Project reports

Your report does not need to be very long or detailed. However, it does need to reflect an understanding of what the experiment was for, it needs a description of the procedures you followed and all the data you collected in legible form, and it needs a concise presentation of the results and their meaning. Traditionally, these reports are written in a bound laboratory notebook along with your measurements (recorded in real time). In this age of word processors and spreadsheets, though, the lab-book-report practice seems a bit restrictive; we will therefore accept word-processed lab reports, so long as you also maintain notes in a bound notebook in real time while you are doing the experiments and have that notebook available for backup and reference.

The following is an example of a lab report to which I would give a score of 100 out of 100. Note that the contents of the report do not refer to the experiment we are doing this semester; it is provided only as an example of format and level of detail. Do not slavishly follow the model — modify according to the nature of the experiment.

Project 3: Doppler velocity and distance measurements of spiral nebulae

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1 Introduction and purpose

In Project 2, we showed that the spiral nebula M 31 is too far away for an object within the Milky Way Galaxy, but instead is itself a galaxy much like the Milky Way. Here we will proceed under the assumption that the other spiral nebulae are also galaxies and explore the dynamics of this population of objects by measuring the speeds of some prominent examples. For simplicity, we use a selection of spiral nebulae that all have the same shape and overall color but cover a range of brightness and angular size. We will obtain the distance to each nebula by scaling each one's brightness to that of M 31, for which we measured the distance last week. In turn, we can determine the velocity along the line of sight for each nebula by a measurement of the Doppler shift of spectral lines. With these data, we can look for trends in the motions of spiral nebulae and their distances from the Milky Way.

2 Procedure and measurements

It was clear last Wednesday night, 10/3/29, and with the TAs and one other group (F. Pease and V. Slipher), we drove down to the observatory. Previously, we had split up among our teams the list of nebulae presented in the lab manual. Each group tried to observe half, with the idea of sharing the results for our lab reports. As it turned out, we observed all eight of our objects. The other team only got two done before the clouds came in. The TAs told us that ten was enough so we stopped there.

Object	Signal [DN per second]	m (from Eqn. 1)	Δn for H line [mm]	Δn for K line [mm]	λ_H [nm]	λ_K [nm]
NGC 4472	2.35×10^{-1}	12.5	0.013	0.013	398.0	394.6
NGC 7619	1.48×10^{-2}	15.5	0.058	0.057	401.8	398.4
NGC 385	1.62×10^{-2}	15.4	0.070	0.069	402.9	399.5
NGC 2563	9.34×10^{-3}	16.0	0.073	0.072	403.2	399.7
NGC 1277	6.46×10^{-3}	16.4	0.079	0.078	403.7	400.3
NGC 4853	3.72×10^{-3}	17.0	0.113	0.112	406.7	403.2
Baade 24*	1.48×10^{-3}	18.0	0.178	0.177	412.4	408.9
Leo #1	5.90×10^{-4}	19.0	0.296	0.294	422.7	419.1
NGC 6702	7.09×10^{-2}	13.8	0.036	0.035	399.9	396.5
NCG 4051*	5.38×10^{-1}	11.6	0.010	0.009	397.6	394.2

Table 1: Measurements of magnitude and CaII H and K wavelengths

* Objects observed by Pease and Silpher

For each of our galaxies, we took V-band images and spectra using the camera and spectrograph as we had in the lab in Project 1. Our calibration objects were the star Vega, which we observed at the beginning of the night and which we assumed to have a magnitude of zero at all wavelengths, and the star Deneb, which provided spectral lines useful as a wavelength reference. The printer in the lab was not working very well last night, so we only got one good copy of the images and spectra. We agreed for these to appear in Milt Humason's lab report, since he was the one who spent the most time struggling with the printer.

From the images, we determined the total brightness of each nebula by adding up the signal (in "data numbers") at each point in the image, divided by the exposure time. We generated this same summed signal for the image of Vega, and calculating the magnitudes by using

$$m = m_{\mathrm{Vega}} + 2.5 \log \left(\frac{S_{\mathrm{Vega}}}{S} \right) = 2.5 \log \left(\frac{S_{\mathrm{Vega}}}{S} \right) \tag{1}$$

The signal of Vega was $S_{\mathrm{Vega}} = 23470$ data numbers per second. From our spectra, we measured the wavelengths of the H and K lines of singly-ionized calcium. We assumed that the wavelengths of these lines in the spectrum of Deneb were at the rest wavelengths, 396.8 nm and 393.4 nm, and calculated the wavelengths of lines in the spiral nebulae by the relation we used in Experiment 1:

$$\lambda = \lambda_0 + D\Delta n \tag{2}$$

where D is the spectrograph dispersion in nanometers per millimeter, λ_0 is the rest wavelength, and Δn is the displacement of the line from the reference point in millimeters. In Project 1, we determined D to be 87.5 nm mm^{-1}. The results of all of our measurements, and those of the other team, are shown in Table 1.

If we assume all these spiral nebulae to have the same absolute magnitude M as M 31, for which we determined $M = -13.8$ in Project 2, we can derive their distances from their apparent magnitudes, m, by using

$$\log d = 0.2m - 0.2M + 1 \tag{3}$$

where d comes out in parsecs. The velocities can be found from the measured wavelengths λ by using the formula for the Doppler shift,

$$V = c \left(\frac{\lambda - \lambda_0}{\lambda_0} \right) \tag{4}$$

Object	Distance, from Eqn. 3 [Mpc]	Velocity, from Eqn. 4
NGC 4472	1.8	890
NGC 7619	7.2	3810
NGC 385	6.9	4630
NGC 2563	9.1	4820
NGC 1277	11.0	5230
NGC 4853	14.5	7500
Baade 24	22.9	11800
Leo #1	36.3	19600
NGC 6702	3.3	2350
NGC 4051	1.2	630

Table 2: Distances and velocities of our spiral nebulae

where λ_0 is the rest wavelength and c is the speed of light, 299792.458 km/s. In Table 2 we present the results of this set of calculations, and in Fig. 1 we plot the velocities against the distances for our list of spiral nebulae.

We estimate the uncertainties in our nebular magnitudes to be ± 0.2 and the uncertainty in our measurements of Δn to be 0.002 mm. This corresponds to an uncertainty in distances of about 10% and an uncertainty in velocities of about 100 km/s.

There is a trend that emerges at a glance either at Table 2 or at Fig. 1: velocity and distance of spiral nebulae increase in tandem. As suggested in the lab manual, we drew a line through the data points by eye and measured the slope of this line. The line that looked like the best fit had a slope of

$$\frac{\Delta V}{\Delta d} = 558 \text{ km s}^{-1} \text{ Mpc}^{-1} \tag{5}$$

3 Conclusions

Two main conclusions can be drawn from our observations. First, all of the velocities we derive are positive: all the spiral nebulae on our list are *receding* from us. Second, the speed at which a given nebula recedes from us increases with its distance. If we discount the possibility that these objects are being repelled by the Milky Way in some strange way, then our measurements can be taken to indicate an expansion inherent in the population of spiral nebulae.

In class, we learned that models of the Universe that follow Prof. Einstein's recent theory tend either to be expanding or contracting, or — if a constant of the right value is added *ad hoc* to the equations of motion — to be static. The expanding models, in turn, have the property that all points in the universe would appear to recede as viewed from all other points, and to recede faster the more distant they are. Our results support such models.

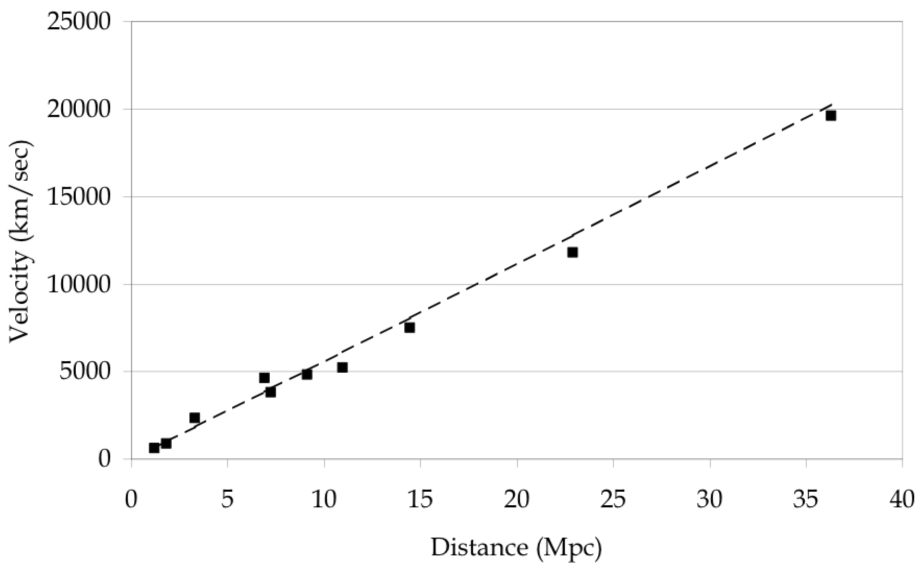

Figure 1: Velocities and distances for our list of galaxies (squares), and a line through the origin with slope 558 km/s/Mpc.