Chapter 16

The Milky Way Galaxy
• Uniform distribution of stars in a band across the sky lead Thomas Wright, Immanuel Kant, and William Herschel in the 18th century to suggest the Milky Way is a disc distribution of stars with the Sun near the center.
William Herschel’s sketch of the Milky Way, from 1748. This sketch led Herschel (and others) to believe the Milky Way was disk-shaped (correct), and that the solar system was near the center of that disk, at the position of the yellow dot (incorrect).
Jacobus Kapteyn determined the diameter of the Milky Way to be 20 kpc with the Sun near the center.

Harlow Shapley found the diameter to be 100 kpc with the Sun 2/3 from the center.

Both were not aware of the dimming effects of dust.

Shapley, using globular star clusters for distances, did not distinguish RR Lyrae from Cepheid variables.
Size of the Milky Way

• Correcting for dust effects and variable star types, astronomers conclude the disc has a 30 kpc diameter with the Sun 2/3 from the center.

• Discovery that nearly all disc-shaped galaxies have spiral arms implied Milky Way is a spiral too.
Structure and Contents of the Milky Way

- **The Disk**
  - *Spiral arms* distribution of stars, gas, and dust with a diameter of about 30 kpc (100,000 light-years) and plane tilted with respect to Earth’s orbit around Sun
  - Differential rotation with all objects circling in the same direction: 240 million-year period at 220 km/sec at the Sun’s orbit (about 8.5 kpc out from center)
Structure and Contents of the Milky Way

- **The Disk**
  - High density of stars near center (10 million stars per cubic light-year) to low density farther out (0.003 stars per cubic light-year at Sun)
  - Dust and gas is nearly 15% of the disc’s mass
Structure and Contents of the Milky Way

• The *Disk*
  - Most of galaxy is hidden from Earth due to dust obscuration including the central *nucleus* with its dense swarm of stars and gas in which a massive black hole may reside
  - Radio and infrared telescopes can “see” entire galaxy: Radio observations suggest larger warped disc of gas (out to nearly 40 kpc)
Structure and Contents of the Milky Way

• **Halo**
  – Roughly spherical region with disk embedded
  – Contains mainly old stars, such as globular clusters
  – Large amounts of dark matter may also be present

• **Bulge**
  – Flattened collection of stars surrounding dense core of galaxy
  – About 1/3 the diameter of the galaxy
Mass and Population of the Milky Way

- From its rotation and effects on nearby galaxies, mass of Milky Way is $2 \times 10^{12} \, M_\odot$
- From large difference between this mass and what is observed, astronomers conclude Milky Way is embedded in vast halo of material that emits no radiation (at any wavelength) – dark matter
- Assuming that the average star has a mass similar to that of the Sun, then based on the Milky Way’s mass, there are roughly 100 billion stars
Age of the Milky Way

• Using stellar aging techniques, astronomers had estimated the galaxy’s most ancient stars to be about 15 billion years old
• More recent model calculations and observations suggests the old star ages are more like 13 billion years
• A rough estimate of the Milky Way then is about 13 billion years
Stars of the Milky Way

• Stellar Censuses
  – Counts that list all known stars of a given type in a region of space is called a stellar census
  • All star types are represented in the Milky Way
  • By analyzing the relative numbers of stars of each type, deducing the galaxy’s history is possible
Stars of the Milky Way

• The Mass Function
  – From a stellar census one can derive the number of stars of each mass, technically known as the mass function
    • Mass determines the life cycle of a star
    • The evolution of the Milky Way will then depend on:
      – How many stars of each type it contains (A galaxy with only massive stars will evolve quickly)
      – How fast each type is created (Fast creation will quickly deplete gas resources)
Stars of the Milky Way

• Some results:
  – Dividing the number of stars in the Milky Way by its age gives a star creation rate of 7-8 stars per year
  – Most numerous stars turn out to be dim, cool, red dwarfs (mass about 0.5 \( M_\odot \))
  – The average mass for Milky Way stars is \( \sim 1 \ M_\odot \)
  – Stars more massive than 100 \( M_\odot \) are rare
  – Current research suggests that brown dwarfs (“failed stars” of mass less than 0.08 \( M_\odot \)) are more numerous than ordinary stars
  – It is important to be aware of “selection effects” when interpreting data: “Absence of evidence is not evidence of absence”; i.e., there may be things there you cannot see)
Two Stellar Populations

- **Population I**
  - Age: generally young (10^6 to a few times 10^9) years
  - Color: blue (generally)
  - Location: disk and concentrated in arms
  - Orbit: approximately circular in disk
  - Heavy-element content: high (similar to Sun)
Two Stellar Populations

- **Population II**
  - Age: old (about $10^{10}$ years)
  - Color: red
  - Location: halo and bulge
  - Orbit: plunging through disk
  - Heavy-element content: low ($10^{-2}$ to $10^{-3}$ Sun)
Two Stellar Populations

• Division of stars into two groups can be oversimplification
  – Sun does not fit in either category, but is usually considered a Pop I star
  – Inspires creating subgroups
    • Subdivide each population into *extreme* and *intermediate*
    • *Old-disk population* sometimes used for stars like the Sun
Two Stellar Populations

- The two populations show that star formation has not occurred continuously
  - Pop II formed in major burst at galaxy’s birth during its initial collapse
  - Pop I formed much later and are still forming today
- Pop I stars used to map spiral arms in vicinity around Sun
Some of the Milky Way’s stars are gravitationally bound together in groups called **star clusters**.

There are two types of star clusters:
- Open Clusters
- Globular Clusters
Open Clusters

- Contain up to a few hundred members in a volume of typically 7-20 light-years across
- Pleiades (or the Seven Sisters) is an excellent example
- Also called “galactic clusters” since most lie in galactic disk
- Formed when interstellar gas clouds are compressed and collapse upon entering the Milky Way’s spiral arm
- About 20,000 open clusters currently exist, many of them obscured by the dust of the galactic disk
Open Clusters

- Within spiral arms, very young stars may group together in loose *associations* a few hundred light-years across
  - Single large open cluster near their center
  - Birthing gas and dust still present
- After hundreds of millions of years, the stars gradually leave and the cluster dissipates
Open Clusters

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Globular Clusters

- Contain far more stars than open clusters, from a few hundred thousand to several million per cluster.
- Have large radii, 40-160 light-years across.
- The strong gravity pulls the stars into a ball denser than that found in open stars.
- About 150-200 globular clusters outline the halo and bulge of the Milky Way.
Globular Clusters

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Star Clusters

• Open and globular clusters reflect the properties of Pop I and II stars – Open clusters are generally Pop I and globular clusters are always Pop II
Gas and Dust in the Milky Way

- The space between stars is not empty: it contains *interstellar matter* composed of gas and dust
  - Most of the gas and dust exists in the galactic plane
  - Even here it clumps into clouds a few light-years to a few hundred light-years across
  - Typical densities are a few gas atoms per cubic centimeter (air has $10^{19}$ atoms per cubic centimeter)
Gas and Dust in the Milky Way

- Interstellar clouds seen directly or detected by their effect on light from distant stars
  - Gas and dust imprint narrow absorption lines on starlight passing through interstellar clouds: such lines can give cloud’s composition, temperature, density, and speed
  - Gas found to be 71% H, 27% He, 2% heavy elements

- Dust is \( \mu \)m to nm in size, made of silicates and carbon compounds, and perhaps coated with ices of water, carbon monoxide, and methyl alcohol
Scattering

- The light from a star dims and reddens as it passes through an interstellar cloud with dust.
- Light is randomly reflected from the dust surfaces in a process called scattering.
• This scattering is most effective when the light’s wavelength is smaller than the dust grain

• The optimum scattering for interstellar dust and molecules in the Earth’s atmosphere is for blue and ultraviolet light

• Earth’s sky is blue and the setting Sun red because of scattering
Reddening

• The loss of blue light from a star due to scattering in an intervening cloud is called *reddening*

• An interstellar cloud that completely obscures the stars behind it is called a *dark nebula*
Reddening and Obscuration

- The large amount of dust in the galactic plane reduces almost to zero the number of distant galaxies that can be seen – this region of the sky is called the **zone of avoidance** (the galaxies can still be “seen” in the radio and infrared)
A nebula may be seen in the visible as the result of starlight reflecting off the dust – such a nebula is called a \textit{reflection nebula}
Interstellar Gas

• Interstellar gas plays a crucial role in providing material for creating stars and a repository for matter blown out by dying stars

• Interstellar gas also helps astronomers map the Milky Way since molecules within the clouds emit at wavelengths that can penetrate dust

• And, of course, the visible wavelengths of many gas clouds provide spectacular images
Interstellar Gas

- Interstellar gas clouds that emit visible light are called **emission nebulas**
  - To emit this light, the cloud must have a source of energy, usually a nearby star
  - Hot, blue stars are especially effective at energizing a gas cloud
Interstellar Gas

- Clouds that are hot enough to ionize hydrogen will give off a very characteristic red color as electrons recombine with protons – these clouds are called **HII regions** (the II indicating ionization).
Interstellar Gas

- Maps of radio and optical observations of HII regions are the best evidence we have that the Milky Way is a spiral galaxy.
Mapping the Milky Way

- Most interstellar gas clouds are too remote from hot stars to be seen in the visible
  - We detect these clouds by measuring their radio output
  - For hydrogen, the 21-centimeter radiation is the radio emission that comes from the “spin flip” of the bound electron
A more refined technique uses the rotation speeds of stars at a variety of distances from the center (the so-called \textit{rotation curve}). This technique can more accurately determine the mass of the entire galaxy – the Sun method only estimates the mass interior to its orbit.
• Because the galactic center is not observable in the visible, astronomers must rely on radio, infrared, X-ray, and gamma-ray observations.
Formation of the Milky Way

• Forming galaxies is still a major unsolved problem

• Originally, it was thought that galaxies form like stars, but only on a larger scale
  – Begin with a million-light-year cloud with 100 billion solar masses of material
  – The cloud gravitationally collapses and breaks up into stars

• Evidence for this galaxy formation process can be found in the Pop I and Pop II stars
Formation of the Milky Way

A few million light-years (ly) ago:
- Some stars begin to form in the pregalactic cloud of pure hydrogen and helium.

In the process:
- There are massive stars that undergo supernova explosions.

Approximately 100,000 ly later:
- Stars form in the disk; higher-mass stars in the halo die, leaving only low-mass red stars behind.
Formation of the Milky Way

- The proto-Milky Way was a giant cloud of pure hydrogen and helium.
- The existence of old Pop II stars with very little heavy elements suggests they formed at the onset of collapse and as they did so, they dropped out of the gas collapse.
Formation of the Milky Way

• The massive Pop II stars exploded early on, seeding the galactic cloud with heavy elements.

• By the time the cloud collapsed into a disc it was rich enough in heavy elements to generate the Pop I stars we see there today.
Formation of the Milky Way

Stars form in disk; higher-mass stars in halo die, leaving only low-mass red stars behind.
Formation of the Milky Way

• However, the collapse model fails to explain two important properties of stars
  – Pop II stars appear to have formed over a longer time scale than the collapse model allows
  – Some stars should have virtually no heavy elements, but no such stars have ever been observed
Formation of the Milky Way

• Today, astronomers also think the collapse model fails to include the effects of galactic mergers on galactic and stellar evolution – merging appears to be the rule, not the exception
The Future of the Milky Way

• Eventually all gas finds its way into stars, which in turn will lock up material in stellar remnants

• Hundreds of billions of years from now the Milky Way will fade, slowly spinning in space, a dark disk of stellar cinders