# Luminous Axion Clusters

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Density fluctuations of axionic dark matter decaying to photons are shown to have possibly measurable luminosities.

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The axion with a mass $m_a$ in the electronvolt range has been termed "invisible" because it interacts very, very weakly. Its lifetime far exceeds the age of the Universe, $\tau_a \sim 10^7[m_a/(1\text{ eV})]^{-5}\tau_{\text{Univ}}$. Its decay channel is to two photons. The number ($N_a$) of axions in a cluster (mass $M$) is $N_a \sim 10^{66}(M/M_\odot)[(1\text{ eV})/m_a]$. It seems to have gone unnoticed that this number may be so large that the cluster luminosity $L = m_a N_a/\tau_a$ is easily measured! In this Letter we explore this possibility of observable axion clusters. Let us first recall a few details about axions and the strong *CP* problem.

The simplest mechanism for the elimination of *CP* nonconservation from strong interactions is to introduce a color-anomalous global U(1) symmetry into the Lagrangean.[1] Because this U(1) symmetry is only approximate (it is broken explicitly by nonperturbative effects), upon spontaneous breaking a pseudo-Goldstone boson, rather than a massless boson, is generated. This particle is the axion.[2] Its coupling to matter is inversely proportional to the scale $f_a$ where the U(1) symmetry spontaneously broke. Terrestrial experiments[3] and astrophysical arguments[4,5] originally led to[6] the bound $10^{12} \gtrsim f_a \gtrsim 10^8$ GeV. The lower bound on $f_a$, which is derived from axion emission rates from stellar interiors, is loosened when plasma screening effects are taken into account.[7] In Kim-Shifman-Vainshtein-Zakharov-type models,[8] in which the axion does not couple directly to the electron,[9] the lower bound is also loosened.[10] Current algebra allows one to derive a relation between $m_a$ and $f_a$, from which there immediately follow axion mass bounds. The plasma effect[7] or axion models with suppressed coupling to electrons[10] each allow an axion mass as heavy as 20 eV. The combined effect allows even heavier axion masses. For our purposes we take the upper bound as 25 eV, that which gives an axion lifetime equal to 10 Gyr, roughly the age of the Universe. Given the assumptions of Ref. 5 and of Turner,[11], there exists the relation between the axion mass and mass density $\Omega_a$ (in units of the critical closure density)

$$\Omega_a \simeq (10^{-6}/h^2)[(1\text{ eV})/m_a]^{1.175}, \tag{1}$$

where the Hubble parameter is $H_0 = 100h$ km/s Mpc. Axions close the Universe if $m_a$ is less than $10^{-5}$ eV.[5,12] So we have

$$10^{-5}\text{ eV} \le m_a \le 25\text{ eV}. \tag{2}$$

Because axions qualify as "cold dark matter," they enjoy unique advantages as the origin of density fluctuations that seed formation of galaxies, clusters, and superclusters. Numerical simulations have shown the axion to be a promising dark-matter candidate.[13] Like the pion, the axion is a pseudoscalar pseudo-Goldstone boson and decays to two photons through the anomaly diagram (a closed fermion loop). Consequently, the axion lifetime is related to that of the neutral pion by the formula

$$\tau_a \cong (m_\pi/m_a)^5 \tau_\pi \sim 10^8[m_a/(1\text{ eV})]^{-5}\text{ Gyr}. \tag{3}$$

Consider an axion cluster at a distance $D$ from the earth. For simplicity we assume that the cluster is transparent to photons and consider only spontaneous emission. This latter assumption is conservative; stimulated emission[14] can only enhance the axion cluster's luminosity. Since self-interactions of invisible axions are so weak that clustered axions cannot cool within the age of the Universe, the clusters are expected to remain extended objects rather than collapse to black holes.[15] The luminosity of the cluster with axion number $N_a$ is

$$L = \frac{m_a N_a}{\tau_a} \sim 4\times 10^{29}\left(\frac{m_a}{1\text{ eV}}\right)^5 \frac{M}{M_\odot}\,\frac{\text{erg}}{\text{s}} \sim 10^{-4}\left(\frac{m_a}{1\text{ eV}}\right)^5 \frac{M}{M_\odot} L_\odot. \tag{4}$$

$M$ is the total mass of axion in the cluster; $M_\odot$ and $L_\odot$ are the solar mass and luminosity. Notice that a solar mass of 1–10-eV axions has a luminosity comparable to that of the sun, and a galactic mass of 1–10-eV axions has a luminosity comparable to that of a galaxy. This is the main point of this Letter, that *depending on the axion mass, clustered axions may have an observable luminosity, possibly even approaching that of stellar matter of comparable total mass.* Being possibly observable, axion clusters should be looked for.

The lifetime of the axion cluster is just the axion lifetime. If stimulated emission is important, the luminosity will of course be larger, and the lifetime shorter. The flux observed at earth is simply

$$F = L/4\pi D^2. \tag{5}$$

If we express the source distance from earth in terms of the cosmological red shift $z_c$, i.e., $D = 300h^{-1}(z_c/0.1)$

 

Mpc, this can be written as

$$F = 4.4\times 10^{-29} h^2 \left(\frac{M}{M_\odot}\right)\left(\frac{0.1}{z_c}\right)^2\left[\frac{m_a}{1\ \text{eV}}\right]^5 \frac{\text{W}}{\text{m}^2}. \quad (6)$$

The maximum axion velocity (in units of $c$), denoted by $\beta$, is related to the cluster mass and radius $l$ by

$$\beta \sim \left[\frac{GM}{l}\right]^{1/2} \sim 2\times 10^{-7}\left\{\frac{M/M_\odot}{l/(1\ \text{pc})}\right\}^{1/2}. \quad (7)$$

This relation neglects any possible cluster rotation. For a sufficiently dense axion cluster (unlikely), some of the observed red shift would have a gravitational origin. A useful relation between source mass, source radius, and the surface gravitational red shift $z_g$ is

$$2GM/l = z_g(2+z_g)/(1+z_g)^2 \equiv f(z_g). \quad (8)$$

Substituting Eq. (8) into Eq. (6) gives the more general result

$$F = 4.7\times 10^{-16} h^2 (0.1/z_c)^2 f(z_g)[l/(1\ \text{pc})][m_a/(1\ \text{eV})]^5\ \text{W/m}^2. \quad (9)$$

For $z_g \lesssim 0.1$, $f(z_g) \simeq 2z_g$. The observed red shift is $z = z_c + z_g$.

Suppose that a mass fraction $x_a$ of our Milky Way halo is axionic. Using the results of a realistic isothermal sphere model for the distribution of the halo matter, one finds for the local photon intensity

$$\frac{dI}{d\Omega} = \frac{\rho(0) x_a K}{2\pi m_a \tau_a [1+(R/K)^2\sin^2\theta]^{1/2}}\left\{\frac{\pi}{2} + \tan^{-1}\frac{(R/K)\cos\theta}{[1+(R/K)^2\sin^2\theta]^{1/2}}\right\}, \quad (10)$$

where $\rho(0)$ is the mass density at the galactic center, $R \simeq 9$ kpc is the distance of our earth from the galactic center, $K$ is the core radius of the isothermal sphere, and $\theta$ is the angle of observation relative to the galactic center. The velocity dispersion in our galaxy is $\beta \sim 10^{-3}$, leading to a very narrow linewidth, $\Delta\lambda = 16\pi\beta\times 10^3[(1\ \text{eV})/m_a]$ Å. Using the estimates[12] $K/R \simeq \frac{1}{2}$ and $\rho(0) \simeq 3\times 10^{-24}$ g/cm$^3$, we find

$$\frac{dI}{d\Omega\,\Delta\lambda} \sim 10^4 x_a \left[\frac{m_a}{1\ \text{eV}}\right]^5 (\text{cm}^2\cdot\text{s}\cdot\text{sr}\cdot\text{Å})^{-1} \quad (11)$$

is the interval $\Delta\lambda \sim 50[(1\ \text{eV})/m_a]$ Å centered at $\lambda \sim 25000[(1\ \text{eV})/m_a]$ Å.

As an example, the flux from a 10–20-eV axion is $\sim 10^{10} x_a$ (cm$^2\cdot$s$\cdot$sr$\cdot$Å)$^{-1}$, with a width of $\sim 3$ Å (comparable to the resolution of modern UV detectors) in the UV. This is to be compared with a UV background intensity, normal to the galactic plane,[16] of $260 \pm 40$ (cm$^2\cdot$s$\cdot$sr$\cdot$Å)$^{-1}$. Thus, the decay photons from 10–20-eV axions are detectable if $x_a \gtrsim 10^{-8}$. Conservative assumptions are that axionic matter tracks baryonic matter (implying $x_a = \Omega_a/\Omega_{\text{baryon}}$), and that Eq. (1) holds. The primordial-nucleosynthesis bound of Yang *et al.*[17] is $0.014 \le h^2\Omega_{\text{baryon}} \le 0.035$. Taking $h^2\Omega_{\text{baryon}} \sim 0.02$, one then gets

$$x_a \simeq 5\times 10^{-5}[(1\ \text{eV})/m_a]^{1.175}. \quad (12)$$

Equation (11) then yields an axion signal exceeding the background by a factor of 20 to 300 for an axion in the 10–20-eV mass range.

The axion signal from Andromeda (M31) may also be observable. One obtains

$$I/\Delta\lambda \simeq 20 x_a [m_a/(1\ \text{eV})]^5 (\text{cm}^2\cdot\text{s}\cdot\text{Å})^{-1}. \quad (13)$$

Again for the 10–20-eV axion mass range, the photon intensity from Andromeda is $10^7 x_a$ (cm$^2\cdot$s$\cdot$Å)$^{-1}$. This result is to be compared with the background weighted by the solid angle subtended by Andromeda ($\sim 10^{-2}$ sr). With $x_a \sim$ few times $10^{-6}$ the signal is a factor of 4 to 60 above background. We expect this signal-to-background estimate for Andromeda to apply in fact to most aperture-filling clusters, if Andromeda is a typical galaxy. This is because the ratio of signal of an aperture-filling source to background is independent of the source distance.

The isotropic axion signal from a summation over distant clusters is indistinguishable from a signal due to a homogeneous axion distribution. The isotropic signal is discussed elsewhere.[18]

Since the axion decay is two body, the resulting decay photons are monochromatic at $E = m_a/2$. However, we caution the reader that several mechanisms may broaden the spectrum: (i) Normal matter in the axion cluster could rescatter the monochromatic photons. (ii) Velocity dispersion of the bound axions leads to a ratio $(1+\beta)/(1-\beta)$ for the maximum to minimum photon energy. A large $\beta$ results if either the interiors of such axion clusters are close to the black-hole limit (in which case gravitational red shift contributes to further broadening of the spectrum), or the axion cluster as a whole is rapidly rotating. (iii) In general, a density profile of the axion star can be arranged to yield an arbitrary spectral shape due to gravitational red shifting. This point is illustrated by consideration of the extreme example of a small central region approaching the black-hole limit, $M(r)/r \sim 2/G$, which yields $z_g(r)/z_g(l) \rightarrow \infty$ and a semi-infinite spectral range. (iv) Accreting normal matter from a neighboring star galaxy could generate a spectrum unrelated to axion physics.

Since axions are dissipationless, the standard assumption is that their density is less than that of normal matter. If such is the case, then the first three mechanisms are inoperative. We feel that until the origin and history of large-scale clustering is understood, one should keep an open mind concerning the axion cluster's spectrum.

We consider the assumptions concerning axion cosmology which led to Eq. (12) to be conservative; if axions are clustered where the baryons are not, or if there are axion production mechanisms beyond the one considered in Ref. 5, then $x_a$, and the axion signature/background, can be much larger than our conservative estimate. One may even speculate that dense $10^{10}M_\odot$ clumps of 20-eV axions are providing the power for quasars (luminosity $\sim 10^{13}L_\odot$).

In summary, depending on the axion mass, the luminosity of an axion cluster may approach the luminosity of a star or galaxy or galactic cluster of comparable total mass. For an allowed range of axion mass, the local galactic halo, and Andromeda, give observable signals. The signal is a photon spectrum probably sharply peaked (possibly monochromatic) at half the axion mass.

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