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.

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I. INTRODUCTION

Mirror matter, a hypothetical parity-transformed partner for ordinary matter, is a simple and well-defined extension of the standard model 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, 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. 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, Edelweiss, etc.) or positive (DAMA), as has been explained at length by one of us recently.

Mirror matter also has other desirable properties, as reviewed in Ref.

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 behaviours 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 and M31. These

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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.
observations are consistent with a halo containing a mass fraction of $f \sim 0.2$ in the form of mirror stars\textsuperscript{[11]}, with a 95% confidence interval of $0.08 < f < 0.50$.\textsuperscript{[9]} This suggests that a significant gas component $1 - f \sim 0.8$ should exist in the spheroidal halo.\textsuperscript{[2]} Evidence for a significant gas component also arises from the DAMA annual modulation signal\textsuperscript{[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 behaviour of ordinary and mirror matter in galaxies is related to macroscopic differences 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.\textsuperscript{[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 sub-galactic requires a similar (actually slightly stronger) inequality\textsuperscript{[2, 3]}. Third and most definitively, an impressive body of observational evidence has established that the ratio of ordinary to non-baryonic dark matter must be in the range $0.20 \pm 0.02$\textsuperscript{[13]}, ruling out equal proportions by a comfortable margin.\textsuperscript{[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 $\text{He}'$ 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.

II. 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. Ref.\textsuperscript{[16, 17]}). One first establishes using the virial theorem that the gas will be fully ionised. 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,

$$-2K = U.$$

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

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

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 one. The constant density idealisation is good enough for the present purpose.] Taking a gas of $N$ particles, with a mean mass of $\mu m_p$ ($m_p$ is the proton mass), the virial theorem implies that

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

\[2\] 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 (RRV) thanks M. Yu. Khlopov for emphasising this to him.

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

\[9\] 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.
where \( \langle v^2 \rangle \) is the mean squared-speed of the gas particles. The virial temperature of the gas is defined by

\[
\frac{1}{2} \mu m_p \langle v^2 \rangle = \frac{3}{2} kT_{\text{virial}},
\]

which, combined with Eq. (2.3), yields

\[
kT_{\text{virial}} = \frac{\mu m_p G M}{5R}.
\]

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

Given that \( \text{He}' \) is fully ionised, the electron number density in the proto-galactic nebula is

\[
n_{\text{e}'} = \frac{3M}{4\pi R^3} \frac{2}{3\mu m_p} = 3 \times 10^{-3} \left( \frac{6 \times 10^{11} M_\odot}{M} \right) \left( \frac{100 \text{ kpc}}{R} \right)^3 \left( \frac{1.3 \text{ GeV}}{\mu m_p} \right) \text{ cm}^{-3}.
\]

(2.6)

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,

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

(2.7)
is much larger than a galactic radius. Here \( \sigma_T \) is the Thomson cross section: \( \sigma_T \simeq 6.65 \times 10^{-25} \text{ cm}^2 \). 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 ionised, the mirror ion number density is roughly half the mirror electron number density. Thus, the cooling rate per unit volume, \( \Gamma_{\text{cool}} \), for dissipative processes can be considered as proportional to \( n_{\text{e}'}^2 \):

\[
\Gamma_{\text{cool}} = n_{\text{e}'}^2 \Lambda.
\]

(2.8)

The quantity \( \Lambda \) contains the details of the cross section, temperature, and so on. For a temperature of \( T_{\text{virial}} \sim 100 \text{ eV}, \Lambda \sim 10^{-23} \text{ erg cm}^3 \text{ s}^{-1} \).

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

\[
t_{\text{cool}} = \frac{3}{2} \frac{kT_{\text{virial}} n_{\text{e}'}}{\Gamma_{\text{cool}}} = \frac{3}{n_{\text{e}'} \Lambda}.
\]

(2.9)

For \( n_{\text{e}'} \sim 3 \times 10^{-3} \text{ cm}^{-3}, t_{\text{cool}} \sim 3 \times 10^8 \text{ years} \). 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.

### III. 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 good.
Taking a spherical dark matter halo, the condition of hydrostatic equilibrium gives

\[ \frac{dP(r)}{dr} = -\rho(r)g(r) \quad (3.1) \]

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 \( \mu m_p \) 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

\[ g(r) = \frac{4\pi G}{r^2} \int_0^r \rho(r') r'^2 \, dr' \quad (3.2) \]

where \( G \) is Newton’s constant. Equations (3.1) and (3.2) can now be solved for \( \rho \) to give

\[ \rho = \frac{\lambda}{r^2} \quad (3.3) \]

where \( \lambda \) is a constant that satisfies

\[ kT = 2\pi G \lambda \mu m_p. \quad (3.4) \]

The rotational velocity at radius \( r \) is given by

\[ v_{\text{rot}}^2 = \frac{4\pi G}{r} \int_0^r \rho(r) r'^2 \, dr' = 4\pi G \lambda, \quad (3.5) \]

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

Using Eq.(3.5) to write \( \lambda \) in terms of the rotational velocity, we see that \( \rho \) can be reparameterised as

\[ \rho(r) = \frac{v_{\text{rot}}^2}{4\pi G} \frac{1}{r^2} \approx 0.3 \left( \frac{v_{\text{rot}}}{220 \text{ km/s}} \right)^2 \left( \frac{10 \text{ kpc}}{r} \right)^2 \frac{\text{GeV}}{c^2} \text{ cm}^{-3}. \quad (3.6) \]

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

\[ n_{e'} \approx 10^{-1} \left( \frac{10 \text{ kpc}}{r} \right)^2 \text{ cm}^{-3}, \quad (3.7) \]

having set \( v_{\text{rot}} \approx 220 \text{ km/s} \).

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

\[ L_{\text{halo}} = 4\pi \Lambda \int_{r_{\text{min}}}^{\infty} n_{e'}^2 r^2 \, dr, \quad (3.8) \]

is divergent as \( r_{\text{min}} \to 0 \). However, the inner region of the galaxy should contain a high density of mirror dust, mirror stars, mirror supernovas, blackholes, and so on, which complicates the situation considerably. For example, it is possible that the temperature increases towards the galactic centre 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\[18\]. 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.\[19\]) 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

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

$$\approx \left( \frac{3 \text{ kpc}}{R_1} \right) 10^{44} \text{ erg/s}. \quad (3.9)$$

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.

**IV. 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 two 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 $3 \times 10^{53}$ 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. This particle interaction has the explicit form

$$\mathcal{L} = \frac{\epsilon}{2} F^{\mu\nu} F'^{\mu\nu} \quad (4.1)$$

where $F^{\mu\nu}$ and $F'^{\mu\nu}$ are the electromagnetic field strength tensors for ordinary and mirror electromagnetism. One effect of this interaction is to cause mirror charged particles (such as the mirror electron and mirror proton) to couple to ordinary photons with effective electric charge of $\epsilon e$. Thus the parameter $\epsilon$ determines the strength of this interaction, with $\epsilon \sim 5 \times 10^{-9}$ suggested from a fit to the DAMA/NaI annual modulation signal. Also, for $\epsilon \sim 10^{-9}$ mirror particle emission from an ordinary supernova is comparable to neutrino emission. 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! 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 right the amount of ordinary baryons).

Whatever the intangibles, a significant proportion of a supernova’s total energy may be released into $e'^{\pm}$ and $\gamma'$. 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

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4 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.
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 photoionisation of K-shell mirror electrons (for atomic number $Z$) is\[24\]
\[
\sigma = \frac{16\sqrt{2}\pi}{3}\alpha^8 Z^5 \left(\frac{m_e c^2}{E_{\gamma'}}\right)^{7/2} a_0^2
\]
\[
\simeq 5 \times 10^{-19} \left(\frac{Z}{8}\right)^5 \left(\frac{\text{keV}}{E_{\gamma'}}\right)^{7/2} \text{ cm}^2,
\]
where $a_0$ is the Bohr radius, giving a mean free path of
\[
\ell \approx 7 \left(\frac{8}{Z}\right)^5 \left(\frac{E_{\gamma'}}{\text{keV}}\right)^{7/2} \left(\frac{10^{-4} \text{ cm}^{-3}}{n_{A'}}\right) \text{ kpc},
\]
where $n_{A'}$ is the number density of heavy elments ($M_{A'} \gtrsim M_{C'}$). This is one plausible way that mirror particles, $e'^\pm$ and $\gamma'$, 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\[23\]
\[
E_{\text{in}} = f' E_{SN} \Gamma_{SN}
\]
\[
= \left(\frac{f'}{0.1}\right) \left(\frac{E_{SN}}{3 \times 10^{53} \text{ erg}}\right) \left(\frac{\Gamma_{SN}}{0.01 \text{ yr}^{-1}}\right) 10^{43} \text{ erg/s},
\]
where $\Gamma_{SN}$ 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.\[5\]

V. 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 $10^{43} \text{ erg/s}$. 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 $\gamma'$. 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.

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\[5\] 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 protogalactic nebula into an actual galaxy.
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