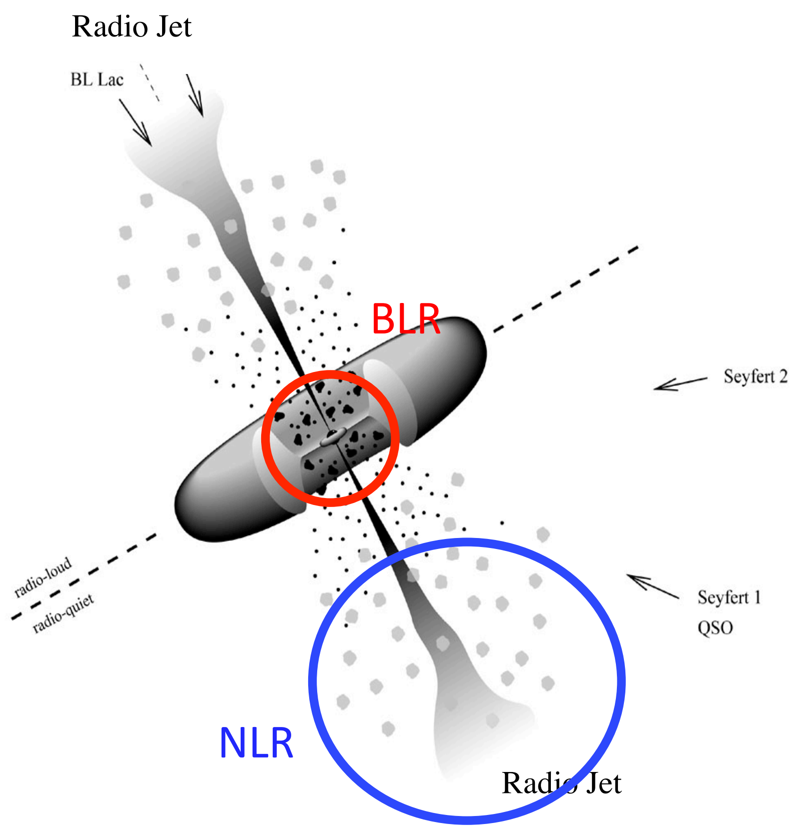
# PHYS2160 – Lecture 9 – Quasars as probes of the Universe

Last time

- Active Galaxies – Radio structures: Jets & Lobes – Superluminal Motion – Emission
- Seyfert galaxies and Quasars and their optical spectra
- Narrow-line Regions/Forbidden lines
- Broad-line Regions/Permitted Lines
- AGN/Quasar structure model …
  what we see depends on size/power of the nucleus (relative to galaxy) and orientation the line of sight.




This Time

- Quasars as “lamposts” for studying Universe
- Numbers
- Optical spectra – emission lines, absorption lines
- The Distance Ladder I

# PHYS2160 – Lecture 9 – Quasars as probes of the Universe

Quasars/QSOs

We looked last lecture at the discovery of AGN (quasars, Seyferts etc) and what they tell us about how active galaxies work.

Recall Redshift ….

$$z = \Delta\lambda/\lambda = (\lambda - \lambda_0)/\lambda = \lambda/\lambda_0 - 1$$

and since

$$\Delta\lambda/\lambda = v/c \qquad \Rightarrow \qquad v = zc$$

Hubble law then gives $v = H_0 d$ (with modern values for $H_0$=72±2 km/s/Mpc)

When the first quasar (3C273) was finally understood as being at z=0.15 (v=cz=45,000 km/s or d ~ 600 Mpc), it became clear that quasars are incredibly luminous and can be easily found at enormous distances.

Indeed for most of the 1980's and 1990's the 'distance record' for the highest redshift object known was *always* a quasar …

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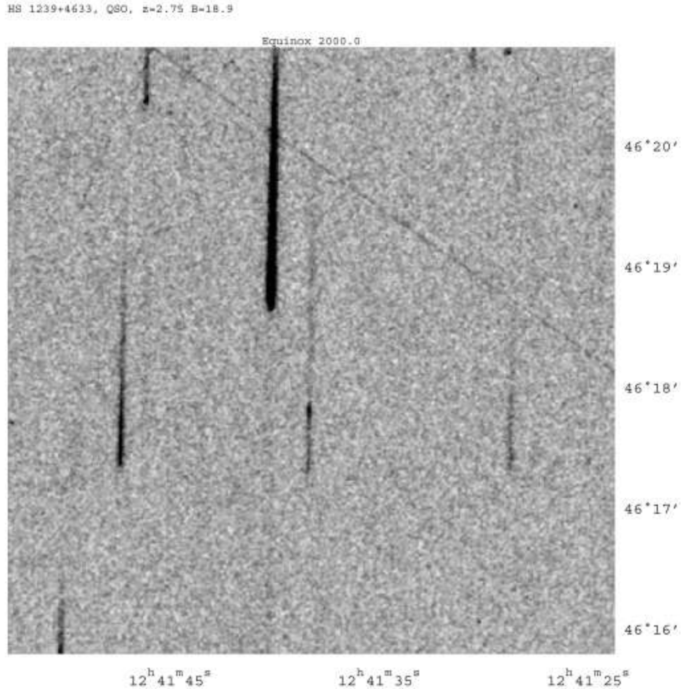
Finding Quasars

- Radio surveys looking for compact sources with either flat or steep spectra.
- Colour-colour diagrams from optical surveys (e.g. SDSS-UKIDDS data to right)
- Objective prism surveys – placing a prism in your telescope turns every image into a tiny low-resolution spectrum (e.g. Hamburg survey – data shown below)




www.hs.uni-hamburg.de/EN/For/Exg/Sur/hes/qso_**surveys**.html

Wu & Jia (2010)

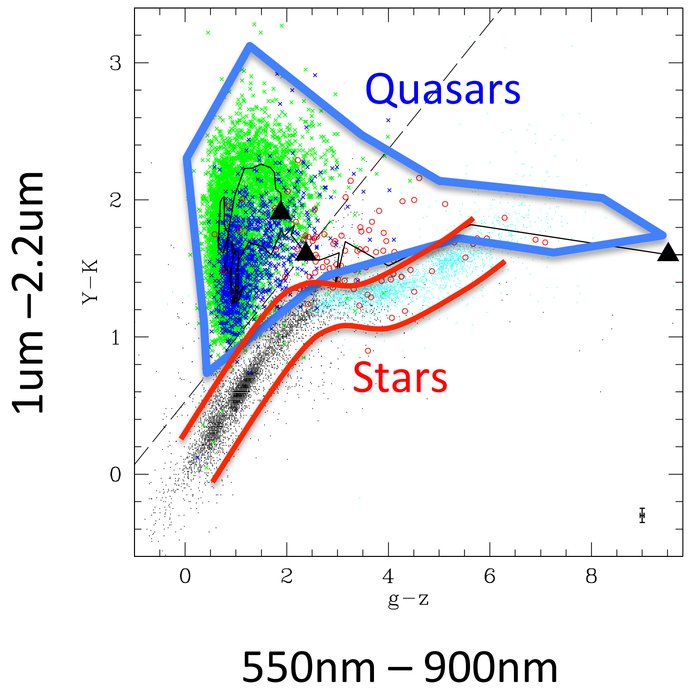



**Figure 5.** The $Y-K$ vs. $g-z$ colour-colour diagram of the SDSS-UKIDSS quasar and star samples. Green crosses, blue crosses and red circles denote quasars with $z \leqslant 2.2$, $2.2 < z \leqslant 4$ and $z > 4$, respectively. Black dots and cyan dots denote stars classified as 'STAR' and 'STAR_LATE' by SDSS spectroscopy. Dashed line indicates the separation criterion $Y-k > 0.46*(g-z)+0.53$. Solid curve is derived from the median colour-z relation (see section 3) of quasars. The solid triangles, from left to right, mark the colours of quasars with z=0.02, 4, and 5 respectively, derived from the colour-z relation. Typical error bars are shown in the lower-right corner.

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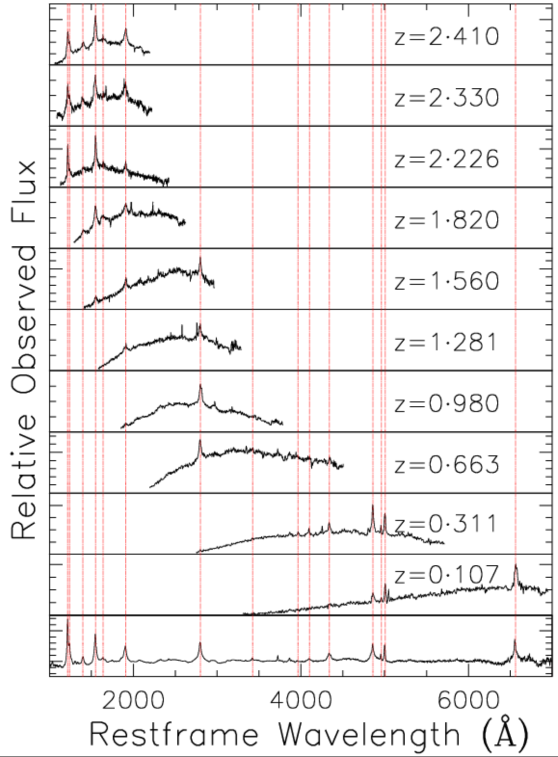
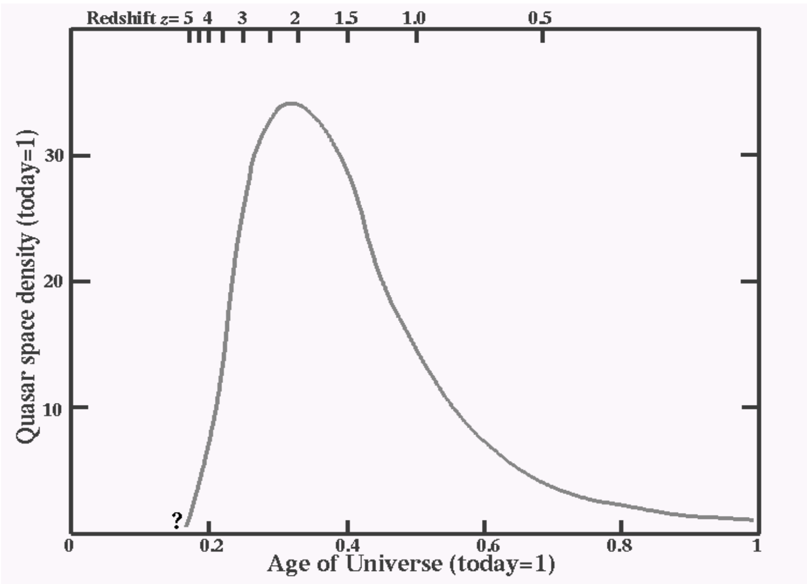


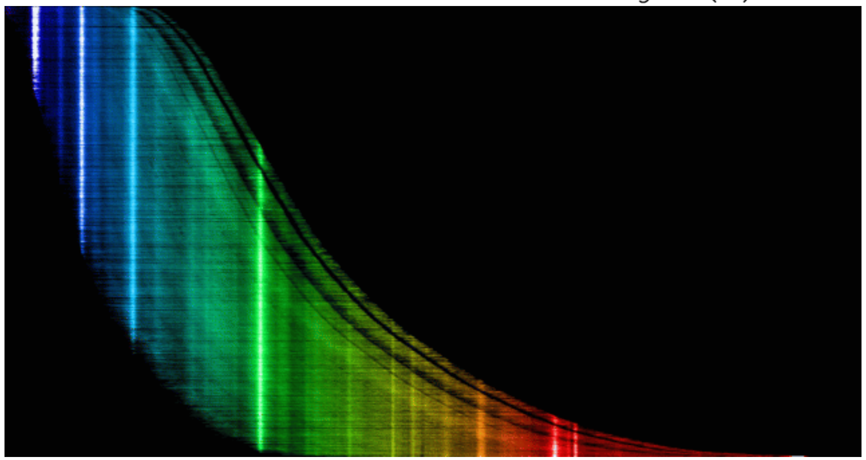

## Quasar numbers

Large surveys over the last decade (2QZ, SDSS) have enabled us to further explore the evolution of the number density of quasars over the lifetime of the Universe.

In the diagram below (due to Shaver et al. 1996, Nature 384, 449) quasar numbers are shown as a function of *co-moving coordinates* to remove cosmological effects.

Few at z>5, almost none in local Universe today, and lots in between.



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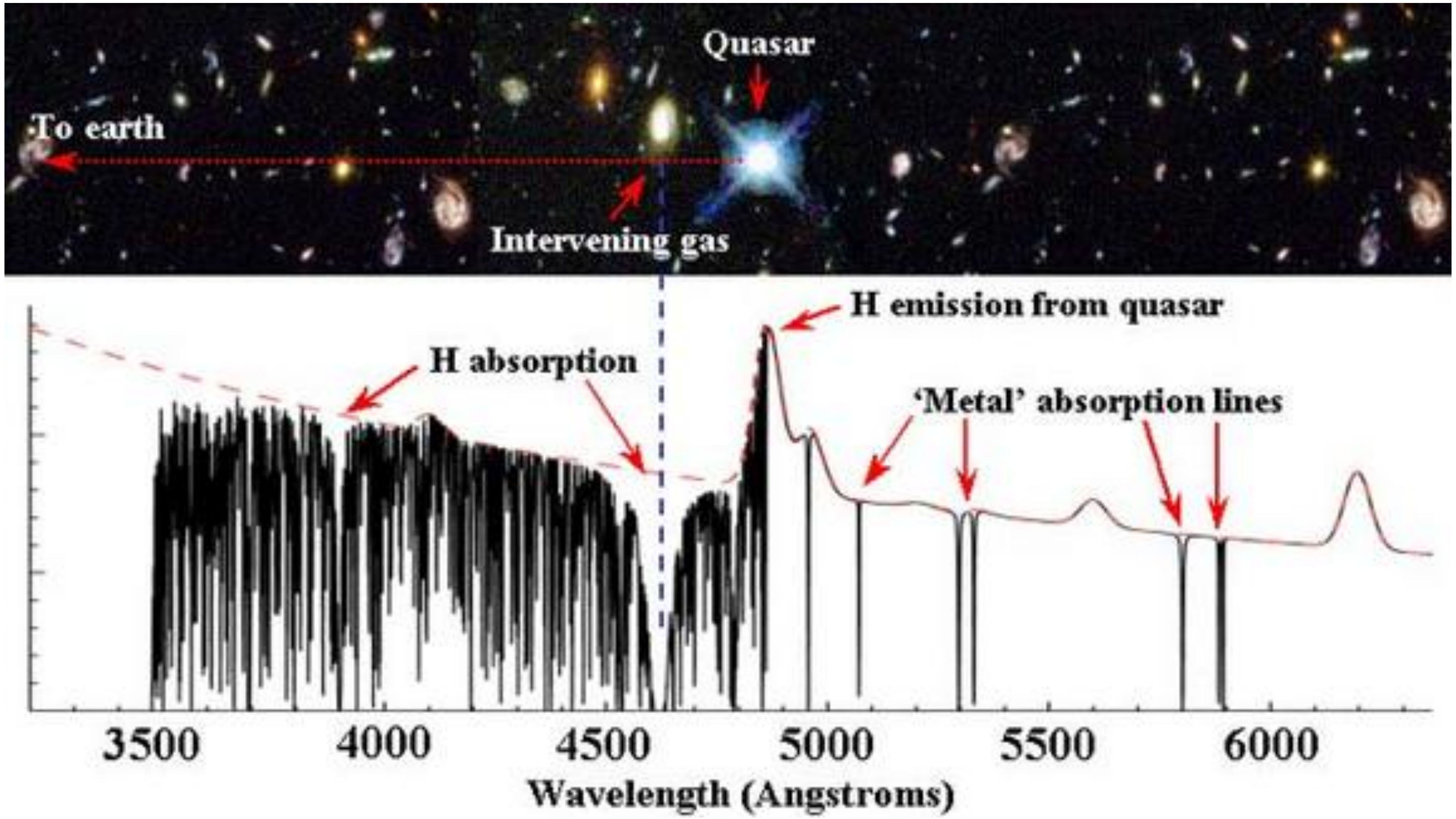
## An Exmaple Quasar Spectrum … the emission Spectrum

The emission redshift of this quasar is $z = \lambda/\lambda_0 - 1 = 4862.68 / 1215.67 - 1 = 3.0$

The continuum emission is synchrotron, and so is reasonably well modelled by by a power law.

Emission lines are broad (as noted last lecture) – few thousands of km/s. Emission lines in this example include Lyman alpha (the transition from hydrogen's first excited state back to its rest state at 1215.67), quadruply-ionised nitrogen (NV), singly ionised silicon (SiII) and triply-ionised carbon (CIV).



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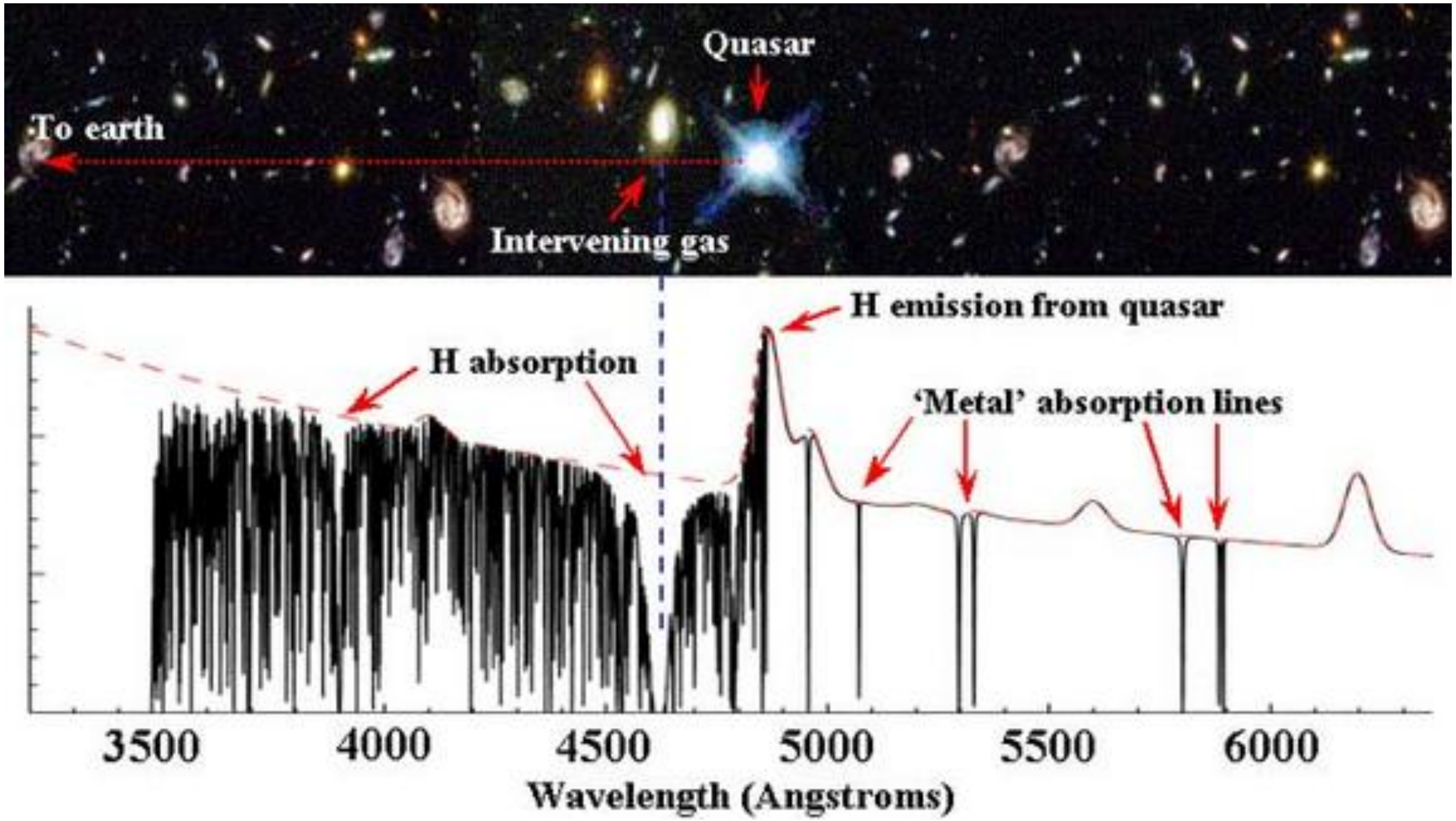
## An Example Quasar Spectrum … in a bit more detail

- Underlying unabsorbed quasar continuum
- Quasar emission lines
- A “damped” Lyman alpha absorption system (DLA) at 4620A
- A “Lyman limit” break at 3466A (wavelengths shorter than this can always ionise H).
- Multiple heavy element absorption lines + a Lyman alpha forest



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## Quasar Spectra … the absorption spectrum

The absorption spectrum enables the quasar to be used as a probe of the intervening Universe between us and the quasar.

Clouds of hydrogen along the line of sight will readily absorb in their Lyman alpha line at their individual redshifts. The sensitivity of these absorption signatures is several orders of magnitude greater than for the detection of objects by their Lyman alpha emission (since emission is isotropically emitted, while absorption only happens along the lines of sight).

The result is a detailed probe of the physics and chemistry of the early Universe.

We can characterise the density of the clouds responsible for the absorption by their *column density*, *N*, measured as the number of atoms/$cm^3$.

The systems seen get classified into a variety of types.

– Lyman-limit systems (LLSs) : $17.2 < \log N(HI) < 20.2$
– Damped Lyman alpha clouds (DLAs): $\log N(HI) > 20.2$
– Broad Absorption Line (BAL) systems: are strong absorptions seen at close to the QSO redshift, and are considered to arise from gas being emitted by the QSO itself.

# PHYS2160 – Lecture 9 – Quasars as probes of the Universe

## Quasar Summary

- Quasars/QSOs are some of the most luminous objects in the Universe.
- *The light from quasars travels through the intervening Universe, and absorption lines in quasar spectra therefore tell us about conditions between us and them.*
- Survey techniques to identify them are now quite sophisticated – known numbers of quasars now exceed 100,000. While they are uncommon at very high redshifts ($z>4$), they *can* be found (e.g. the distant quasar, ULAS J1120+0641 at $z=7.1$ around 750 million years after the big bang) and are amongst the best available probes of the very young universe.


- Damped Lyman alpha systems – deep absorptions thought to be the gas disks of young galaxies in which both Lyman alpha (i.e. H) and some heavier elements can be observed, telling us about element enrichment in the early Universe.
- Lyman alpha forest – weaker absorptions along the line of sight.
- Observations and modelling of the absorptions on the blue and red sides of Lyman alpha can probe the extent of the Inter-Galactic Medium's ionisation, and so the amount of hydrogen 'left over' and residing between galaxies *and* the source of ionising photons.

Much more on quasars as cosmological probes in Part II of the course …

# PHYS2160 – Lecture 9 – The Distance Ladder - I

Galaxy Redshifts

By 1916 Vesto Slipher had obtained spectra for some 50-odd galaxies – the results confounded both him and the other astronomers of the day because almost every galaxy was *redshifted!*

In the 1920's Edwin Hubble began observing these galaxies with the (then) world's most powerful telescope – the 100 inch reflector at Mt Wilson, near Los Angeles.

Hubble had already used a class of variable stars called "Cepheids" (discovered to be useful as standard candles in 1908 by Henrietta Leavitt) to determine that the Andromeda galaxy could not be part of the Milky Way. **And** then classified different types of galaxies using his "tuning fork" system.

In the 1920s he began using Cepheid distances to estimate the maximum brightness that stars had in nearby galaxies. And then used the observed apparent magnitude of the brightest stars to estimate distances to more distant galaxies and compare them with Slipher's velocities.

# PHYS2160 – Lecture 9 – The Distance Ladder - I

The “Hubble Diagram”

Hubble’s results (Proceedings of the National Academy of Sciences, 15, 1929 – replotted below) were remarkable – *the distances were correlated with the redshifted velocities*! If we parameterise the velocity shift with redshift, $z$

$$z = \Delta\lambda/\lambda = \lambda/\lambda_0 - 1$$

then

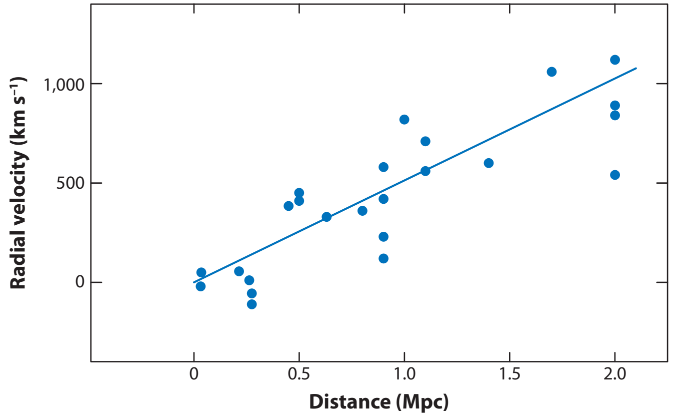
$$\Delta\lambda/\lambda = v/c$$

or

$$v = zc$$

The correlation observed can then be paramaterised with a constant $H_0$ to give the Hubble law

$$v = H_0 d$$




Freedman & Madore (2010)

**Figure 1**

Radial velocities, corrected for solar motion, plotted versus distances estimated from stars and mean luminosities of galaxies in clusters. The solid dots and line represent the solution for solar motion using individual galaxies. Hubble wrote, “The outstanding feature, however, is the possibility that the velocity-distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of space.” (Adapted from Hubble 1929a.)

Most commonly $H_0$ is given in units of km/s / Mpc. The “0” subscript is used to refer to the fact that this is the present-day value of the Hubble constant. This relation was actually predicted earlier as an outcome of General Relativity by Georges Lemaître for an expanding universe, in 1927. (A rare case of an observer who confirmed a law getting it named after him, rather than the theorist who predicted it!)

# PHYS2160 – Lecture 9 – The Distance Ladder - I

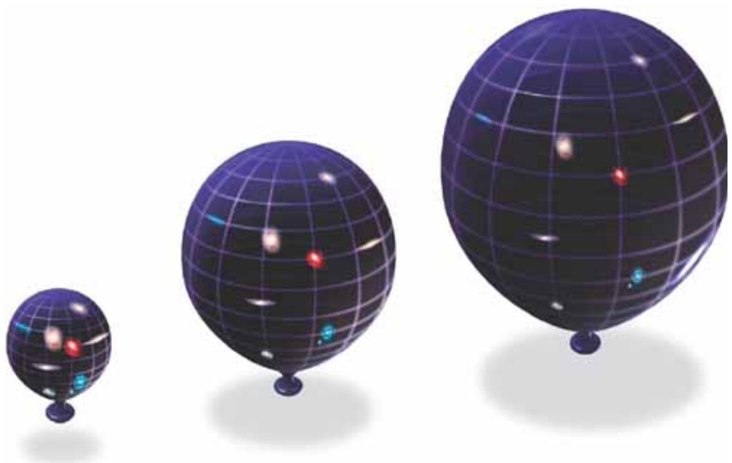
The “Hubble Diagram”

It turns out Hubble’s value for the Hubble constant (500 km/s/Mpc) was ***hugely*** wrong – in the most distant galaxies the objects he thought were the “brightest” stars were actually globular clusters. Nonetheless while the value for $H_0$ was wrong, the general principle (that distance and redshift were correlated) was correct.

The meaning of this discovery is remarkable – wherever you look in the sky, galaxies are receding away from you, and the further they are away, the faster they are receding.

At first glance this violates the “Copernican principle” that we, as observers, should not lie in a special place within the Universe!

The modern interpretation of this discovery is that our location is **not** special. Rather, **all** of space is expanding, as as a result no matter **where** you are, all directions will appear to expand away from you.



Moreover, because expansion effects light as well, the radiation is “stretched” or redshifted the further it travels.

# PHYS2160 – Lecture 9 – The Distance Ladder - I

The Hubble's Constant and the Age of the Universe

Hubble's constant provides a "first order" constraint on the age of the Universe. Assume the Universe has been expanding at a constant rate since its birth. One can then imagine running it "backwards" to an initial time.

Since $v = H_0 d$ and a velocity can be written as a distance divided by a time, then

$$H_0 d = v = d / t \quad \text{… or equivalently …} \quad t = 1 / H_0$$

So if $H$ always had value $H_0$, then $t$ would correspond to the age of the Universe. Hubble's 500km/s/Mpc implied an age of about 1.8Gyr, which was a problem even in 1930, because there was substantial geological evidence that the Earth was older than this.

Modern values of $H_0$ are closer to 70 ± 1 km/s/Mpc (though still with some scatter between the various methods that is larger than their individual uncertainties – e.g. Planck and WMAP cosmic microwave background experiments, HST Cepheid Key Project). In which case the above calculation gives a rough age of 14Gyr.

Note that this is only a first-order approximation since H will actually have varied over time since the birth of the Universe.

# PHYS2160 – Lecture 9 – The Distance Ladder - I

Measuring Distances

To measure Hubble's constant, one needs observations of two things –

galaxy velocities/redshifts (**easy**) and

galaxy distances (**hard**). [There are no tape measures in astronomy.]

To do the latter we invoke the idea of a "standard candle". If you know the intrinsic luminosity of something – or even just that the intrinsic luminosity doesn't change – you can measure distances via the $1/r^2$ law … i.e. flux $\propto L/d^2$

This is the same physical law that drives our old friend the relationship between apparent and absolute magnitude expressed as the distance modulus (DM):

$m - M = DM = 5 \log d - 5$ (where d is in pc, and so DM=0 at 10pc).

# PHYS2160 – Lecture 9 – Quasars as probes of the Universe

- References
  - http://www.2dfquasar.org and http://www.2slaq.info
  - Freedman, W. L., Madore, B. F., Gibson, B. K., et al. 2001, ApJ, 553, 47 (http://arxiv.org/abs/astroph/0012376 ); Freedman & Madore (2010), ARAA, 48, 673 (see Materials page)
- Bibliography
  - Wendy Freedman (2013) “The cosmic distance scale and H0: Past, present, and future” http://dx.doi.org/10.1017/S1743921312021047

**Useful constants, units, and formulae:**

| | | | | | | |
|---|---|---|---|---|---|---|
| Gravitational constant | $G$ | $=$ | 6.67 | $\times$ | $10^{-11}$ | N m$^2$ kg$^{-2}$ |
| Speed of light | $c$ | $=$ | 3.00 | $\times$ | $10^{8}$ | m s$^{-1}$ |
| Planck constant | $h$ | $=$ | 6.626 | $\times$ | $10^{-34}$ | J s |
| Boltzmann constant | $k$ | $=$ | 1.38 | $\times$ | $10^{-23}$ | J K$^{-1}$ |
| Stefan-Boltzmann constant | $\sigma$ | $=$ | 5.67 | $\times$ | $10^{-8}$ | W m$^{-2}$ K$^{-4}$ |
| Mass of the hydrogen atom | $m_H$ | $=$ | 1.67 | $\times$ | $10^{-27}$ | kg |

| | | | | | | |
|---|---|---|---|---|---|---|
| Solar mass | $M_\odot$ | $=$ | 1.99 | $\times$ | $10^{30}$ | kg |
| Solar radius | $R_\odot$ | $=$ | 6.96 | $\times$ | $10^{8}$ | m |
| Earth mass | $M_\oplus$ | $=$ | 5.98 | $\times$ | $10^{24}$ | kg |
| Equatorial radius of Earth | $R_\oplus$ | $=$ | 6.378 | $\times$ | $10^{6}$ | m |
| Mass of moon | $M_{moon}$ | $=$ | 7.3 | $\times$ | $10^{22}$ | kg |
| Astronomical unit | AU | $=$ | 1.496 | $\times$ | $10^{11}$ | m |
| Parsec | pc | $=$ | 3.086 | $\times$ | $10^{16}$ | m |
| Hubble's constant | $H_0$ | $=$ | 70 | | | km s$^{-1}$ Mpc$^{-1}$ |

| | | | |
|---|---|---|---|
| Distance modulus | $m - M$ | $=$ | $5 \log d - 5$ ($d$ in pc) |
| Apparent magnitude | $m_2 - m_1$ | $=$ | $2.5 \log \frac{f_1}{f_2}$ |
| For small recession velocities | $v/c$ | $=$ | $\Delta\lambda/\lambda$ |
| Definition of redshift | $(1+z)$ | $=$ | $\lambda_{obs}/\lambda_{rest}$ |
| Energy and frequency | $E$ | $=$ | $h\nu$ |
| Frequency and wavelength | $c$ | $=$ | $\nu\lambda$ |