THE GALACTIC CENTER

GRO J1655-40 – another stellar-mass black hole

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

Wide-angle photo and overlay key of the Sagittarius region of the Milky Way, showing the effect of obscuration by dust clouds. The very center of the Milky Way lies behind particularly heavy dust obscuration (Bill Keel, U. Alabama)
DISCOVERY OF “STELLAR” BLACK HOLES: GRO J1655-40


- Rapidly-variable emission in its X-ray bursts: the X-ray object is a few hundred km around.
- The X-ray source has a stellar companion, a star rather similar to the Sun (about $1.1M_\odot$); the X-ray source and the visible star revolve around each other with a period of 2.6 days. Their distance from us is measured to be 6500 ly.
- A stroke of luck: it is an eclipsing system, so the orbit is known to be tilted edge-on to our line of sight.
- Therefore, we know the mass of the X-ray bright companion rather accurately: it must be between 5.5 and $7.9M_\odot$, with a most probable value of $7.0M_\odot$ (Shahbaz et al. 1999).
- Also has radio jets with motions close to the speed of light!

From last lecture

GRO J1655-40
Two jets, perpendicular to the plane of the orbit, with ejection speed 0.92c.

Radio images: R. Hjellming & M. Rupen, NRAO
We expect it to spin, but now we can demonstrate this:

A $7M_\odot$ black hole has a horizon circumference of 130 km, and if it does not spin, its innermost stable orbit circumference is 390 km. Material in this orbit will circle the black hole $314$ times per second.

- However, the X-ray brightness of GRO J1655-40 has been seen to modulate $450$ times per second for long stretches of time (Strohmayer 2001).
- Nothing besides very hot material in a stable orbit can do this so reproducibly at this frequency.
- Therefore, there are stable orbits closer to the black hole than they could be if it did not spin.

Most probably, the black hole in GRO J1655-40 is spinning at about 40% of its maximum rate. Within the uncertainties, the spin rate lies in the range 12%-58% of maximum; zero spin is quite improbable.

In blue: innermost stable orbits per second for a $7.0M_\odot$ black hole, with uncertainties

In red: measured orbits per second, with uncertainties

(by Tod Strohmayer, with the Rossi X-ray Timing Explorer)
GRO J1655-40

The invisible companion object:

• X-ray bright
• Too small to be a white dwarf star
• Too massive to be either a white dwarf or a neutron star
• Associated with ejecta traveling at 92% of the speed of light
• Associated with orbital frequencies appropriate for a spinning black hole

These properties make GRO J1655-40 more likely to harbor a black hole than most other objects we know.

DISTINCTIVE FEATURES THAT INDICATE THE PRESENCE OF A BLACK HOLE

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 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 easily explained by normal stellar energy generation
• Direct observation of a large, massive accretion disk
IS THERE A BLACK HOLE THERE?

HH 111 (HST images by Reipurth et al. 1999):
• Starlike object obscured by dusty disk
• Luminosity is $9.6 \times 10^{34}$ erg/s
• Shines mostly at visible and infrared wavelengths
• Twin jets, each 24 ly long, of material flowing out from the central object at 500 km/s

How many black hole characteristics does HH 111 have?

IS THERE A BLACK HOLE THERE?

PSR 0531+21 (Chandra X-ray Observatory image):
• Starlike object with luminosity $10^{30}$ erg/s surrounded by a very hot disk
• Brightest at radio and X-ray wavelengths
• Twin jets
• Surrounding material flowing outwards at several hundred km/s
• Brightness oscillates extremely regularly: 30 pulses per second

How many black hole characteristics does PSR 0531+21 have?
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 many more stars per cubic light year – and presumably, many 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 into the galactic center.

ORBITAL MOTION & 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 is the brightest radio source in the constellation Sagittarius (abbreviated Sgr). It was also the first extraterrestrial object discovered at radio frequencies, by Karl Jansky in 1933.
ORBITAL MOTION & THE CENTER OF THE MILKY WAY,
SAGITTARIUS A WEST

Within the central 10 ly, 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 it has a much smaller luminosity.
- Sgr A* lies **precisely** at the center of our Galaxy – 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 & Falcke 2001). Interstellar dust hides Sgr A* at wavelengths from the shorter infrared through the longer X-ray.
X-RAY IMAGE OF THE 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).

RADIO IMAGE OF THE CENTRAL 3 LY OF SGR A WEST

Sgr A* is the red eclipse in the center of this false-color image by Yusef-Zadeh & Wardle (1993) with the NRAO Very Large Array (VLA).
NEAR-INFRARED IMAGE OF THE CENTRAL 3 LY OF SGR A WEST

Sgr A* does not appear in this image, 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

NEAR-INFRARED IMAGE SEQUENCE OF THE CENTRAL 30 LIGHT-DAYS OF SGR A WEST

• Adaptive-optical imaging has made it possible to finally see Sgr A* 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
ORBITAL MOTION & THE CENTER OF THE MILKY WAY, SAGITTARIUS A WEST

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:

- 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, it is possible to calculate the mass enclosed by each orbit in much the same way as calculating the mass of one star from the spectrum of another orbiting star.

In this case, the conversion of the Doppler-shift velocities into enclosed mass is 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 math (provided only for those curious; not on any exam):

\[ F = ma \]

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

\[ M_{\text{enclosed}} = \frac{rV^2}{G} \]
GAS CLOUDS IN ORBIT AROUND SGR A*

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

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

ORBITAL SPEEDS GET LARGER THE CLOSER TO SGR A* YOU GET

Line-of-sight velocities for ionized gas clouds Sgr A West, measured with infrared light. Some clouds are found in the infrared measurements that do not appear in the radio image.

Data: Roberts & Goss (1993), using the NRAO VLA

Genzel & Townes (1987)
STARS 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.

Image by Eckart & Genzel (1996); http://www.mpe.mpg.de/ir/GC

STELLAR ORBITAL SPEEDS INCREASE AS THEY GET CLOSER TO SGR A*

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

- Note the high speeds (over 5000 km/s) 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); http://www.mpe.mpg.de/ir/GC
STELLAR MOTIONS CLOSE TO SGR A* 

From the MPE group (Genzel et al.)

ORBITAL MOTION & THE CENTER OF THE MILKY WAY

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 you 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.
ORBITAL MOTION & THE CENTER OF THE MILKY WAY

Summary of the results from stellar and gas-cloud Doppler shifts and proper motions (Schödel et al. 2003).

THE SPIN OF THE BLACK HOLE OF SGR A*

Occasionally, in the “flare” emission from Sgr A* seen at near-infrared wavelengths, a periodic series of peaks is detected (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 the innermost stable orbit, and thus a sign of rotation?
THE SPIN OF THE BLACK HOLE OF SGR A*

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 $3.6 \times 10^6 M_\odot$ black hole, with uncertainties.

In red: measured orbits per hour, with uncertainties (Genzel et al. 2003).

THE BLACK HOLE AT THE CENTER OF THE MILKY WAY

The evidence is compelling: there is a black hole at the center of the Milky Way, its mass is $(4.02 \pm 0.16) \times 10^6 M_\odot$, 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.

• No jets are seen, though, relativistic or otherwise.
THE BLACK HOLE AT THE CENTER OF THE MILKY WAY

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 does not 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 is also not quite massive enough for quasar-size luminosity, as we will see next lecture.

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 do not yet know for sure – 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 (~1.2x10^10 years old).