Supernova Brightening from Chameleon-Photon Mixing

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Abstract
Measurements of standard candles and measurements of standard rulers give an inconsistent picture of the history of the universe. This discrepancy can be explained if photon number is not conserved as computations of the luminosity distance must be modified. I show that photon number is not conserved when photons mix with chameleons in the presence of a magnetic field. The strong magnetic fields in a supernova mean that the probability of a photon converting into a chameleon in the interior of the supernova is high, this results in a large flux of chameleons at the surface of the supernova. Chameleons and photons also mix as a result of the intergalactic magnetic field. These two effects combined cause the image of the supernova to be brightened resulting in a model which fits both observations of standard candles and observations of standard rulers.

1 Introduction
Observations of standard candles and of standard rulers allow us to learn how the universe has evolved in recent times. Both sets of observations favour a universe containing a large component of dark energy.

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but the cosmoologies preferred by the two sets of data are not consistent; in fact at higher redshifts they appear to diverge. This indicates that there is still something missing in our understanding of the accelerated expansion of the universe. In this paper I will show how the discrepancy between the two sets of observations can be explained if photon number is not conserved because photons are allowed to mix with chameleon particles.

In metric theories of gravity where photons travel on unique null geodesics there is a well-defined notion of distance as long as photon number is conserved. The luminosity distance, \( d_L(z) \), to an object at redshift \( z \) and the angular diameter distance, \( d_A(z) \), to the same object are related by the reciprocity relation \( 1 \)

\[
d_L(z) = d_A(z)(1 + z)^2
\]

If photon number is not conserved then this relation no longer holds and a discrepancy in the distance measures should be observed. There are a number of current proposals which do not conserve photon number; the light from distant objects could be scattered by dust or free electrons in the intergalactic medium, photons may decay, or the photon could mix with another light state such as the axion.

It had been thought that loss of photons in the intergalactic medium could explain the observed dimming of type 1a supernovae without the need for dark energy \( 2, 3, 4 \). Photon number non-conservation changes the luminosity distance to an object but does not affect distance measurements from standard rulers. Therefore, if loss of photons is the explanation for the dimming of supernova, angular diameter distance measurements should be consistent with an \( \Omega_\Lambda = 0 \) universe. This is not the case; observations of standard rulers imply a universe with a significant dark energy component.

When luminosity distances and angular diameter distances are compared there is a noticeable disagreement at \( z \gtrsim 0.5 \) \( 5, 6 \). This is shown in Figure 1 where distance modulus (compared to a \( \Lambda \)CDM universe) is plotted against redshift for measurements coming from standard rulers and standard candles. The standard candles used are type 1a supernovae \( 7, 8, 9, 10 \) and the standard rulers used are FRIIb radio galaxies \( 11, 12 \), compact radio sources \( 13, 14, 15 \) and X-ray clusters \( 16 \). Considering the two sets of data separately the best fit to the angular diameter distance data is a universe with \( \Omega_m = 0.22, \Omega_\Lambda = 0.79 \) but the best fit to the luminosity distance data is a very closed universe with \( \Omega_m = 0.46, \Omega_\Lambda = 0.98 \), such a universe is al-
Figure 1: Distance modulus \[ m - M = 5 \log(d_L) - 25 = 5 \log(d_A(1 + z)^2) - 25 \] compared to a ΛCDM universe plotted against redshift, showing the best fits to observations of standard candles and standard rulers.
ready ruled out by measurements of the CMB. If the explanation for
this apparent violation of the reciprocity relation is that photon num-
ber is not conserved, then computed luminosity distances need to be
modified.

Photon number non-conservation does not affect the angular di-
ameter distance to an object so the cosmology which best fits obser-
vations of standard rulers is the correct one. If this is the case Figure
implies that non-conservation of photon number actually brightens
the image of a supernova. This is in contrast to all previously studied
mechanisms for non-conservation of photon number which all predict
that photons should be lost in the intergalactic medium, and thus that
the supernova is dimmed \[5, 6\]. In this paper I show that the images
of supernova can be brightened if photons are allowed to mix with
chameleons.

The chameleon is a scalar particle which arises in certain models
of scalar-tensor gravity \[17, 18\]. In the Einstein frame the action is

\[
S = \int d^4x \sqrt{-g} \left( \frac{M_P^2 R}{2} - \frac{1}{2} (\partial \phi)^2 - V(\phi) \right) - \int d^4x L_m(\psi^{(i)}_m, g^{(i)}_{\mu\nu})
\]

where \( \psi^{(i)}_m \) are matter fields which couple to the metric \( g^{(i)}_{\mu\nu} = e^{-2\phi/M_i} g^{\mu\nu} \). Assuming that the chameleon couples to all forms of matter in the
same way so that \( M_i = M \forall i \) the current bound on \( M \) is \( 10^6 \) GeV < \( M \) \[19\]. I assume a runaway potential of the form

\[
V(\phi) = \Lambda^4 e^{n \phi^n} \tag{3}
\]

but the chameleon feels an effective potential

\[
V_{eff}(\phi) = V(\phi) + \rho e^{\phi/M} \tag{4}
\]

which depends on the local matter density \( \rho \). The chameleon sits in
the minimum of the effective potential with a mass which depends on
the local matter density. In high density regions such as on earth the
chameleon becomes very massive and so evades current experimental
bounds, but in low density regions it can become almost massless.
The way in which the scalar field can change its mass is known as the
‘chameleon mechanism’ and this allows the scalar field to evade all
current searches for fifth-force effects or violations of the equivalence
principle if \( \Lambda \sim 10^{-3} \) eV. In addition it has been shown that the chameleon is compatible with recent searches for axion like particles at PVLAS and CAST \cite{20, 21}.

As the universe evolves the local energy density falls and the chameleon changes its properties as the universe cools. In particular at early times the chameleon behaves like dust but as the universe cools below temperatures \( T \approx 10 \) MeV the chameleon begins to behave like a fluid with equation of state \( \omega = -1 \) \cite{22, 23}. In this way the chameleon is a natural explanation for dark energy.

The paper is organised as follows. Section 2 shows how photons mix with chameleon particles and gives the probability of a photon converting into a chameleon in a homogeneous magnetic field. Section 2.1 discusses the probability of conversion as the particles pass through a magnetic field made up of many randomly oriented domains and section 2.2 explains how photons can be converted into chameleons in the interior of a supernova, resulting in a flux of chameleons at the surface. Then Section 3 describes how this can account for the brightening of the image of the supernova. In Section 4 I show that chameleon-photon mixing is in agreement with observations of the CMB. I conclude in section 5.

## 2 Photon-Chameleon Mixing

In the presence of a magnetic field the chameleon couples to photons. Assuming that the coupling of the chameleon to matter is universal, the interaction term in the Lagrangian is

\[
\mathcal{L}_{\text{int}} = \frac{\phi B^2}{M} \quad (5)
\]

In a homogeneous magnetic field where the particles propagate along the \( x \) axis which is aligned in the direction of the magnetic field the equations governing the evolution of the fields \cite{24} are

\[
\begin{bmatrix}
\omega^2 + \partial_x^2 + \begin{pmatrix}
-\omega_p^2 & 0 & 0 \\
0 & -\omega_p^2 & \frac{B \omega}{M} \\
0 & \frac{B \omega}{M} & -m_e^2
\end{pmatrix}
\end{bmatrix}
\begin{pmatrix}
A_\parallel \\
A_\perp \\
\phi
\end{pmatrix}
= 0 \quad (6)
\]

where \( \omega \) is the frequency of the photons and \( B \) is the magnitude of the magnetic field. As photons and chameleons propagate through the intergalactic medium they pass through a plasma of ionised electrons \cite{25}. \( \omega_p \) is the frequency of this plasma; \( \omega_p^2 = 4\pi e^2 n_e / m_e \approx \)
\( 10^{-47} \text{ GeV}^2 \), where \( n_e \) is the electron number density and \( m_e \) is the electron mass. \( A_\parallel \) and \( A_\perp \) are the polarisations of the photon parallel and perpendicular to the magnetic field and \( \phi \) is the chameleon field. Note that the chameleon only mixes with the polarisation of the photon which is orthogonal to the magnetic field. \( m_c \) is the chameleon mass which, given the potential (3), is

\[
m_c^2 = n(n+1)\frac{\Lambda^{4+n}}{\phi_{\text{min}}^{2+n}} \tag{7}
\]

where

\[
\phi_{\text{min}} = \left( \frac{n\Lambda^{4+n}M}{\rho} \right)^{\frac{1}{n+1}} \tag{8}
\]

is the value of \( \phi \) at the minimum of the effective potential. In what follows I will assume \( n = \mathcal{O}(1) \).

The probability of an orthogonally polarised photon converting into a chameleon whilst travelling a distance \( x \) through this homogeneous field is

\[
P(x) = \frac{4\omega^2 B^2}{M^2(\omega_p^2 - m_e^2)^2 + 4\omega^2 B^2} \times \sin^2 \left( \frac{x}{4\omega M} \right) \left( \frac{M^2(\omega_p^2 - m_e^2)^2 + 4\omega^2 B^2}{4\omega M} \right) \tag{9}
\]

The observed dimming of type Ia supernova is achromatic. hence if chameleon-photon mixing modifies observations of supernovae the effect must also be achromatic. If the particles pass through a magnetic domain of size \( L_{\text{dom}} \) there are two regimes in which the conversion probability (9) is independent of frequency: In the limit of high energy photons \( M|\omega_p^2 - m_e^2| \ll B\omega \) the mixing is maximal and independent of the photon energy.

\[
P \approx \sin^2 \left( \frac{L_{\text{dom}}B}{2M} \right) \tag{10}
\]

Alternatively if the oscillation length

\[
L_{\text{osc}} = \frac{4\pi \omega M}{\sqrt{M^2(\omega_p^2 - m_e^2)^2 + 4\omega^2 B^2}} \tag{11}
\]

\[
6
\]
is much greater than the size of a magnetic domain \(2\pi L_{\text{dom}} \ll L_{\text{osc}}\) then the probability of conversion \(P\) is

\[
P \approx \frac{B^2 L_{\text{dom}}^2}{4M^2}
\]  

which is independent of photon energy. It should be noted that both \(10\) and \(12\) are also independent of the mass of the chameleon.

Current observations suggest that the intergalactic magnetic field has coherence length \(L_{\text{dom}} \sim 1\) Mpc and magnitude \(B \lesssim 10^{-9}\) G \([26, 27, 28]\). The density of the intergalactic medium is \(\rho_{\text{IGM}} \sim 10^{-44}\) GeV\(^4\) so the mass of the chameleon is \(m^2_c \lesssim 10^{-45}\) GeV\(^2\). An optical photon \(\omega \approx 10\) eV passing through the intergalactic medium is in the high energy regime if

\[
M \lesssim 10^{10}\ \text{GeV}
\]  

so that the probability of conversion is given by \(10\). For this probability to be small requires \(BL_{\text{dom}} \lesssim 2M\).

### 2.1 Conversion in a Varying Background

The intergalactic magnetic field is not homogeneous on large scales; it is made up of many randomly orientated magnetic domains. To calculate the probability of a photon converting into a chameleon whilst travelling through the intergalactic medium I assume that: Particles traverse \(N\) domains of equal length, \(B\) is homogeneous in each domain and there is a discrete change in \(B\) from one domain to another. The component of the magnetic field parallel to the direction of flight has a random orientation but equal size in each domain.

The initial state is

\[
\alpha_1(0)|\gamma_1\rangle + \alpha_2(0)|\gamma_2\rangle + \alpha_c(0)|c\rangle
\]  

where \(|\gamma_i\rangle\) are the photon states parallel and perpendicular to the magnetic field in the first domain and \(|c\rangle\) is the chameleon. The initial photon and chameleon fluxes are

\[
I_\gamma(0) \sim |\alpha_1(0)|^2 + |\alpha_2(0)|^2
\]

\[
I_c(0) \sim |\alpha_c(0)|^2
\]
In the n-th domain the magnetic field is tilted by an angle $\theta_n$ compared to the first domain, so that

$$|\gamma^n_\parallel\rangle = \cos \theta_n |\gamma_1\rangle + \sin \theta_n |\gamma_2\rangle$$  \hspace{1cm} (17)$$

$$|\gamma^n_\perp\rangle = -\sin \theta_n |\gamma_1\rangle + \cos \theta_n |\gamma_2\rangle$$  \hspace{1cm} (18)$$

and the transition probability $P$ in each domain is given by (9). Assuming that $P$ is small and that $\theta_n$ is a random variable so that on average $\cos^2 \theta_n \sim \sin^2 \theta_n \sim 1/2$ then at the end of the n-th domain

$$I_c(y) = \frac{1}{3} (I_c(0) + I_\gamma(0)) + \frac{Q(y)}{3} (2I_c(0) - I_\gamma(0))$$  \hspace{1cm} (19)$$

$$I_\gamma(y) = \frac{2}{3} (I_c(0) + I_\gamma(0)) + \frac{Q(y)}{3} (I_\gamma(0) - 2I_c(0))$$  \hspace{1cm} (20)$$

where

$$Q(y) = \left(1 - \frac{3P}{2}\right)^{y/L_{\text{dom}}}(21)$$

and $y(z)$ is the proper particle distance to the astronomical object. If $P$ is small then at large distances $Q(y)$ becomes exponentially small and the system reaches an equilibrium configuration with a third of the initial flux in chameleons and two thirds in photons.

The probability of a single photon converting to a chameleon in a distance $y$ is

$$P_{\gamma \rightarrow c}(y) = \frac{1}{3} (1 - Q(y))$$  \hspace{1cm} (22)$$

$$\lesssim \frac{y^2 B^2}{8 M^2 N}$$  \hspace{1cm} (23)$$

It can be seen from (19), (20) that if the ratio of the initial chameleon flux to the initial photon flux is large enough more photons will be received than were emitted; the image of the supernova is brightened.

### 2.2 Conversion in the Supernova

A flux of chameleons is emitted by a supernova if some photons are converted into chameleons in the interior of the supernova. A type 1a supernova is thought to be the thermonuclear explosion of a white dwarf whose mass is close to the Chandrasekhar limit. To compute the probability of conversion between photons and chameleons inside the
supernova I consider a simple model: The supernova is a sphere of uniform density with initial radius $R_0 \sim 10^9$ cm. The supernova expands with outer velocity $v = c/30 \sim 10^9$ cm/s. I also assume that the size of a magnetic domain in the supernova is roughly equal to the length of the mean free path of the photons $L_{\text{dom}} \approx L_{\text{mfp}}$. I assume that only photons are produced by the reactions driving the explosion of the supernova and that the photons are emitted uniformly throughout the volume of the supernova. Peak luminosity occurs about 10 days after the start of the explosion.

The explosion of a supernova is homologous and so the magnetic field obeys
\begin{equation}
\frac{B_{\text{SN}}(t)}{B_{\text{WD}}} = \left( \frac{R_{\text{WD}}}{R_{\text{SN}}(t)} \right)^2
\end{equation}
where $B_{\text{SN}}(t)$ and $R_{\text{SN}}(t)$ are the magnetic field and radius of the supernova at time $t$ after the start of the explosion and $B_{\text{WD}}$ and $R_{\text{WD}}$ are the magnetic field and radius of the initial white dwarf. Models of the magnetic field of a white dwarf vary, but all predictions lie in the range $10^5 \, \text{G} \lesssim B_{\text{WD}} \lesssim 10^{11} \, \text{G}$. The size of the mean free path of photons at peak luminosity of the supernova is also not well known but is expected to satisfy $10^6 \, \text{cm} \lesssim L_{\text{mfp}} \lesssim 10^{14} \, \text{cm}$. At peak luminosity the mean free path of photons is much smaller than the radius of the supernova and the path of the photons can be modelled as a random walk so that it takes the photon $N = 3R^2/L_{\text{mfp}}^2$ steps to escape from a region of radius $R$.

Inside the supernova the chameleon is more massive than in the intergalactic medium, however because the oscillation length of optical photons is much greater than the coherence length of the magnetic field the oscillations are still independent of frequency \cite{12}. The probability of a photon converting into a chameleon inside the supernova is thus
\begin{equation}
P_{\gamma \to c}(R_{\text{SN}}) \lesssim \frac{3B_{\text{SN}}^2 R_{\text{SN}}^2}{8M^2}
\end{equation}
\begin{equation}
\lesssim 9.4 \times 10^{32} \left( \frac{B_{\text{WD}}^2}{\text{GeV}^2 M^2} \right)
\end{equation}
Therefore even though only photons are produced by the thermonuclear reactions in the supernova, the relatively high probability for a photon to convert into a chameleon in the interior of the supernova means that there is a significant flux of chameleons at the surface of the supernova.
In [29] the possibility of producing a flux of axions from the supernova was considered in a similar way to that described above. In the photon-axion coupling model $M \approx 10^{11}$ GeV which means that the probability of conversion in the supernova is negligible. The chameleon mechanism, which changes the mass of the scalar field, means that the experimental constraints on $M$ in the chameleon model are less severe. $M$ can be much smaller than in the axion model and therefore the probability of conversion can be much higher.

3 Supernova Brightening

If there is a flux of chameleons at the surface of the supernova, the ratio of the flux of photons received on earth to the flux of photons leaving the supernova is

$$P_{\gamma \rightarrow \gamma}(y) = \frac{I_{\gamma}(y)}{I_{\gamma}(0)} = \frac{2}{2 + (1 - \frac{3}{2}P_{SN})^N} + Q(y) \left( \frac{(1 - \frac{3}{2}P_{SN})^N}{2 + (1 - \frac{3}{2}P_{SN})^N} \right)$$

(27)

where $y = 0$ is now the surface of the supernova. $P_{SN}$ is the probability of conversion in one domain in the supernova and $Q(y)$ is given in (21) with $P = P_{IGM}$ the probability of conversion in one domain in the intergalactic magnetic field. If photon number is not conserved in the intergalactic medium then the reciprocity relation between luminosity distance and angular diameter distance $d_L = d_A$ must be modified by sending $d_L \rightarrow d_L / \sqrt{P_{\gamma \rightarrow \gamma}}$.

Writing the photon survival probability as

$$P(z) = A + (1 - A)e^{-y(z)H_0/c}$$

(28)

where $A$ and $c$ are real constants. I consider the effect of chameleon-photon mixing on predictions for supernova observations. As chameleon-photon mixing has no effect on the angular diameter distance I assume that measurements of standard rulers give the correct relation between distance and redshift. It is possible to fit the observed supernova well if $c < 0$. The example in Figure 2 has $1 - A = 7 \times 10^{-5}$ and $c = -0.056$. However $c < 0$ corresponds to $\ln |1 - 3P_{IGM}/2| > 0$ which is not possible within this model. If $c > 0$ the tension between the $d_A$ and $d_L$ measurements can be eased by photon-chameleon mixing. Suitable
Figure 2: Assuming standard rulers give the correct relation between $\Delta(m-M)$ and $z$, the solid line shows the prediction for observations of type 1a supernova if the probability of photon survival has the form (28) with $A = 0.99993$ and $c = -0.056$.

values of the parameters are $A = 1.271$ and $c = 1.10$ and the resulting prediction for the supernova is shown in Figure 3. For $z \lesssim 0.5$ the prediction is close to a $\Lambda$CDM universe and for larger $z$ there is a constant brightening from the radio galaxy data. Clearly more observations of high redshift supernova or smaller error bars would significantly improve the constraints on our model.

The values of $A$ and $c$ used in Figure 3 correspond to $P_{SN} N \approx 0.95$ and $P_{IGM} \approx 10^{-4}$ where

$$P_{SN} N \approx \frac{3B_{WD}^2 R_{WD}^4}{4M^2 R_{SN}^5}, \quad P_{IGM} \approx \frac{B_{IGM}^2 L_{dom}^2}{4M^2}$$

(29)

This implies the following relations between parameters

$$B_{WD} \sim 10^3 \left( \frac{M}{\text{GeV}} \right) \text{ G}, \quad B_{IGM} \sim 10^{-20} \left( \frac{M}{\text{GeV}} \right) \text{ G}$$

(30)

which are consistent with all current experimental bounds.
Figure 3: Assuming standard rulers give the correct relation between $\Delta(m - M)$ and $z$, the solid line shows the prediction for observations of type 1a supernova if the probability of photon survival has the form (28) with $A = 1.271$ and $c = 1.10$. 
In these calculations I have neglected the effect of the galactic magnetic field. The probability of conversion in one domain \( BL_{\text{dom}} \) depends on the combination \( BL_{\text{dom}} \). The galactic magnetic field has strength \( B_G \approx 10^{-5} \) G and coherence length \( L_{\text{dom}} = 100 \) pc so that \( B_G L_{\text{dom}} \approx 10^9 \) GeV. This is the same order of magnitude for \( BL_{\text{dom}} \) as for an intergalactic magnetic field with \( B_{\text{IGM}} \approx 10^{-9} \) G and coherence length \( L_{\text{dom}} \approx 1 \) Mpc. So in this case passing from the intergalactic magnetic field to the galactic magnetic field does not affect the probability of conversion. If \( B_{\text{IGM}} \ll 10^{-9} \) G then there will be a change in the probability of conversion when the photons move into the galaxy, however the distance travelled through the galaxy is small compared to the total distance from the supernova so the effects of the galaxy will at most be a small correction on the above result.

4 CMB Photons

If microwave photons from the CMB oscillate into chameleon states in the intergalactic magnetic field their anisotropy could be large due to variations in the magnetic field and thus disagree with observations. The frequency of a photon from the CMB is \( \omega \sim 10^{-4} \) eV so microwave photons fall into the low energy regime \( M|\omega^2_p - m^2| \gg B\omega \) where the mixing is small and the probability of chameleon-photon mixing is bounded by

\[
P \leq 4B^2\omega^2/M^2(\omega^2_p - m^2)^2 \quad (31)
\]

\[
\lesssim 10^{-6} \quad (32)
\]

for all allowed values of \( M \). The anisotropy sourced by one magnetic domain is less than the primordial CMB anisotropy \( \Delta T/T \sim 10^{-5} \).

If intergalactic magnetic fields are a relatively recent phenomenon and only exist out to redshifts of a few then the photons from the CMB have not travelled far enough through a magnetic field to reach their equilibrium configuration. The probability of conversion is not significantly enhanced by travelling through the many magnetic domains in the intergalactic medium and therefore chameleon-photon mixing does not conflict with observations of the CMB. The effect on the CMB of axion-photon mixing was considered in [30] but because we do not require a large probability of conversion in the intergalactic medium we are able to avoid the strict bounds that observations of
the black body spectrum of the CMB put on the axion photon mixing model.

An observation of a primordial magnetic field would put severe constraints on the chameleon model because then photons from the CMB would travel for large distances through a magnetic field. Conversely if the existence of chameleons is demonstrated, observations of the CMB would put strict bounds on the existence of a primordial magnetic field.

5 Conclusions

The chameleon model provides an explanation for the observed accelerated expansion of the universe. Observations of standard candles and standard rulers do not give a consistent picture of this acceleration which implies that the reciprocity relation does not hold. This can be explained if the chameleon couples to photons in the presence of a magnetic field. The strong magnetic field inside a supernova means that chameleons and photons mix in the interior of the supernova and so there is a flux of chameleon particles at the surface of the supernova. This is in contrast to axion-photon coupling which does not allow for a flux of axions at the surface of the supernova. Photons and chameleons also mix as they travel to earth through the intergalactic magnetic field. This requires $M \lesssim 10^{10}$ GeV to ensure the effect of the mixing is achromatic for optical photons. A chameleon model with a coupling of this strength should be detectable in future experiments looking for chameleonic afterglow or Casimir forces.

The overall effect of mixing between photons and chameleons is that observers on earth see a brightened image of the supernova. The brightening of supernovae eases the tension between observations of standard candles and standard rulers. Future observations of high redshift supernova will significantly improve the constraints on this model.

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