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Radial Velocity And Dark Matter Analysis of Spiral Galaxy UGC 9039

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ABSTRACT

Aims. This project examined a long-slit spectroscopic exposure of the UGC 9039 spiral galaxy in an attempt to derive the galaxy's edge-on spectrum, radial velocity, redshift and mass versus galactic radius. From this data, I aimed to derive the existence of dark matter in the galaxy to explain the behavior of the galaxy's rotational curve.
Methods. The data was processed through several standard procedures to remove noise, including creating dome flat images and background sky spectra; to remove intrinsic distortion in the present spectral lines, and then analyzed to extract the galaxy's spectra and measurements derived from it.
Results. With the data produced by this project, I was unable to conclusively derive the existence of dark matter in the UGC 9039 spiral galaxy. However, the overall results of the project imply the existence of unexplained mass in the galaxy, which has a visible effect on its rotation curve.

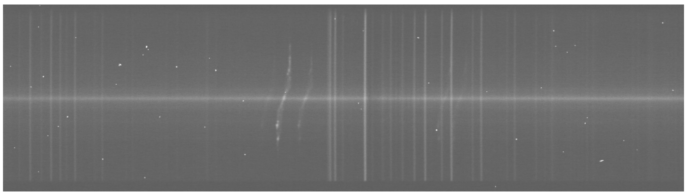

Fig. 1. The raw frame of the galaxy image, before any processing or noise removal.

1. Introduction

Spectroscopy is a branch of astronomy that analyses the electromagnetic spectra emitted or absorbed by astronomical objects. With a prism, diffraction grating, or a combination of both, light from an object of interest is split into discrete wavelengths that make up it's spectrum and captured by a telescope-mounted CCD.

Being able to observe and measure the wavelengths of light emitted by a galaxy, for instance, is of particular interest. Given its characteristic wavelengths, calculations can be made to determine the stellar makeup of the galaxy and by observing how the Doppler effect shifts the wavelengths, we can calculate the radial velocity, and the mass of the objects inside.

In this project, I analyzed an observation of the spiral galaxy UGC 9039 [3] in an attempt to calculate the radial velocity of the galaxy, its mass, and derive the existence of dark matter in the galaxy, to explain discrepancies in the profile of its radial velocity and mass.

2. Methods

2.1. Noise Removal

Before any useful information could be extracted from our data, a number of noise sources needed to be removed from our exposure data. The simplest among these to remove was instrument and bias noise from the telescope / CCD array itself. While the CCD provided automatic bias offsets to the image, another pass of noise removal was performed using provided bias frames and dome flat exposures to bring the galaxy image's background noise to a minimum. This process was performed using simple median combination and normalized median combination subtraction.

In order to remove singular and grouped bad pictures, a reduced version of our image was made by dividing it horizontally into 5 pixel tall "stripes". Taking the median of each 5 pixel stack in our stripes removed bright pixel spots across our image, caused by either CCD malfunction or cosmic-ray strikes.

2.2. Spectral Line Removal

The greatest source of unwanted signals in our image was the presence of distinct sky emission spectra. A number of steps were necessary to remove these lines to satisfactory degree.

In order to create a spectrum that consisted only of our background noise, I selected a band at the top of the image that appeared to contain no galaxy flux, while avoiding bad pixels on the edges of our image. Taking the median of the approximately 40 pixel band produced our background sky spectrum. However, when this spectrum was simply subtracted from the image, an unsatisfactory amount of the spectral lines were still visible. The optics of the Double Spectrograph introduced an intrinsic shift into all spectra in the image, that would need to be accounted for.

Much like before, I created a "striped" reduced image of the NeAr lamp calibration spectrum that was provided. Using the center stripe of the spectrum as a reference, every other stripe in the image was cross-correlated with the reference stripe, creating discrete shifts for every spectra in the image. This process was repeated for the galaxy image, using the center spectrum of the galaxy as reference compared to every other spectrum in the image.

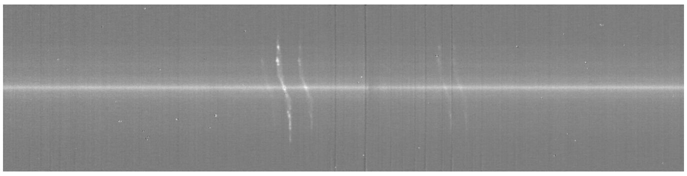

Fig. 2. Our galaxy frame, corrected for background noise, bad pixels and spectral line removal.

Most of the intrinsic shifts in the image were at the sub-pixel level, which meant simple cross-correlation and rolling of the sky spectrum would not suffice. Spline interpolation at 10x resolution was performed to create enough data points to allow adequate comparison and subtraction. A standard background shift was created using our previously chosen sky region and the difference between it and the subsequent galaxy spectra were used to shift and subtract our sky spectrum. The image produced was much cleaner, with the visible majority of the spectral lines now removed.

2.3. Spline Interpolation / Cross Correlation

Spline interpolation allows for interpolation of functions or data without some of the oscillatory end effects of polynomial interpolation. In our case, this allows us to create sub-pixel data, allowing the comparison of spectra where don't have points provided. Rather than implement the spline interpolation algorithm ourselves, I used the splrev and splev functions that are part of the Numpy package. The splrev function creates a spline matching x-y data provided to it, and the splev function then evaluates that spline at a new set of data points, returning the interpolated y values.

Additionally, our cross correlation function uses the correlate Numpy function to do the heavy lifting. When provided with two sets of functions, our cross correlation method pads either end of the data with zeros to prevent overlapping and subtracts the data's mean to 'ground' the data to the x-axis. The two functions are then 'rolled' across each other over a range of provided steps, and the correlate function is used to generate the highest correlation value between the two. Obtaining our desired shift is as simple as matching the index of the highest correlation to the provided shift values.

2.4. Doppler Shifts / Spectrum Matching

In order to determine how much any of our given spectra in the image were shifted, cross correlation between the galaxy's reference spectrum and the rest of the spectra in our image was performed again. This time, any regions not containing galaxy flux, mostly the outermost edges of the image, were thrown away. This provided a clear graph of the spectrum being shifted, however, it only provided those shifts in terms of the images pixels.

In order to determine the wavelengths the shifts represent, we needed to match our image's spectra to a line atlas. By simply downloading [2] a plot of a synthetic HeNeAr lamp spectrum and using a graphics program to line up the image to our galaxy spectrum (seen in Fig.3), we could assign wavelengths to our pixels. Note the wavelength intensities do not necessarily match. From here, the dispersion of the wavelengths in our image, (the angstrom value per pixel) could be determined using by calculating the ratio between the center-center distance of the two outermost spectral lines in our lamp image, and their spread in angstroms, given by:

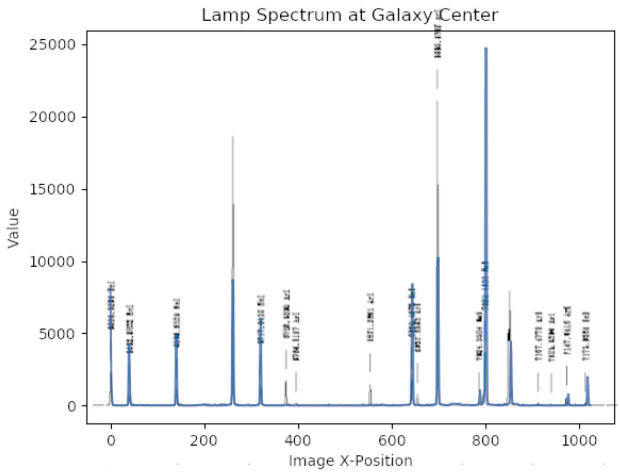

Fig. 3. An overlay of our calculated galaxy spectrum and a HeNeAr line atlas.

$$dispersion = \frac{\Delta\lambda}{\Delta pixels}$$

2.5. Distance / Radial Velocity

With the wavelength value per pixel in hand, the radial velocity for our galaxy spectra could now be calculated. First, the wavelength shift values were calculated by the determining the pixel distance between a galactic spectrum, and one of our calculated lamp spectral lines. The radial velocity of the spectrum could then be determined by the following Doppler shift equation:

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

where v is our radial velocity.

Using provided values for the for the redshift of the galaxy, and the Hubble constant, the approximate distance to the galaxy was found to be approximately 150 Mpc, however current Simbad measurements puts the galaxy at ≈194 Mpc.

2.6. Galactic Radius / Mass Enclosed

Using the CCD spatial scale reference (arc-seconds/pixel) present in the header data of the FITS file, and the small-angle approximation, the approximate radius of the galaxy was calculated using:

$$\frac{\theta_{arcseconds}}{206265} = \frac{d}{D}$$

where d is the radial distance per pixel, and D is the distance to the galaxy. The galaxy was determined to be approximately 50 kpc in radius, which plants it firmly within the spiral galaxy range of 5-100 kpcs.

Assuming the orbits of the mass of the galaxy to be circular, the mass enclosed within each striped radius of the galaxy was determined using the Kepler relation:

$$M = \frac{v^2 r}{G}$$

where v is the radial velocity at that stripe, r is the radial distance and G is the gravitational constant.

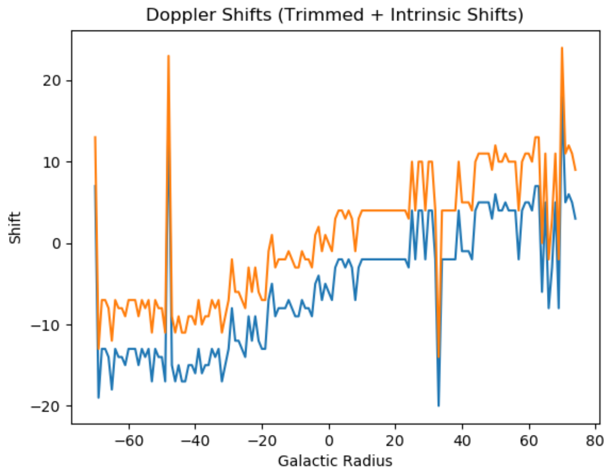

Fig. 4. Pixel doppler shifts of galaxy flux above and below zero-velocity center.

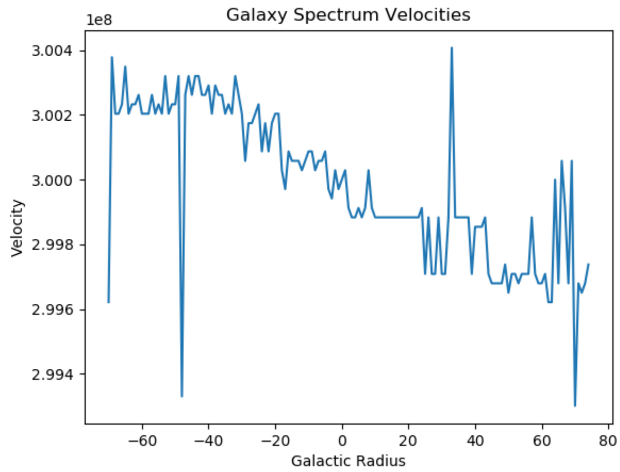

Fig. 5. Radial velocities as a function of distance from the galactic center.

3. Analysis

3.1. Doppler Shifts

The Doppler shift values calculated appear to follow what one can visually see in the galaxy image. When the shifts are trimmed to only include galaxy flux, and are corrected for intrinsic shift due to the instrument, the data forms a curve that resembles the S-shape of the galaxy itself, seen in Fig.4

However, in my data there are a great number of outlier shifts visible, spiking past ±20 pixels. I believe these irregularities are caused by an issue with my cross-correlation function, discussed in the Error Analysis section of is paper.

3.2. Radial Velocity / Radial Distance

Using the data from our Doppler shift calculations, I was able to determine the approximate radial velocities of each galactic spectrum. Much like the Doppler shift values (and because of them) my calculated values for the radial velocities have a number of spikes in them that seem to be errors. However, the approximate shape of the curve itself appears to be correct as can be seen in Fig.5. Unusually, this also means that some of the velocities appear to be exceeding the speed of light, which almost certainly cannot be true. As discussed in the Error Analysis portion, residuals for the curve were not calculated, however I am not sure how useful they would have been considering the state of the data.

As it was much more easily calculated, our values for the galactic radius at each pixel are much more reasonable, providing more or less a straight curve. Because there is no variation in the size of the pixels (as a result of a faulty detector) the radial distances are uniform over the pixel values, and gave us an overall radius of ≈25Kpcs. This falls within the expected diameters of spiral galaxies of between 5-100 Kpcs[1].

3.3. Galaxy Mass

The largest issue with the data comes with the calculation of the mass enclosed (Fig.6). Realistically, this result should not be a straight line, but should have a bulge toward the center of the radius, and taper off on either side. Even by strictly observing the image, we can see the fall-off of luminous matter.

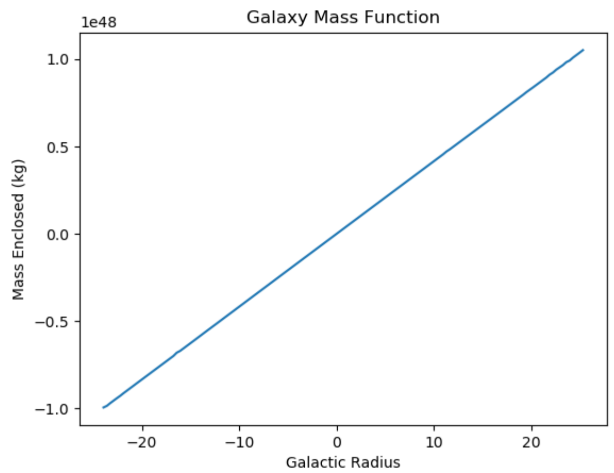

Fig. 6. Mass enclosed in galaxy per spectral radius.

Now, taking what we know of the existence of dark matter already, the mass function should technically approach somewhat of a straight line as it reaches the edges of the galactic radius. This is the principle idea of dark matter, that there is non-visible matter in the arms of these galaxies. This is the cause of the straightening effect seen in the radial velocity graph.

3.4. Error Analysis

Unfortunately, due to time constraints, a comprehensive analysis of error propagation in the project was not performed. Calculating uncertainties in our radial velocities, radial distances and enclosed masses are unfortunately critical in being able to provide a valid and solid analysis of the data. Because of this, I have elected not to make any definitive statements about the results; it would be improper to do so without knowing what uncertainties the data might have. Since the velocity, distance and mass data all rely on one another, not knowing the uncertainty in one set of values can drastically affect the rest. However, I can look at some general error topics that were present in the analysis.

One of the largest sources of trouble in the project was my cross-correlation function. While some correlation / shift calculations provided clear results, like those done on the lamp data, calculating shifts with the correlation function on the galaxy data seemed to be somewhat unreliable. While, the analysis produced plausible data for the radial distances in the end, the data it returned was often irregular, with shifts jumping to erratic values. One source of that behavior may have been the presence of some bad pixels in the galaxy frame. While creating the 'reduced' image removed many bad pixels, the cross correlation routines were run on the full-frame galaxy image to provide the maximum amount of signal. This was especially present in the removal of the sky spectral lines. While the correlation function provided somewhat reasonable shift values, a constant shift of -8 pixels needed to be added so the shifts sat squarely on the spectral lines. This may have also been the contributing factor to the erratic values seen in the shifts of some of my galaxy spectra.

Without a clear grasp of the error present in my data, and an awareness of a major contributor of error in my cross-correlation function, I don't feel confident making definite statements about the results, but can only look at the broader picture they indicate.

4. Conclusions

This project was met with mixed success, and an overall inconclusive result.

While there was some difficulty calculating the intrinsic shifts in the sky spectral lines for noise removal, the comparison of the corrected vs raw galaxy frames shows a marked improvement in background/bias noise, bad pixels, and spectral line removal. However, what artifacts did remain may have been a contributing factor in the problems with my cross-correlation function. On the other hand, the data produced by our Doppler shift, wavelength matching and radial velocities are not too far from where they should be, though they all do have erratic values and outliers in them. This is the best evidence my project produced of the existence of dark matter. As can be seen in the edges of the velocity graph, the velocities tend to straighten out, which would imply the presence of additional mass not accounted for by Keplerian dynamics. Without an 'invisible' mass, the velocity curve would decline as it moved outward.

Unfortunately, I cannot conclusively say I derived the existence of dark matter. There seems to be an issue in my calculation of the enclosed mass of the galaxy, as the plot produced does not resemble even the non-dark matter mass function, and without any signficant error analysis, I cannot draw any definite conclusion.

References

[1] Spiral Galaxies, http://astronomy.swin.edu.au/cosmos/S/Spiral+Galaxy
[2] HeNeAr Spectral Atlas, http://iraf.noao.edu/specatlas/henear/henear.html
[3] Simbad UGC 9039, http://simbad.u-strasbg.fr/simbad/sim-basic?Ident=UGC+9039