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NEUTRAL FERMIONS AS THE MISSING MASS MATTER IN GALACTIC HALOS

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Abstract. We point out that several independent considerations rule out the hypothesis that the missing mass in galactic halos is dominated by massive neutral fermions such as neutrinos, gravitinos or photinos.

1. Introduction

Masses of galaxies in a cluster, as estimated from the virial theorem to account for their observed velocity dispersion, are known to be inadequate by a factor ~ 10 (Faber and Gallagher, 1979), the proportion of the so-called missing mass showing a rising trend with rising dimensions. Explanations for this have mainly been in terms of non-baryonic matter, the more recently suggested candidates being primordial neutral fermions such as the (massive) neutrino, gravitino, and photino. The purpose of this note is to show that such fermions all fail to satisfactorily account for the missing mass.

2. The Neutrino Hypothesis

The neutrino hypothesis has received support because of developments in particle physics (both theoretical and experimental) that accommodate the idea of a finite rest mass for the neutrino. The hypothesis involves the analysis firstly, of the dynamics of the formation of localized self-gravitating systems and, secondly, of the structure of such systems. The simplest approach would be to assume the primordial neutrinos to be completely degenerate (Cowsik and McClelland, 1973; Gao and Ruffini, 1981; Zhang *et al.*, 1983). The condition for this to be valid is that the degeneracy parameter

$$f = (4\pi^2 m_\nu k T_\nu)^{3/2}/n_\nu h^3 , \tag{1}$$

must be $\ll 1$. Here m_ν, T_ν, and n_ν are the rest mass, temperature, and number density of the (non-relativistic) neutrinos; k, the Boltzmann constant; and h, the Planck constant. Assuming three (Dirac-type) neutrino species in nature, having a present

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background temperature of 2 K, we find that

$$n_\nu = 200\ \mathrm{cm}^{-3}\,. \tag{2}$$

This gives $f \gg 1$, for a reasonable choice of m_ν (say, 30 eV). Thus, complete neutrino degeneracy is not a good assumption, except in the very early universe. Furthermore, since $n \propto R^{-3}$; $T \propto R^{-1}$ in an (adiabatically) expanding universe with scale factor R,

$$f \propto R^{3/2}\,. \tag{3}$$

This implies that the primordial neutrino gas becomes less and less degenerate as the Universe undergoes expansion.

The assumption of complete neutrino degeneracy is also in contradiction with the observational information (Zhang *et al.*, 1983). Equilibrium configurations of self-gravitating, non-relativistic, degenerate neutrinos do not yield the density distribution ($\rho \propto r^{-2}$) needed to explain the observed (a) flat rotation curves of many galaxies in a cluster as well as (b) linear mass-radius dependence (one gets $M \propto R^{-3}$ instead).

The inclusion of thermal effects does not support the neutrino hypothesis (Chau *et al.*, 1984), except for the limiting case of a purely isothermal neutrino distribution. In that case one does get the required density dependence. However, this would require very large values of m_ν ($\gtrsim 300$ eV) to ensure that the thermal velocities do not become too high leading to a disintegration of the neutrino halo. Such high velocities can be contained by requiring that neutrinos be trapped by the gravitational potential wells of massive systems that eventually form single galaxies or clusters of galaxies. One consequence of this is the fact that the ratio of the unseen mass to the luminous mass is directly proportional to m_ν (Tremaine and Gunn, 1979). Observationally, this ratio is known to vary (Faber and Gallagher, 1979), being largest in clusters of galaxies and smallest in single galaxies. This would then suggest the existence of a wide range of values of m_ν. In this connection it is relevant to note that very massive neutrinos will lead to a closed universe and may give an age of the universe that is embarrasingly small for the standard hot big-bang cosmology. On the other hand, with comparatively low values of m_ν, the gravitational clumping on the scale of a single galaxy may not be possible.

Schramm and Steigman (1981) give a relation between m_ν, the baryon-to-photon ratio ($\sim 10^{-10}$) and the photon-to-neutrino ratio ($\frac{22}{18}$, for three 2-component neutrinos). This gives $m_\nu < 2$ eV (assuming an 80% ν content) or $m_\nu < 6$ eV if only one neutrino flavour has mass. Neutrinos of mass $<(5\text{–}10)$ eV are adequate for providing the missing mass in large clusters like Virgo or Coma, but for large spiral galaxies and the Milky Way, one needs $m_\nu > 50$ eV. This range of m_ν is rather wide, and shows that a single value of m_ν fails to account for the same amount of missing matter in different objects.

3. Phase-Space Considerations

Since neutrinos are fermions, their phase space density must satisfy the inequality

$$\mathrm{d}^3x\,\mathrm{d}^3p \geq h^{-3}\,. \tag{4}$$

For non-relativistic neutrinos with an isotropic velocity V, this gives

$$n_\nu/(m_\nu V)^3 \leq h^3 , \tag{5}$$

where n_ν is the neutrino number density. This implies that

$$m_\nu \geq (h^3 \rho/V)^{1/4} , \tag{6}$$

where ρ ($= n_\nu m_\nu$) is the density of the halo population. A reasonable choice for ρ is 10^{-24} g cm^{-3} (Caldwell and Ostriker, 1979). Now, if we consider a galaxy like the Milky Way, with a velocity dispersion $\sim$(200–300) km s^{-1} and which may have as much unseen matter as luminous matter (Hawkins, 1983), Equation (6) implies that

$$m_\nu \geq 50 \text{ eV} . \tag{7}$$

This is outside the range of the experimentally suggested value (Lyubimov *et al.*, 1980), and may lead to too small a value for the age of the universe.

Recent data on Draco imply that unseen matter dominates the gravitational potential of dwarf spheroidal galaxies (Aaronson, 1983; Lin and Faber, 1983). This, from the above arguments on phase space density of neutrinos, Equation (6), would push up the required neutrino mass (to dominate the dynamics) to several hundred electron volts, incompatible both with experimentally suggested values (Lyubimov *et al.*, 1980) and those derived on the basis of cosmological constraints (Greenstein and Zel'dovich, 1966; Cowsik and McClelland, 1972; Szalay and Marx, 1976).

4. Non-Primordial Neutrinos

Since, as shown earlier, the big-bang relic neutrinos face several inconsistencies in explaining the missing mass, we consider, as an alternative, non-primordial neutrinos. An important source of such neutrinos is supernova explosions. Nuclear fusion processes in massive stars (which are thought to lead to supernova explosions) terminate with the production of a large quantity ($\sim 1\ M_\odot$) of the isotope ^{56}Ni at the peak of the binding energy curve. ^{56}Ni decays by electron capture and positron decay to ^{56}Co, which further decays to ^{56}Fe by positron emission. Both the processes are accompanied by generation of neutrinos with energy ~ 1 MeV. Thus, each supernova, with the decay of $\sim 1\ M_\odot$ of ^{56}Ni, would produce $\sim 2 \times 10^{57}$ neutrinos (assuming one supernova event per galaxy every 50 yr and taking 10^{11} galaxies). This would then result in a production of at most $\sim 10^{78}$ neutrinos during a Hubble-age. Even to account for most of the missing mass with $m_\nu = 10$ eV for the Coma cluster, we require $\sim 10^{80}$ neutrinos for this cluster alone. Thus, neutrinos from supernova or neutron stars (which are the most intense source of non-primordial neutrinos), even when added up over an entire Hubble-age, will provide too few neutrinos to account for the missing mass in a large galactic cluster such as Coma, let alone all the other clusters. Moreover, such neutrinos, being energetic, are unlikely to get bound to galaxies or clusters.

The situation is not better with population III objects. Even if such objects produced all the helium and heavy elements, these would produce at most $\sim 10^{79}$ neutrinos – inadequate by a wide margin even to dominate large clusters.

5. Gravitinos and Photinos

It has been suggested (Silk, 1982) that gravitinos are more suitable candidates than neutrinos for the unseen mass, since there are problems with galaxy formation scenarios involving massive neutrinos. From supersymmetry considerations, Pagels and Primack (1982) find that gravitinos could be the major material constituent of the Universe and could provide the dark matter in galactic halos and small clusters of galaxies.

The cosmological constraints that (primordial) gravitinos should not contribute excessive mass density or entropy (when these decay) give the following limits on the gravitino mass

$$m_g \lesssim 0(1)\,\mathrm{keV}\,, \qquad m_g \gtrsim 0(10^4)\,\mathrm{GeV}\,. \tag{8}$$

The lower mass limit in (8) is in the right range of masses needed for galaxy formation. However, it is in conflict with the limit

$$m_g \lesssim 0(10^2)\,\mathrm{GeV}\,, \tag{9}$$

derived on the basis of supersymmetry theory (Ellis and Nanopoulos, 1982). The value (9) can be retained without violating any cosmological constraint by introducing a relatively modest amount of inflation in the evolution of the Universe which can suppress the primordial gravitino number density sufficiently to make the conditions (8) redundant (Ellis *et al.*, 1982). The conclusion is that if current supersymmetry theories and the inflationary universe ideas are viable, the gravitino is an unacceptable candidate for the unseen mass.

A further constraint on the gravitino mass can be derived from general relativistic considerations. It has been shown (e.g., Chandrasekhar and Tooper, 1984 for white dwarfs, and Fowler, 1966 for supermassive objects) that general relativistic instabilities set in when the radius of the self-gravitating object is sufficiently higher than the corresponding Schwarzschild radius, leading to eventual collapse to a black hole. The instability condition is

$$R \geq 250 R_{\mathrm{Sch}} = 500 GM/c^2\,. \tag{10}$$

For a self-gravitating system of degenerate gravitinos, this gives (here g is the helicity parameter),

$$m_g \lesssim \frac{\hbar^{3/4} c^{3/4}}{(500)^{3/8} g^{1/8} G^{3/4} M^{1/2}}\,. \tag{11}$$

For typical values of $M \sim 10^{12} M_\odot$, this gives

$$m_g \lesssim 500\ \mathrm{eV}\,. \tag{12}$$

This value is way below the value (9) obtained on the basis of supersymmetry. It will also rule out gravitinos with keV range mass as possible candidates for the missing mass (Silk, 1982).

Another light neutral fermion, predicted by supersymmetry and possibly relevant in the present context, is the photino. If the photino rest mass is ~(10–100) eV), these could replace massive neutrinos as dark matter in galactic halos (Sciama, 1983). However, most particle theory considerations give a lower limit on the photino mass in the range (0.5–2) GeV (Ellis, 1983; Goldberg, 1983; Barbieri *et al.*, 1983). This will rule out 'warm' photinos with mass (100 eV–1 MeV) as candidates for the missing mass.

6. Conclusions

The requirement of a very wide range of neutrino masses (from a few eV to ~100 eV) to account for the missing mass in different classes of galactic objects implies a mass hierarchy of neutrinos. This is incompatible with known elementary particle mass data, and is outside the range (14–46 eV) suggested from experiment (Lyubimov *et al.*, 1980). Moreover, the hypothesis that galactic halos are composed of degenerate massive primordial neutrinos does not naturally account for the observational features of such halos like the flat rotation curves and density distributions. The inclusion of non-degenerate neutrino distributions does not improve the situation. We have also shown the inadequacy of non-primordial neutrinos to explain the discrepant mass. Thus, massive neutrinos are unsatisfactory candidates for the missing matter in galactic halos. Furthermore, if current theoretical ideas about supersymmetry are correct, then other neutral fermions such as gravitinos and photinos would also be ruled out as alternative candidates for the missing mass.

References

Aaronson, M.: 1983 *Astrophys. J.* **266**, L11.

Barbieri, R., Cabibbo, N., Maiani, L., and Petrarca, S.: 1983, *Phys. Letters* **127B**, 458.

Caldwell, J. A. R. and Ostriker, J. P.: 1981, *Astrophys. J.* **251**, 61.

Chandrasekhar, S. and Tooper, R. F.: 1964, *Astrophys. J.* **139**, 1396.

Chau, W. Y., Lake, K., and Stone, J.: 1984, *Astrophys. J.* **281**, 560.

Cowsik, R. and McClelland, J. M.: 1972, *Phys. Rev. Letters* **29**, 669.

Cowsik, R. and McClelland, J. M.: 1973, *Astrophys. J.* **180**, 7.

Ellis, J.: 1983, CERN preprint TH-3773.

Ellis, J. and Nanopoulos, D. V.: 1982, *Phys. Letters* **116B**, 133.

Ellis, J., Ferrara, S., and Nanopoulos, D. V.: 1982, *Phys. Letters* **114B**, 231.

Faber, S. M. and Gallagher, J. S.: 1979, *Ann. Rev. Astron. Astrophys.* **17**, 135.

Fowler, W. A.: 1966, *Astrophys. J.* **144**, 180.

Gao, J. G. and Ruffini, R.: 1981, *Phys. Letters* **100B**, 47.

Goldberg, H.: 1983, *Phys. Rev. Letters* **50**, 1419.

Greenstein, S. S. and Zel'dovich, Ya. B.: 1966, *Soviet Phys. JETP Letters* **4**, 120.

Hawkins, M. R. S.: 1983, *Nature* **303**, 406.

Lin, D. and Faber, S. M.: 1983, *Astrophys. J.* **266**, L21.

Lyubimov, V. A., Novikov, E. G., Nozik, V. Z., Tretyakov, E. F., and Kosik, V. S. : 1980, *Phys. Letters* **94B**, 266.

Pagels, H. and Primack, J.: 1982, *Phys. Rev. Letters* **48**, 223.

Schramm, D. and Steigman, G.: 1981, *Astrophys. J.* **243**, 1.

Sciama, D. W.: 1983, in G. O. Abell and G. Chincarini (eds.), 'Early Evolution of the Universe and its Present Structure', *IAU Symp.* **104**, 493.

Silk, J.: 1982, *Nature* **297**, 102.

Szalay, A. S. and Marx, G.: 1976, *Astron. Astrophys.* **49**, 437.

Tremaine, S. and Gunn, J. E.: 1979, *Phys. Rev. Letters* **42**, 407.

Zhang, J. L., Chau, W. Y., Lake, K., and Stone, J.: 1983, *Astrophys. Space Sci.* **96**, 417.