Measurement of Galaxy Rotation by CCD Spectroscopy

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Abstract

I created spectra of the NGC 7448 and NGC 1068 galaxies from spectrographic CCD images. I used the Doppler-shift dispersion of the Hα emission lines to determine the rotational velocity of the galaxies. I compared my rotational velocities with published results: those of van Driel et al. [5], who studied NGC 7448 and its neighboring galaxies extensively, and those of Richstone & Morton [4], who studied NGC 1068.

1 Introduction

1.1 Determining rotational velocity

The basic method of determining a galaxy's rotational velocity from the Doppler shift of lines in its spectrum is outlined in Hayes [3]:

Suppose a galaxy has a known emission line at a wavelength λ_0. Now if the galaxy is rotating about an axis perpendicular to the direction of the spectrograph slit used to image it, then the emission line from the half of the galaxy rotating toward the observer will be blue-shifted. Likewise, the emission line from the half of the galaxy rotating away from the observer will be red-shifted.

If an image of the galaxy is taken with sufficently high spatial resolution to distinguish the emission lines from the two halves of the galaxy, separate consideration of the spectra from the two halves of the galaxy can be used to draw a velocity dispersion curve for the galaxy.

Alternatively, if the spectrum has high wavelength resolution, then it will be visible on the spectrum that prominent emission lines are "spread out," since different parts of the galaxy appear to be emitting at different frequencies. Ideally, one would see two peaks for each emission line, a redder peak from the receding arms of the galaxy and a bluer peak from the approaching arms of the galaxy.

In this experiment, I have used this latter method to measure the rotational velocities of NGC 7448 and NGC 1068.

1.2 Galaxies studied

NGC 7448 is a spiral galaxy in Pegasus, with RA $23^h00^m03.76^s$ and Dec $+15°58'48.2''$. Its apparent magnitude is about 11.7.

NGC 1068 (also known as M 77) is a Seyfert spiral galaxy in Cetus, at RA $02^h42^m40.83^s$ and Dec $-00°00'48.4''$. Its apparent magnitude is about 8.8. (Epoch 2000 data, from ICRS)

2 Methods

2.1 Source of images

The spectrographic images of NGC 7448 and NGC 1068 were taken on 9/30/2002. We used a liquid N_2-cooled Thompson 7882 CCD camera (582×384 pixel array) mounted on the 25-inch telescope at Hartung-Boothroyd Observatory in Mount Pleasant, NY, owned by Cornell University.

We used a diffraction grating with 600 lines/mm and a 55 mm focal-length camera lens. This produced a dispersion of 6.5 Å/pix, and thus a wavelength range of approximately 3783 Å.

We also used the spectrograph to take images of mercury and neon lamps in order to calibrate the spectra.

2.2 Producing the spectra

I used the `SPPHOT` software written by Prof. Jim Houck to convert all CCD images to tables of column numbers and DNs. Using the software I selected a horizontal band across the slit corresponding to the vertical extent of the galaxy on the slit, and another horizontal band of equal width corresponding to empty sky. The software tabulated the difference between the integrated DN of the galaxy band and the sky band. This helped to eliminate distortions of a galaxy's spectrum caused by atmospheric absorption.

I used the `FINDP` software, also by Prof. Houck, to align the column numbers of the CCD images to physical wavelength values. I identified several emission lines of Hg and Ne and the program used these to find a cubic function that accurately mapped the pixel numbers onto wavelength values for these spectra:

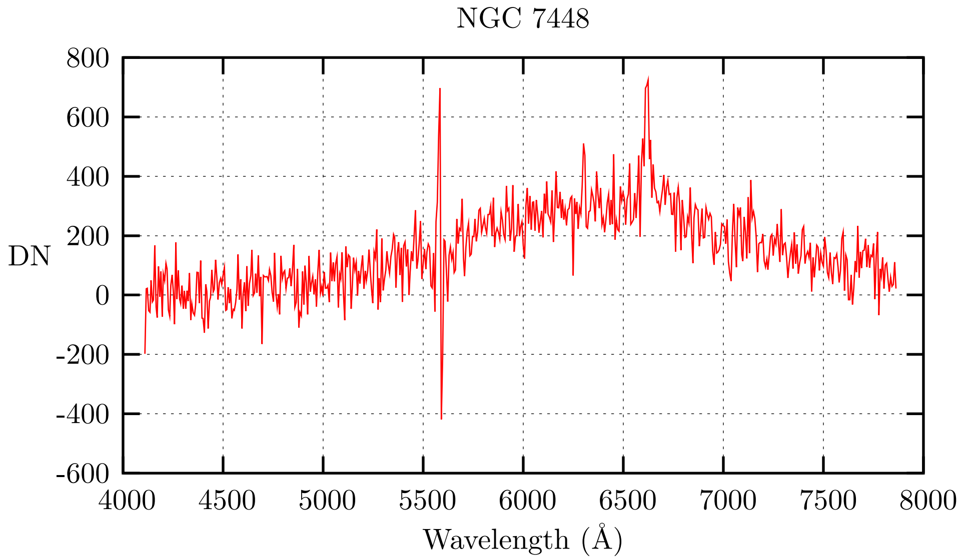
$$\lambda = (-6.67159 \times 10^{-7})x^3 + (9.55198 \times 10^{-4})x^2 + (6.13983)x + (4.10348 \times 10^3)$$

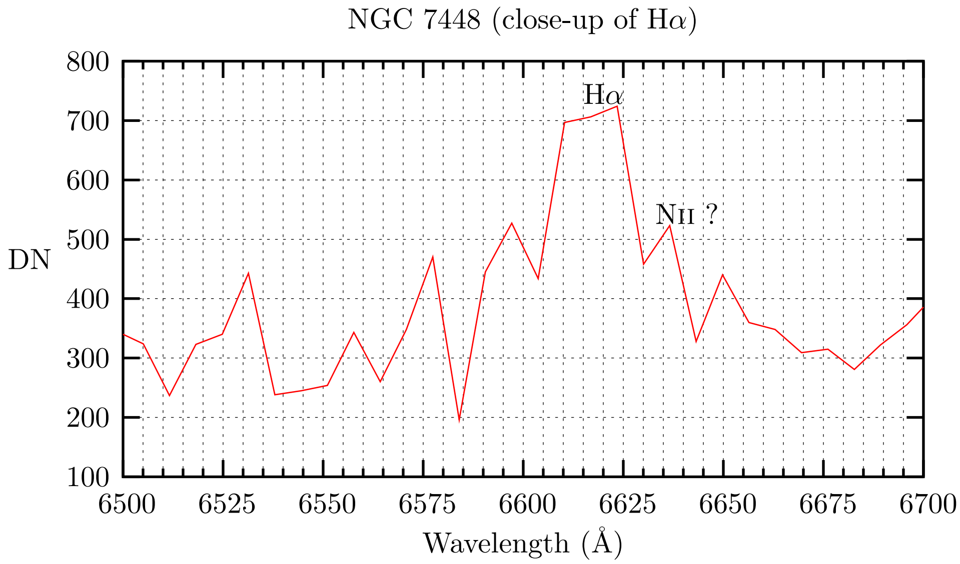
where λ is the wavelength in Å and x is the column number of a pixel on the CCD image of the spectrum. As expected, λ is very nearly a linear function of x, as can be seen by plotting it over the interval $[0, 581]$.

I wrote a Perl script to tabulate these values of $\lambda(x)$ along with the integrated DNs for each galaxy, produced by `SPPHOT`. I then plotted DN vs. λ with these values to produce a graphical spectrum for each galaxy.

3 Results and discussion

3.1 Spectra

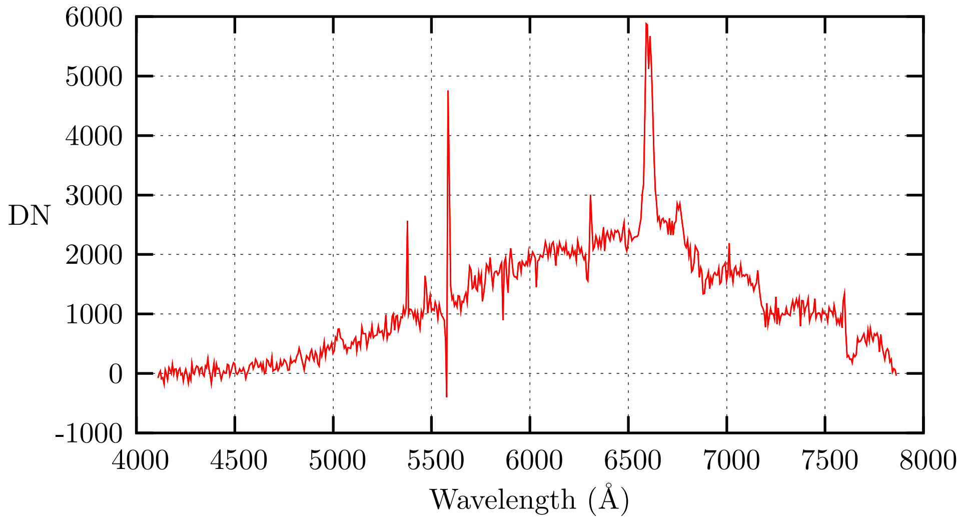




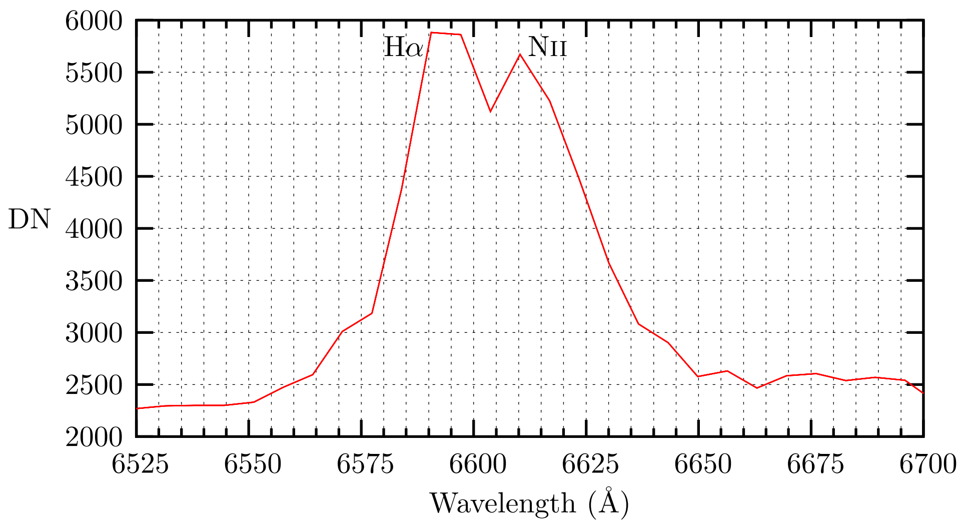
This spectrum differs from the spectra of NGC 7448 presented in [5, page 78]. First, the noise in my spectrum is significantly greater, which probably explains why none of the emission lines except for very bright Hα are readily apparent in my spectrum. The difference in noise is probably due to the fact that we used a smaller telescope at high airmass in less-than-ideal observing conditions. Also, our spectrograph and CCD equipment are probably of a somewhat lower quality than that used at major research telescopes.

Second, the continuum spectrum in my image appears to peak at around 6400 Å, whereas the continuum appears to be extremely flat around this wavelength in the images from [5]. Wien's Law states that the peak of a blackbody radiation spectrum occurs at $\lambda_{max} = (2.9 \times 10^7 \text{ Å K})/T$, thus the temperature of the blackbody is $T = (2.9 \times 10^7 \text{ Å K})/\lambda_{max}$. So it would appear from my spectrum that the temperature of NGC 7448 is around 4.5×10^3 K. However, van Driel et al. [5] state that NGC 7448 is "quite blue" with a $B - V$ color magnitude corresponding to a temperature of approximately 6.3×10^3 K.

NGC 1068



NGC 1068 (close-up of Hα)



There is much less noise in my spectrum of NGC 1068 than in that of NGC 7448. This is not surprising since NGC 1068 is almost 3 magnitudes brighter than NGC 7448, and therefore spectral details are much more prominent above the noise in a CCD spectrum image.

In this spectrum, the Hα line is clearly visible, as is a fairly broad band at around 6745-6766 Å (corresponding to rest wavelengths of 6716-6736 Å, see calculation of red shift below). I believe that these are the SII emission lines which occur in this region of the spectrum, 6717-6731 Å, and which are noted in [4]. There appears to be another emission line at around 5377 Å (rest wavelength 5354 Å). This is possibly a NI line (5354.388 Å). I am unsure of this, since the line in my spectrum seems too bright, but the NI line is the only light-element emission line within several angstroms of 5354 Å.

3.2 Anomalies in the Spectra

My spectra of NGC 7448 and NGC 1068 both show very strong up/down or down/up spikes at around 5550 ± 3 Å (rest wavelength) and again at 6204.55-6256.64 Å in NGC 7448 (rest wavelengths) and 6261.62-6281.21 Å in NGC 1068. I am not at all sure of the source of these spikes (which do not appear in any published data that I could find).

When I first looked at my spectrum for NGC 7448, I thought that the spikes at around 5550 Å must be due to a cosmic ray or other defect that I had failed to eliminate from the CCD images, and that the spikes around 6200-6250 Å were probably just a bit of unusually high-amplitude noise. However, I realized this wasn't the case when I looked at the spectrum for NGC 1068, and saw the same features.

I searched the NIST Atomic Spectra Database [1], and found that there are no lines around 5550 Å for any elements that might be present in galaxies, so the spikes I find in my spectra in that region are probably *not* due to emission or absorption by the galaxies being studied.

I looked at spectra of other objects that we imaged on the same night, including the planetary nebulae NGC 7009, NGC 7027, and M 57, and the star BD 20. These spikes were not apparent on any of those spectra, which in general looked much smoother and very close to published spectra of those objects (probably since they are brighter, closer, and easier to image).

3.3 Radial velocity and distance of the galaxies

Since there are parts of my spectra for NGC 7448 and NGC 1068 which I am unable to explain adequately, I wanted to verify that some features of the spectra made correct predictions about known properties of the galaxies. I chose to measure the red-shift of the center of the Hα line in each spectrum and to determine the radial velocities of the galaxies and their Hubble's Law distances. I hoped that this would show that the position of the Hα lines on my spectra was accurate, and therefore that the wavelength calibration was accurate.

In my spectrum for NGC 7448, the center of the Hα emission line occured around 6615 Å, and in the spectrum for NGC 1068 it occured around 6600 Å, whereas the canonical rest wavelength for this line is 6563 Å. I computed the velocities at which the two galaxies are receding from Earth as follows:

$$\frac{\lambda}{\lambda_0} = \sqrt{\frac{1+v/c}{1-v/c}} \qquad \text{(relativistic Doppler shift)}$$

$$\frac{v}{c} = \frac{(\lambda/\lambda_0)^2 - 1}{(\lambda/\lambda_0)^2 + 1}$$

Thus for NGC 7448, $v \approx 7.892 \times 10^{-3} \times 2.998 \times 10^5$ km s^{-1} $= 2.366 \times 10^3$ km s^{-1}. And for NGC 1078, $v \approx 4.864 \times 10^{-3} c = 1.458 \times 10^3$ m s^{-1}.

Hubble's Law posits a linear relationship between the velocity of a distant galaxy and its distance from the observer: $V = H_0 D$, where $H_0 \approx 75$ km s^{-1} Mpc^{-1} according to van Driel et al. [5]. For NGC 7448, $D \approx 31.55$ Mpc. This is off van Driel et al.'s figure of 29.5 Mpc by 6.9%. And for NGC 1068, $D \approx 19.44$ Mpc, deviating from the accepted value of 60 Mly ≈ 18.4 Mpc by 5.7% [2].

Perturbing the measured values of the peak of Hα by 6.5 Å affects the final value for the galaxies' distance by slightly *more* than the percentage errors just stated. Since 6.5 Å is the granularity of the spectra (due to the spectrograph settings and CCD pixel size), the values that I found for the distance to the galaxies are shown to be just about as accurate as possible given the equipment used.

3.4 Measuring rotational velocity

In order to measure the rotational velocity, we must look at the width of the Hα line. To get an estimate of the rotational velocity of a galaxy, assume that the true wavelength of the Hα line (given that it is already red-shifted due to the overall expansionary velocity of the galaxy) lies right in the middle of the observed line. This should be a good approximation as long as the galaxy is performing roughly uniform circular motion.

For NGC 7448, the width of the flattish peak of the Hα line is 13.16 Å (reading directly from the data tables) centered at 6616.88 Å, while for NGC 1068 it is 6.58 Å centered at 6593.85 Å.

Using the Doppler shift formula in the preceding section, I find for NGC 7448, $v_{rot} \approx 9.933 \times 10^4 c = 297.8$ km s^{-1}, and for NGC 1068 I find $v_{rot} \approx 4.988 \times 10^4 c =$ 149.5 km s^{-1}. These results are not terribly inaccurate, although very rough. Published data indicate the rotation velocity of NGC 7448 is approximately 150 km s^{-1} [5], while that of NGC 1068 is similar, 150 ± 50 km s^{-1} [4], where the large uncertainty is due to uncertainty as to the orientation of that galaxy's rotation axis.

Given that the resolution of my spectra is about 6.5 Å, it is impossible to measure the width of the Hα peaks to better than ± 6.5 Å, and thus the rotational velocity cannot be measured by this method to better than $\sim \pm 150$ km s^{-1}.

4 Problems and improvements

The method that I used to measure the rotational velocity is not very accurate, because I measured the dispersion of the Hα line as a single flat plateau. This would only give an accurate result if the rotational velocity decreased linearly outward from the center of the galaxy, and if the intensity of emission by each piece of the galaxy were the same. Clearly, this is not a realistic model.

Another problem with my model is that, for each galaxy, I used a single spectrum covering the whole width of the galaxy on the spectrograph slit. Thus the shifted Hα

lines from all parts of the galaxy are smeared together on the spectrum, making it very hard to determine the intensity of the line at different wavelengths. Also, this prevents me from drawing an actual curve showing rotational velocity as a function of distance from the center of the galaxy.

A difficult problem is that the true rotational velocity may be greater than the measured value if the axis of rotation is not perpendicular to the line from the observer to the galaxy. There is no easy way to precisely determine the rotational axis of a spiral galaxy. van Driel et al. note that they were unable to come up with reasonable rotational velocities for some of the galaxies they measured, probably because the axes were tilted.

To improve the accuracy of the rotational velocity measurements, there are several things that I could do:

- Use a finer diffraction grating or a longer focal-length lens on the spectrograph. This would improve the resolution of the spectra. For example, by using a 1200 lines/mm diffraction grating and a lens with a focal length of 135 mm, the dispersion of the spectrum would be 1.3 Å/pix. This would allow me to measure the width of the Hα line more accurately, and to get a better ballpark estimate for the rotational velocity using the above method.

- Measure multiple emission lines, and average the estimated rotational velocity determined from each of them. Multiple measurements would improve the accuracy of my estimated rotational velocities. Unfortunately, I could not use this method because on the spectrum of NGC 7448, the Hα line was the only one that I could identify with great certainty.

- Create separate spectra of thin slices of the galaxy outward from the center. This would allow me to produce a graph of $v_{rot}(r)$ for each galaxy, like the example in [3]. In the CCD images I used, I could not discern separate branches of the Hα line from each half of a galaxy, so I did not think I could reliably use this method.

A second observing session with a finer diffraction grating, longer focal-length lens, and longer exposures would probably be the most helpful next step to improve the accuracy of my rotational velocity measurements. It would allow me to state the results with less uncertainty that the current $\pm 150\ \mathrm{km\,s^{-1}}$.

Appendix: Spectral Data

Here are the wavelength and intensity (DN) data for the spectra of NGC 7448 and NGC 1068, around the region of the Hα and N II lines.

The intensity values were the output of `SPPHOT` and the matching wavelengths were the output of `FINDP`, as explained above.

	Intensity (DN)	
Wavelength (A)	NGC 7448	NGC 1068
6531.36	443	2295
6537.93	238	2300
6544.51	245	2301
6551.09	254	2330
6557.67	343	2474
6564.24	260	2595
6570.82	348	3009
6577.40	470	3184
6583.98	196	4378
6590.56	445	5881 H-al
6597.14	527	5862 H-al
6603.72	434	5122
6610.30	697 H-al	5672 NII
6616.88	706 H-al	5226
6623.46	724 H-al	4471
6630.05	458	3666
6636.63	523 NII?	3081
6643.21	328	2903
6649.79	440	2576
6656.38	360	2630
6662.96	348	2466
6669.54	309	2584
6676.13	315	2606
6682.71	281	2539
6689.29	322	2568
6695.88	356	2542

References

[1] 2002, NIST Atomic Spectra Database, ⟨http://physics.nist.gov/cgi-bin/AtData/main_asd⟩

[2] Dreyer, J. 1988, The Complete New General Catalogue and Index Catalogue of Nebulae and Star Clusters, ed. R. Sinnott (Cambridge: University Press)

[3] Hayes, M. 2002, Example: Galaxy Rotation Curve, ⟨http://astrosun.tn.cornell.edu/courses/astro201/rotcurve.htm⟩

[4] Richstone, D. O. & Morton, D. C. 1975, ApJ, 201, 289

[5] van Driel, W., Augarde, R., Bottinelli, L., Gouguenheim, L., Hamabe, M., Maehara, H., Baan, W. A., Goudfrooij, P., & Groenewegen, M. A. T. 1992, A&A, 259, 71