Supernova explosions, 511 keV photons, gamma ray bursts
and mirror matter

R. Foot\textsuperscript{a} and Z. K. Silagadze\textsuperscript{b} 1

\textsuperscript{a} School of Physics, 
University of Melbourne, 
Victoria 3010 Australia

\textsuperscript{b} Budker Institute of Nuclear Physics, 
630 090, Novosibirsk, Russia

There are three astroparticle physics puzzles which fire the imagination: the origin of the “Great Positron Producer” in the galactic bulge, the nature of the gamma-ray bursts central engine and the mechanism of supernova explosions. We show that the mirror matter model has the potential to solve all three of these puzzles in one beautifully simple strike.

\textsuperscript{1}E-mail address: foot@physics.unimelb.edu.au, silagadze@inp.nsk.su
Recent observation of a 511 keV annihilation line by the SPI spectrometer on the INTEGRAL satellite, indicating a powerful source of positrons in the central regions of the Galaxy, has spurred a great deal of activity and imagination among astroparticle physics community. This is not surprising. In our matter dominated universe any antimatter source of that magnitude certainly is extraordinary and deserves close attention. What is surprising is why this has not happened earlier, because the 511 keV photon emission from the galactic bulge was first detected more than 30 years ago[1]. Maybe the explanation is given by the Andre Gide’s aphorism: “Everything has been said before, but since nobody listens we have to keep going back and beginning all over again.”

The INTEGRAL-SPI measured flux [2] confirms earlier findings and equals

\[ \text{flux} \approx 10^{-3} \text{ photons cm}^{-2} \text{ s}^{-1}. \] (1)

Besides, these new measurements provide crucial information on the geometry of the source and firmly establish that the bulk of annihilation takes place in the Galactic bulge at the distance of about 8 kpc [3]. The flux suggests a positron annihilation rate of

\[ R \approx 1.3 \times 10^{43} \text{ s}^{-1}, \] (2)

if it is assumed that the annihilation proceeds via positronium and the positronium fraction is 0.93, as implied by observations [3].

The origin of the positrons is unclear. Certainly a conventional explanation might be possible, and several have been proposed (see e.g.[4]). More exotic mechanisms are also possible, including the recent suggestion of decays or annihilations of hypothetical dark matter particles in the MeV mass range[5, 6]. In this note, we would like to point out that a natural mechanism for positron production occurs in the mirror matter model and that this mechanism can help supernovas to explode and also explain gamma ray bursts.

Recall, mirror matter is predicted to exist if nature exhibits an exact unbroken mirror (exact parity) symmetry[7]. The general idea, as well as some details, have been reviewed many times (see e.g. Ref.[8]). But since, perhaps, only a small part of the astroparticle physics community listens, we will go back and repeat the main points again.

From modern perspectives, symmetry principles play a crucial role in the Grand Design of the Universe, space-time and gauge symmetries being the most important players. The proper Lorentz group is isomorphic to the $SL(2, C)$ group and this enables one to define notions of left and right chirality at the fundamental level of spinor fields. One can expect that the gauge symmetry group $G$ (where $G = SU(3) \otimes SU(2) \otimes U(1)$ is the simplest case) treats the left and right chiral fields on an equal footing. Surprisingly this is not the case: weak interactions are left-handed and no right-handed neutrinos have been observed. Perhaps the best explanation of this puzzle is given by the anthropic principle.

One needs neutrinos and weak interactions to ensure our existence, because they play an important role in the Sun’s energetics. But neutrinos cannot be too massive otherwise they will overclose the Universe [9] and make the existence of intelligent
observers impossible. In fact this cosmological bound implies \[ \sum (m_\nu) \leq 40 \text{ eV}. \] In the presence of right-handed neutrinos nothing will prevent neutrinos to acquire Dirac masses of the order of the accompanying lepton masses. Therefore the Designer of our universe is bound to violate parity invariance in order for the universe to be hospitable to observers\(^2\).

In spite of the apparent parity non-invariance of the ordinary particles, the universe could still be left-right symmetric if CP were an exact symmetry\(^1\). But this option is not allowed too, because in the CP-symmetric universe there will be no baryonic asymmetry and hence no observers \(^1\) (it is also ruled out by experiments on kaons and B-mesons!)

However, there is a subtle way out. It is possible to build a left-right symmetric universe by doubling the gauge symmetry so that the full gauge group becomes \(G \otimes G\). Then for each type of ordinary particle (electron, quark, photon etc) there is a mirror partner (mirror electron, mirror quark, mirror photon etc), of the same mass. The two sets of particles form parallel sectors each with gauge symmetry \(G\) – except that where the ordinary particles have left-handed (V-A) weak interactions, the mirror particles have right-handed (V+A) weak interactions. The unbroken mirror symmetry maps ordinary particles into mirror particles and includes space inversion (the explicit transformation is given in Ref.[\(^7\)]. Exact unbroken time reversal symmetry also exists in this model \(^7\). Therefore the full Poincaré group, including improper Lorentz transformations, becomes an exact symmetry group of nature. This is certainly appealing esthetically. However, an even more subtle point is the realization that this restoration of left-right symmetry might be necessary for anthropic reasons, just like the previous two steps (P and CP violations). Justification comes from considering possible interactions between two parallel sectors as we will now explain.

Ordinary and mirror particles should interact with each other by gravity. Some other interactions are also allowed\(^3\) and for our goals the most important one is the possible photon-mirror photon kinetic mixing interaction:

\[
\mathcal{L} = \frac{\epsilon}{2} F^{\mu\nu} F'^{\prime \mu\nu},
\]

where \(F^{\mu\nu} (F'^{\prime \mu\nu})\) is the field strength tensor for electromagnetism (mirror electromagnetism). Photon-mirror photon mixing causes mirror charged particles to couple to ordinary photons with a small effective electric charge, \(\epsilon e\)\(^7, 14, 15\).

Mirror matter is necessarily dark and stable and is an impressive dark matter candidate which has been extensively studied in recent years\(^1\). Hard experimental evidence for mirror matter-type dark matter comes from the impressive DAMA/NaI experiment\(^1\). It turns out that this experiment is consistent with halo dark matter

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\(^2\)One consequence of this is that the right-handed neutrinos can be gauge singlets which means that they are able to gain a large Majorana mass, leading to small effective \(\nu_L\) masses (see-saw mechanism).

\(^3\)Given the constraints of gauge invariance, renomalizability and mirror symmetry it turns out\(^7\) that the only allowed non-gravitational interactions connecting the ordinary particles with the mirror particles are via photon-mirror photon kinetic mixing and via a Higgs-mirror Higgs quartic coupling, \(\mathcal{L} = \lambda \phi^4 \phi'^4\). If neutrinos have mass, then ordinary - mirror neutrino oscillations may also occur \(^1\).
consisting of mirror particles interacting with ordinary particles via the photon-mirror photon kinetic mixing interaction, Eq.(3)[18]. A fit to the DAMA annual modulation signal suggests[18]

$$\epsilon \sim 5 \times 10^{-9}$$  \hspace{1cm} (4)

Importantly, the mirror matter explanation of the DAMA signal is not in conflict with any other experiment[18, 19].

We now consider the effect of photon-mirror photon kinetic mixing, Eq.(3), in the core of an ordinary type II supernova (the more interesting case of a mirror supernova will be considered in a moment). The main production process for minicharged particles in the core of a mirror supernova is the plasmon decay process (see e.g. [20] for a review). The energy loss rate for production of minicharged particles has been calculated in Ref.[20]:

$$Q_p = \frac{8\zeta(3)}{9\pi^3} \epsilon^2 \alpha^2 \left( \frac{\mu_e^2 + \frac{\pi^2 T^2}{3}}{T^3} \right) T^3 Q_1$$  \hspace{1cm} (5)

where $Q_1$ is a factor of order unity. $Q_p$ exceeds the energy loss rate due to neutrino emission for $|\epsilon| \gtrsim 10^{-9}$[20]. This of course assumes that the minicharged particles freely stream out of the core. This will not be the case for $e'^\pm, \gamma'$ (we denote mirror particles with a prime) because they will be trapped by their own mirror electromagnetic interactions. So for $\epsilon \sim 5 \times 10^{-9}$, we expect $e'^\pm, \gamma'$ to roughly thermalize with the ordinary particles in the core of the supernova. This means that the energy loss rate due to emission of $e'^\pm, \gamma'$ need not be much greater than that due to neutrino emission (however it should be comparable). Of course, direct detection of $e'^\pm, \gamma'$ from a supernova seems to be difficult if not impossible for ordinary matter observers.

Let us stress that $\epsilon \sim 5 \times 10^{-9}$, implied by the DAMA annual modulation signal [18], is just in the interesting range where the effects of the photon-mirror photon kinetic mixing becomes important for supernova energetics and dynamics. For $\epsilon$ of that magnitude the supernova energy loss through mirror channels becomes comparable to that due to neutrino emission. This raises an interesting question.

It is believed that neutrinos drive the evolution of the collapsing supernova core because they dominate the event energetically. Supernova explosions of massive stars are explained by convectively supported neutrino-heating mechanism [21]. But recent refined simulations showed [22] that there is insufficient neutrino energy transfer behind the stalled supernova shock to produce the explosion. This suggests some missing physics. In light of what was said above, we suggest that this missing physics is provided by the 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) which might help produce the explosion. Let us see if this is reasonable. The cross section for MeV $\gamma'$ (and large angle $e'^\pm$) scattering with ordinary electrons and positrons (i.e. $\gamma' + e^\pm \rightarrow \gamma + e^\pm$ and $e'^\pm + e^\pm \rightarrow e'^\pm + e^\pm$) is of order

$$\sigma \sim \epsilon^2 \pi r_0^2 \sim 10^{-41} \left( \frac{\epsilon}{5 \times 10^{-9}} \right)^2 \text{cm}^2$$  \hspace{1cm} (6)
where $r_0 = \alpha/m_e$ is the classical radius of the electron. Remarkably this is roughly the same size as the neutrino nucleon cross section,

$$
\sigma(\bar{\nu}_e p \rightarrow n e^+) = \frac{4G_F^2 E^2_{\nu}}{\pi}
\approx 10^{-41} \left(\frac{E_{\nu}}{10 \text{ MeV}}\right)^2 \text{cm}^2
$$

(7)

where $E_{\nu}$ is the energy of the neutrino. Importantly, the energy dependence is different: compared with neutrino interactions, the mirror particle interactions with ordinary matter are larger at lower energies[23]. Evidently 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. This seems to be rather nice for supernova explosions!

It appears, therefore, that the anthropic argument outlined above becomes beautifully complete. One needs supernovas to explode to make heavy elements which are crucial for our existence. But in a universe without mirror particles supernovas do not explode, therefore such universe is devoid of observers. The Designer has to restore the left-right symmetry by introducing mirror particles and arrange the photon-mirror photon kinetic mixing of the right magnitude to ensure the appearance of intelligent observers.

In the case of a mirror type II supernova, things are no less 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. During a mirror supernova explosion an enormous energy will be deposited in a short time and a small volume in mildly relativistic $e^+e^-\gamma$ plasma. The resulting fireball will lead to a gamma ray burst (GRB) [24] provided that the number of ordinary baryons in the mirror supernova is sufficiently low. In fact the gamma ray burst has roughly the right characteristics (energy release, time scale, and potentially small baryon load) to be identified with the observed gamma ray bursts as pointed out by Blinnikov[25]4. In this case one might expect that the distribution of GRBs should be correlated with the distribution of dark matter which is not excluded [27].

For the purposes of this paper we will simply define $f_{e^+}, f_{e^-}, f_\gamma$ as the fraction of the total energy of the collapsing mirror star released as $e^+, e^-, \gamma$ respectively (of typical energy of order 10 MeV). We will not attempt to precisely calculate $f_i$, since the details are quite complicated with many sources of uncertainty. Crudely speaking, $f_i$ would be expected to be of order 0.1.

The total energy released in mirror supernova should be similar to ordinary supernova which is of order

$$
E_{SN} \sim 10^{53-54} \text{ ergs.}
$$

(8)

4Blinnikov 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. However, Volkas and Wong[26] showed that that mechanism was not viable due to matter effects which suppress neutrino-mirror neutrino oscillations.
This means that the number of $e^\pm, \gamma$ produced in a mirror type II supernova should be roughly:

$$N_{e^+} \simeq N_{e^-} \sim N_{\gamma} = \frac{f_i E_{SN}}{\langle E_i \rangle} \sim 10^{57} \left( \frac{f_i}{0.1} \right)$$

(9)

where $i$ labels $e^+, e^-, \gamma$ and we have used $\langle E_i \rangle \sim 10$ MeV.

The positrons (and electrons) will be confined by the magnetic field of the galaxy and eventually thermalize and annihilate (with stopping distance of order $10^{25}$ cm[5] and time scale $\gtrsim 10^8$ years) producing two 511 keV gamma rays. Thus, the 511 keV gamma ray production rate is

$$\frac{dN_{\gamma}}{dt} \sim \left( \frac{f_{e^+}}{0.1} \right) 10^{57} R_{SN}$$

(10)

where $R_{SN}$ is the rate of mirror supernova explosions with sufficiently small ordinary baryon load in the galactic bulge. Equating this rate to the measured rate, Eq.(2), gives a rate of roughly,

$$R_{SN} \sim 10^{-2} \text{ per million years}$$

(11)

Of course this is only an order of magnitude estimate with many sources of uncertainty. For example, it may turn out that a significant fraction of positrons annihilate before becoming non-relativisitic, which would mean that $R_{SN}$ would be somewhat larger than our estimate above. Anyway, according to the estimate in Ref.[5], the positrons should be confined (by the magnetic field) to a region of order a parsec from their production point. Thus, we would not expect a uniform positron emission from the bulge, but rather a finite set of sources, each in the vicinity of a mirror type II supernova. This is one way, in principle, to distinguish this explanation from explanations involving exotic MeV particle decays or annihilations[5, 6]. The observations are consistent with a uniform distribution but future observations may reveal some substructure.

Interestingly, the rate, $R_{SN}$, inferred above is also roughly consistent with the observed rate of gamma ray bursts: a mirror supernova rate of $10^{-2}$ per million years in our galaxy, would suggest a rate of about $10^2$ per year per 10 billion galaxies (of order the number of galaxies in the observable universe). This is roughly the observed rate of gamma ray bursts. Of course there is no reason for this rate to be exactly uniform – so this extrapolation cannot be rigorous.

Note that $R_{SN}$ is much less than the rate of ordinary type II supernova explosions in our galaxy. This probably means that most mirror type II supernova do not lead to gamma ray bursts. This might occur if most mirror supernova have enough ordinary baryons to absorb the energy of the expanding $e^\pm, \gamma$ fireball. Even a relatively small proportion of ordinary baryons ($\sim 10^{-5} M_\odot$) might be enough, since one must take into account the effect of proton-mirror proton collisions which could rapidly cool the protons, dumping energy into the collapsing mirror star and potentially also help...
power the explosion. In this way a small baryon load might act as a type of catalyst allowing energy from the relativistic $e^\pm, \gamma$ fireball to be converted into heating the mirror baryons. Very small baryon load ($\ll 10^{-5} M_\odot$) is also problematic for observations. Associated clean fireballs produce intense, extremely short (subsecond) gamma-ray transients with very energetic ($\gg 10$ MeV) gamma-rays. Such events are hard to detect because of dead time and sensitivity limitations of previous gamma-ray detectors [28].

Finally, note that idea that the 511 keV annihilation radiation might be connected with gamma ray bursts is not new. In particular, Ref.[29] considered the possibility of a gamma ray burst occurring in the galactic center within the past $10^6$ yr might explain the 511 keV photon emission. Irrespective of the nature of the GRB central engine, copious pair production is expected during fireball bursting phase due to $\gamma - \gamma$ absorption between high energy photons with estimated number of produced pairs $\sim 10^{54} E_\gamma^2$, where $E_\gamma$ is the GRB energy released in gamma-rays in $10^{52}$ ergs units [30]. This estimation does not depend on any special model, but only assumes that the observed intrinsic GRB spectrum can be extrapolated to very high energies [30]. Nevertheless it is close to our rough estimation Eq.(9). Even more important is that the new born $e^\pm$ pairs survive and do not annihilate with each other into $\gamma$ rays again because their annihilation time for typical GRB parameters is much longer than the hydrodynamic time in the comoving frame [30].

In conclusion, we have shown that mirror matter provides a simple physical picture in which to explain three astroparticle puzzles: origin of positrons in the galactic center, the nature of the gamma-ray bursts central engine and the mechanism of supernova explosions. This is of course, just a beginning – more detailed calculations would be helpful, along with additional experiments to more precisely pin down the parameter, $\epsilon$, which couples the ordinary world to the mirror one. However, the fact that the mirror particles are expected to be generated in a supernova core and their cross sections with ordinary matter turns out to be about the same as the neutrino one (for energies relevant for supernovas) gives significant encouragement that we are on the right track: if the cross section turned out to be much larger than the neutrino one then the $e^\pm, \gamma$ would never escape the mirror supernova which means that we could not explain gamma ray bursts or galactic positrons, if the cross section turned out to be much smaller, it could not help supernovas to explode. Of course, we need supernovas to explode, not just to agree with observations, but more importantly, to generate heavy elements. From this anthropic point of view, gamma-ray bursts and galactic bulge positrons could be viewed as simply byproducts of our own existence!

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References


[23] The energy dependence of the cross section for mirror particle interactions with ordinary matter is quite different to neutrino interactions since the former is an electromagnetic interaction while the latter is a weak interaction. Considering the process $\gamma' e^\pm \to \gamma e^\pm$, the total cross section is

$$\sigma = \epsilon^2 \pi r_0^2 \left[ y(1 - 2y - 2y^2) \ln (1 + \frac{2}{y}) + 4y^2 + \frac{2y(1 + y)}{(y + 2)^2} \right]$$

where $y = m_e/E_{\gamma'}$. This cross section has the following limits: $\sigma = 8\epsilon^2 \pi r_0^2 / 3 \approx 2 \times 10^{-41} \left( \frac{\epsilon}{5 \times 10^{-9}} \right)^2 \text{cm}^2$ for $y \gg 1$ (Thomson limit) and $\sigma = \epsilon^2 \pi r_0^2 \left[ y \left( \ln \frac{2}{y} + \frac{1}{2} \right) \right]$ for $y \ll 1$. In other words, the cross section becomes energy independent at low energies $E_{\gamma'} \ll \text{MeV}$ and slowly falls at high energies $E_{\gamma'} \gg \text{MeV}$.


