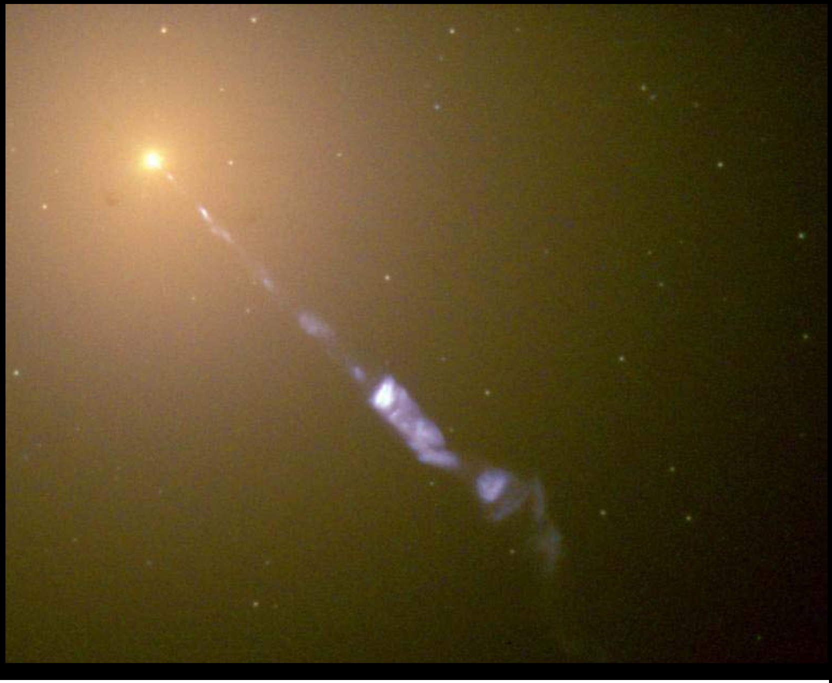
Today in Astronomy 102: energy and black holes

- ☐ Einstein’s mass-energy equivalence ($E = mc^2$).
- ☐ Generation of energy from black holes.
- ☐ The search for black holes, part 1: the discovery of active galaxy nuclei, and the evidence for the presence of black holes therein.



Jet and disk around a supermassive black hole in the center of the elliptical galaxy M87, as seen by the Hubble Space Telescope (NASA/STScI).

Equivalence of mass and energy in Einstein's special theory of relativity

- ☐ **Mass is another form of energy**. Even at rest, in the absence of electric, magnetic and gravitational fields, a body with (rest) mass m_0 has energy given by

$$E = m_0 c^2 \quad .$$

- ☐ Conversely, **energy is another form of mass**. For a body with total energy E, composed of the energies of its motion, its interactions with external forces, and its rest mass, the relativistic mass m is given by

$$E = mc^2 \qquad \text{or} \qquad m = E/c^2 \quad .$$

(You will need to know how to use this formula!)

Equivalence of mass and energy in Einstein's special theory of relativity (continued)

Consequences:

- ☐ Even particles with zero rest mass (like photons and neutrinos) can be influenced by gravity, since their energy is equivalent to mass, and mass responds to gravity (follows the curvature of spacetime).
- ☐ There is an **enormous** amount of energy stored in rest mass.

Note on energy units

- ☐ Since $E = mc^2$, the units of energy are

$$\mathrm{gm}\left(\frac{\mathrm{cm}}{\mathrm{sec}}\right)^2 = \frac{\mathrm{gm\ cm}^2}{\mathrm{sec}^2} = \mathrm{erg}$$

  Luminosity is energy per unit time, so its units are erg/sec, as we have seen.

- ☐ “Erg” comes from the Greek ′έργον, which means “work” or “deed.”
- ☐ 1 watt = 1 W = 1 joule/sec = 10^7 erg/sec
- ☐ 1 joule = 10^7 erg
- ☐ 1 kWh = 1000 W×1 hour = 3.6×10^{13} erg (Power-bill units).
- ☐ 1 megaton = 4.18×10^{22} erg (Nuclear-weaponry units)

Equivalence of mass and energy in Einstein's special theory of relativity (continued)

Example: Liberate energy, in the form of heat or light, from 1000 kg (1 metric ton) of anthracite coal.

- ☐ Burn it (turns it all to CO_2 and H_2O): $\Delta E = 4.3 \times 10^{17}$ erg = 12,000 kWh .

A year's supply, for a typical American family.

- ☐ Maximum-efficiency fusion in a star (turns it all to iron): $\Delta E = 4.1 \times 10^{24}$ erg $= 1.1 \times 10^{14}$ kWh .

And, for something we can calculate in AST 102,

- ☐ Convert all of its rest mass (m_0) to energy ($m_0 c^2$):

$$\Delta E = m_0 c^2 = ?$$

A. 9×10^{23} erg B. 9×10^{24} erg C. 9×10^{25} erg

D. 9×10^{26} erg E. 9×10^{27} erg

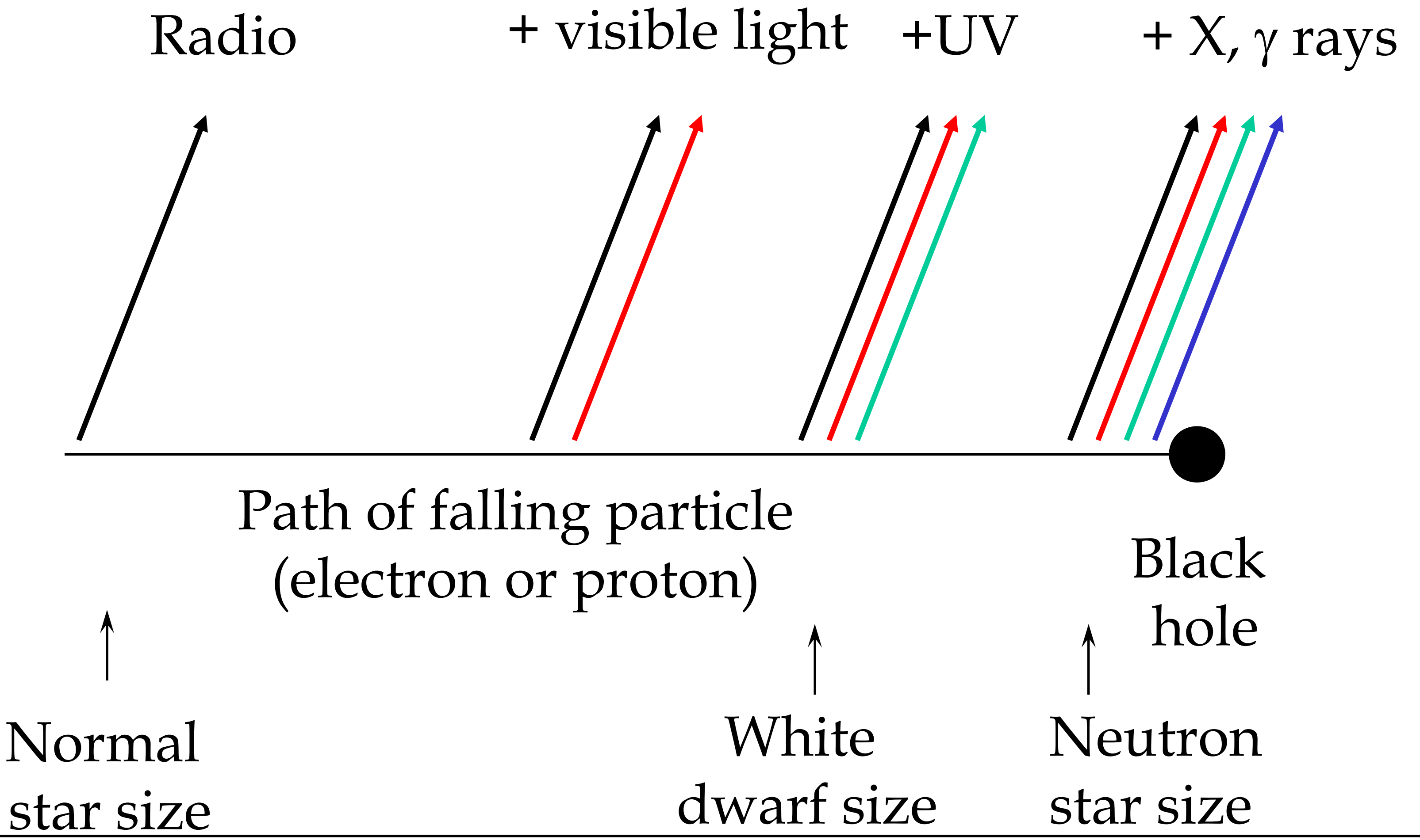
“Converting mass to energy” with a black hole

...by which we mean converting rest mass to heat or light.

Black hole accretion:

- As matter falls into a black hole, it is **ionized** and **accelerated** to speeds close to that of light, and radiates light as it accelerates.
- The faster it goes, the higher the energy of the photons. The surface of planets or stars would stop an infalling particle before it approached the speed of light, but such speeds are possible when falling into a black hole.
- **About 10% of the rest mass of infalling particles can be turned into energy** (in the form of light) in this manner. (The other 90% is added to the mass of the black hole.)

“Converting mass to energy” with a black hole (continued)



Radio

+ visible light

+UV

+ X, γ rays

Path of falling particle (electron or proton)

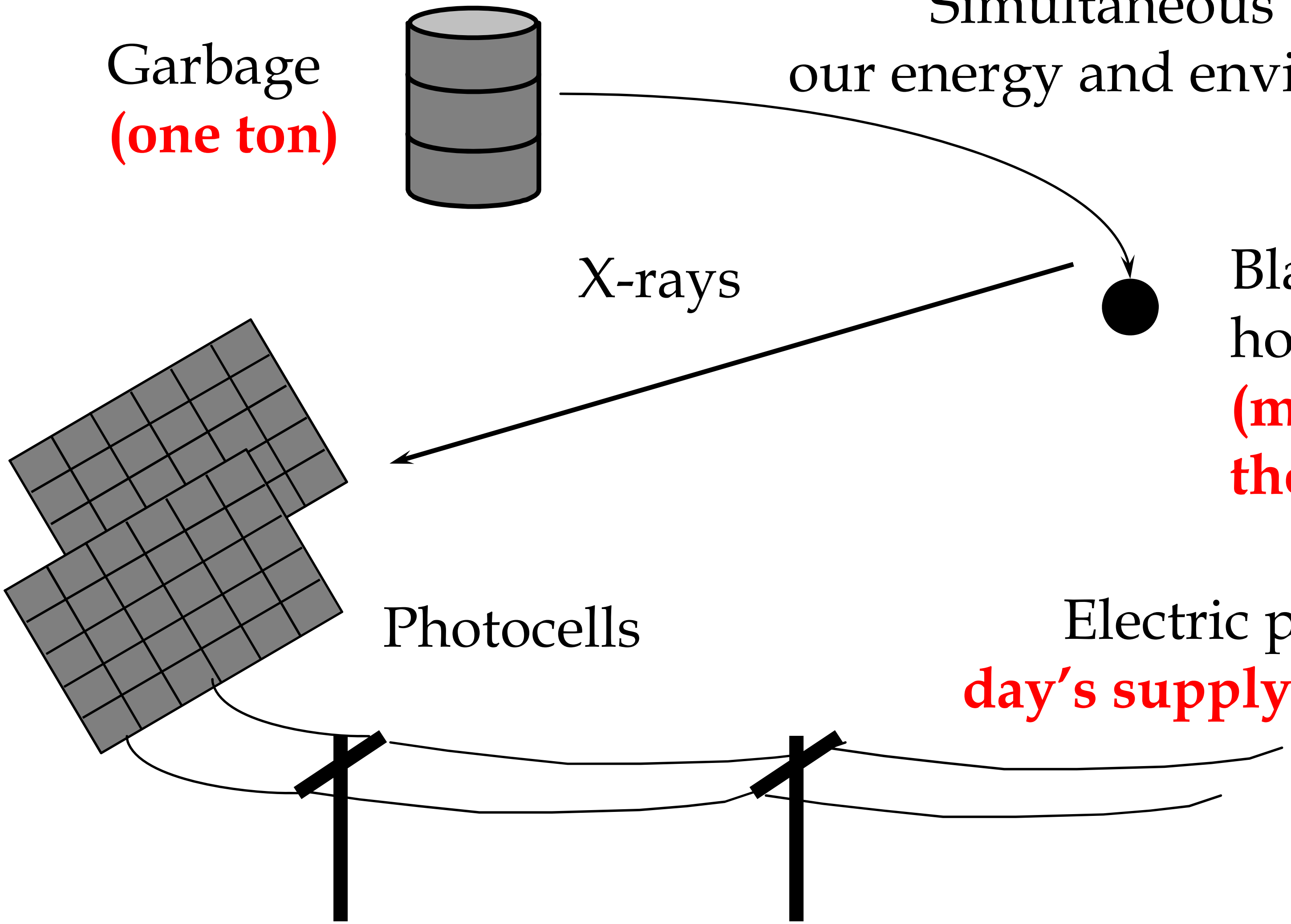
Black hole

Normal star size

White dwarf size

Neutron star size

“Converting mass to energy” with a black hole (continued)



Simultaneous solution of our energy and environmental problems?

Garbage **(one ton)**

X-rays

Black hole **(mass of the moon)**

Photocells

Electric power **(one day’s supply for Earth)**

“Converting mass to energy” with a black hole (continued)

Spinning black holes (Penrose 1969, Blandford & Znajek 1977)

- ❑ Since spacetime in the ergosphere rotates along with the horizon, and 0-30% of the hole’s total energy is there, one can (in principle) anchor a “crank handle” there and have the black hole turn a distant motor.
  - That’s a lot of energy: for a 10 $M_\odot$ black hole, 30% is

    $$0.3 m_0 c^2 = 0.3\left(10\times 2\times 10^{33}\ \mathrm{gm}\right)\left(3\times 10^{10}\ \frac{\mathrm{cm}}{\mathrm{sec}}\right)^2$$

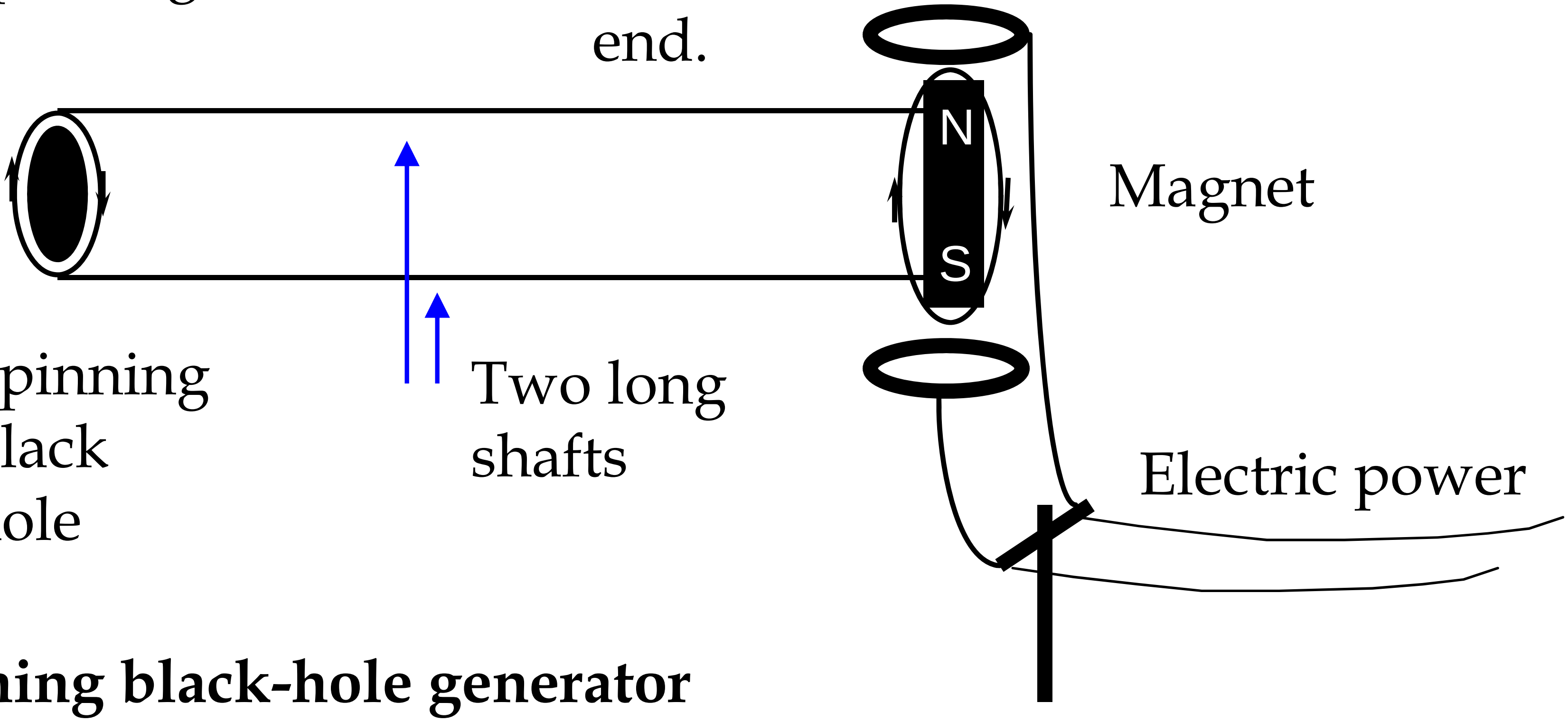
    $$= 5.4\times 10^{54}\ \mathrm{erg}\ \ .$$

    The Sun will emit “only” about 2x10^{51} ergs in its whole life.
- ❑ The motor could be used to generate electricity at fairly high efficiency, until the hole stops spinning (a very long time).

“Converting mass to energy” with a black hole (continued)

Ends of shafts placed in the ergosphere of a spinning black hole.

Shafts turn magnet end over end.



Coils

N

S

Magnet

Spinning black hole

Two long shafts

Electric power

Spinning black-hole generator

Guess about accretion and energy conservation

Energy is conserved – neither created nor destroyed, but often changed in form.

As a rock falls into a black hole, its speed (and *kinetic* energy) increases and its mass (and relativistic mass-energy) increase, so something must be losing energy. What?

A. It is drawing heat from the black hole's surroundings – material in the surroundings is cooling down.

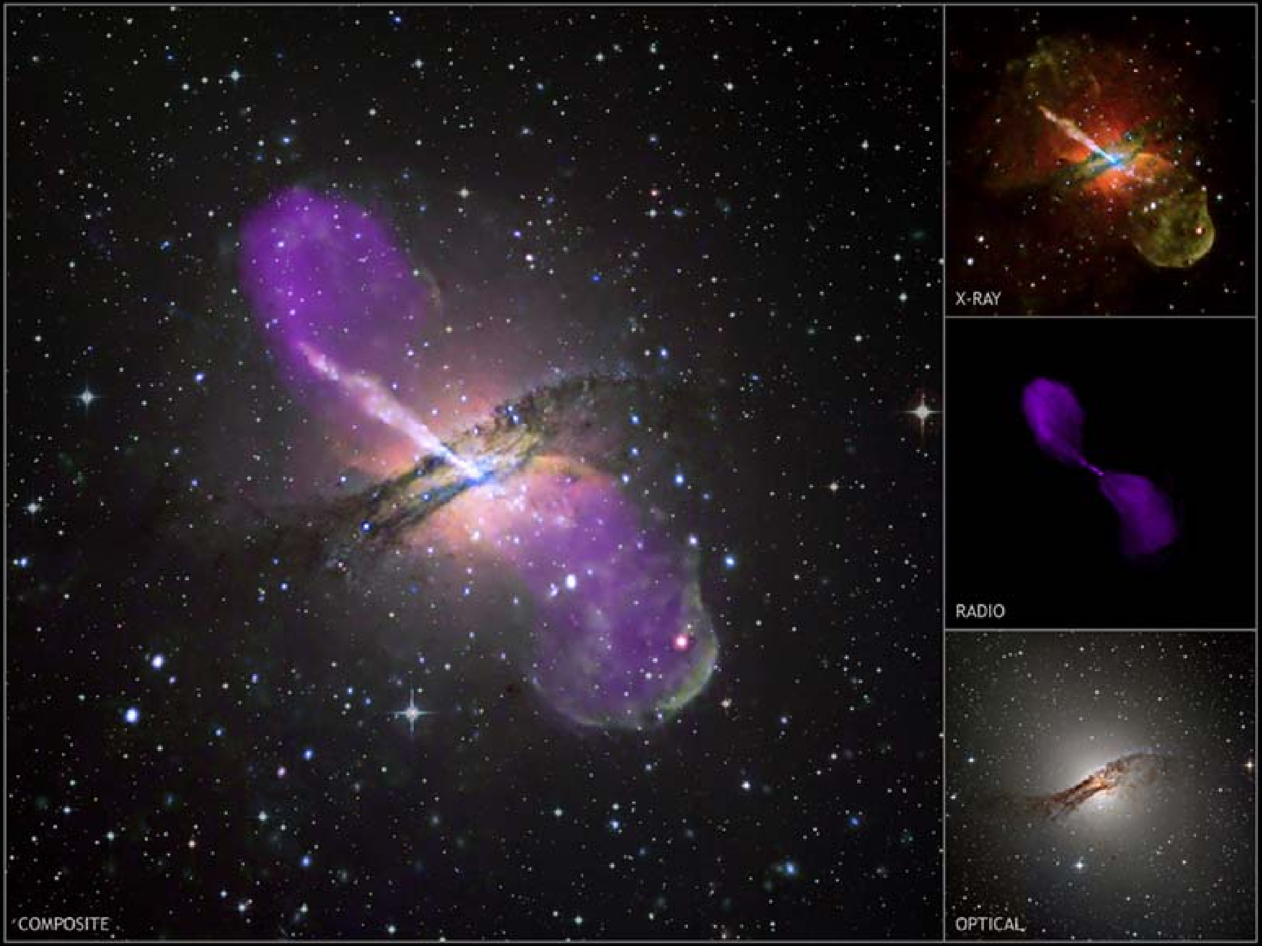
B. Gravity is doing the work; the gravitational (binding) energy of the rock and the black hole must be decreasing.

C. The rock gets ionized and starts radiating light, UV and X-rays, and this is an energy loss.

D. The rock would start burning up: chemical energy is lost.

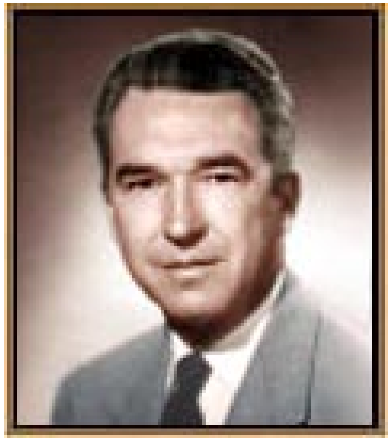
Please fill out the online TA evaluations, one for every TA with whom you've been working.

Mid-lecture break.



X-ray, visible-light, and radio images , and a composite of all three, of Centaurus A, home of the nearest supermassive black hole (CXO/CfA/NASA).

The (retrospective) discovery of black holes: Seyfert galaxy nuclei



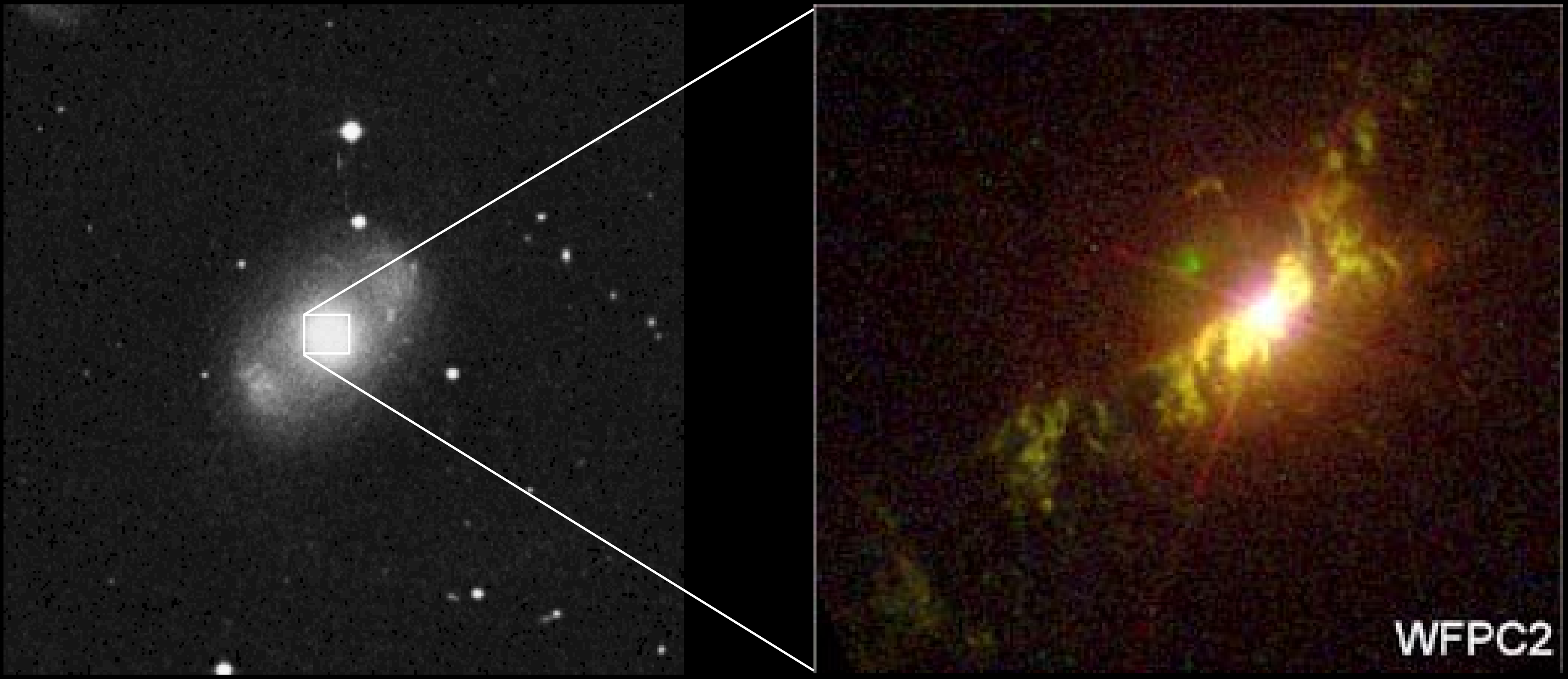
Seyfert

In 1943, Carl Seyfert, following up a suggestion by Milton Humason, noticed a class of unusual spiral galaxies, now called Seyfert galaxies.

- ☐ Unlike other galaxies, in short-exposure photographs they look like stars; long exposures reveal that each bright starlike object actually lies at the nucleus of a galaxy.
- ☐ The starlike nucleus has lots of ionized gas, with a peculiar, broad range of ionization states and Doppler shifts indicative of very high speeds (thousands of km/s).
- ☐ The starlike nucleus is also much bluer than clusters of normal stars.

Seyfert noted that there didn't seem to be a plausible way to explain the starlike nucleus as a collection of stars.

Seyfert galaxy NGC 4151

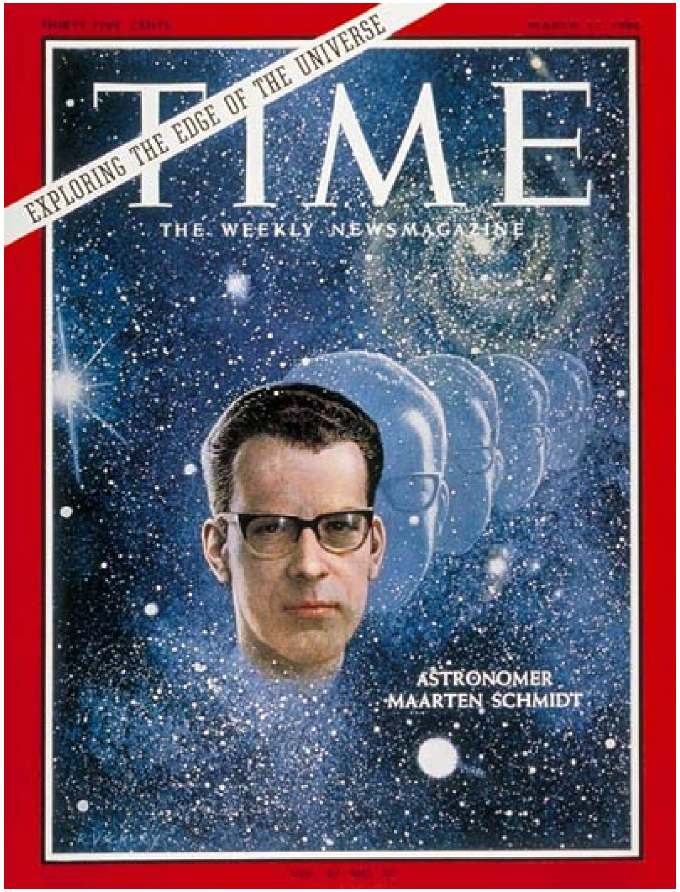


Long exposure, showing the central “bulge” and spiral arms (Palomar Observatory).

Short exposure, showing the starlike active nucleus (NASA Hubble Space Telescope).

The discovery of black holes: quasars

- Discovered by radio astronomers: small, “starlike,” bright sources of radio emission (1950s).
- Identified at first by visible-light astronomers as stars with extremely peculiar spectra (1950s).
- Maarten Schmidt (1963) was the first to realize that the spectrum of one quasar, 3C 273, was a lot like a common galaxy spectrum, but seen with a Doppler shift of about 48,000 km/sec –16% of the speed of light.



Maarten Schmidt in 1963 (Time Magazine)

The discovery of black holes: quasars (continued)

  - High speed with respect to us: the **quasars are very distant**. 3C 273 is measured to be about 2 billion light years away, much further away than any galaxy known in the early 1960s.
  - Yet they are bright: the **quasars are extremely powerful**. 3C 273 has an average luminosity of $10^{12}\ L_{\odot}$, about 100 times the power output of the entire Milky Way galaxy.
- ❑ Observations also show that the powerful parts of **quasars are very small**.
  - Radio-astronomical observations show directly that most of the brightness in 3C 273 is concentrated in a space smaller than 10 light years in diameter, a factor of about 20,000 smaller than the Milky Way galaxy.

The search for black holes: discovery of quasars (continued)

- ❑ The brightness of quasars is highly, and randomly, variable.
  - 3C 273 can change in brightness by a factor of 3 in only a **month**.
  - This means that its power is actually concentrated in a region with diameter no larger than **one light-month**, 7.9×10^{11} km. For comparison, Pluto's orbit's diameter is about 10^{10} km.
- ❑ ***Major*** problem: how can so much power be produced in such a small space?

Why does rapidly-variable brightness mean small size?

If a quasar’s brightness varies a lot in a month, why does that mean that the power comes from a region no bigger than a light month?

A. If it were any bigger, the energy input that “throws the switch” would have to travel faster than light.

B. Relativistic length contraction: it just looks smaller, to a distant observer.

C. Gravitational time dilation: the slow arrival over a month of the brighter signal must mean the region near the horizon of a black hole is involved.

How are quasars powered?

Requirements: need to make 10^{12} $L_\odot$ in a sphere with circumference 2.5×10^{12} km (0.26 ly) or smaller.

Here are a few ways one can produce that large a luminosity in that small a space.

- ☐ **10^7 stars of maximum brightness, 10^5 $L_\odot$.**
  Problem: such stars only live 10^6 years or so. We see so many quasars in the sky that they must represent a phenomenon longer lived than that.
- ☐ **10^{12} solar-type stars: each with $L = 1\ L_\odot$, $M = 1\ M_\odot$.**
  Problems:
  - stars would typically be only about $6\text{x}10^{12}$ cm apart, less than half the distance between Earth and Sun. They would collide frequently.

How are quasars powered (continued)?

- they would weigh $10^{12}\ M_\odot$. The Schwarzschild circumference for that mass is

$$C_S = \frac{4\pi GM}{c^2} = \frac{4\pi\left(6.67\times10^{-8}\ \frac{\text{cm}^3}{\text{gm sec}^2}\right)\left(10^{12}\times2\times10^{33}\ \text{gm}\right)}{\left(3\times10^{10}\ \frac{\text{cm}}{\text{sec}}\right)^2}$$

$$= 1.9\times10^{18}\ \text{cm}\left(\frac{\text{light year}}{9.46\times10^{17}\ \text{cm}}\right) = 2.0\ \text{light years}\ \ ,$$

larger than that of the space in which they're confined. Thus if you assembled that collection of stars in that small a space, you would have made a **black hole**, not a cluster of stars.

How are quasars powered? (continued)

☐ **Accretion of mass onto a black hole.**

- Luminosity = energy/time. ($10^{12}\ L_\odot = 3.8\times10^{45}$ erg/sec)
  Energy = luminosity × time.
  But Energy (radiated) = total energy × efficiency
  = mc^2 × efficiency, so
  Mass = luminosity × time / (efficiency × c^2)
- For a time of 1 year (3.16×10^{7} sec), and an efficiency of 10%, we get
  Mass = (3.8×10^{45} erg/sec)(3.16×10^{7} sec)/(0.1)(3×10^{10} cm/sec)^2
  = 1.3×10^{33} gm = 0.7 $M_\odot$.

The black hole would have to swallow 0.7 $M_\odot$ per year, a very small amount on a galactic scale. **No problem**.