There are six main things which any non-baryonic dark matter theory should endeavour to explain: (1) The basic dark matter particle properties [mass, stability, darkness]; (2) The similarity in cosmic abundance between ordinary and non-baryonic dark matter, $\Omega_B \sim \Omega_{dark}$; (3) Large scale structure formation; (4) Microlensing (MACHO) events; (5) Asymptotically flat rotation curves in spiral galaxies; (6) The impressive DAMA/NaI annual modulation signal. Only mirror matter-type dark matter is capable of explaining all six of these desirable features. The purpose of this article is to provide an up-to-date and pedagogical review of this dark matter candidate.

Keywords: Dark matter; Extensions of the standard model

1. Introduction

There is a very strong scientific case that most of the matter in the Universe consists of non-baryonic stable particles. Since the standard model of particle physics does not contain any heavy stable non-baryonic particles new particle physics is required. But what is this new physics?

It is widely assumed that the particles comprising non-baryonic dark matter are weakly interacting in the sense that they interact with ordinary matter via exchange of W, Z gauge bosons, Higgs bosons or more exotic heavy particles. From collider bounds (e.g. lack of new particles in decays of the W and Z gauge bosons), the masses of any new weakly interacting particles should be (typically) greater than about 30-45 GeV$^a$ – depending on the model. However, such heavy weakly interacting particles should decay with a lifetime of order $\sim 1/(g^2 M_{wimp}) \sim 10^{-24}$ seconds (for $M_{wimp} \sim M_Z$) – about 41 orders of magnitude too short-lived to be suitable as dark matter candidates$^b$. Thus, one must make additional ad hoc assumptions in order to stabilize such hypothetical particles. In the end, theories with such particles require multiple unrelated assumptions and become very ugly from a particle physics point of view. A well known example is the popular neutralino model which requires at least three independent hypothesis: a) broken low energy

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$^a$Throughout this article we use units where $\hbar = c = k = 1$, unless indicated otherwise.

$^b$E.g. the Z-boson is a weakly interacting massive particle – a WIMP – and has lifetime of about $3 \times 10^{-25}$ seconds.
supersymmetry exists which provides WIMP candidates, b) an exact unbroken r-parity symmetry is proposed to prevent the lightest superpartner from decaying\(^c\) and c) the lightest superpartner is hypothesized to be neutral to make it suitable for dark matter.

It seems to me that a more plausible candidate for this new physics arises from the hypothesis of exact unbroken mirror symmetry \([x \rightarrow -x, \ t \rightarrow t]\). It is more plausible because it involves only a single well motivated hypothesis. Improper space-time symmetries, such as parity and time reversal symmetries, stand out as the only obvious symmetries which are not respected by the interactions of the known elementary particles. It is an interesting and non-trivial fact that these symmetries can be exact, unbroken symmetries of nature if a set of mirror particles exist. Even more interesting is that the mirror particles have the right broad properties to be identified with the non-baryonic dark matter in the Universe.

The ordinary and mirror particles form parallel sectors each with gauge symmetry \(G\) (where \(G = G_{SM} \equiv SU(3)_c \otimes SU(2)_L \otimes U(1)_Y\) in the simplest case) so that the full gauge group is \(G \otimes G\). Mathematically, mirror symmetry has the form:

\[
x \rightarrow -x, \ t \rightarrow t, \\
G^\mu \leftrightarrow G'_\mu, \ W^\mu \leftrightarrow W'_\mu, \ B^\mu \leftrightarrow B'_\mu, \\
\ell_iL \leftrightarrow \gamma_0 \ell'_iR, \ e_iR \leftrightarrow \gamma_0 e'_iL, \ q_iL \leftrightarrow \gamma_0 q'_iR, \ u_iR \leftrightarrow \gamma_0 u'_iL, \ d_iR \leftrightarrow \gamma_0 d'_iL, \
\]

where \(G^\mu, W^\mu, B^\mu\) are the standard \(G_{SM} \equiv SU(3)_c \otimes SU(2)_L \otimes U(1)_Y\) 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, \(\phi'\). Importantly, there is a large range of parameters of the Higgs potential for which mirror symmetry is not spontaneously broken by the vacuum (i.e. \(\langle \phi \rangle = \langle \phi' \rangle\)) so that it is an exact, unbroken symmetry of the theory\(^d\). Interestingly, despite doubling the number of particle types the number of free parameters have not (yet!) been increased; mirror symmetry implies that the masses and couplings of the particles in the mirror sector are exactly the same as the corresponding ones in the ordinary sector.

Ordinary and mirror particles couple with each other via gravity and possibly by new interactions connecting ordinary and mirror particles together. Constraints from gauge invariance, mirror symmetry and renormalizability, suggest only two types of new interactions\(^e\): a) Higgs-mirror Higgs quartic coupling \(\mathcal{L} = \)

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\(^c\)Note that r-parity has, of course, nothing to do with space-time parity but is an ad hoc discrete symmetry.

\(^d\)It is theoretically possible to have mirror symmetry spontaneously broken by the vacuum \((\langle \phi \rangle \neq \langle \phi' \rangle)\), but the simplest models of this type are disfavoured for a variety of reasons\(^f\).

\(^e\)More complicated models with broken mirror symmetry are still possible and have been studied in the literature, see e.g. ref.\(^g\).
\[ \lambda \phi'^\dagger \phi' \phi^\dagger \phi, \text{ and } b) \text{ via photon-mirror photon kinetic mixing:} \]

\[ \mathcal{L}_{\text{int}} = \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu}, \tag{2} \]

where \( F_{\mu\nu} \) (\( F'_{\mu\nu} \)) is the field strength tensor for electromagnetism (mirror electromagnetism). The effect of the Higgs-mirror Higgs quartic coupling is to modify the properties of the standard Higgs boson. This interaction will be tested if/when scalar particles are discovered. One effect of photon-mirror photon kinetic mixing is to cause mirror charged particles (such as the mirror proton and mirror electron) to couple to ordinary photons with effective electric charge \( \epsilon E \). As we will see, this non-gravitational interaction between ordinary and mirror particles provides a key way to experimentally test the theory.

To summarize: the only obvious space-time symmetries that are not respected by the interactions of the known elementary particles are the improper Lorentz symmetries (such as parity and time reversal). These symmetries can be unbroken symmetries of nature provided that the Universe contains both ordinary and mirror particles. The mirror particles have identical masses to the corresponding ordinary particles and have identical, but separate gauge interactions (the gauge group is \( G_{\text{SM}} \otimes G_{\text{SM}} \)). The mirror particles couple to the ordinary ones via gravity and possibly via Higgs-mirror Higgs interactions and photon-mirror photon kinetic mixing. It turns out that the mirror particles lead to an elegant explanation for the inferred non-baryonic dark matter component of the Universe, as we will explain in more detail in the following sections.

2. Identifying mirror matter with the inferred non-baryonic dark matter in the Universe

There is a substantial range of evidence for non-baryonic dark matter in the Universe. We have already emphasised in the introduction that a basic requirement is that the massive particles comprising dark matter need to be stable and have no

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8Allowing the ordinary and mirror sectors to interact with each other leads to two new free parameters \((\lambda', \epsilon)\). However, compared to other ideas beyond the standard model, many of which have literally hundreds of new parameters, mirror symmetry is a fairly minimal extension of the standard model. Also note, if the neutrinos have mass, mass mixing between ordinary and mirror neutrinos is also possible, and might be implicated by the observed atmospheric, solar and LSND neutrino anomalies. However, the experimental situation is still not clear.

9Technically, the photon-mirror photon kinetic mixing arises from kinetic mixing of \( U(1)_Y \), \( U(1)' \), gauge bosons, since only for abelian \( U(1) \) symmetry is the mixing term, \( FF' \), gauge invariant. Therefore there is both \( \gamma - \gamma' \) and \( Z - Z' \) kinetic mixing. However, experiments are much more sensitive to \( \gamma - \gamma' \) kinetic mixing which is why it is more important. In the case of theories without \( U(1) \) gauge symmetries, such as GUTs, the \( \gamma - \gamma' \) mixing can arise radiatively provided that there exists a mixed form of matter carrying both ordinary and mirror electric charge. Interestingly, there is a class of such models where \( \epsilon \) vanishes at one and two loop level, and therefore naturally of the order of \( \epsilon \sim 10^{-8} \).
or small coupling to ordinary photons. There are other desirable features that are also required, including (in random order):

- An explanation for $\Omega_{\text{dark}} \sim \Omega_B$.
- It should be capable of explaining the large scale structure of the Universe.
- Asymptotically flat rotation curves in spiral galaxies suggest that dark matter is (roughly) spherically distributed in a ‘halo’ in spiral galaxies. This is in contrast to ordinary matter which is distributed in the disk and bulge.
- A substantial fraction ($\sim 20\%$) of the mass of the halo appears to be in the form of massive ($\sim 0.5M_\odot$) compact invisible objects (MACHOs). What are the MACHOs and why are they invisible?
- The direct experimental detection of halo dark matter particles has been achieved by the DAMA/NaI collaboration. Other experiments report only negative results. Why?

We now examine each of these items from a mirror matter perspective.

2.1. $\Omega_{\text{dark}} \sim \Omega_B$

Precision cosmic microwave background measurements (culminating with the recent WMAP results\cite{12}) have established that the Universe is spatially flat, i.e. $\Omega_{\text{tot}} \approx 1.0$. Furthermore, the WMAP results, together with observations of high redshift Type Ia supernovae\cite{13} and other measurements, suggest that the Universe consists predominately of three components: ordinary matter ($\Omega_B \approx 0.05$), non-baryonic dark matter ($\Omega_{\text{dark}} \approx 0.22$) and dark energy ($\Omega_\Lambda \approx 0.7$). It is striking that each of these three different components should have energy densities of the same order of magnitude. Since $\Omega_\Lambda$ scales differently in time with $\Omega_{\text{dark}}$ and $\Omega_B$, the similarity between $\Omega_\Lambda$ and $\Omega_{\text{matter}} = \Omega_{\text{dark}} + \Omega_B$ might simply be a coincidence. However, the similarity in magnitude of the ordinary and dark matter densities:

$$\Omega_B/\Omega_{\text{dark}} \approx 0.20,$$

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 apparent disparate properties.

The 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 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. However if dark matter is identified with mirror baryons, then it seems to be possible to explain the similarity of $\Omega_{\text{dark}}$ and $\Omega_B$ because the microscopic properties of the
Mirror matter-type dark matter

mirror particles mirror those of the ordinary particles. In fact, \( \Omega_{\text{dark}} = \Omega_B \) would occur 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) \(^{14}\) does suggest that \( T' \) was somewhat less than \( T \) during the BBN epoch,

\[
T'/T \lesssim 0.6 \quad \text{at} \quad T \sim 1 \text{ MeV},
\]

in order for the expansion rate of the universe to have been within an acceptable range\(^8\). 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 early evolution of the universe. Actually, within the inflation paradigm it is quite easy to generate the required temperature asymmetry\(^15\). In particular, it is natural to have 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 \( \Omega_{\text{dark}} \). 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.\(^16\) for a couple of examples). Even if there is a large hierarchy in temperatures for the two sectors, similar abundances of ordinary and mirror particles can be achieved if there are interactions which can transfer lepton or baryon asymmetry between the two sectors\(^17\). The simplest such interaction is given by the dimension 5 operator:

\[
\mathcal{L} = \frac{1}{M_N} \ell_L \phi^c \ell_R \phi' + \text{H.c.}
\]

where \( \ell_L \) is a left-handed ordinary lepton doublet, \( \ell_R \) is its mirror partner, \( \phi \) is the ordinary Higgs doublet and \( \phi' \) is its mirror partner (\( \text{H.c.} = \text{Hermitian conjugate} \)). With such operators and some plausible assumptions about the physics governing the early evolution of the Universe, it is even possible\(^17\) to quantitatively explain the inferred non-baryonic dark matter proportion, \( \Omega_B / \Omega_{\text{dark}} = 0.20 \pm 0.02 \).

We will not discuss much more about the very early Universe (the era prior to BBN). These were the cosmic dark ages where much is speculated but little is known. A more recent development (in the history of the Universe) was the formation of large scale structure, which is also the next topic.

\(^8\)If \( T' = T \) then the energy density at the BBN epoch would be double the standard value – significantly increasing the expansion rate of the Universe at that time. The equilibration of the three mirror neutrinos, mirror electron/positron and mirror photons is equivalent to an extra \( \delta N_{\nu} \approx 6.14 \) neutrino species. More generally, \( \delta N_{\nu} = 6.14(T'/T)^4 \), so that demanding \( \delta N_{\nu} < 1 \) would imply \( T' < 0.64T \).
2.2. Large Scale Structure formation

We know from measurements of the cosmic microwave background that the Universe was extraordinarily homogeneous in the past. At the present epoch, however, the Universe is no longer particularly homogeneous: it contains galaxies, clusters of galaxies, superclusters etc. This large scale structure is believed to arise from small primordial inhomogeneities that grow via gravitational instability. However ordinary baryonic density perturbations cannot begin to grow until photon decoupling occurs at a temperature of around \( T_{\text{dec}} \approx 0.25 \) eV, corresponding to a red shift of \( z_{\text{dec}} \approx 1100 \). [Prior to photon decoupling, the radiation pressure prevents the growth of perturbations]. But this is too late: perturbations which have amplitude of order \( \delta \sim 10^{-5} \) (as inferred from the anisotropies of the cosmic microwave background) do not have enough time to grow into galaxies, where \( \delta \sim 10^2 \). This suggests that inhomogeneities begin to grow prior to photon decoupling. This is one role that non-baryonic dark matter is expected to fill: it should be weakly coupled to the ordinary particles in the plasma so that density perturbation growth can begin prior to photon decoupling.

Mirror particles are weakly coupled to the ordinary ones. However, mirror baryonic density perturbations can only begin to grow after mirror photon decoupling occurs (roughly when \( T'_{\text{dec}} \sim 0.25 \) eV). The key point is that if \( T' < T \) [which we infer from BBN, see Eq.(4)] then mirror photon decoupling necessarily occurs earlier than ordinary photon decoupling. Thus, we expect that mirror baryonic structure formation should begin earlier than ordinary baryonic structure. According to Refs. [16-18], they find that for \( T' \approx 0.2T \), large scale structure formation with mirror matter-type dark matter closely resembles the standard cold dark matter scenario (but with some intriguing differences) and would provide a successful framework to understand the large scale structure of the Universe [16-18,19].

A consequence of \( T' < T \), required for successful big bang nucleosynthesis and large scale structure formation, is that mirror BBN occurs earlier than ordinary BBN. This will mean that the proportion of mirror helium \((H'\!\!')\) to mirror hydrogen \((H')\) synthesised in the early Universe will be different to their ordinary matter counterparts. In fact, since the expansion rate of the Universe is faster at earlier times the mirror neutron/mirror proton ratio should be closer to unity c.f. ordinary BBN. This means that the \( \He'/H' \) ratio is expected to be significantly greater than the corresponding ordinary \( \He/H \) ratio. This chemical imbalance between the ordinary and mirror sectors will no doubt have important effects. For example, the initial mass function for mirror stars can be quite different than for ordinary stars. Ultimately, this chemical imbalance might even be responsible for the different distribution of ordinary and mirror matter in galaxies, as we will now discuss.
2.3. Asymptotically flat rotation curves and the radiative cooling problem

We have briefly mentioned cosmological evidence for non-baryonic dark matter in sections 2.1 and 2.2. There is also strong astrophysical evidence for a large amount of dark matter in galaxies and galaxy clusters. Asymptotically flat rotation curves in spiral galaxies, illustrated in Figure 1, imply that there must exist invisible ‘halos’ in galaxies such as our own Milky Way. These halos are, roughly, spherical distributions of invisible matter which dominate the mass of the galaxy. For example, the mass of the invisible halo of the Milky Way galaxy is estimated to be \( \sim 6 \times 10^{11}M_\odot \), which is about an order of magnitude more than the estimated mass of the galactic disk component.  

![Figure 1: The observed rotation curve for the spiral galaxy M33 superimposed on its optical image.](image)

There is strong evidence that this galactic halo dark matter must be something exotic; ordinary baryons simply cannot account for it. Taking the case of white dwarfs as an example, these would be dim enough to escape detection (unless they are very young). However, in the collapse process where they are formed the outer layers of the star are ejected into space. This ejected material is rich in heavy elements such as oxygen and nitrogen. If such material were present in the halo it would have been revealed from characteristic absorption/emission lines. Alternatively, if the ejected material were to collapse onto the galactic disk due to collisional
processes, its estimated abundance would be greater than the entire mass of the disk. Thus, old (ordinary) white dwarfs cannot provide a consistent picture for halo dark matter. All other conventional candidates for galactic dark matter run into similar severe difficulties.

Obviously a (roughly) spherical halo containing mirror stars, mirror planets, mirror dust and mirror gas would be much less problematic since any absorption/emission lines would be absent\(^h\). Of course, there is still the important problem of explaining the roughly spherical mirror matter distribution in the galaxy, with ordinary matter collapsed onto the disk. A priori this is possible: although ordinary and mirror matter have identical microscopic interactions, there is no macroscopic mirror symmetry. Recall this macroscopic asymmetry is necessary to explain a) different abundance of ordinary and mirror matter in the Universe (\(\Omega_{\text{dark}} \neq \Omega_B\), but \(\Omega_{\text{dark}} \approx 5\Omega_B\)) and b) the different temperatures of the ordinary and mirror sector (in the early Universe) required by successful BBN and large scale structure (as discussed earlier). Because of this macroscopic asymmetry, the evolution of the ordinary and mirror sectors can be significantly different.

Assuming that the halo is dominated by a mirror gas component which is approximately spherical and isothermal, its distribution can be obtained from the condition of hydrostatic equilibrium\(^i\):

\[
\frac{dP}{dr} = -\rho g(r)
\]

where \(P\) is the pressure and \(g(r)\) is the local acceleration at a radius \(r\). For a dilute gas, the pressure is related to the mass density, \(\rho\), via \(P = \rho T/(\mu M_p)\), where \(\mu M_p\) is the average mass of the particles in the gas (\(M_p\) is the proton mass). The local acceleration can be simply expressed in terms of the energy density, via:

\[
g(r) = G \frac{4\pi}{r^2} \int_0^r \rho 4\pi r'^2 dr' ,
\]

where \(G\) is Newton’s constant.

The solution of Eq.\(^6\) is \(\rho \propto 1/r^2\):

\[
\rho = \frac{\lambda}{r^2} ,
\]

\[
T = G\lambda 2\pi\mu M_p .
\]

The rotational velocity at a radial location \(R_0\), \(v_{\text{rot}}(R_0)\), can be obtained from \(v_{\text{rot}}^2/R_0 = g(R_0)\) which implies:

\[
v_{\text{rot}}^2(R_0) = \frac{G}{R_0} \int_0^{R_0} \rho 4\pi r'^2 dr'
 = G\lambda 4\pi .
\]

\(^h\)Technically, ordinary photon absorption/emission lines would still be there due to the effect of photon-mirror photon kinetic mixing. However the intensity would be reduced by a factor of \(\epsilon^2\) (and \(\epsilon^2 \sim 10^{-17}\) given the fit of the DAMA/NaI experiment, see later discussion in section 2.5).

\(^i\)The material in this subsection follows Ref.\(^{23}\).
Clearly, $\rho = \lambda / r^2$, implied by a spherically symmetric self gravitating gas in hydrostatic equilibrium, gives the required asymptotically flat rotation curve (a well-known result). Furthermore, from the above equation, $\lambda = v_{\text{rot}}^2 / (4 \pi G)$, which means that we can express $\rho$ and $T$ in terms of $v_{\text{rot}}$:

$$\rho = \frac{v_{\text{rot}}^2}{4 \pi G r^2} \approx 0.3 \left( \frac{v_{\text{rot}}}{220 \text{ km/s}} \right)^2 \left( \frac{10 \text{ kpc}}{r} \right)^2 \text{ GeV/cm}^3$$

$$T = \frac{\mu M_p v_{\text{rot}}^2}{2} \approx 300 \left( \frac{\mu M_p}{1 \text{ GeV}} \right) \left( \frac{v_{\text{rot}}}{220 \text{ km/s}} \right)^2 \text{ eV}.$$  \hspace{1cm} (10)

Henceforth we focus on the Milky Way galaxy, for which $v_{\text{rot}} \approx 220 \text{ km/s}$.

Since $T$ is much greater than the ionization energy for the light mirror elements ($H', H'e'$), these elements should be ionized. It follows that bremsstrahlung and other processes will radiate off energy at a rate per unit volume of

$$r_{\text{cool}} = n_{e'} \Lambda$$  \hspace{1cm} (11)

where $n_{e'}$ is the (free) mirror electron number density and $\Lambda$ is a calculable function (which depends on cross section, temperature, composition etc). For a temperature of $T \sim 300 \text{ eV}$, $\Lambda \sim 10^{-23} \text{ erg cm}^3 \text{ s}^{-1}$ (see Ref. 24 for details).

Note that $n_{e'} = 2 n_{H'e'} \approx 2 \rho / M_{He'}$ (for $He'$ mass dominated halo), which implies [using Eq. (10)]

$$n_{e'} \approx 10^{-1} \left( \frac{10 \text{ kpc}}{r} \right)^2 \text{ cm}^{-3}.$$  \hspace{1cm} (12)

Because $n_{e'} \propto 1/r^2$, the total halo luminosity,

$$L_{\text{halo}} = \int_{r_{\text{min}}} r^2 n_{e'} \Lambda 4 \pi r^2 dr$$  \hspace{1cm} (13)

is divergent as $r_{\text{min}} \to 0$. However, the inner region of the galaxy should contain a high density of mirror dust, stars, supernova, blackholes etc which will make things very complicated. Energy sources (such as supernova) can heat the inner region. This effect, as well as the effect of mirror dust particles (which can potentially make the inner region opaque to mirror radiation) could potentially lead to an increasing temperature towards the galactic centre – breaking the isothermal approximation. This would be consistent with observations which imply that the rotation curves in spiral galaxies fall in the inner region (as shown in the example of figure 1), suggesting that the mass density is not increasing, but roughly constant there.25

In other words, the observations themselves imply that the halo density appears to be “heated up”26, inexplicable in the standard cold dark matter scenario, but possible for mirror matter-type dark matter.

In view of the above discussion, we introduce a phenomenological cutoff, $R_1$, and consider only the energy produced at $r > R_1$. In this case, the energy radiated
from the halo is roughly

\[ L_{\text{halo}} = \int_{R_1}^{100 \text{kpc}} n_e^2 \Lambda 4\pi r^2 \, dr \]

\[ \sim \left( \frac{3 \text{ kpc}}{R_1} \right) 10^{44} \text{ erg/s}. \]  

(14)

The above calculation assumes that the halo contains only a gas component. From general considerations, as well as specific evidence from microlensing studies (as will be discussed in the following subsection), a significant component of the halo will be in the form of compact mirror objects: mirror stars, planets etc. Furthermore compact mirror objects can potentially dominate the mass in the inner regions of the galaxy – which would alleviate the cooling problem to some extent. Still, a heat source of order \(10^{43} - 10^{44} \text{ erg/s}\) seems to be required to compensate for the energy lost due to radiative cooling.

Supernova offer promising candidate heat sources. An obvious possibility is that mirror supernova can heat the halo; during an explosion the outer layers of the star are ejected into interstellar space, with energy of order \(10^{51} \text{ erg per explosion}\). In order to achieve a rate of around \(10^{43} \text{ erg/s}\) would require a mirror supernova rate in our galaxy of around one every few years, which is about an order of magnitude greater than the rate of ordinary supernova. Presumably this is possible given the uncertainties in the mirror sector. For example, as discussed at the end of the previous subsection, it is possible that the initial mass function for mirror stars is very different to ordinary stars because of the different chemical composition (different light element ratios etc). This would mean that the rate of ordinary supernova could be quite different to mirror supernova.

A more subtle, but equally promising possible energy source might come from ordinary supernova explosions. Due to the effects of photon-mirror photon kinetic mixing, Eq. (2), in the core of the supernova a significant fraction, \(f'\), of an ordinary supernova’s total energy, \(E_{\text{SN}}\), can be converted into mirror photons and mirror electrons/positrons, which can provide a significant heat source for the halo. The amount of energy going into the halo from ordinary supernova explosions, is of order

\[ E_{\text{in}} = f' E_{\text{SN}} R_{\text{SN}} \]

\[ = \left( \frac{f'}{0.1} \right) \left( \frac{E_{\text{SN}}}{3 \times 10^{53} \text{ erg}} \right) \left( \frac{R_{\text{SN}}}{0.01 \text{ yr}^{-1}} \right) 10^{43} \text{ erg/s}. \]

(15)

Evidently, ordinary supernova’s can potentially supply about the right amount of energy to replace the energy lost in radiative cooling, if ordinary supernova’s occur

\(^1\)Mirror photons will not be observable to ordinary matter observers. However, mirror supernova explosions should produce a significant burst of ordinary \(\gamma, e^\pm\) particles which are potentially observable. In fact, they may have already been observed in the form of Gamma Ray Bursts and positron annihilation radiation from the galactic bulge \(^2\) (this will be briefly reviewed in section 3.1).
at a rate, $R_{SN}$, of order once per hundred years and of order 10% of the supernova’s energy is converted into mirror $e^\pm, \gamma'$.

Presumably the heating of the mirror sector and ordinary sector needs to be different in order to explain why ordinary matter has collapsed onto the disk and mirror matter has not. This is not impossible given the lack of macroscopic mirror symmetry, leading to e.g. asymmetric ordinary and mirror supernova rates. It seems therefore that asymmetric heating of the ordinary and mirror sectors is feasible and we conclude that mirror matter-type dark matter is capable of explaining the dark matter halo in spiral galaxies.

In one sense the existence of a dark halo is more directly explained within the standard WIMP paradigm. WIMPs being collisionless are non-dissipative and could not collapse onto the disk. However this cure has serious side-effects which are potentially fatal. WIMPs being collisionless particles are relatively simple, macroscopically, and their distribution can be predicted. The result is a dark matter density profile that goes like $\rho \propto 1/r^\gamma$, with $\gamma \sim 1.5$. This prediction is in clear disagreement with the observations (see e.g. ref. 25). In other words, the standard WIMP paradigm can simply explain the existence of dark matter in galaxies, but fails to explain the detailed distribution of dark matter within the halo. This ‘fact’ seems to support the idea that the dark matter is, macroscopically, more complicated than collisionless WIMPs. More evidence for the complexity of the dark halo is provided by microlensing surveys of stars in nearby galaxies, which brings us to the next topic.

2.4. MACHOs

If non-baryonic dark matter is identified with mirror matter, then a substantial fraction of the non-baryonic dark matter should be in the form of compact bodies such as mirror stars. This leads naturally to an explanation for the mysterious Massive Astrophysical Compact Halo Objects (or MACHO’s) discovered by the MACHO collaboration.

The MACHO collaboration has been studying the nature of halo dark matter with the gravitational microlensing technique, using source stars in the Large Magellanic Cloud. This Australian-American experiment has collected 5.7 years of data and provided statistically strong evidence for dark matter in the form of invisible star sized objects which is what you would expect if there is a significant amount of mirror matter in our galaxy. The MACHO collaboration has done a maximum likelihood analysis which implies a MACHO halo fraction of $f \sim 0.2$ for a typical halo model with a 95% confidence interval of

$$0.08 < f < 0.50.$$  \hfill (16)

Their most likely MACHO mass is between $0.15M_\odot$ and $0.9M_\odot$ depending on the halo model. On the other hand, the EROS team studying microlensing towards the Small Magellanic Cloud did not find evidence for a significant population of
compact halo objects. This yielded a constraint which was however consistent with the $f \sim 0.2$ halo mass fraction reported by the MACHO collaboration. More recently, a new survey\cite{33} has begun examining stars across the face of M31. They find significant evidence for a population of halo microlensing dark matter objects, inferring a halo mass fraction of $f = 0.29^{+0.30}_{-0.13}$. This result is consistent with the positive results of the MACHO collaboration and provides important independent confirmation of their positive signal. Furthermore, they find significant evidence for an asymmetry in the distribution of microlensing events across the face of M31, which is expected if their events are correctly interpreted as a large population of invisible massive compact halo objects.

It is important to realize that the inferred MACHO halo fraction, $f \sim 0.2$, is consistent with a mirror matter halo; the entire halo need not be in the form of mirror stars. Mirror gas and dust would also be expected as they are a necessary consequence of stellar evolution and can significantly populate the halo.

2.5. Implications of mirror matter-type dark matter for the DAMA/NaI experiment

As we have just seen, the results of the microlensing surveys suggest a MACHO halo fraction of $f \sim 0.2$. Within the mirror matter theory, this gets a natural interpretation in terms of mirror stars, mirror white dwarfs etc. The remaining fraction, $1 - f \sim 0.8$ should presumably be in the form of mirror gas. Assuming a roughly spherical and isothermal distribution for this ionized gas, it would have a mass density (at our location, $r \sim 10$ kpc) and temperature [using Eq.\ref{eq:17}]:

$$\rho \approx 0.3 \text{ GeV/cm}^3$$

$$T \approx \frac{\mu M_p v_{rot}^2}{2} \sim 300 \text{ eV}. \tag{17}$$

Considering a particular chemical element, $A'$ (e.g. $A' = H', He', O'$ etc), the velocity distribution for these halo mirror particles is then:

$$f_A'(v) = \exp[-\frac{1}{2} M_{A'} v^2 / T]$$

$$\equiv \exp[-v^2/v_0^2], \tag{18}$$

where $v_0^2 \equiv 2T/M_{A'}$. Using Eq.\ref{eq:18}, we have:

$$\frac{v_0^2(A')}{v_{rot}^2} = \frac{\mu M_p}{M_{A'}}. \tag{19}$$

Recall, $\mu M_p$ is the mean mass of the particles comprising the mirror (gas) component of the halo and $v_{rot} \sim 220$ km/s is the local rotational velocity. Evidently the characteristic velocity, $v_0(A')$, for a particular halo component element, $A'$, depends on the chemical composition of the halo (through the dependence on $\mu M_p$). Mirror BBN will generate $H', He'$ and, possibly, heavier mirror elements as well, quite
unlike the ordinary matter case. Heavy mirror elements can also be generated in mirror stars. In any case, we consider two representative possibilities: first that the mass of the halo is dominated by \( \text{He}' \) and the second is that the halo is dominated by \( \text{H}' \). The mean mass of the particles in the halo are then (taking into account that the light halo mirror atoms should be fully ionized):
\[
\mu M_p \simeq 1.3 \text{ GeV} \quad \text{for \( \text{He}' \) dominated halo}, \\
\mu M_p \simeq 0.5 \text{ GeV} \quad \text{for \( \text{H}' \) dominated halo.} 
\] (20)

The \( v_0 \) values can then be easily obtained from Eq.(19):
\[
v_0(A') = v_0(\text{He}') \sqrt{\frac{M_{\text{He}'}}{M_{A'}}} \approx 220 \sqrt{3} \sqrt{\frac{M_{\text{He}'}}{M_{A'}}} \text{ km/s} \quad \text{for \( \text{He}' \) dominated halo}
\]
\[
v_0(A') = v_0(\text{H}') \sqrt{\frac{M_{\text{H}'}}{M_{A'}}} \approx 220 \sqrt{2} \sqrt{\frac{M_{\text{H}'}}{M_{A'}}} \text{ km/s} \quad \text{for \( \text{H}' \) dominated halo.} 
\] (21)

It is important to realize that halo atoms can potentially be detected in conventional dark matter experiments via the nuclear recoil signature. The reason is that the photon-mirror photon kinetic mixing interaction, Eq.(2), gives the mirror nucleus, with (mirror) atomic number \( Z' \), a small effective ordinary electric charge of \( \epsilon Z' e \). This means that ordinary and mirror nuclei can elastically scatter off each other (essentially Rutherford scattering). The basic Feynman diagram for this process is given in the figure 2 (on the following page).

For a mirror atom of mass \( M_{A'} \) and (mirror) atomic number \( Z' \) scattering on an ordinary target atom of mass \( M_A \) and atomic number \( Z \), the differential cross section is given by:
\[
\frac{d\sigma}{dE_R} = \frac{\lambda}{E_R^2 v'^2},
\] (22)

where \( \lambda \equiv 2\pi\epsilon^2 \alpha^2 Z^2 Z'^2 F_A^2 F_{A'}^2 / M_A \) (the \( F_{A,A'} \) are the nuclear form factors). In Eq. (22), \( v' \) is the velocity of the mirror nucleus relative to the Earth and \( E_R \) is the recoil energy of the ordinary (target) nucleus.

\(^{k}\)The abundance of ordinary heavy elements produced during BBN is negligible. This is because the number density is too low for three-body processes, such as the triple alpha process, to occur at a significant rate. The situation in the mirror sector could be quite different. Because \( \Omega_{\text{BBN}} \approx 5 \Omega_B \) and also if \( T' \ll T \), then the number density of mirror nucleons present during the mirror BBN epoch can be several orders of magnitude greater than the number density of ordinary nucleons at the time of ordinary BBN. The greater mirror nucleon number density can dramatically increase the rate of three-body processes such as the triple alpha process. Thus, it seems to be an interesting possibility that a significant abundance of heavy mirror elements (such as \( \text{C}', \text{O}', \text{Ne}', \text{Si}' \)) could be generated in the early Universe.

\(^{l}\)Note that the shielding effects of atomic electrons (or mirror electrons in the case where the mirror atom is not fully ionized) can be safely neglected if the recoil energy of the target nucleus is in the keV region.
Figure 2: Ordinary and mirror nuclei can elastically scatter via the photon-mirror photon kinetic mixing interaction (indicated by a ‘cross’ in this Feynman diagram).

In dark matter direct detection experiments (such as DAMA/NaI), the measured quantity is the recoil energy, $E_R$, of the target nucleus. The differential interaction rate is

$$\frac{dR}{dE_R} = \sum_{A'} N_T n_{A'} \int_{v'_{\text{min}}(E_R)}^{\infty} \frac{d\sigma}{dE_R} \frac{f(v', v_E)}{k} |v'| d^3v'$$

$$= \sum_{A'} N_T n_{A'} \frac{\lambda}{E_R} \int_{v'_{\text{min}}(E_R)}^{\infty} \frac{f(v', v_E)}{k|v'|} d^3v'$$

(23)

where $N_T$ is the number of target atoms per kg of detector (for detectors with more than one target element we must work out the interaction rate for each element separately and add them up to get the total interaction rate). In the above equation

$f(v', v_E)/k$ is the velocity distribution of the mirror element ($k$ is the normalization factor), $A'$, and $v_E$ is the Earth velocity relative to the galaxy. Since $v = v' + v_E$ is the velocity of the mirror particles relative to the galaxy, it follows from Eq. (18), that $f(v', v_E)/k = (\pi v_0^2)^{-3/2} e^{-v'^2/v_0^2}$. In Eq. (23) the lower velocity limit, $v'_{\text{min}}(E_R)$, is the minimum velocity for which a mirror atom of mass $M_A'$ impacting on a target atom of mass $M_A$ can produce a recoil energy of $E_R$ for the target atom. This minimum velocity satisfies the kinematic relation:

$$v'_{\text{min}}(E_R) = \sqrt{\frac{(M_A + M_A')^2 E_R}{2 M_A M_{A'}}}.$$  

(24)

Interestingly, most of the existing dark matter experiments are not very sensitive to mirror matter-type dark matter because $v'_{\text{min}}$ [Eq. (24)] turns out to be too high. This is because they either use target elements which are too heavy (i.e. large $M_A$) and/or have a $E_R$ threshold which is too high.

The dark matter experiment most sensitive to halo mirror matter-type dark matter is the DAMA/NaI experiment. The aim of the DAMA/NaI experiment is
to measure the nuclear recoils of Na, I atoms due to the interactions of halo dark matter particles. Because of the dependence of the interaction rate, Eq. (23), on $v_E$, the interaction rate of halo dark matter with a detector depends on the Earth’s velocity relative to the halo. Because of the Earth’s annual motion, its velocity satisfies:

$$v_E(t) = v_\odot + v_\oplus \cos \gamma \cos \omega(t - t_0)$$

where $v_\odot \approx 230 \text{ km/s}$ is the Sun’s velocity with respect to the galaxy and $v_\oplus \approx 30 \text{ km/s}$ is the Earth’s orbital velocity around the Sun ($\omega = 2\pi/T$, with $T = 1 \text{ year}$). The inclination of the Earth’s orbital plane relative to the galactic plane is $\gamma \approx 60^\circ$, which means that $\Delta v_E \approx 15 \text{ km/s}$. Thus, the differential interaction rate in an experiment will thus contain an annual modulation term:

$$R_i = R^0_i + R^1_i \cos \omega(t - t_0)$$ (26)

where

$$R^0_i = \frac{1}{\Delta E} \int_{E_i}^{E_i + \Delta E} \left( \frac{dR}{dE_R} \right)_{v_E = v_\odot} dE_R$$
$$R^1_i \approx \frac{1}{\Delta E} \int_{E_i}^{E_i + \Delta E} \frac{\partial}{\partial v_E} \left( \frac{dR}{dE_R} \right)_{v_E = v_\odot} \Delta v_E dE_R.$$ (27)

According to the DAMA analysis, they indeed find an annual modulation over 7 annual cycles at more than $6\sigma$ C.L. Their data fit gives $T = (1.00 \pm 0.01) \text{ year}$ and $t_0 = 144 \pm 22$, consistent with the expected values. [The expected value for $t_0$ is 152 (2 June), where the Earth’s velocity, $v_E$, reaches a maximum with respect to the galaxy]. Their signal occurs in the energy range $2 - 6 \text{ keVee}$ and the amplitude of their signal is $R^1 = (0.019 \pm 0.003) \text{ cpd/kg/keVee}$ [cpd $\equiv$ counts per day].

These are extremely impressive results. The self consistency of their signal is highly non-trivial: there is simply no reason why their data should contain a periodic modulation or why it should peak near June 2. In fact, the known systematic errors are several orders of magnitude too small to account for the signal. It therefore seems probable that DAMA has indeed discovered dark matter. Interestingly the interpretation of the DAMA/NaI signal in terms of standard WIMPs appears to be disfavoured by a number of experiments, the most impressive of which is the recent null CDMSII/Ge results. However, if we interpret the DAMA/NaI signal in terms of mirror matter-type dark matter then the positive DAMA/NaI signal and the negative results of the other experiments can be reconciled.

The DAMA experiment is not particularly sensitive to very light dark matter particles such as mirror hydrogen and mirror helium. Impacts of these elements

---

The unit keVee corresponds to the detected energy, $E_R$, which is related to the actual energy, $E_R$, by $E_R = E_R / q_A$, where $q_A$ is the quenching factor corresponding to a given target element, A. For the DAMA/NaI experiment, $q_I \approx 0.09$, $q_{Na} \approx 0.3$. 

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(typically) do not transfer enough energy to give a signal above the detection threshold. If stellar nucleosynthesis in the mirror sector is sufficiently similar to the ordinary sector, then the next most abundant element should be mirror oxygen. In the analysis of ref. the spectrum of heavy mirror elements were approximated by just two components, $O', Fe'$. Naturally this is just a crude approximation: in general there will be a distribution of mirror elements which is very difficult to theoretically predict (because of e.g. unknown initial mass function for mirror stars etc). Of course, it may turn out that approximating the spectrum in terms of the two components, $O', Fe'$, will be insufficient in the future as more detailed data is obtained. Anyway, interpreting the DAMA/NaI annual modulation signal in terms of $O', Fe'$, it was found that

$$|\epsilon| \sqrt{\frac{\xi_{O'}}{0.10} + \frac{\xi_{Fe'}}{0.026}} \approx 4.8^{+1.0}_{-1.3} \times 10^{-9}$$

(28)

where the errors denote a 3 sigma allowed range and $\xi_{A'} \equiv \rho_{A'}/(0.3 \text{ GeV/cm}^3)$ is the $A'$ proportion (by mass) of the halo dark matter (at the Earth’s location). This fit to the data is shown in figure 3.

![Figure 3: DAMA/NaI annual modulation signal (taking data from the second paper of ref.36) together with the mirror matter prediction (initial time is August 7th).](image)

$^{a}$The value of $\epsilon$ suggested by the DAMA experiment, Eq. (28), would also have important implications for the orthopositronium system. The current experimental situation, summarized in Ref. implies that $|\epsilon| \approx 5 \times 10^{-7}$, which is easily consistent with Eq. (28). Importantly, a new orthopositronium experiment has been proposed which can potentially cover much of the $\epsilon$ parameter space suggested by the DAMA experiment. Such an experiment is very important – not just as a check of the mirror matter explanation – but also because dark matter experiments are sensitive to $\epsilon \sqrt{\xi_{A'}}$ and an independent measurement of $\epsilon$ would allow the extraction of $\xi_{A'}$ values.
In Ref. 35 it was found that a DAMA/NaI annual modulation signal dominated by an $F^e$ component, is experimentally disfavoured for three independent reasons: a) it predicts a mean differential energy spectrum rate larger than the measured DAMA/NaI rate b) potentially leads to a significant diurnal effect (sidereal daily variation)\(^9\) and c) should have been observed in the CDMSI experiment. Thus it is probable that lighter mirror elements, such as a mirror oxygen component, dominates the DAMA annual modulation signal. From Eq. (28) this means that $\xi_{F^e}/4 < \xi_{O^e}$. Recently, a more stringent limit of $\xi_{F^e}/40 < \xi_{O^e}$ was obtained in Ref. 42 using the recent CDMSII/Ge result 41.

If the DAMA signal is dominated by $O^e$, then things depend on only one parameter, $\epsilon \sqrt{\xi_{O^e}}$. This parameter is fixed from the annual modulation signal, Eq. (28), which means that the event rate (due to $O^e$ interactions) can be predicted for other experiments. It turns out that, with the exception of one experiment (CRESST\(^{47}\)), all of the other experiments are not sensitive to $O^e$ interactions. For example, the predicted rate for CDMSII/Ge due to $O^e$ interactions is given in figure 4 (taken from Ref. 42).

![Figure 4: Predicted differential event rate, $dR/dE_R$, (binned into 10 keV bins) due to $O^e$ dark matter with $\epsilon \sqrt{\xi_{O^e}}/0.10 = 4.8 \times 10^{-9}$ (DAMA/NaI annual modulation best fit) for the CDMSII/Ge experiment. The solid line corresponds to a standard halo model with $He^e$ dominated halo while the dashed line assumes a $H^e$ dominated halo.]

\(^9\)Currently there is no experimental evidence for any diurnal variation in the DAMA/NaI data.\(^{49}\)
As the figure shows, the event rate is predicted to be very low. For the CDMSII/Ge experiment the predicted event rate is just 1 event per $2.6 \times 10^6$ kg-days for $He'$ dominant halo and 1 event per $5 \times 10^{12}$ kg-days if $H'$ dominates the halo. Given that CDMSII has only 52.6 kg-day raw exposure in Ge, this implies a predicted number of events of just $2 \times 10^{-5}$ (assuming $He'$ dominant halo) and even less if $H'$ dominates the mass of the halo. Clearly this prediction is nicely consistent with the null result of CDMSII/Ge\(^p\).

In the case of standard spin independent WIMPs, the CDMSII experiment is more sensitive than the DAMA/NaI experiment. However, as we have discussed above, this is clearly not the case for $O'$-type dark matter (with dominant $He'/H'$ component). The diverse behaviour of the two types of dark matter candidate has to do with their basic differences:

- The mass of $O'$ is only 15 GeV, while standard WIMPs are typically assumed to have masses which are greater than 30 – 45 GeV (depending on the model).
- For $O'$-type dark matter in an $He'/H'$ dominated halo, $v_0(O') \ll 220$ km/s [Eq. (21)], while the characteristic velocity of standard WIMPs are assumed to be approximately 220 km/s.
- The differential cross section for mirror matter-type dark matter is inversely proportional to the square of the recoil energy, while that for standard WIMPs is energy independent (excepting the energy dependence of the form factors).

These three key differences mean that experiments with low threshold energy and light target elements are much more sensitive (to $O'$-type dark matter) than experiments with higher threshold energy and/or heavy target elements. In the case of DAMA/NaI, the event rate for mirror matter-type dark matter is dominated by interactions with the light Na component. The actual threshold energy of 6.7 keV (for Na), implies a threshold impact velocity, obtained from Eq. (21), of 290 km/s for $O'$ impacts. In the case of CDMSII/Ge, the threshold energy of 10 keV and heavy Ge target gives a threshold impact velocity of 450 km/s (see Ref. 44 for a table of threshold velocities for the various experiments). Given the low value of $v_0(O')$ [Using Eq. (21), $v_0(O') = \frac{10}{\sqrt{3}}$ km/s (\(\frac{3}{2}\) km/s) for $He'$ ($H'$) dominated halo] the number of $O'$ atoms with impact velocity above threshold is clearly much lower for CDMSII/Ge compared with DAMA/NaI (in fact it is exponentially suppressed). Note that the Edelweiss I/Ge (ref. 39) and Zeplin I/Xe (ref. 40) experiments are even less sensitive than CDMSII/Ge because the threshold impact velocity of those experiments is even higher.\(^p\)

\(^p\)Although the CDMSII/Ge experiment is relatively insensitive to interactions of halo $O'$, it is much more sensitive to interactions of heavier mirror elements such as $Fe'$. Future CDMS data may well find a positive signal due to these heavier elements because they should be there at some level.
There is one experiment, besides DAMA/NaI, which was potentially sensitive to mirror matter interactions, namely the CRESST I experiment. That experiment had a target consisting of Sapphire crystals ($\text{Al}_2\text{O}_3$), with a low recoil energy threshold of 0.6 keV. However, the results of that experiment turned out to be roughly consistent with the mirror matter prediction (i.e. with parameters fixed by the DAMA/NaI annual modulation signal), providing tentative support for the mirror matter interpretation of the DAMA/NaI experiment. Unfortunately, this experiment did not collect enough data to do an annual modulation analysis (it has now been discontinued, replaced by a new experiment, CRESST II, which will use a $\text{CaWO}_4$ target, and has an expected threshold energy of 10 keV, which will be less sensitive than CRESST I, but should still be useful).

3. Unconventional implications of mirror matter-type dark matter

In section 2 we have examined the conventional cosmological and astrophysical implications of mirror matter-type dark matter including direct experimental evidence from the DAMA/NaI experiment. However mirror matter-type dark matter is an unconventional dark matter candidate with numerous unconventional implications. Included among these is the possibility of binary ordinary/mirror systems, possible manifestations of mirror matter in our solar system, implications for supernova etc. We now briefly examine some of these applications.

3.1. Supernova dynamics, Gamma Ray Bursts and photon-mirror photon kinetic mixing

Photon-mirror photon kinetic mixing, Eq. (2), of magnitude $\epsilon \sim 5 \times 10^{-9}$ (as suggested by the DAMA annual modulation signal) will lead to important implications for core collapse supernova – both ordinary and mirror types. Recall, that in the core of ordinary supernova, the temperature reaches, $T \sim 30$ MeV, leading to a plasma of $e^\pm, \gamma, \nu_\alpha (\alpha = e, \mu, \tau)$. Because of the photon-mirror photon kinetic mixing, mirror $e^\pm$ can also be produced via a variety of processes (the most obvious being $e^+ + e^- \rightarrow e'^+ + e'^-$. Actually the main production process for mirror particles in the core of a mirror supernova is expected to be the plasmon decay process (see e.g. ref. 48 for a review). The energy loss rate for production of minicharged particles has been calculated in Ref. 15:

$$Q_p = \frac{8\zeta(3)}{9\pi^3} \epsilon^2 \alpha^2 \left( \mu_e^2 + \frac{\pi^2 T^2}{3} \right) T^3 Q_1$$

(29)

where $Q_1$ is a factor of order unity. $Q_p$ is comparable to the energy loss rate due to neutrino emission for $\epsilon \sim 10^{-9}$.

$^a$The material in this subsection follows Ref. 27.
Thus, the production of mirror particles in the core of ordinary supernova must lead to important effects as a significant part of the emission of ordinary supernova’s will be in the form of $e^{\pm}, \gamma', \nu'_{\alpha}$. One of these effects is that the $e^{\pm}, \gamma'$ produced in the core will help supernova’s to explode as we will now explain.

Supernova explosions of massive stars are believed to be driven by the convectively supported neutrino-heating mechanism. But refined simulations have shown that there is insufficient neutrino energy transfer behind the stalled supernova shock to produce the explosion. This is actually a long standing problem in supernova dynamics. It suggests some missing piece of physics, which might well be photon-mirror photon kinetic mixing: the $e^{\pm}, \gamma'$ produced in the core will interact and heat the matter behind the shock (adding to the effect of neutrino-heating) thereby producing the explosion. For this to be possible we require that the cross section for MeV $\gamma'$ (and/or large angle $e^{\pm}$) scattering with ordinary electrons (i.e. $\gamma' + e^- \rightarrow \gamma + e^-$ and $e'^{\pm} + e^- \rightarrow e'^{\pm} + e^-$) to be of roughly the same magnitude as the neutrino nucleon cross section. The mirror particle cross section is:

$$\sigma \sim e^2 \pi r_0^2 \sim 10^{-41} \left( \frac{e}{5 \times 10^{-9}} \right)^2 \text{cm}^2$$

where $r_0 = \alpha/m_e$ is the classical radius of the electron. The neutrino nucleon cross section is

$$\sigma(\bar{\nu}_e p \rightarrow n e^+) = \frac{4G_F^2 E_\nu^2}{\pi}$$

$$\approx 10^{-41} \left( \frac{E_\nu}{10 \text{ MeV}} \right)^2 \text{cm}^2$$

where $E_\nu$ is the energy of the neutrino. Evidently the cross sections for the two completely different processes are indeed comparable! Importantly, the energy dependence is different: compared with neutrino interactions, the mirror particle interactions with ordinary matter are larger at lower energies. It follows that the heating effect of the mirror particle interactions on the ordinary matter just behind the shock is expected to be comparable to – or may even exceed – the neutrino effect.

A significant portion of the $e^{\pm}, \gamma'$ will escape the supernova, however direct detection of these particles seems to be very difficult for ordinary matter observers. Even if we cannot directly detect this emission it does not mean that it is unimportant; as we discussed earlier in section 2.3, these mirror particles may have an important role in heating the galactic halo to compensate for the energy lost due to radiative cooling.

In the case of a mirror type II supernova is also very interesting. In this case, the core of the mirror supernova would be a source of ordinary electrons, positrons and gamma rays – making such an event easily detectable for ordinary matter observers. In fact, they may have already been detected! Provided that the number of ordinary baryons is sufficiently low the $e^+ e^- \gamma$ ‘fireball’ will lead to a gamma ray
burst (GRB)\textsuperscript{51}. Of course, GRB’s have been observed for some time, and their origin has been a long standing puzzle. It is certainly interesting that the mirror supernova, with photon-mirror photon kinetic mixing interaction has roughly the right characteristics (energy release, time scale, and potentially small baryon load) to be identified with the observed gamma ray bursts.

In addition to being a source of photons, GRB will also eject electrons and positrons into the interstellar medium. This might explain\textsuperscript{27} the 511 keV photon emission from the galactic bulge. This emission was first detected more than 30 years ago\textsuperscript{22} and studied in a number of experiments culminating in the recent INTEGRAL-SPI measurement\textsuperscript{65}.

While GRBs and galactic positron emission are certainly rather spectacular possible manifestations of the mirror world, something even more tantalizing would be the discovery of a mirror world itself.

3.2. Mirror worlds?

If mirror matter exists in our galaxy, then binary systems consisting of ordinary and mirror matter should also exist. While systems containing approximately equal amounts of ordinary and mirror matter are very unlikely due to e.g. differing rates of collapse for ordinary and mirror matter (due to different initial conditions such as chemical composition, temperature distribution etc), systems containing predominately ordinary matter with a small amount of mirror matter (and vice versa) should exist. Remarkably, there is interesting evidence for the existence of such systems coming from extra-solar planet astronomy.

In 1995, the first planet orbiting another star was discovered\textsuperscript{56}. Since that time the field of extra-solar planet astronomy has been moving at a rapid pace. To-date, more than 100 extra-solar planets have been discovered orbiting nearby stars\textsuperscript{57}. They reveal their presence because their gravity tugs periodically on their parent stars leading to observable Doppler shifts. Several transiting planets have been observed allowing for an accurate determination of the planet’s size and mass in those systems. One of the surprising characteristics of the extrasolar planets is that there are a class of large (\(\sim M_J, J = \text{Jupiter}\)) close-in planets with a typical orbital radius of \(\sim 0.05 \text{ AU}\) (which is about eight times closer than the orbital radius of Mercury). Ordinary (gas giant) planets are not expected to form close to stars because the high temperatures do not allow them to form. Theories have been invented where they form far from the star where the temperature is much lower, and migrate towards the star\textsuperscript{58}.

\textsuperscript{51}The idea that GRB’s might be connected to mirror supernova was first suggested by Blinnikov\textsuperscript{52}. Blinnikov considered neutrino-mirror neutrino oscillations (rather than the photon-mirror photon kinetic mixing interaction) as the mechanism to convert mirror particles into ordinary particles in the core of a mirror supernova. Later, it was realized\textsuperscript{53} that neutrino oscillations were not viable due to matter effects which strongly suppress neutrino-mirror neutrino oscillations.
A fascinating alternative possibility presents itself in the mirror world hypothesis. The close-in planets may be mirror worlds composed predominately of mirror matter\textsuperscript{59}. They do not migrate significantly, but actually formed close to the star which is not a problem for mirror worlds because they are not significantly heated by the radiation from the star. This hypothesis can potentially explain the opacity of transiting planets because mirror worlds would accrete ordinary matter from the solar wind which accumulates in the gravitational potential well of the mirror world. It turns out that the effective radius, \( R_p \) at which the planet becomes opaque to ordinary radiation depends sensitively on the mass of the planet, with Ref.\textsuperscript{60} providing a prediction:

\[
R_p \propto \sqrt{\frac{T_s}{M_P}}
\]  

(33)

where \( T_s \) is the surface temperature of the planet and \( M_P \) is the mass of the planet. This was only a rough prediction (especially the dependence on \( T_s \)) but a prediction nevertheless. Heuristically it is very easy to understand: increasing the planet’s mass increases the force of gravity which causes the gas of ordinary matter to become more tightly bound to the mirror planet (thereby decreasing the effective size, \( R_p \)), while increasing the temperature of the gas increases the volume that the gas occupies (thereby increasing \( R_p \)). Of these two effects we expect that the dependence on \( M_P \) should be the more robust prediction. Because the size of ordinary gas giant planets (i.e. planets made mostly of ordinary matter) depends quite weakly on their mass, the dependence on \( M_P \) – which is significant according to Eq.\textsuperscript{33} – should allow a decisive test of the mirror planet hypothesis.

There are currently four extrasolar planets for which measurements of \( R_p \) and \( M_P \) are available: HD209458b\textsuperscript{62}, OGLE-TR-56b\textsuperscript{63}, OGLE-TR-113b\textsuperscript{64} and OGLE-TR-132b\textsuperscript{64} \textsuperscript{64}. We summarize their properties in the following table:

| Transiting planet | \( R_p \) [\( R_J \)] | \( M_p \) [\( M_J \)] | \( T_s \) |
|-------------------|---------------------|---------------------|---------|
| HD209458b         | 1.43 ± 0.06\textsuperscript{62} | 0.69 ± 0.05\textsuperscript{64} | 1370 K |
| OGLE-TR-56b       | 1.23 ± 0.1\textsuperscript{63}  | 1.45 ± 0.2\textsuperscript{63} | 1820 K |
| OGLE-TR-113b      | 1.08 ± 0.03\textsuperscript{63} | 1.35 ± 0.2\textsuperscript{63} | 1210 K |
| OGLE-TR-132b      | 1.15^{+0.84}_{−0.13}\textsuperscript{64} | 1.01 ± 0.3\textsuperscript{64} | 1920 K |

These measurements (ignoring OGLE-TR-132b because of its huge uncertainty in \( R_p \)), together with the 2001 prediction, Eq.\textsuperscript{33}, are shown in figure 5 (from Ref.\textsuperscript{61}). The solid line is the prediction, Eq.\textsuperscript{33}, where we have used HD209458b to fix the proportionality constant.

\textsuperscript{6}The OGLE (= Optical Gravitational Lensing Experiment) transiting planets were identified with radial Doppler shift measurements of transiting objects discovered by the Optical Gravitational Lensing Experiment\textsuperscript{55}. 
Figure 5: The measured effective size, $R_p$, of the transiting planets (from top to bottom) HD209458b, OGLE-TR-56b and OGLE-TR-113b versus $\sqrt{T_s/M_P}$ (in units where $\sqrt{T_s/M_P} = 1$ for HD209458b). The solid line is the prediction, Eq. (33), which assumes that the planets are composed predominately of mirror matter.

Evidently the 2001 prediction, Eq. (33), is in reasonable agreement with the observations. This appears to be non-trivial: in the case of ordinary matter planets, increasing the mass does not significantly affect the radius, and does not generally lead to a decreasing radius (for example, Jupiter is three times heavier than Saturn, but is 15% larger). However, it is possible that the apparent agreement with the rough prediction, Eq. (33), is coincidental – so more data would be welcome. Especially decisive would be the discovery of a much heavier transiting planet, $M_P \gtrsim 2M_J$, which should have a radius less than $R_J$ if it is a mirror world.

3.3. Isolated planets?

If this mirror world interpretation of the close-in planets is correct then it is very natural that the dynamical mirror image system of a mirror star with an ordinary planet could also exist. Such a system would appear to ordinary observers as an “isolated” ordinary planet. Remarkably, such “isolated” planets have been identified in the $\sigma$ Orionis star cluster. These planets have estimated mass of $5 - 15 M_{Jupiter}$ and appear to be gas giants which do not seem to be associated with any visible star. Given that the $\sigma$ Orionis cluster is estimated to be less than 5 million years old, the
formation of these “isolated” planets must have occurred within this time (which means they can’t orbit faint stellar bodies such as old white dwarfs). Zapatero Osorio et al.\cite{68} argue that these findings pose a challenge to conventional theories of planet formation which are unable to explain the existence of numerous isolated planetary mass objects. Thus, the existence of these planets is surprising if they are made of ordinary matter, however their existence is natural from the mirror world perspective since they can be interpreted as ordinary planets orbiting mirror stars.\cite{69} Furthermore, if the isolated planets are not isolated but orbit mirror stars then there must exist a periodic Doppler shift detectable on the spectral lines from these planets. This represents a simple way of testing this hypothesis.\cite{69}

3.4. Anomalous impact events

Perhaps the most fascinating possible implication of mirror matter-type dark matter is that our solar system contains mirror matter space-bodies (SB)\cite{70,71}. There is not much room for a large amount of mirror matter in our solar system. For example, the amount of mirror matter within the Earth has been constrained to be less than $10^{-3} M_{\text{Earth}}$.\cite{72} However, we don’t know enough about the formation of the solar system to be able to exclude the existence of a large number of space bodies made of mirror matter if they are small like comets and asteroids. The total mass of asteroids in the asteroid belt is estimated to be only about 0.05% of the mass of the Earth. A similar or even greater number of mirror bodies, perhaps orbiting in a different plane or even spherically distributed like the Oort cloud is a fascinating possibility.\cite{4} In fact, the comets themselves – and hence the Oort cloud itself – might actually be composed of mirror matter (as we will discuss in the following subsection).

Anyway, collisions of such bodies with themselves and ordinary bodies would generate a solar system population of mirror gas and dust particles and larger bodies. The impact velocity of such solar system objects (relative to the Earth) would be in the range:\cite{11}

$$11 \text{ km/s} \lesssim v \lesssim 70 \text{ km/s}.$$ \hspace{1cm} (34)

If such small mirror matter bodies do in fact exist and happen to collide with the Earth, what would be the consequences? If the only force connecting mirror matter with ordinary matter is gravity, then the consequences would be minimal. The mirror matter space body would simply pass through the Earth and nobody would know about it unless the body was so heavy as to gravitationally affect the motion of the Earth. However, if there is photon-mirror photon kinetic mixing of

\cite{12}Large planetary sized bodies are also possible if they are in distant orbits\cite{70} or masquerade as ordinary planets or moons by accreting ordinary matter onto their surfaces.

\cite{13}The minimum velocity is the result of the local acceleration of the Earth (equivalent to the escape velocity for a particle on the Earth, which is 11.2 km/s).
magnitude, \( \epsilon \sim 5 \times 10^{-9} \), as indicated by the DAMA/NaI experiment, then the mirror nuclei of the space body can interact with the ordinary nuclei in the Earth via elastic Rutherford scattering (see Figure 2).

Small dust particles could thereby be detectable in simple surface experiments. In particular, experiments such as the St. Petersburg experiment\(^\text{73}\) are sensitive to solar system mirror dust particles\(^\text{74}\). Such particles can produce a burst of photons in a scintillator due to elastic collisions between the mirror atoms of the dust particle and the ordinary scintillator atoms. Not only can these photons be detected via a photomultiplier (PM) tube, but the velocity of the mirror dust particle can be determined if the PM tubes are appropriately arranged. This is important because ordinary cosmic rays should be travelling close to the speed of light, and can thereby be distinguished from relatively slow moving mirror dust particles. The St. Petersburg experiment finds a positive signal consistent with a flux of about 1 mirror dust particle per square meter per day.

Impacts of larger bodies should be less frequent, nevertheless there is a fascinating range of evidence for their existence. The largest recorded impact event was the 1908 Tunguska event. Remarkably no significant asteroid or cometary remnants were recovered from the Tunguska site\(^\text{75}\). People have assumed that the impacting body was made of ordinary matter, however there is (literally!) no solid evidence to support this claim. The Tunguska body may have been made out of dark matter – which is a logical possibility if mirror matter is identified with the dark matter of the Universe. In fact, this hypothesis seems to provide a better explanation for the known features of the Tunguska event\(^\text{71}\). There are also many other ‘anomalous’ impact events, on smaller scales\(^\text{77}\), and evidence for anomalous impact events on larger scales. Included among the latter are the impact events responsible for strange glass fields such as Edeowie glass\(^\text{78}\), Libyan desert glass, tektites etc. All of these impact related phenomena share a common feature which is the remarkable lack of clearly defined extraterrestrial material or even chemical traces (such as iridium excess). This fact is obviously explicable if the events were due to the impact of a mirror matter space body.

Other solar system evidence for mirror matter also exists coming from the lack of small craters on the asteroid EROS\(^\text{79,80}\) and also from the anomalous slow-down of both Pioneer spacecraft\(^\text{81,82}\). The overall situation is summarized in figure 6.

\(^\text{vThere is some interesting evidence for microscopic particles in tree resin\(^\text{83}\), which might have originated from the Tunguska space-body. However their tiny abundance is hardly consistent with reasonable expectations.}\)
Direct detection of mirror matter fragments in the ground is also possible at these impact sites. The photon-mirror photon kinetic mixing interaction will lead to a static force which can keep small mirror matter fragments (of size $R$) near the Earth’s surface, provided that

$$R \lesssim f_{ew} \left( \frac{|\epsilon|}{5 \times 10^{-9}} \right) \text{cm}. \quad (35)$$

Such fragments can be experimentally detected via the centrifuge technique\textsuperscript{84} and through the thermal effects of the embedded mirror matter on the surrounding ordinary matter\textsuperscript{85}. Note however that impacts of galactic halo mirror ions/electrons will vaporize these small fragments over time. The flux of halo mirror electrons is roughly $f_h \sim 10^8 \text{cm}^{-2} \text{s}^{-1}$ and defining $X$ to be the mean number of mirror atoms evaporated from the impact of each halo mirror electron ($X \sim 10$), then the rate at which a mirror matter fragment would evaporate would be of order $dR/dt = f_h X/n \sim 1 \text{cm/Myr}$ (where $n \sim 10^{23}/\text{cm}^3$ is the atomic number density of mirror atoms in the mirror fragment). This suggests that mirror matter fragments probably could not be recovered from the remnants of old impact events, such as Edieowie glass, Libyan desert glass, tektites etc (which are of order 1 Myr old or older) but might be recovered from relatively recent anomalous impact events such as the Tunguska event\textsuperscript{75} and small anomalous impact events\textsuperscript{77}. 

Figure 6: Favoured range of $\epsilon$ from various experiments/observations. Also shown are the current direct experimental bound, $\epsilon < 5 \times 10^{-7}$, which comes from orthopositronium lifetime studies\textsuperscript{43,44} and also the limit, $\epsilon < 3 \times 10^{-8}$, suggested by early Universe cosmology (successful BBN)\textsuperscript{83}.
If mirror matter space-bodies do exist in our solar system, then one might expect other unconventional scientific implications. Below we mention just a few more of these things.

3.5. Are comets made of mirror matter?

Comets are believed to originate from an approximately spherically symmetric cloud extending out about half way to the nearest star. This comet cloud, called the Oort cloud, is reminiscent of the dark halo of our galaxy. Both are largely invisible, are distributed differently to the ‘visible’ matter, and are also hypothetical. Of course, this analogy is very simplistic and should not be taken very seriously. Nevertheless, it is also true that comets seem to have a number of puzzling features and are not altogether well understood. One interesting feature of comets is that they seem to contain a very dark nucleus. For example, the nucleus of Halley’s comet has an albedo of only 0.03 making it one of the darkest objects in the solar system – darker even than coal! This has led to the suggestion that the nucleus could be composed predominately of mirror matter. Of course, pure mirror matter would be transparent, but if it contained a small admixture of ordinary matter embedded within, it might appear opaque and dark. If the ordinary matter had a volatile component such as water ice, then this would explain the large head and tail observed when the comet passed close to the sun. Furthermore, such a picture would simply explain the long standing comet fading problem: that many comets lose a large factor (100-1000) in average brightness after approaching the sun for the first time. If this interpretation is correct, then comets may simply become dimmer and dimmer over time rapidly losing all of their volatile ordinary matter component. They may effectively become invisible. Of course, the rate that this occurs will depend on many things such as the proportion of ordinary to mirror matter, the chemical composition, details of the orbit etc.

Interestingly, a recent study has concluded that many old comets must have either become invisible or have somehow disintegrated. The number of cometary remnants (assumed to be asteroid-like objects) is 100 times less abundant than theoretically expected. Clearly, this seems to support (or at least, encourage) the mirror matter interpretation of the comets. Of course, if comets are predominately made of mirror matter then this fits-in nicely with the mirror matter interpretation of the anomalous small impact events (and Tunguska event), which was discussed in the previous subsection. It might also be connected with atmospheric anomalies.

3.6. Atmospheric anomalies caused by small mirror matter space-bodies?

To explain the anomalous small impact events we require that some of the mirror matter space-bodies to survive and hit the ground without completely melting and vaporizing in the atmosphere. Detailed studies have shown that this is possible, especially for non-volatile mirror matter (such as mirror iron). Sometimes, it could
happen that a mirror space-body would heat up enough to completely vaporize in the atmosphere. After vaporizing, the mirror atoms interact with the air atoms by Rutherford scattering. Although initially the mirror matter will heat up the ordinary matter because of its large kinetic energy (since its initial velocity is at least 11 km/s), after a short time, the mirror matter will cool the atmosphere. The mirror atoms will draw in heat from the surrounding ordinary atoms and radiate it away into mirror photons. Since the mirror atoms are not absorbing mirror photons from the environment, heat will be lost from the system. The net effect is a localized rapid cooling of the atmosphere which might lead to the formation of unusual clouds and other strange atmospheric phenomena. This might explain the remarkable observations of falling ice blocks and maybe even the observations of atmospheric ‘holes’. It seems that the answer may indeed be ‘blowing in the wind’ – but only for a sort time! \[^7\]

4. Conclusion

Historically, imposing symmetries of particle interactions has led to the prediction and subsequent discovery of a variety of ‘new’ fundamental particles including:

- Antiparticles – predicted to exist by imposing proper Lorentz symmetry;
- Neutrino – predicted to exist by imposing time translational symmetry (energy conservation);
- Top quark – predicted to exist from \(SU(2) \otimes U(1)_Y\) electroweak gauge symmetry (to partner the bottom quark);
- The \(\Omega^-\) baryon – predicted from \(SU(3)\) flavour symmetry in the quark model.

Mirror matter is also an offspring of this methodology; it is an attempt to follow this historically successful approach. In fact it appears to be theoretically unique, arising from a single well motivated hypothesis: The improper Lorentz symmetries (such as parity and time reversal invariance) stand out as the only space-time symmetries which are not respected by the interactions of the known elementary particles, but can be exact unbroken symmetries of nature if a set of mirror particles exist.

Mirror matter is thus very well motivated from a particle physics point of view. Furthermore it seems to have the right properties to be identified with the inferred non-baryonic dark matter in the Universe. Specifically, mirror dark matter seems to provide a consistent explanation for: a) the basic dark matter particle properties (mass, stability, darkness); b) the similarity in cosmic abundance between ordinary and non-baryonic dark matter, \(\Omega_B \sim \Omega_{\text{dark}}\); c) large scale structure formation; d) microlensing (MACHO) events; e) asymptotically flat rotation curves in spiral galaxies and f) the impressive DAMA/NaI annual modulation signal.

\[^7\] Eventually the mirror atoms will disperse and ultimately be evaporated from the Earth due to interactions with halo mirror atoms.
Of course, any theory of dark matter should also be measured against the standard paradigm – that non-baryonic dark matter consists of hypothetical weakly interacting particles i.e. essentially collisionless particles. However this comparison is actually favourable. In the standard WIMP hypothesis: the basic dark matter properties (stability, darkness) require ad hoc hypothesis; MACHO events cannot be explained; $\Omega_{\text{dark}} \sim \Omega_B$ is mysterious; DAMA/NaI annual modulation signal is difficult to understand consistently with other experiments such as CDMSII. Perhaps the only thing that WIMPs might explain better is the existence of the halo in galaxies. This is because WIMPs are non-dissipative. However this success is significantly eroded by the facts; standard collisionless dark matter predicts overly dense cores in galaxies and over abundance of small scale structures within halos which are not consistent with the observations.

Thus, by either comparing mirror matter-type dark matter with experiments and observations or with the standard WIMP paradigm, it is clear that it is a strong candidate for the non-baryonic dark matter in the Universe, deserving of serious consideration and further study.

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