Today in Astronomy 142: farther

- Hubble's Law
- Active galaxies I: quasars, their rather large luminosities, and the supermassive black holes within them.

M106, a.k.a. NGC 4258: active galaxy, and lynchpin of the cosmic distance scale. Image by R Jay Gabany and the Hubble Heritage Team; processing by Robert Gendler (NASA/ESA/STScI).

Hubble's Law

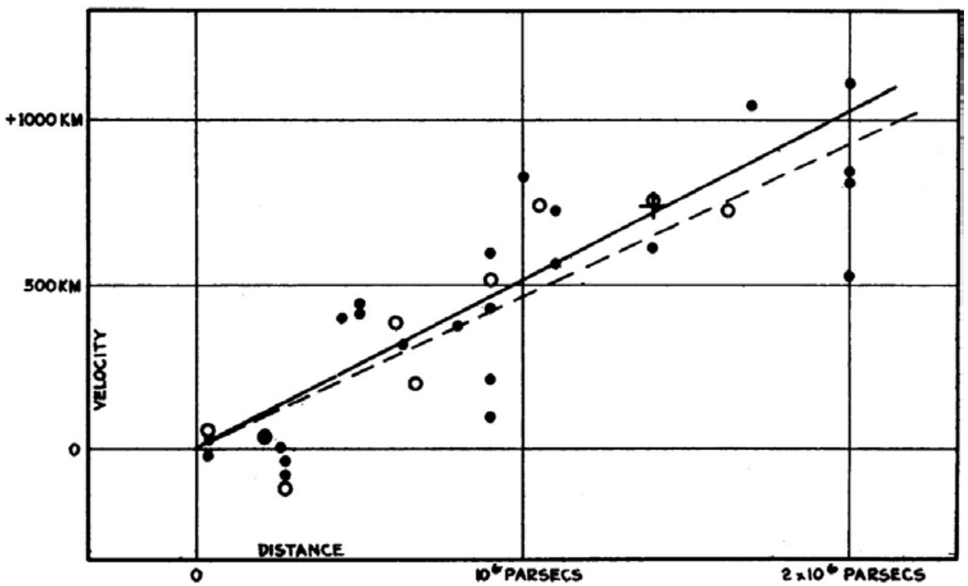
After his Cepheid-variable distance determination to M 31 and M 33, Edwin Hubble continued to search for Cepheids in galaxies for which Slipher, Pease and Humason were spectroscopically determining radial velocities. By 1929 he had detected Cepheids in ten galaxies with measured radial velocities.

- 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:

$$v_r = H_0 d \qquad \textbf{Hubble's Law}$$



Hubble published his results over the course of a few years, with this 1929 compendium the most famous and widely cited:

$$v_r = Kd \quad ,$$

$$K = 500 \text{ km sec}^{-1} \text{ Mpc}^{-1}.$$

Hubble's Law (continued)

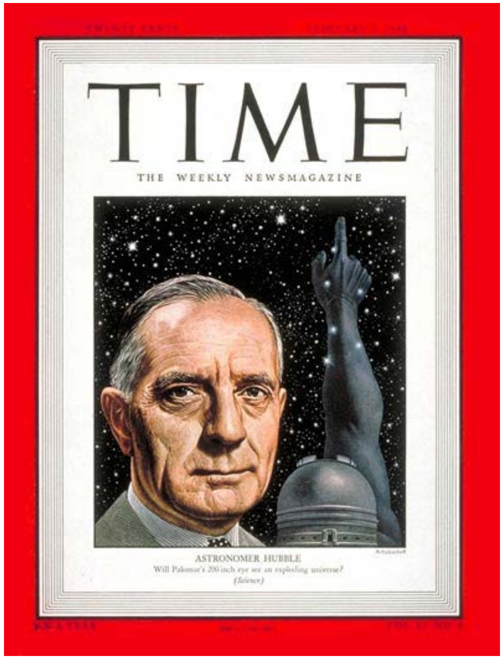
Hubble realized immediately that this relation would be **the ultimate distance indicator**, since **radial velocity of a galaxy can be determined completely independently of brightness or shape** (for which standard candles or rulers need to be used).

- 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, among other shortcomings, was pointed out by Oort (1931), who obtained a much smaller H_0 in his own reanalysis of the data.

Hubble's Law (continued)

- It made the Universe ~2 Gyr old, less than the oldest radiometric ages of terrestrial rocks, ~3 Gyr.

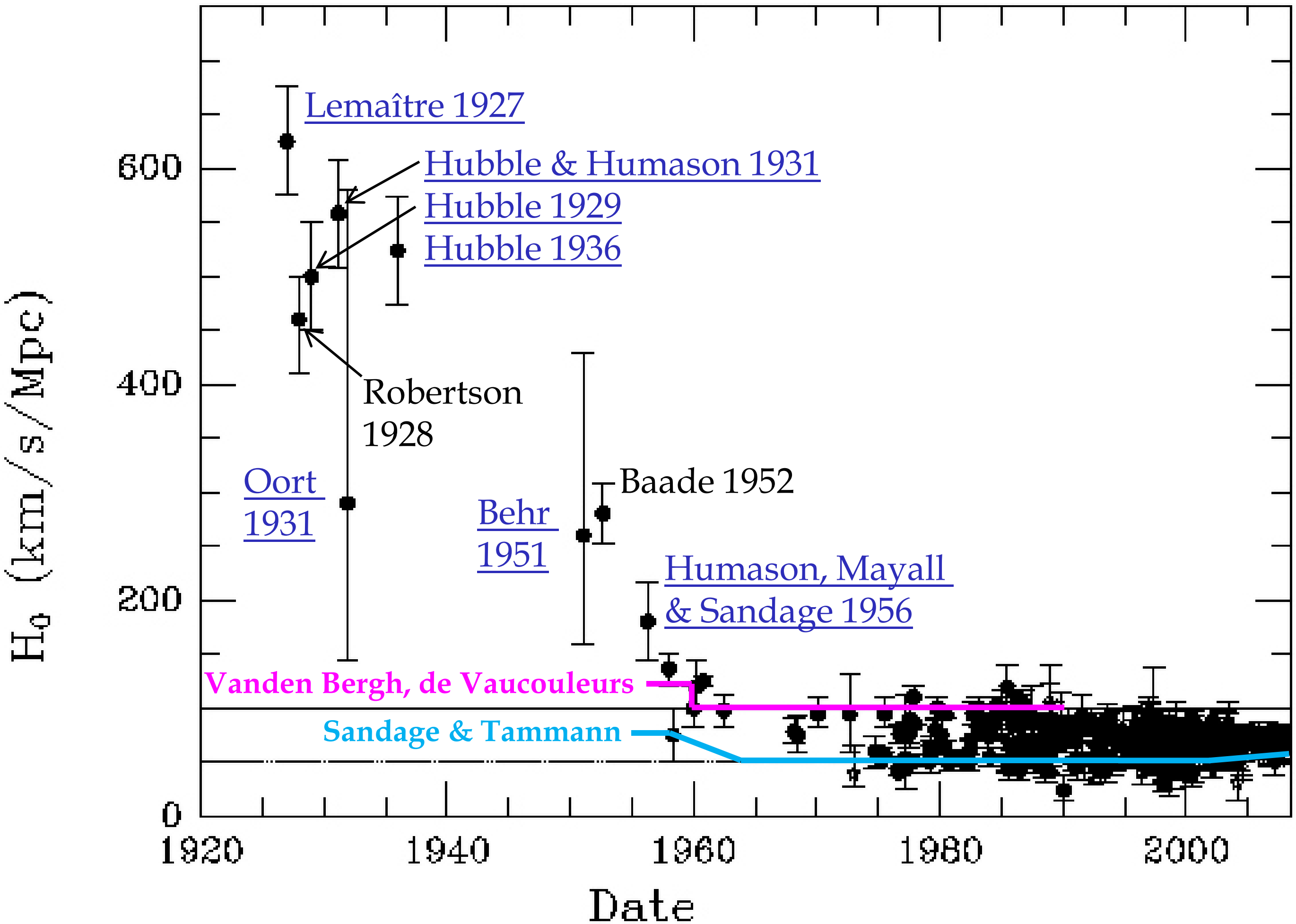
❑ This was because the Cepheid calibration was still corrupted by extinction and multiple populations of pulsating stars. As we have noted, Baade (1944, 1954) eventually cleared it up.



Edwin Hubble, 1948

❑ 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 Hubble Constant through the ages

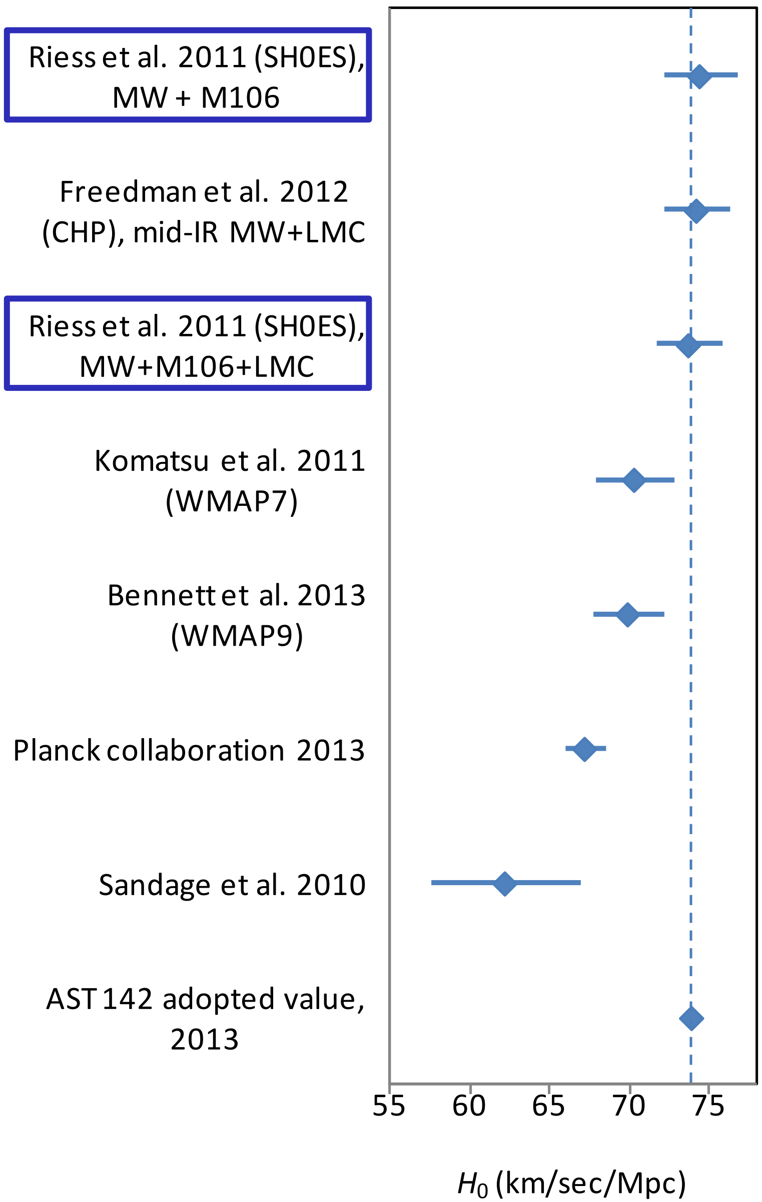


Plot from John Huchra's Hubble Constant Page.

Recent Hubble-constant measurements

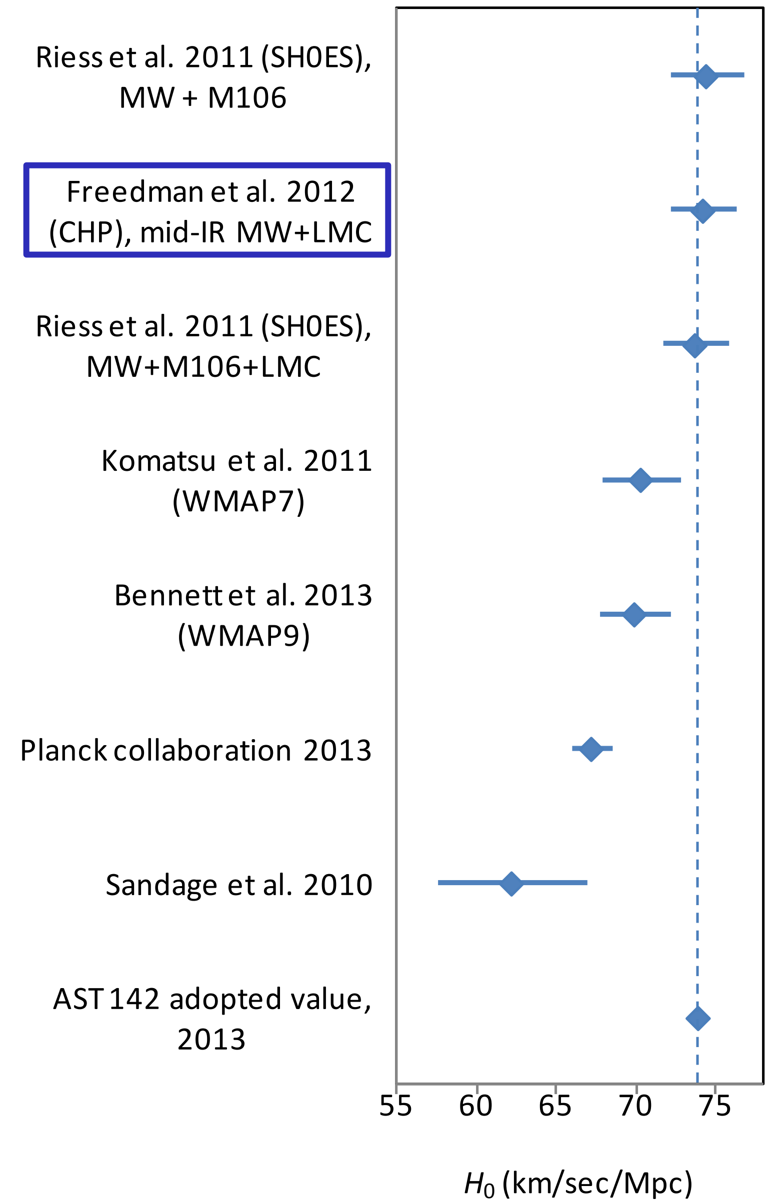
In AST 142 we will adopt the average of measurements by the SH0ES and CHP teams: ***H_0* = 74.2 km sec^{-1} Mpc^{-1}**.

- The SH0ES team's method is thoroughly modern.
  - Only standard candles used are Cepheids and SNe Ia, which now overlap considerably in distance.
  - Could even do without the LMC Cepheids: enough in MW and SN Ia hosts.



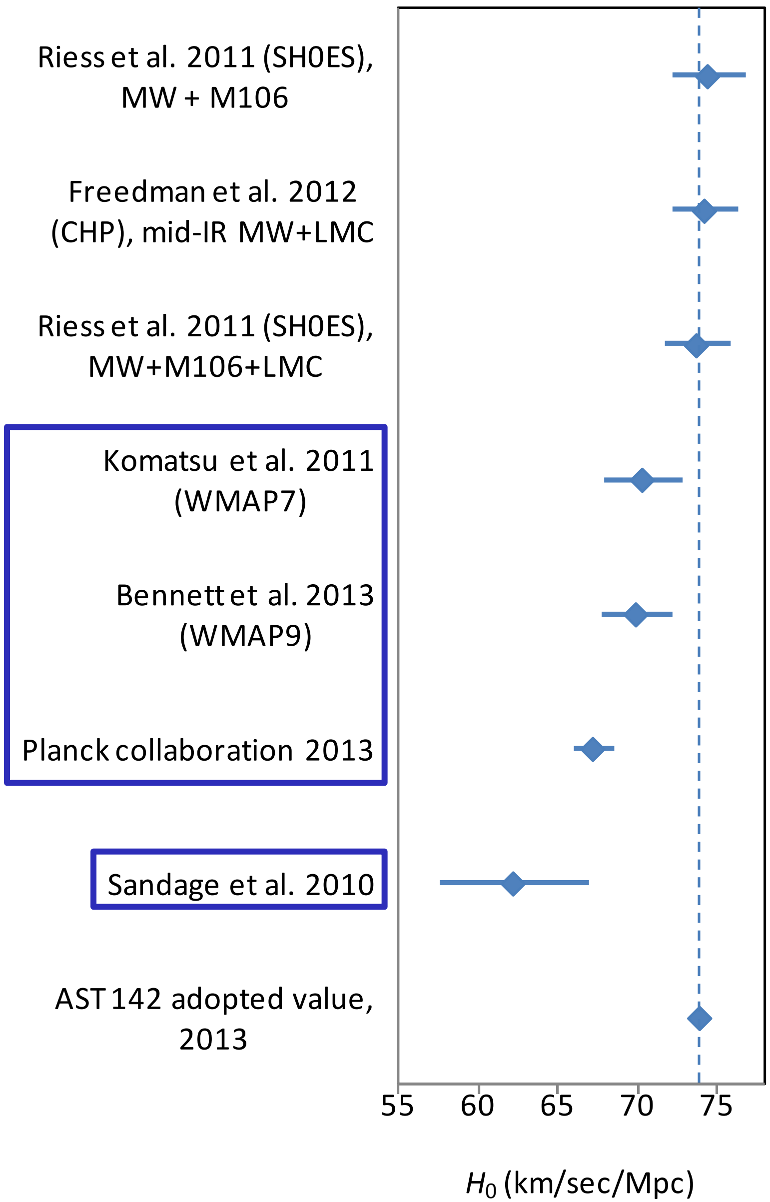
Recent Hubble-constant measurements (continued)

- The CHP team – descended from the HST Key Project – observed MW and LMC Cepheids at mid-IR wave-lengths, and used them in a reanalysis of HSTKP results.
  - HSTKP (1990s) employed four additional Cepheid-calibrated standard candles for the 20-80 Mpc range, as available SNe Ia and Cepheid distances did not overlap much.



Recent Hubble-constant measurements (continued)

- The [WMAP](#) and *[Planck](#)* missions derive H_0 indirectly from model fits to cosmic-background anisotropies, and they get smaller values.
- Despite their early adoption of SNe Ia, Sandage & Tammann et al. use 8 (!) standard candles, and multiple telescopes/instruments, including photographic emulsion. Thus they risk considerable systematic error.



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:

$$\lambda = \lambda_0 (1 + z) \quad \rightarrow \quad z = (\lambda - \lambda_0)/\lambda_0 \quad .$$

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 an unlensed galaxy to date is z = 6.4. Gravitationally-lensed galaxies go up to 8.4.
- The largest in Hubble's original sample was z = 0.004.

SN Ia apparent magnitude and distance

For convenience, apparent magnitudes of SNe Ia are often plotted, or referred to, instead of distance. The translation:

$$m_V^0 = M_V^0 + 5\log\frac{d}{10\ \mathrm{pc}} = M_V^0 + 5\log\left(\frac{d}{10\ \mathrm{pc}}\frac{10^6\ \mathrm{pc}}{\mathrm{Mpc}}\right)$$

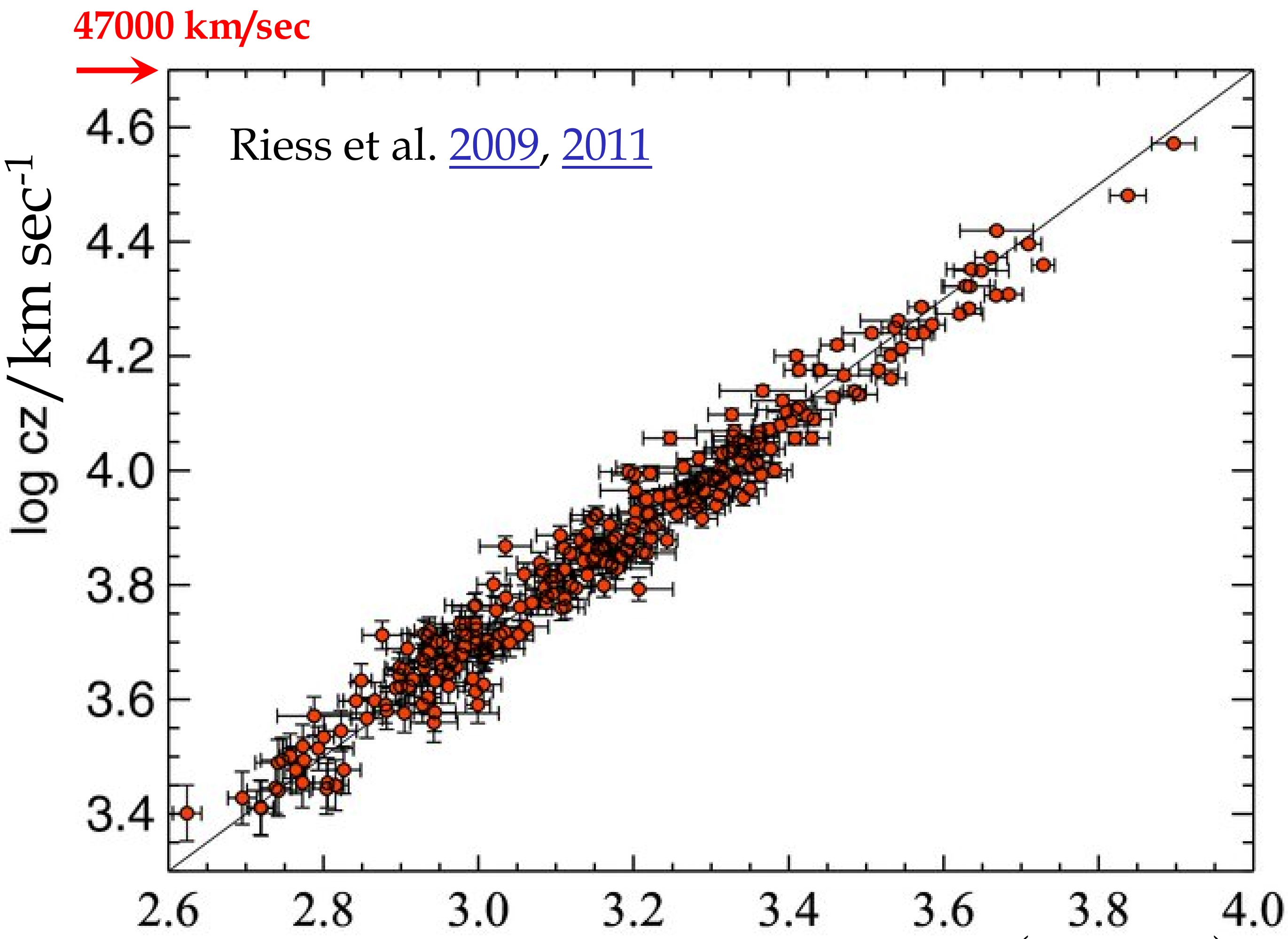
$$= M_V^0 + 5\log\frac{d}{\mathrm{Mpc}} + 25$$

$$\log\frac{d}{\mathrm{Mpc}} = 0.2m_V^0 - 0.2M_V^0 - 5$$

The absolute *V* magnitude of a SN Ia is (Riess et al. 2011):

$$M_V^0 = -19.14$$

SN Ia Hubble diagram



$= \log(d/\mathrm{Mpc}) + 0.2M_V^0 + 5$

$$v_r = cz = H_0 d$$

$$\log cz = \log H_0 + \log d$$

Intercept of the log-log plot gives H_0.

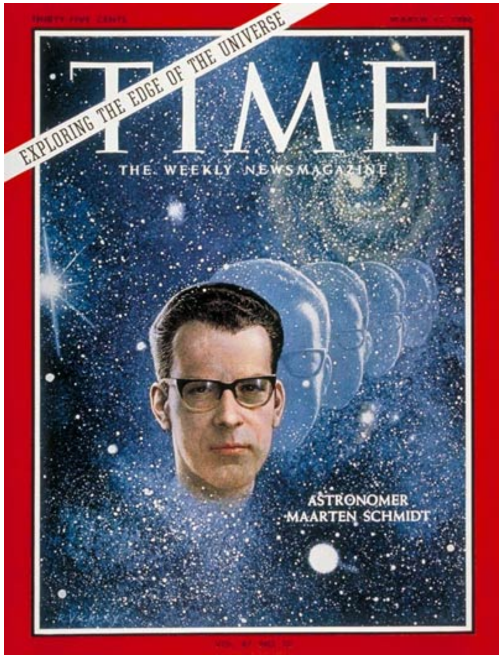
Usually cz is in km/sec and d in Mpc.

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 Milt 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 **47,470 km/sec** (that is, $z = 0.1713$).

Discovery of quasars (continued)

- Thus, *vide* Hubble's Law, the quasars are very **distant**. 3C 273 lies at $d = v_r / H_0 = 639.8$ Mpc.
- Yet they are **bright**: the quasars are very luminous. 3C 273 has a time-average luminosity of $10^{12} L_\odot$, almost 100 times that of the entire Milky Way and similar to that of the most luminous galaxies.
- 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.

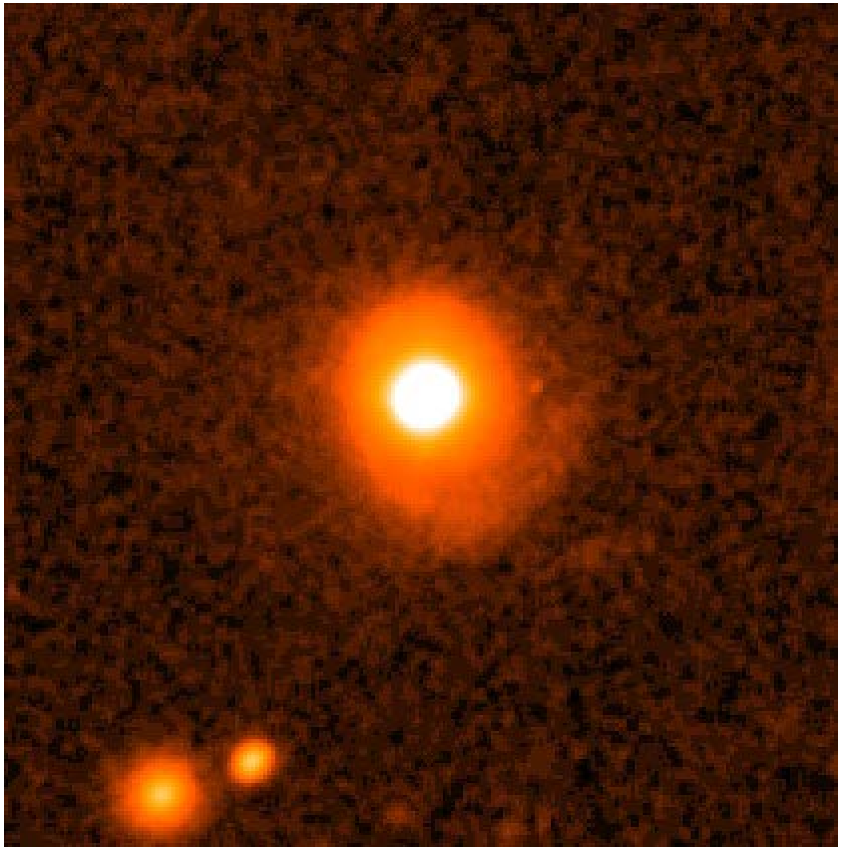


Maarten Schmidt, 1963

Discovery of quasars (continued)

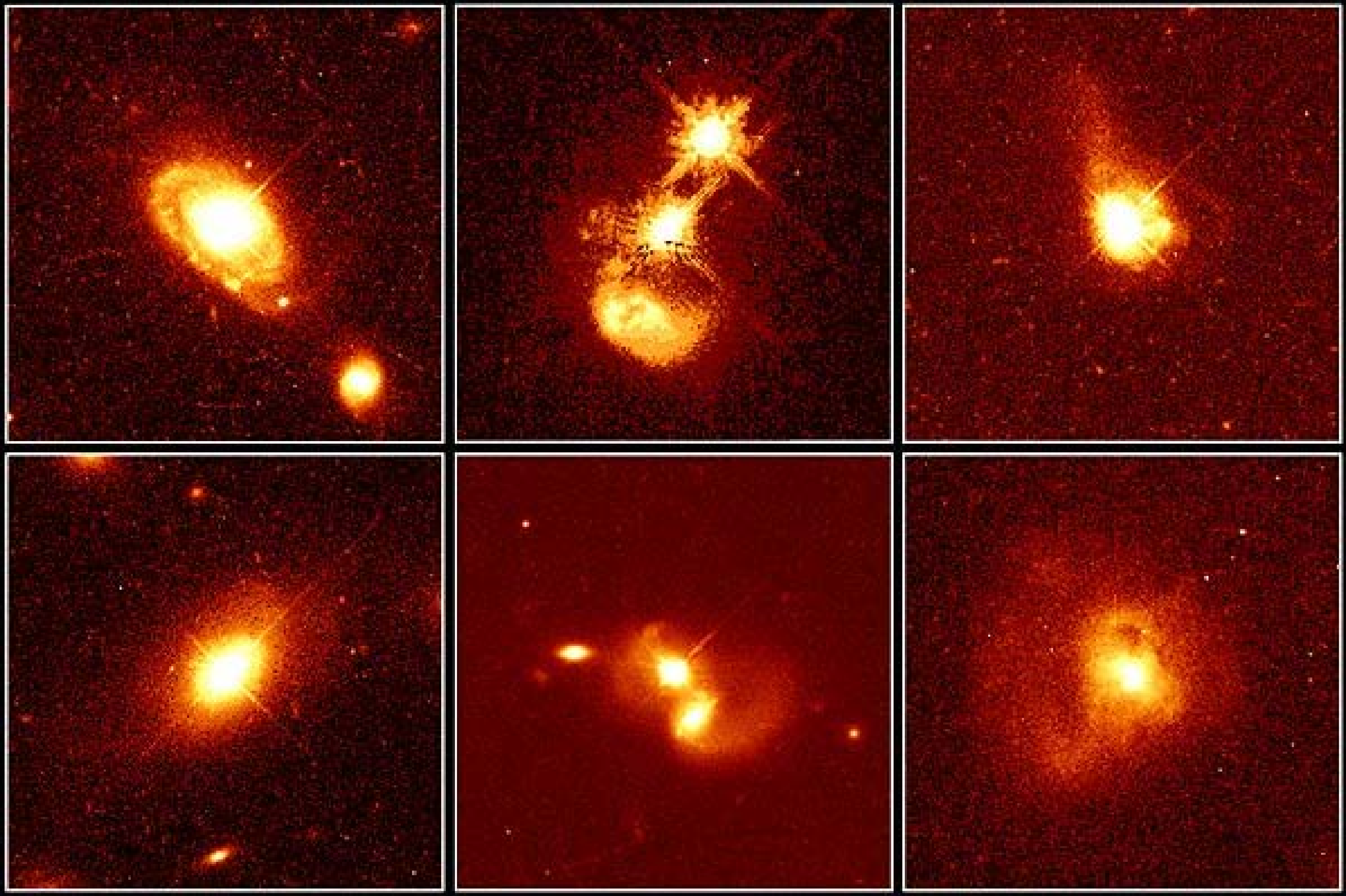
- The brightness of quasar cores is highly, and randomly, variable. 3C 273 can change in brightness by a factor of 3 in only a month. Obedience to cause-and-effect means that its power is actually concentrated in a region with **diameter no larger than one light-month** (= 7.9×10^{16} cm = 5300 AU). 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 $\varepsilon \leq 1$ (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

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

Area of shadow (cross section)

and thus the rate at which it absorbs momentum is

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

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

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

The Eddington luminosity

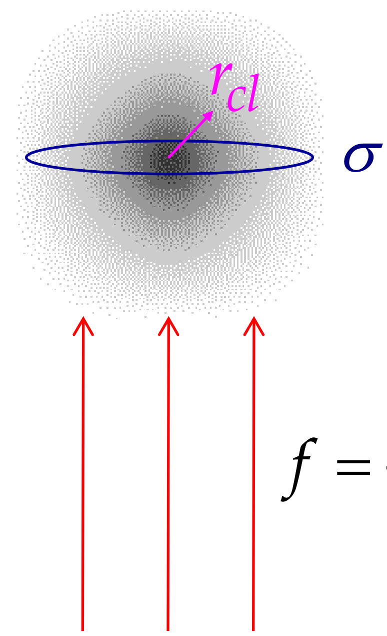
Now, instead of solid particles, we need the radiation pressure on gas, which is mostly hydrogen. So what are the areas of the electron and proton shadows, $\pi R^2 \equiv \sigma_e$ or σ_p ?

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

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

$$R \approx r_{cl} = \frac{e^2}{mc^2} = \begin{cases} 2.8 \times 10^{-13} \text{ cm } (e^-) \\ 1.5 \times 10^{-16} \text{ cm } (p^+) \end{cases}$$

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



$$f = \frac{L}{4\pi r^2}$$

The Eddington luminosity (continued)

- Clearly most of the force is exerted on the electrons.
- Done more carefully, quantum-mechanically and accounting for scattering rather than absorption:

$$\sigma_e = \frac{8}{3}\pi r_{cl,e}^2 = \frac{8\pi e^4}{3m_e^2c^4}$$ **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 $F_{\mathrm{grav},\,p} + F_{\mathrm{grav},\,e} > F_{\mathrm{rad},\,p} + F_{\mathrm{rad},\,e}$

  or, to good approximation, $F_{\mathrm{grav},\,p} > F_{\mathrm{rad},\,e}$.
- Thus in order to accrete while shining at luminosity L, the mass M must be such that $GMm_p \big/ r^2 > 2e^4 L \big/ 3m_e^2 c^5 r^2$.

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

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 $L = 10^{12} L_{\odot}$.

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

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 $100M_{\odot}$, 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.