Our Milky Way Galaxy

After the Sun, Moon, planets and brightest stars, the most prominent object in the nighttime sky is the Milky Way. It is a huge organized collection of stars, gas & dust; on supermassive black hole at the center; and mysterious 'dark matter' dominating the outer halo. The Milky Way is a galaxy, a major building block of matter in the Universe. Our job now is to figure out its properties: size, mass, shape, motions, and composition (what's it made of).

Historical notes

The Greek pholosopher Democritus speculated that, just as matter is formed of many identifical atoms, the Milky Way consists of countless stars. Galileo confirmed this in 1609 using the telescope. In the 1700s, William & Caroline Herschel counted stars in different directions, reasoning that more stars will appear where the Galaxy is bigger. Assuming that the stars were as luminous as our Sun, Herschel's universe was much bigger than the Greek or Renaissance universe. He found that the Sun lies near the center of a flattened collection of stars about 1000 pc or 1 kpc (kiloparsec) in size. (Recall: 1 parsec = 3x10^{16} meters is roughly the distance to the nearest stars like alpha Centauri or Sirius.) .

<>In 1918, a young American named Harlow Shapley came to a different conclusion. He estimated the distances of **globular clusters** lying far from the Milky Way using an indirect indicator developed by Henrietta Leavitt involving **Cepheid variable red giant stars**. These stars pulsate with the property that their luminosity (difficult to measure since their distances were unknown) is proportional to their pulsation period (which is easy to measure). Shapley's results contradicted Herschel's: The globular clusters were mostly 10-50 kpc away, and the Sun was far off-center! The Galactic center lies towards the dense star fields in Sagittarius. Herschel's error was assuming that interstellar space is transparent to light.

The structure of the Milky Way Galaxy is more clearly understood when we observe other nearby spiral galaxies which were not known until **Edwin Hubble** took remarkable photographs with the Mt. Wilson 100-inch telescope in California around 1920. Below is a photo of the **Andromeda Galaxy** , the largest galaxy in the Local Group. Here we clearly see a flattened disk with dusty lanes, and a bright spheroidal (round) bulge around the center. Two smaller satellite galaxies orbit Andromeda.

Milky Way Galaxy properties

Today we know the Galaxy has four principal components:

- **Disk**, shaped like a warped Frisbee, with stars of all ages (including our Sun), lots of interstellar medium and star formation. It is best seen at infrared wavelengths where interstellar absorption is small. The disk is extremely thin: ~100 times thinner than its extent.

- **Spheroidal component**, including a dense bulge around the Galactic center and a diffuse halo. Contains only very old stars (like globular clusters) and has no active star formation.

- **Dark matter** of unknown nature (not normal stars or gas), dominatint the halo far from the Galactic center.

- **Supermassive black hole** at the very center of the galaxy, associated with the remarkable radio source Sgr A*.

The Galactic disk

<>The disk is at least 30 kpc in diameter, with the Sun lying 8.0-8.5 kpc from the center. **This is HUGE:** if Galaxy = Earth, our solar system = cookie! The disk contains all of the star formation now occurring in the Galaxy: molecular clouds, OB associations, T Tauri stars, open clusters, supernova remnants and X-ray binaries. The maps below show the disk at infrared, 21-cm hydrogen, CO molecules, and visible light.

There is an intricate relationship between the interstellar medium and stars in the Galactic disk. Star are born in cold molecular clouds., orbit the Galactic Center for billions of years, become red giants, and return heavy elements like CNO into the interstellar medium via planetary nebulae and supernova remnants. The abundance of heavy elements thus increases with time; this is called **chemical evolution** of the Galaxy. Planets like Earth (made of silicon, iron, oxygen, ...) cannot have existed when the Universe was young, but become possible only by the cycle of star birth <--> star death that continuously occurs in the disk of the Galaxy.

Jan Oort, a Dutch radio astronomer, and others discovered during the 1920-50s that stars and gas showed Doppler redshifts and blueshifts at different places in the Galactic plane. The best studies used an emission line of cold hydrogen which appears at 21 cm in the radio band. Oort correctly interpreted this to mean that disk objects have roughly circular orbits around the **Galactic Center** in the constellation of Sagittarius.

<>Using the 21-cm line, we can map out orbits in the disk. The plot of orbital velocity vs. distance from the Galactic Center is called the **rotation curve** of the Galaxy. The result is very important: it tells us the distribution of mass is the galaxy. The Galaxy's rotation curve is mainly flat with orbit velocity around 220 km/s: this requires that most of its mass lies far from the center in the Galactic halo. But the halo has very few stars! The flat rotation curve of our Galactic disk, and that of other spiral galaxies, is the first evidence that Galaxies are dominated by mysterious **Dark Matter** in their halos.

$$V^2(r) = G\, M(r) / r.$$
$$M(r) = \text{constant} \times r.$$

The mass of the Galaxy within the Sun's orbit is found to be $2 \times 10^{11}\ M_o$, and the mass of the Galaxy including the outer regions is $1\text{-}2 \times 10^{12}\ M_o$.

We know Dark Matter is there (due to its effect on orbital velocity), but we don't know what it is! The existence and nature of dark matter was perhaps the greatest enigma of modern astronomy until ~2000, when we learned of an even greater enigma, Dark Energy.

What could the dark matter be?
Must have lots of mass, but little emission of radio/infrared/visible/X-ray/gamma-ray light.

- Brown dwarfs (Jupiter-like objects). Excluded by Hubble Space Telescope counts of faint red objects in the Galactic halo.

- Black holes. Requires too many OB stars in the past.

- Subatomic particles. This is probably correct, but we don't know what particle. Neutrinos were the favorite candidate for decades, but recent measurements show their is too small by a factor ~50. Probably DM is a supersymmetric WIMP (weakly-interacting massive particle) or gravitino, axion, cosmic string, etc. Physicists have not yet discovered the DM particle in the laboratory despite extensive search. This is a major motivation for building bigger particle colliders.

The Galactic Halo

The halo and bulge, or spheroidal component, of the Milky Way Galaxy consists only of ancient stars (plus the enigmatic Dark Matter). There are not molecular clouds, no current star formation, no short-lived OB stars. Recent theory suggests halo stars are mainly disrupted globular clusters and dwarf galaxies which were cannibalized in the past.

The Galactic Center

The situation is very confused near the **Galactic Center or nucleus** where stars and interstellar clouds are densely concentrated and orbit very quickly. Too much intervening interstellar dust prevents visible light studies, so most studies require radio telescope or infrared and X-ray satellite telescopes.

Massive star clusters quickly form, and their O stars quickly go supernova and make supernova remnants. Rings of dust and gas form and dissipate, and clouds spiral into the center. The left image below shows the inner ~3 pc seen with the Very Large Array radio telescope, while the right image shows a bigger ~150 pc region. The Galactic Center is in a **starburst** phase. Note that we can't see anything at the Galactic Center at visible wavelengths, where the light is absorbed by many dusty clouds in the Galaxy's disk. Our information about the Center comes from radio, microwave, infrared and X-ray wavelengths.

At the exact center of the galaxy, radio astronomers see a strange, unique, highly variable radio source known as **Sgr A*** Recently, infrared astronomers demonstrated clearly that this is a supermassive black hole (SMBH) with mass 2.5×10^6 M_o by tracing the orbits of individual red giants within 0.1 pc of Sgr A*. The rotation curve zooms up to ~1500 km/s (remember most of the Galaxy orbits around 220 km/s). Similar measurements of star motions with the Hubble Space Telescope show that most galaxies have a supermassive black hole at the cores. The X-ray emission from our SMBH is weak, but flares by factors of 10-30 within hours.

Nearby Galaxies

In 1920s, **Edwin Hubble** established that the **Andromeda Nebula, or Messier 31**, is composed of many individual stars using the Cepheid period-luminosity relationship. ***This showed that our Milky Way Galaxy is only a small part of a much bigger universe with many galaxies!***   Below is another nearby spiral galaxy, Messier 100, with closeup images from the Hubble Space Telescope showing a Cepheid variable.

Hubble photographed many galaxies and noted three basic types:

- ***Spiral galaxies*** Two or more curved arms of luminous stars and dust lanes winding out from the nucleus. Population I objects predominate: molecular clouds, OB stars, and older disk stars. Lots of dusty molecular clouds, luminous blue O stars and supernovae explosions occur in the thin disks. A classification scheme was developed: Sa (large bulge, weak arms) ---> Sb ---> Sc ---> Sd (small bulge, prominent arms). Some galaxies are ***barred spirals*** , where spiral arms emerge out of a rigidly rotating bar crossing the nucleus. Some galaxies are ***S0 galaxies*** , which appear to be spirals stripped of most of their interstellar medium.

- ***Elliptical galaxies*** These have little or no disk, no current star fopmation, no cold molecular clouds, no OB stars or supernovae. Only Population II low mass ancient stars and hot gas, similar to our Galactic halo. Classification: E0 (round) ---> E7 (elongated). Some are giant ellipticals, while most are tiny dwarf ellipticals. Below left is M 87, the nearest giant elliptical galaxy (D=16,000 kpc = 16 Mpc, note its hundreds of faint globular clusters). Below right is Leo 1, one of the nearest dwarf ellipticals (D=200 kpc).

- ***Irregular galaxies*** Lumpy or amorphous structure. Star formation may occur in episodic starbursts, rather than continuously in spiral disks. They are seen mainly when a starburst is in progress with blue OB stars.   Below left is a small, nearby dwarf irregular, IC 4182 (D=1.3 Mpc). Below left is the closest and brightest irregular, the Small Magellanic Cloud (D=70 kpc); it can easily be seen with the naked eye in southern skies.

Distances

Cepheid variable distances establish a Local Group of galaxies about 2 Mpc in extent with 3 spirals and a dozen or so dwarf irregulars and dwarf ellipticals (diagram below). The nearest large cluster of galaxies, with hundreds of ellipticals and spirals orbiting each other, is the Virgo Cluster 15 Mpc away, The most distant galaxies visible with the Hubble Space Telescope are >10,000 Mpc away! 10^9 different galaxies can be see

Mass

Using spiral disk rotation curves, we find that all galaxies show much higher masses than expected from the stars & gas we see. This implies that most of the mass in galaxies is the mysterious ***dark matter*** lying in their far halos. Recent Hubble Space Telescope rotation curves near the centers of galaxies show that nearly all have a central SMBH. A typical big spiral galaxy has 10^{6-9} M_o in a central SMBH, 10^{10} M_o in interstellar gas, 10^{11} M_o in stars, and 10^{12} M_o in dark matter.

<>Galaxy interactions

While stars are tiny compared to interstellar distances, galaxies are quite large compared to intergalactic distances, especially with their huge dark matter halos. Thus, galaxy gravitational interactions, tides, collisions and mergers are quite common. If two spirals approach closely, the pull on each other's stars distorts the disks and ejects long arce of stars. Big galaxies 'cannibalize' small galaxies frequently; right now, our Milky Way is eating the Sagitarrius dwarf galaxy, and will soon consume the two Magellanic Clouds. There is growing evidence that massive ellipticals form by the merger of several spirals. Giant ellipticals appear mostly in crowded galaxy clusters where collisions are frequent.

Galaxy clustering

Galaxies are not located randomly in space, but congregate in groups, clusters and huge superclusters. Our Local Group (~4 large and ~20 small galaxies, 1-2 Mpc in size) is on the outskirts of the Virgo Cluster (several hundred galaxies, 15 Mpc away), which is part of a large flattened Local Supercluster (~30 Mpc in size). Superclusters themselves are part of the **large-scale structure** of mass in the Universe -- it looks like a collection of soapbubbles where the galaxies congregate along the walls of the bubbles and surround huge voids with few galaxies. These structures have scales of hundreds of Mpc.

In the 1970s, X-ray satellite observatories discovered that the space between galaxies in dense galaxy clusters like the Virgo and Coma Clusters have an enormous amount of **hot gas between the galaxies (intergalactic medium)** at temperatures $T \sim 10^7$ K. There are more atoms in the gas than in the stars in these rich clusters! In the 1990s, astronomers have studied the **gravitational lensing** by galaxy clusters. The cluster's gravitational field bends the light of a background galaxy, producing multiple images and arcs. Both the X-ray gas and the lensing results require that **clusters are 90% dark matter**, the same result obtained from spiral galaxy rotation curves. A rich galaxy cluster has ~10^{13} M_o in stars, ~10^{14} M_o in hot gas and ~10^{15} M_o in dark matter.

The top pictures below show the Coma Cluster of galaxies in visible light (showing stars) and in X-rays (showing the hot intergalactic medium). The middle picture below shows a Hubble Space Telescope image of the rich galaxy cluster 0024+1654 producing curved lenses images of background galaxies.

The first diagram below plots the locations of 10^5 galaxies in a slice of the sky from the recent Sloan Digital Sky Survey (SDSS) showing a complicated large-scale pattern of galaxies within ~500 Mpc of the Milky Way.
Here distances are determined from galaxy redshifts assuming a linear Hubble flow. The second image shows the deepest image of the sky yet obtained: the clustering is not generally evident without redshift information because foreground and background structures are superposed.

Active Galactic Nuclei

<>Photographs by Carl Seyfert in the 1940s showed a very bright point-like nucleus with very unusual spectra: in addition to continua + absorption lines from normal stars, **Seyfert galaxy nuclei** have very strong emission lines from ionizes gases moving at extremely high velocities. The nuclei vary in brightness in the visible band on timescales of months, requiring them to be <1 pc in size. The total luminosity can be equivalent to 10^{10} L_o!

Later in the 1940s, astronomers began scanning the skies with radio telescopes. They found strange radio structures on opposite sides of radio galaxies, plus a tiny source of radio emission at the nucleus. The nuclei of these **radio galaxies** shoot out narrow beams of extremely energetic electrons and magnetic fields, producing radio synchrotron radiation. The radio components include: **compact core** at the galaxy nucleus, **jets, lobes, and hot spot** where the jet slams into the interstellar medium. The radio structure can be huge: hundreds of kpc in extent, far larger than the host galaxy. The image below shows **Cygnus A**, the brightest radio source in the sky, as mapped with the Very Large Array radio telescope.

In the 1960s, some radio sources seemed to be associated with 'stars', and were called `quasi-stellar radio sources' or **quasars** . But they had spectra similar to Seyfert galaxy nuclei! It became clear that they are Seyferts and radio galaxies where the nucleus outshines all of the stars by factors of 10-1000. The luminosity of quasars can reach 10^{12} L_o.

Some further developments during the 1970-90s:

- X-ray satellite telescopes find strong and very rapidly variable X-ray emission from Seyferts and quasars. The X-ray emission jumps up and down on timescales of days, hours, even minutes.

- Rare **BL Lac objects** and blazars were discovered. These are radio galaxies with jets pointing directly at us, ejected by the active nucleus at velocities near the speed of light!

- Optical astronomers find thousands of faint distant quasars which are not radio-loud. Strangely, there were many more quasars at high redshift (early in the Universe) than there are today.

- NASA's Compton Gamma Ray Observatory discovers incredibly intense gamma-rays from the jets of some blazars. Stronger than X-ray, optical, radio emission combined!

- Some quasars were found to have broad absorption lines in addition to broad emission lines

Explaining AGNs

Long ago when galaxies were young, the stars in their cores were very closely packed. Star collisions and mergers occurred, giving rise to a single **supermassive black hole (SMBH)** with 10^6-10^9 M_o. Gas from the galaxy's interstellar medium, from a cannabilized galaxy, or from a star that strays too close falls onto the MBH. As in X-ray binary star systems, an accretion disk forms, emitting huge amounts of light across the electronagmetic spectrum (infrared to gamma-rays). The MBH plus **accretion disk** produces the phenomena seen in **active galactic nuclei (AGN)**. Sometimes, for unclear reasons, the inner disk shoots out jets of relativistic particles at nearly the speed of light. These are the **radio jets** (also sometimes seen in the visible & X-ray bands).

During the 1980-90s, a **unified model** for active galaxies was formulated, and it looks pretty solid today. Most of the differences between classes (narrow vs. broad line Seyferts; radio galaxies vs. BL Lacs) are due to the angle we happen to be viewing the system. Sometimes we are looking edge-on through the accretion disk and emission from the immediate vicinity of SMBH is entirely blocked and we do not see the broad emission lines around the inner disk. Other times we are looking at the disk along an angle and see absorption lines from clouds evaporating off the disk's surface. Sometimes we are looking directly down on the disk and its jet. Then we seen an intense, rapidly varying radio/X-ray core (BL Lac object). Many galaxies today (including our Galactic center) have a quiet MBH which happens not to have recently accreted gas.