Today in Astronomy 102: the Galactic center

- ❑ The center of the Milky Way Galaxy: compelling evidence for a 3.6-million-solar-mass black hole.

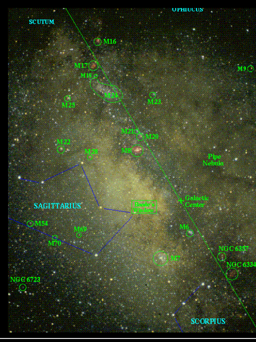

Image: wide-angle photo and overlay key of the Sagittarius region of the Milky Way, showing vividly the effect of obscuration by dust clouds. The very center of the Milky Way lies behind particularly heavy dust obscuration. (By Bill Keel, U. Alabama.)

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Distinctive features that can indicate the presence of a black hole (review from last lecture)

Observe **two or more** of these features to find a black hole:

- ❑ **Gravitational deflection of light**, by an amount requiring black hole masses and sizes.
- ❑ **X-ray and/or γ-ray emission** from ionized gas falling into the black hole.
- ❑ **Orbital motion of nearby stars or gas clouds** that can be used to infer the mass of (perhaps invisible) companions: a mass too large to be a white dwarf or a neutron star might correspond to a black hole.
- ❑ **Motion close to the speed of light**, or apparently greater than the speed of light ("superluminal motion").
- ❑ **Extremely large luminosity** that cannot be explained easily by normal stellar energy generation.
- ❑ Direct observation of a large, massive **accretion disk**.

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Is there a black hole in there?

HH 111 (HST images by Reipurth et al. 1999):

- ❑ Starlike object obscured by dusty disk
- ❑ Luminosity is 9.6×10^{34} erg/sec
- ❑ Shines mostly at visible and infrared wavelengths
- ❑ Twin jets, each 24 light years long, of material flowing out from central object at 500 km/sec

How many black hole symptoms does HH 111 have?

(Enter a number from 1 to 6, or enter 7 if you think the answer is "none.")

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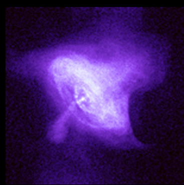
Is there a black hole in there?



PSR 0531+21 (Chandra X-ray Observatory image):

- Starlike object with luminosity 10^{30} erg/sec, surrounded by very hot disk
- Brightest at radio and X-ray wavelengths
- Twin jets
- Surrounding material flowing outwards at several hundred km/sec
- Brightness oscillates extremely regularly: 30 pulses per second.

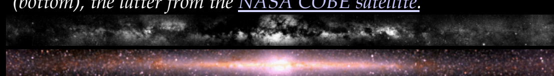
How many black hole symptoms does PSR 0531+21 have? (Enter a number from 1 to 6, or enter 7 if you think the answer is "none.")

Black holes in galaxy nuclei

Why might we expect to find black holes in the centers of galaxies?

- Densest part of the galaxy since birth: there are lots more stars per cubic light year – and presumably lots more of every other kind of object too.
- The galactic garbage can: as objects further out in the galaxy occasionally collide, material (or objects) released in the collision tends to fall in to the galactic center.

Starlight from the Milky Way: visible (top) and near-infrared (bottom), the latter from the NASA COBE satellite.



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

The center of the Milky Way is obscured by interstellar dust; it cannot be seen at visible through longer X-ray wavelengths.

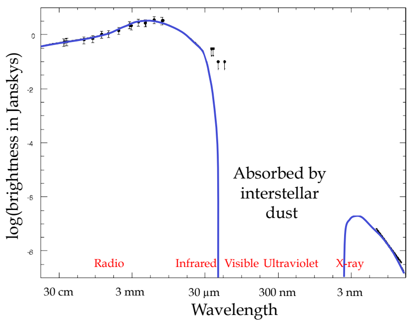
- It is bright at infrared and radio wavelengths, and **hard** (short-wavelength) X rays, which are transmitted through the dust.
- The name Sagittarius A indicates that it's the brightest radio source in the constellation Sagittarius (abbreviated Sgr). In fact, it was also the first extraterrestrial object discovered at radio frequencies, by Karl Jansky in 1933.

Within the central 10 light years, we find a dense cluster of stars, a bright, compact radio source, and a swirl of gas clouds.

- The small, bright radio source (Sagittarius A* = **Sgr A***) resembles the objects at the centers of quasars, but has a much smaller luminosity.
- 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.



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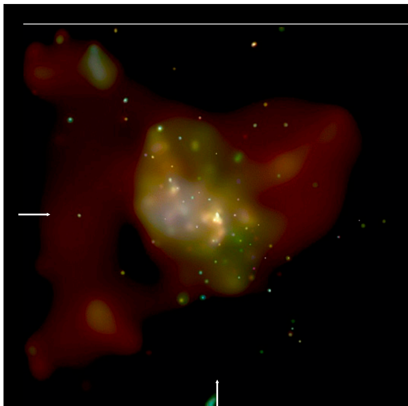
X-ray image, central 3 ly of Sgr A West



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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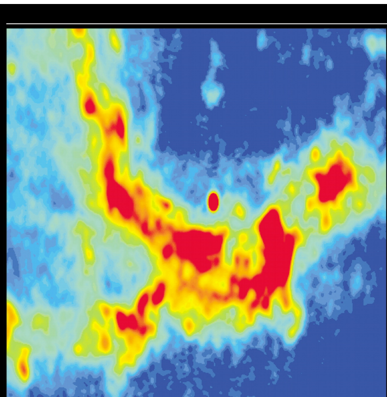
Radio image, central 3 ly of Sgr A West



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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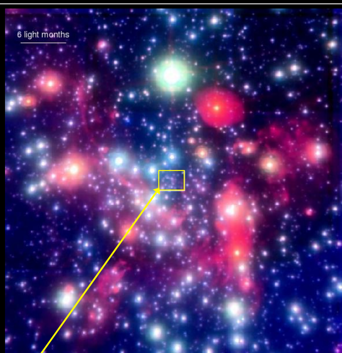


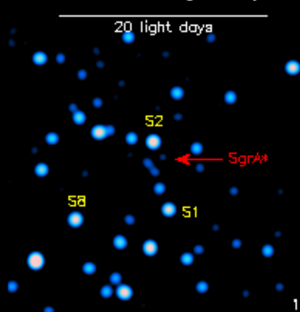
Area in next image

Near-infrared image, central 3 ly 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



- 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

Mid-lecture Break (6 min. 10 sec.)

- Exam #2 is on the radar: Thursday, March 31, again to be given on line using WeBWorK.
- Practice Exam # 2 will be available on on Friday March 25 at 12 pm and will close on Monday March 28 at 12 pm.

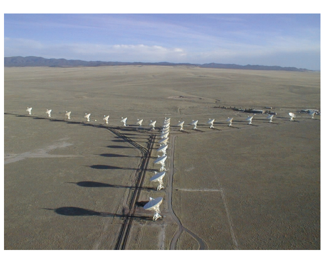


Image: the twenty-seven, 26-meter-diameter dishes of the NRAO Very Large Array, near Magdalena, New Mexico.

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:

- Doppler shifts in the spectra of gas clouds.
- Doppler shifts in the spectra of stars.
- **Proper motions** of stars (motion across the sky, perpendicular to the line of sight).

From the orbital-motion velocities, one can calculate the mass **enclosed** by each orbit, in much the same way that one can calculate the mass of one star from the spectrum of another, orbiting star.

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

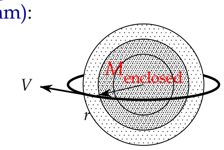
The conversion of the Doppler-shift velocities into enclosed mass is in this case actually simpler than it is for binary stars, since the mass enclosed by orbits around the Galactic center is so much larger than the mass of individual orbiting objects that we can presume the center of the orbit to stay fixed.

The simple physics (provided only for those curious; won't be on the exam):

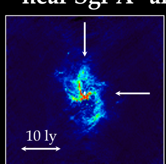
$$F = ma$$

$$\frac{GmM_{\text{enclosed}}}{r^2} = m\frac{V^2}{r}$$

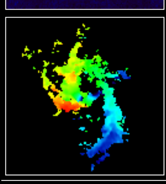
$$M_{\text{enclosed}} = \frac{rV^2}{G}$$



At radio wavelengths most of the bright objects near Sgr A* are gas clouds, in orbit about Sgr A*.

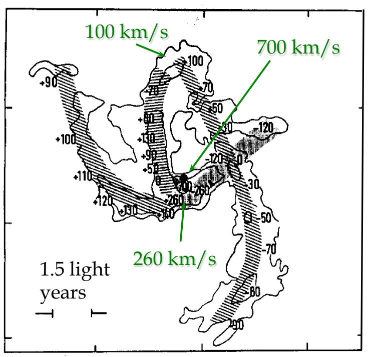


Sgr A* appears in this false-color radio-wave image as a small white dot (follow the arrows). The "swirls" are streamers and clouds of ionized gas, in orbit about the Galactic center.



This image is a color code of the speed of the ionized gas along our line of sight. Red = receding at about 200 km/s; blue = approaching at about 200 km/s.

Data: D. Roberts and M. Goss (1993), using the NRAO Very Large Array radio telescope.



The closer to Sgr A*, the larger the orbital speeds.

Line-of-sight 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.

(R. Genzel and C.H. Townes, 1987)

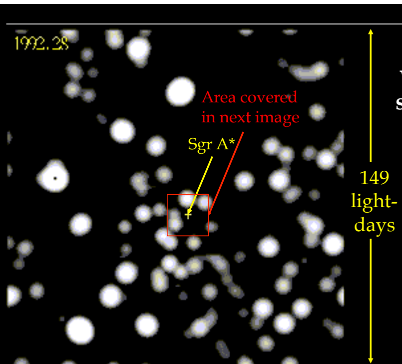


Image by A. Eckart and R. Genzel, 1996; http://www.mpe.mpg.de/ir/GC/

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

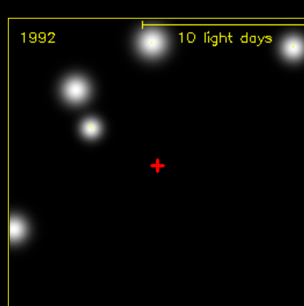
Here are the brightest stars in the central few light years of the Milky Way, seen in near-infrared light over the course of four years. Note the **proper motion** of some of the stars near the center.

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.

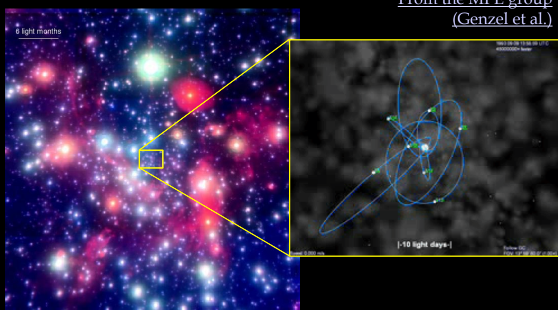
- Note the high speeds (over 5000 km/sec) and close approach to Sgr A* (+) by some of the stars.
- One has an orbital period of only 15.2 years, and passes within 124 Earth-Sun distances of the black hole.

(R. Schödel *et al.* 2003; see www.mpe.mpg.de/ir/GC/)



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

From the MPE group
(Genzel et al.)



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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 stellar cluster were all that were there (no massive black hole), the velocities from Doppler shifts or proper motions would decrease toward zero as one looked closer to the center, because there would be less and less mass enclosed by the stellar orbits.
- ❑ If there were a massive black hole, the enclosed mass derived from the stellar orbits of smaller and smaller size would approach the black hole's mass.

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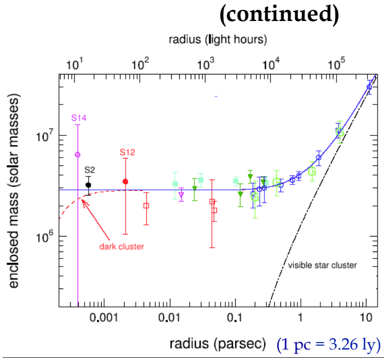
Orbital motion and the center of the Milky Way (continued)



Summary of results from stellar and gas-cloud Doppler shifts and proper motions.

Schödel *et al.* 2003.

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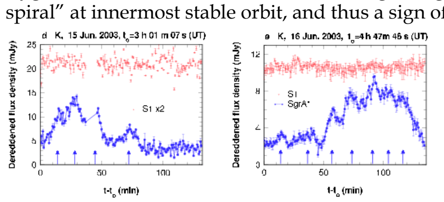
And the Sgr A* black hole spins, too

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 Cygnus X-1 or GRO J1655-40. Is this the beginning of a "death spiral" at innermost stable orbit, and thus a sign of rotation?



R. Genzel *et al.* 2003

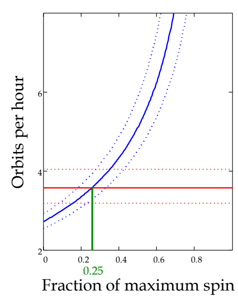
And the Sgr A* black hole spins, too (continued)

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 $3.6\times10^6\ M_\odot$ black hole, with uncertainties.

In red: measured orbits per hour, with uncertainties

(Genzel *et al.* 2003).



The black hole at the center of the Milky Way

Thus the evidence is compelling: **there is a black hole at the center of the Milky Way**, its mass is $(3.6\pm0.3)\times10^6\ M_\odot$, 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 quasiperiod oscillations coming from the innermost stable orbit.
- No jets are seen, though, relativistic or otherwise.

The black hole at the center of the Milky Way (continued)

Some obvious questions:

If Sgr A* contains a massive black hole, why is it so much fainter than those in quasars?

- Most of the answer: at the moment, there just doesn't happen to be enough accrete-able material in the neighborhood of Sgr A*'s black hole to provide a quasar-like luminosity. This would also explain the lack of jets.
- It's also not quite massive enough for quasar-size luminosity, as we shall see next lecture.

The black hole at the center of the Milky Way (continued)

Stellar-mass black holes like those in Cygnus X-1 and GRO J1655-40 were formed by the gravitational collapse of dead stars. There are no million-solar-mass stars; how did the black hole in Sgr A* form?

- We don't know for sure yet - this question describes one of the most active research areas in astronomy - but it may have formed small, in the normal fashion, and have grown by swallowing material slowly during the long life of our Milky Way Galaxy (~1.2×10^{10} years old).

Done!
A Spectre in the Eastern Veil

Image Credit & Copyright: Alfonso Carreño (Observatorio Zonalunar)