ASTR-1020: Astronomy II
Course Lecture Notes
Section IX

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Abstract

These class notes are designed for use of the instructor and students of the course ASTR-1020: Astronomy II at East Tennessee State University.

IX. The Milky Way Galaxy

A. Structure of the Galaxy

1. We live in a spiral galaxy of over 200 billion stars called the **Milky Way Galaxy**. This spiral structure is mapped using the 21-cm line of neutral hydrogen.

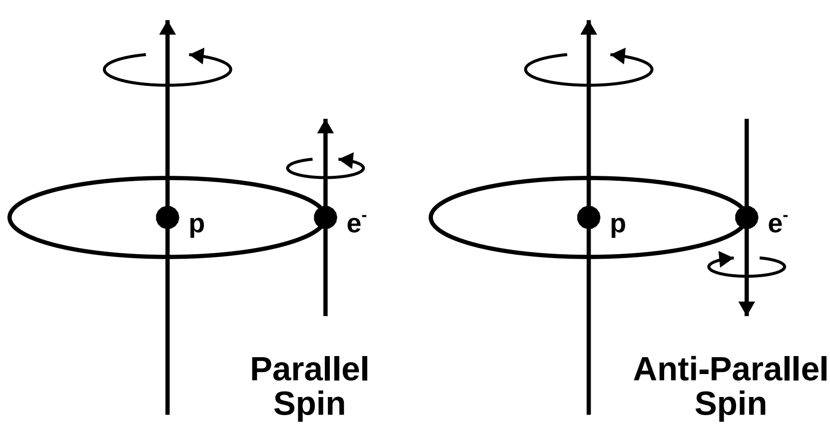
   a) This 21-cm line results from an e^- (electron) spin-flip $\Longrightarrow$ the so-called **hyperfine structure** of the hydrogen atom.

   b) In the lowest *orbital* electron energy-level, e^- & p (proton) can either be spinning in the same (*i.e.*, **parallel**) or opposite (*i.e.*, **antiparallel**) direction.

   c) The antiparallel state is slightly lower energy than the parallel state.

   $\Longrightarrow$ antiparallel $\longrightarrow$ parallel — absorption line at 21-cm.

   $\Longrightarrow$ parallel $\longrightarrow$ antiparallel — emission line at 21-cm.



2. 100,000 ly (30 kpc) in diameter (disk), 1000 ly (300 pc) thick (disk) in the vicinity of the Sun.

3. Two main components:

a) **Disk** contains:

i) Stars (majority Population I).

ii) Open star clusters and associations.

iii) Almost all of the ISM.

iv) Spiral arms (much of the ISM located here).

b) **Spherical component** contains:

i) **Halo** which contains:

— Stars (all Population II).

— Globular star clusters.

— Almost no ISM.

— Large amounts of "**dark matter**."

ii) **Nuclear bulge** which contains:

— Stars (mostly Population II).

— A few globular clusters.

— Perhaps a few million supermassive solar mass black hole at the center.

B. Star Clusters.

1. Galactic (Open) Star Clusters.

a) Composed of young stars ($t_{\rm age} \lesssim 5 \times 10^9$ years) $\Longrightarrow$ many are near giant molecular clouds — proves that stars form in groups.

b) **Population I** stars $\Longrightarrow$ metal (*i.e.*, heavier than helium) rich stars.

c) Found in spiral arms.

d) Contains from 100 to 1000 stars that are somewhat *randomly* distributed.

e) Small clusters with tens of stars are called **associations** (*i.e.*, OB associations & T Tau associations).

2. Globular Star Clusters.

a) Composed of old stars ($t_{\rm age} \approx 12 - 13 \times 10^9$ years) $\Longrightarrow$ oldest stars of the Galaxy! The age of these clusters tell us the age of the Milky Way.

b) **Population II** stars $\Longrightarrow$ metal poor stars.

c) Found in galactic halo.

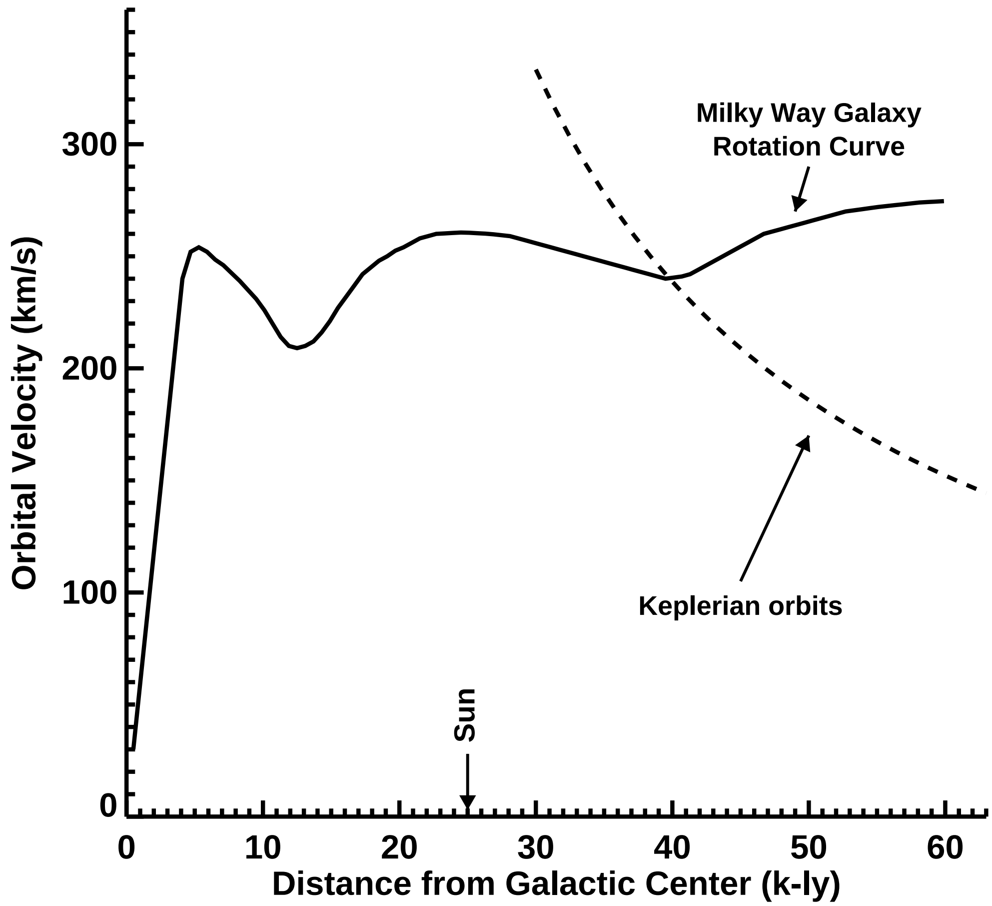
d) Contains from 10^5 to 10^6 stars that are fairly *spherically* distributed.

C. The Rotation of the Galaxy.

1. The Rotation Curve.

a) The Sun is 25,000 ly (8 kpc — 1 kpc = 1000 pc) from the galactic center. It takes the Sun 250 million years (2.5×10^8 yrs) to complete one orbit around the center $\Longrightarrow$ the Sun has completed 18 orbits about the galactic center since its formation!

b) The fact that the rotation curve (*i.e.*, orbital velocity of stars at a given distance from the galactic center) is not *Keplerian* in the outer region of the Galaxy, implies there is a lot of mass outside the Sun's orbit $\Longrightarrow$ the halo of the Galaxy must be massive — a **massive halo**.



c) The light of the Galaxy falls off faster than the mass which means much of the mass in the halo is *dark* $\Longrightarrow$ **dark matter**.

i) Dark matter is seen in all large galaxies in the Universe.

ii) It is thought to be composed of some type of *unknown* matter. To be precise, matter not composed of protons and neutrons.

iii) There are numerous studies underway to try an ascertain the identity of this dark matter.

2. Stellar Populations and their Orbital Motions (*i.e.*, A History of the Galaxy).

a) Stellar orbits are basically determined from the properties of a star at the time when a star formed during the history of the Galaxy.

b) As the spherical, galactic nebula was contracting, some star formation was taking place (though not much in comparison to later epochs).

c) Once stars form, they are *frozen out* of the contraction. These are the Population II stars — located in the spherical halo and are very old.

i) Initially, this *protogalaxy* had only H (90% by number) and He (10%) from the Big Bang — no metals $\Longrightarrow$ the so-called Population III stars, which are no longer in existence, were actually the very first stars to form in the Universe.

ii) These Population III stars were all very massive and supernovaed fairly quickly, dumping some metals into the spherical component.

iii) Further star formation would then contain low levels of metals $\Longrightarrow$ this is the material from which the Population II stars formed.

iv) The Population II stars have very elliptical orbits (and will be very inclined to the disk when it later forms).

d) Similarly to the origin of the solar system, the contracting, rotating protogalaxy formed a flattened gas disk and central bulge.

i) Densities in the bulge are great and star formation takes place rapidly. These stars are still Pop II stars, but they do not have as high an ellipticity in their orbits as compared to halo stars since interaction with gas circularizes their orbits.

ii) Since these stars form later than the halo Pop II stars, they are contaminated further with heavy elements from halo star evolution (*i.e.*, supernovae and stellar winds) giving the Pop II bulge stars a higher metal abundance in comparison to the Pop II halo stars.

e) The stars in the disk are forming more slowly (due to the initial lower gas densities than the bulge) $\Longrightarrow$ they have time to absorb more heavy elements from the evolution of older stars $\Longrightarrow$ metal abundance is so high that we call these a new population, the Pop I stars.

f) Longer formation rates enable the forming stars to circularize their orbits $\Longrightarrow$ disk stars have fairly circular orbits.

g) The Sun is actually one of these disk stars – it is an old Population I star.

h) The remaining gas and dust forms a spiral structure or *spiral wave*, which enables further stars formation. Most of the stars in the spiral arms are the youngest in the Galaxy.

D. The Spiral Structure.

1. On our side of the Galaxy, we can make out 3 spiral arm *pieces*. The Sun is in the **Orion arm**.

2. How do we map the spiral structure from inside? $\Longrightarrow$ Use **spiral tracers**.

a) O & B associations — young, bright objects; born in the spiral arms, do not live long enough to get out of the arms.

b) H II regions — O & B associations light up the surrounding gas from which they were formed.

c) Gas and dust in the galactic plane make it impossible to see very far away from the Sun. Instead we can use radio waves which go right through gas and dust. Most of the H gas in our Galaxy is in the spiral arms. The 21-cm line from this H gas can then be used to map the spiral structure.

3. What causes the spiral structure?

a) **The Density Wave Theory**: A disturbance in the Galaxy's gravitational field propagates around the Galaxy in a spiral structure — like a compression (*i.e.*, sound) wave.

i) Dust and gas get compressed in this wave which triggers star formation $\Longrightarrow$ O & B stars form which outline this spiral wave in our and other galaxies.

ii) The density wave/giant molecular cloud interaction is very efficient in creating stars.

iii) These waves (2 main ones) are thought to have arisen from a gravitational instability in the Milky Way's gravitational potential well through interactions with the Milky Way's satellite galaxies, the Large and Small Magellanic Clouds.

iv) This theory predicts only 2 spiral arms per galaxy (and sometimes a linear bar that goes through the nucleus of the galaxy connecting the inner portion of the arms).

v) Branches and spurs that are seen in our and other galaxies result from supernova explosions and OB association ionization fronts $\Longrightarrow$ this is known as **self-sustaining star formation**.

b) **The Differential Rotation Theory**:

i) Supernova shocks make stars and the differential rotation of the Galaxy causes the spiral structure.

ii) This does not work as a viable theory since differential rotation would rip the spiral structure apart after just a few revolutions

4. Even though the Sun is currently close to a spiral arm (*e.g.*, the Orion arm), there is not a lot of ISM in the Sun's vicinity — the Sun is in a large, somewhat empty, bubble called the **Local Bubble** which is about 300 ly (100 pc) across.

a) This was only realized within the past 20 years through observations with the IUE (International Ultraviolet Explorer) and EUVE (Extreme Ultraviolet Explorer) satellites.

b) Hydrogen is very opaque at the wavelengths in which EUVE and a portion of the IUE detectors are sensitive $\Longrightarrow$ we did not expect to see very far with EUVE, but we did, implying that there is <u>not</u> a lot of ISM in our vicinity of the Milky Way.

c) It has been suggested that there may have been a nearby supernova within the last million years that formed this relatively empty bubble.

d) A pulsar called **Geminga** was recently discover with peculiar properties. It has a large proper motion across the sky meaning that it is relatively nearby (probably less than 300 ly). Its pulsation time indicates that it is about 300,000 years old. The supernova that produced Geminga may be the cause of the Local Bubble. When this supernova went off, it would have had an apparent magnitude of -13 $\Longrightarrow$ brighter than the full Moon!

5. Infrared observations made with the *Spitzer Space Telescope* in 2005 has shown evidence that the Milky Way is actually a **barred spiral galaxy**.

a) Using the orbiting infrared telescope, the group of astronomers surveyed some 30 million stars in the plane of the Galaxy in an effort to build a detailed portrait of the inner regions of the Milky Way.

b) These observations show a bar, consisting of relatively old and red stars, spanning the center of the Galaxy roughly 27,000 light years in length (hence extends out 13,500 light years from the galactic center).

c) It also shows that the bar is oriented at about a 45-degree angle relative to a line joining the sun and the center of the Galaxy.

E. The Galactic Nucleus.

1. The central nuclear region of the Galaxy is completely invisible at visible wavelengths due to dust and gas obscuration.

2. However, we can see it in radio waves, since dust and gas are transparent to radio waves. The center of the galaxy is the brightest radio source in the sky $\Longrightarrow$ called **Sagittarius A**.

3. There is evidence for a small 10 AU in diameter region at the center that has a mass of 3.7 million (3.7×10^6) solar masses! X-rays and gamma rays have been detected from this region as well.

4. Something massive and energetic is at the galactic center $\Longrightarrow$ the only type of object that matches all of the observed characteristics is a 3.7 million solar mass **supermassive black hole**!