Today in Astronomy 142: the Milky Way's shape

- 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 (NOAO/AURA/ NSF). This is probably what the Milky Way looks like from a point high above its north pole. The position the Sun would have is marked with a cross. Inset: short exposure of the galaxy's nucleus.

Molecular- and atomic-line surveys of the Galaxy

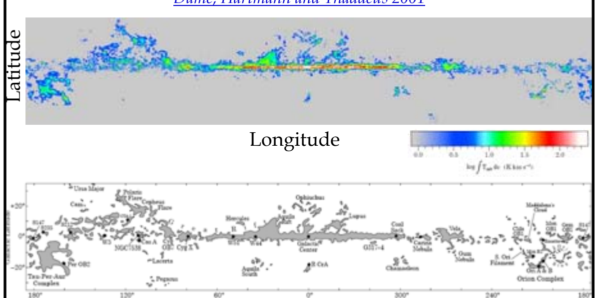
Molecular and atomic clouds are our main probes of the global structure of the Milky Way.

- 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.

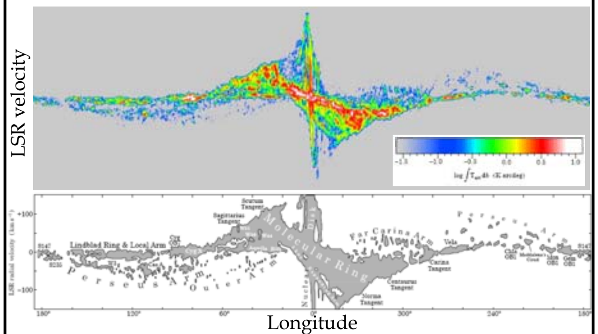
Ultimately Galaxy-wide infrared surveys of stellar radial velocity and parallax will be the best tools, but such surveys are still at least a decade off.

Molecular cloud complexes in the Galactic plane

Dame, Hartmann and Thaddeus 2001

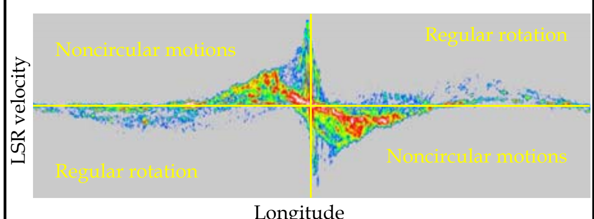


Molecular cloud complexes in the Galactic plane



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.



Structure of the Galaxy's interstellar medium

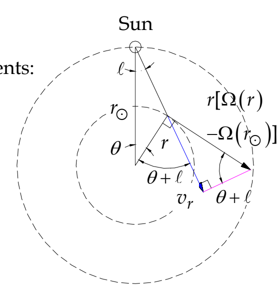
Last time we described how the rotation curve could be derived from radial-velocity measurements:

$$v(r) = \left(v_r\right)_{max} + r_\odot \Omega(r_\odot) \sin\ell$$

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

$$r = r_\odot \frac{v \sin\ell}{v_r + v \sin\ell} \quad .$$

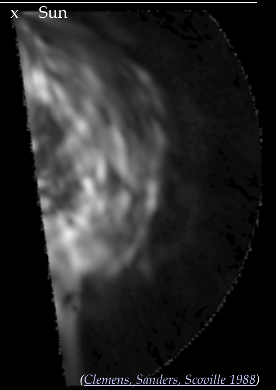
You'll show this in Homework #7.



Spiral structure in the molecular clouds of the first Galactic quadrant

Face-on view of the Galaxy:

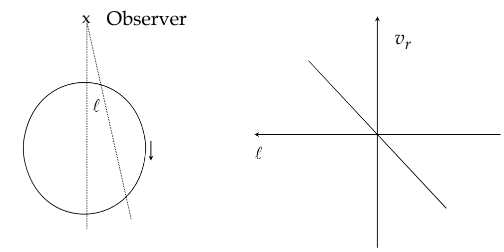
- Spiral arms, here delineated in molecular cloud complexes (i.e. star formation regions).
- **Molecular ring** at r = 3-5 kpc.
- Not much gas within ring (except closer to center than is shown.)
- Spiral arms trail Galactic rotation.



(Clemens, Sanders, Scoville 1988)

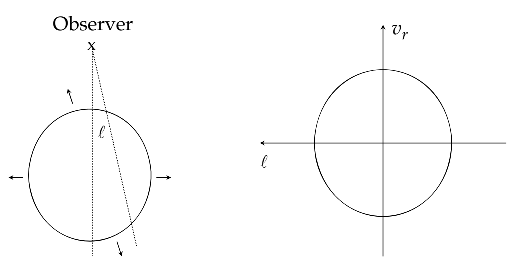
The noncircular motions

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



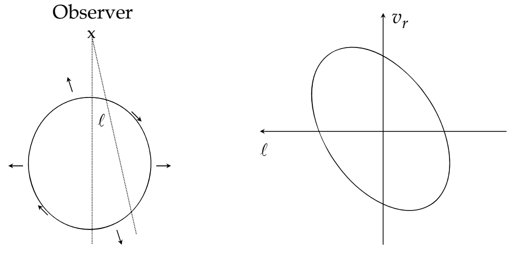
Longitude-velocity diagram of a uniformly-rotating ring.

The noncircular motions (continued)



Longitude-velocity diagram of a nonrotating, expanding ring.

The noncircular motions (continued)

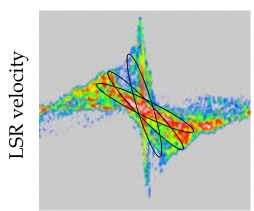


Longitude-velocity diagram of a rotating, expanding ring.

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.

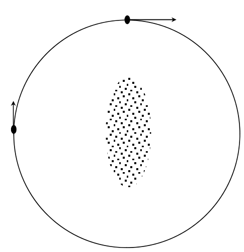
- The origin of these orbits is best described by a **bar-shaped** inner stellar distribution.
- This also would explain the 3-5 kpc ring, as a resonant orbit ("inner Lindblad resonance") in the rotating barred gravitational potential (Weiner and Sellwood 1999).



Why a bar?

Properly a topic for AST 232, but: a non-axisymmetric gravitational potential is not the same as a spherical one.

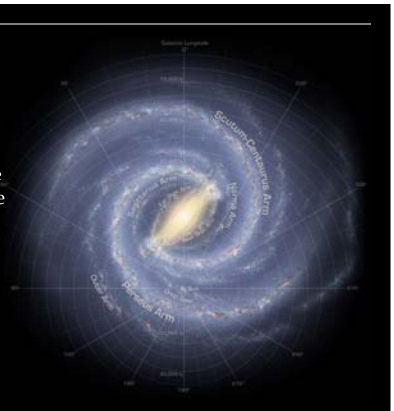
- Force on orbiting objects larger than average when the ends of the oval or bar make their closest approach; smaller than average in between.
- For distant orbits, this alternately speeds up and slows down the orbital speeds. For closer-by ones, significant non-azimuthal velocities develop.



The Milky Way, *c.* 2008

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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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.

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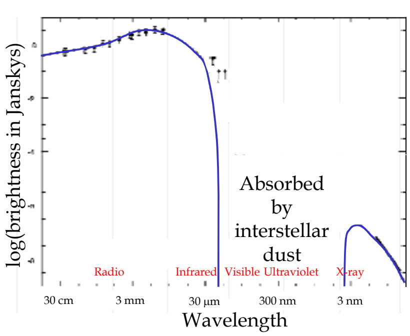
The brightness of Sgr A*, radio through X-rays

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.



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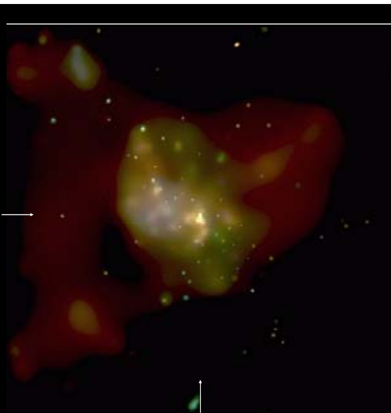

X-ray image, central parsec of Sgr A West

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).

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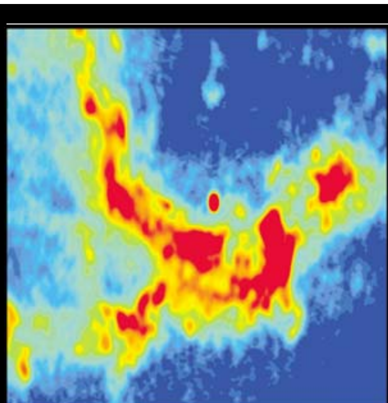

Radio image, central parsec of Sgr A West

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).

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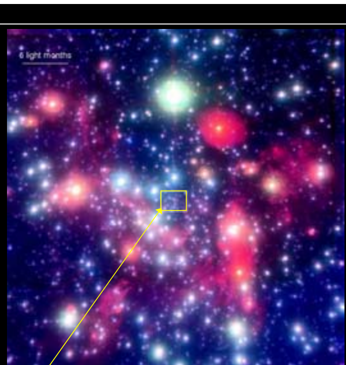

Near-infrared image, central parsec of Sgr A West

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.

Area in next image

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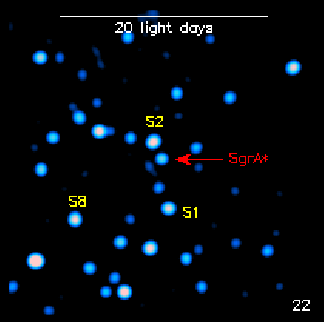
Near-infrared image sequence, central 30 light-*days* of Sgr A West



- Only recently, with new adaptive-optical imaging, has it been possible finally 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.

(Genzel *et al*. 2003; see also Ghez *et al*. 2004, and http://www.mpe.mpg.de/ir/GC/index.php?lang=en

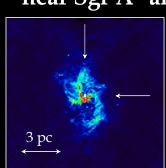
Orbital motion and the center of the Milky Way, Sagittarius A West (continued)

Over the course of the last three 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:

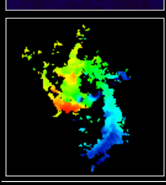
- radial velocities of gas clouds.
- radial velocities of stars.
- proper motions of stars.

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*.



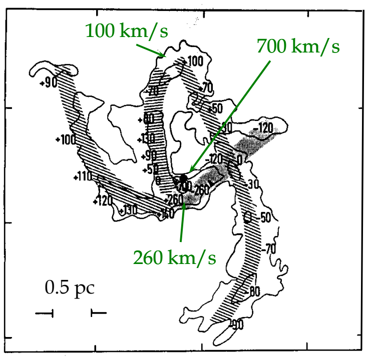
Sgr A* appears in this false-color radio-wave image as a small white dot (follow the arrows). The "swirls" are streamers and clouds of ionized gas, in orbit about the Galactic center.



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)

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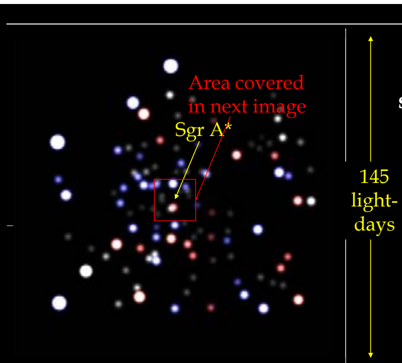
At infrared wavelengths, some stars are seen to orbit Sgr A*.



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
http://www.mpe.mpg.de/ir/GC/res_dance.php?lang=en

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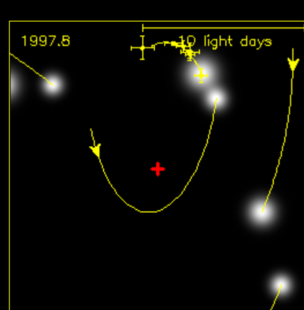
The closer to Sgr A*, the larger the orbital speed for stars, too.

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)



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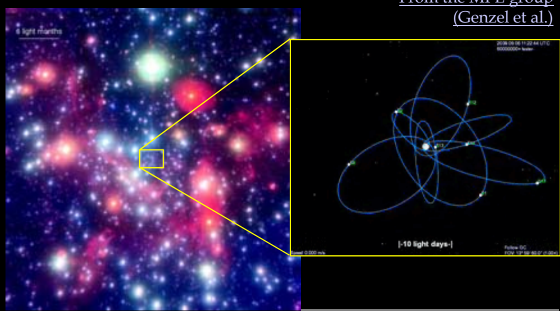
Stellar motions close to Sgr A*, in 3-D

From the MPE group (Genzel et al.)



Orbital motion and the center of the Milky Way (continued)

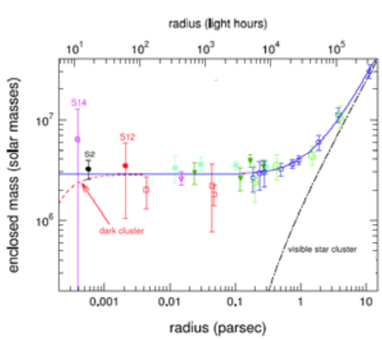
Results:

- 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,

$$M(r) = rv^2/G \quad ,$$

would approach the black hole's mass.

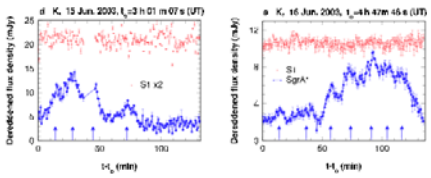
The black hole at the center of the Galaxy



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 orbit, and thus a sign of rotation?



(Genzel *et al.* 2003)

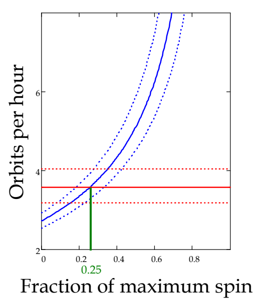
And the Sgr A* black hole spins, too (continued)

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 0.25*c*). Zero spin is ruled out, within the uncertainties.

In blue: innermost stable orbits per hour for a $4.3\times10^{6}\ M_{\odot}$ 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 $(4.3\pm0.4)\times10^{6}\ M_{\odot}$, 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.