5. Low Entropy

The CMB blackbody radiation in equilibrium has maximum entropy, with a volume density

$$s_{\mathrm{cmb}} = \frac{4}{3} a_{\mathrm{rad}} T_{\mathrm{cmb}}^3$$

in terms of the blackbody temperature T cmb and radiation constant a rad . But while T_{cmb} scales as

(1 + z) ≈ a(t) $^{-1}$ with the expansion of the Universe, any given proper volume V scales as ***a(t)*** ^{3}. Thus, the total blackbody entropy, $S_{cmb} = S_{emb}$ V, must have remained constant throughout the Universe's history (Frautschi 1982).

The so-called " past hypothesis " conjecture, however, posits that the overall entropy of the observable Universe is increasing monotonically. It must therefore have been significantly lower at earlier times (Layzer 1975; Price 1996; Albert & von Baeyer 2001; Earman 2006) . But this is clearly at odds with the CMB which suggests the Universe was close to thermal and chemical equilibrium — a state of very high entropy — a mere ~ 377,700 yr after the big bang. And if the entropy soon after the big bang was as high as it appears to have been at decoupling (i.e., z dec ~ 1090) , why are we living in a Universe, or a portion thereof, with anomalously low entropy today (Zemansky et al. 1998; Albrecht 2002; Penrose 2004; Egan & Lineweaver 2010) , when physical processes, such as stellar evolution and black hole accretion, are increasing the cosmic entropy everywhere?

This is the conflict known as the " initial entropy problem (IEP).

The standard model currently has no explanation for why the Universe was initially in a very low entropy state (as required by the second law) , and for how the CMB acquired such high entropy so soon after the big bang. Of course, a very low initial entropy by itself is not necessarily the problem. For example, the Universe may have been created from " nothing " and continues to evolve away from that initial state to which it will never return (Vilenkin 1982; Hartle & Hawking 1983; Linde 1984) . The problem emerges when this very low initial entropy is coupled to the subsequent entropy evolution implied by the CMB and what we see today.

The IEP has been one of the most contentious issues in standard cosmology. It remains unsolved. Neither the equilibrium models nor the in fl ationary paradigm can adequately account for the very low initial entropy without relying on a lack of " naturalness. " If the initial state of the Universe was random, characterized by a uniform probability of microstates, it should have been born with maximum entropy, representing thermal equilibrium, not the extremely unlikely low-entropy configuration required by Λ CDM. At face value, the standard model of cosmology thus appears to be inconsistent with the firrst and second laws of thermodynamics, constituting yet another conflict with our fundamental physical theories.

Cosmology and the Arrow of Time: The Second Law of Thermodynamics- One of the Biggest Problems

All the successfull equations of physics are symmetrical in time. Tbey can be used equally well in one direction in time as in the other. The future and the past seem physically to be on a completely equal footing. Newton's Laws, Hamiltons equations, Maxwell's equations, Einstein's general' relativity,'· Dirac's equation, the Schrodinger eqnation . all remain efffectively unaltered if we reverse the direction of time. (Replace the coordinate t which represents time, by -t.) The whole of Classical Physics and part of quantum mechanics is entirely reversible in time.

Our physical understanding actually contains important ingredients other than just equations of time-evolution and some of these do indeed involve time-asymmetries. The most important of these is what is known as the second law of thermodynamics. The low entropy state seems specially ordered, in some manifest way, and the high entropy state, less specially ordered. Define entropy. In rough terms, the entropy of a system is a measure of its manifest disorder. The second law of thermodynamics asserts that the entropy of an isolated system increases with time (or remains constant, for a reversible system).

The concept of phase space or state space is a space in which all possible "states" of a dynamical system or a control system are represented, with each possible state corresponding to one unique point in the phase space. The entropy of a state is a measure of the volume V of the compartment containing the phase-space point which represents the state.

$$\text{Entropy} = k \log V.$$

The number of baryons in the universe is 10^{80}. Now consider the phase space of the entire universe. Each point in the phase space represents a point where there is a different universe. The quantity k is a constant, called Boltzmann's constant. Its value is about 10^{-23} Joules per degree Kelvin. The essential reason for taking a logarithm here is to make the entropy an additive quantity for independent systems.

Putting this together with the Bekenstein-Hawking formula, we find that the entropy of a black hole is proportional to the square of its mass:

$$S_{bh} = m^2 \frac{kG}{h \cdot c}$$

Mass of Sun:

$$M_{\odot} = 1.99 \times 10^{30}\, kg$$

According to a calculation performed in 1929 by Subrahmanyan Chandrasekhar, white dwarfs cannot exist if their masses are more than about 1.4 times the mass of the sun, 1.4 $M_{\odot}$ Note that the Cbandrasekhar limit is not much greater than the sun's mass, whereas many ordinary stars are known whose mass is considerably greater than this value. But there is now a new limit, anaIogus to Chandrasekhar's (referred to as the Landau-Oppenheimer-Volkov limit), whose modem (revised) value is very roughly 2.5 solar masses. The gravitation attraction for a mass greater than this will result in the formation of a black-hole.

Let us consider what was previously thought to supply the largest contribution to the entropy of the universe, namely the 2.7K black-body background radiation. Astrophysicists had been struck by the enormous amounts of entropy that this radiation contains, which is far in excess of the ordinary entropy figures that one encounters in other processes (e.g. in the sun). The background radiation entropy is something like10^8 for every baryon (using natural units, so that Boltzmann's constant, is unity). (In effect, this means that there are 10^8 photons in the background radiation for every baryon.) Thus, with 10^{80} baryons in all, we should have a total entropy of 10^{88}.

The Bekenstein-Hawking formula tells us that the entropy per baryon in a solar mass black hole is about 10^{20} in natmal units so had the universe consisted entirely of solar mass black holes, the total figure would have been very much larger than that given above, namely 10^{100}.

Let us try to be a little more realistic. Rather than populating our galaxies entirely with black holes, let us take them to consist mainly of ordinary stars-some 10^{11} of them and each to have a million (i.e. 10^6) solar-mass black-hole at its core (as might be reasonable for our own Milky Way galaxy). Calculations by Roger Penrose shows that the entropy per baryon would now be actually somewhat larger even than the previous huge figure, namely now 10^{21}, giving a total entropy, in natural umts, of 10^{101}. This figure will give us an estimate of the total phase-space volume V available to the Creator, since this entropy should represent the logarithm of the volume of the (easily) largest compartment. Since 10^{123} is the log of the volume, the volume must be the exponential of 10^{123},

$$V = 10^{10^{123}}$$