Physics of AGN
Black Holes

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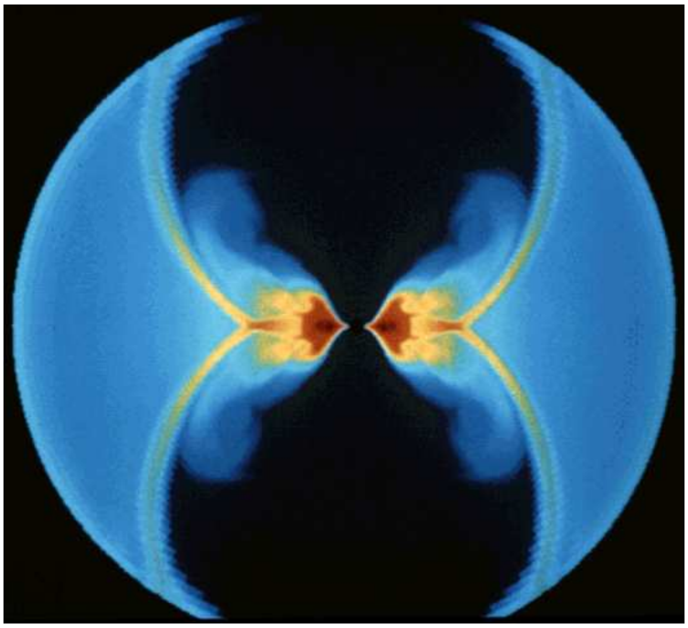


Contents:

- Why Black Holes?
- Luminosity
- What are black holes?
- Observational Evidence

Literature:
"An Introduction to Active Galactic Nuclei", Bradley M. Peterson, Cambridge University Press, Cambridge (Chap. 3)
"Active Galactic Nuclei", Ian Robson, John Wiley & Sons, Chichester (Chap. 7)
J. Frank, A.R. King, & D.J. Raine "Accretion Power in Astrophysics", 2nd edition, Cambridge University Press, Cambridge

Eddington Limit

■ Estimating the mass

Basic question early on: what powers quasars, Seyferts, and radio galaxies?

Remember: the characteristic signatures of quasars are

- high luminosity ($L \simeq 10^{44-48}$ erg/sec, i.e. $10^{10.5-14.5} L_\odot$)
- high compactness (variability on time scales of years, compact radio cores $\lesssim$ 1pc)

Such a high luminosity will produce an enormous radiation pressure. Hence, for material to be gravitational bound to the center of the galaxy, we can calculate a minimum central mass—the Eddington mass—independent of a particular model.

- the momentum of photons is $l = E/c$ (one photon: $E = h\nu$)
- the force $\mathcal{F}$ of photons is $\mathcal{F} = dl/dt = \dot{E}/c$
- the pressure is force per area $P = \mathcal{F}/A$

Hence, the radiation pressure at distance r of an isotropically radiating point source of luminosity L is (L: luminosity, F: flux density)

$$P_{\text{rad}} = \frac{\dot{E}}{Ac} = \frac{F}{c} = \frac{L}{4\pi r^2 c}.$$

The force exerted on a single electron is obtained by multiplying with the electron scattering cross-section (dimension cm^2):

$$\mathcal{F}_{\text{rad}} = \sigma_{\text{e}} \frac{L}{4\pi r^2 c}$$

(for non-radial structure one needs to take vector notation into account)

Here $\sigma_{\rm e}$ is the Thomson cross-section (from classical electron radius)

$$\sigma_{\rm e} = \frac{8\pi}{3}\left(\frac{e^2}{m_{\rm e}c^2}\right)^2 = 6.65 \cdot 10^{-25}{\rm cm}^2.$$

The inward directed gravitational force of a central mass M is given by

$$\mathcal{F}_{\rm grav} = -\frac{GMm_{\rm p}}{r^2}$$

NB: *The radiation pressure is mainly acting on the electrons (factor $[m_{\rm e}/m_{\rm p}]^2$), while gravitation mainly acts on protons (factor $m_{\rm p}/m_{\rm e}$)— Coulomb forces will keep them together!*

In order for matter to be gravitationally bound (to fall inward), we need

$$\begin{aligned} \mathcal{F}_{\rm rad} &\leq -\mathcal{F}_{\rm grav} \\ \sigma_{\rm e}\frac{L}{4\pi r^2\, c} &\leq \frac{GMm_{\rm p}}{r^2} \\ L &\leq \frac{4\pi Gcm_{\rm p}}{\sigma_{\rm e}}M \end{aligned}$$

$(\lg G = -7.2,\ \lg m_{\rm p} = -23.8,\ \lg c = 10.5,\ \lg \sigma_{\rm e} = -24.2,\ \lg M_\odot = 33.3)$

$$L \lesssim 1.26 \cdot 10^{38}\frac{M}{M_\odot}{\rm erg\ sec}^{-1}$$

which is independent of the radius.

This condition is called the **Eddington Limit** and states that for a given luminosity a certain minimum central mass is required (**Eddington mass**) or that for a given central mass the luminosity cannot exceed the **Eddington luminosity**.

Black Hole Paradigm

■ Not really hollow

For typical quasar luminosity of $L = 10^{46} L_{46} \mathrm{erg\ sec}^{-1}$ the Eddington mass is given by

$$M_{\mathrm{E}} = 0.8 \cdot 10^8 L_{46} M_\odot .$$

The Eddington luminosity is defined accordingly.

With the Eddington mass $\gtrsim 10^8 M_\odot$ and the size constraints <1pc one can derive a robust lower limit for the central mass density

$$\rho_{\mathrm{CM}} \gtrsim 10^8 M_\odot\,\mathrm{pc}^{-3}$$

For comparison remember that in our vicinity there are only a few stars within a parsec distance. The central star cluster in our Galaxy has $\sim 4 \cdot 10^6 M_\odot\,\mathrm{pc}^{-3}$.

It was then suggested that the activity in the active nuclei was produced by a accreting black holes. (The term "black hole" was invented by John Wheeler in 1967 well after the concept was invented).

A black hole is a concentration of mass so large, that even light cannot escape its gravitational attraction (i.e. space curvature).

A black hole has only two parameters: the mass $M_\bullet$ and the spin $0 \leq a \leq 1$ in units of $M_\bullet c R_{\mathrm{g}} = G M_\bullet^2 / c$ (we ignore charge).

A non-rotating black hole is called a Schwarzschild hole and a rotating black hole is called a Kerr hole.

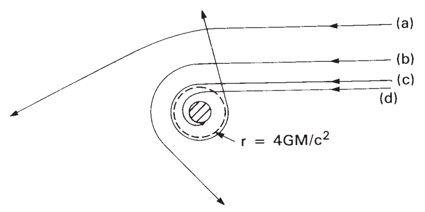
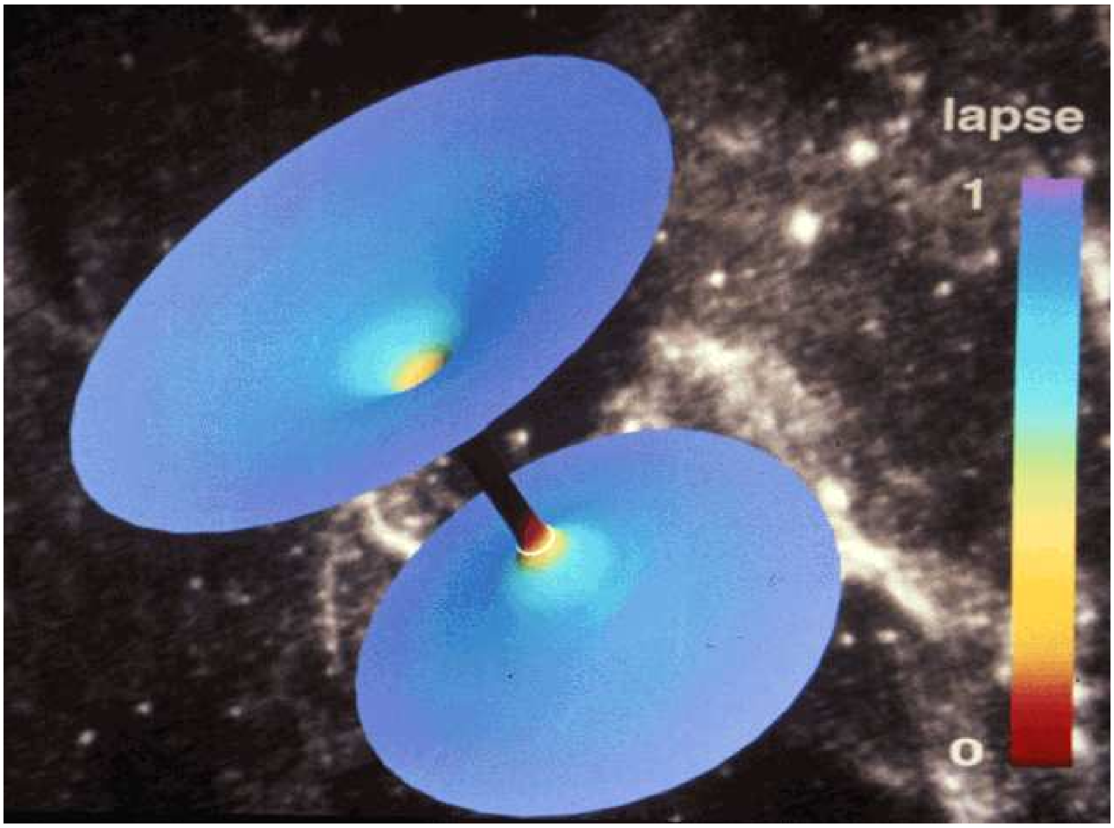


Fig. 7.1. Trajectories of a test particle interacting with a black hole. In the first two cases (a,b) the particle is deflected and escapes to infinity, in case (c) the particle approaches very close to the last stable orbit (the capture radius of 6 GM/c^2) and orbits many times before escaping to infinity, while in (d) the particle is captured and spirals towards the event horizon (2 GM/c^2) shown by the shaded circle.

Black Hole Paradigm

■ Space Warp

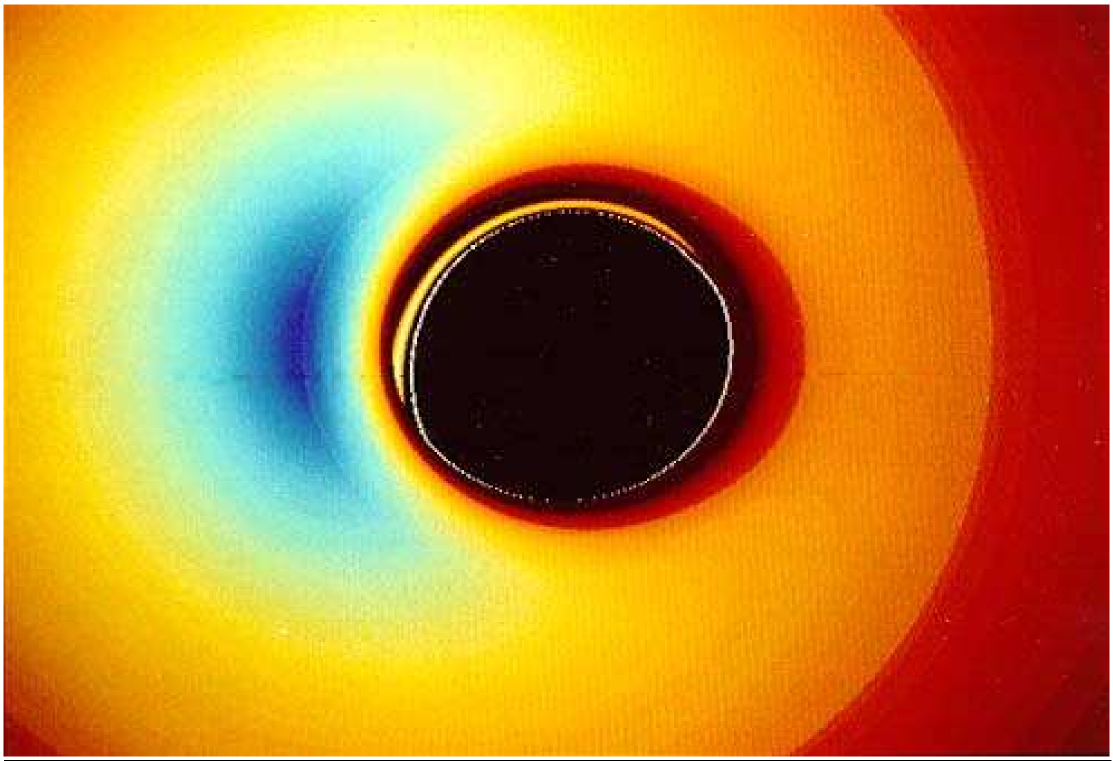


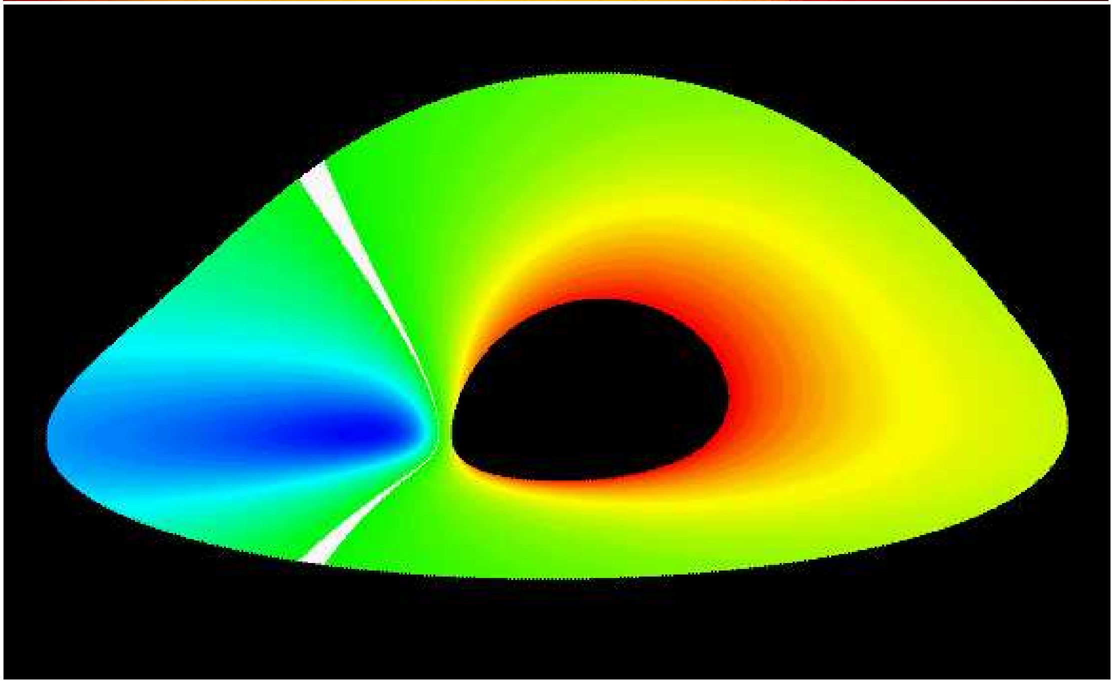
Black Hole Paradigm

■ Gravitational Waves

Black Hole Paradigm

■ Light Bending





Black Hole Paradigm

■ Schwarzschildradius

Equating kinetic and potential energy in a gravitating system yields:

$$\frac{1}{2}mv^2 = \frac{GMm}{R_{\rm S}}$$

setting $v = c$—the speed of photons—and canceling m we get

$$R = \frac{2GM}{c^2} = 3\frac{M}{M_\odot}\text{km}$$

- This is called the Schwarzschild radius and defines the event horizon in the Schwarzschild metrik (non-rotating black hole).
- For the mass of the earth ($3 \cdot 10^{-6} M_\odot$) we have $R_{\rm S} = 1$cm.
- For a quasar with $M_\bullet = 10^8 M_\odot$ we have $R_{\rm S} = 3 \cdot 10^{13}$ cm $= 2$ AU.
- In theoretical papers one often uses $G = M = c = 1$. The unit of lengths then is one gravitational radius $R_{\rm g} = \frac{GM}{c^2}$.
- For a maximally rotating black hole (a=1) the event horizon is $1\ R_{\rm g} = 0.5 R_{\rm S}$
- The mass density of a black hole with $M_\bullet = M_8 \cdot 10^8 M_\odot$ is

  $$\rho_\bullet = \frac{M_\bullet}{4/3\,\pi R_{\rm S}^3} = 1.8\ M_8^{-2}\,\text{g}\,\text{cm}^{-3}$$

  (The mass density of water is 1 g cm^{-3}. So, if you fill the solar system completely with water it will turn into a black hole. Please make sure your faucets are closed when you leave your house!)

Black Hole Paradigm

■ Not so "black" after all

When mass falls onto a black hole, potential energy is converted into kinetic energy. This energy is either advected into and beyond the event horizon or released before.

The potential energy of a mass element dm in a gravitational field is

$$U = \frac{GMm}{r}$$

The available energy (luminosity) then is

$$L = \dot{U} = \frac{GM}{r}\frac{dm}{dt} = \frac{GM\dot{M}}{r}$$

where we call $\dot{M}$ the **mass accretion rate**.

The characteristic scale of the emitting region will be a few gravitational radii, i.e. $r \sim r_{\rm in} R_{\rm g}$.

$$L = \frac{GM\dot{M}}{1}\frac{c^2}{r_{\rm in}GM} = \eta \dot{M} c^2$$

where we define here the efficiency $\eta = r_{\rm in}^{-1}$.

Therefore, for energy dissipation near the black hole with e.g. $r_{\rm in} \sim 10$ we will have $\eta = 0.1$ and hence a 10% efficiency in converting rest mass into energy.

Black Hole Paradigm

■ Not so "black" after all

- The efficiency η will depend on the spin (a) of the black hole: for $a = 0$ (Schwarzschild) we have $\eta = 6\%$ and for $a = 1$ (extreme Kerr) we have $\eta = 40\%$! Note that for nuclear fusion we only have $\eta = 0.007$.
- For $L_{\rm QSO} = 10^{46}$ erg/sec and $\eta = 0.1$ we have $\dot{M} = 2M_{\odot}$ yr^{-2}.
- The accretion rate to obtain the Eddington luminosity is

$$\dot{M}_{\rm E} = \frac{L_{\rm E}}{\eta c^2} \simeq 2.2 M_8 \eta_{-1} M_{\odot}\,{\rm yr}^{-1}$$

- The Eddington accretion rate depends on the mass and the efficiency $\eta = \eta_{-1} 0.1$ (i.e. spin), and the type of accretion:
  - Spherical accretion: Eddington limit is strictly valid only for this type
  - ADAF (Advection Dominated Accretion Flow): Quasi-spherical accretion where energy is not radiated away, but carried into the black hole ($\eta \ll 0.1$). However, the efficiency increases towards the classical case when $\dot{M} \to \dot{M}_{\rm E}$.
  - Disk accretion: much of the radiation escapes along rotation axis. However, strong radiation can induce a disk-wind which becomes significant near the Eddington limit.

$\Rightarrow$ At least for very luminous AGN, the Eddington limit seems to be a robust tool.

Black Hole Paradigm

■ Observational Evidence

Initially the black hole paradigm was based on theoretical arguments and the existence of compact luminous engines. This model made a strong prediction: **in many galaxies one should find a central concentration of (dark) mass!**

We have now compelling evidence that this prediction was correct.

Evidence for the dark mass has been found

- In the Galactic Center: radial and proper motions of stars
- In NGC4258: VLBI observations of moving maser spots in a Keplerian disk
- In many spiral galaxies: HST and groundbased spectoscopy of stellar velocity fields
- In MCG-6-30-15: gravitational redshift of iron line?

Observational Evidence

▪ Stellar velocity dispersion

The velocity dispersion of stars in the nuclei of many galaxies shows a marked peak in the center.

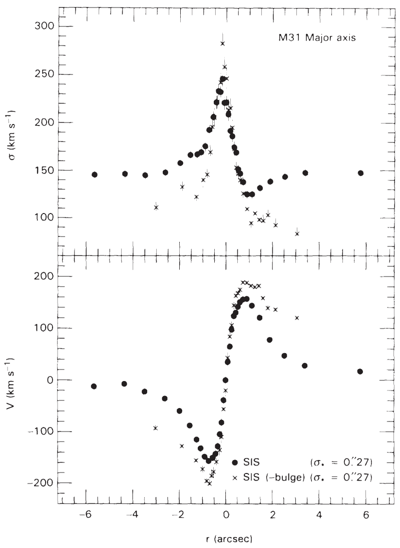
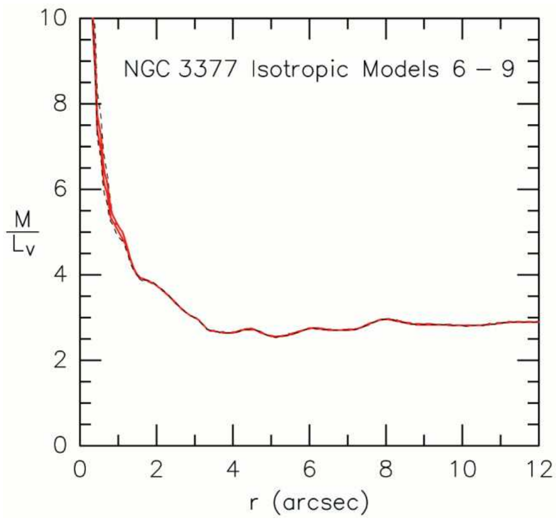


Fig. 7.3. Compelling evidence for the existence of a supermassive black hole of mass > 10^7 $M_\odot$ in the core of M31 obtained from the radial velocity (bottom) and velocity dispersion (top) of stars. The filled circles are for the kinematics of the nucleus plus bulge, the crosses show the kinematics after the bulge component has been removed. (Courtesy of John Kormendy.)

For an isotropic velocity field with net-roation V and velocity dispersion σ we have

$$M(r) = \frac{RV^2}{G} + \frac{R\sigma^2}{G}$$



The mass-to-ligh ratio increases and yields evidence for a compact dark mass.

Observational Evidence

■ Kinematics of Megamasers

Megamasers are very compact clumps of molecular material in the nucleus of an AGN, probably excited by x-ray emission, amplifying a background continuum source through the maser process. The velocity of the clumps can be derived from spectroscopy and their position on the sky is pin-pointed by high-resolution VLBI observations. The motion in NGC4258 can be exactly fitted by Keplerian motion around a dark point mass.

$$M_{\bullet} = \frac{Rv^2}{G} = \frac{0.1\text{pc}(1100\text{km/sec})^2}{6.7 \cdot 10^{-8}\text{cm}^3/\text{g/sec}^2} \simeq 3.6 \cdot 10^7 M_{\bullet}$$

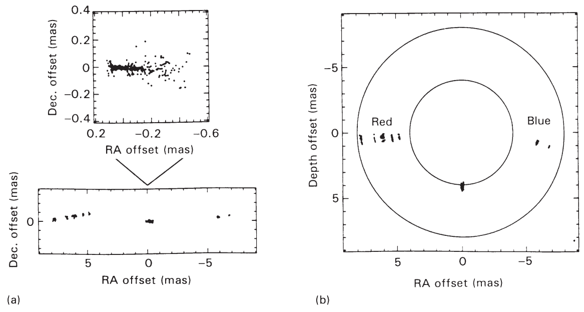


Fig. 7.4. (a) The distribution of the water masers in NGC4258 in units of milli-arcseconds offset from the central region which is also shown in an expanded view above, (b) the calculated positions of the masers along the line-of-sight direction. The circles mark the inner and outer edges of the molecular disk. (From Miyoshi *et al.*, *Nature*, **373**, 128, 1995.)

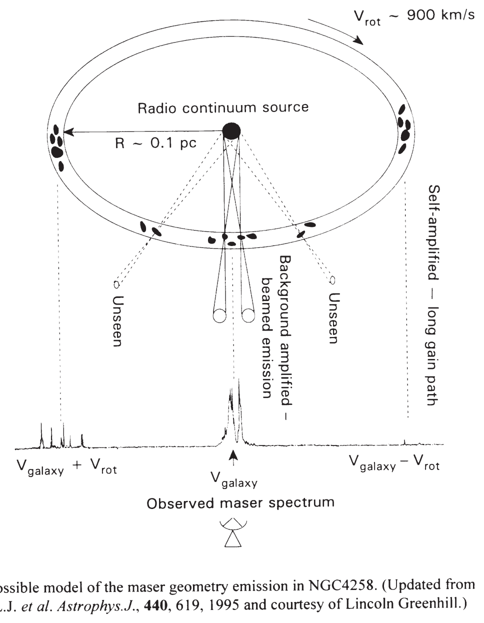


Fig. 7.5. Possible model of the maser geometry emission in NGC4258. (Updated from Greenhill,L.J. *et al. Astrophys.J.*, **440**, 619, 1995 and courtesy of Lincoln Greenhill.)

Black Hole Paradigm

■ Observational Evidence

X-ray spectrosocpy of the galaxy MCG-6-30-15 has revealed an enormously broad emission line (iron K), probably from the innermost disk around a black hole. The shape and width of the line can be explained by Keplerian motion around a black hole plus the effect of gravitational redshift.

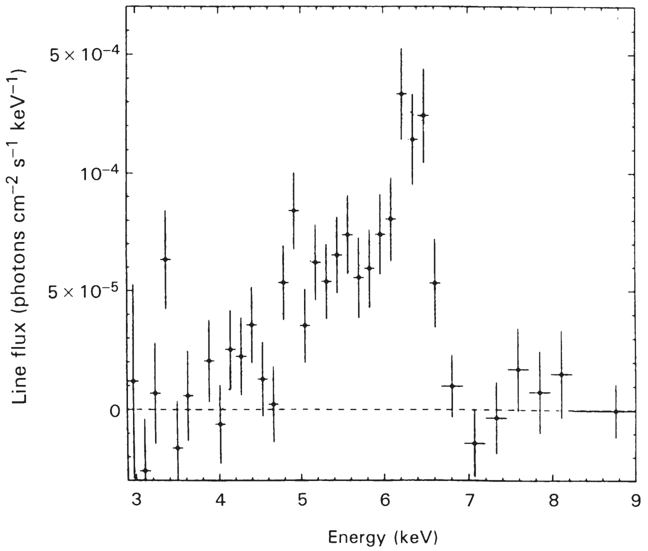
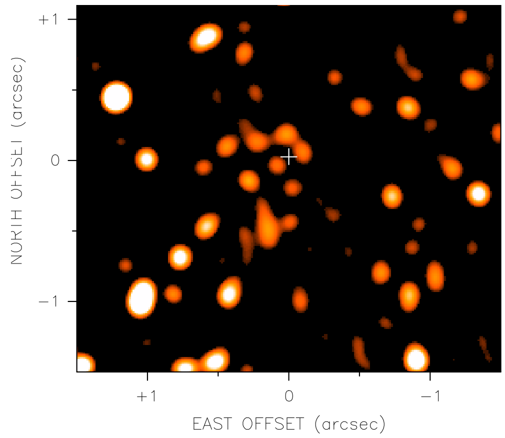


Fig. 7.6. The X-ray spectrum of MCG-6-30-15 after removal of a power-law and reflection components. The fluorescent Kα iron line is clearly visible at an energy of ~6 keV and is very asymmetric, being extended to the red. The velocity width is ~100,000 km s^{-1} and fits with a model of the gas suffering a gravitational redshift in the field of a supermassive black hole. (From Tanaka *et al*, *Nature*, **375**, 659, 1995.)

The Galactic Center

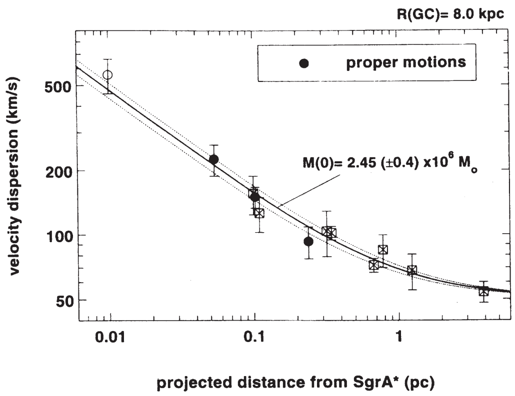
The Galactic Center is the best case for a super-massive black hole: Because it is so close, high-resolution imaging and spectroscopy of stellar motions can be used to probe the gravitational potential.

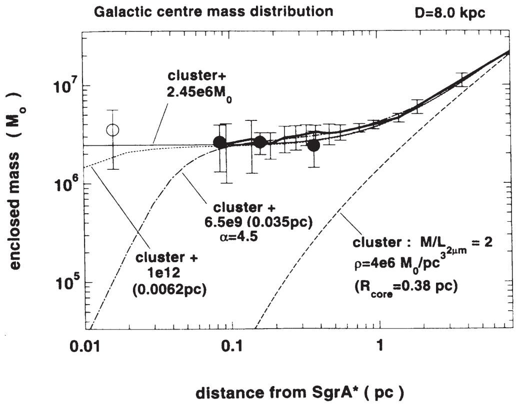


This is the only star cluster where we have 3D information of the stellar velocity field.

$$\Downarrow$$

Compact mass of $(2.6\pm0.2)\cdot10^6 M_\odot$ within 0.01 pc (i.e. $> 10^{12} M_\odot/\mathrm{pc}^3$)!





Such a high mass concentration excludes stellar clusters.

(Eckart & Genzel 1997; Ghez et al. 1998)