Massive Black Holes & Galaxies

Reinhard Genzel
Max-Planck Institut für extraterrestrische Physik, Garching, Germany
& Departments of Physics & Astronomy
University of California, Berkeley, USA
Quasars & the high-z Universe

radio source 3C 273

\[
\begin{array}{c|c|c|c|c}
\lambda & \lambda/1.158 & \lambda_0 & \text{Identifications} \\
\hline
3239 & 2797 & 2798 & \text{Mg II} \\
4505 & 3970 & 3970 & \text{H}^\alpha \\
4753 & 4104 & 4102 & \text{H}^\beta \\
5032 & 4345 & 4340 & \text{H}\gamma \\
5200-5415 & 4490-4675 & & \text{He}^+ \\
5682 & 4864 & 4861 & \text{H}\beta \\
5792 & 5002 & 5007 & \text{He}^+ \\
6005-6190 & 5186-5345 & & \text{[O III]} \\
6400-6510 & 5527-5622 & & \\
\end{array}
\]

→ \( z=0.16, \ D=2.4 \text{ billion light years}! \)
→ \( L\sim10^3 \ L_{\text{milky Way}} \)

by 1973: \( z\sim3.5 \) (lookback time 11.6 Gyr), \( L\sim10^5 \ L_{\text{MW}} \)

Marten Schmidt
1963

Burbidge, Greenstein, Hazard, Matthews, Rees, Sandage, Schmidt 1961-1970
what powers Quasars?

HST WFPC 2

fusion:
\[ E < 0.005 \, \text{Mc}^2 \]

‘Schwarzschild throat’
(Schwarzschild-Kerr)

accreting BH model:
\[ E \sim 0.06 \ldots 0.4 \, \text{Mc}^2 \]
variable X- and \( \gamma \)-radiation
relativistic radio jets

Salpeter, Lynden-Bell, Rees, Shakura, Sunyaev 1964 - 1973
How to prove the existence of BHs?

an unambiguous ‘proof’ for the existence of a black hole requires the determination of the gravitational field/space time metric to the scale of the event horizon.

critical observations:

- emission line widths
- VLBI
- infrared emission/variability
A Journey to the Center of the Milky Way

6cm radio emission
VLA
SgrA*
1 light year
The MPE ‘ARGOS’ GLAO field correction system for the Large Binocular Telescope (LBT)
As seen from Frankfurt

In Bonn

Astrometric precision

0.2"

20 mas

2 mas

10^3

300 μas

10 μas

1990  2000  2010

time

On the Moon

In San Francisco
Motions of stars around SgrA*
a complete orbit: S2 (1992-2013)

\[ M_\bullet = 4.30(\pm 0.20)_{\text{stat}}(\pm 0.30)_{\text{sys}} \times 10^6 \, M_\odot \]

\[ R_0 = 8.28 (\pm 0.15)_{\text{stat}}(\pm 0.29)_{\text{sys}} \, \text{kpc} \]

\[ \rho_\bullet > 10^{16-19.5} \, M_\odot \text{pc}^{-3} \]

\[ M_{\text{extended}}/M_\bullet < \text{a few } 10^{-2} \]

SgrA*

4 light months

$\nu_{pm} \leq 2, 20 \text{ km/s}$

(50 $\mu$arcseconds/Jahr!)

Is SgrA* a black hole?

- 4x10^6 M$_{\odot}$ BH
- 'boson star'

constraints from stellar orbits and SgrA* radio properties

- 'dark' astrophysical clusters with life times > 10^5 years

- fermion ball
- stable astrophysical star clusters

probing the environment of a massive black hole

some key theoretical predictions:

• star formation near BH very difficult if not impossible
• power-law cusp of old stars & remnants centered on BH
• binaries on loss cone orbits get captured and one member ejected out of Galaxy
• $L_{\text{SgrA}^*} \sim 10^{8-9} L_\odot$
massive black holes in nearby galaxies

NGC 4258 (VLBA)

$M_\bullet = 3.6 \times 10^7 M_\odot$ (2 Kpc)

M31 (HST)

$M_\bullet = 10^8 M_\odot$

MCG-6-30-15 (XMM Newton)

Fe Kα

$M_\bullet / M_{\text{bulge}} \approx 1.4 \times 10^{-3}$

Bender, Fabian, Ferrarese, Ford, Gebhardt, Greenhill, Kormendy, Nandra, Moran, Merritt, Tanaka, Tremaine 1995-2009
galaxies and massive black holes in the young Universe

local & early Universe studies suggest that galaxies and massive black holes grew together in a coupled, self-regulated manner

a 3 billion solar mass black hole 800 million years after the Big Bang!

key issue: $M_{BH}(t) \sim M_0 \exp(t/300 \text{ Myr})$

Possible growth processes for massive black holes

- formation of $10^{2-3} \, M_\odot$ seed black holes at $z \sim 10..12$, from super-massive stars, dense clusters or direct collapse

- rapid growth (super-) Eddington triggered by major galaxy mergers

- continuous (sub-) Eddington growth (10 doubling times $\sim 1\text{-}3$ Gyrs) through accretion from the cosmic web and disk instabilities
why is SgrA* so weak?

low $L/L_{\text{Edd}}$ is a combination of:

- low accretion rate at Bondi radius
- low efficiency angular momentum transport
- most of the gas arriving at a few $R_s$ ejected back out

$L_{\text{SgrA}^*} \approx 10^{35-36} \text{ erg/s} \sim 10^{-8} L_{\text{Edd}},$  
$\eta_{\text{radiation}} \approx 10^{-6}$

remarkable: orbit is basically radial (1-e~0.025), \(<T_{\text{peri}}>=2013.5-2014.3\)
Yet another surprise in the Galactic Center: a gas cloud falling straight into the hole.

observed & simulated evolution of the tidal disruption of G2

Gillessen et al. 2013
Schartmann et al. 2012
interaction with SgrA* accretion Flow

*theoretical predictions*

• ‘controlled experiment’ to test the interaction of a cloud of known mass with accretion flow

• cloud ‘ballistic’ to peri

• $t_{\text{crush}} \sim t_{\text{KH}} \sim t_{\text{RT}} \sim t_{\text{dyn}}$

• cooling of cloud shock mostly in EUV, modest increase of SgrA* X-ray emission near peri, particle acceleration leading to factor a few to 10 flare-up in radio emission, increased electron column may increase submm-Faraday rotation measure

• depending on efficacy of circularization and structure of accretion flow, increase of SgrA*’s luminosity by between little, to up to several orders of magnitude in following years

the future: zooming in on the horizon

near-IR precision interferometric astrometry
(10\mu arcsec~R_s, K_s<19)

MPE, Paris, Cologne, Grenoble, Lisbon, MPIA
PI Frank Eisenhauer (MPE)

ESO-VLTI