KYA 320/321

THIRD-YEAR PHYSICS LABORATORY

Individual experiment:
Solar Spectroscopy

Lab Procedure

The Solar Calcium Abundance

Contents

Editors: Andrew A. Cole (2010-2026); Robert D. Watson (August 1998).

Caution: This lab requires working at heights (2.8 metres), outdoor work, and work in reduced lighting conditions. One of the calibration lamps when unfiltered can produce light in the ultraviolet spectrum. You will be using a mirror to reflect the light of the Sun; take care to avoid shining sunlight directly into your eyes or those of your lab partner. Read the accompanying safety manual and be familiar with the emergency procedures and evacuation routes before you begin.

Introduction

In this experiment a heliostat, or sun-tracking mirror, is used to feed a spectrograph. The resulting solar spectrum, obtained for the whole visual region ($380 \text{ nm} \le \lambda \le 700 \text{ nm}$), is studied in order to identify the strongest absorption lines. The spectrum will be recorded on film or a digital camera, and the wavelength scale is calibrated using a mercury-cadmium discharge tube as a comparison source. A quantitative analysis of the spectrum in the far-violet ($390 \text{ nm} \le \lambda \le 400 \text{ nm}$) is undertaken to estimate the abundance of calcium in the Sun. If sunspots are present, they can be used to determine the rotation period of the Sun for bonus marks. **This document assumes you have read the background material and completed the prelab questions prior to attempting to take or analyse data.**

Here, you will use an approximate method to obtain an estimate of the calcium abundance relative to hydrogen, under the assumption that the line is extremely strong and formed in local thermodynamic equilibrium (LTE). A complete understanding of the abundances of chemical elements in the Sun is still being actively pursued by astrophysicists, with emphasis on the details of non-equilibrium radiative transfer, turbulent mixing, and the temperature dependence of certain nuclear reaction rates. An excellent review of the subject and current best estimates for the abundances of ~80 different elements can be found in Asplund, Grevesse & Sauval (2006).

Since 2010, this lab has used a digital camera to record the spectra, and the images have been converted into a typical format used for image processing and data analysis by physicists and astronomers. Computational facilities will be provided for taking your data from camera to analysed spectra by one specific path, but if you have strong programming skills you may wish to develop your own procedure. Creativity in science is rewarded! You may find it necessary to ask a staff member for help with this step. Just make sure you carefully document your procedure so that someone reading your report could repeat your analysis to verify your results. **Read the entire experiment booklet before starting, to make sure you understand all the steps and the order in which to perform them.**

Aims:

The aims of this experiment are to:

1. Gain experience operating a spectrograph and analysing spectral data.
2. Identify strong photospheric absorption lines in the solar spectrum.
3. Calculate the abundance of calcium in the solar atmosphere.
4. (*Bonus*) determine the rotation rate of the Sun.

Principal Data Taken: Raw data collected in the form of digital photographs of the solar spectrum covering the entire visible wavelength range, and calibration photographs of a cadmium arc lamp spectrum. Numerical data derived from processed images will be the functional dependence of of *relative* intensity on wavelength for a bandpass of about 1 nm surrounding one of the Ca II lines. Absolute intensities (e.g., in W m^{-2} sec^{-1} nm^{-1}) will not be measured because no calibration procedure can be done within the time constraints for the apparatus used. From the measured line profile, the calcium abundance in the Sun can be derived. (*Bonus*) Record the position of sunspots as a function of date and time, to allow derivation of the Sun's rotation rate.

Spectrograph Setup:

Access to the roof and the optics lab is by staff permission only. Arrange a time when the lab manager or appropriate staff member can give you a tour of the heliostat (roof) and spectrograph (room 140) and walk you through the procedure of acquiring and tracking the Sun so a stable image is produced. This process will require you to work with a partner, as the heliostat mirrors cannot be reliably positioned to the necessary accuracy by remote control. Access to the roof requires a master key to the physics building, so a staff member will need to open the roof access door for you. When an image of the Sun is formed on the projection screen, adjust the collimator, diffraction grating, and "camera" mirror to produce an image of the solar spectrum on the target. A manual for the heliostat and spectrograph can be found in Appendix A. It is this image (a *spectrogram*) that you will photograph with the digital camera and analyse to measure the Solar calcium abundance. Prelab question 1 should have convinced you that it will be safe to look at and measure the projected solar image here.

Tip: The lab can be done through breaks in the clouds on a partly cloudy day, so don't wait for absolutely perfect weather; the semester will end sooner than you think!

Procedure (Observations):

When you and your partner are comfortable with the mechanical operation of the heliostat, get an image of the Sun and project its spectrum onto the target. Set up the digital camera as close to perpendicular to the target as possible, to minimise distortions in the final spectrogram. You may need to turn off the room lights in order to make the autofocus function work correctly; you can also try manually adjusting the focus. Slightly out-of-focus images can be acceptable, with some loss of accuracy, but badly out-of-focus images will make your analysis far more difficult or impossible. For wavelength calibration purposes, take a cadmium calibration arc spectrum as soon as possible after (or before) taking your solar spectrum, to make sure that none of the components are moved between your calibration and target observations.

Tip: Make sure the camera is taking images at its highest resolution and in RAW mode. Normally a commercial camera does a fair amount of image processing and compression "on-the-fly" before storing the data. While this is artistically useful, it destroys the scientific value of the image: what we want is a faithful image in which increasing intensity is linearly represented by increasing pixel values ("counts", *cts*, or "data number", DN) in the image.

Tip: You will need to manually adjust the camera settings including effective ISO (equivalent film sensitivity) and f/stop (aperture size). Holding those two factors constant, experiment with different shutter speeds (exposure times). In general, you will want the fastest sensitivity (highest ISO number) and largest apertures (lowest f/#). Exposure times of a few to a few tens of seconds may be needed.

It is critically important that you be able to measure the Ca^+ lines at ≈395 nm. Depending on your vision, you may not be able to see these clearly (the cutoff of perception at the violet end of the spectrum varies quite a bit from person to person), but the camera will detect them. Turn the room lights off and let your eyes adapt to the darkness to give yourself the best chance, otherwise you may have to repeat the experiment. You will need to use at least 4 different photos in your analysis, requiring adjustments of the spectrograph between each. You will need to use your 2 best exposures of the Sun's spectrum, and the 2 corresponding arc lamp, calibration exposures. Don't move the camera between exposures of the Sun and the arc lamp, or the calibration will be inaccurate.

1. Adjust the "camera" mirror of the spectrograph until the violet end of the spectrum is visible and you can measure the Ca^+ lines. Making sure the digital camera is in focus, photograph the solar spectrum. Take as many exposures as you need! Data storage is cheap. You will often be able to tell if you got what you need by using the zoom feature on the camera display to check the lines. You should be able to see many, many lines in the solar spectrum; a table of the strongest lines and their wavelengths is given in Appendix B. The violet continuum and lines may not be easily visible- leave yourself a fair amount of what appears to be empty dark space in your spectrum to make sure you get the required Ca^+ lines.

2. Without making any adjustments to the spectrograph, put the Hg-Cd arc lamp in front of the projection screen and create a spectrum of the emission lines of mercury-cadmium vapour on the target. You may need to have your partner move the lamp back or forth in order to produce the best quality image. Photograph the arc lamp spectrum. The lines from the arc lamp will be used to dispersion-correct and wavelength-calibrate your spectrum: the wavelength is a function of position along the detector, but it may not be a linear one, because of the properties of the grating and the positioning of the digital camera. The wavelengths of mercury and cadmium lines are known, so you can determine the functional dependence of wavelength on position, $\lambda = f(x)$ for pixel number x. A table of wavelengths of mercury and cadmium lines is given in Appendix C. **Caution**: Mercury has a strong resonance line at 253.7 nm and several other prominent UV lines, e.g., at 365 nm. Light of these wavelengths can be hazardous if the eye or bare skin is irradiated. While the lamp power is low, you will be working in dark conditions and your pupil will be dilated to become more sensitive. To avoid unnecessary exposure to the UV lines from the calibration lamp, a clear glass filter that strongly absorbs light below ~395 nm is mounted on the front of the Hg-Cd calibration lamp. This will not impact your wavelength calibration, because the shortest wavelength line you will be able to use, for practical purposes will be around 405 nm.

3. Turn off the calibration lamp and re-establish the solar spectrum. Adjust the "camera" mirror of the spectrograph (<u>not</u> the digital camera) so you can see the red end of the spectrum. There should be some overlap in the green region. Again, you may need to turn off the room lights and let your eyes adapt to be able to see the extreme red part of the spectrum. Photograph the red part of the spectrum.

4. Repeat the arc lamp calibration procedure for the red part of the spectrum. **The red calibration lamp uses neon rather than mercury-cadmium.** Neon does not emit significantly in the UV and therefore this lamp doesn't have a filter. You will need to swap the lamps over since they share a single power supply.

Procedure (Image Processing):

Prior to 2010, the spectra were recorded photographically on film, to be developed and scanned by a photodensitometer. This was tricky, time-consuming, and had the disadvantage that you couldn't see the results over your experiment until many hours later, so you wouldn't know if you got things right in real-time. Since 2010, a digital camera has been used to record the spectra.

We suspect that many people will wish to download the spectrograms from the camera to their own computers and process them in their own time using their own favourite software. This is encouraged, but *the full details of the procedure must be given in the report,* so that the reader will know how to reproduce your results (and to identify whether any errors in your results are the fault of software bugs, or student blunders). A typical procedure is given here, but if you have a superior/quicker/easier way of achieving the same results, don't feel forced to follow the script to the letter. Alternatively, if your computer access is limited, see the staff member in charge, who can assist you to process the data on a machine with all the needed software ready to go.

1. Transfer the images from the camera to your computer.

2. Convert the RAW images to a format more easily digestible by image processing software. RAW format images are proprietary to the make of camera used, and can be difficult to analyse directly for that reason. One freely available software package is called DCRaw; a download site can be found using your favourite search engine. Whatever software you use, make sure you set the options so that the conversion is *linear* (i.e., preserves relative intensity), and does not stretch or rotate the pixels. It may be tempting to convert to 16-bit format, but 8-bit images contain sufficient information and are probably going to be easier to manipulate. GIMP (The GNU Image Manipulation Program) and/or Photoshop may also prove useful.

3. Whatever method you use, you want to end up with something in which you can accurately measure the pixel values afterward. Astronomical convention uses the Flexible Image Transport System (FITS, file extension .fits) and there are fits viewers such as SAOimage "DS9" available for free. Most viewers will display pixel values for you, and it is these values that constitute your relative intensity measurements. If you want to do more complex image manipulation with a great deal of control over the algorithms, talk to your lab demonstrator about the possibilities. For instance, you can average over a large number of pixels which all have the same wavelength to improve the precision of your measurement. As

mentioned above, display and image manipulation assistance is available—we won't do the lab for you, but if you have an idea and are not sure how to implement it, ask.

Procedure (Line Measurements):

1. Use the table in the Appendix to identify strong lines in both the red and the blue part of the spectrum to get an approximate wavelength solution (visual identification).

2. Use an exposure from the mercury-cadmium vapour lamp to derive a *dispersion solution*: the function that allows you to convert pixel coordinates (e.g., 1—1024) into wavelength coordinates (e.g., 395—700 nm). This will prove easiest in the blue/green through red end of the spectrum because that is where there are more cadmium lines; feel free to use the wavelengths of other strong lines in your solar spectrum to constraint the violet end of things if necessary, using the cadmium as a reference.

3. The calcium "K" line is the more useful of the two violet Ca II ines for the abundance analysis. Find the centre of the K line as accurately as possible, and measure the intensity at that wavelength. Measure the intensity at as many different wavelengths as possible around the line centre. This will depend on the signal-to-noise ratio of your spectrum, but it should be possible to get reasonable measurements out to at least ±0.8 nm on either side of the intensity minimum.

4. The absolute wavelength is not as critical as the difference in wavelength $\Delta\lambda$ between the measurement point and the line centre. For each $\Delta\lambda$, record the measured intensity, the wavelength difference, and the intensity that **would** have been observed if the line wasn't there. This fictional intensity is called the "continuum level" and can be estimated by fitting a low-order function to the intensity of the spectrum immediately around the line on either side, and taking the intensity of the fit at each wavelength of interest. Record the intensity I_λ, the continuum level I_c, and the wavelengths $\Delta\lambda$ in a table. These are your basic experimental data. Think about averaging, and errors, and confidence limits, and record any information you might find useful when you fit the profile of the line. The raw intensity measurements need to be transformed into something useful for calculations, so it might be good to put them in a spreadsheet. **Take care with continuum fitting! The continuum placement is likely to be the largest source of uncertainty in your results.** Most students tend to underestimate the continuum level, because a large number of weak photospheric absorption lines are mistaken for random noise (see attached plot).

5. Measuring the line strength: In the following, we use some variables that allow us to eliminate the uncertain absolute calibration and work in purely relative intensities. These are defined in the background/introductory material, giving the following quantities:

R_ν	*Residual intensity:* The ratio I_ν/I_c at frequency ν.
R_{min}	The minimum value of R_ν, usually at the line centre.
η_ν	The *line strength*, in dimensionless units: The ratio of (the opacity due to

the spectral line of interest, ℓ_ν) to (the total opacity due to all other sources, κ_ν).

The opacities are mass absorption coefficients, with units of cross section per unit mass (cm^2 gm^{-1}) , i.e., the probability for a photon of frequency ν to be absorbed as it travels through a given column of absorbers. $\eta_\nu >> 1$ at the line centre, and approaches zero far from the line. The goal of an experimentalist is to relate some observed quantities (R_ν, R_{min}) to the physical quantities of interest, which are not directly observable themselves.

The relationship between continuum opacity and line opacity at a given frequency is not easily related to an observational feature of the spectrum in the general case. A complete solution requires numerical integration of a stellar atmosphere model, tracing the path of a photon from the base of the photosphere to the upper chromosphere. See Gray (2005) for as much information as you could hope to digest on stellar spectroscopy and Asplund et al. (2006) for a review of some of the practical complications. Some reasonably accurate approximations have been derived for certain limiting cases. One particularly useful approximation for certain very strong lines formed neat thermodynamic equilibrium is that, if no light is added to or removed from the line of sight by scattering, the ratio of line to continuum opacities η_ν is given by:

$$\eta_\nu = \frac{1 - R_\nu}{R_\nu - R_{\rm min}} \qquad \text{(Equation 1)}$$

Our approximate, analytical method for deriving elemental abundances from a spectral line depends on the line being extremely strong. This means that the total absorption is dominated by the *wings* of the line, i.e., the line is strongly broadened.

6. Measure η_ν for a range of frequencies/wavelengths and confirm the behaviour of this quantity with $\Delta\nu$ (or $\Delta\lambda$). ***If and only if*** $\eta_\nu \propto \Delta\nu^{-2}$ (or $\Delta\lambda^{-2}$), the line is strong enough to use our approximate approach for very broad lines. Use your intensity measurements to derive η_ν and confirm that an inverse quadratic profile is a reasonable fit to η_ν. This profile will always be a bad fit right at the line centre, but should agree well with the observations outside the core. From here on out, we will only need to use a minimum of one value of η_ν and $\Delta\nu$ to find the calcium abundance. At a minimum, use the values for $\Delta\lambda = \pm 4$ Å, although values from ±3-8 Å may be useful.

Analysis: The Solar Calcium Abundance

Use the η_ν value determined at $\Delta\lambda = 4$ Å (0.4 nm) to determine the calcium abundance, as described in the introductory/background material and prelab questions.

If n_{abs} is the number of calcium ions in the lower energy level of the 3933 Å transition per unit mass of material, and σ_ν is the cross section per ion at frequency ν, then

$$\eta_\nu \equiv \frac{\ell_\nu}{\kappa_\nu} = \frac{n_{abs}\sigma_\nu}{\kappa_\nu} \qquad \text{(Equation 2)}$$

As described in the background material, σ_ν is a complicated function determined by atomic physics and the conditions in the solar atmosphere. In general it takes the form of a Voigt profile, the convolution of a Gaussian and a Lorentzian. In this case, the prelab material should have convinced you that we can use a simplified approach where $\sigma_\nu = \sigma_{cl} f \phi_\nu$, the product of a classical cross section, a quantum oscillator strength, and a Lorentzian line profile function with damping parameter Γ (which you calculated in prelab question 2). The values for all of the other parameters can be found in the Tables included with the background material, leading to the all-important equation for n_{abs},

$$n_{abs} = \frac{\eta_\nu \kappa_\nu 4\pi^2 (\Delta\nu)^2}{\sigma_{cl} f \Gamma} \qquad \text{(Equation 3)}$$

In the above, recall that all quantities are in cgs units. Equation 3 can be used to find n_{abs} from data at multiple wavelengths from 3Å < Δλ < 8Å, limited in the core by the deviation from the $(\Delta\lambda)^{-2}$ profile at small Δλ, and in the wings by noise at large Δλ. Feel free to explore your precision and uncertainties by using multiple values of Δν and η_ν—they should all agree!

Correct your value of n_{abs} for the fact that not all of the calcium ions are in the right state to absorb a photon at 3933.7 Å. This correction can be made using the Boltzmann excitation equilibrium equation and the Saha ionization equilibrium equation, which you have done in prelab question 3.

With the statistical mechanical corrections to your derived n_{abs}, you can find $N_{\text{TOT}}(\text{Ca})$, the *total* number of calcium in the solar atmosphere. This quantity is expressed in number of atoms plus ions per unit mass of material, which is is not as useful in calculation as knowing the abundance expressed as number density relative to hydrogen. The hydrogen abundance is usually expressed by the variable X, where X is the mass of hydrogen per unit volume of material, and X = 0.735 for the Sun. The last step in your abundance estimate is to find the relative number abundance of Ca/H (expressed as a logarithm to base 10):

$\text{Log(Ca/H)} = \log[N_{\text{TOT}}(\text{Ca})\, m_H / X]$, where m_H is the mass of a hydrogen atom.

Look up an estimate of the solar calcium abundance in these units (for example in the Asplund et al. reference), and compare to your result. It is possible to get within a factor of a few of the accepted answer with this approach (±0.3-0.7 in the log). Note that in many references the abundances are scaled such that the abundance $A_{\text{Ca}} = 12.00 + \log(\text{Ca/H})$. This notation is used so that elements with truly small abundances (e.g., gold, barium, yttrium, etc) all come out with positive abundance. On this scale, for example $A_{\text{Li}} = 1.05 \pm 0.10$, and $A_{\text{O}} = 8.66 \pm 0.05$.

References:

Asplund, M., Grevesse, N., & Sauval, A.J. 2006, “The Solar Chemical Composition”, Nuclear Physics A, 777, 1.

Böhm-Vitense, E. 1989, *Introduction to Stellar Astrophysics: vol. 2, Stellar Atmospheres*, Cambridge Univ. Pr., Cambridge.

Gray, D.F. 2005, *Observation and Analysis of Stellar Photospheres,* 3rd ed., Cambridge Univ. Pr., Cambridge

Wikipedia 2018, *Fraunhofer lines*, viewed 17 January 2026, http://en.wikipedia.org/wiki/Fraunhofer_lines

— *Heliostat*, viewed 17 January 2026, http://en.wikipedia.org/wiki/Heliostat

— *Spectrograph*, viewed 17 January 2026, http://en.wikipedia.org/wiki/Spectrograph

(yes, we know it is wrong to cite wikipedia in a research report. Fortunately for us, this is a lab script).

Appendix A: Heliostat & Spectrograph Manual

Under construction

See Lab Manager or Andrew Cole, or another staff member for an introduction to the heliostat and spectrograph.

The heliostat consists of two mirrors in a motorised mount on the roof that track the sun and redirect its light through a converging lens, off of a flat mirror, and into the spectrograph. The roof cannot be accessed without a master key to the building.

The spectrograph consists of a slit, a collimating mirror, a diffraction grating, a camera mirror, and a screen onto which the spectrum is projected.

A digital camera is then used to photograph the screen with the spectrum on it (spectrum of the Sun, or of a calibration “arc” lamp)

Appendix B: Strong Lines in the Solar Spectrum

Table B1. The Strongest Lines in the Solar Spectrum

λ (Å)	Element	W (Å)	Name	λ (Å)	Element	W (Å)	Name
3581.21	Fe I	2.14	N	4920.51	Fe I	0.43	
3719.95	Fe I	1.66		4957.61	Fe I	0.45	c
3734.87	Fe I	3.03	M	5167.33	Mg I	0.65	b_4
3749.50	Fe I	1.91		5172.70	Mg I	1.26	b_2
3758.24	Fe I	1.65		5183.62	Mg I	1.58	b_1
3770.63	H_{11}	1.86		5232.95	Fe I	0.35	
3797.90	H_{10}	3.46		5269.55	Fe I	0.41	E
3820.44	Fe I	1.71	L	5324.19	Fe I	0.32	
3825.89	Fe I	1.52		5328.05	Fe I	0.38	
3832.31	Mg I	1.68		5528.42	Mg I	0.29	
3835.39	H_9	2.36		5889.97	Na I	0.63	D_2
3838.40	Mg I	1.92		5895.94	Na I	0.56	D_1
3859.92	Fe I	1.55		6122.23	Ca I	0.22	
3889.05	H_8	2.35		6162.18	Ca I	0.22	
3933.68	Ca II	20.25	K	6562.81	H_α	4.02	C
3968.49	Ca II	15.47	H	6867~	O_2	*Telluric*	B
4045.82	Fe I	1.17		7595~	O_2	*Telluric*	A
4101.75	H_δ	3.13	h	8194.84	Na I	0.30	
4226.74	Ca I	1.48	g	8498.06	Ca II	1.46	
4310 ±10	*Blend*	7.20	G	8542.14	Ca II	3.67	
4340.48	H_γ	2.86	f	8662.17	Ca II	2.60	
4383.56	Fe I	1.01	e	8688.64	Fe I	0.27	
4861.34	H_β	3.68	F	8736.04	Mg I	0.29	

The information above is taken from Moore, Minnaert & Houtgast (1966, U.S. National Bureau of Standards Monograph 61 “The solar spectrum 2935 Å to 8770 Å”). Only a selection of the strongest lines are given. The equivalent widths are approximate and should be used only as a guideline. The line names refer to the designations applied by Fraunhofer.

Appendix C: Wavelengths of Lines in the Hg-Cd Arc Lamp

Wavelength values and relative intensities retrieved from the NIST Atomic Spectra Database (https://www.nist.gov/pml/atomic-spectra-database) search for Cd I and Hg I lines between 300 and 900 nm. Low intensity lines have been omitted. The spectroscopic notation “Cd I” (roman numeral 1) is equivalent to the chemical notation Cd^0, i.e., neutral cadmium. The bibliographic citation is: Kramida, A., Ralchenko, Y., Reader, J., & the NIST ASD Team (2012), *NIST Atomic Spectra Database (v. 5.0)* [online], National Institute of Standards and Technology, Gaithersburg, MD.

Table C1. Recommended wavelengths in air for selected lines of Hg I and Cd I

Intensity[1]	Wavelength[2] (nm)	Species
9000	365.02	mercury
12000	404.66	mercury
12000	435.83	mercury
200	467.81	cadmium
300	479.99	cadmium
1000	508.58	cadmium
6000	546.03	mercury
1000	576.96	mercury
900	579.07	mercury
100	632.52	cadmium
2000	643.85	cadmium
1000	734.57	cadmium

[1] Intensities are relative values based on irradiance measured in a low-pressure lamp, and are arbitrarily normalized. They are rough estimates only, to help you identify the lines.

[2] The wavelength uncertainty is ±0.0001 nm, based on Reader et al. 1980, “Wavelengths and Transition Probabilities for Atoms and Atomic Ions. Part I. Wavelengths”, Nat. Stand. Ref. Data Series, NSRDS-NBS 68, US Government Printing Office, Washington DC.