Dimming Supernovae without Cosmic Acceleration

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We present a simple model where photons propagating in extragalactic magnetic fields can oscillate into very light axions. The oscillations may convert some of the photons, departing a distant supernova, into axions, making the supernova appear dimmer and hence more distant than it really is. Averaging over different configurations of the magnetic field we find that the dimming saturates at about one-third of the light from the supernovae at very large redshifts. This results in a luminosity distance versus redshift curve almost indistinguishable from that produced by the accelerating Universe, if the axion mass and coupling scale are $m \sim 10^{-16}$ eV, $M \sim 4 \times 10^{11}$ GeV. This phenomenon may be an alternative to the accelerating Universe for explaining supernova observations.

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Current observations of supernovae (SNe) at redshifts $0.3 \lesssim z \lesssim 1.7$ reveal that they are fainter than expected from the luminosity-redshift relationship in a decelerating Universe [1]. On the other hand, the large scale structure and cosmic microwave background radiation (CMBR) observations suggest that the Universe is spatially flat, with the matter density about 30% of the critical density [2]. It is therefore usually inferred that the Universe must have become dominated by a dark energy component, which comprises about 70% of the critical energy density, and has the equation of state $p/\rho \lesssim -2/3$, implying that our Universe would be accelerating at present. The dark energy component could be either a small cosmological constant or a time-dependent quintessence energy [3]. Neither possibility is elegant from the current vantage point of fundamental theory because of unnaturally small numbers needed to fit the data: the present value of the energy density, $\rho_c \sim 10^{-12}$ eV^4, and, in the case of quintessence, the tiny mass smaller than the current Hubble parameter, $H_0 \sim 10^{-33}$ eV, and subgravitational couplings to matter to satisfy fifth-force constraints [4].

Because the SNe observations probe length scales $l \sim H_0^{-1} \sim$ few $\times$ 10^3 Mpc which are inaccessible to any particle physics experiments, it is natural to consider alternative explanations to the supernova data without cosmological acceleration. In this paper we consider a model where the dimming of SNe is based on flavor oscillations. Flavor oscillations occur whenever there are several degrees of freedom whose interaction eigenstates do not coincide with the propagation eigenstates. Such particles can turn into other particles simply by evolution and evade detection. We will consider a model with an axion with a mass $m \sim 10^{-16}$ eV, much smaller than the usual [5] QCD axion mass scale, 10^{-5} eV $\lesssim m_{\rm QCD}^{\rm ax} \lesssim 10^{-1}$ eV. This axion couples to electromagnetism, which leads to mixing of the photon and the axion in the presence of an external magnetic field B [6]. Hence light traveling in intergalactic magnetic fields can in part turn into axions, and evade detection on Earth. A source would then appear fainter even if the Universe is not accelerating.

The axion-photon coupling is

$$\mathcal{L}_{\rm int} = \frac{a}{M} \vec{E} \cdot \vec{B}, \qquad (1)$$

where the scale M characterizes the strength of the axion-photon interactions. This induces a mixing between the photon and the axion [6] in the presence of a background magnetic field $\vec{B}$ (as exists in our Universe [7]). We see that the polarization whose electric field is parallel to $\vec{B}$ mixes with the axion. The field equations are, after rotating the coordinate axes such that the propagation is along the y direction,

$$\left\{\frac{d^2}{dy^2} + \mathcal{E}^2 - \begin{pmatrix} 0 & i\mathcal{E}\frac{B}{M} \\ -i\mathcal{E}\frac{B}{M} & m^2 \end{pmatrix}\right\}\begin{pmatrix} |\gamma\rangle \\ |a\rangle \end{pmatrix} = 0, \qquad (2)$$

where we Fourier transformed the fields to the energy picture $\mathcal{E}$ and introduced the state vectors $|\gamma\rangle$ and $|a\rangle$ for the photon and the axion. Here $B = \langle \vec{e} \cdot \vec{B} \rangle \sim |\vec{B}|$ is the averaged projection of the extragalactic magnetic field on the photon polarization $\vec{e}$. The observational bounds [7,8] on the intergalactic magnetic field depends on the distribution of matter (the free electron density) and the coherence length of the magnetic field. Taking into account the variation of the electron density in our Universe, the most stringent bounds on the magnetic field are $B \leq 10^{-9}$ G for a magnetic field with coherence length $L_{\rm dom} = H_0^{-1}$, $B \leq 6 \times 10^{-9}$ G for $L_{\rm dom} = 50$ Mpc, and $B \leq 10^{-8}$ G for $L_{\rm dom} = 1$ Mpc [8]. In this paper we will assume a domain length for the magnetic fields of order 1 Mpc, assume that the averaged value of $\vec{B}$ is close to the applicable observed upper limit, and thus assume that $|\vec{B}| \sim$ few $\times$ 10^{-9} G [8] consistent with the galactic dynamo mechanism. Therefore its energy density is $\vec{B}^2 \sim cH_0^2 M_{Pl}^2$, where $c \sim$ few $\times$ 10^{-11} and the Hubble parameter is $H_0 \sim 10^{-33}$ eV.

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We can now define the propagation eigenstates by diagonalizing the mixing matrix in Eq. (2), which is, using $B/M = \mu$,

$$\mathcal{M}^2 = \begin{pmatrix} 0 & i\mathcal{E}\mu \\ -i\mathcal{E}\mu & m^2 \end{pmatrix}. \tag{3}$$

In this matrix we have ignored the effects of the intergalactic plasma, which induce an effective mass for the photon given by $\mathcal{M}_{11} = \omega_p^2 = 4\pi\alpha n_e/m_e^2$ in (3), where α is the fine structure constant, n_e is the free electron density, and m_e is the electron mass. The plasma-induced mass would not affect our conclusions as long as the electron density is below the value $n_e < 2.5 \times 10^{-8}$ cm^{-3} for most of the volume of space, which is likely to be the case in our Universe. We have performed a detailed analysis in [9] to verify this statement. This matrix (3) is the analog of the usual seesaw matrix for neutrinos. Defining the propagation eigenstates $|\lambda_-\rangle$ and $|\lambda_+\rangle$ which diagonalize the matrix (3), whose eigenvalues are $\lambda_\mp = \frac{m^2}{2} \mp \sqrt{\frac{m^4}{4} + \mu^2\mathcal{E}^2}$, we can solve the Schrödinger equation (2). It is now clear that, as the photon propagates, it mixes with the axion by an amount depending on the energy of the particle. In the limit $\mathcal{E}^2 \gg \lambda_i > m^2$, which covers all of the applications of interest to us, the photon survival probability $P_{\gamma\to\gamma} = |\langle\gamma(y_0)\,|\,\gamma(y)\rangle|^2$ is

$$P_{\gamma\to\gamma} = 1 - \frac{4\mu^2\mathcal{E}^2}{m^4 + 4\mu^2\mathcal{E}^2}\sin^2\left[\frac{\sqrt{m^4 + 4\mu^2\mathcal{E}^2}}{4\mathcal{E}}\,\Delta y\right], \tag{4}$$

and the oscillation length is

$$L_O = \frac{4\pi\mathcal{E}}{\sqrt{m^4 + 4\mu^2\mathcal{E}^2}}. \tag{5}$$

In the limit $\mathcal{E} \gg m^2/\mu$, the mixing is maximal, while the oscillation length is completely independent of the photon energy: $L_O \sim \frac{2\pi}{\mu}$. Thus high-energy photons (including optical frequencies $\mathcal{E} \sim 10$ eV as we will see) oscillate achromatically.

On the other hand, in the low energy limit $\mathcal{E} \ll m^2/\mu$, the probability to find axions $P_{\gamma\to a} = 1 - P_{\gamma\to\gamma}$ is small, bounded from above by $P_{\gamma\to a} \leq 4\mu^2\mathcal{E}^2/m^4$. We can also use Eq. (4) to see the effect of the photon plasma mass by the replacement $m^4 \to (\omega_p^2 - m^2)^2$. This analysis [9] shows that the energy dependence of the photon-axion conversion remains within the experimental limits as long as $n_e < 2.5 \times 10^{-8}$ over most of space.

In our Universe the magnetic field is not uniform. Assuming that a typical domain size for the extragalactic magnetic field is $L_{\rm dom} \sim$ Mpc, it is straightforward to numerically solve for the quantum mechanical evolution of unpolarized light in such magnetic domains with uncorrelated field directions. An analytic calculation shows that in the case of maximal mixing, with $\cos(\mu L_{\rm dom}) > -1/3$, the survival probability is monotonically decreasing:

$$P_{\gamma\to\gamma} = \frac{2}{3} + \frac{1}{3}\,e^{-\Delta y/L_{\rm decay}}, \tag{6}$$

where the inverse decay length is given by

$$L_{\rm decay} = \frac{L_{\rm dom}}{\ln\left(\frac{4}{1+3\cos(\mu L_{\rm dom})}\right)}. \tag{7}$$

For $\mu L_{\rm dom} \ll 1$ this reduces to

$$L_{\rm decay} = \frac{8}{3\mu^2 L_{\rm dom}}. \tag{8}$$

Thus we see that with a random magnetic field the problem becomes essentially classical and after the traversal of many magnetic domains the system is equilibrated between the two photon polarizations and the axion. This leads to the generic prediction that, on average, one-third of all photons converts to axions after large traversed distances. This saturation of the loss of photons is the most important feature of this mechanism which sharply distinguishes this model from other proposed alternative explanations to the SNe observations (for example, the presence of "grey dust"), none of which are capable of explaining naturally the observed saturation of the dimming of the supernovae.

We can now estimate the axion mass and coupling needed to reproduce SN observations. To take the oscillations into account, in the luminosity distance versus redshift formula we should replace the absolute luminosity $\mathcal{L}$ by an effective one:

$$\mathcal{L}_{\rm eff} = \mathcal{L}\,P_{\gamma\to\gamma}. \tag{9}$$

The optical photons must oscillate independently of their frequency. For them, the oscillations should reduce the flux of incoming photons by about 20% for SNe at $z \sim 0.5$. This requires $L_{\rm dec} \lesssim H_0^{-1}/2$. Thus the mass scale M for this should be $M \sim 4 \times 10^{11}$ GeV. Note, that this is above the experimental exclusion limit for M. The astrophysics bound on M quoted by the Particle Data Group [10] is $M \geq 1.7 \times 10^{10}$ GeV [11], which arises from photon-axion conversions in globular cluster stars. However, for ultralight axions there is [12] a more stringent (though also more model dependent) limit from SN1987A given by $M \geq 10^{11}$ GeV, which is still lower than the value required here. In comparison, the best direct experimental bound is [13] $M > 1.6 \times 10^9$ GeV, which will, however, soon be improved upon by the CERN Axion Solar Telescope experiment.

If the microwave photons had fluctuated a lot in the extragalactic magnetic field, their anisotropy would be very large due to the variations in the magnetic field. To avoid affecting the small primordial CMBR anisotropy, $\Delta T/T \sim 10^{-5}$, the axion mass should be large enough for the mixing between microwave photons and the axion to be small. In this limit, we can ignore the averaging over many random magnetic domains and simply treat each domain as a source of CMBR fluctuation. The disturbances of CMBR are controlled by the transition probability into axions

$$P_{\gamma\to a} \le 4 \times 10^{-11} \frac{M_{\rm Pl}^2 H_0^2 \mathcal{E}^2}{M^2 m^4}. \tag{10}$$

For microwave photons $\mathcal{E} \sim 10^{-4}$ eV, and so $P_{\gamma\to a} \le 2.5 \times 10^{-70}$ (eV)$^4/m^4$. Therefore for $m \sim$ few $\times 10^{-16}$ eV we find $P_{\gamma\to a} \le 10^{-7}$, which is smaller than the observed temperature anisotropy. Thus we see that if the axion scales are

$$m \sim 10^{-16}\ \text{eV}, \qquad M \sim 4 \times 10^{11}\ \text{GeV}, \tag{11}$$

the mixing could produce the desired effect of reducing the flux of light from SNe while leaving the primordial CMBR anisotropy unaffected. We stress here that while at early times the CMBR photons were much more energetic there were no sizable extragalactic magnetic fields yet, since their origin is likely tied to structure formation. Hence we can obtain a rough estimate of the influence of our effect on CMBR using their current energy scale.

To compare our model with observations, we assume that the constraint on the total energy density of the Universe $\Omega_{\rm tot} \simeq 1$ is satisfied because the Universe contains some form of dark energy which does not clump, but it need not lead to cosmological acceleration. A simple example is dark energy with the equation of state $w = p/\rho = -1/3$ and energy density $\Omega_S = 0.7$, which could originate from a network of frustrated strings with small mass per unit length. As long as $w = p/\rho > -0.48$ the Universe would presently not be accelerating. These forms of dark energy do not appear to be excluded either by the position of the first acoustic peak in the CMBR measurements or by combined CMBR + large scale structure fits [14]. In Fig. 1 we have plotted the typical prediction of the oscillation model in a spatially flat Universe with $\Omega_m = 0.3$ and $\Omega_S = 0.7$ against the best fit model for the accelerating Universe with a cosmological constant ($\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$). The two curves are practically indistinguishable. We note that the oscillation model predicts limited attenuation of the SN luminosities, unlike some other alternatives to the accelerating Universe. The total attenuation is limited to about one-third of the initial luminosity, as we have explained above. Since for larger values of z the Universe becomes matter dominated, and the disappearance of photons is saturated in the oscillation model, the two curves will continue lying on top of each other for higher values of z. Thus simply finding higher z supernovae [15] will not distinguish between the two models. The main difference between the two is that the curve for the oscillation model is an averaged curve, with relatively large standard deviations. Therefore it may be much easier to explain outlying events than in the case of the accelerating Universe.

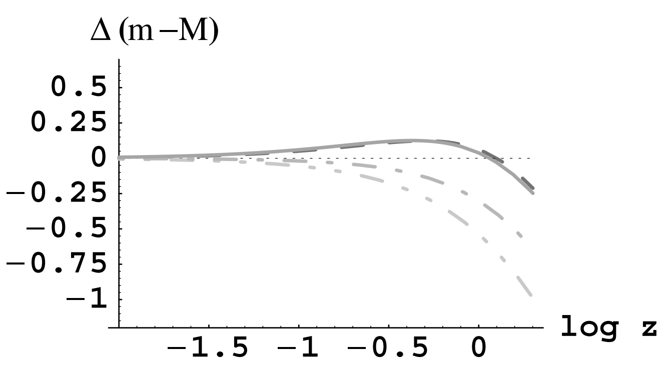

FIG. 1. The luminosity distance versus redshift curve for several models, relative to the curve with $\Omega_{\rm tot} = 0$ (dotted horizontal line). The dashed curve is a best fit to the supernova data assuming the Universe is accelerating ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$); the solid line is the oscillation model with $\Omega_m = 0.3$, $\Omega_S = 0.7$, $M = 4 \times 10^{11}$ GeV, $m = 10^{-16}$ eV; the dot-dashed line is $\Omega_m = 0.3$, $\Omega_S = 0.7$ with no oscillations, and the dot-dot-dashed line is for $\Omega_m = 1$ again with no oscillations.

Let us now consider photons which may pass through the magnetic field of a galaxy, or just skim it. The galactic magnetic fields are much stronger than the extra-galactic ones, $B_G \sim \mu G \sim 10^3 B$. However, the density of baryons (and therefore also of electrons) is large enough in such regions that refraction has to be taken into account, which introduces a diagonal element $\mathcal{M}_{11}$ for the photon in (3) [16]. A simple estimate [6] for this term gives $\mathcal{M}_{11} \sim 10^{-23}$ (eV)^2 for 10 eV photons traveling within a galaxy, while the off-diagonal terms are of the order 10^{-27} (eV)^2. Therefore this term will dominate the mixing matrix, and the oscillations will be highly suppressed while passing through the magnetic field of a galaxy. However, since the electron density between clusters is much lower, this effect is not very important for most of extragalactic space [9].

Another question is whether the oscillations may cause any observable polarization effects on the light arriving from the SNe. If the orientation of the extragalactic magnetic field was constant, and the field perfectly homogeneous, light from the SNe would be partially plane polarized. However, since the coherence length of the extragalactic magnetic field is of order $\sim$ Mpc, the direction of the magnetic field is effectively random, and thus no strong polarization effects are expected for faraway SNe. Rather, the converse effect of depolarizing incoming light is more important, since the oscillations in a random magnetic field may deplete existing photon beam polarizations. Because there are distant sources which are partially polarized, with the polarization direction correlated with the shape of the source, it is important to show that the photon-axion mixing does not completely depolarize light from a polarized source. Numerical simulations show that the polarization decrease is rather slow. This should be expected because the degradation of polarization occurs after an axion produced by a polarized photon conversion regenerates a photon of a different polarization, after the orientation of the $\vec{B}$ has changed. This is a second-order effect, and so polarization is depleted more slowly than intensity. As a result the existing measurements of polarized optical photons from distant sources can be accommodated in this model.

Cosmologically our axion does not have any harmful effects. Since they are weakly coupled, with $M^{-1} \sim 10^{-12}$ GeV^{-1}, they are out of equilibrium from a very early time. If they are not significantly produced during reheating after inflation, their abundance can be harmlessly small. On the other hand, the homogeneous axion background field $a(t)$ will oscillate around its minimum, with its energy density scaling as cold dark matter at late times. In the early Universe, the background field will satisfy the slow roll conditions, and remain frozen until the Hubble scale comes down to $H \sim 10^{-16}$ eV, when the Universe cools to the temperature $T_i \sim 100$ keV. At that moment, the field may start rolling. Its kinetic and potential energy will rapidly virialize, after which the energy density stored in it will scale as $\rho \sim \rho_i (T/T_i)^3$, which for $\rho_i \sim m^2 f_a^2$ is much smaller than the energy density in matter. Furthermore, while an axionic sector can give rise to both domain walls and cosmic strings in the early Universe, because the axion scales in the model we discuss are so low, these defects may remain negligible well into the future of our Universe [17].

In summary, we have presented an alternative explanation of the observed dimming of SNe at large distances. The effect is based on a quantum mechanical oscillation between the photon field and a hypothetical axion field in the presence of extragalactic magnetic fields. This would result, on average, in about one-third of the photons emitted by distant SNe oscillating into axions. If the average magnetic field is of the order 10^{-9} G, and the average domain size is of order $\sim$ Mpc, one would need an axion whose coupling to the photon is given by $M \sim 4 \times 10^{11}$ GeV, and mass $m \sim 10^{-16}$ eV. With these parameters the luminosity-distance versus redshift curve is almost indistinguishable from the curve of an accelerating Universe with $\Omega_m = 0.3, \Omega_\Lambda = 0.7$. Since the precise value of the luminosity distance for a particular supernova depends on the details of the intergalactic magnetic field, we expect more variations in the observed luminosity. However, distinguishing this model from the accelerating Universe paradigm will likely be easier through improving the bounds on the couplings of ultralight axions, by understanding the details of the intergalactic magnetic field, or by a precise independent determination of the equation of state for the dark energy component, for example through the DEEP survey [18].

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Note added.—Subsequently, the effects of the photon plasma mass on this scenario were considered in Refs. [9,19].

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