The black hole in the Galactic Center

MPE Team
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Why should you care about the Galactic Center?

• Template for a galactic nucleus – EMRI rates
  – Black hole mass function
  – In-spiral rate at a given mass

• EMRBs might be observable

• Key advantage: Stellar population is resolved
  – Chance to understand stellar system around a MBH in detail
  – Surprisingly complex dynamical state
Summary

• GC is a unique laboratory for observing a stellar system around a MBH
• At least 3 distinct stellar populations
  – S-stars: orbits
  – Disk stars
  – Old stars
• Future:
  – Gradual improvements
  – A huge step forward due to NIR interferometry
• Exciting astrophysics: Infalling gas cloud
A dense stellar system

NACO, HKL color composite
Cartoon version of the stellar system

- S-stars
  - young, $10^8$ yr
  - $r < 0.05$ pc
  - orbits

- Stellar disk
  - younger, $10^7$ yr
  - $0.05$ pc $< r < 0.5$ pc

- Old stars
  - everywhere

- and more:
  - stellar black holes
  - neutron stars
  - white dwarfs
  - fainter MS stars
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Currently: ≈ 30 orbits known

20 stars shown, Gillessen+ 2009
S2: the showcase star

VLT & Keck data suitably combined

- period: 15.9 years
- semi major axis: 125 mas
- eccentricity 0.88

- $M = 4.30 \pm 0.06 \pm 0.35 \times 10^6 \, M_\odot$
- $R_0 = 8.28 \pm 0.15 \pm 0.30 \, \text{kpc}$
Mass and $R_0$ are highly correlated

pure astrometry:  
$M \sim R^3$

astrometry + radial velocities:  
$M \sim R^{2.0}$

only radial velocities:  
$M \sim R^0$
Surprisingly, the S-stars are young
S-stars: A Paradox of Youth

Ghez+ 2003

diamond Star formation so close the MBH impossible

diamond Stars are too young to have migrated from further out

\[ t_{2BR} \approx 3 \text{ Gyr} \]

\[ \gg \]

\[ t_{MS} \approx 0.1 \text{ Gyr} \]
How well do we know that potential is that of a point mass?

Measured fraction of mass inside of S2 orbit that is not pointlike

Gillessen et al. 2009

98% of 4 million suns in 100 AU

Can we expect much less?
The drain limit

“Require steady state for SBHs”

Rate of SBHs lost

\[ \text{Number of SBHs present} / t_{\text{Hubble}} \]

\[
\max N_\bullet(\leq r_\bullet) \sim \frac{2 \log(2\sqrt{r_\bullet/r_S})}{3 \log(0.4 \max N_\bullet)} \left( \frac{m}{M_\bullet} \right)^2 \frac{P(r_\bullet)}{t_H}
\]

(Alexander & Livio 2004)

\[ \eta \lesssim 0.0011 \times \left( \frac{m_\bullet}{10} \right)^{-0.7} \]
Stellar mass from extrapolation

KLF:

Density profile:
\[ \rho(r) \propto r^{-1.1} \]

Bartko et al. 2009

Genzel et al. 2003

\[ \eta \approx 10^{-4} \]

- stellar black holes
- mass segregation

BUT:
Dynamical modelling

\[ \eta \approx 5 \times 10^{-4} \]

(Freitag et al. 2006):
\[ \eta \approx 10^{-4} \]

(Hopman & Alexander 2006)
Number of X-ray binaries

Muno et al. 2005: 4 X-ray transients in central pc

“Chemical” equilibrium:

\[
\begin{align*}
\gamma_+ &= n_+ n_b \Sigma \sigma_1 = \\
\gamma_- &= \frac{1}{2} n n_{\text{XRB}} \Sigma \sigma_1 + \frac{n_{\text{XRB}}}{\tau}
\end{align*}
\]

\[
\eta \approx 3.8 \times 10^{-7} \frac{N_{X, < 1 \text{pc}}}{f_X} \quad \text{Similar:} \quad \text{Deegan & Nayakshin 2007:} \quad \eta \approx 2.1 \times 10^{-4}
\]

\[
\approx 1.5 \times 10^{-4}
\]
A potential second BH in the GC would need to be light & distant

Merritt, Gualandris, Mikkola 2009
Reid & Brunthaler 2004
Gillessen+ 2009
An IMBH could be detectable directly

Gualandris, Gillessen & Merritt 2010

χ² of fit
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A large concentration of young O/WR-stars between 1″ and 10″

Bartko+ 2009
(Most of) the CW moving O/WR-stars revolve in a disk
The disk has a top-heavy IMF

Bartko+ 2010
Orbital planes: S-stars ≠ disk stars
Eccentricities: S-stars ≠ Disk stars

6 disk stars: $\langle e \rangle = 0.34 \pm 0.18$

17 early-type S-stars: large $<e>$
Two paradoxes of Youth

O/WR stars

12″ (0.5pc)
late (red/orange) – early (blue) – no id (grey)

1″ < R < 10″
age ≈ 6 Myr

B stars

1″ (0.04 pc)
S-star cluster radius ~ 1 light month

R < 1″
age ≈ 10^8 yr
Idea I: Cluster in-spiral

Problems:
• To spiral in within 6 Myr, cluster mass would exceed stellar mass seen by far
• Large IMBH would be required
• Surface density profile of disk is too steep
• Where are the B-stars?

Portegies-Zwart+ 2005
Idea II: In-situ formation in infalling gas cloud

More promising:

• critical density for star formation is reached easily
• moderate eccentricities
• IMF gets top-heavy
• warps possible

Two paradoxes of Youth

O/WR stars

1'' < R < 10''
age ≈ 6 Myr

B stars

R < 1''
age ≈ 10^8 yr
The S-stars puzzle is hard

<table>
<thead>
<tr>
<th>In-situ formation</th>
<th>Fast transport</th>
<th>Rejuvination</th>
</tr>
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<tbody>
<tr>
<td>• Critical density $\sim M/R^3$ $\approx 2 \times 10^{-11} \text{ g/cm}^3$ (for $R = 0.5''$)</td>
<td>• cosmic pool game</td>
<td>• Stars are actually old but look young</td>
</tr>
<tr>
<td>• Core of clump in molecular cloud $\approx 10^6/\text{cm}^3$ $\approx 2 \times 10^{-18} \text{ g/cm}^3$</td>
<td>• fast relaxation processes</td>
<td>• “stripping” of giants, S-stars are the hot cores</td>
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<td></td>
<td>• Migration from O/WR star disks</td>
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Currently a Hills-like mechanism seems to be preferred

**Massive Perturbers**

- Scattering of field binaries into near loss-cone orbits due to “Massive Perturbers”
- Tidal break-up of binaries at pericenter passage
- Fast Relaxation of orbit to match observed properties
- Resonant Migration

**Migration**

- Formation of B-stars in (former) disk
- Interactions to increase $e$
- Low $e$ disk, stellar cusp, IMBH
- Interactions to lower $a$
- Planetary migration
- Fast Relaxation
- IMBH?
The eccentricity distribution might be the clue

More orbits
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Dynamics of the star cluster

Schödel+ 2009
“Standard game”: \( \sigma \rightarrow \text{mass} \)
The old stars: missing towards the center?
If confirmed, that has consequences for the EMRI rates

• Challenges basic stellar dynamics: Bahcall-Wolf cusp:
  – $\rho \approx r^{-7/4}$ for single species;
  – $\rho$ between $r^{-7/4}$ and $r^{-3/2}$ for multiple species

• Proposed solutions:
  – Relaxation time of GC system $>$ Hubble time \hspace{1cm} Merritt 2010
  – Giants are destroyed by stellar collisions \hspace{1cm} Davies+ 2011

• Does the same hold for the sea of stellar black holes, neutron stars, white dwarfs?
Imagine we could zoom in further

Expected in central 100 mas:
-- ~5 stars
-- \( K = 17..19 \) mag

Orbital Period:
1 year

Precession:
~ few ° per year
The next step in angular resolution:

NIR-Interferometry

VLT (8m):
R = 50 mas
Δx = 150 μas

VLTI (120m):
R = 3 mas
Δx = 10 μas
The accretion disk has a diameter 10 x larger than the 10μas accuracy
Dual feed, 4-telescope, adaptive optics assisted, fringe tracking beam combiner instrument
GRAVITY in context:
Astrophysical tests of general relativity

adapted from Psaltis 2004
FEELING THE FORCE
The giant gas cloud heading for the Milky Way’s black hole
PAGES XX & 51

EXPERIMENTS
RISE TO THE CHALLENGE
Five of the hardest tasks left in science
PAGE 14

ETHICS
HOW TO STOP PLAGIARISM
We ask the experts for their prescriptions
PAGE 21

PHYSICS
LOST IN TIME
A ‘time cloak’ shaped by optical manipulation
PAGES XX & 62
A ‘cool’ object: $T \approx 600\text{K}$
The object is a dusty, ionized gas cloud of 3 Earth masses

Integral-field spectroscopy: SINFONI

channel map at Br-γ (2.166 μm)
channel map at Br-γ + 1300 km/s (2.175 μm)
The cloud’s orbit is well-constrained pericenter passage: 2013.5 at 3000 \( R_S \) (S2: 1500 \( R_S \))
A non-gravitating gas cloud cannot survive that
We see the tidal shear develop between 2008 and 2011.
Missing: Interaction with accretion flow

Accretion rate might increase for years
Flux will vary because of changed accretion rate

Yuan et al. 2004
This is different from the flares of Sgr A*

- Typically one flare per night
- Lasts ~ 90 min
- Much redder than the stars

Flares are ‘ignition events’
Flares are synchrotron emission of transiently heated electrons.
What is the origin of the cloud?

- Orbital plane coincides with disk of young stars
- Apocenter of the orbit coincides with the inner edge of the disk
Two scenarios proposed

### Clumplet from stellar winds / wind collisions
- Stellar winds of massive, young stars of disk
- wind speeds ≈ orbital speeds
- Creation of fragment with low angular momentum
- Ballistic infall
- First time event (but frequent events)
- tidal shear leads to a decreasing surface brightness
- Burkert et al. 2012

### Evaporating disk around protostar
- Young stellar object from disk of massive, young stars
- Scattered to low-angular momentum orbit
- Disk around the star glows in UV light of hot stars
- Object on similar orbit for many orbits
- “tidal comet” – surface brightness will increase
- Murray-Clay & Loeb 2012
Simulations of the winds show a very clumpy structure

Cuadra et al. 2006
Problems for the two scenarios

- Expect formation at apocenter – but then cloud should be stretched much more than observed
- Disk around protostar cannot survive scattering to current orbits
- Event rate estimate over-estimated
- Stripped material would be slower than Keplerian orbit, not faster
Summary

• GC is a unique laboratory for observing a stellar system around a MBH

• At least 3 distinct stellar populations
  – S-stars: orbits, constrain the extended mass around Sgr A*, paradox of youth, eccentricity distribution
  – Disk stars: formed 6 Myr during gas infall
  – Old stars: Deficit in the central 0.2pc, “bad” news?

• Future:
  – Gradual improvements
  – A huge step forward due to NIR interferometry

• Exciting astrophysics: Infalling gas cloud
Thanks for your attention!
Backup
Cosmological Dark Matter

$$\eta_{DM} < 10^{-2} \eta_*$$

(Dark Matter will not be detected from stellar orbits)

Vasiliev & Zelnikov 2008
Assume, we continue what we are doing. How well do we do then?

NACO:
Astrometry with 300 μas

SINFONI:
Spectroscopy with 15 km/s
The distance to the GC will be determined to a precision of 1%
2020: 3σ detection of GR precession possible

\[ \Phi = -\frac{GM}{r} + f \frac{GMl^2}{c^2r^3} \]
GRAVITY Key Figures

**Milestones:**
- Final design in 2011/12
- Installation at the telescope in 2014

**Fringe Tracking:**
- UTs: K≈10 mag
- ATs: K≈7 mag

**Astrometry:**
- few 10 μas in 5 minutes

**Interferometric Imaging:**
- UTs: K≈16, ATs: K≈13 in 100s
- K≈18 doable
- SNR(V) = 10 for visibility
- σ(ϕ) = 0.1 rad for referenced phase
GRAVITY: Working principle

- Laser for pupil guiding
- 2" FoV
- Metrology receiver
- Starlight
- MACAO DM
- IR wavefront sensor
- TipTilt Pupil
- dOPD control
- Fiber coupler
- Polarization control
- Beam Combiner Instrument
- IO Beam combiner
- Spectrometer
- Metrology Laser
- Phase Shifter
- Object
- Wavefront reference
- Phase reference
- Telescope #1
- Telescope #2
- 2" FoV
- Delay line

Working principle diagram
The GC offers all GRAVITY needs

IRS7, $K=6.5$, 5.57” separation, AO wavefront reference

IRS16C, $K=9.7$, 1.23” separation, fringe tracking phase reference

IRS16NW, $K=10.0$, 1.21” separation, guide star (for tip-tilt residual)

Galactic Center Black Hole, science object
For \( r > 1'' \):

Hard to measure accelerations

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<tr>
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<th>( r &lt; 1'' )</th>
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\((a, e, i, \omega, \Omega, t)\)
The traces for the young, clockwise moving stars intersect in one point.

Orientation of orbital angular momentum

Bartko+ 2009

Lu+ 2009
Famous astrophysics problem

X-ray luminosity of “Sgr A*” should increase in 2013.
But expect complex interactions

- Orbital period: 137 yr (but highly eccentric orbit)
- Compression time
- Sound crossing time
- Instabilities:
  - Kelvin-Helmholtz: 4 yr
  - Rayleigh-Taylor: 4 yr

All time scales similar
complex hydrodynamics