PHYSICAL REVIEW D VOLUME 47, NUMBER 2 15 JANUARY 1993

Mirror baryons as the dark matter

Hardy M. Hodges*
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138
(Received 2 September 1992)

A "parallel world" with all of the standard particles, which primarily interacts gravitationally with our world, can be motivated via a symmetry principle designed to make a Lagrangian *CP* symmetric, while maintaining a *CP* asymmetry in the observable world. Such a symmetry is easily accommodated in grand unified theory models, and may also arise in superstring theories. The cosmological abundance of mirror particles is investigated after a period of chaotic inflation and subsequent reheating. Contrary to previous studies, I find that mirror and ordinary abundances may naturally be similar at the present epoch, and that mirror baryons can provide the closure density without violating nucleosynthesis constraints.

PACS number(s): 98.80.Cq, 12.10.Gq

When parity violation first became a serious issue in the mid 1950's, Lee and Yang [1] wondered if a left-right inequivalence in the world of observed particles is compensated by a "mirror" set of particles which exhibit the opposite left-right asymmetry; e.g., they suggested there might be two protons, one left handed and the other right handed. Ten years later this idea was refined when electromagnetic and strong interactions between ordinary and mirror particles were ruled out [2]. Another "world" which contains all of the known particles, but only interacts gravitationally with our world, is then a rather natural idea based upon a simple symmetry principle, and the elimination of possible types of interactions between the two worlds. Grand unified theories (GUT's) containing these particles have been constructed [3]. Such theories admit the bizarre Alice string, which enables particles to change worlds upon encircling the string [3]. While very massive GUT particles can bridge the two worlds, such interactions are rather insignificant. Later, it was realized that the promising $E_8 \otimes E_{8'}$ superstring theory automatically contains an overall left-right symmetry, and that it might be retained after compactification of extra dimensions—yielding two sets of all the known particles, with only gravity bridging the two worlds [4–6]. (The superstring-inspired work used different terminology: mirror particles were "shadow" matter.) This mirror matter has a very attractive property: its particle physics is already known, to the extent that we understand the physics of "our" matter. If discovered, through their astrophysical signatures, important constraints could be placed on particle physics theories. Also, perhaps mirror matter is the dark matter. Based upon these considerations, a mirror theory is clearly worthy of close examination, and it is the focal point of this paper.

Previous studies of this model imply that it is rather uninteresting [5,6]. The case of complete symmetry between the abundances of ordinary and mirror particles is ruled out by big bang nucleosynthesis (BBN). Inflation can create an ordinary-mirror asymmetry in particle abundances, but it was thought that the mirror matter would be diluted away by a large exponential factor, e.g., in earlier inflation models involving bubble nucleation [5], as well as the more modern chaotic inflation models [6]. To assess these beliefs, I explicitly examine the survivability of mirror matter after a period of chaotic inflation, and through reheating. I will further establish recent arguments [7] that similar amounts of mirror and ordinary matter may naturally arise after inflation. The seemingly coincidental similarity between the baryonic and dark matter densities may be explained nicely. Schemes designed to repopulate an empty world after inflation [6,8] via particles which mediate both ordinary and mirror interactions (e.g., gravitinos) are unnecessary. One additional source of disinterest in this model remains to be addressed: it has long been argued [5] that it is difficult, if not impossible, for mirror baryons to be the dark matter without overproducing ^{4}He during BBN. However, interest in the theory can be fully restored via a reanalysis of GUT baryogenesis, and the advent of a number of baryogenesis scenarios since the study of Ref. [5]. Complete details of this mirror baryon scenario, along with the astrophysical consequences, will be presented elsewhere [9].

I first consider the evolution of the mirror-to-ordinary energy density during chaotic inflation [10]—perhaps the simplest inflationary theory. For reviews of inflation, see Ref. [11]. I shall assume that there is an "ordinary" inflaton ψ, and an associated mirror inflaton $\bar{\psi}$, which decay exclusively into ordinary and mirror matter, respectively. Symmetry requires that the microphysics describing ψ and $\bar{\psi}$ be the same, and I shall take the full potential to be $V(\psi,\bar{\psi})=V(\psi)+V(\bar{\psi})$ (invariant under $\psi\rightarrow\bar{\psi}$, $\bar{\psi}\rightarrow\psi$). To briefly review the chaotic inflation scenario, first ignore $\bar{\psi}$ and consider ψ initially displaced from the minimum of the potential. An inflationary stage of expansion with $\ddot{a}>0$, where a is the cosmological scale factor, can occur if V is the dominant source of energy density and evolves slowly. The latter requirement can be satisfied if the motion of ψ is friction dominated, or in a

*Present address: Hodges International Institute for Advanced Research, 55-1216 River Drive South, Jersey City, NJ 07310.

"slow-rolling" regime, which is described by the equation of motion $3H\dot{\psi}+V_{,\psi}=0$, where $H\equiv\dot{a}/a\simeq(8\pi V/3m_{\rm Pl}^2)^{1/2}$ is the Hubble parameter and $m_{\rm Pl}\simeq 1.22\times 10^{19}$ GeV is the Planck mass. The slow-roll limit is achieved if $|V_{,\psi}m_{\rm Pl}/V(\psi)|\lesssim\sqrt{48\pi}$ and $|V_{,\psi\psi}|\lesssim 9H^2$. The latter condition is typically the relevant constraint, as it is usually slightly more stringent than the other condition. After inflation, ψ will begin to oscillate about the minimum of the potential, and eventually it will decay into ordinary matter and reheating will occur.

A typical chaotic inflation potential, including the mirror world, is

$$V(\psi,\bar{\psi})=\lambda[\psi^p+\bar{\psi}^p]/p\ , \qquad (1)$$

where $p=2,4,6,\ldots$. The first noteworthy observation of Eq. (1) is that if one field provides the dominant contribution to the energy density during inflation, e.g., ψ, in which case $\psi>\bar{\psi}$, then it follows that $\bar{\psi}$ *must slow roll* while ψ slow rolls. That is, since $|V_{,\psi\psi}|\lesssim 9H^2$ while ψ slow rolls, and Eq. (1) implies $|V_{,\bar{\psi}\bar{\psi}}|\leq|V_{,\psi\psi}|$ for $\psi>\bar{\psi}$, then it follows that $|V_{,\bar{\psi}\bar{\psi}}|\lesssim 9H^2$. [The same conclusion could be reached, by the same reasoning, in a slightly generalized model in which a mass term $m^2\psi^2/2+m^2\bar{\psi}^2/2$ is added to Eq. (1).] The slow-roll approximation for the subdominant field is just as good as that for the dominant field if $p=2$, and is even *better* if $p>2$. This behavior may appear unusual within the context of double-inflation models [12], where one field can oscillate during inflation and have its energy density exponentially diluted away—this is possible in such models [12] because the two fields are usually assumed to have very dissimilar masses and couplings.

A comparison of the rates of energy losses in the fields during inflation $\Gamma_\rho\equiv\dot{\rho}_\psi/\rho_\psi=-3H\dot{\psi}^2/\rho_\psi\simeq -V_{,\bar{\psi}}^2/3HV(\psi)$ and $\Gamma_{\bar{\rho}}\equiv\dot{\rho}_{\bar{\psi}}/\rho_{\bar{\psi}}\simeq -V_{,\bar{\psi}}^2/3HV(\bar{\psi})$ [here, $\rho_\psi\simeq V(\psi)$ and $\rho_{\bar{\psi}}\simeq V(\bar{\psi})$ is the total ψ and $\bar{\psi}$ energy density, respectively] yields $\Gamma_{\bar{\rho}}/\Gamma_\rho=(\bar{\psi}/\psi)^{p-2}$. Hence, if ψ is the dominant field (i.e., $\psi>\bar{\psi}$), then $\Gamma_{\bar{\rho}}\leq\Gamma_\rho$, and dilution of the energy density in $\bar{\psi}$ cannot occur. The energy density associated with the two worlds becomes more *similar* (if $p>2$) as inflation proceeds. The physics behind this is simple: the force term (i.e., the slope of the potential) driving the motion of the subdominant field is necessarily smaller (if $p>2$) than that of the dominant field, and the energy densities of the two forms of matter will tend to converge during inflation. If $p=2$, the relative energy densities of the two worlds remain the same during inflation. As the $p=2$ model is rather generic in the sense that it is a (low-energy) limit of most models, it might be treated as a potentially important case—and its consequences shall be analyzed in detail.

Dilution of one of the worlds during inflation is possible, and can be realized in the following models [9]: $V=\lambda(\psi^2-\eta^2)^2+\lambda(\bar{\psi}^2-\eta^2)^2$ $(\eta\gtrsim m_{\rm Pl})$ and $V=\Lambda^4[1+\cos(\psi/f)+1+\cos(\bar{\psi}/f)]$ $(f\gtrsim m_{\rm PL})$ [13]. It is important to note that both fields slow roll during inflation in all models considered thus far, and exponential dilution (or convergence) appears unnatural. Exponential dilution could occur if a potential existed that had a strong curvature near its minimum, corresponding to an effective mass that was much larger than an inflationary scale set by a relatively flat region somewhere else on the potential. An important property is a maximum limit to the amount that mirror (or ordinary) matter can be diluted. Even if a classical analysis implies $\rho_{\bar{\psi}}=0$, quantum fluctuations in $\bar{\psi}$ at the end of inflation will yield

$$\rho_{\bar{\psi}}/\rho_\psi\simeq H_{\rm end}^4/\rho_\psi\simeq H_{\rm end}^2/m_{\rm Pl}^2\ . \qquad (2)$$

This estimate comes from considering the typical gradient energy $(\nabla\bar{\psi})^2/2$ over a Hubble region (size $\approx H_{\rm end}^{-1}$) at the end of inflation, and assuming that the effective mass of $\bar{\psi}$ is less than $H_{\rm end}$—in which case rms fluctuations in $\bar{\psi}$ are $\simeq H_{\rm end}/2\pi$ [14].

In the previous analyses the mirror matter is solely associated with a mirror inflaton, and a natural next step is to consider reheating, i.e., the conversion of ρ_ψ and $\rho_{\bar{\psi}}$ into ordinary and mirror radiation energy density ρ_r and $\rho_{\bar{r}}$, respectively. Reheating is potentially important since the decays of the fields inherently involve exponentials, and it is conceivable that the particles in one of the worlds could be significantly diluted. To examine this possibility, I have solved the standard phenomenological reheating equations for the two fields (see, e.g., Ref. [11]):

$$\dot{\rho}_\psi+3H\rho_\psi+\Gamma_\psi\rho_\psi=0\ ,\quad \dot{\rho}_{\bar{\psi}}+3H\rho_{\bar{\psi}}+\Gamma_{\bar{\psi}}\rho_{\bar{\psi}}=0\ , \qquad (3)$$

$$\dot{\rho}_r+4H\rho_r=\Gamma_\psi\rho_\psi\ ,\quad \dot{\rho}_{\bar{r}}+4H\rho_{\bar{r}}=\Gamma_{\bar{\psi}}\rho_{\bar{\psi}}\ , \qquad (4)$$

where Γ_ψ $(\Gamma_{\bar{\psi}})$ is the decay rate of ψ $(\bar{\psi})$ into ordinary (mirror) radiation. These equations implicitly assume that a mass term in the potential is relevant when reheating occurs—a relatively standard assumption. For a discussion of the evolution of $\rho_{\bar{\psi}}/\rho_\psi$ in the interim between the end of an inflation phase that had $p>2$ and a reheating period with $p=2$, or for the possibility that reheating occurs while $p>2$, see Ref. [9]. In the standard analyses the decay rates are just constants, and in the present example $\Gamma_\psi=\Gamma_{\bar{\psi}}$ remains constant throughout the reheating process. Then, the left-hand sides of Eqs. (4) are the same, up to a proportionality constant, and they can be integrated. The asymptotic value of $\rho_{\bar{r}}/\rho_r$ is just given by $\rho_{\bar{\psi}}/\rho_\psi$—independent of the decay rate. Hence, dilution (or convergence) of one of the worlds does not arise in this analysis. The preceding conclusions are rather general, but there are potential loopholes, e.g., the resultant value of $\rho_{\bar{r}}/\rho_r$ may depend upon the details of the decay rates if $\Gamma_\psi,\Gamma_{\bar{\psi}}$ explicitly depend upon $\psi,\bar{\psi}$ (and perhaps $\dot{\psi},\dot{\bar{\psi}}$)—this might be a consideration in unconventional particle physics models.

A complete picture of the expected amount of mirror radiation requires information on the likelihood of various initial values of ψ and $\bar{\psi}$. I shall first address this issue for the massive scalar-field potential described by Eq. (1) with $p=2$, which is particularly easy to analyze. Rotational symmetry of the potential requires that inflationary trajectories in the $\psi-\bar{\psi}$ plane are straight lines that evolve toward the origin. Any trajectory can be labeled by the angle θ it subtends to the positive ψ axis. The ratio of the mirror-to-ordinary temperatures $\bar{T}/T$ after inflation and reheating is then given by

$$r \equiv \bar{T}/T \simeq (\rho_{\bar{r}}/\rho_r)^{1/4} = (\bar{\psi}^2/\psi^2)^{1/4} = |\tan\theta|^{1/2} . \quad (5)$$

For simplicity, I have ignored possible terms involving particle degrees of freedom. Now, one would like to obtain information on θ, and hence r.

Strong arguments suggest that θ is randomly drawn from the distribution:

$$dP/d\theta = 1/2\pi . \quad (6)$$

First, a long period of inflation (in particular, eternal inflation [15]) can highly randomize the value of θ over very large length scales, and Eq. (6) is expected. Or, the initial values of $\psi,\bar{\psi}$ could be determined by some other quantum process. In this case, the expectation (by analogy with other branches of physics) is that the likelihood of various configurations is some function of $V(\psi,\bar{\psi})$—but this is rotationally symmetric and Eq. (6) again results. If one could ignore the details of the superstring theory and the higher dimensions, the quantum cosmology of two massive scalar fields $\psi,\bar{\psi}$, with identical masses, would also yield Eq. (6). Combining Eqs. (5) and (6), one finds that r should be drawn from the distribution

$$dP/dr = (4/\pi)r/(1+r^4) . \quad (7)$$

Note that this contains no undetermined parameters. Also,

$$P(0<r<r_*) = (2/\pi)\arctan(r_*^2) , \quad (8)$$

and there should be similar amounts of ordinary and mirror radiation.

It is a nontrivial matter to perform similar calculations for more general inflationary potentials that do not have rotational symmetry, as dP/dr may now depend upon the specific details of the probability distribution of initial-field configurations, which is uncertain. Another issue arises when considering such models: what is the appropriate probability measure? In the previous exercise, rotational symmetry provided ambiguous-free results. In general, one may have to be careful. For example, fundamental physics might provide a distribution of initial-field configurations $\psi,\bar{\psi}$ for the creation of a universe. However, different initial conditions may lead to differing amounts of inflation—and one may want a probability measure which appropriately weights initial conditions that lead to more inflation. These issues aside, it appears that there are three "generic" possibilities for r.

One possibility is that significant dilution of one of the worlds occurred, presumably the mirror world, and that Eq. (2) sets the scale for r:

$$r \sim \sqrt{H_{\rm end}/m_{\rm Pl}} . \quad (9)$$

If $H_{\rm end}$ corresponds to a typical GUT scale, then this translates to $r \sim 10^{-3}$–10^{-2}. Another possibility is the massive scalar-field model, which unambiguously predicts r to be of order unity. Lastly, the case of strong convergence of energy densities during inflation might yield a prediction of r very close to unity. This latter possibility might naively be discarded as being inconsistent with BBN. However, (1) under the simplest assumptions about the initial probability distribution, the convergence may not be strong enough to warrant such a conclusion [9], (2) the details of the probability distribution of initial values are uncertain and the extent to which the distribution of r's is peaked about unity is not clear, and (3) there is additional leeway because it is difficult to convert these probability distributions into ones we can use to assess the likelihood of our Universe, e.g., it is conceivable, from astrophysical considerations, that it is more likely for life to arise in Universes where r is not tuned to unity, and our distributions for r should be weighted accordingly. Convergent models may easily be viable. All three "generic" cases for r may be of cosmological interest.

Since a Universe filled with roughly similar amounts of ordinary and mirror radiation appears natural, mirror baryons might easily account for the dark matter. This is only possible if the following constraints are compatible:

$$8 \lesssim \bar{n}_b/n_b \lesssim 50 \quad \text{and} \quad r \lesssim 0.68 . \quad (10)$$

The first constraint is on the mirror-to-ordinary baryon density ($\equiv \bar{n}_b/n_b$), and arises from the range of ordinary baryon densities allowed by the most recent BBN analysis [16], along with the assumption that mirror baryons provide the remaining closure density. The second condition arises from requiring that the mirror radiation density be small enough so that it does not overproduce ^{4}He during BBN [5] (assuming three neutrino species). [The latest BBN analysis [16] may tighten this constraint to $r \lesssim 0.51$.] The second constraint is automatically satisfied by Eq. (9), and the massive scalar-field model is acceptable since $P(r_* = 0.68) \simeq 0.28$—see Eq. (8).

To address the aforementioned issue, GUT ordinary and mirror baryogenesis was considered in Ref. [5], and they concluded that the prospects for mirror baryons dominating over ordinary baryons are dismal if the mirror radiation cannot dominate over ordinary radiation. However, a regime of GUT baryogenesis models (reviewed in Ref. [17]), that is consistent with Eq. (10), was overlooked. The appropriate limit is $K \gtrsim 300/A\alpha$, where K is the ratio of a baryon-violating interaction rate to the expansion rate at a temperature equal to the mass scale of the baryon-violating boson, $A \simeq \text{few} \times 10^3$, and α is the GUT coupling $\simeq \frac{1}{45}$ for gauge bosons (but could be somewhat smaller for Higgs bosons). The resulting baryon asymmetry, expressed in terms of the baryon number-to-entropy ratio $B \equiv n_b/s$ [inferred to be $\simeq (6-10)\times 10^{-11}$] is given by

$$B \simeq (\epsilon/g_*)(AK\alpha)^{1/2}\exp[-4(AK\alpha)^{1/4}/3] , \quad (11)$$

where ϵ is the mean net baryon number produced in the decay of a boson-antiboson pair and $g_* \approx 160$ is the particle degrees of freedom near the GUT scale. This regime can lead to the required value of B if $\epsilon \gtrsim 10^{-7}$. This is acceptable, as it has been estimated that an ϵ as large as $\sim 10^{-2}$ may be reasonable [17]. For mirror matter $\bar{K} = Kr^2$ (Ref. [5]), and the resulting ratio of mirror-to-ordinary baryons is

$$\bar{n}_b/n_b = r^3\bar{B}/B \simeq r^4 \exp[4(AK\alpha)^{1/4}(1-r^{1/2})/3] \ . \quad (12)$$

The possibility of $\bar{n}_b > n_b$, for $r<1$, arises because the relevant ordinary interactions *maintain equilibrium longer than their mirror counterparts,* this can favor mirror baryon production by an exponential Boltzmann factor. The $AK\alpha$ dependence in Eq. (11) can be substituted with that in Eq. (12), and an equation can be obtained which relates ϵ to r (and $\bar{n}_b/n_b$). In Fig. 1 I have plotted the $r-\epsilon$ parameter space consistent with Eq. (10). Compatibility of the constraints in Eq. (10) is therefore easily achieved in this scenario. Even for small r, e.g., values suggested by the quantum limit in Eq. (9), conditions (10) might be satisfied, however, this may require unnaturally large values of ϵ. There are presently numerous baryogenesis scenarios, and one could analyze each theory for consistency with Eq. (10)—see Ref. [9] for further analyses, where the conclusion is that dark-matter mirror baryons are easily compatible with nucleosynthesis constraints.

At this point, mirror baryons have emerged as a reasonable dark-matter candidate. A remaining issue is whether or not this scenario is compatible with astrophysical observations [9]. After specifying the nature of the primordial fluctuation spectrum, all of the relevant astrophysics and cosmology depends upon only one parameter: r, which is expected to lie somewhere in the range $10^{-3}-10^{-2} \lesssim r \lesssim 0.68$. This is a highly predictive theory. We have argued that mirror baryons might quickly condense into stars, "Jupiters," etc., which significantly curtails further mirror dissipation, and may provide a reasonable picture for dark-matter galactic halos [9]. Presumably, the mirror matter might be found in searches for massive compact halo objects (MACHO's). In many respects, this scenario might appear similar to cold dark-matter models. However, in very dense regions of mirror baryons, where dissipation might be important, there could be observational signatures that are unique to this model. Also, adiabatic perturbations in the mirror photon-mirror baryon plasma can be damped by mirror photon diffusion, which introduces a characteristic mass scale (a mirror Silk mass) below that of the ordinary Silk mass [9]. As a new alternative to standard structure formation scenarios, which all appear to have problems, the details of the mirror baryon scenario warrant full exploration.

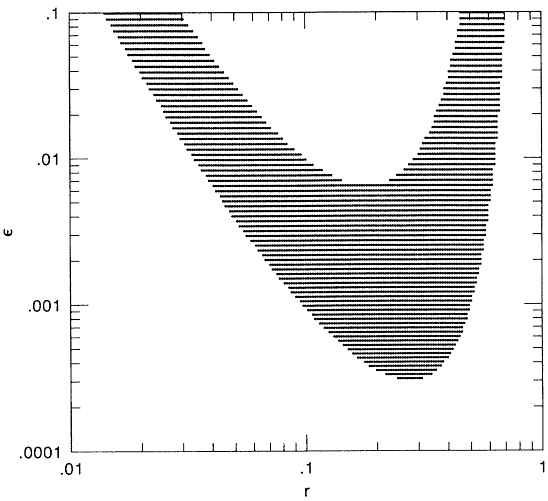

FIG. 1. Shown is the $r-\epsilon$ parameter space which yields dark-matter mirror baryons in the simple GUT baryogenesis scenario. The lower (upper) boundary corresponds to $\bar{n}_b/n_b=8$ (50). Mirror baryons naturally account for the dark matter if CP violation arises at the one-loop level.

I thank G. Blumenthal, M. Kamionkowski, J. Schwarz, D. Seckel, and C. Vafa for discussions and/or comments. This work was supported by NAGW-931.

[1] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).
[2] I. Yu. Kobzarev, L. B. Okun, and I. Ya Pomeranchuk, Yad. Fiz. **3**, 1154 (1966) [Sov. J. Nucl. Phys. **3**, 837 (1966)].
[3] A. S. Schwarz and Yu. S. Tyupkin, Nucl. Phys. **B209**, 427 (1982).
[4] M. B. Green and J. H. Schwarz, Phys. Lett. **149B**, 117 (1984); D. J. Gross, J. A. Harvey, E. Martinec, and R. Rhom, Phys. Rev. Lett. **54**, 503 (1985).
[5] E. Kolb, D. Seckel, and M. Turner, Nature (London) **314**, 415 (1985).
[6] M. Khlopov, G. Beskin, N. Bochkarev, L. Pustilnik, and S. Pustilnik, Fermilab Report No. 89/193-A, 1989 (unpublished).
[7] H. Hodges, Phys. Rev. D **45**, 1113 (1992).
[8] L. Krauss, A. Guth, D. Spergel, G. Field, and W. Press, Nature (London) **319**, 748 (1986).
[9] G. Blumenthal and H. Hodges (unpublished).
[10] A. Linde, Phys. Lett. **129B**, 177 (1983).
[11] K. Olive, Phys. Rep. **190**, 307 (1990); E. Kolb and M. Turner, *The Early Universe* (Addison-Wesley, Redwood City, CA, 1990).
[12] A. A. Starobinsky, Pis'ma Zh. Eksp. Teor. Fiz. **42**, 124 (1985) [JETP Lett. **42**, 152 (1985)]; J. Silk and M. Turner, Phys. Rev. D **35**, 419 (1987); L. Kofman and D. Pogosyan, Phys. Lett. B **214**, 508 (1988).
[13] K. Freese, J. Frieman, and A. Olinto, Phys. Rev. Lett. **65**, 3233 (1990).
[14] A. Vilenkin and L. Ford, Phys. Rev. D **26**, 1231 (1982); A. Starobinsky, Phys. Lett. **117B**, 175 (1982); A. Linde, *ibid.* **116B**, 335.
[15] A. Linde, Phys. Lett. B **175**, 395 (1986).
[16] K. Olive, D. Schramm, G. Steigman, and T. Walker, Astrophys. J. **236, 454** (1990).
[17] E. Kolb and M. Turner, Annu. Rev. Nucl. Part. Sci. **33**, 645 (1983).