Astronomy 218

Our Place in the Milky Way
Orbiting Sun

The Sun’s proper motion relative to the Galactic center, $\mu'' = 5.8$ milliarcseconds yr$^{-1} = 2.8 \times 10^{-8}$ rad yr$^{-1}$ and its distance from the Galactic center, $R_0 = 8$ kpc, indicate an orbital velocity of $v_0 = 225$ kpc Gyr$^{-1} = 220$ km s$^{-1}$.

The Sun’s orbital period around the Galactic Center is then

$$P_0 = \frac{2\pi R_0}{v_0} = \frac{50.3 \text{ kpc}}{225 \text{ kpc Gyr}^{-1}} = 0.22 \text{ Gyr} \approx \frac{t_\odot}{20}$$

Maintaining this orbit requires that the mass inside of the Sun’s orbit must be

$$M_\odot + M_{cen} = \frac{a^3}{P^2} = \frac{(1.65 \times 10^9 \text{ AU})^3}{(2.2 \times 10^8 \text{ yr})^2} M_\odot = 9.3 \times 10^{10} M_\odot$$

This 93 billion $M_\odot$ for the inner galaxy compares to 23 billion $L_\odot$, indicating that the galaxy’s $M/L > M_\odot/L_\odot$. 
Measurements of the position and motion of gas clouds throughout the Milky Way reveals that the solar environment includes several spiral arms.

- Scutum-Centaurus Arm
- Norma Arm
- Sagittarius Arm
- Central Bar
- Orion Spur
- Perseus Arm
- Outer Arm
Galactic Coordinates

The Galactic plane defines a **galactic coordinate system**, in the same way the Equator defines the terrestrial latitude and longitude.

The line from the Sun to Sagittarius A* defines the zero of **galactic longitude**, $\ell$, which increases counter-clockwise viewed from the north.

The **galactic latitude**, $b$, is measured from the plane of the galaxy to the object using the Sun as vertex.
One interpretation of the spiral arms would be the winding up of an initial linear pattern.

However, the differential rotation of the galaxy would have wound up the spiral pattern so tightly that it would effectively disappear, contrary to observations.

Thus the spiral arms are not tied to disk material.
Density Waves

Instead spiral arms are density waves, similar to the over density of cars in a traffic jam. The jam persists even though individual cars move steadily through it.

Such density waves persist long after the event that triggered them is forgotten.

In the case of galaxies, the waves are regions of locally higher density, which accelerate stars into them and decelerate them as they leave, perpetuating the over density.
Not just the density of stars becomes enhanced as they move through the spiral arms, but clouds of gas and dust are actually compressed.

Their increased density triggers star formation.

This affects the propagation of spiral arms as the formation of stars leads to supernovae and stellar winds which further compress the gas and dust, leading to waves of ongoing star formation.
It is this ongoing star formation which makes the spiral arms so **visible**. Newly formed massive stars, and their attendant **HII regions** and **supernova remnants**, line the spiral arms, shining bright and dying before leaving the arm.

In contrast, older stars **move through the arms** and have a smoother angular distribution.

As one moves to progressively **longer wavelengths**, the spiral arms become less noticeable. The actual over-density is small, only a few %. 

**Spiral Lights**
The Orion Spur is also referred to as the Orion-Cygnus Arm or the Orion Arm.

The Sun sits near the center of the Local Bubble, close to the inner rim of the arm,

Facing in the leading direction points in the direction of Deneb and the constellation Cygnus.

Facing in the trailing direction points toward Betelgeuse and the constellation Orion.
We can measure the relative motions of nearby stars in two steps.

The **space velocity** $v$ can be decomposed into 2 components, relative to the line of sight.

The **radial component**, $v_r$, along the line of sight, can be measured by doppler shift.

The **tangential** (or transverse) **component**, $v_t$, across the line of sight, can be measured by **proper motion**, $\mu$.

To achieve the desired accuracy, these measurements must be corrected for the Earth’s orbital velocity ($v_{\text{orb}} \approx 30 \text{ km s}^{-1}$) and the Earth’s rotational velocity ($v_{\text{rot}} \approx 0.5 \text{ km s}^{-1}$), as well as any binary motions of the distant star.
Examination of the radial velocities of the 40 stars closest to the Sun, $d < 5\ pc$, results in this figure.

The number of redshifted stars approximately equals the number of blueshifted stars.

Kapteyn’s star, at a distance of $3.9\ pc$, is a noticeable outlier, with a velocity of $250\ km\ s^{-1}$ away from the Sun.

Ignoring Kapteyn’s star, the root-mean-square velocity dispersion is $\sim 35\ km\ s^{-1}$ in radial velocity.
Proper Motion

Measuring the motion of a star across the line of sight is much more **time-consuming** than measuring the radial velocity via the Doppler Shift. Time must pass for the star to move **perceptively** on the sky.

In the **small angle limit**, the proper motion \( \mu = v_t/d \). If \( \mu \) is measured in rad yr\(^{-1} \) and \( d \) in parsecs,

\[
\frac{v_t}{\text{pc yr}^{-1}} = \left( \frac{d}{\text{pc}} \right) \left( \frac{\mu}{\text{rad yr}^{-1}} \right)
\]

\( \mu \) is more naturally **measured** in arcseconds yr\(^{-1} \), with 1 radian = 206,265 arcseconds. Comparison of \( v_t \) to \( v_r \) favors km s\(^{-1} \) with 1 pc yr\(^{-1} \) = 976,582 km s\(^{-1} \). Simplifying

\[
\left( \frac{v_t}{\text{km s}^{-1}} \right) = 4.74 \left( \frac{\mu}{\text{arcsec yr}^{-1}} \right) \left( \frac{d}{\text{pc}} \right) = 4.74 \left( \frac{\mu''}{\pi''} \right)
\]
Local Tangential Velocity

Examination of the tangential velocities of the 40 stars closest to the Sun results in this figure.

The red line marks \( \mu = 5 \text{ arcsec yr}^{-1} \).

Again Kapteyn’s star shows its uniqueness with a large \( v_t \) producing a large proper motion, \( \mu = 8.7 \text{ arcsec yr}^{-1} \).

Barnard’s star, despite its smaller tangential velocity, has the highest proper motion, \( \mu = 10.4 \text{ arcsec yr}^{-1} \).

61 Cygni, \( \mu = 5.2 \text{ arcsec yr}^{-1} \), has the highest proper motion of any star visible to the naked eye.
Local Space Velocity

Combining the radial and tangential velocities for the 40 closest stars reveals that 39/40 belong to a group with a mean relative velocity $v \sim 50 \text{ km s}^{-1}$.

These velocities will rearrange their proximity to the Sun on a timescale of $t \sim 5 \text{ pc} / 50 \text{ pc Myr}^{-1} \sim 0.1 \text{ Myr}$. For example, Gliese 710, currently 19 pc away, will pass within $\frac{1}{3} \text{ pc}$ in 1.4 Myr, brightening from $m_v = 9.7$ to 0.9.

Kapteyn’s star, with twice the velocity of any other nearby star, is in a class by itself, the nearest halo star.
Local Standard of Rest

The aspherical and time varying distribution of mass within the Galaxy prevents stars from moving in closed elliptical orbits. Instead, stars follow complex rosette patterns. These patterns make actual stellar orbits a poor basis for a coordinate system.

We create an idealized reference frame, the Local Standard of Rest, which moves in a circular orbit at $\nu_0 = 220 \text{ km s}^{-1}$ from the Sun’s location at $R_0 = 8 \text{ kpc}$.

Coordinates relative to the LSR are $(R, \theta, z)$, with the Sun at $(R_0, 0, 0 \text{ kpc})$. Velocities are $(\Pi, \Theta, Z)$, with $\nu_{LSR} = (0, \nu_0, 0)$. 
Sun’s Peculiar Motion

The LSR is moving steadily in the direction of Cygnus.

But, the LSR is not the orbit of the Sun. Using a statistical analysis of the radial velocities of neighboring stars, we can determine the Sun’s motion. Relative to the LSR, the Sun has a peculiar velocity \((u_\odot, v_\odot, w_\odot)\)

\[= (\Pi - \Pi_\odot, \Theta - \Theta_\odot, Z - Z_\odot) = (-10.4, 14.8, 7.3) \text{ km s}^{-1}\]

Thus the Sun is moving inward (toward the Galactic Center) at 10 km s\(^{-1}\), forward (faster than the LSR in the azimuthal direction) at 15 km s\(^{-1}\) and northward (toward the north Galactic pole) at 7 km s\(^{-1}\).

This places the Sun’s apex or direction of motion toward the constellation Hercules and its antapex, opposite direction from the apex, toward the constellation Columba.
Combining tangent point method observations toward the Galactic center with stellar observations in the outer Galaxy reveals the rotation curve of the Galaxy.

The expectation was that beyond a radius that contained the mass of the galaxy, the velocity should diminish with radius following Kepler’s law.

Instead mass continues to increase with radius, well into the region where the light is exponentially declining. Something dim but massive lurks in the Galaxy.
The visible structure of the Galactic Disk extends $\sim 15$ kpc from the center.

Beyond this radius, atomic gas (molecular gas is found for $R \leq 10$ kpc) and halo stars map the “missing” mass, whose density is $\propto R^{-2}$.

But the mass is present, it is the light that is missing.

What could the “dark matter” be? Many suggestions have been raised; red dwarves, white dwarves, brown dwarves, stellar-mass black holes, elementary particles, ….
One possibility is that dim red dwarfs are even more numerous than suspected. Many searches, most recently by Hubble, have looked for such red dwarfs, but turned up too few to account for dark matter.

Our best accounting of the full stellar population yields $M/L \sim 10$ while the rotation curve indicates $M/L \sim 50$. 

**Not Red Dwarfs**
Our study of stars suggests several other candidates for dim but massive objects, black holes, neutron stars, white dwarves and brown dwarves. This very dimness makes them difficult to observe directly. However, gravitational lensing can allow us to directly observe their mass by bending more light into the line of sight.

Observations have found numerous MACHOS (Massive Compact Halo Objects), mostly low-mass white dwarves, but only ~20% of the missing mass.
Not Neutrinos

The universe is in fact flooded with neutrinos, relics of the Big Bang and the lives and deaths of stars.

Neutrinos interact extremely rarely, and we’ve learned from neutrino oscillations that they have mass, both promising characteristics for the dark matter.

Neutrino oscillation measurements reveal mass differences $\Delta m_{12}^2 = 0.00008 \text{ eV}^2$ and $\Delta m_{23}^2 = 0.003 \text{ eV}^2$, but not the masses. A number of other experiments place limits on the mass of the neutrino $< 1 \text{ eV}$. At this mass, neutrinos are not the dark matter.

Particle physics predicts a myriad of similar, as yet undetected, Weakly Interacting, Massive Particles (WIMPs) with masses $> 100 \ m_p \sim 100 \text{ GeV}$ that could be the dark matter.
Next Time

Rotation Curves and Missing Mass