LA-UR- 96-3842

CONF-9607178--1

Title: NEUTRINO CLOUDS AND DARK MATTER

Author(s): T. Goldman, T-5, MS B283, Los Alamos National Laboratory,
P.O. Box 1663, Los Alamos, NM 87545, USA

B. H. J. McKellar, University of Melbourne, Parkville, Victoria
3052, Australia

G. J. Stephenson, Jr., University of New Mexico, Albuquerque,
NM 87131, USA

Submitted to: Proceedings of Dark Matter 1996 Conference, Sesto, Italy,
2-5/JUL/96

Los Alamos
NATIONAL LABORATORY

Neutrino Clouds and Dark Matter

T. Goldman

Los Alamos National Laboratory
Los Alamos, NM 87545, USA

B. H. J. McKellar

University of Melbourne
Parkville, Victoria 3052, AUSTRALIA

G. J. Stephenson Jr.

University of New Mexico
Albuquerque, NM 87131, USA

Abstract. We have examined the consequences of assuming the existence of a light scalar boson, weakly coupled to neutrinos, and not coupled to any other light fermions. For a range of parameters, we find that this hypothesis leads to the development of neutrino clusters which form in the early Universe and which provide gravitational fluctuations on scales small compared to a parsec (i.e., the scale of solar systems). Under some conditions, this can produce anomalous gravitational acceleration within solar systems and lead to a vanishing of neutrino mass-squared differences, giving rise to strong neutrino oscillation effects.

1. Introduction

We have recently examined (Stephenson, Goldman and McKellar, 1996) the possibility that, in addition to the Standard Model interactions, neutrinos interact with each other through an extremely light scalar field ϕ. The neutrinos with mass m_i couple to ϕ with constants g_i. For values of the scalar mass and coupling constant which are compatible with known experimental data, the coherent attraction arising from scalar exchange drives clustering of neutrinos in the early Universe. This causes them to decouple from the general expansion at about the epoch of recombination and to provide a source of gravitational fluctuations on a scale small compared to a parsec yet large enough to influence stellar formation. Consistent with known phenomena, these neutrino clouds could form in the early Universe and influence the evolution of structures on stellar scales. The existence of such clustering, persisting to the present epoch, could provide sufficient neutrino capture events to modify the beta spectrum in Tritium beta decay at the end point, affect the motion of interplanetary probes, and amplify oscillations between neutrino types as they propagate outwards from the Sun.

2. The Infinite Problem

The Lagrangian for a Dirac Field interacting with a scalar field is well known:

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m_\nu)\psi + \left[\phi(\partial^2 - m_s^2)\phi/2\right] + g\bar{\psi}\psi\phi \tag{1}$$

which gives as the equations of motion

$$\begin{aligned} \left[\partial^2 + m_s^2\right]\phi &= g\bar{\psi}\psi && (2) \\ \left[i\gamma^\mu \partial_\mu - m_\nu\right]\psi &= -g\phi\psi. && (3) \end{aligned}$$

We omit nonlinear scalar selfcouplings here, even though they are required to exist by field theoretic selfconsistency, as they may consistently be assumed to be sufficiently weak as to be totally irrelevant.

These equations are simply the equations of Quantum Hadrodynamics (Serot and Walecka, 1986), and we will be using them in a small coupling regime where there is no question of the validity of neglecting higher order processes.

To discuss the solutions of this system, we reduce it to dimensionless form, dividing by $m_\nu^{(0)}$, and introducing the parameter $K_0 = \frac{g^2 w (m_\nu^{(0)})^2}{2\pi^2 m_s^2}$, and the variables $y = \frac{m_\nu^*}{m_\nu^{(0)}}, x = \frac{k}{m_\nu^{(0)}}, x_F = \frac{k_F}{m_\nu^{(0)}}$. Then the fundamental equation becomes

$$\begin{aligned} y &= 1 - yK_0 \int_0^{x_F} \frac{x^2\, dx}{\sqrt{y^2 + x^2}} && (4) \\ &= 1 - \frac{yK_0}{2}\left[e_F x_F - y^2 \ln\left(\frac{e_F + x_F}{y}\right)\right], && (5) \end{aligned}$$

where the subscript F indicates the Fermi level value and $e_F = \sqrt{x_F^2 + y^2}$. One can regard Eq.(5) as a non-linear equation for y as a function of either e_F or x_F. As a function of e_F, y is multiple valued (when a solution exists at all), whereas y is a single valued function of x_F.

3. Early Universe

Consider the effects of such clustering on the evolution of structures in the early Universe. Throughout the following discussion, we assume that K_0 is large enough to produce bound systems. At an early enough epoch the density will be sufficiently high that the effective mass is negligible. At that epoch, there is no difference between the interacting neutrinos and the relativistic, non-interacting gas that is usually assumed. Consequently, these neutrinos will expand and decrease in density according to the standard scenario until the increase in the effective mass begins to make a difference, which will occur at about the value of the density (x_F) corresponding to the minimum energy per particle for infinite matter.

As energy is removed from the neutrino gas by scalar bremsstrahlung and redshifted away in the expansion of the Universe, the gas could be viewed as having zero temperature, and that would be the end of the discussion. We would, however, be left with a conundrum. The neutrinos could tolerate no further expansion but the Universe, being driven by all sources of energy density, would be required to continue to expand. This would result in one enormous neutrino cloud.

That, of course, is not the situation. The neutrinos will keep a temperature comparable to that obtained for an expanding, non-interacting gas. As the expansion continues, that temperature will be converted into (effective) mass and the gas will become supercooled, followed by fragmentation into clouds. Note that no additional dissipation is required, unlike the case where clouds coagulate from free particles. The point here is that the neutrinos were born within a cloud and never achieve a state in which the effective mass rises to its vacuum value.

Many neutrinos have been born at later times through normal stellar burning, supernova explosions or other processes. When they encounter a neutrino cloud, the coherent forward scattering is easily large enough, even for very small values of the coupling to the scalar field so that individual scatterings are small, to cause the neutrinos to lose energy through the Bremsstrahlung of scalars, providing additional dissipation.

Two factors drive the size distribution of these clouds. The first is the distribution of fluctuations, which we assume follows Harrison-Zel'dovich (Harrison, 1970; Zel'dovich, 1972). The second is the increase in energy per neutrino with decreasing cloud size for finite clouds. The latter effect provides for a mechanism to cut off the distribution of cloud sizes below some smallest value, the actual efficacy of which depends on the detailed parameter values. The general form of the distribution is

$$P(N) \propto N^{-2} \exp(-C/N^{1/3}).$$

Should this process occur before recombination, then the existence of neutrino clouds would have a profound effect on the evolution of small size structures. (By small, in this context, we refer to structures of the size of solar systems, stars or a bit smaller.) At recombination, when matter decouples from the background photon gas, there will be a pre-existing collection of gravitational sources. The longer the time between cloud formation and recombination, the more these will appear to be point sources, but that does not strongly affect the following argument. Whatever the spectrum of fluctuations in the baryon distribution, these pre-existing sources will nucleate baryon condensation with a distribution that more or less follows the size distribution of the clouds.

Many of these collections of baryons will be large enough to initiate nuclear burning and become stars; others will not. Of the latter, some will attract more baryonic matter from the ejecta of exploding stars to form later generation stars, while others will remain too small to evolve into stars and can provide cold, massive objects. Note that, even if a given cloud does not attract a compliment of baryonic matter, it will still function as a gravitational source. In either case, the increase in the energy per neutrino with decreasing cloud radius, discussed above, will provide a lower limit to the distribution of system sizes. Thus, the existence of neutrino clouds can serve as a seed mechanism for stars and could provide a similar seed for (or be themselves) smaller objects such as MACHOs (Alcock, C. *et. al.*, 1993; Aubourg, E. *et. al.*, 1993).

This scenario suggests that all stars will have their associated neutrino cloud, not because stars attract neutrinos but, rather, because stars form within the gravitational well provided by pre-existing neutrino clouds. One may then ask if, during subsequent evolution, the star and its cloud remain together or if the star, buffeted by forces which ignore the neutrinos, is stripped away leaving the cloud to catalyze another object.

4. Gravitational Effect in the Solar System

Such a neutrino cloud would create a gravitational attraction due to its energy density (note that the static scalar field contributes here). The gravitational acceleration due to various clouds is displayed in Figure 1. Nieto, et al. (Nieto *et al.*, 1995) have recently discussed an anomalous acceleration observed on the Pioneer spacecraft, essentially constant from 10 to 50 AU with a value of $10^{-9} m/s^2$. While Figure 1 raises the possibility of a nearly constant acceleration over a wide range of distances, the magnitude would require an average energy, at a density of $2 \times 10^{15}/cm^3$, of $\approx 50 eV$, far in excess of the values considered here. For this discussion (one generation only), this implies that no useful constraints are likely from gravity. On the other hand, such considerations add strength to the argument that the range of the interaction ought to be of the order of several AU, since the extent of the surface is given by that range. Even though the clouds could be much larger than the scalar range, such clouds would have a relatively sharp surface and would not produce a radial dependence that was gentle enough to appear constant.

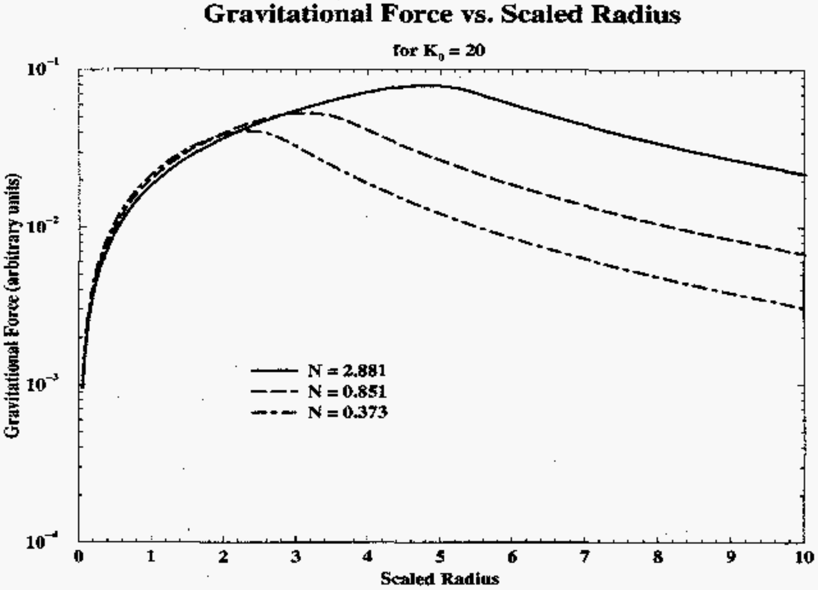

Figure 1. Gravitational Effect of Neutrinos for Three Finite Size Clouds. (N = 1 corresponds to $(m_\nu^0/m_s)^3$ total neutrinos.)

5. Cloud Dynamics

To analyze the dynamics of the system of cloud plus star in a galactic environment, and, in particular, to determine if a star stays within the cloud that seeded its formation, would require a modified Fokker-Planck treatment (Binney and Tremaine, 1987). While a complete treatment would require the complications of at least three generations of neutrinos, we consider only one generation, to illustrate some of the issues.

The primary mechanism for altering a star's trajectory is the gravitational scattering between two stars that pass relatively near each other and, to lowest order, the clouds simply follow along. Since the cloud-star system is polarizable, there will be an induced dipole-dipole interaction, analogous to atomic scattering, which will produce a Van der Waals like interaction. While this may alter the specifics of the velocity distribution slightly, it should not have a major impact on the issue of the cloud remaining with its star.

A more serious question involves the interaction between two clouds when they touch. If we assume that the cloud contains an energy equivalent to about $1M_\odot$, uniformly distributed to 10^{17} cm., then the gravitational binding energy of the star to the cloud is $\approx 10^{39}$ eV or about 10^{-27} eV/ν. For $K_0 = 200$, the surface contribution to the energy per neutrino is $\approx 10^{-3} m_0/\mathrm{N}^{1/3}$. Thus, for the cases of interest here, the surface tension of the clouds overwhelms the gravitational interaction with the stars and the stable final configuration would have one star denuded and the other dressed with twice as many neutrinos. Binney and Tremaine (Binney and Tremaine, 1987) present the estimate that 2 stars, with $R \approx R_\odot$, would actually collide once every 10^{19} yr. If, however, clouds extend to 10^{17} cm. the ratio of geometric cross sections is $\approx 2 \times 10^{12}$, so the encounter rate would be about 2 in 10^7 yr., which is relatively fast on Galactic timescales.

Note, however, that the cloud stays with one star or the other. The evolutionary result of such collisions would be that neutrino clouds would be found only with a fraction of the stars and that that fraction would be smaller in more densely populated regions. Furthermore, the simple argument presented above takes no account of other neutrino generations. The possibility that the Sun has remained with an attendant cloud remains viable.

6. Neutrino Oscillations

With more than one mass eigenstate, it is possible for some m_j^* to become negative. The richness of the system can be demonstrated with a spherically symmetric model in which the various couplings are all equal to the same constant g. Consider, for simplicity, two mass eigenstates, let the vacuum mass of the heavier be denoted by m_h and that of the lighter by m_l. In this case, the shift from the vacuum mass to the effective mass is the same for both neutrinos,

$$\begin{aligned} \Delta m &= g\phi & (6) \\ m_h &= 1 - \Delta m & (7) \\ m_l &= 1 - \Delta m & (8) \end{aligned}$$

For large enough shift this can lead to m_l becoming very negative. If

$$\begin{aligned} m_l^* &= -m_h^*, \quad \text{then} &\qquad (9)\\ {m_h^*}^2 - {m_l^*}^2 &= 0, &\qquad (10) \end{aligned}$$

and there is a degeneracy between the two neutrinos arising from a very different mechanism than that involved in the usual MSW effect (Wolfenstein, 1979; Mikheyev and Smirnov, 1986). Since the change in the effective mass is due to a scalar interaction, it is the same for both ν and $\bar{\nu}$ and the degeneracy will occur at same density, hence the same radius, for both.

If, in addition, there is a normal MSW effect which, being an energy shift due to a vector interaction, has the opposite sign for ν and $\bar{\nu}$, degeneracies will occur at different radii.

To illustrate these points we have generated Figure 2 by representing the results of solving the nonlinear differential equation for the selfconsistent effective mass (Stephenson, Goldman and McKellar, 1996) with a simple analytic form and assuming a linear effect for the vector MSW (clearly, this is far too simple for a real system, but the trends are correctly represented).

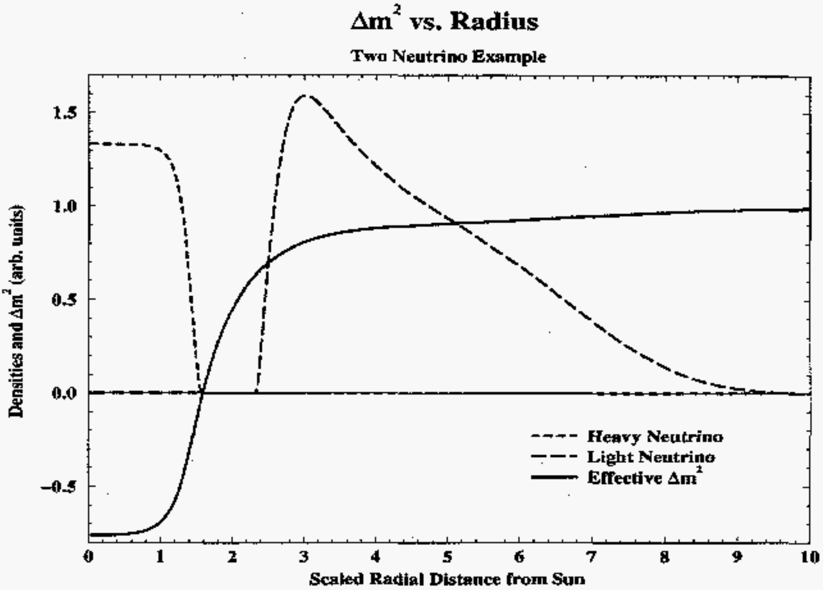

Figure 2. Two neutrino example of Δm^2 for central spherical cloud with spearated spherical annulus cloud.

This result has possible physical implications. It has recently been shown (Fuller, Primack and Qian, 1995; Qian and Fuller, 1995) that r-process nucleosynthesis in the exterior of a Supernova can give a credible account for abundances, provided there is an excess of neutrons over protons. To achieve this, it is desirable to have the $\bar{\nu}$ at a higher temperature than the ν, which can be achieved through enhanced flavor transitions if the $\bar{\nu}$ transition occurs outside the ν transition (Fuller, Primack and Qian, 1995; Qian and Fuller, 1995). These authors suggest that this can be achieved by an inverted spectrum (m_{ν_e} larger than some other mass); it could also be achieved through a scalar interaction.

The extension of these considerations to three generations is straightforward and will be presented elsewhere.

7. Conclusions

For a wide range of parameters, the effect of a weakly coupled scalar boson is that neutrinos will tend to condense into clouds, with dimensions the scale of the inverse boson mass. In fact, for parameters which cause no conflict with laboratory measurements, such clouds could easily be the right size and density to affect experiments on and around the earth.

We have shown that it is likely that any such condensation would have occurred before recombination and that the formation of neutrino clouds could form a natural seeding mechanism for the formation of hadronic objects on the scale of stars. Neutrino cloud formation, being a phase change, occurs very quickly, so these seeds are available at the earliest possible epoch for star formation.

If the density of the electron component of the neutrinos and antineutrinos around the Sun is high enough, there could be observable effects on very sensitive experiments such as the study of Tritium beta decay to search for antineutrino mass effects or double beta decay measurements seeking evidence that neutrinos are Majorana particles.

One consequence of the existence of such an interaction would be that all such measurements would have to be interpreted in terms of effective masses, rather than the vacuum masses that are relevant to model building.

Whether terrestrial effects are observed or not, evidence for or against the existence of such a scalar interaction is most likely to come from astronomy and astrophysics. The implications of the existence of neutrino clouds, with respect to both the time scale and the distribution of sizes, should be amenable to testing through modelling and observation. The gravitational effects within our own Solar system, while subtle, could be observable in very high accuracy satellite tracking data. Depending on the precise model for several generations, one may be able to observe the modifications of oscillation and propagation in the extremely dense neutrino fluxes associated with supernovae.

Finally, we note that although we have focused here on parameters that would be immediately relevant to local tests, there are no obstacles, especially in the more complex case of multiple scalars associated with the multiple families, to significantly different values. For light enough scalars, virtually whatever their coupling, it is easy to imagine that the neutrino clouds could be coincident with the scale of galaxies and be the inferred dark matter that maintains the rotation curves on the largest measured scales.

Acknowledgments. This work has been supported in part by the United States National Science Foundation, the United States Department of Energy, the Australian Research Council and the Australian DIST. We want to thank our colleagues at Los Alamos and at the University of Melbourne for many long and helpful discussions.

References

Stephenson Jr., G. J., Goldman, T. and McKellar, B. H. J., 1996, hep-ph/9603392; Los Alamos preprint LA-UR-96-949; University of Melbourne preprint UM-P-96/29

Serot, B. D. and Walecka, J. D., Adv. in Nucl. Phys. Vol. 16, 1 (1986)

Harrison, E. R. Phys. Rev. D1, 2726 (1970)

Zel'dovich, Ya. B., Mon. Not. Roy. Astron. Soc. 160, 1 (1972)

Alcock, C. *et. al.*, Nature (London), 365, 621 (1993); Aubourg, E. *et. al.*, Nature(London), 365, 623 (1993).

Nieto, M. M., Anderson, J. D., Goldman, T., Lau, E. L., and Pérez-Mercader, J. 1995, in Proceedings of the Third Biennial Conference on Low-Energy Antiproton Physics, LEAP'94, G. Kernel, P. Krizan & M. Mikuz, World Scientific: Singapore, 1995, 606

Binney J. and Tremaine, S., Galactic Dynamics, Princeton University Press: Princeton 1987.

Wolfenstein, L. , Phys. Rev. D17, 2369 (1978); D20, 2364 (1979)

Mikheyev S. P. and Smirnov A. Yu., Nuovo Cimento Soc. Ital. Fis. 9C, 17 (1986)

Fuller, G. M. , Primack, J. R. and Qian, Y.-Z., Phys. Rev. D52, 1288 (1995)

Qian, Y.-Z. and Fuller, G. M. , Phys. Rev. D52, 656 (1995)