Galaxy Groups & The Big Bang

Interacting galaxies
Homogeneity and Isotropy of the Universe
Big-Bang and Steady State Cosmology
Detection of the Big Bang

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Galaxy groups & Cosmology: The Big Bang

- Interacting galaxies
- The expanding, isotropic, and homogeneous Universe
- Big-Bang and steady-state cosmology
- Alpher, Herman, and decoupling
- Penzias and Wilson’s detection of the Big Bang’s blast
- Big Bang nucleosynthesis

Reading: Kutner Ch. 20.1–20.2, & 21.2, Ryden Ch. 23.1, and Ned Wright’s cosmology tutorial
Interacting galaxies

Galaxies have extents (tens of kpc) that are a significant fraction of the typical separations of galaxies in groups or clusters (hundreds of kpc). Thus, collisions between galaxies are not all that rare.

The stellar disks can be relatively unaffected by galaxy-galaxy encounters because the stars themselves do not collide.

However, the interstellar clouds are big and they suffer inelastic collisions and tidal “stripping” that can result in the transfer of ISM from one galaxy to another. We will consider two possibilities:

1. Transfer with large angular momentum: ISM settles into the disk and/or polar rings.
2. Transfer with small angular momentum: ISM falls into the galactic nucleus, leading to starbursts.
Interacting galaxies: Polar ring galaxies

Transferred material which has substantial angular momentum in the frame of its new host galaxy quickly adopts appropriate orbits.

If the orbital plane is not coaxial with one of the host galaxy’s principal axes, or if the host has substantial ISM, the transferred material settles into the host’s disk plane.

But material which winds up in a polar orbit in a galaxy without much ISM can be stable for very long periods of time.

Thus polar ring galaxies, which look like spiral galaxies in one plane and elliptical or lenticular galaxies in a perpendicular plane, can form and be readily observed.
Polar Ring Galaxy NGC 4650A

Rotation axes of galaxy and ring are almost ⊥.
Interacting galaxies: Starbursts

A starburst is a brief but dramatic increase in the rate of production of stars by a factor of 100 to 1000 more than the normal rate in the disks of spiral galaxies.

Starbursts are identifiable from their large numbers of OB stars and supernovae.

Very close encounters can result in galaxy mergers. If such galaxies are gas-rich, then collisions among their interstellar clouds can result in compression or loss of angular momentum (with subsequent infall to one of the galactic nuclei), again resulting in a starburst.
Galaxy mass transfer: M81, M82, and NGC 3077

**Left:** visible light from M81-M82 system (Palomar).  

**Right:** HI 21 cm observations (VLA) (Yun et al. 1994).
Galaxy interactions & active galaxies

AGN activity is very frequently detected among interacting galaxies.

This suggests that active-galaxy accretion disks form in galaxy interactions, presumably from the lowest angular-momentum material transferred.

This also suggests that the formation of the central black holes themselves is related to galaxy interaction.

On the other hand, as previously discussed, currently inactive galaxies have central supermassive black holes with masses that scale with global properties of their host galaxies (Gultekin et al. 2009). So:

- Big galaxies $\implies$ big black holes…
- or lots of mass capture $\implies$ big black holes…
- or both?
The distribution of galaxies in the universe

Superclusters are more easily seen in 3D maps of the Universe; they appear as elongated highly dense clusters of galaxies (the “Finger of God” effect).

Clusters (and superclusters) are connected by thin filaments of galaxies. The extremely underdense, spherical regions of the galaxy distribution outlined by these clusters and filaments are voids.

A slice of the sky from the CfA Redshift Survey. Each dot represents a galaxy.
Recall that Hubble showed the Universe expands according to
\[ v_r = H_0 d \]

Two more conclusions Hubble made based on a large collection of worldwide observations:

1. The Universe is **isotropic** on large scales, looking the same in all directions.

2. The Universe is **homogeneous** on large scales, looking the same at all locations.

*Hubble at the 100” reflector on Mt. Wilson* (*Life*).
Isotropy and homogeneity

Note that by **small scale** we mean similar to or smaller than the typical distance between galaxy clusters.

By **large scale** we mean much greater than the typical distance between clusters, but still small compared to the observed size of the Universe.

- Recall: Galaxies are typically 1 Mpc apart. Cluster cores are typically less than \( \sim 3 \) Mpc in radius. Clusters are typically 10 Mpc apart.

- The Universe is obviously not uniform on small scales: the sky is full of stars, galaxies, and galaxy clusters, all containing mass of relatively high density with virtually empty space between.

- By this definition of “large” and “small” scale we will turn out to be OK with the assumption of Euclidean geometry, despite what comes next.
Isotropy on large scales

Galaxies in the Sloan Digital Sky Survey (SDSS) are shown below. The survey covers $3.55 \text{ sr} = 11700 \text{ deg}^2$, or 28% of the sky, centered on the Galactic poles, and identified all galaxies brighter than $R = 22.2$. 

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Isotropy on large scales

Each dot in the image is a galaxy. Each “smudge” or filament is a cluster or supercluster.

Isotropy on the scale represented by these circles means that approximately the same number of galaxies are contained within them, no matter where on the sky they are placed.

I.e., the Universe basically looks the same in every direction.
Homogeneity on large scales

The **homogeneity** of the Universe means that the number density of galaxies is uniform on **large scales**. In other words, the Universe looks the same from any viewpoint.

Hubble found this by observing great numbers of galaxies in selected parts of the sky and plotting the number per solid angle brighter than flux $f_0$ as a function of $f_0$, and seeing that

$$N(f > f_0) \propto f_0^{-3/2}$$

Recall our discussion of the distribution of stars in the Milky Way; $f_0^{-3/2}$ is expected in a uniform distribution.

Since the Universe is homogeneous and expanding, we would observe the same recession velocities no matter our location. That is, there is no unique center in space for the expansion, as in an ordinary explosion and blast wave.
Understanding the expansion

A classic metaphor: Imagine that we are on the surface of an expanding balloon. At any location, all points around us will appear to be receding, with no point being the “center” of the expansion.
Homogeneity on large scales

This is a 2.5°-thick slice in declination of the SDSS survey along the celestial equator ($\delta = 0$).

Redshifts are indicated by the horizontal axis, and galaxy luminosities are indicated by color (red = bright, blue = faint).

Note that the Galactic Plane has been cut out.
Homogeneity on large scales

Homogeneity on the scale of these circles’ diameters means that approximately the same numbers of galaxies are contained within them, no matter where we put them within the volume of the Universe.

The map is complete out to $z = 0.13$ ($\sim 550$ Mpc) and it is self-evidently homogeneous.
Understanding the expansion

In Euclidean (flat) space, $v = \frac{dr}{dt}$ is along $r$, so

$$v_{BC} = v_{BA} - v_{CA} = H_0(r_{BA} - r_{CA}) = H_0 r_{BC}$$

Thus, observers in galaxies $B$ and $C$ see the same Hubble Law that we do: the expansion looks the same from points $A$, $B$, and $C$. 

(Milky Way)
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; see Hawking & Penrose (1970).

▶ Such singularities — unphysical at first glance — arouse the suspicion of theoretical physicists.
Early post-Hubble cosmology

Accordingly, many leading cosmologists such as Einstein, de Sitter, Hoyle, Gold, Burbidge, and Arp promulgated steady-state models of the Universe, in which singularities are not realized.

- Example singularity that is not realized: At $r = 0$, the force between two finite-size masses in Newtonian gravity is infinite.

The steady-state models also maintained the Universe at constant density on (time) average despite the Hubble expansion.

- This was accomplished by positing the steady creation of matter out of nothing; they considered this violation of energy conservation less serious than mass-density singularities!

“Big Bang” was Fred Hoyle’s pejorative term for models with mass-density singularities.
Early post-Hubble cosmology

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

Observational tests gradually started going in favor of Big Bang cosmology in the 1950s:

- E.g., the 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).
- If we were in a steady-state universe, then there would be no expected evolution in the density of galaxies. I.e., Hubble’s $f_0^{-3/2}$ observation should be true everywhere. But this is not the case…
Early post-Hubble cosmology

The count of radio sources as a function of brightness (Pooley & Ryle 1968).

If the Universe were uniform and constant in density and galaxies never changed, then

\[ N(f > f_0) = Af_0^{-3/2} \]

shown by the dashed line with slope \(-3/2\) in the figure.
Alpher, Herman, & decoupling

Proposed in the late 1940s by Gamow’s students Ralph Alpher and Bob Herman (Gamow 1948, Alpher & Herman 1948), 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, they identified an event undergone at the expansion at a specific temperature: decoupling.

- The early Universe was so hot and dense that matter and photons were in thermal equilibrium (coupled), and all atoms were ionized.
- The photons eventually cooled (redshifted) to the point that they were incapable of ionizing atoms.
- In the laboratory, this takes place at about $T = 3000$ K for hydrogen.
This event is called **decoupling** because matter is opaque to radiation at the same blackbody temperature at temperatures above 3000 K; 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.

By the same token, matter below 3000 K is very transparent to radiation at the same temperature.

Therefore, radiation and matter decouple — live separate thermodynamic lives, no longer in equilibrium — after the Universe cools past this point.
Alpher and Herman realized this meant that 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 blackbody.
- The light started off in the visible range but, due to our great distance to the source, it would be redshifted to much longer wavelengths.