Ay 127

Cosmology and Galaxy Formation

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Problem Set 1

Due **in class**, Thursday 18 January 2018

Reading: See the on-line syllabus for lecture-by-lecture readings.

Collaboration policy: See the on-line collaboration policy.

Homework Problems:

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1. **Measure a redshift yourself:** Figure 1 shows the spectrum of a (real) galaxy, randomly selected from the millions in the SDSS database. You are to identify the spectral lines and figure out its redshift. The rest (laboratory-measured) wavelengths of some famous strong spectral lines commonly observed in absorption in the atmospheres of the old sun-like stars which make up galaxies like this are given in the table below (not all of these may be easily apparent in the spectrum). See if you can identify *at least* five absorption lines in the spectrum, and determine the redshift of the galaxy. [hint: one approach is to measure the wavelengths of the absorption features in the spectrum, make a matrix of the ratios of all those wavelengths with those in the table below, and look for a commonly repeated number, which will be $1 + z$. Or you may think of faster methods.]

ion	wavelength (Å)
Ni I	3524
Fe I	3815, 3820,3825
Mg I	3832, 3838
Ca II, K	3934
Ca II, H	3968
Fe I, G	4308
Ca I	4227
Hγ	4340
Hβ	4861
Mg I	5167, 5172, 5183
Na I, D	5890, 5896
Hα	6563

2. **Practice with Galaxy data:** Use the NASA Extragalactic Database (NED) `http://ned.ipac.caltech.edu` to look up the galaxy NGC 2639.

   a) Click on the Images box in NED's Detailed Data on NGC 2639. Browse through the images until you find one which you feel will be useful for determining the Hubble type (see Figs 2.7 and 2.8 on p 38-39 of the Mo, van den Bosch & White text), and do your best to determine the Hubble type. Hint: if you download a FITS file, the extreme dynamic range of astronomical images may require manipulation of the map between photons/pixel and brightness on your computer screen to show the features of the galaxy best. A free tool to do this is DS9: `http://hea-www.harvard.edu/RD/ds9/`. Try the "scale" menu and the "zscale" therein.

   b) Estimate the inclination angle between the vector normal to the disk and the vector from earth to NGC 2639, in degrees (90 for edge-on disk, 0 for face-on)

   c) The observed radial velocity of the stars in the disk as a function of position along the center of the long axis of NGC 2639's disk are shown in figure 2. If you consider stars orbiting in a circle, the observed radial velocity in the orbit along the major axis of the circle's projected ellipse is less than the orbital velocity unless the inclination is 90 degrees (it is 0 if the inclination is 0 degrees!). Figure out the inclination correction for the inclination you estimated in the previous part, and apply it to the data, to determine

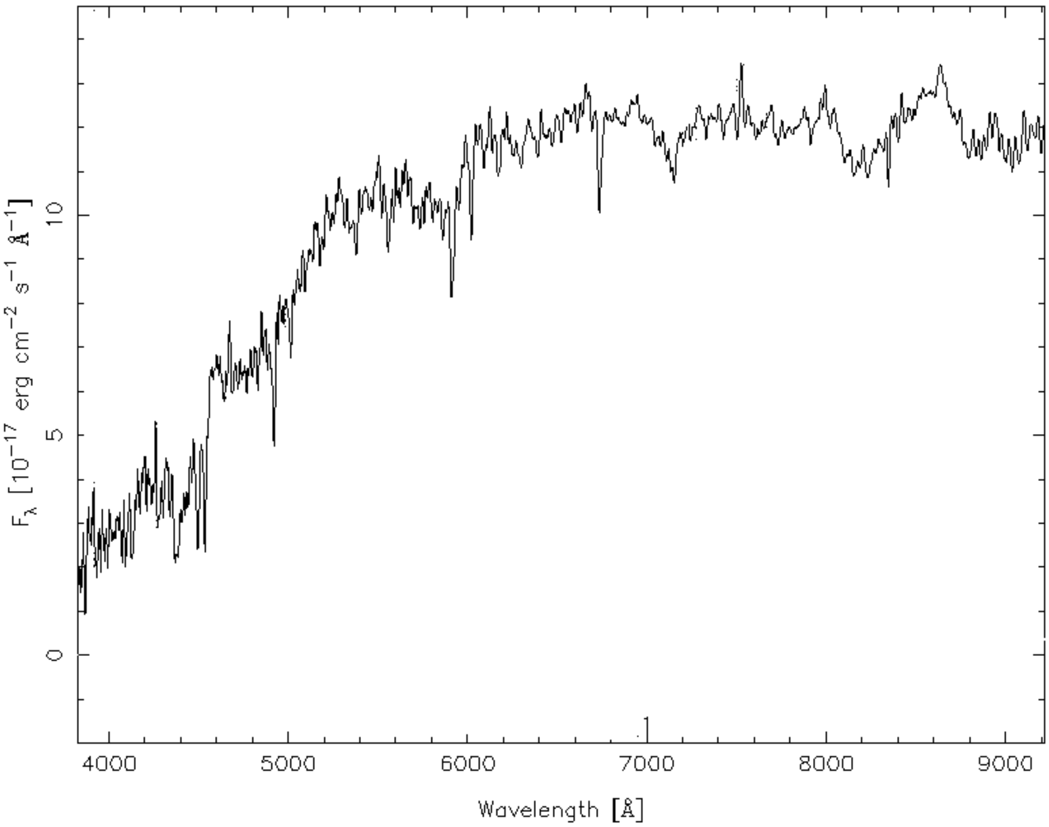

Figure 1: The spectrum of an elliptical galaxy. The vertical axis shows the flux of radiation per unit of wavelength. The horizontal axis shows the wavelength in Ångstroms (1Å=0.1nm), blue on the left, red and then near infrared on the right.

i. the heliocentric radial recession velocity of the center of NGC 2639, and

ii. the maximum rotational orbital velocity about that center of the stars in NGC 2639.

iii. The distance to NGC 2639. Pretend both it and the sun are cosmic observers (actually the sun is not, moving at a few hundred km/s around the Milky Way, which in turn is falling towards the Virgo cluster. This introduces only a 10% distance error, which you may neglect for the purposes of this problem. NGC 2639 is presumably moving at a similar, but unknown, velocity relative to cosmic observers). Use a Hubble constant $H_0 = 73\text{km s}^{-1}\text{Mpc}^{-1}$.

d) Go to the Sloan Digital Sky Survey server, `http://skyserver.sdss3.org/dr8/en/tools/chart/navi.asp` and enter the coordinates (in decimal equatorial) that NED gives you for NGC 2639. You should get an image, with sky-subtracted magnitudes (integrating flux from each solid angle over solid angle out to the limits where the galaxy is detectable) in 5 color bands (u,g,r,i,z). [1] The absolute magnitude of the sun in those bands is respectively (6.55, 5.12, 4.68, 4.57 and 4.60). Calculate the luminosity of the galaxy in $L_{\odot,g}$ —i.e. how many suns would be required to produce the NGC 2639's luminosity in g band?

3. **Measuring distances with standardish candles** Suppose you have identified a "standard candle" which (somehow) you have established has an intrinsic "scatter" of 0.35 magnitudes in luminosity (1

[1]If you are curious about what exactly the filter bands are, see http://www.sdss.org/dr5/instruments/imager/#filters. As you might have guessed, g band covers green and blue light, and r band covers red and yellow light.

sigma), and can be used successfully to measure relative distances (independent of measured radial velocities) out to $cz = 10,000$ km s^{-1}.

a) How many measurements of such objects, over the whole sky, would be required to verify that the volume probed is "at rest" with respect to the cosmic microwave background (the net error in velocity should be smaller than 150 km s^{-1})?

b) How many measurements of the same objects would be necessary, in principle, to measure H_0 to $\sim 10\%$ accuracy if the volume is not subject to large scale flows or significant peculiar velocities? State all of your assumptions–there is no exact "right" answer, but your reasoning is important. Comment on why, in the real world, things aren't so easy. [Hint: remember that the direction of peculiar velocities will not always be along our line of sight...]

4. **Fiat lux:** Suppose that at some time in the very recent past all the hydrogen and helium (baryon density $\rho_b = 4.2 \times 10^{-31}$g cm^{-3}, about 75% hydrogen (= 1 baryon) by mass and 25% helium (= 4 baryons) by mass) in the universe had been instantly fused into iron in stars, and the released energy thermalised into black body radiation (Fred Hoyle, in a valiant attempt to save the steady-state theory, proposed that iron needles could have large enough cross-section at the relevant wavelengths to do this).

   a) Calculate the current temperature of this black body radiation.

   b) At what wavelength would the black body spectrum peak, and what region of the electromagnetic spectrum would this be (e.g. gamma-ray, infrared, radio, etc?).

   c) The mean bolometric luminosity per unit volume emitted by stars in the universe today is about $3 \times 10^8 L_\odot$Mpc^{-3}. How long would it take stars at this rate to fuse all the hydrogen and helium in the universe? Compare to the present age of the universe.

   d) Explain how your results above may be applied to Olber's paradox.

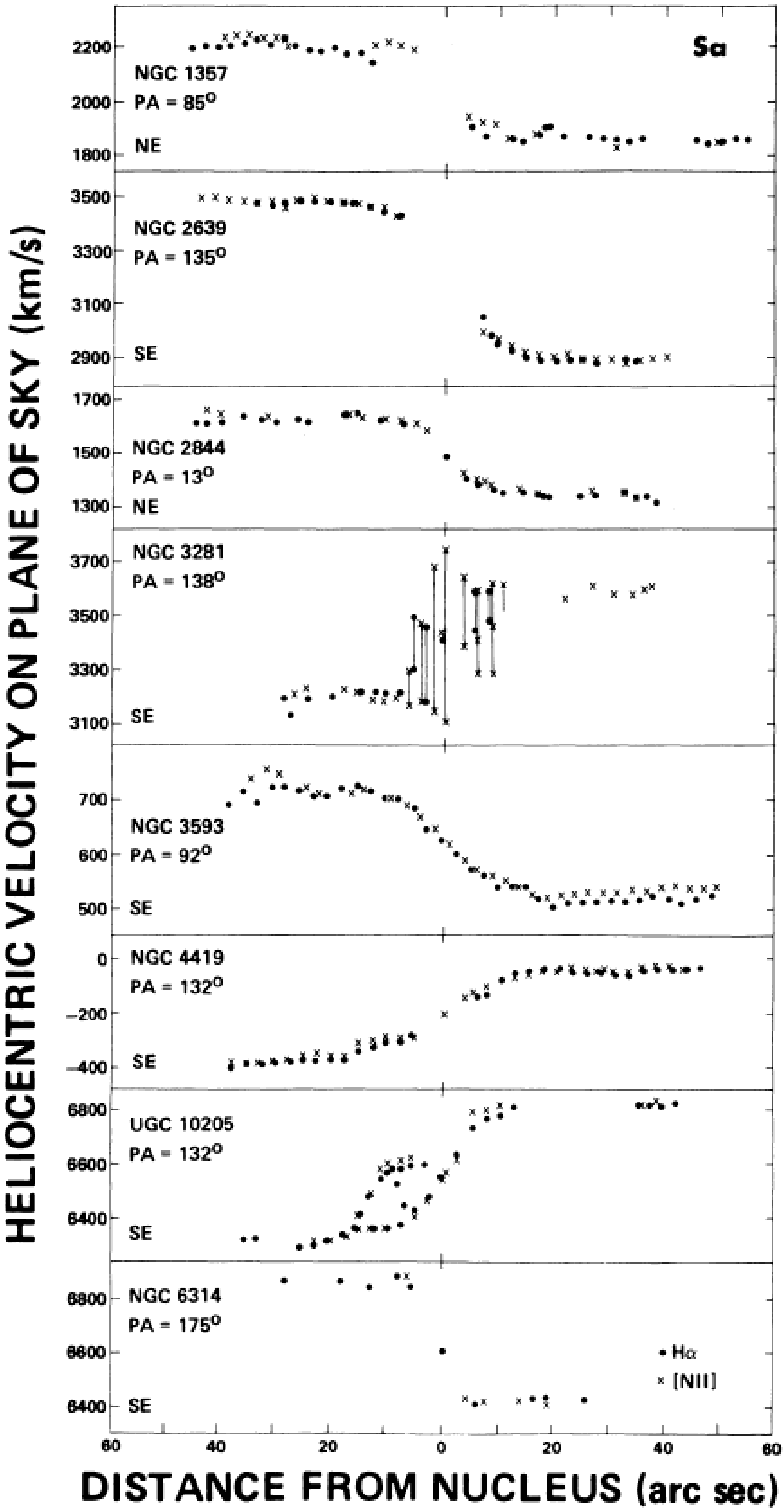

Figure 2: The radial velocity (relative to the sun) versus sky position (in arcseconds from the galaxy center) along the observed major axis for several galaxies, including NGC 2639.