

Astronomy 102.
October 20, 2005.



What's causing a huge jet to emanate from the center of galaxy M87? A massive black hole?

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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

$$E=m_0c^2$$

- 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

$$E=mc^2 \quad \text{or} \quad m=\frac{E}{c^2}$$

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

- 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 space-time).



- There is an **enormous** amount of energy stored in rest mass.

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The unit of energy.

- The unit of energy we are using in this course is the erg.
- The name erg comes from the Greek $\epsilon\rho\gamma\omega\nu$, which means 'work'.
- We can express the erg in terms of the units of mass, distance, and time:

$$1 \text{ erg} = 1 \frac{\text{g cm}^2}{\text{s}^2}$$

- Related units:
 - Joule (J): $1 \text{ J} = 10^7 \text{ erg}$.
 - Watt (W): $1 \text{ W} = 1 \text{ J/s} = 10^7 \text{ erg/s}$.
 - Luminosity (L): $1 L_{\text{sun}} = 3.8 \times 10^{33} \text{ erg/s}$.
 - Kilowatt hour (kWh): $1 \text{ kWh} = 1000 \text{ W} \times 1 \text{ h} = 3.6 \times 10^{13} \text{ erg}$.
Note: the kWh is usually the unit used on bills from your electric company.

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

- Consider for example the energy we can extract from 1000 kg of coal:
 - If we burn the coal, we convert it into CO_2 and H_2O . The chemical energy released in this process is $4.3 \times 10^{17} \text{ erg} = 12,000 \text{ kWh}$.
 - If we fuse the coal (primarily carbon) to form iron (which is the most tightly bound nucleus) we would be able to generate $4.1 \times 10^{24} \text{ erg} = 1.1 \times 10^{14} \text{ kWh}$.
 - If we would be able to convert all of its rest mass into energy, we would be able to generate $9 \times 10^{29} \text{ erg} = 2.5 \times 10^{17} \text{ kWh}$.

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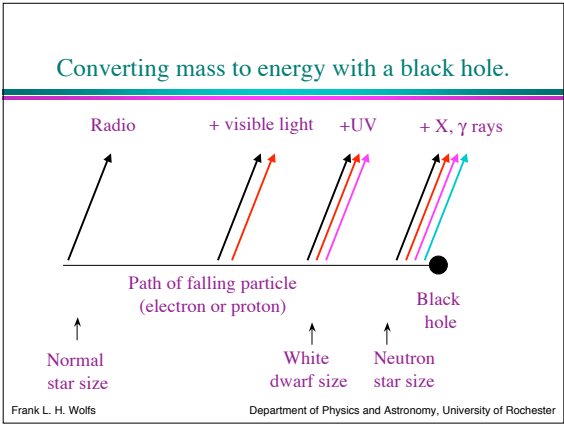
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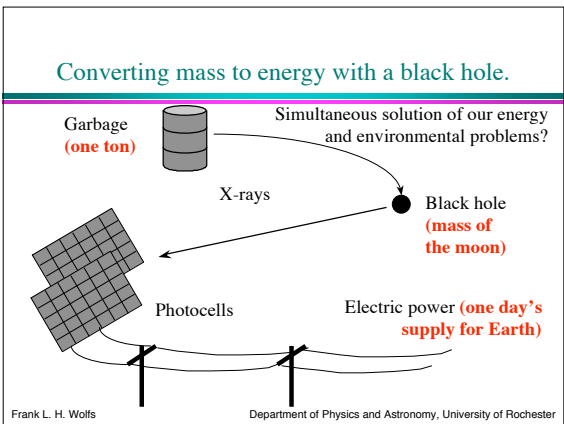
Converting mass to energy with a black hole.

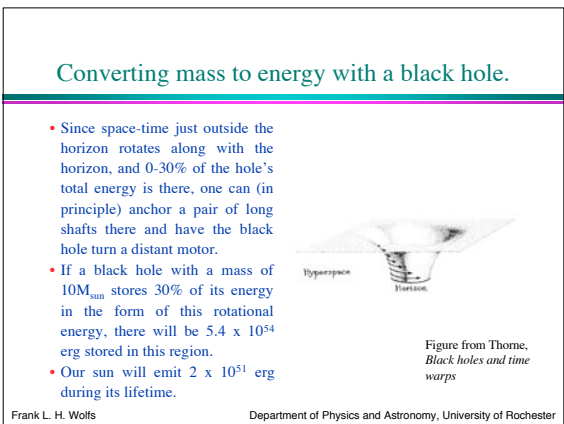
- As matter falls into a black hole, it is **ionized** and **accelerated** to speeds close to that of light, and radiates light as it accelerates.
- The faster it goes, the higher the energy of the photons. The surface of planets or stars would stop an in-falling particle before it approached the speed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

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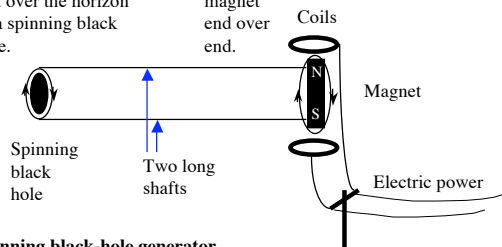




Converting mass to energy with a black hole.

Ends of shafts hovering just over the horizon of a spinning black hole.

Shafts turn magnet end over end.



Spinning black-hole generator

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Finding black holes. Where do we look?

- The search for black holes started in our own solar system. The closer you look, the easier it will be to observe a black hole.
- The motion of the planets in our solar system can be fully explained by the gravitational forces generated by the sun and the other planets. Clearly there is no black hole in our solar system.
- Looking in our galaxy, we can estimate that any black hole will be no closer to us than the closest star (which is 4 light-years from us).

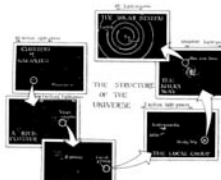


Figure from Thorne, *Black holes and time warps*

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Finding black holes. Where do we look?

- A black hole with a circumference of 50 km at a distance of 4 light-years will subtend an angle that is similar to the angle subtended by a human hair on the moon, as seen by an observer on earth.
- This would require a resolution that is 10,000,000 times better than the resolution of the best telescope in the world.
- We must conclude that we can not observe a black hole directly.



Figure from Thorne, *Black holes and time warps*

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Finding black holes. How do we look for them?

- **What are quasars?**

- Quasars were discovered by radio astronomers in the 1950s. They are small, "star-like", and bright sources of radio waves.
- The quasars were identified in the visible spectral range, and appeared to generate extremely peculiar spectra.
- In 1963 Maarten Schmidt was the first one to realize that the spectra of quasars are similar to those of galaxies, except that they appeared to be Doppler shifted as if their source has an extremely high velocity (up to 20% of the speed of light).



High Redshift Quasars
Credit: Sloan Digital Sky Survey

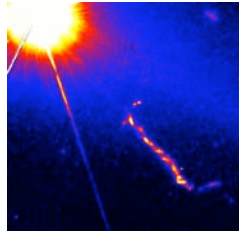
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Finding black holes. How do we look for them?

- **What are quasars?**

- The quasar 3C-273 moves away from us with a velocity of 48,000 km/s (0.16 c).
- The speed of 3C-273 indicates that it is very far away from us (about 2,000,000,000 light years).
- The brightness of the quasars, combined with their huge distance, suggests that they have a very high luminosity. The luminosity of 3C-273 is $10^{12} L_{\text{sun}}$, about 100 times the luminosity of the entire Milky Way.
- The source of the energy appears to be very small; the brightness of 3C-273 appears to come from a space with a diameter of 10 ly (1/20,000 of the the Milky Way).



An optical image of the quasar 3C273 as observed by the Hubble Space Telescope. (Credit: NASA/STScI)

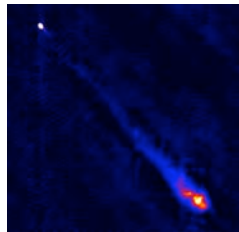
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Finding black holes. How do we look for them?

- **What are quasars?**

- The brightness of quasars are highly variable.
- The quasar 3C-273 can vary by as much as a factor of 3 in only 1 month.
- In order of the quasar to be able to change its collective brightness in less than a month, it can be no bigger than 1 light-month.
- The size of 3C-273 can thus be no larger than 7.9×10^{11} km (this is about a factor of 80 larger than the size of the orbit of Pluto).
- How can so much power be produced in such a small space?



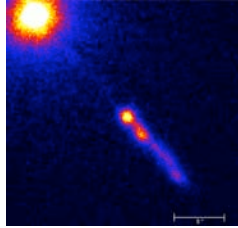
This image of 3C273 was taken by the radio array of telescopes around Great Britain known as the Multi-Element Radio Linked Interferometer Network (MERLIN).

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How are quasars powered?

- How can we generate a luminosity of $10^{12} L_{\text{sun}}$ in a region with a circumference of less than 2.5×10^{12} km?
 - Put 10^7 stars, each with a luminosity of $10^5 L_{\text{sun}}$ in this volume. These super heavy stars would only live 10^6 years, and can not account for the many quasars we observe.
 - Put 10^{12} sun-like stars in this volume. This would resolve the life-time problem, but the stars would be so close (less than half the distance between the earth and the sun) that there would be frequent collisions.



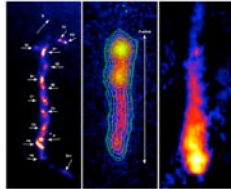
Chandra X-Ray image of 2C-273.
(Credit: NASA/CXO/SAOHL/ Marshall et al.)

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How are quasars powered?

- How can we generate a luminosity of $10^{12} L_{\text{sun}}$ in a region with a circumference of less than 2.5×10^{12} km?
 - Put 10^{12} sun-like stars in this volume. Such a system would have a mass of $10^{12} M_{\text{sun}}$. The circumference of the volume occupied by this system is smaller than the Schwarzschild circumference for a black hole with a mass of $10^{12} M_{\text{sun}}$. Thus, if you would be able to assemble such a system of stars, it would collapse and form a black hole.



Study of the jet blasting out of the core of quasar 3c273.
From left to right, the images are optical (HST), X-ray (Chandra), and radio (MERLIN).

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How are quasars powered?

- How can we generate a luminosity of $10^{12} L_{\text{sun}}$ in a region with a circumference of less than 2.5×10^{12} km?
 - Luminosity = energy/time. Thus a luminosity of $10^{12} L_{\text{sun}}$ corresponds to 3.8×10^{45} erg/sec.
 - Assume that the energy is generated by the mass swallowed by the black hole, and assume that 10% of this mass is converted into energy. This would require a rest mass of 3.8×10^{46} erg to be swallowed every second.



Artist's conception of a $16 M_{\text{sun}}$ black hole accreting material from a $10 M_{\text{sun}}$ companion star (from Chaisson and McMillan, *Astronomy today*).

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How are quasars powered?

- How can we generate a luminosity of $10^{12} L_{\text{sun}}$ in a region with a circumference of less than 2.5×10^{12} km?
 - Over the period of a year, the rest mass that must be swallowed is equal to

$$3.8 \times 10^{46} \text{ erg/s} \times 3.16 \times 10^7 \text{ s}$$
 or

$$1.2 \times 10^{54} \text{ erg}$$
 - The equivalent mass is equal to

$$\frac{E}{c^2} = \frac{1.2 \times 10^{54} \text{ erg}}{(3 \times 10^{10} \text{ cm/s})^2} = 1.33 \times 10^{33} \text{ gm} = 0.7 M_{\text{sun}}$$
 - The black hole would have to swallow $0.7 M_{\text{sun}}$ per year, a very small amount on a galactic scale.



Artist's conception of a $16 M_{\text{sun}}$ black hole accreting material from a $10 M_{\text{sun}}$ companion star (from Chaisson and McMillan, *Astronomy today*).

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Other evidence for black holes in quasars: apparent faster-than-light motion.

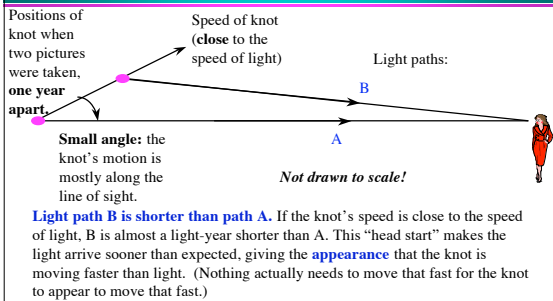
- The innermost parts of the radio jet in 3C-273 consists mainly of small "knots" with separation that changes with time, as shown in these radio images taken over the course of three years (Pearson *et al.* 1981, *Nature* **290**, 366). The brightest (leftmost) one corresponds to the object at the center of the quasar.
- One tick mark on the map border corresponds to 20.2 light years at the distance of 3C 273. Thus the rightmost knot looks to have moved about 21 light years in only three years (!).



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Faster-than-light motion in quasar jets: an optical illusion.



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Other evidence for black holes in quasars:
apparent faster-than-light motion.

- Thus apparent speeds in excess of the speed of light can be obtained. The apparent speeds only turn out to be much in excess of the speed of light if **the actual speed of the radio-emitting knots is pretty close to the speed of light.**
- Ejection speeds in astrophysics tend to be close to the **escape speed** of the object that did the ejecting. What has escape speeds near the speed of light?
 - **Neutron stars:** but they can't produce the quasar's luminosity.
 - **Black holes:** like the one that can produce the quasar's luminosity!

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That is all for today!
See you next week on Tuesday.



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