ASTRO 4410 LAB 3

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1 Objectives

1. Obtain the rotation curve of the galaxy NGC 7331

2 Setup

2.1 Target object

The object observed was the spiral galaxy NGC 7331, located at a distance of12.2 ± 1.0 Mpc from Earth. It is located in the constellation Pegasus, and its equatorial coordinates are 22h 37m 04.1s RA and$+34°24'56"$ Dec.

2.2 Bias and flat noise

Before observations began, 5 images with exposure time of 0.00001 seconds were taken in order to obtain data that was later used to compensate for bias. No photons were allowed to enter the CCD while these images were taken. In addition to this, 5 images of exposure time of 2 seconds under a flat bright light field were performed in order to properly compensate for imperfections in the subsequent image acquisition.

2.3 Image acquisition

Observations were made during the night of October 7th, 2015 at the Hartung-Boothroyd Observatory (HBO) located at Mount Pleasant, Ithaca, NY. The HBO houses the James R. Houck telescope, a fork mounted cassegrain reflector telescope whose primary mirror is 25 inches (0.635 meters) in diameter. It has a f/13.5 lens, with a native plate scale of 24 arcsec/mm. Photon detection was performed using an Andor iDus 440 CCD, which sports a coated e2v CCD 42-10 BV sensor. Image resolution was of 2048 by 512 pixels, with a pixel size of 13.5e-6 m, a plate scale of 0.3"/pixel, a field of view of 10.7' by 2.6', and a read noise of 4 e^-. A spectrograph was used in order to decompose the light coming from the target object into a spectrum. This spectrum can be regarded as a three dimensional plot, with decreasing wavelength from left to right along the x-axis, and the value of each pixel correlates with the intensity of the corresponding spectral line. The bright band that covers the entire image near the vertical center from left to right is NGC 7331, so different values for the y-axis correlate with different distances away from the galaxy's center. Two separate spectra were produced, each with a different exposure time. Figure 1 shows the spectrum obtained after a 300 second exposure, and Figure 2 shows the spectrum obtained after a 600 second exposure.

2.4 Calibration spectrum

The analysis performed required the x-axis on Figures 1 and 2 to be a measure of the wavelength being observed. The spectrum by itself does not provide the means to do this: each value in the x-axis is simply a pixel number. Since the resolution is 2048 by 512 pixels, there are 2048 pixels in the x-direction, and so the x-axis can be regarded as a scale that goes from 0 to 2048. With this in mind, the CCD/spectrograph was exposed for 5 seconds to light produced by a mercury lamp. Since the wavelengths of the spectral lines of mercury are known, this spectrum was later used to establish a relationship between pixel number and wavelength, which was subsequently used to scale the galactic spectra's x-axis.

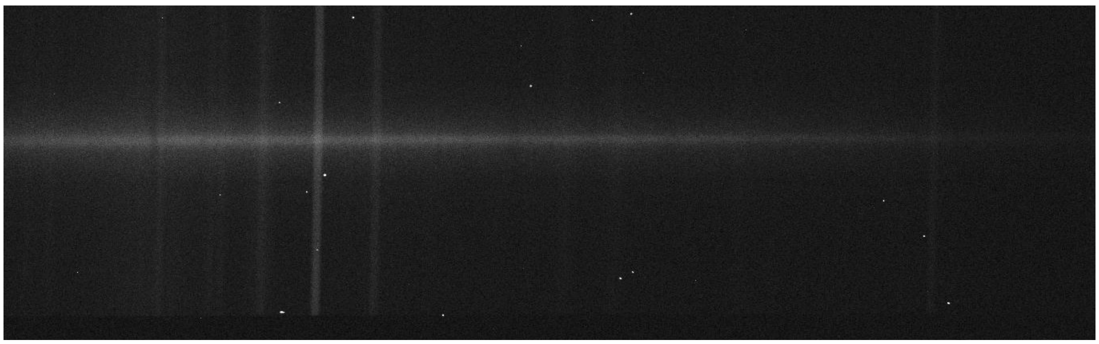

Figure 1: Galactic spectrum obtained after a 300 second exposure

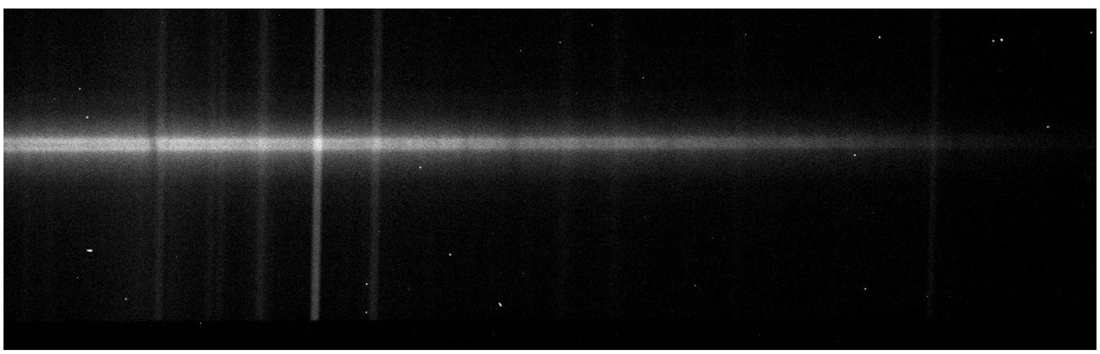

Figure 2: Galactic spectrum obtained after a 600 second exposure

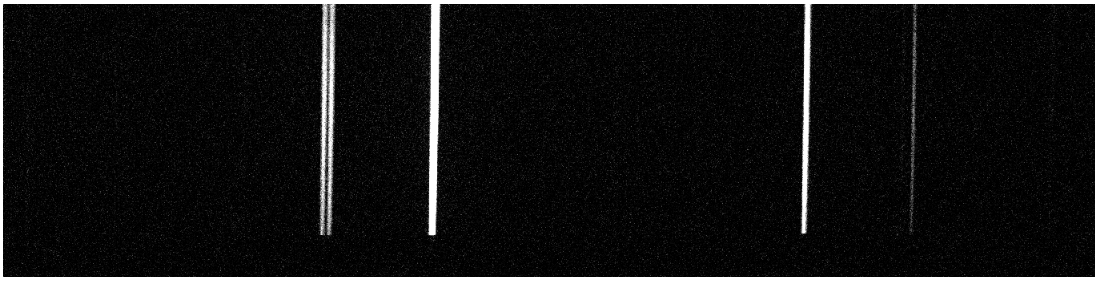

Figure 3: Mercury spectrum

3 Data reduction

3.1 Calibration

The calibration spectrum (Figure 3) contains five spectral lines. Given the characteristics of the mercury spectrum, we know that the two closely spaced lines seen close to the left edge have wavelengths of 5770 and 5790 Å. The wavelength decreases from left to right, and the next line has a wavelength of 5461 Å, and the following one has a wavelength of 4358 Å. The fifth line is faint so it was ignored. Plotting the value of a row of pixels at a fixed y-position, which was chosen to coincide with the center of the galaxy as seen in the spectrum shown in Figure 1, the location of the pixels corresponding to the 5461 and 4358 Å lines was identified. The 5461 Å line was located at pixel # 807, while the 4358 Å was located at pixel # 1504. Since the relationship between pixel number and wavelength is linear, the wavelength λ as a function of pixel number p was found to be:

$$\lambda = -1.582p + 6738\ \mathring{A} \tag{1}$$

This predicts the location for the $H\alpha$ line in the galactic spectra, which was used in the subsequent analysis, to be around pixel # 110, which is consistent with visual inspection of the spectra.

3.2 Redshift and velocity

The redshift z of a certain spectral line with rest wavelength λ_{rest} and an observed wavelength λ_{obs} is given by:

$$z = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}} \tag{2}$$

At velocities v much smaller than the speed of light c, i.e. $v \ll c = 3.00 \cdot 10^5\ km\, s^{-1}$,

$$z \approx \frac{v}{c} \tag{3}$$

In this case, the expected velocities are in the range 0-300 km/s, so the condition is fulfilled and (3) applies almost perfectly. Combining (2) and (3) gives

$$v = c\, \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}} \tag{4}$$

Thus, the rotation curve was obtained in the following manner. The spectral line used was the $H\alpha$ line, which has a rest wavelength of 6563 Å. First, both spectra obtained were added together, after compensating for the differing exposure times. Next, the resulting combined spectrum was adjusted in order to account for the bias and the flat noise. The location of the horizontal collection of pixels corresponding to the center of the galaxy was found by looking at all the 512 horizontal collections of pixels contained in the spectrum and locating the brightest one. This was used, as explained in 3.1, to find equation (1), and also to create an 80 by 2048 rectangular matrix of values with the row at the bottom corresponding to the galactic center and the top row corresponding to the last row in which the $H\alpha$ line was detectable. Visual inspection of the spectrum reveals that the line is the first noticeable spectral line going from left to right, that it is located around pixel # 110, as noted above, and that the next visible spectral line is located around pixel # 240. With this in mind, the matrix was reduced to an 80 by 30 size, by ignoring all pixels before location 90 and after location 120. This matrix was binned vertically, twice, by adding adjacent rows together in order to improve the signal, thus transforming the 80 by 30 matrix into a 20 by 30 matrix. The location of the $H\alpha$ line for each row was then obtained by finding the location of the maximum valued pixel on each of them. Equation (1) was then used in order to transform this location into a wavelength, which would correspond to λ_{obs}. The absolute velocity of each of the rows with respect to us was found by applying equation (4), with λ_{rest} equal to 6563 Å. However, since the galaxy as a whole is receding away from us, finding the actual velocity of the rows with respect to the galactic center involved calculating this receding velocity and subtracting it from each of the absolute velocities obtained. This receding velocity was taken to be the absolute velocity of the brightest row, which is the one closest to the center. This was plotted as a function of arbitrary radius.

4 Results and Analysis

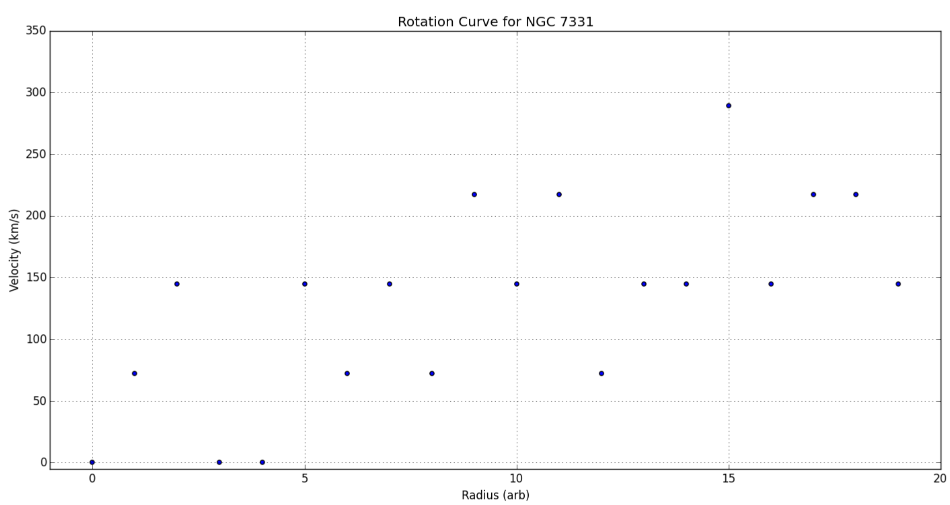

Figure 4: Rotation curve for NGC 7331 [1]

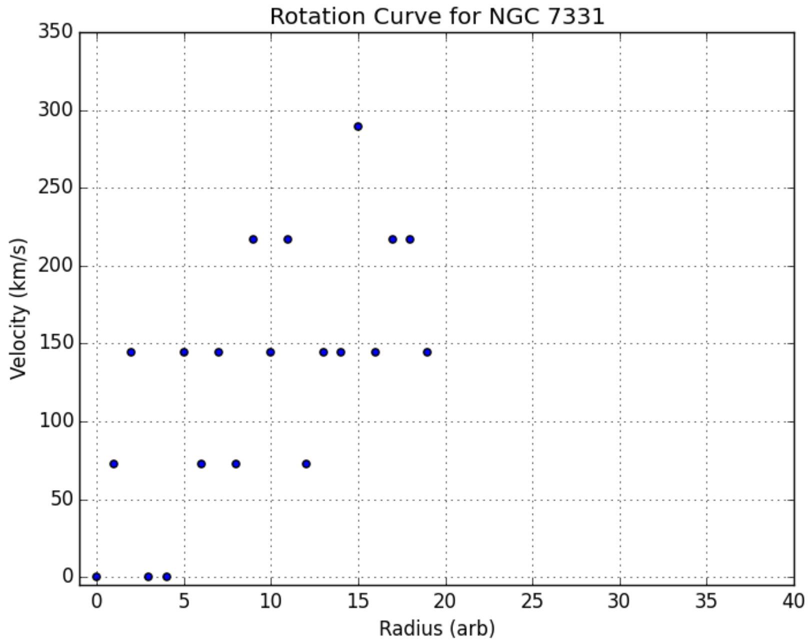

Figure 5: Rotation curve for NGC 7331 [2]

4.1 General analysis

Figures 3 and 4 show the resulting rotation curve with the x-axis scaled in two different ways. A few things become immediately apparent. First, the overall shape of the plot is consistent with the form of a galactic rotation curve for distances relatively close to the galactic center, but it cannot be regarded as a complete rotation curve for the galaxy. In other words, the relative lack of sensitivity of the observations implied that the $H\alpha$ line was only detectable at distances relatively close to the galactic center, which is to be expected given the instrumentation used and the fact that the amount of hydrogen gas decreases with distance from the center. More precise observations are needed in order to fill the empty space on the right half of Figure 4. These observations would be expected to produce points of approximately constant velocity between 240 and 300 km/s. A second aspect to note is the fact that even though there is a large margin of error for the velocities obtained, their values are reasonable. The "steps" that can be observed, where the same velocity was obtained for more than one value of the radius, is a product of the poor sensitivity of the observations, and the subsequent steps taken during the data reduction process in order to obtain a clear signal.

4.2 Error analysis and prospects for improvement

A consequence of the relationship between wavelength and pixel number derived in 3.1 is that the number of Å contained in a single pixel is about 1.5. Because of the large value of the speed of light in comparison to the velocity of a galaxy's rotation, this places a strict limit on the accuracy of the velocities obtained, since a redshift of 1.5 Å is equivalent to about 70 km/s in terms of velocity. This means that when determining the location of the $H\alpha$ line, an error of one pixel produces a 70 km/s discrepancy between the actual velocity and the calculated velocity. In addition, the signal produced by the $H\alpha$ line is not considerably larger than the background noise, severely limiting the amount of radial points that can be sampled. These are the reasons why the plot obtained appears to be so crude in comparison with galactic rotation curves that can be found in other studies.

There are two ways to improve this study in order to obtain better results. First, the resolution of the observations needs to be increased by using both a more sensitive CCD and a larger telescope, as well as obtaining more spectra with the use of different spectrometers. Second, the method used for data reduction can be improved by using more sophisticated code that could locate the $H\alpha$ line more accurately, in order to get a better estimate of the redshift of each of the radii sampled. Analyzing the velocities of the gas at different radii of the other half of the galaxy would also probably help.

5 Conclusion

The purpose of this lab was to use the spectra of the galaxy NGC 7331 captured by the HBO telescope in order to obtain its galactic rotation curve. Even though the extracted curve is crude under certain standards, it is nonetheless as good as can be expected given the sensitivity of the observations, so the objective was fulfilled. Better results can be obtained by following the advice given at the end of section 4.2.

References

NASA/IPAC Extragalactic Database (NED). "NGC 7331". NASA/IPAC. Accessed on 1/12/2015. <http://ned.ipac.caltech.edu/cgi-bin/nph-objsearch?objname=NGC+7331&img_stamp=yes&extend=no>