Mirror Matter MACHOs

Rabindra N. Mohapatra\textsuperscript{1} and Vigdor L. Teplitz\textsuperscript{2}

\textsuperscript{1}Department of Physics, University of Maryland, College Park, MD, 20742
\textsuperscript{2}Department of Physics, Southern Methodist University, Dallas, TX-75275.
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Abstract

We propose that the massive compact halo objects (MACHOs) observed in the recent microlensing experiments with an apparent best fit mass of about $0.5\,M_\odot$ are objects made out of “mirror” baryonic matter rather than familiar baryons. Such a possibility arises naturally within the framework of mirror matter models proposed recently to accommodate the sterile neutrinos that seem necessary to solve all the neutrino puzzles simultaneously. We show that for mirror matter parameters that fit the neutrino observations, the maximum mass of mirror stars are of order $0.5\,M_\odot$ and their main sequence lifetime is much less than the age of the universe. They are therefore likely to be black holes. Mirror matter machos have the advantage that they do not suffer from the problems encountered in the conventional red, brown or white dwarf interpretation. The calculations also apply to the question of how the world of familiar matter would be different if all fundamental mass parameters were.

I. INTRODUCTION

The nature of the dark matter in the universe, for which there is considerable observational evidence, is a mystery \cite{1}. There are a number of experiments in progress to resolve this mystery. Here we will address the issues raised by the microlensing experiments \cite{2} which monitor millions of stars in the neighbouring Large Magellanic Cloud (LMC) to see if any them suddenly brighten for a certain duration of time and then fade away again. The brightening observed is attributed to a lensing effect due to passage of a dark massive object, presumably from our galaxy, in front of the LMC star. The duration $\Delta t$ of the brightening of a MACHO event has been calculated and is proportional to $\sqrt{m/v}$ where $m$ is the mass of the object and $v$ is its velocity. If one assumes that the object is from our galaxy, its velocity is determined; as a result, from $\Delta t$, one can deduce the macho mass. Based on the 14 events from the MACHO and the EROS collaborations that are attributable to MACHO events, one obtains a best fit mass \cite{2} of $0.5M_\odot$ for the MACHOs. Also it has been established that there are no MACHO candidates with masses between $10^{-7}M_\odot$ to $10^{-2}M_\odot$. It is also
expected that these objects can comprise as much as 30 to 50% of the halo mass fraction [3]. The question then arises: “what are these objects?”.

The simplest possibilities are conventional baryonic objects such as red, brown or white dwarfs whose masses are expected to be in this range or that they are neutron stars. It has however been argued by Hegyi and Olive [4] that a large class of baryonic candidates are incompatible with observations. More recently, Freese et al. [5] have made a detailed study of the possibility that they could be red, brown or white dwarfs and have found such interpretations to be highly problematic. (For a more recent analysis of some of these issues, see [6].) We will summarize these difficulties in a subsequent section. Accepting them for the moment their conclusion then leads us to search for alternative explanations. Our finding in this paper is that if there exists a mirror universe with identical particle and force content to the visible universe prior to gauge symmetry breaking [12,10,8], then for certain choice of the symmetry parameters, the maximum mass of the “mirror” stars is of order 0.5\(M_\odot\) and they could therefore be the machos observed in the microlensing experiments. Since they are made of mirror baryons, they avoid all the problems encountered by machos made of conventional baryonic matter [13,8]. We also estimate the main sequence lifetime of the mirror stars and find that in the parameter range of interest it is much less than the age of the universe. As a result, the machos are in the form of black holes. Let us note that precisely such models [8] have recently been proposed to accomodate all the neutrino observations by identifying the lightest of the mirror neutrinos with the sterile neutrino needed in understanding the LSND result together with the solar and the atmospheric neutrino results.

While this is the main result of our paper, our study also applies to the question of how the world of familiar matter would look if the masses are all scaled by a common factor. Similar questions have been studied in the past [7–9].

The main results of this letter are the following: we review the scaling laws for maximum and minimum values for the stellar masses as the masses of the electrons, W-bosons, protons and neutrons vary together (\(m_i \rightarrow \zeta m_i\)). The maximum value, which is of particular interest for us is derived by using an argument in the literature that the radiation pressure inside a stable compact stellar object should not exceed the gas pressure inside it and by finding how that condition scales as the elementary particle masses vary. We find that, for \(\zeta\) of order 15, mirror stars have maximum mass of the order of the 0.5\(M_\odot\) needed for MACHOs in the halo. We give qualitative arguments to support the hypothesis that the initial stellar mass function (IMF) for the mirror sector is likely to peak near the maximum value for \(\zeta\) in the parameter region of interest to neutrino physics. These two arguments (\(\zeta \sim 15\) explains both MACHO masses and the neutrino results) in our opinion strengthen the conjecture that mirror matter machos are the dark massive halo objects in our galaxy seen in the microlensing data.

II. SCALING LAWS FOR STELLAR MASSES AND MAIN SEQUENCE LIFETIMES

We begin with a brief overview of the mirror universe model and the the parameters describing fundamental forces in the mirror sector. As mentioned, one considers a duplicate version of the standard model with an exact mirror symmetry which is broken in the process of gauge symmetry breaking. All particles and parameters of the mirror sector will be
denoted by a prime over the corresponding familiar sector symbol—e.g. mirror quarks are $u', d', s'$, etc and mirror Higgs field as $H'$, mirror QCD scale as $\Lambda'$. We assume that $<H'> / <H> = \Lambda'/\Lambda \equiv \zeta$. Since one expects the masses of the neutron and proton to be given by the scale $\Lambda$ and charged lepton (and current quark) masses to be given by $<H>$, scaling both parameters by the same amount implies that all fermion masses that are relevant to the discussion of stellar structure scale by the same amount, i.e. we have $m_i \to \zeta m_i$ with $i = n, p, e, W, Z$. Furthermore, this gives weak cross sections varying as $\zeta^{-4}$ for fixed values of energy. With these simple rules, assuming that electroweak and strong coupling constants do not change, we can say a great deal about how the properties of stars would change.

We start with the four equations of stellar structure:

$$dP/dr = -G\rho(r)M(r)/r^2$$  \hspace{1cm} (1)$$

$$dM(r)/dr = 4\pi r^2 \rho(r)$$  \hspace{1cm} (2)$$

$$L(r)/4\pi r^2 = -(16/3)\sigma_{SB}(T^3/\rho\kappa)dT/dr$$  \hspace{1cm} (3)$$

$$dL/dr = 4\pi r^2 \epsilon(r)\rho(r)$$  \hspace{1cm} (4)$$

where $\kappa(r)$ is the opacity (cross section per unit mass) at radius $r$, $\sigma_{SB}$ the Stefan-Boltzmann constant, $L(r)$ the luminosity at radius $r$, and $\epsilon(r)$, the rate of energy generation per unit mass at radius $r$. We will need three terms in the equation of state (below) taken one or two at a time:

$$P = (\rho/m)kT + (4\sigma_{SB}/3c)T^4 + (h^2/2m_e)(3/8\pi)^2(\rho/m)^{5/3}$$  \hspace{1cm} (5)$$

where the three terms represent gas pressure, radiation pressure, and (non-relativistic) degenerate electron pressure. $m$ is the nucleon mass, $m_e$ that of the electron. We have neglected such niceties as keeping track of how many objects there are for each $m$ of gas (2 for H, 3/4 for He, etc)

We will make standard, illuminating if crude, approximations [14] in order to understand the $\zeta$ behavior of the solutions to the above equations. First we write

$$P = \rho GM/R, \quad \rho = 3M/4\pi R^3$$  \hspace{1cm} (6)$$

where $P$ and $\rho$ are roughly core averages. Here $M$ and $R$ are mass and radius of core or star; our approximations are not good enough to be precise on such points. (In practice we will adjust $M$ to be the mass of the whole star and $R$ will fall short of the core radius for the sun). Equation (6) gives the useful relation

$$P = (4\pi/3)^{1/3}GM^{2/3} \rho^{4/3}$$  \hspace{1cm} (7)$$

To find the minimum mass of a star, we neglect the radiation pressure term in Equation (6), insert into Equation (7), solve for $T$ and maximize with respect to $\rho$, giving

$$kT = (G^2/2)(8\pi/3)^{2/3}M^{4/3}m_e^{8/3}m_e/h^2$$  \hspace{1cm} (8)$$
Following Phillips [14], we set \( T = T_{ig} \), the lowest temperature that gives sufficient burning to match energy escape and solve for \( M \), obtaining

\[
M_{\text{min}} \sim \left[ \frac{h^2 kT_{ig}}{(m_e G^2 m^{8/3})} \right]^{3/4}
\]

(9)

We know from more detailed analysis that \( M_{\text{min}} \) is of the order of \( 0.07M_\odot \) and \( T_{ig} \sim 10^6 K \). We use Equation (9) to obtain the variation with \( \zeta \). \( m \) and \( m_e \) go as \( \zeta \). \( T_{ig} \), in principle, must be found by solving the four coupled Equations (11-14). Roughly, however, nuclear binding energies will go linearly with \( \zeta \) so we will approximate the variation of \( T_{ig} \) as linear as well. We will see below that the solution of approximate equations gives \( T \) varying with \( \zeta \) (numerically) not greatly different. We thus obtain

\[
M_{\text{min}} \sim \zeta^{-2}
\]

(10)

We can also, again following Phillips [14], use Equation (5) to find the maximum mass of a (main sequence) star. As the mass of the star gets bigger, the core temperature rises. Therefore, of the three terms in the expression for the pressure in the Equation 5, we expect \( P_g \) and \( P_r \) to dominate. Following Phillips [14], we parameterize them as fractions of the total pressure \( P \) as below:

\[
P_g = \beta P, \quad P_r = (1 - \beta)P
\]

(11)

We eliminate \( T \) and solve Equation (11) for \( P \), obtaining

\[
\beta P = \left[ \frac{(\rho k/m)^4 (\beta^{-1} - 1)/(4\sigma_{SB}/3c)} \right]^{1/3}
\]

(12)

Using Equation (7) again then gives

\[
M_{\text{max}} \sim \left[ (1 - \beta) c/\sigma_{SB} \right]^{1/2} G^{-3/2} (k/m)^2 / \beta^2
\]

(13)

As \( \beta \) approaches 1, the energy density is increasingly dominated by photons (relativistic particles) and stars become unstable. Taking a cutoff around \( \beta \sim 1/2 \) gives a maximum stellar mass around \( 70M_\odot \). Thus the range for stars is roughly \( 0.07M_\odot \) to \( 70M_\odot \). From Equation (13) one sees, in the approximation that instability sets in at the same \( \beta \) independent of \( \zeta \), that \( M_{\text{max}} \) varies as \( \zeta^{-2} \) (like \( M_{\text{min}} \)). It is similarly easy to see from the standard expression for the Chandrashekar mass that it too varies as \( \zeta^{-2} \). Note that, in a model with \( m_e \) varying linearly with \( \zeta \), but \( m \) constant, both \( M_{CH} \) and \( M_{\text{max}} \) would be independent of \( \zeta \) while \( M_{\text{min}} \) would go as \( \zeta^{-3/4} \) (since higher mass for the electron would permit contraction to higher densities before Pauli repulsion becomes important). Note that such is the case for the mirror matter model investigated in references [8] in order to solve the neutrino puzzles.

We now consider stellar burning as \( \zeta \) varies. We approximate Equation (3) as

\[
L = \left( \frac{16\pi}{3} \right)^2 \sigma_{SB} (RT)^4 / (\kappa M)
\]

(14)

where \( \kappa \) is the opacity, for which we keep just \( \gamma - e \) scattering contribution i.e. we take \( \kappa \) as

\[\]

1^1\text{Omitting other contributions to opacity tends to overestimate } \kappa \text{ as } \zeta \text{ increases and hence underestimate the luminosity and overestimate the main sequence lifetime. For our purpose, therefore, our assumption about } \kappa \text{ is a conservative one.}
\[ \kappa = \frac{\sigma_T}{m_e} \sim \zeta^{-3} \kappa_\odot \tag{15} \]

Since the rate of energy generation is determined by the weak interaction rate for \( p + p \rightarrow e^+ + d + \bar{\nu} \), we approximate Equation (4) by

\[ L = \epsilon M \tag{16} \]

with

\[ \epsilon = \frac{\sigma v E_{pp} \rho}{m^2} \tag{17} \]

We take \( \sigma v \) from Clayton \[14\] and, as above, continue in \( \zeta \), obtaining

\[ \epsilon = \left( \frac{E_{pp}}{m^2} \right) \zeta^{-3} f(T_6/\zeta) \tag{18} \]

where \( T_6 = T/10^6, E_{pp} \) is the energy release for the full \( pp \) chain into other than neutrinos, and

\[ f(x) = 3 \times 10^{-37} x^{-2/3} e^{-33.81 x^{1/3}} \left[ 1 + 0.021 x^{-1/3} + 0.01 x^{2/3} + 9.5 x \times 10^{-4} \right] \tag{19} \]

One factor of \( \zeta^{-1} \) in Equation (18) comes from the parenthesis preceding \( \zeta^{-3} \) and two come from the behavior of the weak cross section, taking into account energies increasing with \( \zeta \).

Equating the two expressions above for \( L \) permits us to solve for \( RT \) as a function of \( T \), while Equations (5) and (7) give \( RT = M G m / k \). Combining these results we can write,

\[ M^4 = 4(3/16\pi)^3 \left( \frac{k}{mG} \right) \left( \frac{\epsilon_\odot \kappa_\odot}{\rho_\odot \sigma_{SB}} \right) T^3 \zeta^{-13} f(T_6/\zeta) / f(15) \tag{20} \]

where we have normalized to the temperature \( (T_6 = 15) \) at the center of the sun.

Equation (20) gives an approximation to the variation of stellar masses with \( \zeta \). With it, we can solve for \( R, \rho, L, \) and the main sequence lifetime \( t_{MS} = (0.1 M c^2 / L) \). In Figure 1 (a,b) we give the results, as a function of \( M \), for temperature \( T \), radius \( R \), and main sequence lifetime, \( t_{MS} \) for \( \zeta = 1.0, 15 \). We have inserted an overall factor to scale the main sequence lifetime of the sun \( (\zeta = 1, < T_6 > \sim 7.5) \) to \( 10^{10} \) years. The scale units are \( 10^6 K, 10^{16} cm, \) and \( 10^9 \) years for the three quantities. It should be noted that, in the approximations made, the solar (core) radius comes out to about \( 0.3 \times 10^{10} cm \) while, in real life, two thirds of the sun’s mass (with temperature \( T_6 > 7 \)) extends out to about \( 1.5 \times 10^{10} cm \).

We see from Figure (1) that the ranges of radii and main sequence lifetimes fall with increasing \( \zeta \) while that of temperatures increases. In Figure (2) we address this increase in more detail by plotting \( T \) against \( \zeta \) for four values of an index that runs from 1-100 as \( M \) varies from \( M_{min} \) to \( M_{Max} \) in equal logarithmic increments. Roughly, we see that \( T \) goes as \( \zeta^{4/3} \), so that the assumption above that \( T_{ig} \sim \zeta \) is not grossly out of line. It should be noted that, for massive stars (with \( \zeta = 1 \)), the pp cycle on which the above considerations are based is replaced by CNO cycles (Clayton, ref. [4]), in which C, N, and O catalyze He production from H at high enough temperatures. Since the weak interactions in the cycle are all weak decays, which increase, in rate, linearly with \( \zeta \), we expect that massive stars, for large \( \zeta \), should have even shorter main sequence lifetimes than those of Figure 1. Thus the lifetimes in Figure 1 should be considered upper bounds. However estimating the abundances of C, N, O could be quite complicated (see below).

We will use, below, the unsurprising result from Figure (1), that for \( \zeta > 5 \) main sequence lifetimes are all much shorter than the age of the universe; they fall roughly as \( \zeta^{-3} \).
III. MIRROR VS BARYONIC MACHOS

In this section we show that mirror matter MACHOs (MMMs) provide a good explanation of microlensing events within which microlensing data can determine the parameter $\zeta$. Finally, we discuss briefly tests of the model.

First, mirror matter resolves a number of MACHO problems. Fields, Freese and Graff [5], in a very detailed work, raise several problems with baryonic MACHO candidates, including:

– All baryonic candidates require that the MACHO population be near the minimum of the range permitted by observations and that $\Omega_B$ be near the maximum of the range permitted by BBNS theory if the sum of individual baryon components is to be less than the total baryon number. MMMs avoid this problem completely since mirror matter does not enter into the baryon budget.

– Neutron stars and black holes from supernovae cannot fit the fact that lensing events point to MACHO masses around $0.5 M_\odot$. We will see below that mirror matter does provide an explanation of the mass observation.

– Brown dwarf explanations conflict with a growing number of observations that show that the index $\beta$ in the initial stellar mass function (IMF), $N(m) \sim m^{-\beta}$, which is over 2 (2.35 is a commonly accepted value [15]) for $m > M_\odot$ whereas it is well under 2 for $m < M_\odot$; under 2 means that most of the mass is in the higher mass stars. The conflict is because the frequency of microlensing events appears to require a MACHO population with a total mass on the order of up to half $\Omega_B$ while the decrease in $\beta$ for low masses precludes such a result. Since mirror matter is not baryonic, it has no such problem.

– Finally, the “favorite candidate,” white dwarfs, suffer from several problems raised by Fields, Freese and Graff [5], including: (i) not being seen – for example in the Hubble deep field (see Flynn, Bahcall, and Gould [16]) as they should be since $0.5 M_\odot$ dwarfs can only cool slowly; (ii) a need for a large population of galactic massive stars and their supernovae to produce galactic winds to cleanse the galaxy of the processed material in the white dwarf ejecta; and (iii) a contradiction between the amount of carbon the progenitors would produce and the amount observed. None of these problems would arise with MMM progenitors.

We turn now to the question of why the MMMs should have masses around $0.5 M_\odot$. This would be the case (see Figure (1)) if we have $\zeta$ greater than say, 15, since the maximum stellar mass then falls in the region between 0.5 and 1.0 solar masses. The work of [8] shows in some detail that such values are just what is required to provide simultaneous solution of the atmospheric, solar, and LSND neutrino problems (and provide warm dark matter in addition). There are, furthermore, reasons why (a) the mirror matter stellar IMF would peak near the maximum mass and (b) remnant masses would be similar to initial masses. Both stem from the decrease in cross sections with increasing $\zeta$.

Current theories of star formation (see, for example, Adams and Fatuzzo [15] and references therein) from molecular cloud core collapse require a mechanism to stop accretion during collapse, i.e. to limit the size of the star. Such mechanisms are based on scattering, but cross sections for scattering of molecules, atoms, ions, and electrons off photons, atoms and molecules will fall as $\zeta^{-2}$. Thus it is not unreasonable to expect that the mirror matter IMF should become more and more strongly peaked near $M_{\text{Max}}$ as $\zeta$ increases. Additionally, we might expect a modest increase in $\zeta^2 M_{\text{max}}$ in the Section 2 estimate since scattering processes that create instability as $\beta \to 0$ will become less effective leading to smaller $\beta$ values.

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and, through Equation (13), larger values of $M_{\text{max}}$.

Cross section decrease also predicts that there should be little mass loss between the initial star and the remnant. As $\zeta$ increases, the radius of the star decreases and neutrino cross sections decrease. Thus neutrino confinement times decrease sharply and it is doubtful that (Type II) supernova shocks can be formed, thereby creating the population of $M_{\text{Max}}$ black holes that are detected as MACHOs. These two $\zeta > 15$ features – decreased mass loss and mirror star masses peaking around 0.5$M_{\odot}$ – result in fixing $\zeta$ in a range optimal from the point of view of fitting neutrino results in reference [8].

In sum, MMMs appear to have a number of positive features as the explanation of microlensing events.

Finally, we turn to the question of observational tests of the MMM hypothesis. The following come to mind:

– Absence of any optical observations of lensing objects as lensing events accumulate;
– Within the qualitative picture above, relatively strong peaking of lens masses into a narrow range;
– Possible detection of the black holes by some new method; unfortunately estimates by Heckler and Kolb [17] show that, even with new instruments (the Sloan digital sky survey telescope), black holes under 10$M_{\odot}$ could saturate the halo mass without being detectable from the signal from interstellar material infall.
– Possible future detection of black hole MACH binaries [18] that if they exist in sufficient number through the emission of gravitational waves in experiments such as LIGO, VIRGO, TAMA and GEO.

IV. LUCKY TO BE ALIVE

Finally we note some of the implications for the familiar world from the above results on varying $\zeta$. As noted in Section I, there is a growing literature on the changes that would obtain if standard model, and other parameters, were different [7–9]. The present investigation adds to those results.

The two most important changes as $\zeta$ grows would appear to be the absence of supernovae and the decrease in stellar lifetimes. These imply that, as $\zeta$ grows, there would be lower abundances of heavy elements in the interstellar medium with which to form planets and carbon based life forms on them, as well as less time in orbit around main sequence stars during which it would be possible for the latter to occur. Although rates for radiative processes would increase linearly with $\zeta$, main sequence lifetimes would fall as $\zeta^{-3}$ as shown in Figure 1. It is the factor of $p^3$ in phase space that, apparently results in increasing rates and decreasing cross sections.

As $\zeta$ decreases, the combination of decreasing rates and increasing cross sections would be likely to interfere with current models of star formation cited above. For example, collapse times ($[G\rho]^{-1/2}$) would increase like $\zeta^{-2}$ while cross sections for scattering that would tend to disperse the collapsing cloud would increase like $\zeta^{-2}$.

In conclusion, we have studied the variation of stellar mass and lifetimes as the masses of the elementary particles $m_e, m_p, m_n, M_W$ all vary in the same way (given by the parameter $\zeta$). We conclude that for a value of $\zeta \simeq 15$, the maximum mass of the mirror stars is around half a solar mass; as a result, they could be viable candidates for the MACHOs observed in
the various microlensing searches\textsuperscript{2}. The many problems encountered in trying to explain the $0.5M_\odot$ machos white dwarfs and brown dwarfs etc are now easily avoided. We do a crude analysis of the dependence of the “main sequence” life time of the mirror stars as a function of the $\zeta$ variable and find that for similar $\zeta$ values, the mirror macho is most likely a black hole since main sequence stellar lifetimes are few times shorter than the age of the universe. We also propose several tests of this hypothesis.

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\textsuperscript{2}Note that, in the mirror matter model of references \textsuperscript{[8,9]} the neutron is unstable for $\zeta$ in the range of interest, so stellar structures become either mirror white dwarfs or black holes. Our considerations with respect to the maximum mass of such objects would still obtain. The result would be prompt black hole formation and the application to the MACHO problem would be the same as in this letter.
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Figure Caption
Figure 1 (a, b): Temperature $T$, radius $R$ and the main sequence lifetime $t_{MS}$ of the mirror stars as a function of the stellar mass $M$ for six different values of $\zeta = 1.0, 15$. The units for the above are $10^6$K for $T$, $10^{10}$ cm for $R$ and $10^9$ yrs. for $t_{MS}$.

Figure 2. Variation of temperature $T$ as a function of $\zeta$ for 4 of 100 equal mass steps between $M_{min}$ (step 1) and $M_{max}$ (step 100). Step 3 for $\zeta = 1$ corresponds to the sun.
FIGURES

Fig 1a

Fig 1b
