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DYNAMICAL FRICTION AND MASSIVE NEUTRINOS

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ABSTRACT

The requirement that dynamical friction by massive neutrinos not damp out all peculiar motions of galaxies places a weak upper bound of about 100 eV on the sum of masses of neutrinos which were once in equilibrium with the cosmic microwave radiation background.

INTRODUCTION

There has been much recent interest in neutrino masses in cosmology, as massive neutrinos can reconcile the large mass density required by the virial theorem applied to the dynamics of clusters of galaxies and the smaller upper bound on the baryon density inferred from cosmological helium synthesis.[1] Neutrinos which were in equilibrium early in the universe and which decouple at $kT \sim$ (few) MeV are roughly as abundant as photons today, whereas there is only one baryon per 10^9 photons, so even a small neutrino mass can contribute significantly to the total mass density of the universe. If the neutrinos are light enough to be bound to large clusters but not to individual galaxies, thus providing a "natural" explanation of the increasing mass-to-light ratio seen with increasing length scale, then galaxies are in some sense test particles moving in a sea of neutrinos which define the gravitational potential. That these test particles are in fact moving, that galaxies have peculiar velocities relative to the cosmological expansion, allows us to place an upper limit on m_ν, for in this situation the motions are damped by a process which has become known as dynamical friction.

DYNAMICAL FRICTION

As a massive object moves through a distribution of lighter objects, it deflects gravitationally those bodies which pass near it, with an exchange of momentum $\Delta p_\perp = mv \sin\Theta$, $\Delta p_{||} = mv\,(1 - \cos\Theta)$, where m and v are the mass and asymptotic velocity of the light particle, and Θ is the deflection angle. Summarizing over a large number of collisions, there is no average transverse force, but there is a net transfer of momentum in the logitudinal direction. This is the effect called dynamical friction, first studied by Chandrasekhar[2] in the context of stellar clusters. In our picture, the time scale of dynamical friction is

$$\tau^{-1} = \frac{1}{v_g}\frac{dv_g}{dt} = 4\pi G^2 M_g \rho_\nu v_g^{-3} \ln\Lambda\, F(v_g), \qquad (1)$$

where v_g and M_g are the speed and mass of a galaxy, ρ_ν is the mass density of neutrinos (by assumption the dominant contribution to the total density), Λ is the ratio of maximum and minimum impact parameters, and F is the fraction of neutrinos with $v_\nu < v_g$ $(0 \leq F \leq 1)$.

ASTROPHYSICAL DATA

Unfortunately, from the start none of these parameters are well determined, not because of any measuring difficulty but because of a large intrinsic spread in values. As "typical" values, I take $M_g \sim 4 \times 10^{44}$g and $v_g \sim 100$ km s^{-1} (ref. 4). The galaxy distribution is clumpy, but the average space density of galaxies is $n_g \sim 0.02$ Mpc^{-3} (1 Mpc = 3.086×10^{24} cm), while the average size of a galaxy is of order 10 kpc (again ref. 4), so $\Lambda \sim 100$.

The phase space distribution N of neutrinos is assumed to be known, as once neutrinos decouple they propagate freely with momentum reshifted by the cosmological expansion:

$$N_\nu = [\exp(p_\nu c/kT_\nu) + 1]^{-1}. \qquad (2)$$

This gives a number density $n_i = \frac{3}{4}\zeta(3)\pi^{-2} g_i (kT_\nu/\hbar c)^3$ for each species [$\zeta(3) = 1.20206$]. Electrons and positrons annihilate after neutrinos decouple, heating the photons; from conservation of entropy $T_\nu^3 = \frac{4}{11} T_\gamma^3$ ($T_\gamma = 2.7^\circ$K today). Thus,

$$\rho_\nu = 9.7 \times 10^{-32} \text{ g cm}^{-3}(\Sigma gm/1 \text{ eV}). \qquad (3)$$

From the momentum distribution,

$$F(x) = [\tfrac{3}{2}\zeta(3)]^{-1} \int_0^x x^2 dx (e^x + 1)^{-1}, \qquad (4)$$

with $x = m_\nu v_g c/kT_\nu$, is the final factor in equation (1). For $x \gg 1$, $F = 1 - O(x^2 e^{-x})$, while as $x \to 0$, $F \to 2x^3/9\zeta(3)$.

Thus, we have the dynamical friction lifetime,

$$\tau = 5 \times 10^{19} \text{ sec } [\Sigma\, (g_\nu/2)\, (m_\nu/1\text{eV}) F(x)]^{-1} \qquad (5)$$

Figure 1 shows τ vs. m_ν for $g_\nu = 2$, assuming only one heaviest neutrino species dominates. Also plotted are two bounds on the lifetime of the universe. With a Hubble constant $H_0 = 50$ km s^{-1} Mpc^{-1} and $\Omega_0 = \rho/\rho_{crit} \sim 0$, $t = 6 \times 10^{17}$ s, while from $H_0 = 100$ km s^{-1} Mpc^{-1} and $\Omega_0 \sim 1$, $t = 2 \times 10^{17}$ s. From requiring that the decay time be not too much shorter than the age of the universe, so that peculiar velocities of galaxies are not damped completely, we obtain $\Sigma m_\nu \lesssim 100$ eV.

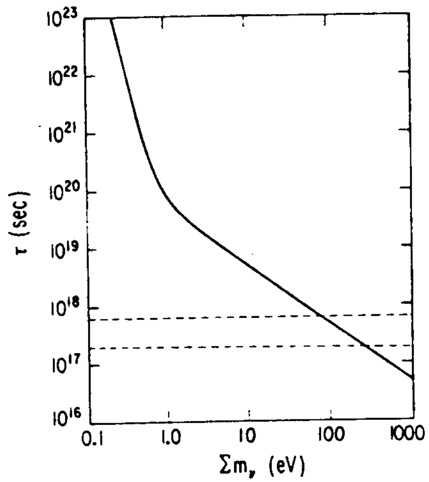

Fig. 1. Dynamical friction lifetime as a function of neutrino mass.

RICH CLUSTERS

The original objective[5] was to try to obtain tighter limits by using clusters of galaxies, where densities and velocities are much higher. Unfortunately, in this case we have no direct knowledge of ρ_ν in terms of m_ν except by assuming neutrinos have the same density contrast seen in the galaxy distribution. The problem is further complicated by having density a function of position rather than uniform. Results[5] are of the same order of magnitude, as might be expected: in forming a cluster, linear separations become smaller by some factor, but to conserve the phase space occupied, velocities must be amplified by the same factor. Thus, ρ_ν/v_g^3 and v_g/v_ν remain roughly constant, and the lifetime as well.

DISCUSSION

Due to the wide ranges of values for the parameters involved, the limit from dynamical friction can not be regarded as anything but a suggestion. Some manifestations of such an effect actually occurring have seen: at the centers of certain classes of rich clusters of galaxies there are bright but dispersed, low surface brightness galaxies, called type cD, which are believed to be created by the merger of ~30 smaller galaxies.[6] Further, masses as large as 100 eV would allow neutrinos to bind to individual galaxies, no longer providing the uniform background assumed above. However, it is a striking coincidence that the limit calculated here, with all the uncertainties involved, is similar to those from other cosmological considerations, and even hints from β-endpoint measurements.

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REACTOR ANTINEUTRINO SPECTRUM AND ITS IMPLICATIONS

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ABSTRACT

Calculation of the reactor associated antineutrino and electron spectra is reviewed and various theoretical spectra are compared to each other and to experimental electron spectra. The available data on reactor antineutrino induced reactions are compared to theoretical expectations. It is concluded that the charged current proton reaction results do not indicate (with one notable exception) neutrino oscillations, in contradiction to the evidence based on the deuteron disintegration reactions.

It is obvious that the only method allowing us to learn something about neutrino masses smaller than about 10 eV is the study of neutrino oscillations. Nuclear reactors are a favorable place for such a study. They provide quite a large flux of electron antineutrinos, namely

$$F(\bar{\nu}_e/cm^2 s) \simeq 1.5 \times 10^{12}\ P/L^2. \quad (1)$$

Here P is the reactor thermal power in MW and L is the distance to the detector in meters. Besides, the neutrino energy is small, E = 2-8 MeV, and the figure of merit for oscillations, L/E, is very advantageous.

There are, however, also problems. Due to the low energy one can study only the disappearance of antineutrinos. Thus in order to prove the existence of oscillations, one has to know or deduce the expected signal without oscillations. This could be achieved in three ways:

a) Use a movable detector and observe deviations (possibly energy dependent) from the $1/r^2$ dependence. Such a device will not be available for another year. Even when it becomes available, one has to know how to treat the (relatively small) time dependence of