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Effects of the Intergalactic Plasma on Supernova Dimming via Photon-Axion Oscillations

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Abstract

We have recently proposed a mechanism of photon-axion oscillations as a way of rendering supernovae dimmer without cosmic acceleration. Subsequently, it has been argued that the intergalactic plasma may interfere adversely with this mechanism by rendering the oscillations energy dependent. Here we show that this energy dependence is extremely sensitive to the precise value of the free electron density in the Universe. Decreasing the electron density by only a factor of 4 is already sufficient to bring the energy dependence within the experimental bounds. Models of the intergalactic medium show that for redshifts $z < 1$ about 97% of the total volume of space is filled with regions of density significantly lower than the average density. From these models we estimate that the average electron density in most of space is lower by at least a factor of 15 compared to the estimate based on one half of all baryons being uniformly distributed and ionized. Therefore the energy dependence of the photon-axion oscillations is consistent with experiment, and the oscillation model remains a viable alternative to the accelerating Universe for explaining the supernova observations. Furthermore, the electron density does give rise to a sufficiently large plasma frequency which cuts off the photon-axion mixing above microwave frequencies, shielding the cosmic microwave photons from axion conversions and significantly relaxing the lower bounds on the axion mass implied by the oscillation model.

We recently proposed [1] that photon-axion oscillations [2] in external magnetic fields, could explain the observed [3] dimmer supernovae at redshifts $0.3 \leq z \leq 1.7$. This mechanism requires the photon-axion coupling scale to be $M \sim 4 \cdot 10^{11}$ GeV and assumes an axion mass $m \sim 10^{-16}$ eV, and an intergalactic magnetic field $B \sim 5 \cdot 10^{-9}$ G, with a domain size of order a Mpc, in agreement with observational bounds [4]. Detailed properties of the model were investigated in [5]. The oscillation mechanism rests on two key ingredients:

- The photon-axion oscillation probability of photons with energy $\mathcal{E}$ induced by the off-diagonal element $|\mathcal{M}_{12}| = \mathcal{E}B/M = \mathcal{E}\mu$ of the mixing matrix $\mathcal{M}$ [1] should be non-negligible over a significant fraction of the line of sight, e.g. over a few thousand magnetic domains;
- The magnetic field of essentially random direction over many domains will induce a decrease of photon flux saturating at about 2/3 of its original value, independently of the detailed structure of the magnetic field and the precise form of the mixing, provided the mixing is not negligibly small.

Subsequently the authors of [6] argued that photon rescattering in the ionized gas comprising the intergalactic medium (IGM) could have rendered the oscillations very energy-dependent, which would have been inconsistent with observations. Namely in the presence of ionized electrons the mixing matrix is

$$\mathcal{M} = \begin{pmatrix} \omega_p^2 & i\mathcal{E}\mu \\ -i\mathcal{E}\mu & m^2 \end{pmatrix} , \tag{1}$$

where ω_p is the plasma frequency [2] $\omega_p^2 = 4\pi\alpha n_e/m_e$, with n_e the electron density, m_e the electron mass, and α the fine structure constant. Then the conversion probability of photons into axions over a domain of size L_{dom} is given by

$$P_{\gamma\to a} = \frac{4\mu^2\mathcal{E}^2}{(\omega_p^2 - m^2)^2 + 4\mu^2\mathcal{E}^2} \sin^2\left[\frac{\sqrt{(\omega_p^2 - m^2)^2 + 4\mu^2\mathcal{E}^2}}{4\mathcal{E}} L_{dom}\right] . \tag{2}$$

Using this formula one can estimate the largest allowed value of ω_p^2 for which the energy dependence of the dimming effect is within the observational bounds. Here we assume that the magnetic domain size is ~ 1 Mpc [4], and that there are about 3000 domains for supernovae at redshifts $z \lesssim 1$. We consider photons of average energy of 4.3 eV in the B band and average energy of 3.4 eV in the V band, and require that the total difference in oscillation probabilities, i.e. for photon survival as a function of energy, is less than 3 percent [3]. These energy values are slightly higher to reflect the redshift of the photon energies as they journey from $z = 1$ to $z = 0$; we simply pick the energies at $z = 0.5$. The resulting difference in the oscillation probabilities is displayed in Fig. 1. This figure is probably an overestimate of the energy dependence since we have simply added the probabilities over all the domains, while in reality the photon conversion saturates at a value of 1/3 due to the random direction of the magnetic field in different domains. Even so, we can see that if the plasma frequency obeys

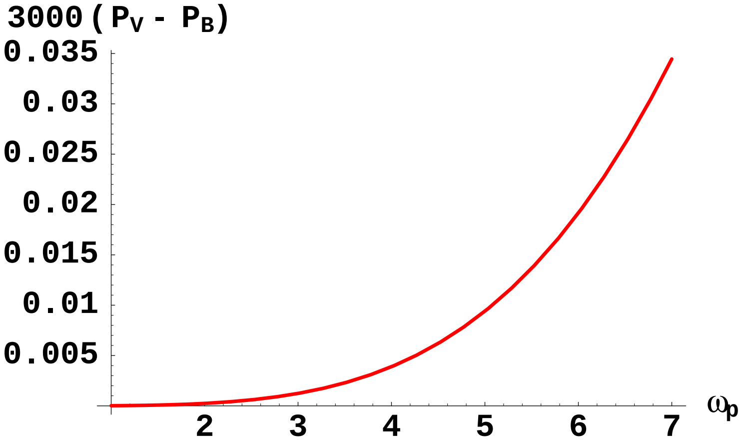

Figure 1: The difference in photon survival probability difference for two energy bands summed over 3000 domains of size 1 Mpc. The horizontal axis is the photon plasma frequency in units of 10^{-15} eV.

$\omega_p \leq 6 \cdot 10^{-15}$ eV the energy dependence disappears very rapidly, and becomes undetectable by present observations. This threshold value of ω_p corresponds to a free electron density of $n_e = 2.5 \cdot 10^{-8} \mathrm{cm}^{-3}$.

The authors of [6] chose the value of the electron density to be $n_e = 1 \cdot 10^{-7} \mathrm{cm}^{-3}$. This is barely above the threshold below which the energy dependence of oscillations becomes unobservable. On the other hand, if all of the baryons in our Universe had been uniformly distributed and fully ionized, the electron density would have been* $n_e = 1.8 \cdot 10^{-7} \mathrm{cm}^{-3}$. The value assumed in [6] corresponds to roughly a half of all baryons being uniformly distributed and ionized. This estimate is very likely too high, by at least a factor of 15, in the region $z \lesssim 1$ which is the relevant regime for our model since most of the observed supernovae reside in this range. This reduction of n_e would render the energy dependence unobservable at present.

Let us now discuss why the electron density has to be reduced. It is well known that the distribution of baryons at low redshifts $z \sim 0$ is an open problem in cosmology [7]. At low redshifts the baryons are thought to be divided among the following structures in the Universe [7, 8, 9, 10]:

- Condensed baryons in stars and galactic gas
- Hot baryons in galaxy clusters and groups
- WHIM: warm-hot intergalactic matter
- photoionized intergalactic gas (Lyman α forests).

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*Assuming that $\Omega_B \simeq 0.045$ is the baryon fraction of the energy density of the Universe, the Hubble parameter is $H = 65$ km/s/Mpc, the critical density is $\rho_c \simeq 4.3 \cdot 10^3$ eVcm^{-3}, and that 10% of baryons are neutrons in helium nuclei. We are ignoring the tiny fractions of heavier elements.

At low redshifts the baryons are roughly equally distributed between the condensed and hot baryons, the WHIM, and the Lyman α forests. The former structures are very strongly clumped, occupying a tiny fraction of total volume of space at $z \lesssim 1$. Therefore they are unimportant for the photon-axion oscillations.

Thus the only relevant baryons are about 1/3 of the total, residing in the Lyman α forests. They comprise a diffuse photoionized gas with relatively low temperature, $T < 10^5$ K. But even if all of this gas were uniformly distributed, the electron density would have been at most $6.1 \cdot 10^{-8}\text{cm}^{-3}$. However, the low temperature and the highly ionized nature of this gas makes the low density regions extremely difficult to observe directly. There are no direct observational bounds on the distribution of low density Lyman α forests, and hence no direct evidence for the distribution at $z \lesssim 1$ to be uniform. Instead, most of the standard lore concerning low-density, low-redshift plasma comes from model-dependent simulations.

While the assumption for uniformity would be very accurate for large values of redshifts ($z > 4 - 5$), for low z even the low-density gas in the Lyman α forests tends to clump. The simulations and the existing observations about the regions of gas with significantly higher than average density show that it is unlikely that gas in the Lyman α forests would be uniformly distributed in space. Indeed, at $z \sim 0$ the average overdensity of these kinds of structures is in the range 10–100 [11]. Their characteristic radial size is $\lesssim 100$ kpc [12], and they take up only a small fraction of space. Almost all the observed Lyman α forests fall into this category. These forests are correlated with galaxies: they tend to reside around the halos of galaxies. The simulations also display a correlation of even the low density forests with the large scale structure of the Universe, supporting the claim that for low redshifts even this gas is clumped. In the analytic model of ref. [13] at low redshifts about 97 % of space is filled with low-density gas, which is underdense by at least a factor of 10. Therefore it is reasonable to assume that over most of space at redshifts $z \lesssim 1$ the electron density is at most $n_e \leq 6 \cdot 10^{-9}\text{cm}^{-3}$, and probably even less than that. In the absence of direct observational evidence one cannot of course completely exclude somewhat larger densities, but all the indirect evidence favors the above number as a reasonable bound at low redshifts. With this value of the electron density the plasma frequency is $\omega_p \leq 3 \cdot 10^{-15}$ eV. This places it safely in the regime where the energy dependence of the supernova dimming is below the current experimental sensitivity.

A closer scrutiny actually reveals that the effects of intergalactic plasma are beneficial for our model because they make it insensitive to the axion mass as long as it is below the plasma frequency. Previously, we had selected the value of the axion mass to suppress the mixing between cosmic microwave background (CMB) photons and axions, giving $m \sim \text{few} \cdot 10^{-16}$ eV. However, the plasma-generated effective photon mass has the right magnitude to suppress the photon-axion mixing at an energy above the CMB photon energies. This relaxes the lower bound on the axion mass for the model, since now the axion mass could be considerably smaller[†].

[†] We refrain from attempting to formulate the precise bounds on the axion mass since it is believed that at some value of redshift $z > 6$ the IGM was neutral, removing the plasma and therefore the photon mass. At present it is not known how the background magnetic fields emerged, and so they could still have been large enough at such high redshifts to affect CMBR if the axion was too light.

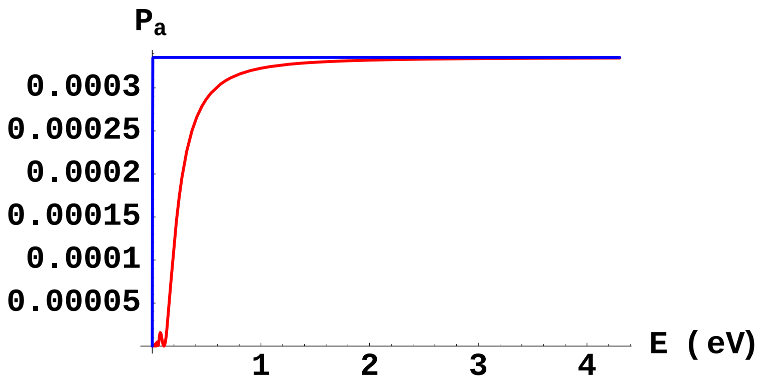

Figure 2: The photon oscillation probability for one domain of size 1 Mpc versus photon energy. The top curve is for the model with an axion mass of 10^{-16} eV and no plasma, while the bottom curve is for a photon plasma frequency of $3 \cdot 10^{-15}$ eV.

One may also ask if the axion-photon coupling should be changed because of the plasma-induced photon mass. In Fig. 2 we have plotted the oscillation probability in a magnetic domain as a function of energy for the original scenario with $\omega_p = 0$, and for the case with $\omega_p = 3 \cdot 10^{-15}$ eV. One sees immediately that for optical photons, $\mathcal{E} > 2$ eV, the change of the oscillation probability in a domain is very small, with the main difference being that the oscillations are cut off at energies closer to the optical regime than before. Thus the plasma effects do not require a significant alteration of the axion-photon coupling.

In summary, we have considered the effect of the IGM on our proposed mechanism [1] for supernova dimming via photon-axion oscillations. We have found that the effects of the intergalactic plasma are very sensitive to the precise value of the plasma frequency. We have put a conservative bound on the plasma frequency by combining the observations and the simulations of the IGM, and found that the plasma effects would not strongly influence the oscillations of optical photons. Instead they would provide a natural cutoff on the oscillations at energies below the optical range; this relaxes the lower bounds on the mass of the axion. We conclude that the photon-axion oscillation mechanism remains a viable alternative to the accelerating Universe for explaining the supernova observations.

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