PHYSICAL REVIEW D **70,** 123508 (2004)

Spheroidal galactic halos and mirror dark matter

R. Foot* and R. R. Volkas†

School of Physics, Research Centre for High Energy Physics, The University of Melbourne, Victoria 3010, Australia

(Received 25 July 2004; published 3 December 2004)

Mirror matter has been proposed as a dark matter candidate. It has several very attractive features, including automatic stability and darkness, the ability to mimic the broad features of cold dark matter while in the linear density perturbation regime, and consistency with all direct dark matter search experiments, both negative (e.g. CDMS II) and positive (DAMA). In this paper we consider an important unsolved problem: Are there plausible reasons to explain why most of the mirror matter in spiral galaxies exists in the form of gaseous *spheroidal* galactic halos around ordinary matter *disks*? We compute an order-of-magnitude estimate that the mirror-photon luminosity of a typical spiral galaxy today is around 10^{44} erg/s. Interestingly, this rate of energy loss is similar to the power supplied by ordinary supernova explosions. We discuss circumstances under which supernova power can be used to heat the gaseous part of the mirror matter halo and hence prevent its collapse to a disk. The *macroscopic* ordinary-mirror asymmetry plays a fundamental role in our analysis.

DOI: 10.1103/PhysRevD.70.123508 PACS numbers: 95.35.+d

I. INTRODUCTION

Mirror matter, a hypothetical parity-transformed partner for ordinary matter, is a simple and well-defined extension [1] of the standard model (SM) of particle physics that has interesting cosmological consequences. In particular, since the microphysics within the mirror sector is identical to that of the ordinary sector,[1] mirror electrons e' and mirror protons p' will be as long-lived as ordinary electrons and protons (we will denote mirror partners of ordinary particles by a prime). Mirror atoms or ions thus pass the first important test for dark matter candidature: if they were created in the early Universe, they will still exist today. Another important test—very weak coupling to ordinary photons—follows naturally if the ordinary and mirror sectors are in general almost decoupled in all senses except the gravitational, a circumstance that is easily arranged (see below). Further, mirror dark matter behaves similarly to, but not identically with, cold dark matter at galactic and larger scales during the linear regime of density perturbation growth [2,3]. Moving partially to the terrestrial domain, *all* existing direct dark matter detection experiments are consistent with the mirror dark matter hypothesis, whether those experiments have yielded negative results (e.g., CDMS II [4], Edelweiss [5], etc.) or positive (DAMA) [6], as has been explained at length by one of us recently [7]. Mirror matter also has other desirable properties, as reviewed in Ref. [8].

But mirror matter has a potential Achilles heel. The purpose of this paper is to discuss aspects of this important problem, and to suggest possible solutions. The problem is familiar to astrophysicists: For mirror matter to be an important dark matter component, its distribution in spiral galaxies such as the Milky Way must be spheroidal. Ordinary matter, on the other hand, has collapsed into the bulge and disk. These different macroscopic behaviors of ordinary and mirror matter demand an explanation.

Mirror matter can exist in compact form (mirror stars, planets, and so on) and as a gas component. Evidence for compact halo objects has emerged from microlensing surveys of the Large Magellanic Cloud [9] and M31 [10]. These observations are consistent with a halo containing a mass fraction of $f \sim 0.2$ in the form of mirror stars [11], with a 95% confidence interval of $0.08 < f < 0.50$ [9]. This suggests that a significant gas component $1 - f \sim 0.8$ should exist in the spheroidal halo.[2] Evidence for a significant gas component also arises from the DAMA annual modulation signal [6,7]. The gas component must be supported against gravitational collapse via its pressure (being spherically distributed, it cannot be rotationally supported). To be consistent, the cooling time scale of the mirror gas needs to be long—comparable to the age of the galaxy.

We suspect that the different behavior of ordinary and mirror matter in galaxies is related to macroscopic dif-

*Electronic address: foot@physics.unimelb.edu.au

†Electronic address: r.volkas@physics.unimelb.edu.au

[1]Except that mirror weak interactions are right-handed while ordinary weak interactions are left-handed, a distinction that will not be important for the physics discussed in this paper.

[2]This is true if mirror matter comprises the entire dark matter sector, the hypothesis we adopt here. It is of course possible that mirror matter contributes to but does not exhaust the dark matter sector. For instance, spheroidally distributed mirror matter compact objects at the level of 8%–50% of the halo could explain the MACHO observations, with the diffuse dark component ascribed to something else (axions, etc.). Mirror matter gas would then be free to exist in cooled form in the disk, provided it is not overabundant. It is the roughly spherical distribution of the mirror *gas* component that is the main problem. One of us (R. R. V.) thanks M. Yu. Khlopov for emphasizing this to him.

ferences between the ordinary and mirror sectors, which is possible even if the microphysics is exactly symmetric. There are three main reasons for this macroscopic mirror asymmetry. As has been studied at length (see, e.g., Ref. [2,12]) successful big bang nucleosynthesis requires the mirror sector temperature during that epoch to be less than about half the ordinary sector temperature. Second, to make the mirror Silk damping scale subgalactic requires a similar (actually slightly stronger) inequality [2,3]. Third and most definitively, an impressive body of observational evidence has established that the ratio of ordinary to nonbaryonic dark matter must be in the range 0.20 ± 0.02 [13], ruling out equal proportions by a comfortable margin.[3] Because of the temperature and density asymmetries, all the details of chemical abundances and star and galaxy formation and evolution will be quite different in the two sectors. For instance, mirror primordial nucleosynthesis will produce more mirror helium He$'$ than mirror hydrogen H$'$, in contrast to the ordinary case. It is possible that the spheroidal-mirror-halo versus ordinary-disk dichotomy is another instance of the different initial conditions and subsequent histories.

The outline of this paper is as follows: In Sec. II we very briefly review the mirror matter model; in Sec. III we estimate the cooling time of the mirror halo in the absence of any significant heat source. In Sec. IV, we estimate the halo mirror-photon luminosity. In Sec. V we examine possible heating sources that could compensate for the energy lost due to radiative cooling. Finally, in Sec. VI we conclude.

II. THE MIRROR MATTER MODEL

The existence of nonbaryonic dark matter in the Universe suggests that the standard model of particle physics is incomplete—new particles are required. In view of the long and successful history of connections between new particles and fundamental symmetries[4] it is sensible to relate the required new particles to a fundamental symmetry. From this perspective, very obvious candidates are the improper space-time symmetries such as parity and time reversal invariance. These symmetries are not respected in the standard model of particle physics but can exist as exact unbroken symmetries of nature if new particles exist.

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

$$\begin{aligned} &x \to -x, \quad t \to t, \quad G^\mu \leftrightarrow G'_\mu, \quad W^\mu \leftrightarrow W'_\mu, \\ &B^\mu \leftrightarrow B'_\mu, \quad \ell_{iL} \leftrightarrow \gamma_0 \ell'_{iR}, \quad e_{iR} \leftrightarrow \gamma_0 e'_{iL}, \\ &q_{iL} \leftrightarrow \gamma_0 q'_{iR}, \quad u_{iR} \leftrightarrow \gamma_0 u'_{iL}, \quad d_{iR} \leftrightarrow \gamma_0 d'_{iL}, \end{aligned} \tag{2.1}$$

where G^μ, W^μ, and B^μ are the standard $G_{\rm SM} \equiv {\rm SU}(3)_c \otimes {\rm SU}(2)_L \otimes {\rm U}(1)_Y$ gauge bosons, and ℓ_{iL}, e_{iR}, q_{iL}, u_{iR}, and d_{iR} are the ordinary leptons and quarks ($i = 1, 2, 3$ is the generation index), with the primes denoting the mirror particles. There is also a standard Higgs doublet ϕ with a mirror Higgs doublet partner, ϕ', and, for a large range of parameters of the Higgs potential, the mirror symmetry is *not* spontaneously broken by the vacuum (i.e., $\langle\phi\rangle = \langle\phi'\rangle$). It is then an exact, unbroken symmetry of the theory [1].[5] Importantly, despite the doubling of particle types, the number of free parameters has not yet increased: mirror symmetry requires the masses and couplings of the particles in the mirror sector to be exactly the same as the corresponding ones in the ordinary sector.

Ordinary and mirror particles couple with each other via gravity and possibly by nongravitational terms connecting the ordinary and mirror particles. Constraints from gauge invariance, mirror symmetry, and renormalizability allow only two types of new interactions [1][6]: (a) Higgs-mirror Higgs quartic coupling ($\mathcal{L} = \lambda' \phi'^\dagger \phi' \phi^\dagger \phi$), and (b) via kinetic mixing of the ${\rm U}(1)_Y$ and ${\rm U}(1)'_Y$ gauge bosons,

$$\mathcal{L}_{\rm int} = \frac{\kappa}{2} F^{\mu\nu} F'_{\mu\nu}, \tag{2.2}$$

where $F^{\mu\nu}$ ($F'_{\mu\nu}$) is the field strength tensor for the ${\rm U}(1)_Y$ [${\rm U}(1)'_Y$] gauge boson. There are no other renormalizable Lagrangian terms which are also gauge and Lorentz invariant. For example, kinetic mixing of SU(2) and SU(3) gauge bosons is forbidden since only for the Abelian U(1) symmetry is $F^{\mu\nu}$ gauge invariant [21]. Also, mixings between charged ordinary and mirror fermions are not allowed as they would break (both ordinary and mirror) electromagnetic gauge invariance (the same reason that mixings between quarks and leptons are not allowed in the standard model).

The Higgs-mirror Higgs quartic coupling modifies the properties of the standard Higgs boson [1,18,22]. This will be tested if or when scalar particles are discovered. The kinetic mixing of the ${\rm U}(1)_Y$ and ${\rm U}(1)'_Y$ gauge bosons

[3]One way the required cosmological ordinary/mirror asymmetry can be explained is through inflationary models [14,15].

[4]Examples include the theoretical prediction of antimatter from proper Lorentz symmetry, and the neutrino from time translational symmetry (energy conservation).

[5]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 disfavored for a variety of reasons [16]. More complicated models with broken mirror symmetry are still possible and have been studied in the literature; see, e.g., Ref. [17].

[6]With massive neutrinos, mass mixing between ordinary and mirror neutrinos is also possible [18,19], and might be implicated by neutrino physics experiments; however the situation is not yet clear [20].

leads to both $\gamma - \gamma'$ and $Z - Z'$ kinetic mixing, however experimentally $\gamma - \gamma'$ mixing is much more important. 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 ϵe [1,23,24] ($\epsilon = \kappa \cos^2\theta_w$ where θ_w is the weak mixing angle). The observational effects of the photon–mirror-photon kinetic mixing interaction have been explored in Ref. [7,25,26].

Mirror protons and mirror electrons necessarily have the same lifetime as ordinary protons and electrons and thus are natural candidates for the nonbaryonic dark matter in the Universe. A necessary condition for the dark matter to be successfully identified with mirror particles is that the latter have to be able to form spheroidal halos around spiral galaxies so as to explain the observed asymptotically flat rotation curves. As we will see, this requirement is nontrivial in view of the dissipative nature of mirror dark matter.

III. ESTIMATE OF THE COOLING TIME

The purpose of this section is to estimate the cooling time of the mirror gaseous "halo" in the absence of any significant heat source. Estimates of the cooling time of a mirror gaseous halo can be determined using the standard calculation for the cooling time of the proto-galactic nebula (see, e.g., [27,28]). One first establishes using the virial theorem that the gas will be fully ionized. This fact is then used to justify the computation of the energy loss rate and hence cooling time of the nebula due to dissipative processes such as bremsstrahlung.

Taking the gas to be undergoing quasistatic evolution, the total kinetic energy K of the gas is related to the total potential energy U via the virial theorem,

$$-2K = U. \tag{3.1}$$

The potential energy of a gravitationally bound, spherical distribution of constant density is

$$U = -\frac{3}{5}\frac{GM^2}{R}, \tag{3.2}$$

where M is the total mass of the nebula and R is its radius. [Departures from constant density will change the prefactor 3/5 to another number of order 1. The constant density idealization is good enough for the present purpose.] Taking a gas of N particles, with a mean mass of μm_p (m_p is the proton mass), the virial theorem implies that

$$-2N\frac{1}{2}\mu m_p\langle v^2\rangle = -\frac{3}{5}\frac{GM^2}{R}, \tag{3.3}$$

where $\langle v^2\rangle$ is the mean squared-speed of the gas particles. The virial temperature of the gas is defined by

$$\frac{1}{2}\mu m_p\langle v^2\rangle = \frac{3}{2}kT_{\rm virial}, \tag{3.4}$$

which, combined with Eq. (3.3), yields

$$kT_{\rm virial} = \frac{\mu m_p GM}{5R}. \tag{3.5}$$

Using characteristic numbers for the Milky Way Galaxy, $M = 6 \times 10^{11} M_\odot$, $R = 100$ kpc, and $\mu m_p \simeq 1.3$ GeV (which takes the mass of the halo to be dominated by completely ionized He$'$, as suggested by mirror big bang nucleosynthesis) we find: $kT_{\rm virial} \approx 100$ eV. The assumption of complete ionization is justified because the temperature is greater than the ionization energy of He$'$ (which is about 55 eV for the second electron).

Given that He$'$ is fully ionized, the electron number density in the proto-galactic nebula is

$$\begin{aligned} n_{e'} &= \frac{3M}{4\pi R^3}\frac{2}{3\mu m_p} \\ &= 3\times 10^{-3}\left(\frac{M}{6\times 10^{11}M_\odot}\right)\left(\frac{100\ \text{kpc}}{R}\right)^3 \\ &\quad\times\left(\frac{1.3\ \text{GeV}}{\mu m_p}\right)\text{cm}^{-3}. \end{aligned} \tag{3.6}$$

Interactions of mirror electrons with mirror ions will produce mirror photons via several processes, including bremsstrahlung, mirror electron capture, and so on. The halo is expected to be optically thin to such mirror photons since their mean scattering length,

$$\ell = \frac{1}{n_{e'}\sigma_T} \approx \left[\frac{3\times 10^{-3}\ \text{cm}^{-3}}{n_{e'}}\right] 2\times 10^5\ \text{kpc}, \tag{3.7}$$

is much larger than a galactic radius. Here σ_T is the Thomson cross section: $\sigma_T \simeq 6.65 \times 10^{-25}$ cm^2. Thus, any mirror photons produced should escape the Galaxy, thereby cooling it. The cooling rate will be proportional to the product of the mirror electron and mirror ion number densities. Since the gas is highly ionized, the mirror ion number density is roughly half the mirror electron number density. Thus, the cooling rate per unit volume, $\Gamma_{\rm cool}$, for dissipative processes can be considered as proportional to $n_{e'}^2$:

$$\Gamma_{\rm cool} = n_{e'}^2\Lambda. \tag{3.8}$$

The quantity Λ contains the details of the cross section, temperature, and so on. For a temperature of $T_{\rm virial} \sim 100$ eV, $\Lambda \sim 10^{-23}$ erg cm^3 s^{-1} [28].

At the virial temperature, the energy per unit volume is of order $n_{e'}\frac{3}{2}kT_{\rm virial}$. It follows that the time scale for which the radiative cooling would remove all the energy from the gas is

$$t_{\rm cool} = \frac{3}{2}\frac{kT_{\rm virial}n_{e'}}{\Gamma_{\rm cool}} = \frac{3}{2}\frac{kT_{\rm virial}}{n_{e'}\Lambda}. \tag{3.9}$$

For $n_{e'} \sim 3 \times 10^{-3}$ cm^{-3}, $t_{\rm cool} \sim 3 \times 10^8$ years. This suggests that a halo composed predominantly of a gas of mirror ions and mirror electrons would be expected to dissipate energy too quickly to long endure. We shall call this the *radiative cooling problem*.

IV. ESTIMATE OF THE HALO MIRROR-PHOTON LUMINOSITY

The radiative cooling problem would be solved if there was a heating mechanism, so that the energy lost due to radiative cooling could be replaced (possible heating mechanisms will be discussed later on). Assuming for now that this does indeed occur, then the collapse of the gas is halted and hydrostatic equilibrium holds well.

Taking a spherical dark matter halo, the condition of hydrostatic equilibrium gives

$$\frac{dP(r)}{dr} = -\rho(r)g(r) \tag{4.1}$$

where $P(r)$ is the pressure, $\rho(r)$ the mass density, and $g(r)$ the local acceleration, at radius r. For a dilute gas, the pressure is related to the mass density via $P = \rho kT/(\mu m_p)$, where μm_p is the average mass of the particles in the gas, m_p being the proton mass. Taking the usual case of an isothermal halo, T does not depend on r. The local acceleration can also be simply expressed in terms of the mass density via

$$g(r) = \frac{4\pi G}{r^2}\int_0^r \rho(r')r'^2 dr', \tag{4.2}$$

where G is Newton's constant. Eqs. (4.1) and (4.2) can now be solved for ρ to give

$$\rho = \frac{\lambda}{r^2}, \tag{4.3}$$

where λ is a constant that satisfies

$$kT = 2\pi G\lambda\mu m_p. \tag{4.4}$$

The rotational velocity at radius r is given by

$$v_{\rm rot}^2 = \frac{4\pi G}{r}\int_0^r \rho r'^2 dr' = 4\pi G\lambda, \tag{4.5}$$

which is a constant. This is just the usual result that a $\rho = \lambda/r^2$ behavior of a spherically symmetric, isothermal, self-gravitating gas in hydrostatic equilibrium gives a flat rotation curve.

Using Eq. (4.5) to write λ in terms of the rotational velocity, we see that ρ can be reparametrized as

$$\rho(r) = \frac{v_{\rm rot}^2}{4\pi G}\frac{1}{r^2} \approx 0.3\left(\frac{v_{\rm rot}}{220 \text{ km/s}}\right)^2\left(\frac{10 \text{ kpc}}{r}\right)^2\frac{\rm GeV}{\rm c^2} \text{ cm}^{-3}. \tag{4.6}$$

Note that $n_{e'} = 2n_{\rm He'} \simeq 2\rho/m_{\rm He'}$ (for a He$'$ mass dominated halo), which implies

$$n_{e'} \approx 10^{-1}\left(\frac{10\text{kpc}}{r}\right)^2 \text{ cm}^{-3}, \tag{4.7}$$

having set $v_{\rm rot} \approx 220$ km$/s$.

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

$$L_{\rm halo} = 4\pi\Lambda\int_{r_{\rm min}}^{\infty} n_{e'}^2 r^2 dr, \tag{4.8}$$

is divergent as $r_{\rm min} \to 0$. However, the inner region of the Galaxy should contain a high density of mirror dust, mirror stars, mirror supernovas, black holes, and so on, which complicates the situation considerably. For example, it is possible that the temperature increases towards the galactic center due to the presence of: (a) heat sources such as supernovas (see later discussion) and (b) mirror dust particles, which can potentially make the inner region optically thick to mirror radiation. If this were the case, then the isothermal approximation would be invalid and then the mass density need not continue to increase as $1/r^2$ as $r \to 0$. This would also be consistent with observations of rotation curves in spiral galaxies [29]. These observations suggest that the mass density is roughly constant in the inner and central regions of spiral galaxies, as if the halo were "heated up" (in the vernacular of Ref. [30]) in the inner region.

Thus, we introduce a phenomenological cutoff, R_1, and consider only the energy produced for $r > R_1$. In this case, the energy radiated from the halo is roughly

$$L_{\rm halo} = 4\pi\Lambda\int_{R_1}^{100 \text{ kpc}} n_{e'}^2 r^2 dr \sim \left(\frac{3 \text{ kpc}}{R_1}\right)10^{44} \text{ erg/s}. \tag{4.9}$$

The above calculation assumes that the halo contains only a gas component. As discussed earlier, a significant component of the halo will be in the form of compact mirror objects. Furthermore, they 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 at least 10^{43} erg/s seems to be required to replace the energy lost due to radiative cooling.

V. GALACTIC HEATING SOURCES

We now examine possible heating sources that could compensate for the energy lost due to radiative cooling. Perhaps the most obvious energy sources are supernova explosions, both ordinary and mirror types. Mirror supernovas can supply the mirror halo with around 10^{51} erg per explosion (this is the kinetic energy of the outer layers ejected into the interstellar medium). To account for the radiative energy loss would require a galactic mirror supernova explosion rate of around one per year. This rate is about 2 orders of magnitude larger than the rate of ordinary supernovas in our galaxy. However, the ordinary and mirror sectors have different chemical compositions, abundances, and distributions. There is no macroscopic mirror symmetry. It follows that there is no reason for the rates of ordinary and mirror supernovas to be the same.

Another interesting possibility is that ordinary supernovas could supply this missing energy. While the kinetic energy of the ejected outer layers of a supernova is of order 10^{51} erg, a supernova has a total energy output E_{SN} of about 3×10^{53} erg. In standard theory, this energy is released into neutrinos. However, a substantial portion of this energy can be converted into mirror electrons, mirror positrons, and mirror photons if photon–mirror-photon kinetic mixing exists [26].[7] Recall, the parameter ϵ determines the strength of this interaction, with $\epsilon \sim 5 \times 10^{-9}$ suggested from a fit [7] to the DAMA/NaI annual modulation signal [6]. Also, for $\epsilon \sim 10^{-9}$ mirror particle emission from an ordinary supernova is comparable to neutrino emission [26,31]. In other words, a significant fraction, f', of an ordinary supernova's *total* energy can be released into mirror electrons, positrons, and mirror photons for epsilon values near what is preferred by DAMA/NaI. If $f' \sim 0.1$, then the energy converted into mirror particle production is actually an order of magnitude larger than that converted into ordinary particle kinetic energy of the ejected outer layers.[8] In some circumstances, shocks will develop which will accelerate the plasma to form a mirror gamma ray burst. This may require special circumstances (such as the right amount of ordinary baryons).

Whatever the intangibles, a significant proportion of a supernova's total energy may be released into $e'^{\pm}$ and γ'. If so, the mirror electrons and mirror positrons would not escape out of the Galaxy because they would plausibly be confined by the mirror magnetic field and so could give up most of their energy into heating the mirror particles in the halo. Furthermore, mirror photons could be absorbed by heavy mirror elements in the halo if their energies were in the keV range. The point is that elements heavier than about mirror carbon, C', can retain their K-shell mirror electrons, since the binding energies are greater than the temperature of the particles in the halo. The cross section for photoionization of K-shell mirror electrons (for atomic number Z) is [33]

$$\sigma = \frac{16\sqrt{2}\pi}{3}\alpha^8 Z^5 \left(\frac{m_e c^2}{E_{\gamma'}}\right)^{7/2} a_0^2 \simeq 5 \times 10^{-19}\left(\frac{Z}{8}\right)^5 \left(\frac{\text{keV}}{E_{\gamma'}}\right)^{7/2} \text{cm}^2, \quad (5.1)$$

where a_0 is the Bohr radius, giving a mean free path of

$$\ell \approx 7\left(\frac{8}{Z}\right)^5 \left(\frac{E_{\gamma'}}{\text{keV}}\right)^{7/2} \left(\frac{10^{-4}\ \text{cm}^{-3}}{n_{A'}}\right) \text{kpc}, \quad (5.2)$$

where $n_{A'}$ is the number density of heavy elements ($M_{A'} \gtrsim M_{C'}$). This is one plausible way that mirror particles, $e'^{\pm}$ and γ', produced in ordinary supernova explosions could potentially be absorbed in the halo—providing a significant heating source. The amount of energy going into the halo from ordinary supernova explosions is roughly [26]

$$E_{\text{in}} = f' E_{SN} \Gamma_{SN} = \left(\frac{f'}{0.1}\right)\left(\frac{E_{SN}}{3 \times 10^{53}\ \text{erg}}\right)\left(\frac{\Gamma_{SN}}{0.01\ \text{yr}^{-1}}\right) 10^{43}\ \text{erg/s}, \quad (5.3)$$

where Γ_{SN} is the galactic supernova rate. Evidently, ordinary supernovas can potentially supply about the right amount of energy to replace the energy lost in radiative cooling, if ordinary supernovas occur at a rate of order once per hundred years and about 10% of a supernova's energy is converted into mirror electrons, positrons, and photons.[9]

VI. CONCLUSION

We have examined an important problem facing mirror dark matter: because mirror dark matter is dissipative, spheroidal halos around spiral galaxies can cool and potentially collapse on a time scale much shorter than the age of the Galaxy. We estimated the total halo luminosity to be at least 10^{43} erg/s. In the absence of any significant heat source, the time scale of the collapse would be around 300 Myr.

However there are potentially significant heat sources. In particular, both ordinary and mirror supernovas are candidates. Mirror supernovas can supply the energy if they occur at a rate of around one per year. Alternatively, ordinary supernovas can do the job if there exists photon–mirror-photon kinetic mixing, with $\epsilon \sim 10^{-9}$, roughly consistent with the value suggested by the DAMA experiment. The effect of this interaction is to modify the dynamics of supernova explosions allowing for a significant fraction of the total energy to be released into $e'^{\pm}$ and γ'. The energy of these particles can be absorbed by the halo and can potentially supply the required energy. Presumably, there needs to be a significant asymmetry in the heating rates during the evolution of the Galaxy to explain why the ordinary matter has collapsed onto the disk and the mirror matter has not. But this is possible because of the lack of any macroscopic mirror symmetry.

[7] Likewise, a mirror supernova would be a source of ordinary electrons, positrons, and photons and may be related to observations of gamma ray bursts and galactic 511 keV photons [26].

[8] Significant modifications to the dynamics and energetics of supernova explosions cannot be excluded by the observations of the supernova, SN1987a, since large theoretical uncertainties exist due to, e.g., the effects of rotation of the presupernova [32].

[9] One can speculate that the apparent coincidence between the energy loss rate and the supernova energy injection rate might arise as the steady state limit of dynamical evolution of the ordinary-plus-mirror proto-galactic nebula into an actual galaxy.

ACKNOWLEDGMENTS

R. R. V. thanks Maxim Khlopov for interesting discussions, and Paolo Lipari and Maxim Khlopov for fine hospitality at the Universitá di Roma ''La Sapienza'' where the discussions took place. We would also like to thank Stuart Wyithe for valuable comments on a draft of this article. This work was supported by the Australian Research Council.

[1] R. Foot, H. Lew, and R. R. Volkas, Phys. Lett. B **272**, 67 (1991). The idea that exact unbroken parity symmetry can be respected by the fundamental interactions if a set of mirror particles exist was earlier discussed, prior to the advent of the standard model of particle physics, in T. D. Lee and C. N. Yang, Phys. Rev. **104**, 256 (1956); I. Kobzarev *et al.*, Sov. J. Nucl. Phys. **3**, 837 (1966); M. Pavsic, Int. J. Theor. Phys. **9**, 229 (1974); with application to dark matter first suggested by S. I. Blinnikov and M. Yu. Khlopov, Sov. J. Nucl. Phys. **36**, 472 (1982); Sov. Astron. **27**, 371 (1983).
[2] Z. Berezhiani, D. Comelli, and F. L. Villante, Phys. Lett. B **503**, 362 (2001); Z. Berezhiani, P. Ciarcelluti, D. Comelli, and F. L. Villante, astro-ph/0312605.
[3] A. Yu. Ignatiev and R. R. Volkas, Phys. Rev. D **68**, 023518 (2003).
[4] CDMS Collaboration, D. S. Akerib *et al.*, astro-ph/0405033 [Phys. Rev. Lett. (to be published)].
[5] Edelweiss Collaboration, A. Benoit *et al.*, Phys. Lett. B **545**, 43 (2002).
[6] DAMA Collaboration, R. Bernabei *et al.*, Phys. Lett. B **480**, 23 (2000); Riv. Nuovo Cimento **26**, 1 (2003).
[7] R. Foot, Phys. Rev. D **69**, 036001 (2004); astro-ph/0403043; R. Foot, Mod. Phys. Lett. A **19**, 1841 (2004).
[8] See, e.g., A. Yu. Ignatiev and R. R. Volkas, hep-ph/0306120; R. Foot, astro-ph/0407623.
[9] MACHO Collaboration, C. Alcock *et al.*, Astrophys. J. **542**, 281 (2000).
[10] R. Uglesich *et al.*, astro-ph/0403248.
[11] Z. Silagadze, Phys. At. Nucl. **60**, 272 (1997); S. Blinnikov, astro-ph/9801015; R. Foot, Phys. Lett. B **452**, 83 (1999).
[12] R. Foot and R. R. Volkas, Astropart. Phys. **7**, 283 (1997).
[13] WMAP Collaboration, D. N. Spergel *et al.*, Astrophys. J. Suppl. Ser. **148**, 175 (2003), and references therein for earlier work.
[14] E. W. Kolb, D. Seckel, and M. S. Turner, Nature (London) **314**, 415 (1985); H. M. Hodges, Phys. Rev. D **47**, 456 (1993); Z. G. Berezhiani, A. D. Dolgov, and R. N. Mohapatra, Phys. Lett. B **375**, 26 (1996); V. Berezinsky and A. Vilenkin, Phys. Rev. D **62**, 083512 (2000).
[15] R. Foot and R. R. Volkas, Phys. Rev. D **68**, 021304 (2003); Phys. Rev. D **69**, 123510 (2004); see also L. Bento and Z. Berezhiani, Phys. Rev. Lett. **87**, 231304 (2001); hep-ph/0111116.
[16] R. Foot, H. Lew, and R. R. Volkas, J. High Energy Phys. 007 (2000) 032.
[17] R. N. Mohapatra, S. Nussinov, and V. L. Teplitz, Phys. Rev. D **66**, 063002 (2002), and references therein.
[18] R. Foot, H. Lew, and R. R. Volkas, Mod. Phys. Lett. A **7**, 2567 (1992).
[19] R. Foot, Mod. Phys. Lett. A **9**, 169 (1994); R. Foot and R. R. Volkas, Phys. Rev. D **52**, 6595 (1995).
[20] R. Foot, Phys. Lett. B **496**, 169 (2000); R. Foot and R. R. Volkas, Phys. Lett. B **543**, 38 (2002); R. Foot, Mod. Phys. Lett. A **18**, 2079 (2003); Mod. Phys. Lett. A **18**, 2071 (2003).
[21] R. Foot and X-G. He, Phys. Lett. B **267**, 509 (1991).
[22] A. Yu. Ignatiev and R. R. Volkas, Phys. Lett. B **487**, 294 (2000).
[23] B. Holdom, Phys. Lett. **166B**, 196 (1986).
[24] R. Foot, A. Yu. Ignatiev, and R. R. Volkas, Phys. Lett. B **503**, 355 (2001).
[25] S. L. Glashow, Phys. Lett. **167B**, 35 (1986); E. D. Carlson and S. L. Glashow, *ibid.* **193**, 168 (1987); S. N. Gninenko, *ibid.* **326**, 317 (1994); R. Foot and S. Gninenko, *ibid.* **480**, 171 (2000); R. Foot and R. R. Volkas, *ibid.* **517**, 13 (2001); R. Foot, Acta Phys. Pol. B **32**, 3133 (2001); R. Foot and T. L. Yoon, *ibid.* **33**, 1979 (2002); R. Foot and S. Mitra, Phys. Rev. D **66**, 061301 (2002); Astropart. Phys. **19**, 739 (2003); Phys. Lett. B **558**, 9 (2003); Phys. Lett. A **315**, 178 (2003); Phys. Rev. D **68**, 071901 (2003); R. Foot, Int. J. Mod. Phys. A **19**, 3807 (2004); Z. Silagadze, astro-ph/0311337.
[26] R. Foot and Z. K. Silagadze, astro-ph/0404515.
[27] B. W. Carroll and D. A. Ostlie, *An Introduction to Modern Astrophysics* (Addison-Wesley, Reading, MA, 1995).
[28] J. Binney and S. Tremaine, *Galactic Dynamics* (Princeton University Press, Princeton, NJ, 1987).
[29] See, e.g., P. Salucci and A. Borriello, Mon. Not. R. Astron. Soc. **323**, 285 (2001); E. D'Onghia *et al.*, astro-ph/0107423.
[30] P. Salucci and A. Borriello, astro-ph/0106251.
[31] G. Raffelt, *Stars as Laboratories for Fundamental Physics* (Chicago University Press, Chicago, 1995).
[32] See, e.g., V. Berezinsky, Yad. Fiz. **66**, 451 (2003) [Phys. At. Nucl.**66**, 423 (2003)].
[33] See, e.g., B. H. Bransden and C. J. Joachain, *Physics of Atoms and Molecules* (Longman, 1983), p. 193.