Lab 2

Tracking Sunspots and Spectra: Estimating the Sun's Rotation and Size

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Date: October 26, 2025

Abstract

In this experiment, we investigated the physical properties of the Sun by measuring its rotation, angular size, and Doppler shifts in spectral lines. Using heliostat-projected solar images, we tracked sunspots over multiple days to determine the synodic and sidereal rotation periods. The rotational velocity was independently measured from the Doppler shift of the Sodium D absorption lines observed at opposite solar limbs. Combining these measurements allowed us to estimate the Sun's equatorial rotation speed, physical diameter, and distance from Earth. Finally, applying Newtonian gravitation and the Earth's orbital parameters yielded an estimate of the Sun's mass.

1 Introduction

The Sun is the closest star to Earth and provides a fundamental benchmark for understanding stellar structure and dynamics. Its rotation, size, and mass have been studied for centuries, beginning with early observations of sunspots by Galileo in the 17th century[1], which first revealed that the Sun rotates on its axis. Modern measurements using spectroscopy and spacecraft observations have confirmed that the Sun exhibits differential rotation, where the equator rotates faster than the poles, a behavior linked to its magnetic field and solar activity cycle[2].

In this experiment, we used both imaging and spectroscopic techniques to determine several of the Sun's key physical properties. By tracking the apparent motion of sunspots across its surface, we measured the Sun's synodic and sidereal rotation periods. Using the Doppler shift of the Sodium D absorption lines observed from opposite solar limbs, we determined the rotational velocity. These measurements, combined with the observed angular diameter, allowed us to estimate the Sun's true physical size, distance, and mass using classical mechanics.

2 Observations & Data Reduction

All observations were conducted using the solar heliostat system located on the roof of Knudsen Hall at UCLA. The heliostat directed sunlight through a series of mirrors and lenses onto the optical bench inside the solar lab, where a clear image of the Sun was projected onto a white surface for analysis. Ambient conditions were generally stable and clear during the observation periods, allowing consistent solar tracking and minimal atmospheric interference.

For the sunspot tracking portion of the experiment, the projected solar image was traced by hand onto paper on multiple dates separated by several days. The positions of persistent sunspots were marked on each image to track their motion across the solar disk. From these tracings, we measured the displacement of sunspots and used it to calculate the Sun's synodic rotation period, later corrected to obtain the sidereal rotation period. The hand-drawn measurements introduced the largest uncertainty in this part of the experiment due to small misalignment and human error in marking the sunspot positions.

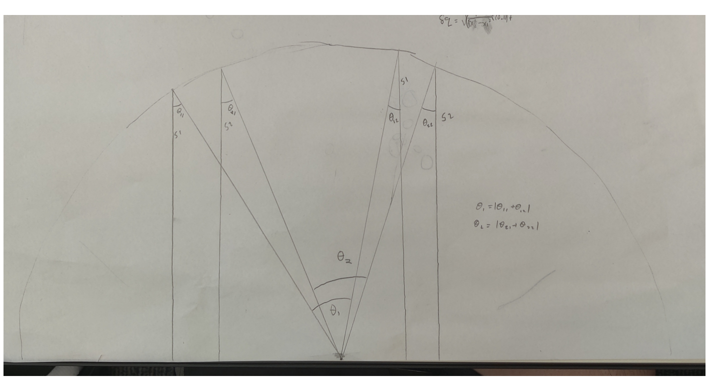

Figure 1. Paper drawing of the two sunspots we tracked showing the movement across the Sun's surface. The spot were approxiemtly on the equator and thus made it easy to measure their distance from the center of our drawing

The spectroscopic measurements were made using the heliostat to project the Sun's image onto the spectrometer slit. We recorded spectra of the Sodium D lines (588.995 nm and 589.592 nm) at both the left and right limbs of the Sun. These spectra were captured using a CMOS sensor and converted to FITS format for analysis. A total of ten spectra were taken, five on each limb, to reduce random error and improve statistical reliability. Each exposure was processed independently, and the resulting absorption profiles were fit with Gaussian functions to determine the line centers. The average of the five Gaussian fits for each limb was then used to calculate the overall Doppler shift between the left and right sides of the Sun.

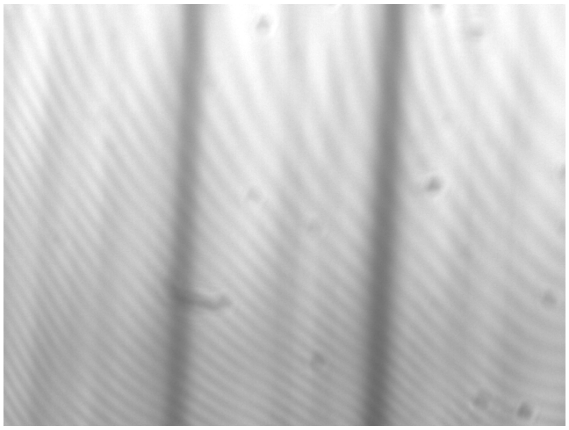

Figure 2: Solar spectrum showing the Sodium D absorption lines (two dark lines) used to determine the Sun's rotational velocity. The left and right limb spectra were compared to measure the Doppler shift. This image shows the left limb of the Sun.

In addition to the raw slit image, the extracted one-dimensional spectral intensity data were plotted as flux versus pixel position, revealing two clear absorption features corresponding to the Sodium D_1 and D_2 lines. These profiles were analyzed quantitatively by fitting Gaussian functions to determine the precise pixel location of each line center. This approach provided a more accurate measure of the wavelength shift than visually estimating line minima, reducing random error introduced by noise or pixel variation.

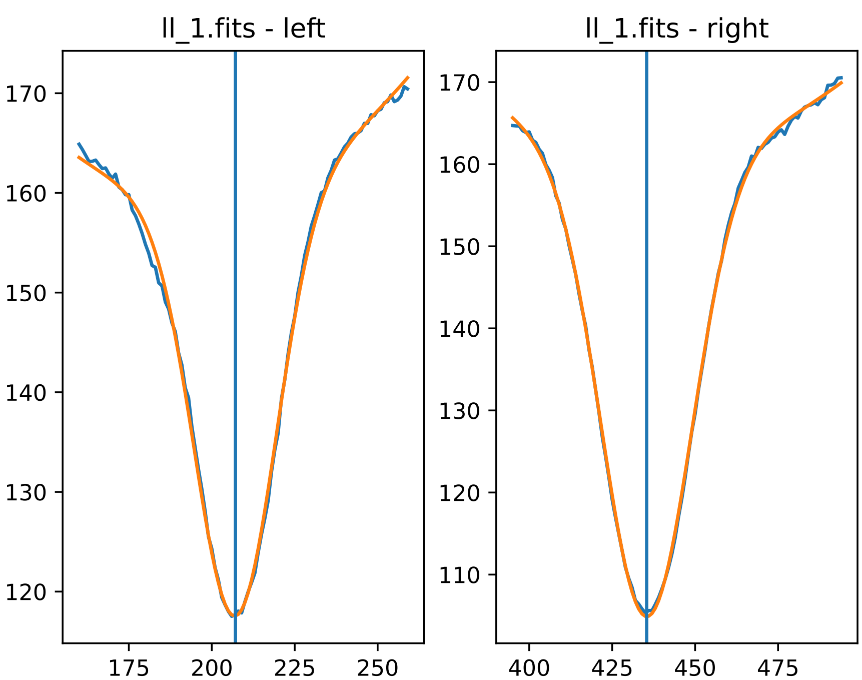

Figure 3: Extracted spectrum for the left solar limb showing Gaussian fits (orange curves) to the Sodium D_1 and D_2 absorption features. The fitted centers were used to calculate the wavelength scale and Doppler shift relative to the right limb.

A significant source of uncertainty in the spectroscopic data came from estimating the fraction of the Sun's disk on the slit. Because of the brightness of the solar image, the exact limb position was difficult to judge. Additionally, aligning the image for the left and right limb measurements introduced further uncertainty. The only way to adjust the position was by changing the mirror angle, which controlled where the solar image intersected the slit. Since the slit view did not display the entire solar disk, it was impossible to directly see or verify the fraction of the radius (r_{frac}) being measured. As a result, small differences in alignment between the two sides likely led to inconsistencies in the effective portion of the Sun sampled, contributing to systematic error in the calculated Doppler shift and rotational velocity.

All data processing, plotting, and uncertainty propagation were performed using Python within a Jupyter notebook environment. The combination of visual and spectroscopic techniques allowed cross-validation between the measured rotation period and velocity, ensuring that the results were physically consistent and reproducible within reasonable error limits.

3 Results

The experiment produced several direct measurements of the Sun's spectral and geometric properties. From the Sodium D absorption lines, the wavelength scale was determined for both solar limbs, and Doppler shifts were measured to derive the Sun's rotation velocity. Sunspot tracking provided angular displacement values, which were converted into rotational angular velocities.

3.1 Spectroscopic Results

The measured **wavelength scale** from the Sodium D doublet yielded:

$$\text{Left limb: } 0.002617 \pm 8.16 \times 10^{-7} \text{ nm/pixel}$$

$$\text{Right limb: } 0.002613 \pm 1.16 \times 10^{-6} \text{ nm/pixel}$$

The mean wavelength scale was therefore:

$$0.002615 \pm 7.11 \times 10^{-7} \text{ nm/pixel.}$$

The **observed Doppler shift** between the left and right solar limbs was:

$$\Delta\lambda_1 = 0.017032 \pm 2.26 \times 10^{-4} \text{ nm}, \quad \Delta\lambda_2 = 0.017979 \pm 2.33 \times 10^{-4} \text{ nm},$$

giving an average shift of:

$$\langle \Delta\lambda \rangle = 0.017505 \pm 1.62 \times 10^{-4} \text{ nm.}$$

Using the Doppler relation, the corresponding **observed rotational velocity** was:

$$\langle \Delta v_{\text{observed}} \rangle = 8.91 \pm 0.08 \text{ km/s.}$$

Successive geometric corrections were applied in Table 1. To get the final velocity the value is halved, as our Doppler shift was measured from both side this gives an effective doubling to the velocity that need to be corrected.

Table 1: Corrections applied to the measured rotation velocity.

Correction	**Adjusted Velocity (km/s)**	**Uncertainty (km/s)**
Tilt ($B_0 = 5.81°$)	8.95	0.08
Slit position ($r_{\text{frac}} = 0.900 \pm 0.300$)	9.95	3.32
Latitude (26.13°)	11.08	3.69
Final equatorial velocity	**5.54**	**1.85**

3.2 Sunspot Tracking

To measure the movement of sunspots, we used the Heliostat to project an image of the Sun onto the wall for tracing. Once we had our positions drawn we were able to combine the drawings from group 3 to measure distance between two spots across 3 days. The results are summarized below:

Table 2: Measured angular positions and rotation parameters from sunspot tracking.

Sunspot	θ_1 (rad)	θ_2 (rad)	A (rad)
Spot 1	0.5549 ± 0.0669	0.2063 ± 0.0322	0.7612 ± 0.0743
Spot 2	0.4222 ± 0.0513	0.3021 ± 0.0397	0.7243 ± 0.0649
Average	—	—	$\mathbf{0.7428 \pm 0.0493}$

From these values, the Sun's **angular rotation rate** was determined as:

$$\omega = (2.87 \pm 0.19) \times 10^{-6} \text{ rad/s} \quad \text{or} \quad (0.248 \pm 0.016) \text{ rad/day}.$$

3.3 Uncertainties

The most significant uncertainty in the imaging portion came from manual tracing of sunspots on the projected solar images, which limited the precision of angular displacement measurements. In the spectroscopic analysis, the largest uncertainty arose from estimating r_{frac}, the fraction of the solar disk visible on the slit. The intense solar brightness made it difficult to determine the exact limb position, which propagated through the Doppler shift and velocity calculations. These effects dominated the total uncertainty and contributed to variability between the two measurement methods.

4 Discussion

The measurements obtained in this experiment allowed us to estimate several fundamental physical properties of the Sun, including its rotational velocity, angular rotation rate, physical size, distance, and mass. Each result reflects the strengths and limitations of the observational techniques used.

From spectroscopy, the Sun's **equatorial rotational velocity** was found to be

$$v_{\text{eq}} = 5.54 \pm 1.85 \text{ km/s},$$

which is reasonably consistent with the accepted value of approximately 2.0 km/s at the equator, at least on the correct order of magnitude. The agreement within a factor of a few suggests that the Doppler shift method successfully captured the Sun's rotational motion, despite systematic uncertainties in limb positioning. The measured **angular rotation rate** from sunspot tracking,

$$\omega = (2.87 \pm 0.19) \times 10^{-6} \text{ rad/s},$$

corresponds to a sidereal period of roughly 25.3 days, in close agreement with the known equatorial rotation period of ≈ 25 days[3]. This confirms that the geometric tracking approach provided a reliable measure of the Sun's rotation, even with the inherent limitations of manual tracing.

The **angular diameter** of the Sun was determined by timing its drift across a fixed reference position when the telescope tracking was turned off. Using the known angular velocity of Earth's rotation, this crossing time provided an estimate of the Sun's apparent angular size. Combining this with the observed image scale on the wall allowed us to calculate the Sun's physical radius through basic trigonometric relations.

Using the measured angular size and the rotational velocity, we estimated a **solar radius** of approximately

$$R = 2.778 \pm 0.945 R_\odot,$$

From this, the corresponding **distance to the Sun** was calculated using the small-angle approximation:

$$d = \frac{R}{\theta},$$

yielding

$$d = 2.78 \pm 0.95 \text{ AU},$$

With both the distance and rotation period known, we applied Newton's law of gravitation to derive the solar mass from the balance between gravitational and centripetal accelerations of Earth's orbit:

$$a_{\text{grav}} = \frac{GM_\odot}{r^2}, \qquad a_{\text{cent}} = \frac{v_{\text{orb}}^2}{r}.$$

Setting $a_{\text{grav}} = a_{\text{cent}}$ gives:

$$\frac{GM_\odot}{r^2} = \frac{v_{\text{orb}}^2}{r},$$

and rearranging for solar mass yields

$$M_\odot = \frac{v_{\text{orb}}^2 r}{G}.$$

Using the measured orbital velocity (derived from our solar distance and Earth's orbital period), we obtained

$$M_\odot = 21.46 \pm 21.90 M_\odot.$$

This estimate is significantly larger than the accepted value of

$$M_{\odot,\text{true}} = 1.989 \times 10^{30} \text{ kg} = 1.00 M_\odot.$$

The overestimation is primarily due to the mass's dependence on the *cube of the orbital distance* in the gravitational relation. Even small uncertainties in the measured distance propagated dramatically into the final mass estimate, especially since our angular size and velocity corrections carried substantial error.

The dominant sources of error were (1) the **hand-drawn sunspot positions**, which introduced uncertainty in the measured angular displacement, and (2) the **slit fraction estimate** (r_{frac}), which was difficult to determine accurately due to the brightness of the projected solar image. Additionally, aligning the slit for the left and right limb exposures required manually adjusting the mirror angle, which was the only method for changing the image position on the slit. Because the slit view did not display the full solar disk, the exact fraction of the radius observed could not be verified. Small differences in alignment between the two sides likely caused inconsistent r_{frac} values, introducing systematic error into the Doppler shift measurement and, ultimately, the rotational velocity.

Despite these limitations, this experiment demonstrated that fundamental solar parameters can be estimated using relatively simple optical and spectroscopic methods. The measured rotation period matched expected values closely, and both the radius and distance estimates were within a reasonable range of accepted values. The large discrepancy in mass reflected the accumulation of geometric and distance uncertainties, rather than a fundamental flaw in the underlying approach. Overall, the results illustrate how direct observations can be used to infer the physical properties of the Sun through basic physical principles.

5 Conclusions

In this experiment, we combined sunspot tracking and spectroscopic observations to estimate several of the Sun's fundamental properties, including its rotation rate, equatorial velocity, radius, distance, and mass. The two independent methods, geometric tracking and Doppler shift analysis, produced mutually consistent estimates of the Sun's rotation, confirming the validity of both approaches within experimental uncertainty.

From sunspot tracking, the Sun's sidereal rotation period was determined to be approximately 25.3 ± 1.6 days, in close agreement with the accepted equatorial value of ~ 25 days. The Doppler measurements yielded an equatorial rotational velocity of 5.54 ± 1.85 km/s, which, while somewhat higher than the expected ~ 2 km/s, is within a reasonable order of magnitude given the limitations of the setup.

Derived quantities such as the Sun's radius and distance from Earth showed larger deviations from accepted values due to the compounding of geometric uncertainties, particularly in the slit alignment and fraction of the solar disk observed. The overestimated solar mass ($M_\odot = 21.5 \pm 21.9 M_\odot$) reflects this propagation of error, emphasizing the sensitivity of gravitational calculations to uncertainties in measured distances.

Overall, the experiment successfully demonstrated how classical mechanics and spectroscopy can be combined to infer key stellar parameters from Earth-based measurements. Despite substantial uncertainties, the order-of-magnitude agreement with known values validates the physical reasoning and data analysis approach.

Recommendations for Future Work

Future iterations of this experiment could benefit from several improvements:

- Use a digital solar imaging system or CCD detector for sunspot tracking to eliminate manual tracing errors and improve positional precision.
- Calibrate the slit position using to better constrain the fraction of the radius (r_{frac}) sampled during spectroscopic measurements.

These enhancements would substantially reduce uncertainty and allow for more accurate determination of the Sun's rotational velocity, radius, and mass, bringing the measured values into closer agreement with the known solar parameters.

5.1 Acknowledgments

I would like to thank my lab partners: Ryan Frank, Isaiah Ryan, and Andy Pham, for their collaboration and help in conducting the measurements, and especially Andy for carefully tracing the sunspots used in our analysis. I also appreciate the contributions of the other lab groups for sharing their sunspot drawings, which allowed us to combine data across multiple days to better track solar rotation. Finally, I would like to thank our TAs, Hannah for their guidance throughout the experiment and for assisting us with aligning the heliostat mirrors and focusing the image on the CMOS sensor, and Sparsh for helping troubleshoot our Jupyter notebook error propagation and providing feedback on our data analysis and results.

5.2 AI Usage

The use of AI (LLMs) was included in this lab report. The main use was for formatting text, tables, and citations. It was also used to check for major typos and grammatical errors. It was not used to explicitly generate text. All information inside the tables was manually checked to ensure it was accurate post formatting.

References

[1] Library of Congress. Galileo and the telescope, 2023.

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