Can Galactic Halos Be Made of Axions?

J. Ipser and P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611
(Received 29 December 1982)

If axions exist, they contribute significantly to the present energy density. These axions have been collisionless and nonrelativistic since their appearance at ~1 GeV. Hence axion density perturbations survive on essentially all scales, and once the axions are dominant, grow and in turn create and amplify baryon fluctuations. Axions can cluster into galactic halos even though the axion mass $\lesssim 10^{-2}$ eV. If galactic halo matter is mainly axions, the Peccei-Quinn order parameter $\gtrsim 10^{10}$ GeV.

PACS numbers: 98.50.Eb, 14.80.Gt, 95.30.Cq

The evidence[1] that individual galaxies possess massive dark halos with masses exceeding that of the luminous galactic matter by a factor ~10 has generated extensive investigation into the makeup, origin, and influence of such halos. While alternative possibilities, e.g., involving black holes,[2] have been considered, perhaps the most popular of all has been the suggestion[3] that the dark halo material is composed mainly of massive neutrinos.[4] It has become increasingly clear recently, however, that neutrino-halo models run into rather serious cosmological problems.

First of all, it appears that the neutrino mass is constrained to lie in a somewhat narrow range. An upper limit arises from measurements of the deceleration parameter, which suggest that

$$\Omega_{\nu 0} = (0.31)\left(\frac{\sum m_\nu}{30\ \text{eV}}\right)\left(\frac{100\ \text{km s}^{-1}\,\text{Mpc}^{-1}}{H_0}\right)^2 \lesssim 2, \tag{1}$$

where $\Omega_{\nu 0}$ is the present ratio of neutrino density to closure density, H_0 is the present Hubble constant and $\sum m_\nu$ is the sum of the neutrino masses. It is thus required that $\sum m_\nu \lesssim 200$ eV. On the other hand, a lower limit arises because neutrinos, being collisionless, preserve their maximum phase-space density. Following Tremaine and Gunn,[5] one finds that a given neutrino type can cluster sufficiently to make galactic halos only if

$$m_\nu \gtrsim (30\ \text{eV})\left(\frac{300\ \text{km/s}}{V_g}\right)^{1/4}\left(\frac{10\ \text{kpc}}{r_c}\right)^{1/2}, \tag{2}$$

where r_c is the galactic core radius and V_g the galactic velocity dispersion. The Pauli exclusion principle places a limit on m_ν similar to (2) and only less severe by a factor $2^{1/4}$.

But even if the neutrino mass satisfies the above constraints, there are other problems: Neutrino free streaming implies that all primordial neutrino density fluctuations in a Friedman universe are wiped out on mass scales less than the effective maximum neutrino Jean's mass[6,7]

$$M_{J,\nu,\max} \lesssim 4\times 10^{15}(30\ \text{eV}/\sum m_\nu)^2 M_\odot, \tag{3}$$

where $M_\odot$ is 10^{33} g. Moreover, the growth of baryon fluctuations on scales smaller than $M_{J,B,\max} = (\Omega_B/\Omega_\nu)M_{J,\nu,\max}$ is greatly inhibited.[6,7] Ω_B is the ratio of baryon density to closure density. One is apparently forced to conclude that either large nonlinear baryon perturbations already exist on galactic scales ($10^6 M_\odot \lesssim M_B \lesssim 10^{13} M_\odot$) at recombination, or condensations first appear on scales appropriate to rich clusters of galaxies and only later do processes within clusters lead to galaxy formation. The former alternative appears unnatural. The latter one presents the stark problem of explaining how neutrinos that pick up random velocities of order 1500 km/s during the initial cluster collapse can subsequently be trapped around galaxies in halos whose velocity dispersions are only about 300 km/s.

It is our purpose in this Letter to point out that the above problems can be circumvented in one fell swoop by replacing the neutrinos in galactic halos with other weakly interacting particles, the axions. These spin-0 pseudo-Goldstone bosons arise as a consequence of incorporating the Peccei-Quinn[8] $U(1)_{PQ}$ quasisymmetry into the standard model of elementary particles to explain in a natural way the absence of CP invariance violation in the strong interactions. The mass of the axion[9] $m_a \simeq f_\pi m_\pi/v$ and its couplings $[\sim ia(m_f/v)\bar{f}\gamma_5 f$ to fermions and $\sim N(g^2/32\pi^2)(a/v) \times F_{\mu\nu}\tilde{F}^{\mu\nu}$ to photons and gluons$]$ depend inversely on the vacuum expectation value[10] v of the scalar field φ that spontaneously breaks $U(1)_{PQ}$. Constraints on axion models arise from laboratory experiments, from astrophysics,[11] and from cosmology.[12,13] The fact that axions have not been found in the laboratory requires that $v \gtrsim 300$ GeV (although some varieties of heavy axions might still be compatible with the data). The astrophysical constraint[11] arises because axion emission can lead to excessive energy loss from stars. To avoid this one must exclude the range $300\ \mathrm{GeV} \lesssim v \lesssim 10^8$ GeV. Further, it has been shown[13] recently that axions close the universe several times over unless $v \lesssim 10^{12}$ GeV. It thus appears that if axions exist, v should lie somewhere between 10^8 and 10^{12} GeV, in which case axions are an important component of the present energy density and hence may have important cosmological consequences. Before going on, we should mention that another cosmological constraint[12] arises because axion models have spontaneously broken discrete symmetries and hence domain walls.[14] In the standard cosmological model, the domain walls will dominate the energy density before decoupling and produce the unacceptable behavior $R \sim t^2$. The domain-wall problem can be avoided either by adopting an inflationary cosmology[15] where the inflation occurs after the $U(1)_{PQ}$ symmetry is spontaneously broken, or by expressly constructing the axion model in such a way that its vacuum is unique.[12,16]

Concerning the formation of galactic halos, it might at first appear that axions present worse problems than do neutrinos, since their mass

$$m_a \simeq 10^{-3}\ \mathrm{eV}\,(10^{10}\ \mathrm{GeV}/v) \tag{4}$$

badly violates (2) for $10^8 \leq v \leq 10^{12}$ GeV. This is not so, however. To show this, we describe briefly how the $v \lesssim 10^{12}$ GeV cosmological constraint is derived. $U(1)_{PQ}$ is spontaneously broken when the temperature drops below a critical temperature T_{PQ} of order v. The Peccei-Quinn order parameter $\langle \varphi \rangle$ now lies at a random point on a circle:

$$\langle \varphi \rangle = v e^{i\alpha}\,. \tag{5}$$

When the temperature reaches about 1 GeV, QCD effects switch on. The vacuum energy becomes α dependent and has its minimum value at a particular point on the circle, say at $\alpha = 0$, for which there is no *CP* invariance violation in the strong interactions. The square of the axion mass is $(1/v^2)$ times the second derivative of the vacuum energy density with respect to α at $\alpha = 0$. The misalignment of α (with respect to $\alpha = 0$) when QCD switches on at $t_{QCD} \simeq 10^{-4}$ s corresponds to a coherent state of nearly zero momentum axions [initial velocity dispersion $V_i \sim (1/t_{QCD} m_a) \sim 10^{-8} \times (v/10^{10}\ \mathrm{GeV})$]. It is these axions which close the universe[13] unless v is well below 10^{12} GeV. They have the unusual property of being nonrelativistic when they first appear at temperatures (~1 GeV) much larger than their mass. However, for $10^8 \leq v \leq 10^{12}$ GeV, these axions are effectively decoupled[13] and hence collisionless. The present axion energy density was found[13] to be

$$\rho_{a,0} \simeq \rho_{\mathrm{crit},0}\left(\frac{v}{10^{11}\ \mathrm{GeV}}\right)^{7/6}, \tag{6}$$

where $\rho_{\mathrm{crit},0}$ is the present closure density.

Since the velocity dispersion of these axions is so small, their phase-space density is much larger than what is required to cluster into galactic halos. Another consequence is that the axion free-streaming distance is very short and thus axion density fluctuations are preserved on all scales. Hence, axions easily obviate the two difficulties confronting neutrino galactic halos.

Consider then the growth of fluctuations in a universe whose matter density is dominated by axions. While it is not the purpose of this paper to discuss what caused the primordial density perturbations, we do note that these could be caused by the presence of domain walls for a limited time period after $t \simeq 10^{-4}$ sec, as has been proposed earlier by one of us.[12] Since these axions are pressureless and decoupled, axion density fluctuations are preserved and permitted to grow on essentially all mass scales that have come within the horizon at a given time. For length scales greater than $Vt \sim [t/R(t)]$, they obey the equation

$$\ddot{\delta}_a + 2\frac{\dot{R}}{R}\dot{\delta}_a \simeq 4\pi G\rho_a\delta_a\,, \tag{7}$$

where ρ_a is the axion energy density, $\delta_a = (\delta\rho_a/\rho_a)$, R is the scale factor, and a dot denotes differentiation with respect to cosmic time. The solution[17] is as follows:

$$\delta_a \simeq \mathrm{const}(1 + \tfrac{3}{2}\rho_a/\rho_R) \tag{8}$$

with $\rho_R \sim R^{-4}$ and $\rho_a \sim R^{-3}$. By the time of recombination initial axion perturbations have amplified by $\sim 100\% \times (\Omega_a/\Omega_B)$, and in the matter dominated phase their growth accelerates. Hence, unlike neutrinos, axions are afforded the opportunity to condense first on galactic scales rather than on significantly larger scales. As was mentioned earlier, the reverse scenario (condensation first on the scale of clusters of galaxies) suffers from the serious difficulty of trapping fast particles in gravitational potentials whose virial velocities are smaller than the velocities of the particles by factor ~5.

Once the baryonic matter decouples from the radiation, it is free to pick up existing axion perturbations. $\delta_B = \delta\rho_B/\rho_B$ obeys Eq. (7) with δ_a replaced by δ_B on the left-hand side. The resulting inhomogeneous equation yields a solution $\delta_B = C_1 + C_2 t^{-1/3} + \delta_a$ (C_1 and C_2 are integration constants) that grows and approaches δ_a on the Hubble time scale, even if δ_B vanishes initially. Hence in this picture there is no problem with having $\delta_B \lesssim 10^{-4}$ at recombination in order to guarantee consistency with the observed isotropy of the cosmic radiowave background.

In summary, axions might be useful in constructing galactic halos. Their utility derives from the following key properties: They are pseudo-Goldstone bosons, they have a "soft" mass (i.e., their mass falls off sharply above a certain temperature T_0; $T_0 \sim 1$ GeV for axions), and they are sufficiently well decoupled ($v \gg T_0$). Any other such particle is potentially useful to construct galactic halos. But the axion fits the bill remarkably well.

This work was supported in part by the National Science Foundation and by the U. S. Department of Energy under Contract No. DSR 80136je7. We would like to thank Pierre Ramond for useful discussions.

[1]J. P. Ostriker, P. J. E. Peebles, and A. Yahil, Astrophys. J. Lett. 193, L1 (1974); J. Einasto, A. Kaasik, and E. Saar, Nature (London) 250, 309 (1974).

[2]J. Isper and R. Price, Astrophys. J. 216, 578 (1977).

[3]R. Cowsik and J. McClelland, Phys. Rev. Lett. 29, 669 (1972).

[4]M. Gell-Mann, P. Ramond, and R. Slansky, unpublished; P. Ramond, California Institute of Technology Report No. CALT-68-709, 1979 (to be published); T. Yanagida, in Proceedings of the Workshop on the Unified Theory and Baryon Number in the Universe, Tsukub, Ibaraki, Japan, 1979 (unpublished).

[5]S. Tremaine and J. E. Gunn, Phys. Rev. Lett. 42, 407 (1979).

[6]J. R. Bond, G. Efstathiou, and J. Silk, Phys. Rev. Lett. 45, 1980 (1980).

[7]M. Davis, M. Lecar, C. Pryor, and E. Witten, Astrophys. J. 250, 423 (1981).

[8]R. D. Peccei and H. Quinn, Phys. Rev. Lett. 38, 1440 (1977).

[9]S. Weinberg, Phys. Rev. Lett. 40, 223 (1978); F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).

[10]J. Kim, Phys. Rev. Lett. 43, 103 (1979); M. Dine, W. Fischler, and M. Srednicki, Phys. Lett. 104B, 199 (1981).

[11]D. A. Dicus, E. W. Kolb, V. L. Teplitz, and R. V. Wagoner, Phys. Rev. D 22, 839 (1980); M. Fukugita, S. Watamura, and M. Yoshimura, Phys. Rev. Lett. 48, 1522 (1982).

[12]P. Sikivie, Phys. Rev. Lett. 48, 1156 (1982).

[13]L. Abbot and P. Sikivie, to be published; J. Preskill, M. Wise, and F. Wilczek, to be published; M. Dine and W. Fischler, to be published.

[14]Y. B. Zel'dovich, I. Y. Kobzarev, and L. B. Okun, Zh. Eksp. Teor. Fiz. 67, 3 (1974) [Sov. Phys. JETP 40, 1 (1975)].

[15]A. Guth, Phys. Rev. D 23, 347 (1981).

[16]G. Lazarides and Q. Shafi, Rockefeller Institute Report No. RU89-B-27, 1982 (to be published); B. Holdom, Stanford University Reports No. ITP-712, 1982 (to be published) and No. ITP-713, 1982 (to be published); H. Georgi and M. Wise, Harvard University Report No. HUTP-82-A037, 1982 (to be published); S. Dimopoulos, P. Frampton, H. Georgi, and M. Wise, Harvard University Report No. HUTP-82-A040, 1982 (to be published); S. Barr, D. Reiss, and A. Zee, University of Washington Report No. 40048-18P2, 1982 (to be published); S. Barr, X. C. Gao, and D. Reiss, University of Washington Report No. 40048-22P2, 1982 (to be published); Y. Fujimoto, K. Shigemoto, and Zhao Zhi-yong, International Centre for Theoretical Physics Report No. IC-82-140, 1982 (to be published).

[17]P. Meszaros, Astron. Astrophys. 37, 225 (1974).