Was ordinary matter synthesised from mirror matter?
An attempt to explain why $\Omega_{\text{Baryon}} \approx 0.2\Omega_{\text{Dark}}$.

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The cosmological dust has begun to settle. A likely picture is a universe comprised (predominantly) of three components: ordinary baryons ($\Omega_B \approx 0.05$), non-baryonic dark matter ($\Omega_{\text{Dark}} \approx 0.22$) and dark energy ($\Omega_{\Lambda} \approx 0.7$). We suggest that the observed similarity of the abundances of ordinary baryons and non-baryonic dark matter ($\Omega_B/\Omega_{\text{Dark}} \approx 0.20$) hints at an underlying similarity between the fundamental properties of ordinary and dark matter particles. This is necessarily the case if dark matter is identified with mirror matter. We examine a specific mirror matter scenario where $\Omega_B/\Omega_{\text{Dark}} \approx 0.20$ is naturally obtained.

PACS numbers: 95.35.+d,98.80.Cq,11.30.Er,12.90.+b

Data obtained from high redshift supernovae [1], cosmic microwave background anisotropy measurements (culminating with the recent WMAP results [2]), and other sources, have greatly enriched cosmology. These data are consistent with a spatially-flat universe ($\Omega_{\text{tot}} \approx 1.0$), composed (predominantly) of ordinary matter ($\Omega_B \approx 0.05$), non-baryonic dark matter ($\Omega_{\text{Dark}} \approx 0.22$) and dark energy ($\Omega_{\Lambda} \approx 0.7$), although an alternative interpretation of the data with a zero $\Omega_{\Lambda}$ has also been proposed [3].

One striking feature of these results is the fact that the dark energy is currently of the same order of magnitude as the present mass density, $\Omega_m = \Omega_B + \Omega_{\text{Dark}}$, of the universe. Because dark energy and matter densities scale differently with time, it is expected that this feature was not true at earlier epochs. The present day similarity of dark energy and matter densities has been called the cosmic coincidence problem.

A fascinating related feature, which has not been emphasised so much in the literature, is the similarity in magnitude of the ordinary and dark matter densities:

$$\Omega_B/\Omega_{\text{Dark}} \approx 0.20.$$  \hspace{1cm} (1)

In contrast to $\Omega_m/\Omega_{\Lambda}$, the ratio of dark matter to ordinary matter is expected to be constant in time until a very early epoch. This means that the amount of dark matter produced in the early universe is of the same order of magnitude as the ordinary matter, despite their obviously disparate properties.

The observed similarity in the abundances of ordinary and dark matter hints at an underlying similarity between the microscopic properties of the elementary particles comprising the ordinary matter and the dark matter. Clearly, the standard exotic weakly interacting dark matter scenarios seem to offer no hope in explaining this cosmic coincidence because these particles have completely different properties (different masses and interactions) from the ordinary baryons. A priori, a dark matter/ordinary matter ratio of, say, $10^6$ would appear to be equally likely in these scenarios.

Interestingly, there is one obvious candidate for the dark matter which does actually require a similarity between the properties of ordinary and dark matter. This is “mirror matter”, a sector whose existence is required if nature respects a fundamental exact parity (mirror) symmetry [4, 5]. In this scenario, each ordinary particle has a distinct ‘mirror partner’ of the same mass connected with the ordinary particles via the parity symmetry:

$$x \rightarrow -x, \quad t \rightarrow t, \quad W^\mu \leftrightarrow W^\mu, \quad B^\mu \leftrightarrow B^\mu, \quad G^\mu \leftrightarrow G^\mu$$
$$\ell_iL \leftrightarrow \gamma_0 \ell'_iR, \quad e_iR \leftrightarrow \gamma_0 e'_iL, \quad q_iL \leftrightarrow \gamma_0 q'_iR, \quad u_iR \leftrightarrow \gamma_0 u'_iL, \quad d_iR \leftrightarrow \gamma_0 d'_iL,$$  \hspace{1cm} (2)

where $G^\mu, W^\mu, B^\mu$ are the standard $G_{SM} \equiv SU(3) \otimes SU(2) \otimes U(1)$ gauge particles, $\ell_iL, e_iR, q_iL, u_iR, d_iR$ are the standard leptons and quarks ($i = 1, 2, 3$ is the generation index) and the primes denote the mirror particles. There is also a standard Higgs doublet $\phi$ with a mirror Higgs doublet partner $\phi'$, and it can be shown that $\langle \phi \rangle = \langle \phi' \rangle$ for
a large range of parameters of the Higgs potential. We adopt this parameter regime, making the mirror symmetry exact (i.e. not spontaneously broken) if

Clearly, in this theory the properties of the mirror particles exactly mirror those of the ordinary ones. In particular, the mirror baryons are stable and do not couple to ordinary photons so they necessarily have the right broad properties to be the non-baryonic dark matter. Furthermore, recent detailed studies of large scale structure formation have confirmed that mirror baryons are a viable dark matter candidate from that point of view. Thus, if mirror symmetry is a fundamental symmetry of nature, it is natural to set \( \Omega_{\text{Dark}} = \Omega'_B \), the mirror baryon mass density. Of course, if dark matter is identified as mirror matter then mirror stars, mirror planets and even mirror space-bodies should exist; there is actually fascinating evidence for these things (for reviews and references, see Ref. [9]).

In this interpretation one would expect \( \Omega_B = \Omega'_B \) if the initial conditions of the universe were also mirror symmetric and no macroscopic asymmetry (such as a temperature difference) was produced during the early evolution of the universe. However, the success of standard big bang nucleosynthesis (BBN) does suggest that \( T' \) was somewhat less than \( T \) during the BBN epoch,

\[
T'/T \lesssim 0.5 \quad \text{at} \quad T \sim 1 \text{ MeV},
\]

in order for the expansion of the universe to have been within an acceptable range. If the temperatures are different, then this means that either the initial conditions of the universe were asymmetric or that the asymmetry was induced during the evolution of the universe, due to, for example, an asymmetric fluctuation that became enhanced in some way. One such way is via inflation. One can imagine having an ‘ordinary inflaton’ coupling to ordinary matter, and a ‘mirror inflaton’ coupling to mirror matter. If inflation is triggered by some random fluctuation, then it can occur in the two sectors at different times, leading to \( T \neq T' \) after reheating in the two sectors. In such a scenario, one expects the baryon number and mirror baryon number to be unequal (since baryogenesis or leptogenesis depends on the temperature and expansion rate).

Provided that the temperatures of the two sectors are not too different this might explain the fact that \( \Omega_B \) is within an order of magnitude of \( \Omega'_B \). Clearly, the details will depend on the precise model for baryogenesis used by nature, which is of course not known (see the first paper of Ref. [3] for a couple of examples).

We consider instead an alternative possibility: that immediately after reheating, either \( \Omega'_B \gg \Omega_B \) or the opposite obtains, perhaps due to a very large initial temperature hierarchy (e.g. \( T' \gg T \)). Instead of specifying models in great detail, we will try to explain the ratio \( \Omega_B/\Omega'_B \approx 0.2 \) in an almost model independent way using sphaleron and other processes to transfer asymmetries.

In particular, consider the following scenario:

- **Step 1.** A period of inflation sufficiently long to solve the standard cosmological problems (flatness, homogeneity and so on). If this period of inflation is driven by the vacuum energy of a ‘mirror inflaton’, then after reheating one is left with a large temperature asymmetry, \( T' \gg T \).

- **Step 2.** At a certain temperature, \( T' = T_1 \), an asymmetry generation process takes place: the out-of-equilibrium decay of a heavy mirror lepton for example. This generates initial \( B' \) and/or \( L' \) asymmetries. No significant \( B \) or \( L \) will be generated if the temperature \( T' \) of the ordinary sector is sufficiently low.

- **Step 3.** Ordinary baryon number (and lepton number) will be generated from \( B' \) or \( L' \) if there is some process that can transfer asymmetries from the mirror sector to the ordinary sector. The simplest interaction that can do this (involving standard model particles and mirror particles) is the non-renormalisable dimension-5 operator,

\[
L = \frac{1}{M_N} \bar{\ell}_L \phi^c \ell_R \phi' + \text{H.c.},
\]

where \( M_N \) is a large scale. Such an operator can be related to the neutrino masses, \( m_\nu \sim \langle \phi \rangle^2/M_N \), and can be motivated by neutrino physics experiments. This interaction will bring the ordinary and mirror sectors into thermal equilibrium for temperatures \( M_N \gtrsim T \gtrsim 10^{10}(eV/m_\nu)^2 \text{ GeV} \), combining with other interactions (such as those induced by sphalerons) to generate \( B \) and \( L \) from the initial \( B' \) and/or \( L' \) asymmetries produced in step 2.

- **Step 4.** We require a second, but relatively short period of inflation (or some other type of mechanism) to induce the mild hierarchy \( T'/T \lesssim 0.5 \) suggested by BBN. It is tempting to associate the second period of inflation with the existence of an ordinary inflaton [perhaps the mirror partner of the mirror inflaton of step(i)]. In addition to generating the temperature asymmetry (\( T'/T \lesssim 0.5 \)), the reheating associated with the ordinary inflaton will dilute both the ordinary and mirror baryon numbers relative to the entropy; the amount of reheating after the
second period of inflation must therefore be moderate, consistent with the quite mild temperature asymmetry required for consistency with BBN.¹

It turns out that this scenario allows for a definite prediction of the ratio \( \Omega_B/\Omega'_B \), typically about 0.2 as we will show, consistent with the observations.

For definiteness, we will assume the existence of only one operator of the form of Eq. (4), coupling to the second generation,

\[
L = \frac{1}{M_N} \tilde{e}_L \phi^c e_R' \phi^c + H.c. \tag{5}
\]

We expect that similar results would arise if the interaction, Eq. (5), was replaced by some other type of interaction, so long as it coupled ordinary to mirror particles. The use of the specific form of Eq. (5) is only meant to provide a definite illustration of our idea.

In order to proceed, we need to know the temperature above which the interaction, Eq. (5), is efficient enough to bring the ordinary sector into equilibrium with the mirror sector. We expect this to be quite high, \( T \gtrsim T_2 \sim 10^{10} \) GeV (for \( m_\nu \sim 1 \) eV). For temperatures less than about \( 10^{12} \) GeV, the QCD and electroweak sphaleron processes plus the Yukawa interactions for the \( c, t, \bar{b}, \tau \) fermions are faster than the expansion rate of the universe. However, until the temperature drops below about \( 10^{10} \) GeV, Yukawa interactions are not strong enough to keep \( \bar{c}_R, \mu_R, \bar{s}_R, \bar{d}_R \) and \( u_R \) (and their mirror counterparts) in chemical equilibrium and we can neglect these processes for now. Thus, for a temperature \( T \sim 10^{10} \) GeV, we have the following chemical potential constraints:\(^2\)

\[
\begin{align*}
9\mu_q + & 3 \sum_{i=1}^3 \mu_{e_i} = 0 \quad \text{[Electroweak sphaleron]}, \\
6\mu_q - & 3 \sum_{i=1}^3 (\mu_{u_i} + \mu_{d_i}) = 0 \quad \text{[QCD sphaleron]}, \\
3\mu_q + & 2\mu_\phi + 3 \sum_{i=1}^3 (2\mu_{u_i} - \mu_{d_i} - \mu_{e_i} - \mu_{\ell_i}) = 0 \quad \text{[Hypercharge neutrality]}, \\
\mu_q - & \mu_\phi - \mu_{d_1} = 0 \quad \text{[Yukawa interactions]}, \\
\mu_q + & \mu_\phi - \mu_{u_2} = 0 \quad \text{[Yukawa interactions]}, \\
\mu_q + & \mu_\phi - \mu_{u_3} = 0 \quad \text{[Yukawa interactions]}, \\
\mu_{\ell_3} - & \mu_\phi - \mu_{\ell_3} = 0 \quad \text{[Yukawa interactions]}. \tag{6}
\end{align*}
\]

For each of the above equations there is a mirror equation (for the mirror particles) which is of the same form except with primes on all the chemical potentials. Note that the dimension-5 operator, Eq. (5), couples the ordinary and mirror particles together, leading to one more equation:

\[
-\mu_{\ell_2} - \mu_\phi + \mu_{\ell_2}' + \mu_\phi' = 0. \tag{7}
\]

Thus, we have a total of fifteen equations constraining twenty-eight chemical potentials. This leaves thirteen independent linear combinations of chemical potentials, correlated with thirteen easily identified conserved charges.

There are six conserved charges in the ordinary sector and six in the mirror sector,

\[
\begin{align*}
L_1 &= \frac{1}{3} B - L_1, & L'_1 &= \frac{1}{3} B' - L'_1 \\
L_2 &= \frac{1}{3} B - L_2, & L'_2 &= \frac{1}{3} B' - L'_2
\end{align*}
\]

¹ Note, however, that neither inflation nor the reheating processes directly affect the final value of the ratio \( \Omega_B/\Omega'_B \). To see this note that the (current) value of the ratio, \( \Omega_B/\Omega'_B \), can be related to the absolute numbers of baryons (\( N_B \)) and mirror baryons (\( N'_B \)) as follows: \( \Omega_B/\Omega'_B = (N_B m_B / V / \rho_c) / (N'_B m_B / V / \rho_c) = N_B / N'_B \) where \( V \) is the characteristic volume and \( \rho_c \) is the critical density. Since the absolute numbers of baryons and mirror baryons are not affected by inflation or reheating, it follows that the ratio \( \Omega_B/\Omega'_B \) is also not directly affected by either of these processes.

² Note that the \( SU(2) \) gauge interactions ensure that \( \mu_{u_3L} = \mu_{d_3L} = \mu_{b_3L} = \mu_{\ell_3L} \). (due to processes such as \( \bar{u}_{3L} d_{3L} \rightarrow \bar{u}_{3L} d_{2L}, \bar{u}_{2L} d_{2L} \rightarrow \bar{u}_{2L} d_{1L} \)). Also, to simplify notation, we have used the abbreviations \( \mu_{u_i} = \mu_{u_i R}, \mu_{d_i} = \mu_{d_i R}, \mu_q = \mu_{qL}, \) and \( \mu_{\ell_i} = \mu_{\ell_i L} \).
where \( L_{1,2,3} \) are family lepton numbers, \( L_{e_1 R} \) is the right-handed electron number (which has a value of one for \( e_1 R \) and zero for all other fields) and with the other charges defined similarly. To identify the thirteenth conserved charge, observe that the interaction of Eq. (5) implies that only the sum of \( \frac{1}{3} B - L_2 \) and \( \frac{1}{3} B' - L'_2 \),

\[
\mathcal{L}_0 = \frac{1}{3} B - L_2 + \frac{1}{3} B' - L'_2,
\]

is conserved. It is straightforward to write down the chemical potential linear combinations that correspond to each of these charges, using, for instance,

\[
B \leftrightarrow 6 \mu_q + \sum_{i=1}^{3} (2 \mu_{u_i} + \mu_{d_i}),
\]

\[
L_1 \leftrightarrow 2 \mu_{\ell_1} + \mu_{e_1},
\]

and so on.

Equations (6) and (7) can be solved to obtain the baryon and lepton numbers (after chemical reprocessing), in terms of the conserved quantities \( \mathcal{L}_i, \mathcal{L}'_i \) and \( \mathcal{L}_0 \):

\[
B = \alpha_0 \mathcal{L}_0 + \sum_{i=1}^{6} \alpha_i \mathcal{L}_i + \sum_{i=1}^{6} \alpha'_i \mathcal{L}'_i,
\]

\[
L = \beta_0 \mathcal{L}_0 + \sum_{i=1}^{6} \beta_i \mathcal{L}_i + \sum_{i=1}^{6} \beta'_i \mathcal{L}'_i. \tag{11}
\]

Under mirror symmetry, \( B \leftrightarrow B', \ L \leftrightarrow L', \ \mathcal{L}_i \leftrightarrow \mathcal{L}'_i \) (and \( \mathcal{L}_0 \to \mathcal{L}_0 \)). Hence,

\[
B' = \alpha_0 \mathcal{L}_0 + \sum_{i=1}^{6} \alpha_i \mathcal{L}'_i + \sum_{i=1}^{6} \alpha'_i \mathcal{L}_i,
\]

\[
L' = \beta_0 \mathcal{L}_0 + \sum_{i=1}^{6} \beta_i \mathcal{L}'_i + \sum_{i=1}^{6} \beta'_i \mathcal{L}_i. \tag{12}
\]

The values of the \( \alpha \) and \( \beta \) parameters are given in Table I.

**Table I** The \( \alpha \) and \( \beta \) coefficients in the expansions of \( B \) and \( L \) defined in Eqs. (11) and (12).

| \( \alpha \) | \( \alpha' \) | \( \beta \) | \( \beta' \) |
| --- | --- | --- | --- |
| \( \frac{69}{316} \) | \( \frac{345}{98276} \) | \( \frac{-39}{316} \) | \( \frac{-445}{98276} \) |
| \( \frac{43263}{98276} \) | \( \frac{-6003}{98276} \) | \( \frac{31443}{98276} \) | \( \frac{-534}{24569} \) |
| \( \frac{7059}{24569} \) | \( \frac{414}{24569} \) | \( \frac{-16571}{24569} \) | \( \frac{-343}{24569} \) |
| \( \frac{45189}{98276} \) | \( \frac{15801}{98276} \) | \( \frac{55803}{98276} \) | \( \frac{-16571}{24569} \) |
| \( \frac{23385}{98276} \) | \( \frac{2829}{49138} \) | \( \frac{5515}{24569} \) | \( \frac{-20381}{98276} \) |
| \( \frac{-663}{24569} \) | \( \frac{2829}{49138} \) | \( \frac{5515}{24569} \) | \( \frac{-20381}{98276} \) |
| \( \frac{-963}{49138} \) | \( \frac{2829}{49138} \) | \( \frac{5515}{49138} \) | \( \frac{-3649}{49138} \) |
Of course the values of the conserved charges, $\mathcal{L}$, $\mathcal{L}'$, and $\mathcal{L}_0$ depend on the initial asymmetry generation mechanism. We consider, for definiteness, the simple case of non-zero $B'$ and/or $L'$: $B' = X'_0$, $L' = Y'_0$, $B = L = 0$ (with $L'_{e_1} = L'_{t_2} = L'_{t_3} \equiv Y'_0/3$ and $B'_{d_{1R}} = B'_{d_{2R}} = B'_{t_{1R}}$). In this case the only non-zero conserved charges are $\mathcal{L}_1'$, $\mathcal{L}_2'$ and $\mathcal{L}_0$ with $\mathcal{L}_1' = \mathcal{L}_2' = \mathcal{L}_0 = \frac{1}{3}(X'_0 - Y'_0) \equiv Z$. After chemical processing, with Eqs.\(^\text{13}\) and \(^\text{14}\) summarising the consequences, we are left with the baryon and mirror baryon asymmetries given by

$$
B = Z(\alpha_0 + \alpha'_1 + \alpha'_2), \\
B' = Z(\alpha_0 + \alpha_1 + \alpha_2),
$$

\(^\text{(13)}\)

where Eqs.\(^\text{13}\) and \(^\text{14}\) have been used. So, the ordinary matter/dark matter ratio is given by

$$
\frac{B}{B'} = \frac{\alpha_0 + \alpha'_1 + \alpha'_2}{\alpha_0 + \alpha_1 + \alpha_2} \simeq 0.24.
$$

\(^\text{(14)}\)

This is the ratio of ordinary baryon-number density to mirror baryon-number density at $T \sim 10^{10}$ GeV. The value of this ratio changes somewhat at lower temperatures as different species come into chemical equilibrium. However, at temperatures near the electroweak phase transition, $T = T_{EW} \sim 200$ GeV, the ‘final’ values of $B$ and $B'$ depend only on the values of $B - L$ and $B' - L'$. These charges are separately conserved for $T \ll 10^{10}$ GeV, because the interaction in Eq.\(^\text{5}\) is slower than the expansion rate. This yields the well-known relation between $B$ and $B - L$ \(^\text{12}\), \(^\text{3}\)

$$
B = \frac{28}{79}(B - L),
$$

\(^\text{(15)}\)

with an identical relation for $B'$ in terms of $B' - L'$ (equally well-known to mirror physicists). Thus the final value of the ratio $B/B'$, denoted $B^f/B'^f$ below, is equal to the ratio $(B - L)/(B' - L')$, that is,

$$
\frac{B^f}{B'^f} = \frac{\alpha_0 + \alpha'_1 + \alpha'_2 - \beta_0 - \beta'_1 - \beta'_2}{\alpha_0 + \alpha_1 + \alpha_2 - \beta_0 + \beta'_1 - \beta'_2} \simeq 0.21.
$$

\(^\text{(16)}\)

Of course, if there is some brief period of inflation between $T \sim 10^{10}$ GeV and $T_{EW}$ then the above result is only valid provided that the reheating temperature of $T'$ and $T$ are both greater than $T_{EW}$. In the alternative case where the reheating temperatures satisfy $T' < T_{EW}$ and $T > T_{EW}$, then the final asymmetry ratio is

$$
\frac{B^f}{B'^f} = \frac{28}{79} \frac{\alpha_0 + \alpha'_1 + \alpha'_2 - \beta_0 - \beta'_1 - \beta'_2}{\alpha_0 + \alpha_1 + \alpha_2} \simeq 0.20,
$$

\(^\text{(17)}\)

which is not very different from the previous result.

While these quantitative results are quite impressive when compared to the observations, $\Omega_b/\Omega_{\text{dark}} = 0.20 \pm 0.02$ according to Ref.\(^\text{2}\), one should be cautious. It is probably unlikely that the standard model description of the ordinary particle interactions remains valid up to $T \sim 10^{10}$ GeV; new particles and interactions may exist. The interaction of Eq.\(^\text{5}\) may not occur, or if it does it might not be strong enough to thermalise the ordinary and mirror sectors. Some other interaction might be responsible for this, perhaps involving other exotic heavy fermions or scalars.

On the positive side, it is quite easy to see why we obtained an $\Omega_b/\Omega_{\text{dark}}$ value of about the right size – given our assumption that $B$ and $L$ are generated from $B'$ and $L'$. The point is that this creates a fundamental asymmetry: there are more non-zero mirror charges than ordinary ones. In the particular scenario studied, the only non-zero conserved charges were $\mathcal{L}'_{1,2}$ and $\mathcal{L}_0$. These are mainly mirror charges, with only $\mathcal{L}_0$ involving ordinary particles. Thus, the observation that ordinary matter is a small, yet significant fraction of the total matter density in the universe seems to be explicable, at least in principle, if mirror matter is the dark matter.

\(^\text{3}\) Higher order corrections exist, but are quite small ($\lesssim$ few percent) and depend on whether the electroweak phase transition is first order or second order \(^\text{12}\).
Acknowledgments

This work was supported by the Australian Research Council.

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