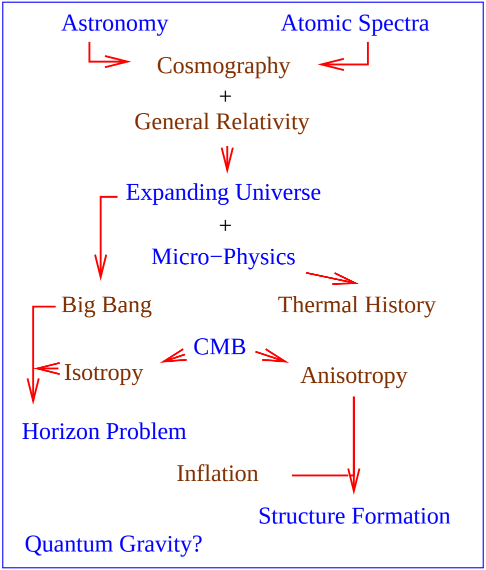
Modern View of Our Universe

Ghanashyam Date
The Institute of Mathematical Sciences, Chennai

National Seminar on
Astronomy Over the Ages

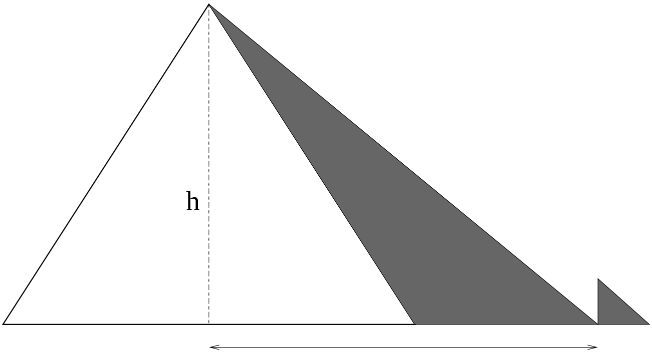
Dept of Theoretical Physics, University of Madras
$22 \cdot 02 \cdot 2011$

Flow Chart


Astronomy
Atomic Spectra
Cosmography
+
General Relativity
Expanding Universe
+
Micro−Physics
Big Bang
Thermal History
CMB
Isotropy
Anisotropy
Horizon Problem
Inflation
Structure Formation
Quantum Gravity?

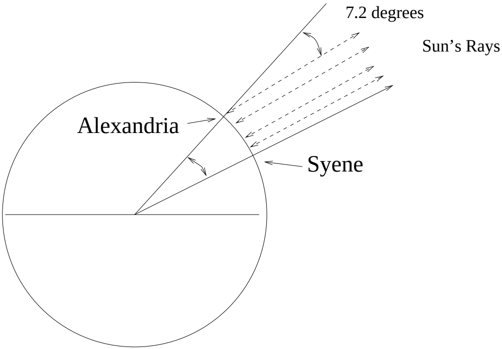
Height of the Great Pyramid?

(Thales $\sim$ 600 BC : $\sim$ 150 m) uses of shadows and similar triangles –



Radius of Earth

(Eratosthenes $\sim$ 240 BC: $\sim$ 4000 miles).

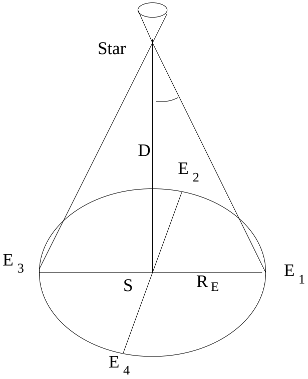


Accepted value (Poseidonius-Ptolemy: 2800 miles) was wrong but encouraged explorers!

Nearby Stars – Parallax Method

A star should appear to perform an annual elliptical motion on the celestial sphere:

parallax $:= \pi_* := R_E/D$.



Discovering something else...

Halley discovers Proper motion of Sirius, Arcturus, Betelgeuse and Aldebaran $\Longrightarrow$ no celestial sphere with stars attached. (~ 1720);

Bradley discovers instead Aberration of Light $\Longrightarrow$ speed of light is finite, earth indeed moves around the Sun and position of stars must be fixed accounting for the aberration. (~ 1730);

Herschel discovers binary systems (~ 1800);

These enabled Struve to set criteria for selection of candidates for parallax determination – should be bright with large proper motion or wider binaries.

Parallax at last!

Bessel finally detected the annual parallax for 61 Cygni in 1838. Within weeks, Struve reported for Vega and Henderson for α Centauri. The distances are: α Centauri 278,000 AU, 61 Cygni 719,000 AU and Vega 1,650,000 AU.

A new unit of distance is called for: The ParSec which is a distance at which a star would have a parallax of 1 arc second ($\sim$ 3.26 light years). Then the three nearest stars are at 1.35, 3.48 and 8 pc.

Method is reliable up to about 90 pc. One has exhausted the relatively direct method based on geometry to estimate distances and many more objects are still left!

Enter Laws of Micro-physics

Not only can we spot the stars but we can measure the flux of light energy received (apparent luminosity). Knowing the distance, the inverse square law gives their absolute luminosity. The nearby stars reveal diverse absolute luminosities!

Fortunately, we can also analyse the stellar spectra and these reveal the surface temperatures of the stars. This yields a spectral classification : O B A F G K M (R N S) in decreasing order of temperatures from 30,000 to 3,000 ^{0} K.

With the known atomic spectra from labs, we can also determine the Doppler Shift to infer the Radial Velocity of stars and we measure their proper motion.

(Open) Clusters of Stars

Moving Cluster Method: If we can determine the transverse velocity, we can obtain the distance from the proper motion.

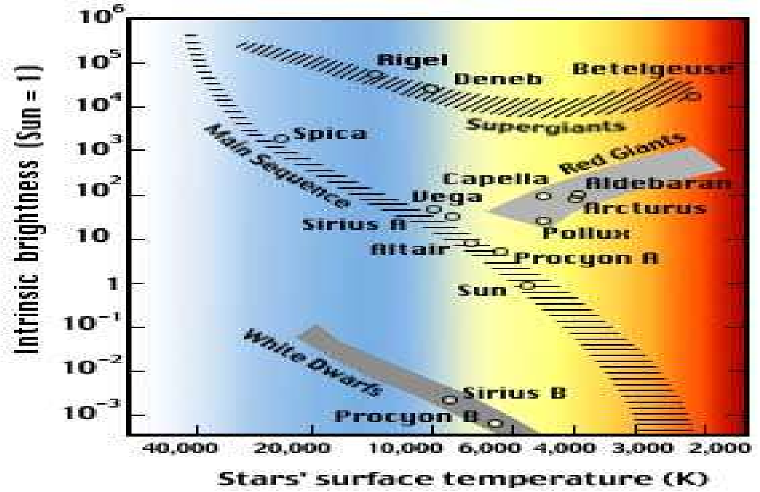
Identify an open cluster whose stars move together and appear to converge to a common point (direction). This gives the transverse velocity. The cluster identification and common direction is inferred by statistical analysis.

This is applied to the Hyades open cluster (1908) and gives the distance to be $\sim$ 46 pc.

This cluster has many different spectral types and is useful for next method.

Hertzsprung-Russell Diagram: Plot absolute luminosity versus spectral type.

observe.arc.nasa.gov/nasa/space/stellardeath/stellardeath_1ai.html



Main Sequence Fitting Method: Pick a cluster, identify its main sequence band in terms of apparent luminosity, match with a known cluster's main sequence in terms of absolute luminosity and infer the distance to the cluster.

This gives distance up to about 100,000 pc.

Astrophysical theory: Variable Stars

Certain stars are known to vary periodically, in their brightness: Mira Variables with periods of months, Cepheids with days and RR-Lyrae with hours.

In 1907, Henrietta Leavitt discovered a a brightness-period power law relation for Cepheids in the Small Magellanic Cloud. In 1913, Hertzsprung calibrated it. Now, period determination immediately gives the distance to other Cepheid variables.

In 1923 Hubble observed Cepheids in the Andromeda ‘nebula’ and estimated the distance to be about 275,000 pc:

Andromeda ‘nebula’ is extra-galactic!

Standard Candles

In effect, one looks for some regular feature of groups of stars or special types of stars to ascertain an absolute luminosity. Such features are called Standard Candles. The main sequence stars in an open cluster and the Cepheid variables are examples of a standard candle. These candles give distances up to 10^6 pc. For distances beyond, one needs brighter candles!

Novae and brightest stars of a galaxy $\longrightarrow 10^7$pc.

Brightest galaxies of a galactic cluster and Super-novae $\longrightarrow 10^{10}$pc.

Summary of the Distance Ladder

Rung	Distances up to	Method
I	< 30 parsecs	Kinematic (Parallax) Methods
II	$< 10^5$ parsecs	Main Sequence Photometry
III	$< 10^6$ parsecs	Variable Stars
IV	$< 10^7$ parsecs	Novae, Brightest Stars etc
V	$\sim 10^{10}$ parsecs	Brightest Galaxies, Super-Novae etc

Important Features

Isotropy: If we look at galaxies and their clusters roughly on a scale of about 200 Mpc, their number count is roughly the same in every direction i.e. they are distributed *isotropically*;

Hubble Law: The red shifts of galaxies are correlated with their distance from us. The farther the galaxy, larger is its red shift in a roughly *linear* manner.

Either we are in a special location in the universe *OR* galaxy distribution will also look isotropic from any other galaxy.

Cosmological Principle:

We do not occupy special position in the universe!

Perfect Cosmological Principle:

Neither our location nor our epoch has any special significance!

Cosmological Principle	$\longrightarrow$	**Big Bang** cosmology.
Perfect Cosmological Principle	$\longrightarrow$	**Steady State** cosmology.

We will assume only the cosmological principle.

Relativity

Principle of Special Relativity: All observers in uniform relative motion infer the same laws of physics (excluding gravity);

Constancy of speed of light: Speed of light in vacuum is same for all observers in uniform relative motion.

Space-time is the Minkowski Space-Time.

Principle of General Relativity: Observers in arbitrary relative motion infer same laws of physics including gravity;

Principle of Equivalence: Gravitational mass = Inertial mass.

Space-Time is a dynamical, Pseudo-Riemannian manifold.

The space-time geometry is determined by the matter distribution via the Einstein's Field Equation.

$$\boxed{G_{\mu\nu} := R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} \ = \ 8\pi G T_{\mu\nu}}$$

'systematic denial of special location' $\longleftrightarrow$ the space-time geometry must be spatially homogeneous and isotropic.

Robertson-Walker Space-Times

Imagine the four dimensional universe to be made up of a stack of three dimensional spaces (slices) with each space-like slice labelled by a 'time parameter' identified as the cosmic time.

Each slice has no distinguishing feature as one moves from point to point on it (homogeneity). If one looks around from any point, again there is no distinguishing feature (isotropy).

Mathematics then implies that each spatial slice must have constant curvature, parameterized by a single number which can be positive, negative or zero. The non-zero values of curvatures, the scale factor, can vary from slice to slice.

RW Space-Times (Cont . . .)

Such space-times are called Robertson-Walker geometries. Most of modern cosmography – mapping of the cosmos – is based on these geometries.

Properties:

- The Hubble law for red shifts of galaxies is automatic.
- Identifies new red-shift: The Cosmological Red Shift.
- Interpretation of distance to sources is geometry dependent.

Basic Equations

$$
\begin{aligned}
3\frac{\ddot{a}}{a} &= -4\pi G(\rho + 3P) && \text{(Raychoudhuri equation)} \\
3\frac{\dot{a}^2}{a^2} &= 8\pi G\rho - \frac{3}{a^2}k \quad k = \pm 1, 0\ ; && \text{(Friedmann equation)} \\
\dot{\rho} &= -3(\rho + P)\frac{\dot{a}}{a} && \text{(Conservation equation)} \\
P &= P(\rho) && \text{(Equation of State)}
\end{aligned}
$$

If ρ, P are both positive, universe cannot be static.

$\ddot{a} < 0$ implies $\dot{a}$ is monotonically decreasing implies. Hence the universe is always expanding or always contracting except for a possible change over from expanding to contracting phase.

If the density and pressure were always positive, then the universe must have had zero physical size a finite time ago.

Universe must have a finite age and must have evolved from a highly singular state.

This is BIG BANG!

Types of Constituent Matter:

Non-Relativistic:(Dust) characterized by constituents such as galaxies moving with non-relativistic speeds thereby exerting negligible pressure ($P_{NR} = 0$) and energy density ρ_{NR}. This is made up of visible matter and Cold Dark Matter;

Relativistic matter: Radiation (photons, neutrinos and other highly relativistic particles) with equation of state $P_R = \frac{1}{3}\rho_R$;

Cosmological constant: This is thought of as an example of Dark Energy which is required to explain observations. Its equation of state is: $P_\Lambda = -\rho_\Lambda = \Lambda$.

Thus our model has $P = \frac{1}{3}\rho_R - \Lambda, \ \rho = \rho_{NR} + \rho_R + \Lambda$.

Basic Observables of the Expanding Universe

- Hubble parameter $H(\tau) := \frac{\dot{a}}{a}$;
- Deceleration parameter $q(\tau) := -\frac{a\ddot{a}}{\dot{a}^2}$;
- Critical density $\rho_c(\tau) := \frac{3H^2}{8\pi G}$.

The first two can be determined from a plot of Luminosity distance vs red-shift for sufficiently large red-shifts while the matter densities are estimated from source counts. These have large error margins.

Luckily, better methods are available, but for this we have to shift attention to (Thermo)-dynamics of matter.

Thermal History of the Universe

In the past, universe must have been a Hot Soup of elementary constituents. The thermodynamic equilibrium determines number densities of various constituents as well as various reaction rates.

Due to the universal expansion, the soup cools and both the number densities and reaction rates decrease. Consequently, earlier species of constituents transform into different constituents eg nucleons forming nuclei.

Observe that constituents of the visible matter can be studied in the Laboratory.

The relative abundances of various constituents are determined by the micro-physics rates of reactions and the universal expansion rate. In particular, this leads to a definite prediction of abundances of lighter nuclei. This phase of Primordial Nucleo-Synthesis has been verified observationally.

Subsequent phase of synthesis of atomic hydrogen, also known as decoupling era, is particularly important.

$$\text{proton} + \text{electron} \leftrightarrow \text{Hydrogen} + \text{photon}.$$

At about 4000 degrees Kelvin, the reverse reaction is halted. The photons decouple, and photons stream freely hereafter.

This is the famous Cosmic Background Radiation which is a snap-shot of the decoupling era.

Cosmic Microwave Background Radiation

First predicted by Gamow in the late 40's in an attempt to obtain abundances of all naturally occurring chemical elements. This failed and was forgotten.

In 1966, CBR was accidentally discovered by Penzias and Wilson. Gamow had estimated the temperature of CBR to be about 5^o K. The measurements have been refined since then and the temperature is found to be $2.73\ ^oK$.

This is the most perfect example of the black body radiation and constitutes the the most direct evidence of the expanding universe with a Hot Big Bang.

CMBR (Cont...)

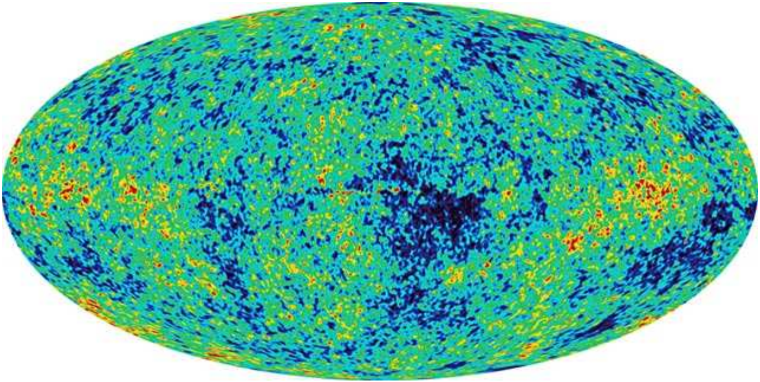
The earliest direct snapshot that we can possibly have (modulo cosmic neutrino background).

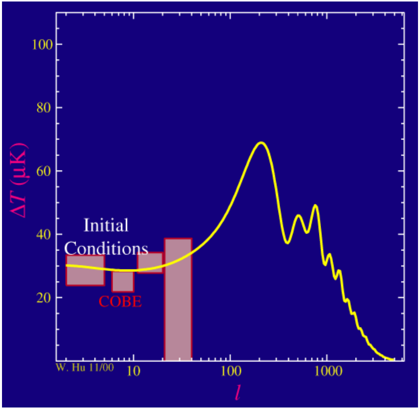
CMBR is isotropic to 1 part in 10^5!

But it *must* have anisotropies since we *do* see non-isotropic distribution on *smaller length scales* eg. Galaxies!

Are they there? What is the angular *distribution*?

Indeed there are anisotropies and their distribution is correlated with the distribution of galaxies! Here are some pictures.





100
80
60
40
20
ΔT (μK)
Initial
Conditions
COBE
W. Hu 11/00
10
100
1000
l

Acoustic Peaks

While the universe is largely homogeneous and isotropic, it is not exactly so. There *are inhomogeneous* perturbations of matter and hence also geometry. Non-uniform density leads to gravitational instabilities and generate sound waves in the Baryon-Photon fluid prior to decoupling.

These result in inhomogeneities in temperature distribution which translate into temperature anisotropies of CMBR.

Since the universe and the fluid are expanding, the amplitudes of these inhomogeneities evolve in time. These evolutions depend on the cosmological parameters as well as the wavelength of the perturbations.

Acoustic Peaks (Cont...)

The location of the first peak ($\ell \sim 200$) and its height are sensitive to the spatial curvature and to the matter densities.

The existence and location of the second peak confirm acoustic oscillation. Its amplitude is sensitive to the Baryon densities.

Since CMBR is measured very accurately by Wilkinson Microwave Anisotropy Probe (WMAP) and now by Planck, we have accurate determination of the basic parameters of our universe.

Our current understanding is . . .

Universe is made up of trillions of galaxies having trillions of stars;

Among them are white dwarfs, neutron stars, black holes ...;

There are invisible components such as Dark Matter in the galactic halos and all pervading Dark Energy;

Universe is about 13.7 billion years old;

Beyond Hot Big Bang

Horizon Problem: The wonderful isotropy of the CMBR also leads to a Problem! The temperatures at diametrically opposite points on the celestial sphere are highly correlated. Yet, regions separated by more than about a degree, *could not* have been in causal contact. Then, how is isotropy established?

Flatness Problem: For normal matter we have $\ddot{a} < 0$ which means $\dot{a} = aH$ decreases and its inverse increases with τ. Consequently, $\Omega - 1$ increases. So if the present $\Omega_0 \approx 1$ as indicated by the observations, it must have been extremely close to 1 in the past. Such extreme fine tuning seems unnatural.

Beyond Hot Big Bang (Cont . . .)

Enter Inflation:

There was a phase in the evolution of the early universe during which the universe underwent an accelerated expansion, in particular an Exponential expansion.

- Early universe was very, very small and so causal contact was possible. (No Horizon problem.)
- The enormous expansion in the early stage would make any non-zero curvature essentially small. (no flatness problem.)
- Even quantum fluctuations can grow and become 'classical' providing seeds for subsequent structure formation.

Beyond Hot Big Bang (Cont . . .)

How/why an inflationary phase exists? What decides its initial conditions? How does it end? Does it last long enough?

Singular Initial State: The FRW models predict a singular beginning for the universe. At a singularity however our understanding of physics is suspect. So one needs a better framework, possibly a quantum theory of gravity.

There are indications that at least in one version of quantum gravity - the so called Loop Quantum Gravity, quantum theory is singularity free.

Summary

- Kinematics of the universe:
  - Distribution of optical sources;
  - Isotropy on scales of about 200 Mpc; Hubble Law;
  - Cosmological Principle;
  - General Theory of Relativity and Dynamical Space-Time;
  - Homogeneity and Isotropy, Robertson-Walker space-times;
- Dynamics of space-time:
  - FRW Cosmology and identification of Observable parameters;
- Dynamics of matter:
  - Micro-physics of matter and Thermal History ;
  - Relic Radiation (CMBR), its isotropy and anisotropies;
- Imperfections in Homogeneity and Isotropy:
  - Acoustic Peaks and determination of cosmological parameters;
- Short comings of Hot Big Bang and Inflation;
- Quantum Gravity?