STRUCTURE AND ORIGIN OF THE UNIVERSE (COSMOLOGY)

THE LARGE-SCALE STRUCTURE OF THE UNIVERSE

Galaxy Clusters

Galaxies come in groups called *galaxy clusters*.
Tens to thousands of galaxies in a cluster.
Clusters are organized in clumps, sheets, and filaments separated by empty voids.
Universe has a foamy, sponge-like structure.

The "Hubble Ultra Deep Field" (2004)
Let's pick an empty place in the sky and point our *upgraded* most powerful telescope there for an 11.3 days exposure.....

Reminder: The Structural Hierarchy of the Universe

Edwin Hubble observed (and Georges Lemaitre theoretically proposed) that ***nearly all galaxies are moving away from the Milky Way.*** Hubble (and others like Vesto Slipher) used the Doppler effect: all spectra are **redshifted.**

Hubble's Law

The further away a galaxy is, the faster it is moving away from us:
Hubble's Law: $v = H_0 d$

H_0 is a constant, ~ 70.4 (+/- 1.4) km/s/Mpc (H_0 pronounced "H-naught")
v is in units of km/s ; d is in units of Mpc

"Hubble Diagram": a figure of galaxies' velocities versus their distances from us.

Hubble's Law: $v = H_0 d$
For example, say that **H_0** ~ 71 km/s/Mpc
Then a galaxy at a distance of d=1 Mpc recedes at v=71 km/s.

This is a linear relationship:
- a galaxy 2x further away moves 2x faster (galaxy at 2 Mpc moves at 142 km/s)
- if 100x further way, 100x faster.

Georges Lemaitre and Hubble and realized that *if the entire Universe is expanding*, then every galaxy & cluster moves away from every other galaxy.

We live in an expanding universe. Space itself is stretching.

Galaxies are hardly moving - they are almost stationary. *Space* itself is expanding! Galaxies are pulled along for the ride. *Analogy: think of pieces on an expanding chessboard...*

This discovery led to the modern branch of astronomy called "cosmology".

Cosmology: the study of the size, origin, and evolution of the Universe.

As space expands it will take matter with it, unless a force (like gravity or chemical bonds) holds the matter in place. Objects themselves do not expand.

As space expands, it stretches light with it: light becomes redshifted.

This is the cause of Hubble's law.
The redshift is not really due to the Doppler effect. It is due to space itself stretching.
Redshifts of galaxies are therefore called *cosmological redshifts.*

Let's pause and think for a minute…

If the Universe is expanding, then each day it gets bigger.
So it was smaller yesterday. Even smaller last year.
As we turn back the clock, the Universe gets smaller and smaller….
Turn back the clock enough (~ 13 Gyr), and the Universe shrinks smaller than the size of an atom!
Universe was a tiny, incredibly dense, incredibly hot, point that "exploded".

This event is called the "**BIG BANG**"

How do we know when the big bang occurred?
We know the rate at which the Universe is expanding today: it is the Hubble constant H_0.
(In the past, the Hubble constant was larger – the expansion is slowing down due to gravity.
Think of a ball thrown upwards – gravity slows it down.)

The age of the Universe is related to the inverse of the rate of expansion: $t = 1/ \mathbf{H_0}$
Age t = 1 / (70 km/s / Mpc)
t = ~ 13 billion years
(give or take some correction factors that depend on the total amount of mass in the universe)

Ah, but what if the rate is not constant? What if the change of H_0 is different from what we expect due to gravity? What if the expansion of the Universe is wildly accelerating or decelerating??
We can actually measure the acceleration of the expansion: it is called the acceleration parameter q_o. ("q naught")

The deviation from a straight line in the Hubble diagram tells us q_o.
Deviation from a straight line is small (and hard to measure!).
Rate of expansion is *close* to constant.
So the age estimate using $1/H_o$ won't be far from the correct value.

Bottom line: the Universe is roughly 13-14 Gyr old.

Do not confuse the data with the explanation for the data:

Observation:
We live in an expanding universe. Space itself is stretching.

Theory:
Universe started with a Big Bang.

Nearly all astronomers think that the Universe was created in the big bang. Why?

Evidence strongly supports the theory:

- Hubble's law
- ages of the oldest stars and star clusters (no ancient M stars or white dwarfs)
- large-scale structures: galaxies, clusters of galaxies and foamy-filamentary structure
- abundances of the elements*
- cosmic microwave background*
- Olbers' paradox

Abundances of the elements:
Moments after the big bang, the density and temperature of the Universe were incredible high - so high that no matter could exist. The universe was pure energy.
Hot - very hot. VERY, VERY HOT. Like 10^{32} K !!

As the Universe expanded, it rapidly cooled.
When it reached "only" 10 trillion K, protons an neutrons could form out of quarks. Thus hydrogen nuclei were formed. This occurred about 1 microsecond after the big bang.

After about 2 minutes, the temperature had plummeted to below 10^9 K.

Nuclear reactions can now occur. Protons and neutrons can combine to form more complex nuclei. This is called "big bang nucleosynthesis".
At this time, the Universe had a temperature and density similar to the core of the Sun.

But the Universe continued to expand and cool.
It cooled so fast that after a few minutes the density was too low for nucleosynthesis.

Thus:
About 25% of the hydrogen was turned into helium. A very small amount of other lightweight nuclei were formed, like lithium (Li).

Big bang theory predicts that the Universe will start out with mostly hydrogen, about 25% helium and tiny amounts of other light elements such as lithium.

This is indeed what the data show. The "data" = spectroscopy of starlight, esp. the oldest stars.

The Cosmic Microwave Background:

For the first ~400,000 years, the Universe was too hot to allow atoms to form; electrons were not bound to nuclei (all atoms were fully ionized)

Free electrons strongly interact (absorb) photons of all energies (not quantized).

So the Universe was opaque.

But after ~400,000 years, the temperature fell to a few thousand K. This is cool enough that electrons and nuclei combine to form atoms. Once you have atoms, the electrons can only absorb very specific energies (corresponding to differences in electron energy levels). Most photons do not have these specific energies.

So fairly suddenly, the Universe became transparent.

Photons could then fly freely though space. They "decoupled" from matter. Over the next 13 billion years most photons never interacted with matter again.

This is the limit as to how far back in time we can see – the universe becomes opaque at times earlier than this.

All of space was filled with light that had a thermal (blackbody) spectrum corresponding to the temperature of the Universe when the Universe became transparent: ~ a few thousand degrees K, in the UV-optical-near IR part of the spectrum.

But as the Universe continued to expand, the photons experienced cosmological redshift.

The blackbody spectrum got stretched into the radio part of the spectrum.

This radio light corresponds to only a few degrees K today.

Big bang theory predicted that at the present time, *all of space* should be filled with light that corresponds to blackbody thermal radiation of a few Kelvin. The thermal spectrum of an object at a few K will peak in the microwave (radio) part of the electromagnetic spectrum. (Wien's law).

This "cosmic microwave background" radiation was discovered in 1965. This added tremendous credibility to the big bang theory.

Even more support came from the "COBE" satellite (1989-1994). It measured the temperature to be 2.725 +/- 0.002 K, and showed the spectrum perfectly followed Planck's law.

Some years later, the WMAP: Wilkinson Microwave Anisotropy Probe studied the "CMB" in more detail. *WMAP* measured tiny *fluctuations* in the cosmic microwave background allowing us to precisely determine cosmological parameters.

Latest results as of 2010 Jan 26:

- Hubble constant: 70.4 +/- 1.4 km/s/Mpc
- age of the Universe: 13.75 +/- 0.11 billion years

Concluding Cosmological Thoughts

The big bang was *not an explosion in space.*
It was an explosion of space.
And of time.
Where did the big bang occur?
Where is the Universe expanding into?
Where is the center of the Universe?
Where is the edge of the Universe?
There is no "edge", but there is a limit to how far we can see: the "horizon", which would be ~13.7 billion light years away *in a static universe*. Since the Universe is expanding, the horizon is actually ~ 46 billion lt-yrs away.

We can't see beyond that because the Universe isn't old enough for light to have traveled that far in 13.7 billion years. Each moment our horizon is expanding at the speed of light.
We *can* detect light from objects more distant than 14 billion light years away because the Universe is expanding. The light has traveled far more than 14 billion light years to reach us.

What came before the big bang?
Nothing.
The big bang was the start of time, as well as space.
Some questions do not have answers: It is like asking what is more north than the North pole?

Key Concepts

The Universe is expanding.
Hubble's constant is about 70 km/s/Mpc.
Universe has a finite age, ~13.8 Gyr, and began with the "big bang".
Big bang created H and He, but essentially no other elements. They were created later…. inside stars
.
Key Concepts Supporting the theory:
Abundance of the elements
Cosmic Microwave Background:
The Universe is filled with background photons, the "ghost" signal from over 13 billion years ago when the Universe was only ~400,000 years old.

Olbers' Paradox

"Why isn't the night sky bright, if the Universe is infinite?"
It is a very simple, but very powerful question.
If the Universe is infinite, then in *every* direction there is a star, and every little area of the sky has *many* stars in it.

So why isn't it bright???

Solution to Olbers' Paradox:

1) The Universe is not infinitely old, so photons that originated infinitely far away have not had time to reach us.

2) Because space is stretching, light is redshifted to lower energies. Light waves from infinitely far away have been stretched to zero energy.

Big bang cosmology easily explains Olbers' paradox.

Weighing a Galaxy

There are two ways to measure the total mass of a galaxy:
(1) use the total starlight
(2) use the total gravity

(1) Measure all the light from a galaxy; based on the amount of light, we can estimate the number of stars. We know how much mass a star has. So we can estimate the total mass of a galaxy from the amount of starlight.

(2) Spiral galaxies rotate: most stars are moving in the same direction on circular orbits.
Measure a star's distance from the nucleus and its velocity (via Doppler shift)
This gives us the semi-major axis of the orbit (a) and the orbital period (P)
....and by using our old friend Kepler's 3rd law we can measure the mass of the galaxy.

For circular orbits, a=r and the distance a star travels is the circumference: $d= 2\pi r$
Since distance d=vt, then time $t = d/v = 2\pi r/v$. The time to make one orbit is the period P.
So $P = 2\pi r/v$

Plug into Kepler's III and solve for $(M_1 + m_2)$
Note that m_2 is negligible compared to M_1

So by using Kepler's III law we can measure the mass of the galaxy:

What we expect (via Kepler's 3rd law) is that the further away a star is from the center of the galaxy, the slower the star orbits.
This is just like objects in the Solar System: the inner planets move quickly while the outer planets move more slowly.

Orbital speed should slow down the further the star is from the nucleus.
But the data show that the stars keep orbiting quickly. Huh?!!!

A galaxy rotation curve: shows orbital velocity vs. distance from center

Orbital speed should slow down the further the star is from the nucleus.
But the data show that stars keep orbiting quickly!

A lot more gravity (hence mass) must be present to keep the stars from flying away.

Furthermore, galaxies in clusters are moving with high speeds – much faster than expected.
➔ Cluster should fly apart.
Something must be holding the cluster together...

More furthermore (!), gravity bends light, and the amount of *lensing* by a galaxy cluster requires more mass than we measure using starlight.

And finally, the cosmic microwave background from the big bang has "ripples", suggesting there's something missing…

Something is dreadfully wrong!

Masses of galaxies based on their light is *much* less than the masses based on their gravity.

Either Newton's + Einstein's theory of gravity is wrong, or *there's something else out there... something non-luminous, mysterious...*

"DARK MATTER"
There is a lot more "stuff" out there than we can see.
We know it's there - we can measure its gravity - but we can't see it.
And it cannot be ordinary matter (protons, neutrons). We do not know what it is.

How much dark matter?

- 5-10 times more than what we can see!
- 85% of the mass of a galaxy is in some form that we have not yet identified.
- Not stars, nebulae, dust, planets, white dwarfs, black holes, comets, etc...

Everything you know of is only a small fraction of what's actually out there!

But it's even worse:

The latest data (using Type Ia supernova to get distances to galaxies) show that the expansion of the Universe is actually speeding up! The expansion is now accelerating.

Why?

We don't know, but it means there's another component of the Universe. We call this "dark energy", since it acts like a pressure or anti-gravity force. We have no idea what dark energy is, but we are measuring its effect on the expansion of the Universe.

All the matter+energy we know of accounts for only ~4% of the total mass+energy from the big bang....

~ 96% of the Universe consists of something completely unknown (dark matter and dark energy)!!

Best estimate for the composition of the Universe: 73% dark energy, 23% dark matter, 4% ordinary matter

What's the ultimate fate of the Universe?
The latest data suggest that the Universe will expand forever.

Eventually, all gas & dust will be used up: no more star formation.
After a many cycles, all the H will be used up: no more fusion.
Stars will no longer shine; white dwarfs will cool off and stop glowing.
All that will be left are cold "rocks" and isolated black holes, drifting further & further apart…
The Universe will grow cold and dark.....