Today in Astronomy 142: the Big Bang

- The Universe: expanding, isotropic, and homogeneous.
- Big-Bang and Steady-State cosmology.
- Alpher, Herman and decoupling.
- Penzias and Wilson and the detection of the Big Bang’s blast.

Bob Wilson (left) and Arno Penzias (right) with the horn antenna they used to discover the cosmic microwave background (Bell Laboratories).
Hubble and the structure of the Universe

When last seen (in lecture on 4 April 2013), Hubble had shown that the Universe expands, according to

\[ v_r = H_0 d. \]

Two more of Hubble’s conclusions about the distribution of galaxies in the Universe, based on a huge collection of observations with the world’s largest telescopes during the 1920s and early 1930s (Hubble 1934):

- The Universe is isotropic: on large scales the distribution of galaxies on the sky looks the same in all directions, from our viewpoint.

Edwin Hubble at the Newtonian focus of the Hooker 100-inch (Life).
Hubble and the structure of the Universe (continued)

By **small scale**, here, we mean similar to or smaller than the typical distance between galaxy clusters; by **large scale**, much greater than the typical distance between clusters, but still small compared to the observed size of the Universe.

- Recall: galaxies are typically 1Mpc apart; cluster cores are typically less than a few Mpc in radius; clusters are typically 10 Mpc apart.

- Obviously the Universe is not uniform on small scales; the sky is full of stars, galaxies, and clusters of galaxies, containing mass at relatively high density, with virtually empty space in between.

- By this definition we will turn out still to be OK with the assumption of Euclidean geometry, despite what comes next…
The Hubble Space Telescope/ACS Ultra Deep Field (Beckwith et al. 2004).
Isotropy of the Universe on large scales: modern measurements

Galaxies in the Sloan Digital Sky Survey: SDSS covered 28% of the sky (3.55 ster = 11700 °²) centered on the Galactic poles, and identified all the galaxies brighter than $R = 22.2$. 

Next page
Isotropy of the Universe on large scales: modern measurements (continued)

Each dot is a galaxy; each smudge or filament a cluster or supercluster.

- Isotropy on the scale represented by these circles's diameter means that approximately the same numbers of galaxies are contained within them, no matter where on the sky we put them, which is evidently true here.
Hubble and the structure of the Universe (continued)

- The Universe is **homogeneous**: the number density of galaxies is uniform on **large scales**. In other words, the Universe looks the same from any viewpoint.

- This Hubble found by observing great numbers of galaxies in chosen parts of the sky and plotting the number per solid angle brighter than flux $f_0$, $N(f > f_0)$, as a function of $f_0$, thus seeing that

$$N(f > f_0) = Af_0^{-3/2}.$$  

(See [Homework #6](#), and the lecture notes for [19 March](#).) Nowadays you can see this in a glance, too (next page).

- Since the Universe is homogeneous and expanding, **we would see the same recession no matter where we stood**. That is, there is no unique center in space for the expansion, as in an ordinary explosion and blast wave.
Homogeneity of the Universe on large scales: modern measurements

Redshifts and color-coded luminosity (blue-red = low-high) of the galaxies in the SDSS stripes along the celestial equator, 2.5° wide, ignoring the Milky Way.

Sloan Digital Sky Survey
Homogeneity on the scale of these circles’s diameter means that approximately the same numbers of galaxies are contained within them, no matter where we put them within the Universe’s volume, which is evidently true in this picture.

Sloan Digital Sky Survey
Why the expansion looks the same from all viewpoints

In Euclidean (flat) space, \( v = dr/dt \) is along \( v \), so

\[
\nu_{BC} = \nu_{BA} - \nu_{CA} = H_0 (r_{BA} - r_{CA}) = H_0 r_{BC}.
\]

Thus observers in galaxies B and C see the same Hubble law that we do: the expansion looks the same from A, B and C.
Early post-Hubble cosmology

Theorists immediately applied Einstein’s general theory of relativity to isotropic, homogeneous, expanding universes, and revealed a problem:

- All such model universes displayed a **mass-density singularity** at the origin.
- In fact it can be proven, quite generally, that this is so ([Hawking and Penrose, 1970](#)).
- Such singularities – unphysical at first glance – *should* arouse the suspicion of theoretical physicists.
Early post-Hubble cosmology (continued)

- Accordingly, many leading cosmologists – Einstein, de Sitter, Hoyle, Gold, Burbidge, Arp, Chairman Mao – promulgated steady-state models of the Universe, in which singularities are not realized...
  - like, for example, the singularity at \( r = 0 \) for the force between two finite-size masses in Newtonian gravity.
- ... and in which the density of the Universe is constant on the (time) average despite the Hubble expansion.
  - which they did by positing steady creation of matter out of nothing, considering this violation of energy conservation less fishy than mass-density singularities.
- “Big Bang” was originally Sir Fred Hoyle’s pejorative term for models with mass-density singularities.
Early post-Hubble cosmology (continued)

- Unintimidated, those who worried less about singularities than energy conservation – notably George Gamow – adopted “Big Bang” as the short description of their class of models.

- Observational tests gradually started going in favor of Big Bang cosmology in the 1950s…
  - e.g. number counts of faint radio galaxies, which indicated a peak in the volume density of these objects in the early Universe (= higher density at earlier times and galaxy evolution).

- … but the best observational test, proposed in the late 1940s by Gamow’s students Ralph Alpher and Bob Herman, was ignored and almost forgotten.
Early post-Hubble cosmology (continued)

\[ N(f > f_0) = A f_0^{-3/2} \]

again: radio source count as a function of brightness (Pooley & Ryle 1968). If the Universe were uniform and constant in density, and galaxies never changed, a line with slope \(-3/2\) (dashed line) would have been obtained.
Alpher, Herman and Decoupling

Alpher and Herman presumed that the Universe started off very hot and dense, and cooled as it expanded, down to the very low temperature range corresponding to the darkness of the night sky.

Then A&H identified an Event undergone by the expansion at a specific temperature: **decoupling**, meaning that

- atoms could suddenly form in large quantities from free electrons and nuclei, because...
- the photons had cooled (redshifted) sufficiently during the expansion that they were incapable of ionizing atoms.
- In hydrogen, in the laboratory, this transition takes place at about $T = 3000$ K.
This event is called decoupling because…

… at temperatures above 3000 K, matter is opaque to radiation at the same (blackbody) temperature, as the average photon will be absorbed by ionization of the first neutral atom it finds.

• Thus matter and radiation are tightly coupled by ionization and recombination in the early Universe.

But, by the same token, matter below 3000 K is transparent to radiation at the same temperature.

Thus radiation and matter decouple – live separate thermodynamic lives, are no longer in equilibrium – after the Universe cools past this point.
Alpher, Herman and Decoupling (continued)

A&H realized that this means the Universe has a photosphere, just like a star does: the **decoupling surface**.

- Since the Universe is transparent after decoupling, we should be able to see all the way to the 3000 K surface.

- Since the Universe is opaque before decoupling, the surface emits like any other 3000 K black body.

- The light started off visible, but owing to our great distance of its source it would be redshifted to much longer wavelengths.

![Graph showing intensity vs. wavelength for different temperatures]

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A&H also realized that, since the decoupling surface is close to the original singularity, the light should appear isotropic to us. In analogy with a black-hole singularity:

- Light emitted from within a black hole horizon cannot escape (and therefore must fall into the singularity), no matter what direction it is emitted: all light paths within the horizon end at the singularity. (See next slide.)

- By the same token – since light can travel in either direction along these paths – light emitted from the surroundings of the singularity would seem to an observer within the horizon to arrive from all directions, rather than one particular direction. It would look as if the singularity’s surroundings filled the sky. (See the slide after next.)
Within a black-hole horizon

- Paths of light through warped space
- Singularity
- Us (emitting light)
Analogies with the Universal singularity

- Us (looking at the sky)
- Paths of light through warped space
- Singularity
- Decoupling surface
Alpher, Herman and Decoupling (continued)

Finally, A&H realized that the spectrum of redshifted blackbody radiation would appear to be that of a colder, black body (they estimated 5 K), and noted that a steady-state Universe would be incapable of producing such radiation.

- Recall:

\[
\frac{\lambda_0}{\lambda} = 1 + z \quad (z = \text{redshift}, \text{sub-0 = present time})
\]

- At decoupling surface, the energy per unit time, area, solid angle and bandwidth it emits, \( S_\lambda \), is given by the Planck function at the decoupling temperature \( T \):

\[
S_\lambda = B_\lambda (T)
\]
Alpher, Herman and Decoupling (continued)

Other quantities in small bandwidth $d\lambda$ at wavelength $\lambda$:

Energy density

$$d u_\lambda = \frac{4\pi}{c} B_\lambda (T) d\lambda$$

Photon number density

$$dn_\lambda = \frac{4\pi}{hc} \frac{\lambda}{B_\lambda (T)} d\lambda$$

Number of photons in cube $\ell$ on a side

$$dN_\lambda = \frac{4\pi \ell^3}{hc} \frac{\lambda}{B_\lambda (T)} d\lambda$$

Same as for a present-day cube $\ell_0$ on a side.

Thus we can obtain the present, observed spectrum of the decoupling surface, $S_{\lambda_0}$.
Alpher, Herman and Decoupling (continued)

\[ S_{\lambda_0} = \frac{\ell^3}{\ell_0^3} \frac{\lambda}{\lambda_0} \frac{d\lambda}{d\lambda_0} B_\lambda(T) \]

But these lengths change by the same factor as the U expands:

\[ \ell/\ell_0 = \lambda/\lambda_0 = d\lambda/d\lambda_0. \]

\[
= \frac{\ell^5}{\ell_0^5} \frac{2hc^2}{\lambda^5} \exp\left(\frac{hc}{\lambda k T}\right) - 1 = \frac{2hc^2}{\lambda_0^5} \exp\left(\frac{hc}{\lambda_0 k \ell T}\right) - 1
\]

\[ = B_\lambda(T_0), \]

where \( T_0 = T \ell/\ell_0 \).

That is, the spectrum of the decoupling surface, as presently observed, should be a **blackbody** at temperature \( T_0 = T \ell/\ell_0 \).
Penzias, Wilson and the Cosmic Background

In 1965, Bob Wilson and Arno Penzias (Bell Telephone Laboratories) were working on a very sensitive microwave receiver and antenna they built for satellite communication. They were trying to tune it up to reach ideal performance, but persistently found extra noise power for which they couldn’t account. They knew nothing of the Alpher-Herman prediction.

- The extra power was like that of a blackbody with temperature 2.7 K.
- It was the same no matter which direction they pointed their antenna. (If it comes from the sky, it’s isotropic.)

They were grasping at straws for an explanation, when they were paid a visit by radio astronomer Bernie Burke, a professor at MIT.
Penzias, Wilson and the Cosmic Background
(continued)

Burke knew of efforts at Princeton led by Dicke and Peebles to build a sensitive microwave receiver and antenna to look for the Big Bang radiation predicted by Alpher and Herman, but were having technical troubles. He introduced the Bell Labs group to the Princeton group.

- It was **quickly noticed** that Penzias and Wilson had **indeed detected that relict radiation**, now called the **cosmic microwave background (CMB)**.

- Thus the blast from **the Big Bang is seen directly**. This is the sturdiest support for Big Bang models of the origin of the Universe.

- For this immensely influential discovery, Penzias and Wilson shared the 1978 Nobel Prize in Physics.
The cosmic microwave background

The CMB is extremely isotropic.

- COBE image of the sky at $\lambda = 5.7$ mm. Color code: blue (red) is 0 K (4.0 K).
- Same, with blue (red) 2.725 K (2.731 K); dominated by the “dipole” anisotropy from our Galaxy’s 570 km/s motion relative to the average expansion.
- Next page: WMAP all-sky image with Galaxy and dipole removed.
The cosmic microwave background (continued)

From WMAP: Bennett et al. 2013

\[(\Delta T/T)_{\text{max}} = 7 \times 10^{-5}\]
The cosmic microwave background (continued)

COBE measurements of the background intensity as a function of frequency. (Courtesy of Ned Wright and the COBE FIRAS team.)

Pretty good blackbody…

For this result, John Mather (NASA/GSFC) shared the 2006 Nobel prize in physics.
How far away is the decoupling surface?

The redshift of decoupling can be obtained almost trivially:

\[ 1 + z = \frac{\lambda_0}{\lambda} = \frac{T}{T_0} \approx \frac{3000 \text{ K}}{2.728 \text{ K}} \approx 1100 \]

\[ \Rightarrow z \approx 1100 \]

The most distant galaxy hitherto detected has \( z = 9.4 \) (detected via gamma-ray burst); the most distant quasar has \( z = 7.1 \). A few hints of higher-redshift objects have appeared at \( z \sim 11 \).

So: substantially further away than any galaxy.