PEU 327 – Spring 2025
Observatinal Astrophysics Laboratory

Lab (9) Manual

Physics of Universe (PU) Program
University of Science and Technology at Zewail City

Contents

Galaxy Photometric Populations, Structure, & Stellar Kinematics

This Lab will be conducted in pairs[1].

[1]Please state explicitly in your report the tasks performed by each group memeber.

Grading Sheet

		Grade
Experiment (XVII)		30
Experiment (XVIII)		30
Jupyter Notebook[2]		10
Total		70

[2]This Lab should be submitted as a Jupyter Notebook file or its PDF version which includes your codes/work, output/results, and answers/discussion. (Please do not submit a Google Colab link.) A LaTeX report could be alternatively submitted as long as it comprehensively and neatly shows your work.

Experiment (XVII)

The Photometry of the Pinwheel (Messier 101) Spiral Galaxy

Introduction

In this experiment, you will study the surface brightness of Messier101 (M101) and use the Tully-Fisher relationship – you learned about in Lab 09 – to estimate its circular velocity. The M101 galaxy is also known as the Pinwheel galaxy, figure 3 is one of the largest images Hubble has ever captured of a spiral galaxy. Assembled from 51 exposures taken during various studies over nearly ten years, this infrared and visiblelight image measures 16,000 by 12,000 pixels. Ground-based images were used to fill in the portions of the galaxy that Hubble did not observe.

The giant spiral disk of stars, dust and gas is 170,000 light-years across — nearly twice the diameter of our galaxy, the Milky Way. M101 is estimated to contain at least one trillion stars. The galaxy's spiral arms are sprinkled with large regions of star-forming nebulas. These nebulas are areas of intense star formation within giant molecular hydrogen clouds. Brilliant, young clusters of hot, blue, newborn stars trace out the spiral arms.

Pierre Méchain, one of Charles Messier's colleagues, discovered the Pinwheel galaxy in 1781. Located 25 million light-years away from Earth in the constellation Ursa Major, M101 has an apparent magnitude of 7.9. It can be spotted through a small telescope and is most easily observed during April.

Figure 3: The Messier 101

Procedures

Surface photometry is a technique to quantitatively describe the light distribution of galaxies recorded in 2-dimensional images. Mihos et al. investigated the photometry of the optical disk of the spiral galaxy M101. The data file attached, M101.dat, includes the surface brightness in B and V ($^{\text{mag}}/_{\text{arcsec}^2}$) as a function of radius (arcminutes).

Plot the B-band surface brightness, μ_B, as a function of radius (scale y-axis so that bright is towards the top), and fit a straight line to the profile. From the parameters of your fit, work out the following information:

1. The central surface brightness, μ_0, ($^{\text{mag}}/_{\text{arcsec}^2}$).
2. The radial scale length of the disk (arcmin).
3. R_{25} (arcmin) — the radius of the $\mu_B = 25\,^{\text{mag}}/_{\text{arcsec}^2}$ isophote.
4. The total apparent B magnitude ($m_{tot,B}$) of the galaxy.

The total luminosity of an exponential disk is given by $L_{tot} = 2\pi I_0 h^2$ where I_0 is the central luminosity density ($^{L_\odot}/_{\text{pc}^2}$) and h is the scale length (pc). The same relationship holds for the observed quantities: $f_{tot} = 2\pi f_0 h^2$; where f_{tot} is the total flux, f_0 is the central flux density ($^{\text{flux}}/_{\text{arcseconds}^2}$), and h is now in arcseconds. Deduce the total apparent magnitude given by $m_{tot} = -2.5 \log f_{tot} + C$ in terms of μ_0.

5. The B-band central luminosity density[4] ($I_{0,B}$) of the galaxy.

On your plot, mark the level of the night sky brightness ($\mu_B \approx 22.5\,^{\text{mag}}/_{\text{arcsec}^2}$), and also mark where the galaxy's surface brightness drops below 1% of that night sky brightness. Now adopt a distance of $d = 6.9$ Mpc, and work out the following:

1. The radial scale length (kpc).
2. The absolute B magnitude (M_B) of the galaxy.
3. The B-band luminosity of the galaxy in solar units.

Finally, use the Tully-Fisher relationship to estimate M101's circular velocity. In the 1910s, Adrian van Maanen claimed to have detected M101's rotation by observing the proper motion of stars in its outer disk. How long would it take a star at R_{25} to move 1 arcsecond due to its orbital motion? If van Maanen's measurement of proper motion was correct (roughly 1 arcsecond motion over 10 yr), how fast would M101 have to be rotating?

[4] The connection between μ and I is $\mu_B = -2.5 \log I_B + 27.07$

Experiment (XVII)

Reproducing Schechter Luminosity Function of Galxies

Introduction

In this Lab, you will build a Luminosity function for galaxies using Data Release 16 provided by the Sloan Digital Sky Survey (SDSS), and compare it with the approximate shape of the typical Luminosity function for galaxies introduced by Schechter in 1976.

It is of great intrest to explore the relative numbers of galaxies of various Hubble types. This is usually represented by the luminosity function, $\phi\left(L\right)dL$, defined to be the number of galaxies in a particular sample that have absolute magnitudes between L and $L+dL$. In an attempt to find a general analytic fit to galactic luminosity functions, Paul Schechter proposed the functional form:

$$\phi\left(L\right)dL = \frac{\phi_*}{L_*}\left(\frac{L}{L_*}\right)^{\alpha} e^{-L/L_*}dL$$

where α and L_* are free parameters that are used to obtain the best possible fit to the available data. So, in this lab you will use the data of SDSS to build your own luminosity function. The Sloan Digital Sky Survey (SDSS) is one of the most ambitious and influential surveys in the history of astronomy. Over eight years of operations (SDSS-I, 2000-2005; SDSSII, 2005-2008), it obtained deep, multi-color images covering more than a quarter of the sky and created 3-dimensional maps containing more than 930,000 galaxies and more than 120,000 quasars.

Procedures

Your First Task: Rewrite the Schechter function defining the number of galaxies per unit luminosity, $\phi\left(L\right)dL$, using the conversion between absolute magnitude and luminosity to give the number of galaxies per unit magnitude, $\phi\left(M\right)dM$. Start with $\phi\left(L\right)$, and replace L with M using the magnitude-luminosity equation:

$$M = -2.5\log L + C$$

Then, take the derivative of M with respect to L to get ${}^{dM}/_{dL}$ so that you can replace dL with dM. Once $\phi\left(M\right)dM$ is worked out, derive the slope of the faint end when luminosity functions are plotted logarithmically (i.e., derive ${}^{d(\log\phi(M))}/_{dM}$ for the faint magnitudes) and show mathematically that in such a plot $\alpha = -1$ corresponds to a flat faint end slope.

Your Second Task: Construct a Luminosity Function (LF) for galaxies and measure this faint end slope. Go to the SDSS DR16 SQL search page and run the following SQL query, downloading the file in any format you can handle using Python.

```
SELECT
  TOP 100000
  P.objID, P.flags_r,
  P.ra, P.dec, P.dered_g, P.dered_r, P.dered_i,
  P.err_g, P.err_r ,P.err_i,
  P.petroR50_g,P.petroR90_g,
  S.z, S.zErr, S.velDisp, S.velDisperr,
  E.oh_p50, E.lgm_tot_p50, E.sfr_tot_p50
FROM Galaxy AS P
  JOIN SpecObj AS S ON P.objID = S.BestObjID
  JOIN galSpecExtra AS E ON S.SpecObjID = E.SpecObjID
WHERE S.z > 0.00001 AND S.z < 0.3 AND P.dered_r < 17.5
  AND ((P.flags_r & 0x10000000) != 0)
  AND ((P.flags_r & 0x8100000c00a0) = 0)
  AND (((P.flags_r & 0x400000000000) = 0) OR (P.err_r <= 0.3))
  AND (((P.flags_r & 0x100000000000) = 0) OR (P.flags_r & 0x1000) = 0)
```

Use the redshifts to get distances using Hubble's law, and then use those distances to work out the absolute r-band magnitude ($\mathrm{M_r}$) of each galaxy[5]. Now, naively we could just make a luminosity function by making a histogram of $\log N$ as a function of $\mathrm{M_r}$ but that would be bad because this is a magnitude-limited dataset, and it is easier to see bright galaxies than faint galaxies, so we would erroneously undercount the faint galaxies. Instead, we will build a weighted histogram, where we weight the counts inversely by the maximum volume out to which we could find each galaxy given its absolute magnitude.

So first, for each galaxy, given its absolute magnitude $\mathrm{M_r}$ and the apparent magnitude limit of the catalog $(m_{r,lim} = 17.5)$, write down an expression for the maximum distance, d_{max} (Mpc), to which we could see it; in other words, at what distance would its apparent magnitude match our limiting magnitude? Then for each galaxy work out the spherical volume, V_{max} (Mpc^3), corresponding to that d_{max}.

Now we are ready to make the LF, properly weighted by $1/V_{max}$. Use the following numpy-based snippet of code to make a plot of the log of the weighted counts in bins of absolute magnitude that run from -24 to -16 in steps of 0.25 mag:

```
mbins = np.arange(-24, -16, 0.25)
hist, edges = np.histogram(absmag_r, bins=mbins, weights=1/Vmax)
bincenters = 0.5*(mbins[1:]+mbins[:-1])
logN = np.log10(hist)
plt.scatter(bincenters, logN)
```

[5]For this problem ignore cosmological effects and just assume that Hubble's law and flat Euclidian geometry work. They actually do not on these scales; we are looking at galaxies that are far enough away that we should actually take into account the proper geometry of space. Ignoring this introduces errors into our calculation, but they are not so large as to render this exercise useless

Your Third Task: Compare the shape of your LF to that of Montero-Dorta & Prada "All Galaxies" LF. (Do not worry that the y-axis values do not match, since we have not normalized the LF the same way. But the shape should look comparable.) On your LF, sketch where the Montero-Dorta & Prada value for M_* lies, making sure to correct their $M_* - 5\log h$ value for the Hubble constant you have used in your analysis; describe what Hubble constant you used, and thus, what you calculate for M_*. Does this M_* seem to be reasonable for your LF? In general, describe how well or how poorly your LF follows the approximate shape of a Schechter function – where does it look reasonable, where (if anywhere) does it not?

Next, choose a range of absolute magnitude over which to fit the faint end power law slope, justify that choice, and fit a straight line to $logN$ vs M_r over that range to derive the parameter α for the Schecter function. Plot your fit over your data to make sure your fit looks reasonable. Discuss any systematic uncertainties that might be affecting your derived value for α.