. MAKEE can be run manually with heliocentric corrections turned "off"; and so I downloaded the same raw science and calibration data that was used to generate the extracted data in the archives, then I re-extracted it using MAKEE without heliocentric corrections. Because I made no effort to account for the effect of the bodies' (or the earth's) axial rotations on Doppler shift, I treated it as a source of error in their calculated radial velocity (see E_{calc} in Table 1). The speed of axial rotation for each object in this study was between ±0.01 and 0.15 km/s, and earth's rotation was estimated at 0.5 km/s, so E_{calc} was never greater than ±0.52 km/s. Putative relativistic effects were calculated to be less than 0.01 km/s and therefore neglected. Finally, the measured Doppler shift in the D lines was compared to radial velocity as given by the NASA/JPL Horizons ephemeris system. More details on methodology are included in Appendix "A."

3 Results

Figure 1 shows plots of the measured and calculated Doppler shifts. While the Sodium absorption lines in Venus' and Ceres' atmospheres appeared at or near their Doppler-predicted positions, the lines in Ganymede and Europa did not. The mean absolute difference (weighted by error) in between measured (Doppler) and calculated (JPL Horizons) velocity for Ganymede and Europa was 9.24 ± 0.72 km/s. These results are also shown in Table 1.

Space-based (Hubble) spectroscopy confirms Na D absorption lines in the atmospheres of both Ganymede and Europa*, which tends to discount telluric interference as a cause for the discrepancy. Its magnitude (9.24 km/s) would also tend to discount atmospheric winds and other internal dynamics.

The discrepancy is less if the lines are compared to the Doppler-predicted shift in solar light reflecting from the body, which is given by:

$$R_{reflect} = R_{helio} + R_{calc} + \frac{R_{helio} R_{calc}}{c} \tag{1}$$

(where R_{helio} is the object's heliocentric velocity, R_{calc} is its geocentric velocity, and c is the speed of light *in vacuo*)†. However, the bodies' spectra do not show separate lines for reflected light (albedo) and light originating from the object, as Doppler's theory would predict.

*See Observation ID "o51u02040" (Ganymede) and "od91l40m0" (Europa) in the ESA Hubble Science Archive, http://hst.esac.esa.int/ehst/.

†For a derivation of this equation, please see Appendix "B."

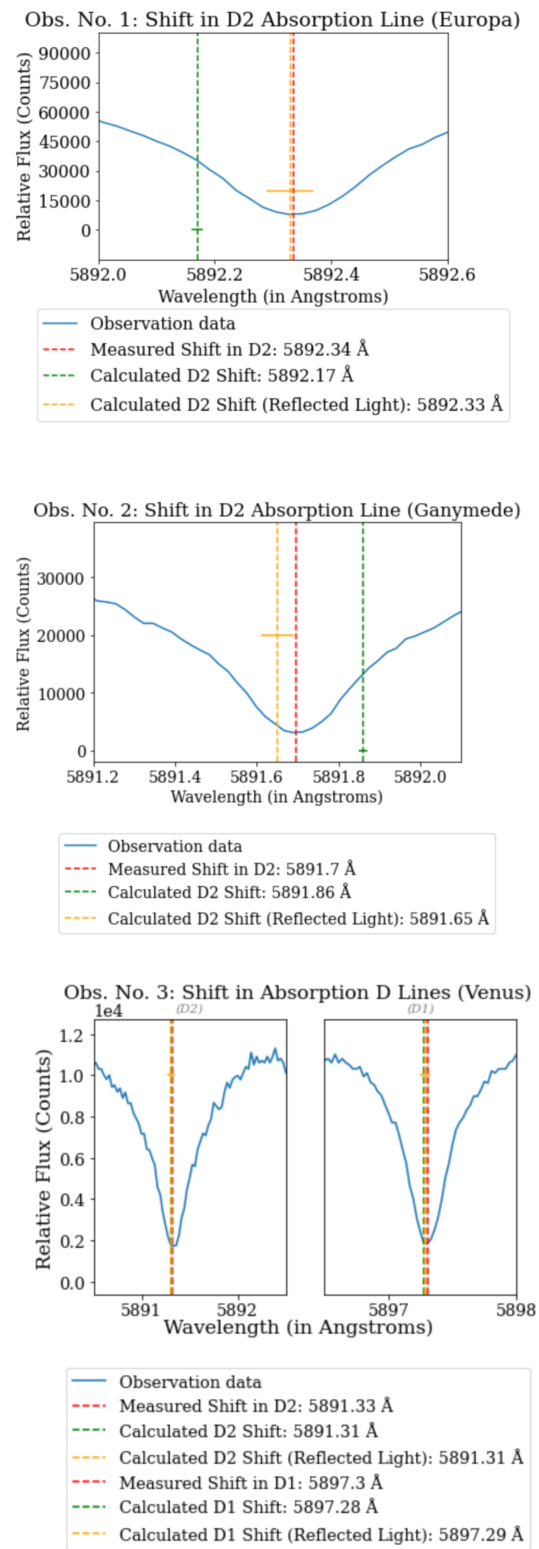

Fig. 1: Plots of the shifts in the D lines (actual and predicted) for the five observations. Error is thinner than the lines, except for the yellow lines (the predicted shifts in albedo), which had more significant error due to the calculated rotation of the sun. (*See also* Table 1.)

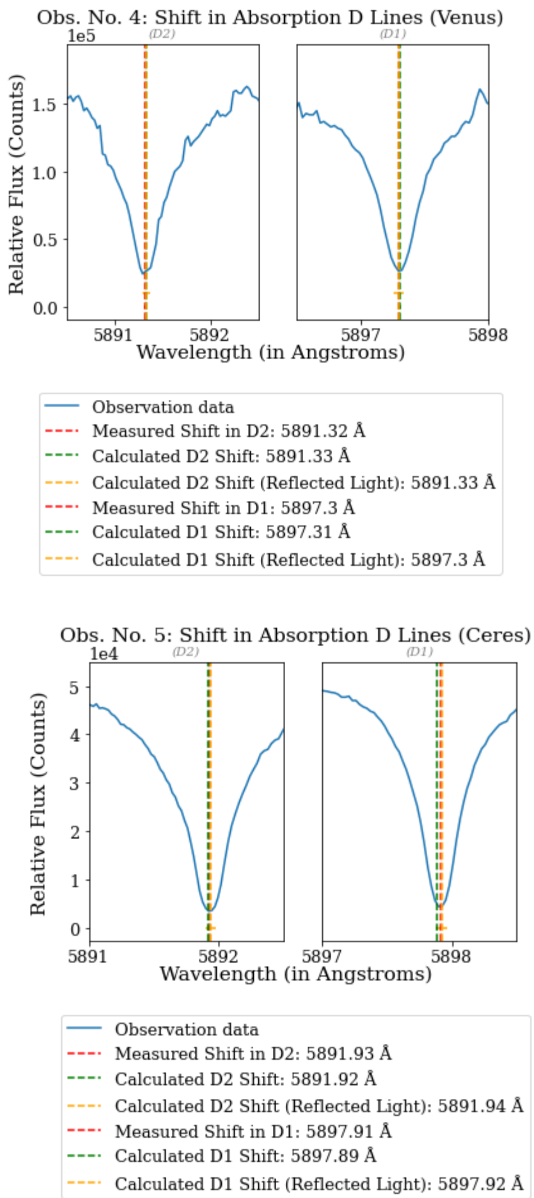

Fig. 1 (cont.)

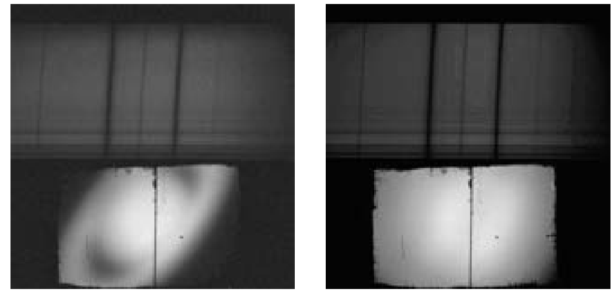

Fig. 2: At top left is an image of the spectrum of Saturn taken on June 25, 2018. Below it is the corresponding camera image of Saturn, which demonstrates the placement of the spectroscopic slit across the face of the planet. At top right is a spectrum of Jupiter taken on June 25, 2018, and below it is the corresponding camera image, which again demonstrates placement of the slit. The linear inclination in both planets' spectra is apparent. (Data source: [10], observations nos. 224 and 225.).

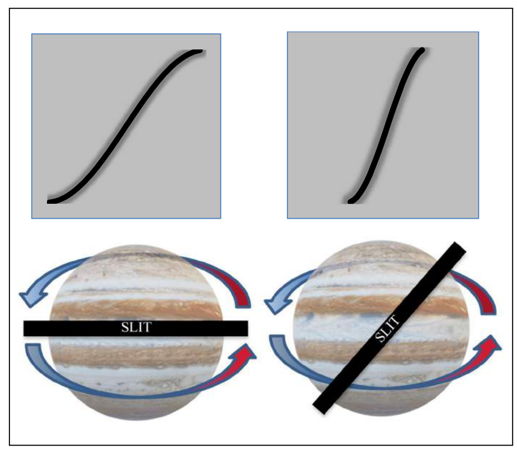

Fig. 3: At top (in gray) are illustrations of the expected sinusoidal pattern of spectral lines that are Doppler-shifted by the rotation of a spherical body. At bottom is shown the corresponding placement of a theoretical spectroscopic "slit" on the planet's surface.

3.1 Concerns with the Doppler modeling of planetary spectral line inclinations

The spectra of Jupiter and Saturn are known to be "tilted", or to exhibit a linear inclination (Figure 2). Historically, the cause of this inclination was deemed to be Doppler shift due to each planet's rotation about its own axis [5, 9]. However, the radial velocities of points across a spherical rotating body should exhibit a curved, sinusoidal pattern (Figure 3). The observed "tilt" is always linear, which suggests a cause other than Doppler shift.

4 Conclusion

Christian Doppler's theory that light Doppler-shifts was accepted and widely applied without an observational test on solar-system planets and moons, due to historical limitations on the resolution of available spectrometers. This "Huggins Test" used a small sample of modern high-resolution spectroscopic observations but nevertheless turned up observations that were inconsistent with their Doppler-predicted values. Further, there is substantial doubt concerning whether the inclined spectral lines of bodies like Jupiter and Saturn can be reasonably explained as a Doppler effect caused by their axial rotation. These results support conducting more expansive tests of the Doppler theory, using modern high-resolution spectroscopy on solar-system objects with well-known velocities.

Disclosures

No outside funding was received to assist with the preparation of this article, and the author declares no conflicts of interest.

Supplemental Documents

A Python script that will reproduce my data reduction and analysis is available on Zenodo, (doi:10.5281/zenodo.6240436) as "Doppler_Test.py". [11].

Data Availability

The data underlying the results presented in this paper are fully contained on Zenodo [11]. They are also available from their original sources on the Keck Observatory Archive, https://www2.keck.hawaii.edu/koa/public/koa.php.

Acknowledgments

This research made use of the Keck Observatory Archive - (KOA), which is operated by the W. M. Keck Observatory and the NASA Exoplanet Science Institute (NExScI), under contract with the National Aeronautics and Space Administration. Profound thanks go to Dr. Zach Cano for his invaluable advice and assistance, as well as to Dr. Francisco Pina, Dr. Rafael Brahm and Dr. Christina Thöne.

Received on August 11, 2022

References

1. Cox A. Allen's Astrophysical Quantities, 4th Ed. Springer, 1999.
2. Vogt S., Allen S., Bigelow B., Bresee L., Brown B., Cantrall T., Conrad A., Couture M., Delaney C., Epps H., Hilyard D., Horn E., Jern N., Kanto D., Keane M., Kibrick R., Lewis J., Osborne J., Pardeilhan G., Pfister T., Ricketts T., Robinson L., Stover R., Tucker D., Ward J. & Wei M. HIRES: the high resolution echelle spectrometer on the Keck 10-m telescope. *Proc. SPIE* 2198, Instrumentation in Astronomy VIII, 1994. doi:10.1117/12.176725.
3. Butler R., Vogt S., Laughlin G., Burt J., Rivera E., Tuomi M., Teske J., Arriagada P., Diaz M., Holden B. & Keiser S. The LCES HIRES/Keck Precision Radial Velocity Exoplanet Survey. *AJ*, 2017, v. 153, 5. doi:10.3847/1538-3881/aa66ca.
4. Doppler C. Über das farbige Licht der Doppelsterne (Concerning the Coloured Light of Double Stars). *Royal Bohemian Society Of Sciences*, 1842. https://bit.ly/3qpUJpc.
5. Giver L. Line Inclinations in Equatorial Spectra of Jupiter and Saturn. *Astrophysical Journal*, 1964, v. 139, 727. doi:10.1086/147798.
6. Horinouchi T., Hayashi Y., Watanabe S., Yamada M., Yamazaki A., Kouyama T., Taguchi M., Fukuhara T., Takagi M., Ogohara K., Murakami S., Peralta J., Limaye S., Imamura T., Nakamura M., Sato T. & Satoh T. How waves and turbulence maintain the super-rotation of Venus' atmosphere. *Science*, 2020, v. 368, 405–409. doi:10.1126/science.aaz4439.
7. Huggins W. VII. Further observations on the spectra of the sun, and of some of the stars and nebulæ, with an attempt to determine therefrom whether these bodies are moving towards or from the earth. *Proc. R. Soc. London Ser. I*, 1868a, v. 16, 382–386. doi:10.1098/rspl.1867.0080.
8. Huggins W. XXI. Further observations on the spectra of some the stars and nebulæ, with an attempt to determine therefrom whether these bodies are moving towards or from the earth, also observations on the spectra of the sun and of comet II. *Phil. Trans. R. Soc. London, Ser. I*, 1868b, 158, p. 529–565. doi:10.1098/rstl.1868.0022.
9. Moore J. Spectroscopic Observations of the Rotation of Saturn. *Publications Of The Astronomical Society Of The Pacific*, 1939, v. 51, 274. doi:10.1086/125081.
10. Schmidt C. Rapid Imaging Planetary Spectrograph: 2018 Mercury Exosphere Data [Dataset, version 1]. *Zenodo*, 2019. doi:10.5281/zenodo.3588493.
11. Wilenchik J. An Observational Test of Doppler's Theory Using Solar System Objects [Dataset, version 2]. *Zenodo*, 2022. doi:10.5281/zenodo.6240436.

Appendix "A"

Version 6.4 of "MAKEE" was used to extract and reduce the Keck Archive data. The version of MAKEE that was used is dated May 2019 and available for download from: https://sites.astro.caltech.edu/~tb/makee/makee_6.4-2019.tar.gz.

MAKEE was run in a command terminal using Ubuntu 20.04.3 LTS. The MAKEE pipeline requires at least four "FITS" (Flexible Image Transport System) images to reduce and calibrate data: an image of the object; an image to find the "trace" of the echelle orders (which can simply be the image itself, although a star is often used); flat image(s); and an image of the arc lamp for wavelength calibration. Each image in the Keck Observatory Archive (KOA) is assigned a unique "KOAID." The KOAID for each of the raw science and calibration images used in this paper (as well as the CCD and orders extracted) are listed in Table 2.

To remove the heliocentric correction, MAKEE was run using the "-nohc" option. The "-koa" option was also used, which outputs the processed data into ".tbl" files. Finally, in order to run MAKEE, the user must specify a CCD number to be extracted (using the "ccd=*" argument). The final command for processing each observation was "makee [Object.fits] [Trace.fits] [Flat.fits] [Arc.fits] ccd = [CCD No.] -nohc -koa." An optional "log=*.txt" argument sends the command-line output into a "*.txt" file.

After running MAKEE, the region of the Sodium D lines (5890 – 5900 Å) was identified in the extracted orders. The wavelength, flux and error spectrum in the region of the D line(s) was then manually extracted into a ".csv" file (which is contained in the Zenodo depository and named "*_full.csv" for each observation). In Observations No. 1 and 2 (Europa and Ganymede), the D1 line fell beyond the extracted orders, and so only the D2 lines were used. The D lines in Observation No. 5 fell across two different orders; and so the data in Order #7 was used for the D1 line and part of the D2 line, with the remaining data for the D2 line coming from Order #6. Postscript images of the orders for all extractions can be found in the "logs" folder on Zenodo, along with the MAKEE command-line output logs.

Table 1: Summary of Observation Data and Results. (All velocities in km/s.)

Observation No.	**1**	**2**	**3**	**4**	**5**
Target Name	Europa	Ganymede	Venus	Venus	Ceres
Epoch (UT)	12/13/09 4:56	12/11/09 4:53	6/6/07 5:32	1/7/09 4:33	6/17/05 5:54
Exposure (sec)	30	20	500	500	300
Keck Image ID	HI.20091213.17797	HI.20091211.17597	HI.20070606.19972	HI.20090107.16390	HI.20050617.21254
R_{calc}	+30.05	+14.29	-14.04	-12.78	+16.89
E_{calc}	±0.51	±0.51	±0.52	±0.52	±0.51
$R_{Doppler}$	+40.34	+6.09	-13.62	-13.88	+18.25
$E_{Doppler}$	±0.03	±0.05	±0.17	±0.36	±0.48
$\Delta_{Doppler}$	+10.29	-9.20	+0.42	-1.10	+1.36
$E_{\Delta Doppler}$	±0.51	±0.51	±0.55	±0.63	±0.70
R_{helio}	+7.83	-10.91	+0.23	-0.23	+1.43
E_{helio}	±1.99	±1.99	±2.00	±2.00	±1.99
$R_{reflect}$	+37.82	+3.38	-13.81	-13.01	+18.32
$E_{reflect}$	±2.05	±2.05	±2.07	±2.07	±2.05
$\Delta_{reflect}$	+2.52	+2.71	+0.19	-0.87	-0.07
$E_{\Delta reflect}$	±2.05	±2.05	±2.07	±2.10	±2.11
A	1.52	1.47	1.72	1.76	1.25

Legend

R_{calc} = the target object's calculated geocentric velocity at the date and time of observation, from the NASA/JPL Horizons ephemeris system.

E_{calc} = uncertainty in the target's calculated geocentric velocity, due to axial rotation of the earth and target body.

$R_{Doppler}$ = Doppler-measured radial velocity.

$E_{Doppler}$ = uncertainty in the Doppler-measured radial velocity (see Appendix "A" for methodology).

$\Delta_{Doppler}$ = $(R_{Doppler} - R_{calc})$, i.e. the discrepancy in between Doppler-measured velocity ($R_{Doppler}$) and Horizons-calculated velocity (R_{calc}).

$E_{\Delta Doppler}$ = uncertainty in $\Delta_{Doppler}$, i.e. $\sqrt{(E_{calc})^2 + (E_{Doppler})^2}$.

R_{helio} = target object's calculated heliocentric velocity, based on the NASA/JPL Horizons ephemeris system.

E_{helio} = error in the object's heliocentric velocity due to rotation of the sun and target (which were combined in quadrature). Solar rotation was estimated at $]pm1.99$ km/s (based on values from [1]. I used a solar equatorial circumference of 2.720984 million miles, then divided by a rotation period of 26.24 days, to obtain a rotational velocity at the solar equator of 1992.86 m/s.)

$R_{reflect}$ = predicted Doppler shift of solar light reflecting from the target, given by $(R_{calc} + R_{helio})$.

$E_{reflect}$ = error in $R_{reflect}$, i.e. $\sqrt{(E_{calc})^2 + (E_{helio})^2}$.

$\Delta_{reflect}$ = $R_{Doppler} - R_{reflect}$, i.e. the difference in between Doppler-measured velocity ($R_{Doppler}$) and predicted Doppler shift in solar light reflecting form the target ($R_{reflect}$).

$E_{\Delta reflect}$ = uncertainty in $\Delta_{reflect}$, i.e. $\sqrt{(E_{helio})^2 + (E_{Doppler})^2 + (E_{calc})^2}$.

A = averaged airmass (as reported in the image's FITS header).

Table 2: Keck Observatory Archive Datasets

Observation No.	1 (Europa)	2 (Ganymede)	3 (Venus)	4 (Venus)	5 (Ceres)
Object KOIAD	HI.20091213.17797	HI.20091211.17597	HI.20070606.19972	HI.20090107.16390	HI.20050617.21254
Trace (star) ID	HI.20091213.08389	HI.20091211.10571	HI.20070607.01296	HI.20090107.16390	HI.20050616.06005
Flat KOAID	HI.20091213.13363	HI.20091211.13478	HI.20070606.17769	HI.20090107.15456	HI.20050617.19496
Arc KOAID	HI.20091213.10643	HI.20091211.12272	HI.20070606.16831	HI.20090107.01375	HI.20050617.11120
CCD	3	3	2	2	2
Order(s)	11	11	13	13	6,7

To calculate the parameters for a Gaussian fit to each of the Sodium D lines, the "curve_fit" function in Python's SciPy package was used ("SciPy: Scientific Library for Python" version 1.7.3). The error spectrum in the MAKEE-generated data tables (column #7, "Error") was input as "sigma" in the "curve_fit" routine. This produced parameters for the best-fit Gaussian function for each D line, as well as an estimated covariance. The standard deviation in the Gaussian centerline was calculated from the covariance; and this standard deviation was used for error in the measured Doppler shift of each D line. Finally, for those observations in which both D lines could be detected, an average of the two shifts was calculated (weighted by error) to reach a final Doppler shift; and the errors in the shift of each D line were combined in quadrature to reach final error values.

Final shifts were recorded as $R_{Doppler}$ in Table 1, and final errors were recorded as $E_{Doppler}$. The Python code used for these calculations is included in the "Zenodo" depository (as "Doppler_Test.py"), and when run it will reproduce the data analysis and figures used in this paper. Python version 3.9.7 was used.

Appendix "B"

The equation for finding the predicted Doppler shift in solar spectra that are being reflected from a target under observation from the earth ($R_{reflect}$), and expressed in terms of velocity (km/s), is:

$$R_{reflect} = R_{helio} + R_{calc} + \frac{R_{helio} R_{calc}}{c} \tag{2}$$

where R_{helio} is the target's heliocentric velocity, R_{calc} is its geocentric velocity, and c is the speed of light *in vacuo*. To derive this equation, we start with the general Doppler equation for wavelength as a function of radial velocity, which represents the initial Doppler-shifted wavelength of solar light reaching the target (λ_{helio}):

$$\lambda_{helio} = \frac{R_{helio}}{c}\,\lambda_0 + \lambda_0 \tag{3}$$

where λ_0 the target's wavelength at rest. To determine the final observed wavelength after light reflects from the target ($\lambda_{observed}$), we must apply a second Doppler shift to account for the target's geocentric velocity:

$$\lambda_{observed} = \frac{R_{calc}}{c}\,\lambda_{helio} + \lambda_{helio} \tag{4}$$

$$\lambda_{observed} = \lambda_{helio}\left(\frac{R_{calc}}{c} + 1\right). \tag{5}$$

Finally, in order to express the observed wavelength as a shift in velocity ($R_{reflect}$), and as a function of the target's heliocentric and geocentric velocities, we must again use the Doppler equation (this time solved for radial velocity) and make the proper substitutions for $\lambda_{observed}$ and λ_{helio}:

$$R_{reflect} = \left(\frac{\lambda_{observed} - \lambda_0}{\lambda_0}\right) c \tag{6}$$

$$R_{reflect} = \left(\frac{\lambda_{helio}\left(\frac{R_{calc}}{c} + 1\right) - \lambda_0}{\lambda_0}\right) c \tag{7}$$

$$R_{reflect} = \left(\frac{\left(\frac{R_{helio}\,\lambda_0}{c} + \lambda_0\right)\left(\frac{R_{calc}}{c} + 1\right) - \lambda_0}{\lambda_0}\right) c \tag{8}$$

$$R_{reflect} = \left(\frac{R_{helio}}{c} + 1\right)(R_{calc} + c) - c \tag{9}$$

$$R_{reflect} = R_{helio} + R_{calc} + \frac{R_{helio} R_{calc}}{c}. \tag{10}$$