A NEUTRINO DOMINATED UNIVERSE

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SUMMARY

Relic neutrinos produced during the early evolution of the Universe will be abundant today ($n_\nu \approx n_\gamma$) and, if they have a small mass ($3 \lesssim m_\nu \lesssim 10$ eV), may supply the dominant contribution to the total mass density. We review the data on the mass on various scales (galaxies, binaries, small groups, large clusters) and conclude that ordinary matter (nucleons) is capable of accounting for the inferred mass on all scales except that of clusters of galaxies. Were the mass in clusters mainly in nucleons, too much helium and too little deuterium would have been produced during primordial nucleosynthesis. Relic neutrinos with $m_\nu \gtrsim 3$ eV are heavy enough to collapse into clusters of galaxies; for $m_\nu \lesssim 10$ eV they are too light to collapse along with binaries and small groups. Such neutrinos would supply the dominant contribution to the mass in the Universe.

INTRODUCTION

The early Universe provided a stage on which was enacted the drama of elementary particle physics.[1] The high temperature and density and comparatively slow expansion rate during the early evolution of the hot, big bang model provided an ideal environment for high energy physics. Particles which are too massive or too weakly interacting to have been discoverd at conventional accelerators would have been produced copiously in the "cosmic accelerator." Some of these "relics" from earlier epochs would have survived to influence the subsequent evolution of the Universe. Indeed, relics which are stable or long lived ($\tau \gtrsim 10^{10}$ years) would be present today.

For weakly interacting relics, direct observation may be virtually impossible. Fortunately, another possibility presents itself. All particles gravitate; through their gravitational interaction, weakly interacting relics may signal their presence. Such signals may already exist.

Indeed, the evidence we assemble in this essay leads us to conclude that massive but light relic neutrinos ($m_\nu \approx 5$ eV) may supply the dominant contribution to the total mass density of the Universe. To this end we first examine the density in ordinary matter (nucleons). An upper limit to the nucleon density follows from considerations of primordial nucleosynthesis[2] and a lower limit from studies of galaxies[3] and hot gas in clusters.[4] A bonus of this approach is that the consistency of the upper and lower limits requires that the present value of the Hubble parameter, H_o, be $\lesssim$ 70 kms^{-1} Mpc^{-1}. Next, we review the data[3] on the mass of astrophysical systems of increasing scale (binary galaxies, small groups of galaxies, large clusters of galaxies) and find that nucleons can account for the inferred mass on all scales up to, but <u>not</u> including, large clusters of galaxies. The "missing light" problem on the largest scale can be solved quite naturally by relic, light neutrinos. Our essay concludes with an outline of other tests of our hypothesis.

THE MASS IN NUCLEONS

It is convenient to express all mass densities in terms of the critical density, $\rho_c = 3H_o^2(8\pi G)^{-1}$, which separates those models which expand forever ($\rho < \rho_c$) from those which eventually collapse ($\rho > \rho_c$). For each contribution to the total mass density, ρ_i, we introduce the density parameter, Ω_i, where $\rho_i = \Omega_i \rho_c$. To allow for the large uncertainty in the present value of the Hubble parameter,[5] write $H_o = 100\ h_o (kms^{-1} Mpc^{-1})$ where $0.4 \lesssim h_o \lesssim 1$. In terms of Ω_i and h_o we have

$$\rho_i = 2 \times 10^{-29}\ \Omega_i h_o^{\ 2} (gcm^{-3}). \qquad (1)$$

Let us first examine the limits to the nucleon density.

During primordial nucleosynthesis, the light elements (D, ^{3}He, ^{4}He, ^{7}Li) are formed in a sequence of two body reactions whose rates depend on the nucleon density.[2] High nucleon density results in the production of more ^{4}He and ^{7}Li and less D. Since nucleons are conserved (for $T \lesssim 1$ MeV, baryon nonconserving processes are entirely negligible), an upper limit to the present density in nucleons may be inferred from an upper limit to the primordial abundance of ^{4}He and ^{7}Li and a lower limit to the primordial abundance of deuterium.[2] Since photons are also conserved (with account taken of the extra photons created when electron-positron pairs annihilate as the Universe cools below m_e), it is convenient to compare nucleons and photons. For an upper limit to the primordial abundance (by mass) of ^{4}He, $Y_p \lesssim 0.25$ (and, for three, two-component neutrinos: ν_e, ν_μ, ν_τ) the nucleon to photon ratio is limited by,[5]

$$\left(\frac{n_N}{n_\gamma}\right)_o \lesssim 4.2 \times 10^{-10}. \qquad (2)$$

The number density of black body photons is $n_{\gamma_o} \approx 400\ (T_o/2.7)$,[3] so that (1) and (2) lead to an upper limit on $\Omega_N h_o^2$,

$$\Omega_N h_o^2 \lesssim 0.014 \left(\frac{T_o}{2.7}\right)^3. \qquad (3)$$

This limit is identical with the one which follows from the deuterium abundance[2,5] and is consistent with (but more restrictive than) the limit from ^7Li. A firm <u>upper</u> limit to Ω_N follows from (3) and from a lower limit to H_o ($h_o \gtrsim 0.4$)[6] and an upper limit to T_o ($T_o \lesssim 3.0°K$).[7]

$$\Omega_N \lesssim 0.12 \tag{4}$$

Before turning to considerations which will lead to an estimate of the <u>lower</u> limit to Ω_N, let us examine the mass density inferred from astrophysical objects of different scales. Here, we will rely extensively on the data assembled in the excellent review article by Faber & Gallagher;[3] where appropriate we have adopted a luminosity density[8] $L \approx 2 \times 10^8\ h_o\ L_\odot\ Mpc^{-3}$ so that we may convert mass-to-light ratios to values of Ω.

The inner, luminous parts of galaxies (mainly Ellipticals and SOs for our purposes) are almost certainly dominated by ordinary matter so that,[3,8]

$$\Omega_N \gtrsim \Omega(E,SO) \approx 0.012. \tag{5}$$

There is, of course, good evidence that galaxies are considerably more massive than is inferred from studying their inner regions where most of the light originates. Indeed, from studies of the dynamics of Binary galaxies and Small Groups of galaxies,[3]

$$\Omega(B,SG) \approx 0.04 - 0.07.$$

There is, however, no direct evidence that the extra mass on these larger scales is in nucleons; notice, though, that this estimate of $\Omega(B,SG)$ is consistent with the upper limit for Ω_N from (4). Indirect evidence that most of this extra mass is, indeed, nucleons comes from the x-ray emission from clusters of galaxies.[4] As is confirmed by observations of iron line emission, the x-rays are the thermal bremsstrahlung emission from a hot intracluster gas. The mass of this hot gas (nucleons) is large.[4]

$$\Omega(\text{Hot Gas}) \approx 0.016\, h_o^{-3/2}. \tag{7}$$

The dependence on the Hubble parameter in (7) reflects the distance dependence inherent in the mass derived from the observed x-ray flux. A reasonable <u>lower</u> limit to the nucleon mass density follows from adding the contribution from hot gas (equation (7)) to that inferred from the inner parts of galaxies (equation (5)).

$$\Omega_N \gtrsim \Omega(E,SO) + \Omega(\text{Hot Gas}) \approx 0.012 + 0.016\, h_o^{-3/2}. \tag{8}$$

Observe, now, that the requirement that the lower bound to Ω_N (equation (8)) be consistent with the upper bound to $\Omega_N h_o^2$ (equation (3)), leads to an <u>upper</u> bound to the present value of the Hubble parameter.

$$\text{For } T_o = 3.0°\text{K}, \quad h_o \lesssim 0.7; \tag{9a}$$

$$\text{For } T_o = 2.7°\text{K}, \quad h_o \lesssim 0.5. \tag{9b}$$

With $h_o \lesssim 0.7$ ($H_o^{-1} \gtrsim 14 \times 10^9$ years), $\Omega_N \gtrsim 0.04$, whereas for $h_o \lesssim 0.5$ ($H_o^{-1} \gtrsim 20 \times 10^9$ years), $\Omega_N \gtrsim 0.06$, so that on scales up to those of binaries and small groups, most of the inferred mass can be in ordinary matter; up to these scales there is no missing mass (or, rather, missing light) problem. The situation changes on the scale of clusters of galaxies.

After years of extensive investigation,[3] the conclusion still remains that clusters of galaxies are very massive.[9]

$$\Omega(\text{Clusters}) \approx 0.4 \pm 0.2. \tag{10}$$

Additional support for such large mass is provided by the x-ray observations;[4] the temperature of the x-ray emitting gas is a probe for the depth of the potential well in which the gas resides: $\Omega(\text{Clusters}) \gtrsim 0.2$.

Here we encounter an apparent dilemma which may be simply summarized as,

$$\Omega_N \lesssim 0.12 \; ; \quad \Omega(\text{Clusters}) \gtrsim 0.2. \tag{11}$$

If the mass inferred from clusters were (at the time of primordial nucleosynthesis) in the form of nucleons (e.g.: today they might be in black holes, neutron stars, etc.), too much ^{4}He and ^{7}Li and too little D would have been produced.

Although nucleons can account for the mass observed on scales up to binaries and small groups, at least half the mass in clusters must be in something else. We propose relic neutrinos with a small mass ($m_\nu \approx 5$ eV).

RELIC NEUTRINOS

During the early evolution of the Universe, all particles, including neutrinos, were produced copiously.[1] Here we focus on the known e^-, μ^- and τ-neutrinos and entertain the possibility that they have a small but finite mass. Neutrinos with full strength, neutral current, weak interactions were produced by reactions of the type,

$$e^+ + e^- \leftrightarrow \nu_i + \bar{\nu}_i \; ; \; i = e, \mu, \tau. \qquad (12)$$

At high temperatures ($T > m_\nu$), these neutrinos were as abundant as photons.

$$\frac{n_\nu}{n_\gamma} = \frac{3}{8} g_\nu . \qquad (13)$$

In (13), g_ν is the number of neutrino helicity states. The known neutrinos are left handed ($g_{\nu_i} = 2$) and, if massive, must be of the Majorana type ($\nu_i = \bar{\nu}_i$). As for the numerical factor in (13), 3/4 comes from the difference between Fermi-

Dirac statistics (neutrinos) and Bose-Einstein statistics (photons); the remaining factor of 1/2 is from the number of photon spin states ($g_\gamma = 2$).

For light neutrinos ($m_\nu << 1$ MeV), equilibrium was maintained until $T \underset{\sim}{\sim} 1$ MeV. At lower temperatures the weak interaction rate is too slow to keep pace with the universal expansion rate so that few new neutrinos are produced and, equally important, few annihilate. Thus, for $T \underset{\sim}{\sim} 1$ MeV, the neutrinos decouple; at this stage their abundance is given by (13). When the temperature drops below the electron mass, electron-positron pairs annihilate heating the photons but not the decoupled neutrinos. The present ratio of neutrinos to photons must account for the extra photons produced when the $e^\pm$ pairs disappeared.[1]

$$N_\gamma(T < m_e) = \frac{11}{4} N_\gamma(T > m_e) \; ; \quad \left(\frac{n_\nu}{n_\gamma}\right)_0 = \frac{3}{22} g_\nu . \tag{14}$$

From the present density of photons and (14), we obtain the present number density of neutrinos; multiplying by the neutrino mass we obtain the neutrino mass density (ρ_ν) which may be expressed in terms of the density parameter,

$$\Omega_\nu h_0^2 = \left(\frac{g_\nu m_\nu}{200}\right) \left(\frac{T_0}{2.7}\right)^3 . \tag{15}$$

In equation (15) and subsequently, m_ν is in eV.

By analogy with the ordinary charged leptons for which $m_e << m_\mu << m_\tau$, it is likely that there will be one heaviest neutrino. We will, therefore, consider one, two-component (Majorana) neutrino ($g_\nu = 2$); this assumption is for convenience only and may be relaxed easily. For $T_0 \lesssim 3.0°K$ and $h_0 \lesssim 0.7$, the neutrino contribution to the total density is,

$$\Omega_\nu \gtrsim 0.028 m_\nu ; \qquad \frac{\Omega_\nu}{\Omega_N} \gtrsim \frac{m_\nu}{1.4} . \tag{16}$$

Where are these heavy neutrinos today?

Massive neutrinos gravitate and they will have participated in gravitational clustering. However, since neutrinos are non-interacting, their phase space density is conserved and they will cluster only in the deepest potential wells;[10] the slowest moving (i.e.: the heaviest) will cluster most easily.[10] Tremaine and Gunn[10] have shown that neutrinos with $m_\nu \gtrsim 10$ eV will contribute to the mass in binary galaxies. But, from (16), $\Omega_\nu \gtrsim 0.28 >> \Omega(B,SG)$ if $m_\nu \gtrsim 10$ eV. As a result, the heaviest neutrino must be ligher than this ($m_\nu < 10$ eV) so that it may avoid clustering on the scale of binary galaxies.

In contrast, neutrinos lighter than ~ 3 eV will not cluster at all.[10] In between these two limits there is a small but crucially important window for the neutrino mass. Neutrinos with a mass between 3 and 10 eV will contribute to the mass of clusters of galaxies (the deepest potential wells) but not (significantly) to the mass on smaller scales. But recall, the scale on which the missing light problem truly emerges is that of clusters of galaxies. We propose, therefore, that the dominant contribution to the mass of clusters of galaxies (and to the mass of the Universe) is from relic neutrinos with a finite mass $m_\nu \approx 6 \pm 3$ eV.

SUMMARY AND OUTLOOK

We have considered the question of the form and the amount of mass on various scales in the Universe. The abundances of the light elements produced in primordial nucleosynthesis set an upper limit to the nucleon density (equations (3) and (4)). Observations of the luminous parts of galaxies and the hot gas in clusters of galaxies lead to a lower limit to the nucleon density (equation (8)). These limits are consistent provided that the Hubble parameter is not too large ($H_0 \lesssim 70$ kms^{-1} Mpc^{-1}) and they suggest the nucleon contribution to the total mass density lies in the range $0.04 \lesssim \Omega_N \lesssim 0.08$. These results are consistent with estimates of the dynamical mass on scales up to and including binary galaxies and small groups of galaxies. On the scale of clusters of galaxies, a severe unseen mass problem exists (Ω(Clusters) $\gtrsim 0.2$). This problem cannot be solved by nucleons without upsetting the successes of primordial nucleosynthesis. This problem <u>can</u> be solved by relic neutrinos which are heavy enough to collapse into clusters of galaxies ($m_\nu \gtrsim 3$ eV) but not so heavy that they collapse on smaller scales ($m_\nu \lesssim 10$ eV).

Fortunately, our hypothesis leads to testable predictions. If neutrinos have masses, the mass eigenstates and the weak interaction eigenstates will differ leading to neutrino oscillations. The discovery of neutrino oscillations would provide evidence for neutrino masses. Indeed, a significant part of the "solar neutrino problem" may be due to neutrino oscillations.[11] Finally, we note that massive neutrinos move at less than the speed of light. If a neutrino burst from a supernova explosion is detected (for example, by the experiment designed to search for nucleon decay[12]), time-of-flight measurements will determine the neutrino mass.

In conclusion then, we have been led to the proposal that relic neutrinos with a small mass provide the dominant contribution to the mass in the Universe. This intriguing possibility will be tested by laboratory experiments in the near future.

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BIOGRAPHICAL SKETCHES

David N. Schramm was born in St. Louis on October 25, 1945. He received a B.S. from M.I.T. in 1967 and a Ph.D. in physics from Caltech in 1971. Schramm was a postdoctoral fellow in the Kellogg Lab (Caltech; 1971-1972) and a Research Fellow in Astronomy at Texas (Austin; 1972). From 1972 to 1974 he was an Assistant Professor of Astronomy and Physics at Texas. In 1974 Schramm moved to the University of Chicago as an Associate Professor of Astronomy and Astrophysics. Schramm was promoted to Full Professor of Astronomy, Astrophysics and Physics in 1977; since 1978 he has served as Chairman of the Department of Astronomy and Astrophysics.

Gary Steigman was born in New York City on February 23, 1941. He received a B.S. from the City College of New York in 1961 and a Ph.D. from New York University in 1968. Steigman was a Visiting Fellow at the Institute of Theoretical Astronomy (Cambridge, England; 1968-1970) and a postdoctoral fellow in the Kellogg Lab (Caltech; 1970-1972). From 1972 to 1978 he was an Assistant Professor Astronomy at Yale University. In 1978 Steigman joined the Bartol Research Foundation of the Franklin Institute where he is an Associate Professor of Physics.