UNIVERSITY COLLEGE LONDON

University Of London Observatory

1B30 Practical Astronomy
1B13 Frontiers of Astronomy

Measuring a Stellar Spectrum

1 Introduction

The primary way astronomers find out about physical conditions in a star is by means of stellar spectroscopy. The aim of this experiment is to gain insight into the relationship between the appearance of a stellar spectrum and the chemical composition of a stellar atmosphere. You will study a spectrum of the B2.5 IV star γ Pegasi to determine the wavelengths of absorption lines in the star; you will then attempt to identify the elements which produce those lines.

2 Items required

You will need:

- access to a Windows or Linux PC (with screen resolution set to 1024 × 768 pixels), to display the spectrum of γ Pegasi (obtained with the Allen telescope at ULO);
- a line-identification chart for the argon comparison spectrum;
- a line-list giving wavelengths and identifications of lines in γ Pegasi.

3 Displaying the spectrum

You will need to be logged in to one of the Unix systems at ULO to run a program (called GAIA) which is used for the display and analysis of the γ Pegasi spectrum. A demonstrator will carry out the login process for you. Once logged in, a *terminal window* will appear, and the image display program can be started simply by typing the command `gammapeg`.

A main image-display window will appear, showing an image of the spectrum, and a `Control Panel` window, which allows you to change the display in various ways. You will need to arrange the image display and control-panel windows so you can see the image of the spectrum clearly. You can move the various windows around the desktop by clicking and dragging on the top line of the window. It will probably be most convenient to move the `Control Panel` window to the right of the screen so that most of the spectrum is visible in a window on the left-hand side.

3.1 Inspecting the image

The central grey band running across the image in the main window is the spectrum of γ Pegasi. When taking stellar spectra with a spectrograph, astronomers also take arc calibration spectra alongside each stellar spectrum; you will see these as bright lines above and below the stellar spectrum. (At least, astronomers used to place the calibration spectra alongside the stellar spectrum when recording spectra on photographic plates; with modern detectors like CCDs, one usually takes an exposure of the target star, and then a separate exposure of the calibration spectrum, taking care to make sure that the detector does not move between exposures!) The image you are using comprises real data obtained with a CCD on the Allen telescope at ULO, but the data have been presented in a ‘photographic’ format to try to clarify the concepts involved here.

3.2 Controlling the image display

It is useful to spend a little time familiarising yourself with the controls. In the `Control Panel`, you can see two other windows: a *pan window* (upper left) and a *zoom window* (upper right). In the pan window, you can always see the whole image, and the white-outlined box shows which part of the image appears in the main display. In the zoom window, the part of the image around the cursor position is displayed, so you always have a close-up view.

In the lower half of the control panel, the position X, Y of the cursor is displayed, and `Value` shows the number of counts in the pixel at that position. The image brightness and contrast are adjusted by filling in new values for `Low` and `High`, or by clicking one of the `Auto Cut` buttons. If you click the `98%` button now, it will set the display values to `Low` = 0 and `High` = 11355, which is about right for displaying the full image.

Buttons are also provided for zooming the main image in (`Z`) and out (`Z`), which you might need. (The other buttons are for rotating and flipping the image, which you should not do.) When the image is zoomed in, clicking and dragging the outlined box in the pan window allows navigation around the image in the main window. This can also be done with the scrollbars.

You need to open up one more window to help you analyse the spectrum: in the main window, click on `View` ↦ `Pixel Table ...` and choose `5x5`. This brings up a table showing the counts in each pixel in a 5 × 5-pixel area around the present cursor position. Drag the pixel table to a convenient location on the right of the screen. (You might need to widen the table slightly to make sure long numbers do not get cropped.)

4 Measuring the spectrum

The calibration spectrum enables the observer to use the known wavelengths of the arc lines to identify the wavelengths of the stellar lines. One problem encountered when using spectrographs is that the wavelength scale is not precisely linear. To state this another way, in the spectrum image there are not the same number of Ångstroms per pixel all the way along the spectrum (1 = 0.1 nm = 10^{-10} m). Using the arc lines, which have precisely known wavelengths, astronomers can get around this non-linear wavelength scale either by fitting a polynomial to the data or, as you will do here, by plotting a correction curve.

In this practical you will measure the positions of a selection of comparison arc lines in order to determine a relationship between pixel number (in the x-direction) and wavelength. You will then measure the pixel positions of about 40 absorption lines in the stellar spectrum and determine their wavelengths using the calibration previously determined. From the wavelengths of the absorption lines, you will use a line list to identify the species responsible for the stellar spectrum lines.

4.1 The comparison arc spectrum

Measure with the cursor the position (in x) of *ten* well-spaced comparison arc lines in the emission spectrum (it does not matter whether you use the one above or below the stellar spectrum).

Note the following:

1. The x-position of the *cursor* is given in the control panel (as X), and is given as well at the top of the central column in the pixel table. Make sure you read the x-value, not y!

2. The emission lines must be selected from those which are identified by wavelength on the chart provided. Make sure that the lines chosen cover a good spread of wavelengths, and are not all tightly bunched around a few points. *Note that only the wavelength range* $\sim$ 3870–4620*Å is visible on the screen!*, *i.e.*, the chart does not extend so far into the blue and extends further into the red, and you can ignore the region on the chart longward of the line at 4610Å.

3. To start, choose the shortest wavelength comparison line near 3995Å. Use the chart to navigate back along the emission spectrum until you can find this line. If you choose to zoom in, you will have to use the pan window to select the blue (left-hand) end of the spectrum for display.

   You might need to adjust the image contrast in order to reveal weak arc lines like this one more clearly: keep `Low` = 0 counts, and lower the `High` level to show up fainter lines more clearly; you will need to reset the `High` level to > 10000 for the stronger arc lines.

4. When you are close to the required line, use the zoom window in the control panel and the L-R direction keys on the keyboard to centre up exactly on the arc line. Take the pixel centres to be exact integer values of X, even if the pointer is slightly shifted when zoomed. (*E.g.*, when zoomed, if the pointer is between pixels 10 and 11, say, the cursor position might be given as 10.5 in the control panel and in the pixel table, but the pixel *centres* are still at $X = 10.0$ and 11.0.)

5. You will perhaps notice that each line is wider than one pixel, and therefore you can interpolate to obtain the centre of the line to a precision of about 0.1 or 0.2 pixels. To interpolate, inspect the values in the pixel table when the cursor is positioned on the brightest part of the line. From the spread of values either side of the line, estimate (don't do a formal calculation!) where the centre of the line is.

   (Try this example: for the line near $X = 132$, the counts in adjacent pixel columns 131, 132, 133 are 1245, 7198, 2249 counts, dropping to 'background' values further away. Hence the line centre is not exactly at $X = 132.0$, but is skewed slightly towards pixel 133. If the counts in pixels 132 and 133 were very similar, then of course the line centre would be at about $X = 132.5$; or if the counts in 133 were half those at 132, one might say the line centre was at 132.2 or 132.3. But since the counts in $X = 132$ still exceed pixel 133 by more than this, one can estimate the line centre to lie at about $X = 132.1$. N.B. When interpolating a zoomed section of the image, take the counts given in the pixel table to refer to the exact centres of the pixels, *i.e.*, integer values of X.)

4.2 The stellar spectrum

Next, measure the position in x of each marked absorption line in the stellar spectrum. These lines are marked on the line plot of the spectrum attached at the end of this script.

1. Estimate all stellar measurements to the nearest pixel number; it is somewhat harder to interpolate the positions of the absorption lines, but it may be possible for some of the strong lines. Interpolate only when you feel it is justified to do so.

2. For this part of the exercise, set the `High` level to be about 10500 counts; the `Low` level should be set to 4000 counts for inspecting the strongest lines, and can be raised up to about 8000 counts to reveal the weaker lines more clearly.
3. Measure *all* the lines marked on the plot. Number them $(1, 2, \ldots, 40, 41)$ in wavelength order on the plot (to avoid cluttering it, you need only label every fifth line on the plot, say). This will help you to identify the lines later on since you will be able to compare directly their relative strengths. Trim and paste this diagram in your book when you write-up the practical.

4.3 Exiting the program and logging out

When you have finished measuring the spectrum, exit the program. Inform a demonstrator you have finished with the machine so that they can log you out properly.

5 Calculations

Call the wavelength of the first measured comparison line λ_1 (Å) and its measured position x_1 (pixel number); call the same quantities for the tenth comparison arc line measured λ_{10} (Å) and x_{10} (pixel number). Calculate the mean *dispersion* D (*i.e.*, number of Å per pixel) of the spectrum and the *zero point* λ_0, where

$$D = (\lambda_{10} - \lambda_1)/(x_{10} - x_1) \quad (/\text{pixel}),$$

and

$$\lambda_0 = \lambda_1 - D x_1.$$

For each comparison line, calculate the wavelength of that line predicted by the dispersion:

$$\lambda_{calc,i} = \lambda_0 + D x_i.$$

Tabulate these calculated wavelengths along with the true wavelengths, $\lambda_{true,i}$, listed on the chart, and the difference between these two quantities, $\Delta\lambda_i$, where

$$\Delta\lambda_i = \lambda_{true,i} - \lambda_{calc,i}.$$

Plot a graph of $\Delta\lambda_i$ *vs.* $\lambda_{calc,i}$. Such a graph is called a *correction curve* because one can plot a smooth interpolated curve on the plot which can then be used to read off corrections to the linear approximation to the wavelengths, λ_{calc}; these can then be added to the values of λ_{calc} determined for the stellar lines. The curve should resemble a parabola with its maximum near the middle of the wavelength range, and it should go through zero near λ_1 and λ_{10}.

Next, tabulate λ_{calc} for all the stellar lines and read the appropriate correction $\Delta\lambda$ from the graph, or calculate the correction from your fitted quadratic function. Tabulate $(\lambda_{calc} + \Delta\lambda)$ and call it λ_{stellar}. Leave two extra columns; one for your line identifications and one for notes or remarks.

6 Line identification

Use the supplied list of stellar spectrum lines to identify the stellar lines in the spectrum. The list is based on very high resolution spectra of the star γ Pegasi, *i.e.*, the star you have been studying. Pay close attention to the equivalent widths of the lines listed to check that your identifications are consistent with their relative strengths; many of the weaker lines (with equivalent widths less than about 0.025Å) will not be visible in your spectrum. Make a note of possible *blends* too: a blend occurs when two or more weak lines fall close together and give the appearance of one stronger line.

7 Questions

1. Given that each pixel in the CCD used to obtain this spectrum is 22 μm across, what is the mean dispersion of the original spectrum in Å per mm?
2. What elements are visible in the spectrum? Are these elements those expected according to the reference given below?
3. Why is it better to obtain wavelengths by the correction curve method ($\Delta\lambda$ *vs* x) rather than with the aid of a plot of λ *vs* x?
4. In general, the wavelength of a line on a grating spectrogram can be expressed as a power series
$$\lambda = \lambda_0 + Dx + Ex^2 + Fx^3 + Gx^4 + \cdots,$$
in which each term contributes a much smaller amount than the one preceding it. What form would the correction curve have if we used $\lambda_{calc,i} = \lambda_0 + Dx_i + Ex_i^2$?

8 References and Background Reading

1. Abell, Morrison & Wolff, *Exploration of the Universe*, pp. 148-155; 439-449 (5th edition).
2. Zeilik & Gregory, *Introductory Astronomy and Astrophysics*, (4th edition), section 13-2; see also sections 8-2 and 8-3.

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