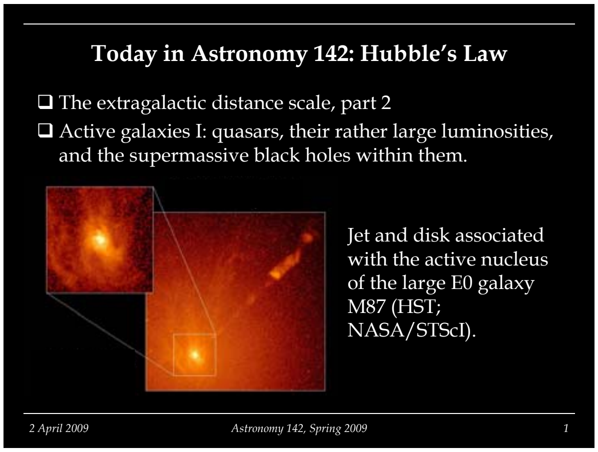
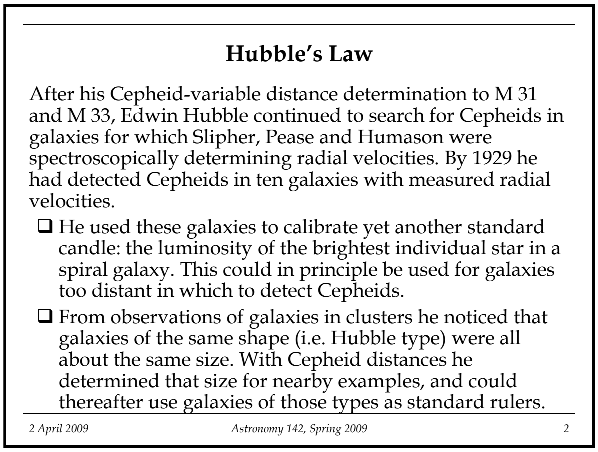


Today in Astronomy 142: Hubble's Law

- ❑ The extragalactic distance scale, part 2
- ❑ Active galaxies I: quasars, their rather large luminosities, and the supermassive black holes within them.

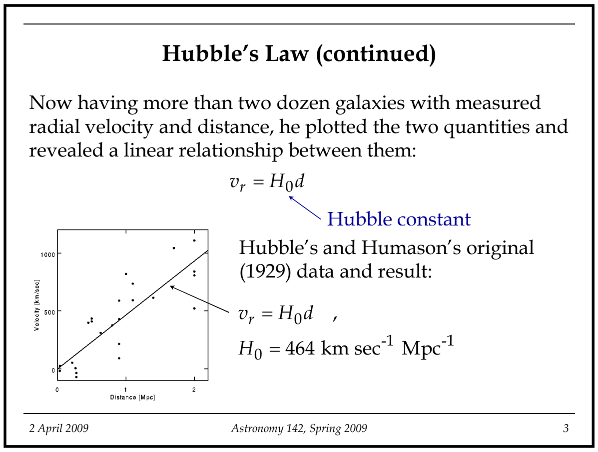
Jet and disk associated with the active nucleus of the large E0 galaxy M87 (HST; NASA/STScI).



Hubble's Law

After his Cepheid-variable distance determination to M 31 and M 33, Edwin Hubble continued to search for Cepheids in galaxies for which Slipher, Pease and Humason were spectroscopically determining radial velocities. By 1929 he had detected Cepheids in ten galaxies with measured radial velocities.

- ❑ He used these galaxies to calibrate yet another standard candle: the luminosity of the brightest individual star in a spiral galaxy. This could in principle be used for galaxies too distant in which to detect Cepheids.
- ❑ From observations of galaxies in clusters he noticed that galaxies of the same shape (i.e. Hubble type) were all about the same size. With Cepheid distances he determined that size for nearby examples, and could thereafter use galaxies of those types as standard rulers.



Hubble's Law (continued)

Now having more than two dozen galaxies with measured radial velocity and distance, he plotted the two quantities and revealed a linear relationship between them:

$$v_r = H_0 d$$

Hubble constant

Hubble's and Humason's original (1929) data and result:

$v_r = H_0 d$,

$H_0 = 464$ km sec^{-1} Mpc^{-1}

The extragalactic distance scale, part 2

Hubble realized immediately that this relation would be the ultimate distance indicator, since the radial velocity of a galaxy could be determined completely independently of brightness or shape (for which standard candles or rulers need to be used).

- Though the form he determined for the law was correct, the value Hubble inferred for H_0 was alarmingly large, enough to cause concern even then. (It made the Milky Way look like the largest galaxy in the Universe, by far.) This was because…
- the Cepheid calibration was still corrupted by the then-unknown effects of extinction and multiple populations of pulsating stars. As we have noted, Trumpler (1930) and Baade (1944, 1954) eventually cleared it up.
- Hubble's Law also, of course, implies that **the Universe expands**. We will soon spend two weeks discussing this aspect of the result, but for a while we'll use it simply as a way to measure distances to galaxies.

The next standard candle

Nowadays one can detect classical Cepheids in galaxies tens of Mpc away, using the Hubble Space Telescope. This is far enough to make a 10%-precision determination of the Hubble constant, but better yet…

- At those distances we find significant numbers of galaxies in which **Type Ia supernovae** have **also** been observed.
- SNe Ia differ observationally from core-collapse supernovae (SNe II) by the shape of their light curves and their spectra when near maximum light, and from these differences a different explosive process has been inferred.

NGC 3370 (Cepheids and SN Ia)

The next standard candle (continued)

SNe Ia appear to happen in close binary systems with C-O white dwarfs whose masses are near the Chandrasekhar maximum, but are still accreting mass from the other star.

- As the maximum is approached, the temperature of the nondegenerate protons increases, and C-C fusion starts.
- But the electron-degeneracy-pressure supported star does not expand in response to the additional heat, so…
- the fusion becomes a runaway thermonuclear deflagration that consumes the whole star; it explodes violently and leaves no remnant. And it's *very* bright, similar to SN II.
- Because of the constancy of the Chandra maximum, the WDs all have nearly the same mass when they explode, and the same "yield": SNe Ia are **standard bombs**.

The extragalactic distance scale, part 2 (continued)

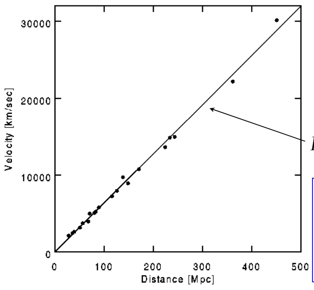
So here are the next rungs of the distance ladder:

6. Observe galaxies that have both Cepheids and SNe Ia, measuring the distance to the supernovae with the Cepheids. This calibrates the SNe Ia as standard candles. (Seems to help if multiwavelength SN Ia light curves are employed; see Riess, Press and Kirshner 1996.)
7. Then measure distances to more distant galaxies with SNe Ia; measure the radial velocities too, and derive the Hubble constant H_0 from these values.
8. Henceforth, one can convert any galaxy's radial velocity that does not have a substantial random component (e.g. from motion within a cluster) to a distance *via* $d = v_r / H_0$.

Modern values of the Hubble constant

$H_0 = 57 \pm 4$ km sec^{-1} Mpc^{-1}	Sandage et al. (1996), using HST Cepheid galaxy distances to calibrate supernovae of type Ia (SNe Ia) as standard candles.
$H_0 = 64 \pm 3$ km sec^{-1} Mpc^{-1}	Riess, Press and Kirshner (1996), using Cepheids and multicolor light curves for SNe Ia.
$H_0 = 69 \pm 7$ km sec^{-1} Mpc^{-1}	The HST Extragalactic Distance Scale Key Project team, using Cepheid distances for galaxies in nearby clusters (e.g. Ferrarese et al. 2000).

SN Ia Hubble-constant determination



From Riess, Press and Kirshner (1996)

$H_0 = 64 \pm 3$ km sec^{-1} Mpc^{-1}

In AST 142, we will use

$$H_0 = 65 \text{ km sec}^{-1} \text{ Mpc}^{-1} = 20 \text{ km sec}^{-1} \text{ Mly}^{-1}$$

Redshift and radial velocity

In analogy with the form of the nonrelativistic Doppler shift expressed in terms of wavelengths,

$$\frac{\lambda-\lambda_0}{\lambda_0}=\frac{v_r}{c} \quad\rightarrow\quad \lambda=\lambda_0\left(1+\frac{v_r}{c}\right)$$

astronomers define the **redshift**, z:

$$\lambda=\lambda_0\left(1+z\right) \quad\rightarrow\quad z=\frac{\lambda-\lambda_0}{\lambda_0} \quad .$$

This form is used for all radial velocities, even if they're close to the speed of light; remember when you use it that cz is only $\approx v_r$ if $v_r \ll c$.

The largest redshift measured for a galaxy to date is $z = 6.4$. The largest in Hubble's original sample was $z = 0.004$.

Active galaxies: the discovery of quasars

- ☐ Discovered by radio astronomers: small, "starlike," bright sources of radio emission (1950s).
- ☐ Identified by visible-light astronomers as stars with extremely peculiar spectra (1950s).
- ☐ Actually reminiscent of the bright, blue, star-like galaxy nuclei of some spiral galaxies discovered in the 1940s by Carl Seyfert (and earlier by Milton Humason), but this went unnoticed at the time because no "nebulosity" was ever photographed in the surroundings of quasars.
- ☐ Maarten Schmidt (1963) was the first to realize that the spectrum of one quasar, 3C 273, is fairly normal, but seen with a radial velocity of about 48,000 km/sec (that is, $z = 0.16$).

Discovery of quasars (continued)

- ☐ Thus, *vide* Hubble's Law, the quasars are very **distant**. 3C 273 lies at

$$d = v_r/H_0 = 740\text{ Mpc} = 2.4\text{ Gly}\,.$$

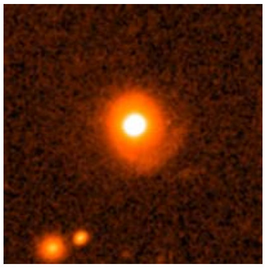
- ☐ Yet they are **bright**: the quasars are extremely powerful. 3C 273 has an average luminosity of $10^{12} L_{\odot}$, almost 100 times that of the entire Milky Way and similar to that of the very brightest galaxies known.
- ☐ Observations show that quasars consist of a bright core and a long, thin jet, and that the cores are very **small**.
  - Radio observations show directly that most of the brightness in 3C 273 is concentrated in a space smaller than 3 pc in diameter.

Maarten Schmidt in 1963

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. Obedience to cause-and-effect means that its power is actually concentrated in a region with **diameter no larger than one light-month** (= 7.9×10^{16} cm = 5300 AU). Some of the more violent quasars vary substantially in an hour (1 light-hour = 7.2 AU).
- In the 1980s, the suspicions of most astronomers were confirmed when imaging observations with CCD cameras revealed that quasars are the nuclei of galaxies. Until good CCDs were available, the "fuzz" comprising the galaxy surrounding each quasar was lost in the glare of the quasar.

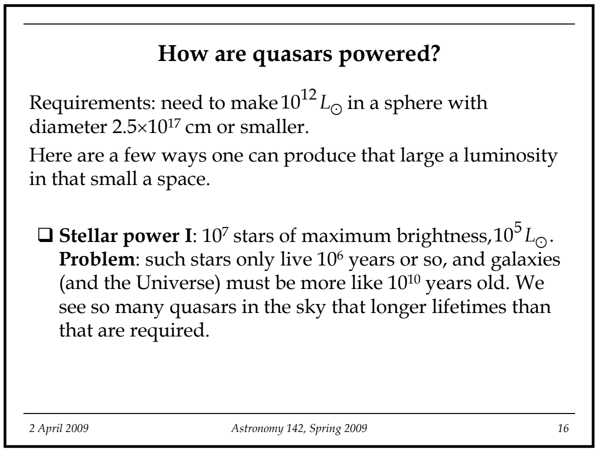
A quasar host galaxy at z = 0.33



A New Technology Telescope (NTT) image of the host galaxy of a quasar at a redshift of 0.33. The quasar's image is heavily overexposed, in order to show the galaxy (Roennback, van Groningen, Wanders and Orndahl 1996).

Quasars and host galaxies

HST observations: Bahcall and Disney 1996.

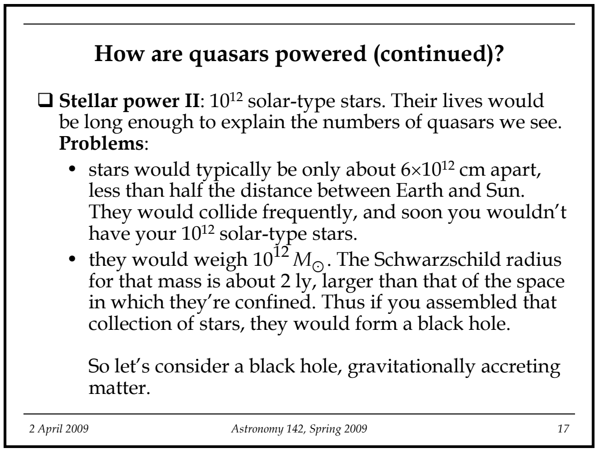


How are quasars powered?

Requirements: need to make $10^{12}\,L_\odot$ in a sphere with diameter 2.5×10^{17} cm or smaller.

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

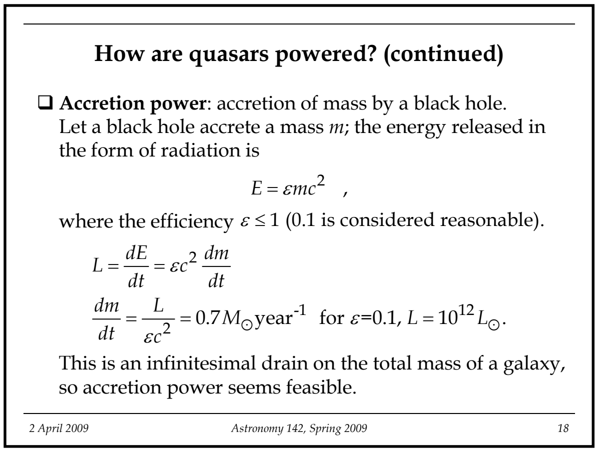
- ☐ **Stellar power I**: 10^7 stars of maximum brightness, $10^5\,L_\odot$. **Problem**: such stars only live 10^6 years or so, and galaxies (and the Universe) must be more like 10^{10} years old. We see so many quasars in the sky that longer lifetimes than that are required.



How are quasars powered (continued)?

- ☐ **Stellar power II**: 10^{12} solar-type stars. Their lives would be long enough to explain the numbers of quasars we see. **Problems**:
  - stars would typically be only about 6×10^{12} cm apart, less than half the distance between Earth and Sun. They would collide frequently, and soon you wouldn't have your 10^{12} solar-type stars.
  - they would weigh $10^{12}\,M_\odot$. The Schwarzschild radius for that mass is about 2 ly, larger than that of the space in which they're confined. Thus if you assembled that collection of stars, they would form a black hole.

  So let's consider a black hole, gravitationally accreting matter.



How are quasars powered? (continued)

- ☐ **Accretion power**: accretion of mass by a black hole. Let a black hole accrete a mass *m*; the energy released in the form of radiation is

$$E = \varepsilon m c^2 \quad ,$$

where the efficiency $\varepsilon \le 1$ (0.1 is considered reasonable).

$$L = \frac{dE}{dt} = \varepsilon c^2 \frac{dm}{dt}$$

$$\frac{dm}{dt} = \frac{L}{\varepsilon c^2} = 0.7\,M_\odot\,\text{year}^{-1} \quad \text{for } \varepsilon\text{=0.1, } L = 10^{12}\,L_\odot .$$

This is an infinitesimal drain on the total mass of a galaxy, so accretion power seems feasible.

Will any black hole do?

Not really. The large luminosity itself can stop the accretion by the outward pressure the light exerts on infalling material.

- ❑ So accretion will be able to take place steadily only if the force of gravity the black hole exerts on the infalling material exceeds the force from radiation pressure.
- ❑ Thus the more massive the black hole, the larger the luminosity it's capable of emitting by accretion.
- ❑ The maximum luminosity *via* accretion, called the **Eddington luminosity**, is that for which the forces of gravity and radiation pressure balance.

We shall now derive a formula for the Eddington luminosity to see what it has to say about quasar black holes. Most of you have already seen this in AST 111. For it is written:

Radiation and the motion of Solar-system bodies

So far, we have only considered the energy brought to the planets and planetesimals by sunlight, but the sunlight brings momentum, too: photons have energy and momentum given by

$$E_{\text{photon}} = hc/\lambda \quad , \quad p_{\text{photon}} = h/\lambda = E_{\text{photon}}/c$$

and force, of course, is the rate of change of momentum, $\boldsymbol{F} = d\boldsymbol{p}/dt$.

- ❑ The forces caused by the momentum of sunlight are small and can usually be neglected if the body in question is very massive and/or a long way from the Sun.
- ❑ But the forces of radiation can be significant for near-Earth and main belt asteroids and can dominate all other forces for very small particles like interplanetary dust grains.

Radiation and the motion of Solar-system bodies (continued)

Consider first a small black body (radius $R \ll r, \gg \lambda$) a distance r from a star with luminosity L. As we have seen many times, the power it absorbs from starlight is

$$P_{\text{in}} = \frac{dE_{\text{in}}}{dt} = \frac{L}{4\pi r^2}\boxed{\pi R^2}$$

Area of shadow (cross section)

and thus the rate at which it absorbs momentum is

$$\frac{dp_{\text{in}}}{dt} = \frac{1}{c}\frac{dE_{\text{in}}}{dt} = \frac{LR^2}{4cr^2}$$

Since it emits blackbody radiation equally in all directions (net momentum zero), there is a force on the body:

$$F_{\text{rad}} = \frac{dp_{\text{in}}}{dt} = \frac{LR^2}{4cr^2} \quad .$$

The Eddington luminosity

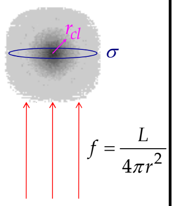
Now, instead of solid particles, we need the radiation pressure on gas, which is mostly hydrogen. So what are the areas of the electron and proton shadows, $\pi R^2 \equiv \sigma_e$ or σ_p ?

- ❑ "Classical radius:" assume rest energy comes from electrostatic potential energy.

$$mc^2 = \frac{e^2}{r_{cl}}$$

$$R \approx r_{cl} = \frac{e^2}{mc^2} = \begin{cases} 2.8\times10^{-13} \text{ cm } (e^-) \\ 1.5\times10^{-16} \text{ cm } (p^+) \end{cases}$$

$$\sigma \approx \pi r_{cl}^2 = \frac{\pi e^4}{m^2 c^4}$$



The Eddington luminosity (continued)

- ❑ Clearly most of the force is exerted on the electrons.
- ❑ Done more carefully, quantum-mechanically:

$$\sigma_e = \frac{8}{3}\pi r_{cl,e}^2 = \frac{8\pi e^4}{3m_e^2 c^4} \qquad \textbf{Thomson cross section}$$

$$F_{\text{rad},\,e} = \frac{dp_{\text{in}}}{dt} = \frac{L\sigma_e}{4\pi c r^2} = \frac{2r_e^2 L}{3cr^2} = \frac{2e^4 L}{3m_e^2 c^5 r^2}$$

- ❑ Each electron will drag a proton with it, whether these particles are bound in an atom or reside in ionized gas, because matter on macroscopic scales has equal numbers of positive and negative charges and the electrostatic force between them is strong.

The Eddington luminosity (continued)

- ❑ Similarly, each proton will drag an electron with it. The gravitational force exerted by the black hole on each proton is of course much larger than that on an electron.
- ❑ Accretion takes place if $F_{\text{grav},\,p} + F_{\text{grav},\,e} > F_{\text{rad},\,p} + F_{\text{rad},\,e}$ or, to good approximation, $F_{\text{grav},\,p} > F_{\text{rad},\,e}$.
- ❑ Thus in order to accrete while shining at luminosity L, the mass M must be such that $GMm_p/r^2 > 2e^4L/3m_e^2c^5r^2$.

$$\text{Given } M: \quad L < \boxed{L_E = \frac{3GMm_p m_e^2 c^5}{2e^4}} \qquad \textbf{Eddington luminosity}$$

$$\text{Given } L: \quad M > \frac{2e^4 L}{3Gm_p m_e^2 c^5}$$

Quasar black holes have to be supermassive

The Eddington luminosity is the maximum luminosity that a body with mass M can produce by accretion.

Now consider a typical quasar like 3C 273, with $L = 10^{12} L_\odot$.

$$M > \frac{2e^4 L}{3Gm_p m_e^2 c^5} = 3\times 10^7\, M_\odot$$

Supermassive black hole required!

- ❑ At least ten times larger than the Milky Way's central BH.
- ❑ There are quasars with luminosities as large as $L = 10^{14} L_\odot$; thus we should expect to find central black holes well in excess of $10^9\, M_\odot$: equivalent to the mass of a good-size galaxy.
- ❑ The event-horizon radius of the minimum-mass black hole that would power 3C273: $R_{\mathrm{Sch}} = 2GM/c^2 = 0.6\mathrm{AU}$.

Quasar black holes have to be supermassive (concluded)

Clearly such a black hole is quite different in origin from those we considered earlier this semester: since stars don't come any larger than a little over $100 M_\odot$, these couldn't have formed from stellar collapse.

- ❑ The origin of supermassive black holes is in fact not yet understood very well. Leading models involve the interaction of galaxies and the transfer of interstellar matter between them during the interaction, as we shall discuss next week.
- ❑ Observational consequences of supermassive BHs in galaxy nuclei: material within a galaxy that passes close to a black hole like this should exhibit very large (even relativistic) speeds, that should show up in Doppler shifts and proper motions.