Astronomy Exercise 7

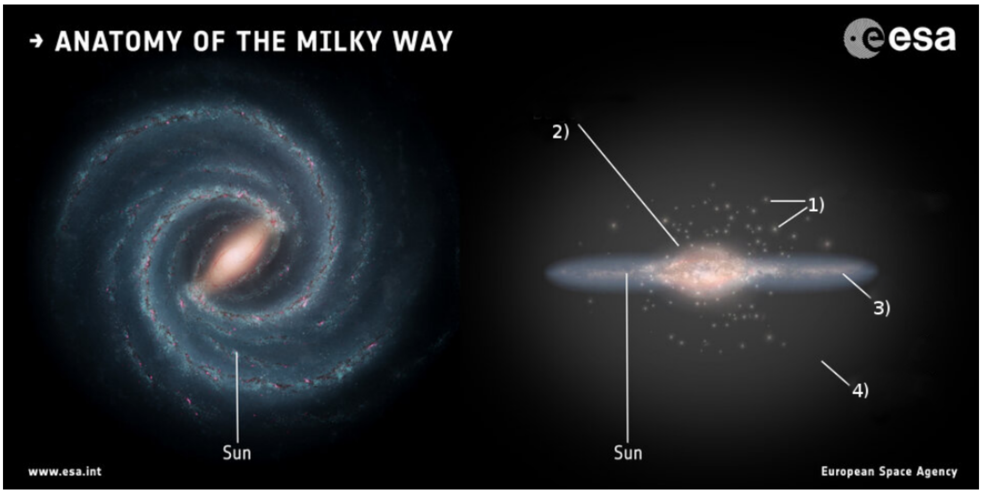
Kilian Calefice (796461)

Janurary 2023

1. Milky Way's Stellar structure

The Milky Way is a barrel spiral galaxy with a visible diameter of approximately 30 kpc. It has as main stellar components a disk, halo, bulge and globular clusters.

a) Give a short description for each one of the Galaxy's components label them according to the Figure below.



1) globular clusters: Are spheroidal groupings of stars. They can contain from tens of thousands to many millions of stars. The milky way has more than 150 known globular clustes one of them is Omega Centauri.
2) bulge: Is the dense central area of a spiral galaxy. The bulge is as well a group of stars located at the center of a spiral galaxy.
3) disk: Is a flattened, rotating structure, which contains stars, gas and dust. The disk of the Milky Way has a diameter of about 100,000 light-years and is around 1,000 light-years thick.
4) halo: Is a spherical region surrounding the disk. The stars and globular clusters located in the halo tend to be old.

b) Estimate how many revolutions around the center of the Milky Way the sun has already completed during its lifetime. You can assume, the sun's age to be 4.6 Gyr, while the angular velocity of the sun's orbit can be computed from the Oort constants by using the equation $A - B = \frac{V_0}{R_0} = \omega$.

With the age of the Sun and the angular velocity we can determine the total distance travelled by our solar system:

$$s = V_0 \cdot t$$

The velocity of the Sun is V_0 in $\omega = \frac{V_0}{R_0}$, where R_0 is the distance from the Sun to the center of the Milky Way. We can then devide the total distance by the circumference of the circle, with the radius of the distance from the Sun to the center of the Milky Way to receive the number of revelations made during the lifespan of the Sun:

$$\begin{aligned} n &= \frac{s}{2\pi R_0} \\ &= \frac{(A - B) \cdot R_0 \cdot t}{2\pi R_0} \end{aligned}$$

The Oorts constants are: $A = 15.3 \pm 0.4\text{kms}^{-1}\text{kpc}^{-1}$ and $B = -11.9 \pm 0.4\text{kms}^{-1}\text{kpc}^{-1}$. Therfore the angular velocity of the sun orbiting around the Milky Way is:

$$\begin{aligned}\omega &= 15.3 \pm 0.4\text{kms}^{-1}\text{kpc}^{-1} - (-11.9 \pm 0.4\text{kms}^{-1}\text{kpc}^{-1}) \\ &= 27.2 \pm 0.8\text{kms}^{-1}\text{kpc}^{-1}\end{aligned}$$

If we insert that into the equation:

$$\begin{aligned}n &= \frac{(A-B)\cdot R_0 \cdot t}{2\pi R_0} \\ &= \frac{27.2 \pm 0.8\text{kms}^{-1}\text{kpc}^{-1} \cdot t}{2\pi} \\ &= \frac{\frac{27.2\pm0.8}{3.086\cdot 10^{16}}\text{kpcs}^{-1}\text{kpc}^{-1} \cdot t}{2\pi} \\ &= \frac{\frac{27.2\pm0.8}{3.086\cdot 10^{16}}\text{s}^{-1} \cdot t}{2\pi} \\ &= \frac{\frac{27.2\pm0.8}{3.086\cdot 10^{16}}\text{s}^{-1} \cdot 4.6 \cdot 10^{9} yr}{2\pi} \\ &= \frac{\frac{27.2\pm0.8}{3.086\cdot 10^{16}}\text{s}^{-1} \cdot 4.6 \cdot 10^{9} \cdot 3.154 \cdot 10^{7} s}{2\pi} \\ &= \frac{\frac{27.2\pm0.8}{3.086\cdot 10^{16}}\text{s}^{-1} \cdot 4.6 \cdot 10^{16} \cdot 3.154 s}{2\pi} \\ &= \frac{\frac{27.2\pm0.8}{3.086}\text{s}^{-1} \cdot 4.6 \cdot 3.154 s}{2\pi} \\ &= \frac{\frac{27.2\pm0.8}{3.086} \cdot 4.6 \cdot 3.154}{2\pi} \\ &\approx 0.748245(27.2 \pm 0.8) \\ n_0 &= 0.748245(27.2 - 0.8) \\ n_0 &= 19.753668 \\ n_1 &= 0.748245(27.2 + 0.8) \\ n_1 &= 20.95086\end{aligned}$$

Therefore we can estimate our solar system made between 19 and 21 full revelations around the center of the Milky Way in its lifespan.

c) Estimate the distance of the following objects to the disc of the Milky Way: (1) the Globular cluster M13 ($l = 59.0°, b = 40.9°$); (2) Orion Nebula ($l = 209.0°, b = 19.4°$). M13 has a distance of 7 kpc to the Sun, while the Orion Nebula has a distance of 450 pc to the sun. Based on the position of M13 and the Orion Nebula in the Milky Way, estimate to which galactic component those objects belong. Justify your answer by taking into account the connection between the distribution of the gas in the Milky Way and the stellar formation.

To make an estimation of the location of the following objects in the Galaxy we can use the following formula:

$$d = d_s \cdot cos(b)$$

where d is the distance from the centre of the disk, d_s is the distance to the Sun and b is the galactic latitude. Therefore we get:

$$\begin{aligned}d_{M13} &= 7\text{kpc} \cdot cos(40.9°) \\ &\approx 5.29097\text{kpc} \\ &= 5,290.97\text{pc}\end{aligned}$$

, and:

$$\begin{aligned}d_{ON} &= 450\text{pc} \cdot cos(19.4°) \\ &\approx 424.4502\text{pc}\end{aligned}$$

Further: within the distance of a few hundered parsec we can say that the object is part of the disk. Is this threshold breached the object is likely part of the halo.

With that in mind we can evaluate our calculations and say that M13 is likely part of the halo and the Orion Nebula is likely part of the disk of the Milky Way. After a quick google search I found out that M13 is not gas rich, while Orion Nebula is. This further supports my assumtion as gas rich clusters are usually located close to the disk and old gas poor clusters are further away from the disk.

2. The Milky Way rotation curve

Our Galaxy, the Milky Way, has a steeply rising rotational velocity near the center, but quickly flattens out to $235\frac{km}{s}$ (See figure below). By observing the density of stars in the Galaxy disk and bulge we estimate a baryonic mass of $40 \cdot 10^9 M_\circ$ solar masses to be contained inside a Radius of 10 kpc.

a) What would be the rotational velocity at 10 kpc if the Milky Way were composed of only the baryonic matter in the bulge and the disk?

We can calculate the velocity with the following formula:

$$v = \sqrt{\frac{G \cdot M}{r}}$$

If we insert the given values and the gravitational constant G we receive:

$$\begin{aligned}
v &= \sqrt{\frac{4.302 \cdot 10^{-3} pc(\frac{km}{s})^2 \cdot \frac{1}{M_\circ} \cdot 40 \cdot 10^9 \cdot M_\circ}{10kpc}} \\
&= \sqrt{\frac{4.302 \cdot 10^{-3} pc(\frac{km}{s})^2 \cdot \frac{1}{M_\circ} \cdot 40 \cdot 10^9 \cdot M_\circ}{10,000pc}} \\
&= \sqrt{\frac{4.302 \cdot 10^{-3} (\frac{km}{s})^2 \cdot 40 \cdot 10^9}{10,000}} \\
&= \sqrt{\frac{4.302 \cdot (\frac{km}{s})^2 \cdot 40 \cdot 10^6}{10,000}} \\
&= \sqrt{\frac{4.302 \cdot (\frac{km}{s})^2 \cdot 4 \cdot 10^7}{10,000}} \\
&= \sqrt{\frac{4.302 \cdot (\frac{km}{s})^2 \cdot 4 \cdot 10^3}{1}} \\
&= \sqrt{4,302 \cdot (\frac{km}{s})^2 \cdot 4} \\
&= \sqrt{17,208 \cdot (\frac{km}{s})^2} \\
&\approx 131.1793 \frac{km}{s}
\end{aligned}$$

b) Given that the true rotational velocity at 10 kpc is $235\frac{km}{s}$, what mass of dark matter must be contained in a halo of radius 10 kpc? What is the ratio of matter to dark matter at this radius?

We expected a velocity of around $131\frac{km}{s}$ but found a velocity of $235\frac{km}{s}$. Therefore we have a difference of

$104\frac{km}{s}$ for which the dark matter must be responsible. If we plug the true velocity into the previous formula:

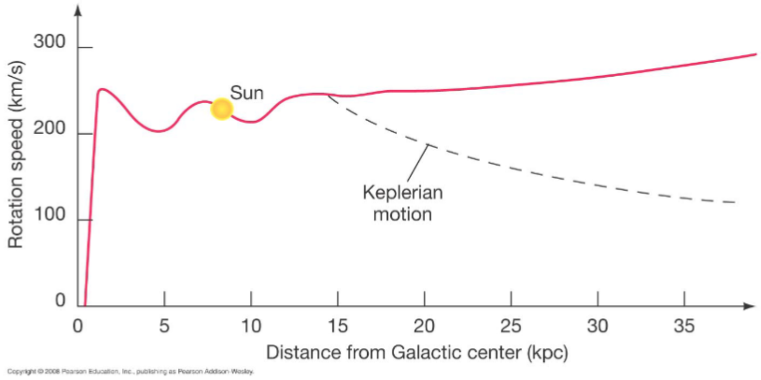
$$
\begin{aligned}
235\frac{km}{s} &= \sqrt{\frac{4.302\cdot 10^{-3}pc(\frac{km}{s})^2\cdot\frac{1}{M_\circ}\cdot M}{10kpc}}\\
1 &= \sqrt{\frac{4.302\cdot 10^{-3}pc(\frac{km}{s})^2\cdot\frac{1}{M_\circ}\cdot M}{10kpc}}\frac{1}{235\frac{km}{s}}\\
1 &= \sqrt{\frac{4.302\cdot 10^{-3}pc(\frac{km}{s})^2\cdot\frac{1}{M_\circ}\cdot M}{10kpc}}\sqrt{\frac{1}{235^2(\frac{km}{s})^2}}\\
1 &= \sqrt{\frac{4.302\cdot 10^{-3}pc(\frac{km}{s})^2\cdot\frac{1}{M_\circ}\cdot M}{10kpc}\frac{1}{235^2(\frac{km}{s})^2}}\\
1 &= \sqrt{\frac{4.302\cdot 10^{-3}pc(\frac{km}{s})^2\cdot\frac{1}{M_\circ}\cdot M}{10kpc235^2(\frac{km}{s})^2}}\\
1 &= \sqrt{\frac{4.302\cdot 10^{-3}pc\cdot\frac{1}{M_\circ}\cdot M}{10kpc235^2}}\\
1 &= \sqrt{\frac{4.302\cdot 10^{-3}pc\cdot\frac{1}{M_\circ}\cdot M}{10,000pc235^2}}\\
1 &= \sqrt{\frac{4.302\cdot 10^{-3}\frac{1}{M_\circ}\cdot M}{10,000\cdot 235^2}}\\
1 &= \sqrt{\frac{4.302\cdot 10^{-3}\frac{1}{M_\circ}}{10,000\cdot 235^2}}\sqrt{M}\\
\frac{1}{\sqrt{\frac{4.302\cdot 10^{-3}\frac{1}{M_\circ}}{10,000\cdot 235^2}}} &= \sqrt{M}\\
\frac{1}{\frac{4.302\cdot 10^{-3}\frac{1}{M_\circ}}{10,000\cdot 235^2}} &= M\\
\frac{10,000\cdot 235^2}{4.302\cdot 10^{-3}\frac{1}{M_\circ}} &= M\\
\frac{10,000\cdot 235^2\cdot M_\circ}{4.302\cdot 10^{-3}} &= M\\
1.2837\cdot 10^{11}\cdot M_\circ &\approx M
\end{aligned}
$$

This should be the mass within the 10 kpc radius if the body is moving at $235\frac{km}{s}$. The difference of the masses is:

$$1.2837\cdot 10^{11}\cdot M_\circ - 4\cdot 10^{10}\cdot M_\circ = 8.837\cdot 10^{10}\cdot M_\circ$$

The difference of the masses must be the mass of the dark matter, which causes the difference in velocity received by the calculation and the true velocity. The ratio of dark matter to matter is therefore:

$$
\begin{aligned}
\frac{8.837\cdot 10^{10}\cdot M_\circ}{4\cdot 10^{10}\cdot M_\circ} &= \frac{8.837}{4}\\
&= 2.20925
\end{aligned}
$$

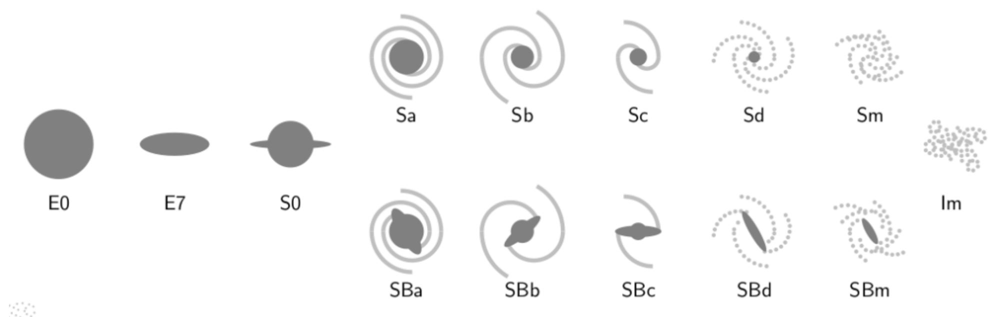


3. Galaxy classification

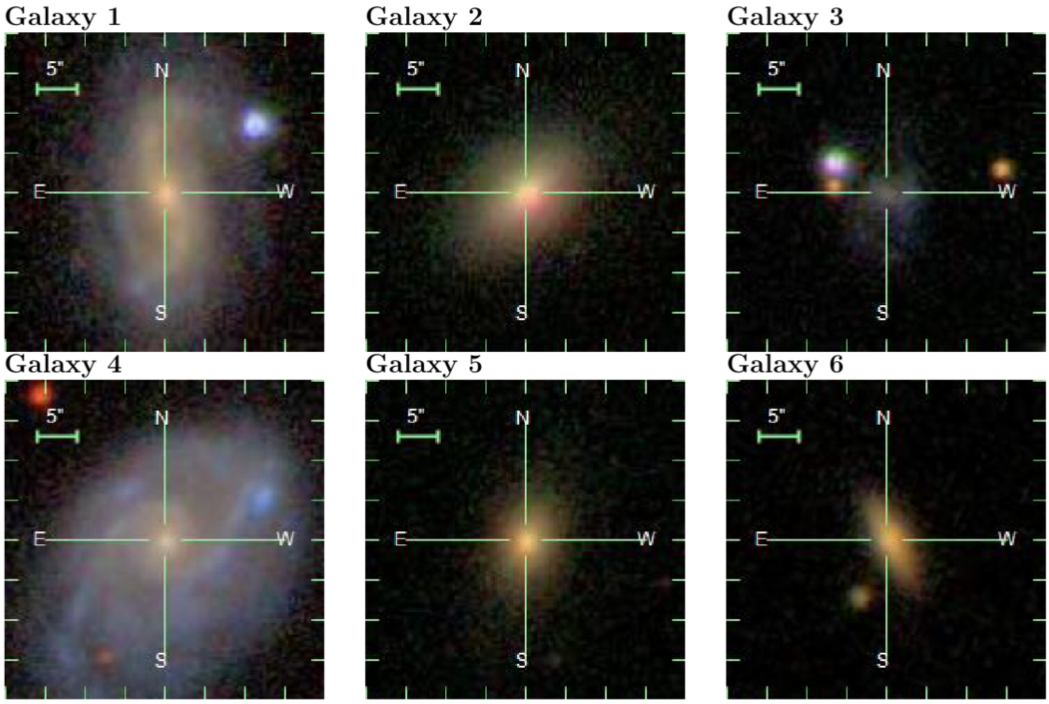
a) Besides their different morphology, describe the main differences between elliptical and spiral galaxies in terms of their kinematics and stellar populations.

Spiral galaxies have a defined rotation pattern, while the stars in an elliptical galaxy have a random or chaotic motion. Elliptical galaxies tend to contain older stars, while spiral galaxies can also contain younger stars besides old stars. Also elliptical galaxies are gas poor throughout while spiral galaxies are only gas poor in their halo.

b) Based on observations, Edwin Hubble derived a classification scheme for Galaxies, which is known as the Hubble sequence. The different classes are depicted in the image below.



I.) Use the Hubble scheme, to classify the following real galaxies shown below.



Galaxy 1: For this galaxy we can see two well defined tails. We can also see a well defined circular center, but the tails only seem to bend after they leave an elliptical extension, which is why I would classify this galaxy as SBc.
Galaxy 2: Again we have a circular center extended by a little less bright ellipses. We can see that the clusters further away from the center do not form any spiral, which is why I would classify this galaxy as E7.
Galaxy 3: We can only see very blurred non bright cluster, which seem to follow lightly a spiral pattern. This is why I would classify it as Sm but it could be argued to fit more as a Im.
Galaxy 4: Just as the Galaxy 1 we can see two tails emerging from an elliptical extension of the circular center. This time the pattern is seen more clearly, which is why this is a SBc as well.
Galaxy 5: Here we can not see any spiral. The bright center is round and the next outer ring of that center seems to be very circular as well. The shape of descirbed outer ring can be argued to be slightly elliptical. But I would classify this as E0 over E7.
Galaxy 6: Just as the previous galaxy we can see a similar pattern. This time the outer ring definetely being elliptical, which is why this is a E7.

II.) Describe two shortcomings of the Hubble scheme.

The Hubble scheme relies heavily on optical observation, which is why the quality of the image highly determines the quality of the classification. The provided images had a very poor quality for example and it was hard to distinguish clusters from one another, which ultimately influenced the ability to find patterns like spirals or ellipses. In the same manner it is dependent on the subjectivity of the astronomer. It really comes to show when a less bright shape shadows a very well defined shape and it is to say if the shape in the background should also be evaluated when trying to match the patterns of the sequence.

4. Measuring galactic distances

a) The cosmic distance ladder describe a chain of measurements that allows us to determine ever greater distances to celestial objects. The distance determination methods in our universe include Cepheid variables, redshift, supernova Ia, radar ranging and parallax. List the methods for determining distances in the correct order, from nearest to farthest.

Radar ranging $\longrightarrow$ Parallax $\longrightarrow$ Cepheid variables $\longrightarrow$ Supernova Ia $\longrightarrow$ Redshift

5. Bonus-Exercise

a) **Galaxy Structure**

A stellar disk is an essentially spherical population of field stars and spiral arms thought to sorround most disk galaxies. A low amount (about 1%) of a galaxy's stellar mass resides in the bulge, it generally has no net rotation and is supported almost entirely by velocity dispersion.

b) **Elliptical Galaxies** Which of the following is not a characteristics of Elliptical Galaxies?
A: Dominated by stars from Population I.

c) **AGN** Active galaxy nuclei are powered by: Matter falling into a very massive black hole.

d) **Dark Matter** Which of the following evidences for Dark Matter are True?
I. Gravitational lensing, or the bending of the light, around Galaxy clusters implies the existence of an unseen mass component.
II. There is not enough visible mass in Galaxy clusters to explain X-rays radiation emitted by hot gas.
III. The observed rotational curve of disk Galaxies in our universe cannot be explained only by the mass of stars and gas.
A: I, II and III are all true

e) **Parallax** Star A has a parallax of 0.5 arcsec. Find the distance to A in parsec.
A: 2 pc.

f) **Distance modulus** Calculate the distance, in parsec, of the globular cluster Omega Centauri using the relation between its apparent magnitude ($m_v = 3.520$) and absolute magnitude ($M_V = -10.04$).
A: About 5200.