Today in Astronomy 142: nonaxisymmetric and compact structures in the Milky Way

- Spiral structure in the Galaxy.
- The 3-5 kpc molecular ring.
- Noncircular motions and the Galaxy’s bar.
- The Galactic center ($r < 3$ pc): Keplerian motion around a black hole.

M 95 = NGC 3351 ([Adam Block, Mt. Lemmon SkyCenter, U. Az]). This is probably what the Milky Way looks like from a point high above its north pole; the image has been flipped to make it look like north rather than south. The position the Sun would have is marked with a cross.

SN 2012aw (16 March 2012)
Structure of the Galaxy’s interstellar medium

Last time we described how the rotation curve could be derived from radial-velocity measurements:

\[ v(r) = \left( v_r \right)_{\text{max}} + r \Omega(r) \sin \ell \]

Once the rotation curve is known, the positions (subject to the distance ambiguity) are also determined:

\[ r = r_\odot \frac{v \sin \ell}{v_r + v \sin \ell} \]

You’ll show this in Homework #7.
Molecular- and atomic-line surveys of the Galaxy

Molecular and atomic clouds are our main probes of the global structure of the Milky Way.

- H I and CO emission are bright and negligibly extinguished, so they offer a view of the whole Galaxy.

- As discussed previously, the clouds have small internal random velocities, so they probe the disk’s rotation a bit more clearly than the stars.

- However, such studies are importantly supplemented by infrared surveys of stars, in which stellar densities of special regions like the bulge, or spiral-arm tangents, can be measured.

Ultimately Galaxy-wide infrared surveys of stellar radial velocity and parallax will be the best tools, but such surveys are still at least a few years off with Gaia.
Molecular cloud complexes in the Galactic plane

Dame, Hartmann and Thaddeus 2001
Molecular cloud complexes in the Galactic plane
Molecular cloud complexes in the Galactic plane

Striking feature of these surveys: the prominence in the inner galaxy of systematic **noncircular motions** that violate the trends of prograde, circular orbits, and non-axisymmetric, *spiral* structure in the outer galaxy.
The noncircular motions

First consider a few simple situations and the resulting $v_r (\ell)$:

Longitude-velocity diagram of a uniformly-rotating ring.
The noncircular motions (continued)

Longitude-velocity diagram of a nonrotating, expanding ring.
The noncircular motions (continued)

Longitude-velocity diagram of a rotating, expanding ring.
The noncircular motions (continued)

The noncircular motions are best described as the superposition of a set of rotating, expanding/contracting orbits, similar to those shown.

- The origin of these orbits is best described by a bar-shaped inner stellar distribution.
- This would explain the 3-5 kpc molecular ring, as a resonant orbit (“inner Lindblad resonance”) in the rotating barred gravitational potential (Weiner and Sellwood 1999).
Spiral structure in the molecular clouds of the first Galactic quadrant

Face-on view of the Galaxy:

- Spiral arms, here delineated in molecular cloud complexes (i.e. star formation regions).
- **Molecular ring** at $r = 3-5$ kpc.
- Not much gas within ring (except closer to center than is shown.)
- Spiral arms trail Galactic rotation.

(Clemens, Sanders, Scoville 1988)
Why would a bar do that?

A bar turns out to explain both the noncircular motions of a ring, and spiral structure in the disk. Properly a topic for AST 232, but:

- If the mass distribution and gravitational potential of the galaxy were **axisymmetric**, the orbits of clouds and stars about the Galactic center would be circular.
Why would a bar do that? (continued)

If the gravitational potential suffered a non-axisymmetric perturbation, such as the exaggerated bar-shaped one sketched here, stars and clouds would suffer a perturbation in orbital speed at the ends of the bar: as there is additional mass closer to the orbit, the speed increases there according to $GM(r)/r^2 = v^2/r$. 

\[ \frac{GM(r)}{r^2} = \frac{v^2}{r}. \]
Why would a bar do that? (continued)

- The disk rotates differentially, but it is possible for bars to rotate like solid bodies, as does the innermost part of the Galaxy’s stellar distribution.
- So the relationship between orbital periods relative to the bar’s varies with radius within the disk.
Why would a bar do that? (continued)

- For orbits with periods in integer ratios to the bar’s rotation period, the perturbations are **resonant**, and large deviation from circularity can accumulate.

- This appears both in space and in $l$-$v$ diagrams as noncircular motion.
Why does this show up in the distribution of molecular clouds?

Lin and Shu, 1964: arms are due to spiral density waves.

- Analogy to road work and traffic jams (in 1-D):
  Imagine a road crew painting lane stripes on a freeway. They move along at a couple of mph. A traffic jam forms behind them and moves along with them. Cars before and behind the jam move at 65 mph and are much further apart than in the jam. Cars enter the jam from behind, slow as they move through it, and resume speed as they leave. From a helicopter it appears that a dense concentration of cars moves along with the road work, but it is composed of different cars at different times.

Normal traffic speed $\iff$ normal stellar orbit speed;
road crew speed $\iff$ spiral-wave pattern speed;
traffic jam $\iff$ density wave $\iff$ spiral arm
Spiral density waves (continued)

What plays the role of the road crew in a spiral galaxy disk? Gravity from the rotating, non-axisymmetric part of the stellar distribution:

- Force on orbiting objects larger than average when the ends of bar make their closest approach; smaller than average in between.
- Other things equal, this alternately speeds up and slows down the orbital speeds.

For more details, take AST 232.
Can we see the bar?

Yes.

- It’s not easy, as the bar indicated by the gas motions extends only about 3-4 kpc from the center, and is thus heavily extinguished.

- But at long near-infrared wavelengths (3-5 μm), star counts reveal the near end of the bar, with properties similar to that indicated by the molecular clouds.

Benjamin et al. 2005
View of the Milky Way from the north

The Galaxy appears to be a barred spiral galaxy with two dominant arms. The molecular ring is the superposition of these arms and the Norma/Sagittarius features. The 3-kpc expanding arms represent flows closer to the bar.

(Robert Hurt, SSC)

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M95 (right; image flipped) is inclined slightly ($i = 21^\circ$) with respect to our line of sight; the cartoon of the Milky Way (left) is face on.
Orbital motion and the center of the Milky Way, Sagittarius A West

The dynamical center of the Galaxy is heavily extinguished; it cannot be seen at visible through longer X-ray wavelengths.

- It is bright at infrared and radio wavelengths, and hard (short-wavelength) X rays, which are transmitted through the dust.

- It was also the first extraterrestrial object discovered at radio frequencies, by Karl Jansky in 1933.

Within the central 3 pc, we find a dense cluster of stars, a bright, compact radio source, and a swirl of gas clouds.

- The small, bright radio source is called Sagittarius A* = Sgr A*.

- Sgr A* lies precisely at the center of our Galaxy – that is, at the place about which everything in the galaxy revolves.
The brightness of Sgr A*, radio through X-rays

Measured brightness of Sgr A* at radio, infrared and X-ray wavelengths (after Melia and Falke 2001). Interstellar dust hides Sgr A* at wavelengths from the shorter infrared through the longer X-ray.

![Graph showing the brightness of Sgr A* at different wavelengths. The x-axis represents wavelength in units of meters and micrometers, and the y-axis represents log(brightness in Janskys). The graph shows a sharp decrease in brightness as wavelength increases from radio to infrared to visible ultraviolet to X-ray.](https://example.com/graph.png)
Sgr A* is the brightest, starlike object in the center of the image (follow the arrows). By Baganoff et al. (2003), with the Chandra X-ray Observatory (CXO).
Sgr A* is the red ellipse at the center of this false-color image by Yusef-Zadeh and Wardle (1993) with the NRAO Very Large Array (VLA).
Near-infrared image, central parsec of Sgr A West

Sgr A* does not appear in this picture, as it is drowned out by the light of all the stars (Genzel et al. 2003).

Color code: blue = 1.6 µm, green = 2.2 µm, red = 3.8 µm.
Near-infrared image sequence, central 30 light-days of Sgr A West

- With adaptive-optical imaging, it is possible to see Sgr A* itself at infrared wavelengths.
- Most of the infrared light it emits comes in the form of short “flares,” as in this image sequence.

Over the course of the last four decades astronomers have measured velocities related to orbital motion about the center for many objects that lie within the central few light years of the Galaxy:

- radial velocities of gas clouds.
- radial velocities of stars.
- proper motions of stars.

The orbits do not lie in the plane of the rest of the galaxy, but that doesn’t matter; these are test particles we can use to determine the gravitational field.
At radio wavelengths most of the bright objects near Sgr A* are gas clouds, in orbit about Sgr A*.

Sgr A* appears in this false-color radio-wave image as a small white dot (follow the arrows). The “swirls” are streamers and clouds of ionized gas, in orbit about the Galactic center.

This image is a color code of the radial velocity of ionized gas. Red = receding at about 200 km/s; blue = approaching at about 200 km/s.

*(Roberts and Goss 1993)*
The closer to Sgr A*, the larger the orbital speeds.

Radial velocities for ionized gas clouds Sgr A West, measured with infrared light. Some clouds are found in the infrared measurements that don’t appear in the radio image.

(Genzel, Hollenbach and Townes 1994)
At infrared wavelengths, some stars are seen to orbit Sgr A*.

Here are the brightest stars in the central few light years of the Milky Way, seen in near-infrared light over the course of 16 years.

Image by the Genzel group, MPE Garching
The closer to Sgr A*, the larger the orbital speed for stars, too.

The brightest stars in the central 18 light-days of the Milky Way, seen at infrared wavelengths over the course of ten years, and extrapolated for five more.

- Note the high speeds (over 5000 km/sec) and close approach to Sgr A* (+) by some of the stars.
- One has an orbital period of only 15.2 years, and passes within 124 Earth-Sun distances of the black hole.

(R. Schödel et al. 2003; see www.mpe.mpg.de/ir/GC/index.php?lang=en)
Stellar motions close to Sgr A*, in 3-D

From the MPE group (Genzel et al.)
Orbital motion and the center of the Milky Way (continued)

Results:

- The stellar and gas-cloud Doppler shifts get larger the closer the stars or cloud is to Sgr A*.
- The stellar proper motions are generally larger the closer the star is to Sgr A*.
- If the central stellar cluster were all that were there (no massive black hole), the orbital velocities would decrease toward zero as one looked closer to the center, because there would be less and less mass enclosed by the orbits.
- If there were a massive black hole, the mass enclosed by stellar orbits of smaller and smaller size,

\[ M(r) = \frac{rv^2}{G} \]

would approach the black hole’s mass.
The black hole at the center of the Galaxy

Summary of results from stellar and gas-cloud Doppler shifts and proper motions (Schödel et al. 2003), assuming a distance to the Galactic center (8.0 kpc) smaller than the current accepted value.
And the Sgr A* black hole spins, too

Occasionally, in the “flare” emission from Sgr A* seen at near-infrared wavelengths, one sees a periodic series of peaks (blue arrows, in the figure below) that is reminiscent of the fast oscillations or pulses seen in stellar-mass black holes like GRO J1655-40. Is this the beginning of a “death spiral” at innermost stable circular orbit, and thus a sign of rotation?

(Genzel et al. 2003)
And the Sgr A* black hole spins, too (continued)

If so, the black hole in Sgr A* is spinning at about 25% of its maximum rate (i.e. the rotational speed at the horizon is $0.25c$). Zero spin is ruled out, within the uncertainties.

In blue: innermost stable orbits per hour for a $4.3 \times 10^6 M_\odot$ black hole, with uncertainties.

In red: measured orbits per hour, with uncertainties (Genzel et al. 2003).
The black hole at the center of the Galaxy (continued)

Thus there is a black hole at the center of the Milky Way, its mass is $(4.3 \pm 0.4) \times 10^6 M_\odot$ (Gillessen et al. 2009), and it spins at about 25% of its maximum rate.

- Presumably the radio and X-ray components of Sgr A* are the outermost and innermost parts of the accretion disk around the black hole.

- The near-infrared flares probably also arise from the innermost, hottest part of the disk, with the quasiperiodic oscillations coming from the innermost stable orbit.

- As we will see, supermassive black holes are very common in galaxy nuclei, but the prominent examples – those in active galaxy nuclei – are much more massive than this.