ZN Notes

I will almost always not indicate specific references in these notes

Introduction

A. Well-Established

Observed isotropy of Universe to <~0.1 - 1.0% via relic radiation

Homogeneity deviations <~0.1 - 1.0% on a scale of 10**10 ly

GTR with cosmo constant is the best basis

Steady state and changing G are not valid

Hubble parameter is 50 km/sec/Mpc to within 50%

Uniform density and pressure

With lambda ~ 0, critical density is 0.5 x 10**29 g /cm**3

If density < critical, Universe will expand unbounded and is infinite

Density is important to know

The use celestial objects of a given type to determine there structure of the Universe is complicated by their intrinsic evolution and the evolution of their number as a function of time

“But the distances over which galaxies can be observed are small compared to cosmological scales. To this day, therefore, the structure of the Universe has not been established through observations of ordinary galaxies wither.”

Important to know average density and particle types

Luminous matter has an average density of ~10**-31 g/cm**3, suggesting average number density of baryons ~6 x 10**8 /cm**3

Galaxy motions suggest dark matter

Antimatter absence suggests charge asymmetry

RR photons now have an average number density of ~400/cm**3, 10**8 - 10**10 more than the number density of baryons. Their T of 2.7 K corresponds to an energy of 0.0007eV, yielding an overall photon mass-energy density now of 5 x 10**-34 g/cm**3, much lower than that of baryons now

Density of neutrinos and gravitational waves is difficult to determine

Thus there is as yet no answer to whether total density now is greater or less than critical density, and consequently whether Universe is finite or infinite.

Going back in time, T increases and radiation and matter are in thermo equilibrium because matter density ~ V**-1, while radiation density ~V**-4/3

At t~ 1 sec in Friedmann solution, T~10**10 or 10**6 eV and matter density ~10**6 g /cm**3. There would have been photons plus electrons and positrons and protons and neutrons.

Expansion leads to disappearance of positrons, while neutrons decay or combine with protons, forming 70% hydrogen and 30% helium by mass, but almost no heavier elements. Also remaining were neutrinos and antineutrinos.

Further expansion means matter mass density exceeds photon mass-energy density of photons.

All RR now seen is from z~1000, the time of last scattering. The corresponding distance is about 97% of the distance to the singularity, the horizon distance. The observable volume is then about 90% of the maximum possible volume.

Existing structure indicates early deviations from homogeneity and isotropy.

B. Not Well-Established

Use perturbation theory by modes on simple time-dependent solution rather than exact solutions of four dimensional spacetime, especially since initial conditions are unknown.

But how large were density perturbations?

Present average density of galaxy clusters is roughly characteristic of the average overall density at their formation time; this leads to an estimation of the formation time. For the plasma state in the RD era, this leads to fractional density oscillations of 10**-3 for delta rho/rho

With theory, observations of RR fluctuations then permit estimation perturbation magnitude was functions of the scale or mass, i.e., the perturbation spectrum.

Summary of Important RecentResult: Universe picture represents a weakly perturbed (almost homogeneous) expanding Universe with a definite iniital(and large) entropy. Measurements oaf the spectrum and spatial distribution of the RR support this picture.

But can this picture explain galaxy rotation, magnetic fields and the origin of quasars?

Primordial magnetic fields are not necessary; plasma motions can generate observed fields.

But galaxy rotation given vortex-free initial perturbations? Possible given galaxy interactions.

Another theory is that galaxies formed from explosions of hyper dense bodies, but this violates known physics.

C. Beginning of Expansion

Anisotropic expansion before t ~ 1 sec?

Is there infinite density at the beginning or is that a characteristic of the isotropic homogeneous model?

There is proof a singularity even if expansion was not homogeneous and isotropic?

Details later, but here consider here aforementioned models plus perturbations. With these bases, do present observations and the laws of physics permit the establishment of the history of the Universe, including after and before (if meaningful) the singularity and the nature of the singularity itself?

Approach this via thermodynamics: many intiutial states can lead to a the same final state, which can serve as the new initial state for further evolution; the actual initial state is *forgotten*.

Thus find that cosmo model which arises from a wide class of initial early states.

Many anisotropic lead to isotropic expansion. But are such statistical arguments applicable?

Why is the entropy of the Universe large? Why hot at the start of expansion? Why are perturbations leading to observed structure of just the correct magnitude?

Laws of physics seem sufficient to explain all. Intense particle creation can occur from intense gravitational filed close to the time right after the singularity, but only given anisotropic expansion.

Finally, there can be new phenomena given quantization of the metric.

Historical remark: Friedmann theory 1922-1924; Einstein mention thereof; Lemaitre 1927. Thus Lemaitre did not “independently” establish the laws of the expanding Universe.

After Hubble discovery in 1929, math solutions became established theory. Einstein remarked in 1931 that Friedmann was the first to follow this way;

I. The Homogeneous, Isotropic Universe: Its Expansion and Geometrical Structure

1. Local Properties of the Homogeneous, Isotropic Cosmological Model

Standard exposition based on Newtonian theory for Hubble expansion, age of the universe, and matter density and pressure

2. Relativistic Theory of the Homogeneous, Isotropic Universe

GTR needed to analyze large regions

See Vol. 1 for a sufficient exposition of GTR; Theory of Fields by Landau and Lifschitz for a complete GTR >> Friedmann eqns, with results the same as for the Newtonian description

Various models for open, closed, and flat (critical density) geometry

3. The Propagation Of Photons And Neutrinos; Observational Methods For Testing Cosmological Theories

Significant effects of relativistic matter on early expansion; cosmological neutrinos would not be observable today, though photons are

As density becomes infinite as size and age approach zero, visibility to an earlier stage is not possible because the optical depth, dependent on particle density, diverges.

Whereas the theoretical particle horizon is at t=0, practically it is at a later time when the optical depth is of order unity.

Observational quantities: red shift, angular size and luminosity of distant objects, amount of matter as a function of red shift, apparent magnitude

Deceleration parameter and the first approximation

Impossibility of determining the cosmo model if sources evolve in an unknown way

Distance ladder to far-away objects

Redshift- vs. apparent magnitude observations rule out steady-state universe

No Olbers paradox in an expanding universe

4. The Cosmological Constant

Cosmo constant would only be manifest on the scale of the universe

History of cosmo constant starting with opinion that universe is static; Einstein desire for corresponding GTR solution and ideas of Mach

Hubble observation of expansion and Friedmann non-static GTR solutions Realization that cosmo constant is not needed, especially given new Hubble value of 75 and longer age for universe

Various cosmo models with nonzero cosmo constant.

II. Physical Processes in the Hot Universe

5. Intro to Part II

Relic radiation (RR = CMB) at T=2.7 K is the most important observational fact, and this RR (nor the equivalent background neutrinos) could not have been produced by astronomical objects

Also, there are about 10**(9+-1) photons per baryon

These two data allow characterization of the composition of the Universe at earlier time given thermodynamic equilibrium with specific entropy of matter conserved and volume changing smoothly during expansion

In later stages, nuclear reactions cease and nucleosynthesis takes place, with only photons, electrons, nuclei, neutrinos and gravitons surviving, with the last two undetectable

Hot universe proved by observations for the period 10 y <= t <= 10**10 y, and likely only consisting of matter in the large, not antimatter too.

Short historical review of RR prediction and discovery

Complete EM spectrum in the universe, of which a small section is the RR (Fig. 27, p. 126)

6. Thermodynamic Equilibrium

Early radiation-dominated era with matter and antimatter

Ratio of photons to baryons hardly changes during expansion: thermo equilibrium during early stages and conservation of RR photons later

Given kT > mc**2 , the number of particles and antiparticles of each king equals the number of photons. Thus ~10**8 nucleon-antinucleon pairs in the early universe for each nucleon today. This suggests that the present nucleons result from a small excess (10**-8) of nucleons over anti nucleons early.

Expansion eras are therefore:

1. Hadron era: with nucleons and antinucleons and ordinary and anti versions of all other particles; t~< 10**-6 s and T>10**13 K

2. Lepton era: with only a small remainder of nucleons, electron and positrons annihilate by the end, leaving a small remainder, and neutrinos decouple; 10**-6 s < t < 10 s and 10**13 K > T > 5 10**9 K

3. Photon-Plasma era: plasma and radiation in equilibrium; 10 s < t <

10**12 s and 5 10**9 K > T > 10**4 K

4. Post-recombination era: t > 10**12 s and T < 10**4 K when the RR becomes transparent

Gravitons, if they exist, would always be present but would not interact with other particles after Planck time ~10**-43 s.

At a sufficiently high temperature T such that kT > Mc**2, where M is the mass of the most massive particle, photons and other relativistic particles dominate

P = e /3 = rho x c**2/3 and e = kappa x sigma x T**4 to take account of all .kinds of relativistic particles

And n ~ e /(3 x k x T) for the particle density

Consider T ~ 1 MeV, t ~ 1 sec, and n(electron) ~ n(positron) ~ 10**-31 cm**-3 and annihilation cross section sigma(annih) ~ 10**-24 and particles move at c, then time to establish equilibrium is

.Tau ~ 10**-17 small compared to 1 sec

Similarly for higher mass particles at higher temperatures and .correspondingly earlier times

When kT > m(nuc), n(nuc then) - n(antinuc then) = n(nuc now) ~ 10**-8 x (n(photons now)

n(nuc then) ~ n(photons then)

One could apply the same considerations to quarks and so on and so forth if kT > m(q) c**2

Hot vs. cold matter as n >> infinity ? Different models of Hagedorn and Omnes

Quark theory for nucleons

Conservation of energy and baryon charge and entropy for slow, adiabatic .processes => evolution can be described

Particle-antiparticle annihilation requires binary collisions, increasingly .unlikely as the Universe expands

Residual n(antiparticle) in charge symmetric theory is very small at the end of hadron era, T ~ 1 MeV because annihilation sigma is large and nucleon excess => exponentially small n(antiparticle) when their .creation ceases

Residual n(q) is large . With respect to photons, it is ~[Gm**2/hc]**1/2 .2 .~10**-18; with respect to nucleons, it is about 10**-9

In spatially homogeneous, charge-sym universe, nucleon problem similar .3 to quarks and leads to 10**-18 nucleons/photon, disagreeing with observations by 10**10. So we should consider charge-asymmetric .universe

This leads to Omnes theory. Charge symmetry of primordial homogeneity is spontaneously broken on the microscopic scale. Strong interaction leads to separation of matter and antimatter drops of size ~10**-3 cm at 10**-6 sec

This separation tendency stops as T decreases and annihilation occurs as usual. But spatial separation means annihilation occurs mainly at the .boundary of regions

There exist regions with 10**-9 nucleons /photon and regions with 10**-9 antinuc/photon => galaxies and antigalaxies. Omnes calculations lead to two characteristic quantities: average n(nuc or antinuc) / n(photons). And .characteristic size of matter or antimatter region

But a consistent calc of separation and following annihilation leads to a much smaller concentration of nucleons and antinucleons, disagreeing with with present density of nucleons

Annihilation continues during radiation-dominated stage, but expected consequences of prolonged annihilation are not observed. Thus, even with account of phase separation, **charge-symmetric theory does not agree .with observation**s

Consider therefore charge-asymmetric Universe with excess baryons always. Early, excess of baryons is small given number of pairs, so Omnes phrase separation is plausible then

For T = 300 MeV, charge asymmetry manifests itself only in at T > 1 MeV, when there is an abundance of electrons and positrons and RR spectrum .takes equilibrium form

Finally, charge asymmetry leads to n(baryon today) = n(baryon charge .density initially)

It would nevertheless be very interesting to find evidence now of hadron .era phase separation

Hagedorn theory that the number of charged particles is infinite is contradicted by experimental results of QED

7. Kinetics of Elementary Particle Processes

Note: Generally speaking I am writing h instead of hbar

In earliest stages of the hot Universe, neutrinos (+anti) are in thermo equilib with other particles. Creation of neutrinos mainly by e- + e+ >> neutrino (+anti) with relativistic cross section

Sigma ~ g**2 x E**2 / h**4 x c**4, where g ~ 10**-49 ergs cm**3 is the weak interaction constant

Given particle energy of kT, time to reach equilibrium tau = 1 / (sigma x n x c) , and previous relation between universe time t and temperature T, we :obtain dependence of tau and t

tau ~ [G**5/4 x h ** 13/4] / [g**2 x c**1/4] x t**5/2 (Landau & Lifschitz for statistical factors). When tau is greater than t, neutrinos no longer interact either with other particles or with one another. Equating them leads to t ~ 0.1 s without consideration of numerical factors but showing the dependencies of G and g . More accurate calculations follow, including .consideration of mu neutrinos

Present temperatures neutrinos compared to photons is then (Peebles(

T(neutrino) = (4/11)**(1/3) x T(photon) ~ 0.7 x 2.7K ~ 2K

But mass of neutrinos could be ~<100 eV, while background cosmic neutrinos would have energy 5 x 10**-4 eV , so observation of the .background would require measurement improvement by 10**6

RR spectrum tells us about z ~ 10**6 at t ~ 1 yr; neutrino spectrum could tell us abut z ~ 10**10 at t ~ 0.1 s

Particles that decay spontaneously disappear exponentially as Universe expands. Stable particles would remain if annihilation reactions do not .occur

FIGURE 30 FOR TEMPERATURE-DEPENDENCE OF PARTICLE RELATIVE ENERGY DENSITY

General gravitational effect very small compared to EM effect because alpha = e**2 / hc = 1/ 137 whereas comparable factor for grav is Gm**2 / hc ~ 10**-38 for protons and 10**-44 for electrons.

Neutrinos have an effect in collapsing stars when the matter density is very high, but gravitons would not enter the picture

In very early stages of the Universe, the cross section for creation of one graviton and two gravitons, respectively, are

sigma1 ~ Gh / c**3 ~ l(Planck)**2 and for the creation of two gravitons,

sigma2 ~ (hc/E)**2 x (G E**2 / h c**5)**2 ~ l(Planck)**2 x (G E**2 / h c**5)

where E is the energy of the interacting particles, say an electron and a positron.

Characteristic time for of graviton decoupling is the Planck time.

Equilibrium early would lead to energy density of gravitons ~ 0.02 energy density of photons, if the entropy of hadrons is transferred to photons but not to gravitons

During the RD period, high graviton density would lead to: a small change in the expansion rate; the time when matter density + photon density + graviton density; and the time of hydrogen recombination. This will not be discussed further.

Grav waves of low frequency and large wavelength can be studied classically because they interact coherently with matter in large volumes. This will be discussed later.

Assumption of charge-symmetric universe with equal numbers of nucleons and anti nucleons and e+ and e- leads to n(nucleon) /

n(photon) ~<10**19 through annihilation.

Thermodynamic equilibrium occurs because of the balance of nucleon-antinucleon annihilation and pair creation for high temperature but less than Mc**2 / k

But annihilation rate becomes negligible much earlier and a “freeze-out” occurs with a nonequilibrium number of nucleons and antinucs remaining. If t(N) is the time before which approximate equilibrium is maintained, then kT(N) ~ Mc**2 / alpha, with alpha ~ 44, at t(N) ~ 2.5 x 10**-3 sec

For T = 2.7 K, , n(photon) ~ 400 / cm**3 so n(nucleon) = 10**-17 / cm**3 or density (nucleon) ~< 10**-41 g / cm**3. **These small values are evidence against the charge-symmetric hypothesis.**

By other considerations, t(N) ~ alpha**2 x G**-.5 x M**-2 x h**1.5 x c **-1.5. With alpha ~ 1 the freeze-out criterion sigma x v x n(nucleon) x t = 1 leads to

n(nucleon) ~ [GM**2 / h c]**1/2 x [M c / h]**3.

With n(photon) ~ [kT(N) / ch]**3 ~ [M c / h]**3, we find

n(nucleon) / n(photon) ~ M / M(Planck) ~ 10**-24 g / 10**-5 g = 10**-19; note that M(Planck) = [hc / G]**1/2.

One can also think of [GM**2 / hc] as the strength of the gravity between nucleons (analogous to [e**2 / hc] for EM interaction)

Thus, few nucleons and antinucleons exist in the charge-symmetric model because of the small size of their grav interaction.

Astrophysical considerations imply that condensing clouds of gas would induce annihilation, but this would occur long after the above considerations that already show the small nucleon density at the gas cloud stage.

If the charge symmetry is an average over separate regions, then the regions must be smaller than the horizon to be visible in principle, but the calculated rate of photons exceeds what is observed, Separation mechanisms between regions would deal with this difficulty and are discussed later.

Generally, an inhomogeneous model charge-symmetric on average is not esthetically pleasing compared to a homogenous, charge-symmetric model. ***[LF????]*** *Note too that charge-symmetry properties of particles do not imply such a property for cosmological expansion.*

In a charge asymmetric model with an excess of nucleons, the equilibrium time t(N) is t(N) ~ 10**6 [omega(0) h(0)**2] s and n(antinuc) / n (photon) ~ < 10**-73 for primordial antinucleons, much smaller than for antibaryons arising from cosmic rays.

Analogous for quarks based on equilibrium followed by freezing out; assumption that m(quark) > m(nucleon); freezing out of quarks at a higher temperature than for nucleons. A result is that at the freeze-out time,

n(quark)/n(baryon) ~ 10**-10. While this value is small, recall that [Au / H] ~ 10**-12 for the earth's crust, so quarks could be more abundant than gold if they exist as free particles.

Nucleosynthesis in the charge-asymmetric model ends at the stage t~< 100 s and T~3 x 10**8 K, producing the chemical composition of first-generation stars

Detailed consideration of neutron-proton reactions, including neutron decay and the reverse lead to fractional neutron abundance of 0.17

The formation of deuterium, helium, and lithium follow. See Figs 32 & 33.

All of the neutrons that survive until freeze-out are converted into

4He during the period 10-100 s, yielding a theoretical max helium mass fraction of 0.33 . This value for helium does not depend strongly on the present value for the average matter density, whereas the value for deuterium does.

Observations of the helium mass abundance of stars give values in the range [.24,.32]. Observations of the deuterium mass relative to hydrogen give upper limits of a few x10**-5. Only these elements can reflect primordial abundances. Higher mass light elements could be produced by cosmic ray interactions