Feeding Sgr A*, the Supermassive Black Hole at the Center of our Galaxy

Thanks to James M. Moran

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Summary

• Astronomical black holes
• Sgr A*: the supermassive black hole at the center of the Milky Way (our Galaxy)
• Images of the “shadow”
• Waiting for G2
Types of Astronomical Black Holes

1. “stellar” sized black holes found through the galaxy in binary stellar systems,
   \[ M \sim 3-10 \ M_{\text{sun}} \]

2. “supermassive” black holes (SMBHs) found in the centers of most galaxies,
   \[ M \sim 10^{6-9} \ M_{\text{sun}} \]

Some evidence for the existence of intermediate mass black holes
Black hole, accretion disk and relativistic jets common to both types of systems (Mirabel & Rodríguez 1998)
Blob of ionized gas

Magnetic field line

Accretion disk
Blandford & Payne (collimation)

Jet

Azimuthal magnetic field lines

Ionized gas particles
Hercules A in optical and radio

Jets detectable in the radio (synchrotron emission)
Observations of Cygnus A with the Jodrell Bank Intensity Interferometer

Square of visibility 125 MHz

Jennison and Das Gupta 1952; see also Sullivan 2010
Cygnus A with Cambridge 1-mile Telescope at 1.4 GHz

3 telescopes

20 arcsec resolution

Cygnus A with Cambridge 5 km Interferometer at 5 GHz

16 element E-W Array, 3 arcsec resolution

The Very Large Array in D Configuration, Socorro, New Mexico
Synchrotron emission from Cygnus A
(VLA at 6 cm)
Do all galaxies have supermassive black holes at their centers?

 Apparently yes, and furthermore there is a correlation between the mass of the black hole and that of the elliptical galaxy or bulge where it resides.

This suggests a poorly understood co-evolution between both objects.

Kormendy & Lo (2013)
Our galaxy, the Milky Way, also has a “starved” supermassive black hole at its center: Sgr A*
INTENSE SUB-ARCSECOND STRUCTURE IN THE GALACTIC CENTER

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ABSTRACT

The detection of strong radio emission in the direction of the inner 1-pc core of the galactic nucleus is reported. The structure is bright (brightness temperature \( \gtrsim 10^7 \) K), unresolved (\( \theta \lesssim 0.1\) arcsec), and distributed within a few seconds of the bright source seen previously.

Subject headings: galactic nuclei — radio sources
THE TEMPERATURE AND DYNAMICS OF THE IONIZED GAS IN THE NUCLEUS OF OUR GALAXY

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ABSTRACT

Observations of the H65α (23.4 GHz), H84α (10.9 GHz), and H94α (7.8 GHz) radio recombination lines from Sgr A West are presented. We suggest that a core-halo model can satisfactorily account for the reported radio and infrared observations of this source. Due to instrumental limitations, the observed infrared lines are dominated by the core, while the observed radio radiation arises mostly in the halo. Although more than a factor of 10 brighter than the halo, the core is responsible for only about one-fourth of the integrated thermal continuum from Sgr A West. Our model implies that the neon abundance determination from infrared observations, previously considered consistent with the solar value, should be revised upward by a factor of 4. This suggested enrichment of neon relates strongly to our derivation of an unusually low electron temperature, $T_e = 5000 \pm 1000$ K, since nebular cooling is expected to be enhanced by an overabundant heavy-element content. The dynamical structure of Sgr A West can be explained in terms of Keplerian rotation due to the gravitational field of the normal stellar population plus a central mass point of $5 \times 10^6 M_\odot$.

However, gas motions can be altered by several mechanisms, so this was not widely accepted.

"...the gravitational field of the normal stellar population plus a central mass point of 5 million solar masses."
Infrared observations with high angular resolution (laser guide star adaptive optics).

Ghez et al.

Genzel et al.
Some Scales at the Galactic Center

$r_s = 1.3 \times 10^{12}\text{cm} \quad \text{(for } 4.3 \times 10^6 \text{ solar masses)} = 10\mu\text{as at } 8.3 \text{ kpc}

Luminosity \sim 300 \, L_{\odot} \quad \text{or } 10^{-9} \text{ Eddington ("starved" black hole)}
• Sgr A* is a relatively weak source but can be detected at several astronomical bands
  – The measured spectrum covers 10 decades in frequency
• $L_{SgrA^*} \sim 300 \, L_{Sun} \sim 10^{-9}$ Eddington limit

Genzel et al. 2004

IR flare (Hornstein et al. 2007)
Black Hole “image” Dominated by GR

The black hole “shadow”
(Bardeen 1973; Falcke, Agol, Melia 2000; Johannsen and Psaltis 2010)

Measuring the shadow gives mass and spin.
(Johannsen, Psaltis et al. 2012)
Seeing Through the Scattering

\[ \theta_{\text{OBS}} \text{ deviates from scattering for } \lambda < 1.35 \text{ cm} \]

\[ \theta_{\text{INT}} \ll \theta_{\text{SCAT}} \text{ for } \lambda > 1.3 \text{ mm} \]

\[ \theta_{\text{INT}} \propto \lambda^{1.4} \]
Plasma Scattering

• Index of refraction in plasma:

\[ n \simeq 1 - \frac{r_e n_e \lambda^2}{2\pi} \]

• This means that radiation refracts (changes direction) as it goes through a region of different electron density (that is, index of refraction).
Radio effect, similar to optical “seeing”
From another angle of view...

Intrinsic deflection

\[ \theta_s = \frac{1}{\pi} r_e \lambda^2 \Delta n_e \sqrt{\frac{L}{a}} \]

Geometry of problem

\[ \theta' = \frac{R'}{R + R'} \theta_s \]

Apparent source size goes as \( \lambda^2 \)

\[ \theta'_s \propto \lambda^2 \]
1.3 mmλ Observations of Sgr A*

VLBI program led by a large consortium led by Shep Doeleman, MIT/Haystack/CfA
Gaussian and Torus Fit to Visibility Data

Gammie et al. 14 Rsch (140µas)

Doeleman et al. 2008; Fish et al. 2011
Progression to an Image

GR Model

7 station

13 station

Sgr A*’s View of the EHT

GLT - Greenland

IRAM

SPole

LMT

ALMA
Large Millimeter Telescope
Cerro La Negra, Puebla

A collaboration INAOE-UMass
VLBA stations + LMT
Fringes at 3mm
Animation of Cloud Discovered by Genzel Group, 2012
Predicted Orbit of G2 – earth mass cloud approaching Sgr A*
G2

Orbit information (Gillessen et al., *ApJ.*, 763, 78, Feb. 1, 2013)

Closest approach 2013.7 at $3 \times 10^{15}$ cm ($2200 R_s$)

Velocity $\sim 3,000$ km/s ($c/1,000$)

Orbital period $\sim 198$ years

Mass $\sim 1.7 \times 10^{28}$ grams $= 10^{-5} M_{\text{Sun}}$

Accretion over 100 years means an increase of $10^{-7} M_{\text{Sun}}$ over ambient $10^{-8} M_{\text{Sun}}$

Could brighten by factor of 10!
Increase of emission predicted by two different episodes:

1. Near periastron (2013.7) strong shock should develop between G2 and ambient medium surrounding Sgr A*. This was expected to produce radio synchrotron emission: strong shock $\Rightarrow$ Fermi acceleration of charged particles $\Rightarrow$ synchrotron emission.

2. In the following years, part of the cloud is expected to be accreted by Sgr A* via a disk $\Rightarrow$ X-ray emission (disk) + radio (jets).
VLA SED Monitoring of Sgr A*

With 10% abs calibration error
Brunthaler & Falcke (2013)
What’s going on?

- Narayan et al. (2013) argue that the excess emission will appear mostly at low frequencies and we have to wait for proper data (October 2013).
- Perhaps a shock was not formed (gas around Sgr A* has to be extremely hot > $10^9$ K)
Gas accreted into Sgr A*

• This process should start within the next few years and may last for a decade or so.
• However, some groups believe that G2 is not a cloud (with little self-gravity) but a star with some kind of envelope. If the second possibility is correct, accretion may be rather weak.
Controversy

• The constant luminosity and the increasingly stretched appearance of the head of G2 in the position-velocity plane, without a central peak, is not consistent with several proposed models with continuous gas release from an initially bound zone around a faint star on the same orbit as G2 (Gillessen et al. 2003).

• While the observations altogether suggest that G2 has a gaseous component which is tidally interacting with the central black hole, there is likely a central star providing the self-gravity necessary to sustain the compact nature of this object (Phifer et al. 2003).

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Evolution of the gas cloud G2

April 2013
Saitoh et al. 2013
Hopefully, things will become clear during 2013-2014

• Need of more observations and fast theoreticians.
Thank you
Very Long Baseline Interferometry (VLBI) at Submillimeter Wavelengths

Figure 3: Existing and upcoming sub-millimeter radio telescopes in the Western hemisphere as seen from Sgr A*. Green telescopes already exist and are ready to be phased into a small array. The Large Millimeter Telescope (LMT) will begin operations at sub-millimeter wavelengths sometime next year. The Atacama Large Millimeter Array (ALMA) is scheduled to be completed by 2012, though it will begin taking data in 2010. Already at the ALMA site, the Atacama Pathfinder EXperiment (APEX) is presently operating. Finally, the South Pole Telescope (SPT) needs only a millimeter receiver to be adapted for sub-mm VLBI. The projected baselines associated with these telescopes are shown in green for telescopes
What is the Central Mass Around Which These Stars Are Orbiting?

\[ T = 15.2 \text{ years} \]

\[ R = 0.12 \text{ arcseconds} = 17 \text{ light hours} \]

\[ M = 4 \text{ million } \times \text{ the mass of the Sun} \]

\[ \text{Density} > 10^{17} \text{ solar masses/pc}^3 \]
U-V Tracks
The Galactic Center on Three Size Scales

1. Circumnuclear (molecular) Disk (CND) and Minispiral (ionized streamers)  
   120 arcs / 5 pc  
   Zhao, Blundell, Downes, Schuster, Marrone

2. Black hole accretion envelope (100 $R_\odot$)  
   1 mas / 0.3 micro pc  
   Marrone, Munoz, Zhao, Rao

3. SgrA* radio source  
   37 microarcseconds / 0.01 microparsec  
   Doeleman et al.
Types of Cosmic Black Holes

1. “stellar” sized black holes found through the galaxy in binary stellar systems, \( M \sim 10 \ M_{\text{sun}} \)

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Summary

• 1.3mm VLBI finds Rsch scale structure in and Sgr A*.
• International collaboration forming strong EHT organization.
• Key technical advances under way and roadmap to full EHT by 2015 clear.
• Most effort low risk: greatest risk is funding.
• EHT is opening a new window on BH study.
• GLT is key new element to the EHT.
Nine Field Mosaic Image of Circumnuclear Disk in Galactic Center

CN
H$_2$CO
SiO

SMA Data
Sergio Martin Ruiz

3 arcmin field
3 arcs resolution
1.3 mm wavelength
Summary of Talk

• The mass of the black hole in the Center of the Galaxy (Sgr A*) is about $4 \times 10^6$ solar masses.
• The accretion rate is about $10^{-8}$ solar masses per year.
• The polarization is LCP at all wavelengths from 1 mm to 30 cm.
• The angular diameter of the radio emission from Sgr A* is about 37 microarcseconds at 1.3 mm wavelength.
• A object of earth mass is approaching the Galactic Center and could increase the accretion rate significantly starting in mid-2013.
• VLBI observations of 1924-293 have also been made at 1.3 mm.
• (EHT) under development
Submillimeter Valley, Mauna Kea, HI

CSO
10 m single dish (79 m²)

JCMT
15 m single dish (177 m²)

SMA
eight 6 m dishes (compact configuration) (226 m²)

(aggregate area 482 m² equivalent of 25 m aperture)