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A Peek into the Shadow World*

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Abstract

At present, the most promising superstring theory has the gauge symmetry $E_8 \times E_8$'. If one of the E_8's describes all the known particles and forces, matter in the other E_8 (shadow matter) would interact with ordinary matter only through gravitational-strength interactions. Here, we review the cosmological and astrophysical implications of shadow matter.

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Superstrings have emerged as a promising theory for unification of the strong and electroweak theories with gravity.[1] A particular superstring theory, the heterotic superstring model of Gross, Harvey, Martinec and Rohm[2] based upon the gauge group $E_8 \times E_{8'}$, seems the most promising one to lead to the observed low energy theory $SU_3 \times SU_2 \times U_1$. The $E_8 \times E_{8'}$ model has the curious property that all of the matter and interactions with which we are familiar come from one of the E_8's, and there is another E_8 that describes a shadow world, which interacts with ordinary matter only through gravitational-strength interactions. This "shadow world" is the subject of this talk.[3] Although the heterotic string provides the motivation for the investigation, the considerations are more general, and apply to any theory with a sector that has only gravitational-strength interactions with ordinary matter.

The cosmological and astrophysical effects of shadow matter depend upon the microphysics and macrophysics of the shadow world. By microphysics we refer to the particle physics, i.e. symmetry breaking patterns, particle spectrum, particle masses, etc. By macrophysics we refer to the cosmological parameters of the shadow world, i.e., entropy, temperature, mass density, etc. It is possible to place some general constraints on the properties of the shadow world by considering its effect in the early and present Universe.

In the early Universe it is quite possible that the gravitational-strength interactions between shadow matter and normal matter resulted in an equilibration between the two worlds. The ordinary $\leftrightarrow$ shadow interaction rate is expected to be (for equal number densities of ordinary and shadow relativistic particles)

$$\Gamma_{O\leftrightarrow S} = n\sigma|v| \simeq T^5 M_{pl}^{-4}$$

which is to be compared with the expansion rate of the Universe

$$H = [8\pi G\rho/3]^{1/2} \simeq T^2 M_{pl}^{-1} .$$

Therefore, $\Gamma_{O\leftrightarrow S}H^{-1} = T^3 M_{pl}^{-3}$, and is greater than unity only for $T \gtrsim M_{pl}$. When the temperature drops below M_{pl}, the ordinary $\leftrightarrow$ shadow interaction rate is less than the expansion rate, and the two worlds decouple, although ordinary $\leftrightarrow$ ordinary and shadow $\leftrightarrow$ shadow interactions can keep each sector separately in equilibrium. If ordinary and shadow matter are originally well mixed, they will remain well mixed until non-gravitational interactions become important.[4] In the standard picture of galaxy formation this occurs rather late in the evolution of the Universe, when density perturbations go non-linear, produce hydrodynamic instabilities (shocks, etc.), which will differentiate between ordinary and shadow matter. The scale of segregation of ordinary and shadow matter depends upon the scale that first goes non-linear. In the pancake picture of galaxy formation[5] the first scales to go non linear are superclusters, while in the hierarchical picture of galaxy formation[6] small sub-galactic scales collapse first. Therefore the segregation of normal and shadow matter can occur on galactic scales (i.e., clusters consisting of normal galaxies and shadow galaxies) or sub-galactic scales (i.e., galaxies consisting of normal stars and shadow stars).

In a Universe with a mirror symmetry between the normal world and the shadow world (mirror symmetry implies the same microphysics and the same macrophysics) there are no direct observations that would exclude the possibility that half of the Universe is shadow matter. We know that less than 10% of the mass of the earth is shadow matter, since the mass of the earth deduced by seismic means[7]

$$M = 4\pi \int \rho r^2 dr$$

is consistent at the 10% level with the measurement of the total mass of the earth determined gravitationally,

$$M_T = M+M_S = 4\pi \int (\rho+\rho_S) r^2 dr \ ,$$

where M_T is the total mass and $M(M_S)$ is the mass of normal (shadow) matter with mass density $\rho(\rho_S)$. We also know that the total mass of the sun is less than 10^{-3} shadow matter. If there were shadow matter in the sun, the shadow matter would be supported against collapse by shadow pressure just as the normal matter is supported against collapse by normal pressure. The equation of hydrostatic equilibrium then reads

$$-\frac{dp}{dr} = G_N \frac{[M(r)+M_S(R)]}{r^2} \rho$$

$$-\frac{dp_S}{dr} = G_N \frac{[M(r)+M_S(r)]}{r^2} \rho_S$$

where a symbol with subscript S refers to shadow matter, and a symbol without subscript refers to normal matter. If the sun is half shadow matter burning shadow hydrogen to shadow helium, then $M(r) = M_S(r)$, $\rho=\rho_S$, and $p=p_S$. Then the equation of hydrostatic equilibrium for the normal matter in the sun, would be that of a star with $M = M_\odot/2$ and an effective Newton's constant of $G = 2G_N$, but with GM constant. It is elementary to demonstrate that the structure of that star would not resemble the sun.[3] If the mass of shadow matter in the sun is less than the mass necessary to ignite shadow fusion, then the shadow matter would settle to the center of the sun and have the structure of a shadow planet. A shadow planet inside the sun would upset the structure of the solar core unless the mass of the shadow planet is less than $10^{-3}M_\odot$.[3] It is clear that there is not much shadow matter in the solar system. However, even if there were an equal amount of shadow and normal matter in the proto-solar nebula, if a shock wave triggered the formation of the solar system segregation of normal and shadow matter would be expected.

There is no other observation that can directly prove or disprove shadow matter in our galaxy. Binary systems of a normal star and a shadow star might be expected, but the invisible companion of a star could also be a white or brown dwarf, black hole, neutron star, etc.

The exact mirror Universe we have been considering is, however, ruled out by the calculation of the light elements produced in big bang nucleosynthesis. The existence of mirror shadow matter during primordial nucleosynthesis would double the effective number of massless degrees of freedom during primordial nucleosynthesis, leading to a gross overproduction of ^{4}He. If the energy density of the Universe is dominated by relativistic particles, we can define g_{eff} by

$$\rho = \frac{\pi^2}{30} g_{eff} T^4 ,$$

where g_{eff} is calculated by summing over the boson and fermion spin degrees of freedom (including a factor of 7/8 for fermions relative to bosons). Detailed calculations of primordial nucleosynthesis require $g_{eff} \lesssim 13$.[8] An exact mirror symmetry would result in $g_{eff} = 11 + 3.5N_\nu$ where N_ν is the number of generations of light neutrinos ($N_\nu \lesssim 4$). The effective number of degrees of freedom in the shadow world $(g_{eff})_S$ must be less than 7.5 - 1.75 N_ν, where

$$(g_{eff})_S = g_{*S}(T_S/T)^4 = g_{*S}r^4$$

with g_{*S} the usual definition of g_* for the shadow world and r the ratio of the temperature of the shadow world to the temperature of the normal world.

Primordial nucleosynthesis implies that the mirror symmetry must be broken, but it doesn't give any indication as to whether the breaking is in the microphysics, the macrophysics, or both. Present theories for the compactification of the ten-dimensional effective field theory on six-dimensional Calabi-Yau manifolds seem to prefer an asymmetry in the microphysics: one E_8 is broken to E_6 in the compactification while the other E_8 remains unbroken.[9] However, it is also possible to have different macrophysics. In inflationary models the shadow world might be inflated away leading to an asymmetry in macrophysics. If the inflaton decays by non-gravitational means it will produce normal entropy but not shadow entropy,[10] making the shadow world exponentially uninteresting. If, however, the decay of the inflaton is gravitational, it would produce roughly equivalent amounts of normal and shadow entropy.

An interesting cosmological limit on the shadow world arises by consideration of the fate of massive shadow states (MSS). If E_8, (or some non-Abelian subgroup) remains unbroken, then at an energy scale, Λ_S, some shadow coupling constant should become strong and lead to the formation of MSS with masses $M_S \approx \Lambda_S$. If Λ_S is large, the MSS will be ineffective at annihilation and must decay (or be inflated away) in order not to give too large a contribution to the present mass density of the Universe. In particular, if the MSS annihilates with a cross section $\sigma_A = \Lambda_S^{-2}$, the remaining shadow states would give today[3,11]

$$\Omega_S \approx 10^{29} r_i (\Lambda_S/M_{pl})^2$$

where r_i is the initial value of r. If the MSS must annihilate by gravitation interactions, then we expect $\sigma_A \approx \Lambda_S^2 M_{pl}^{-4}$, and annihilation is ineffective at ridding the Universe of MSS, and the number today would simply reflect the initial number, giving Ω_S of

$$\Omega_S \approx 10^{27} r_i^3 (\Lambda_S/M_{pl}) .$$

These considerations result in the limits

$$\Lambda_S \leq 3\times10^{-15} r_i^{-1/2} M_{pl} \qquad (\sigma_A = \Lambda_S^{-2})$$

$$\Lambda_S \leq 10^{-27} r_i^{-3} M_{pl} \qquad (\sigma_A = \Lambda_S^2 M_{pl}^{-4}).$$

Both limits have assumed stable MSS.

If all the MSS are unstable, then decay may be effective in ridding the Universe of MSS or their effects. If the decay width of the MSS is $\Gamma_S = \Lambda_S$, then the MSS are not dynamically important. If however the MSS must decay by gravitational interactions, then we expect $\Gamma_S = \Lambda_S(\Lambda_S/M_{pl})^4$, and the requirement that the entropy produced in MSS decay not ruin primordial nucleosynthesis implies[3]

$$\Lambda_S \gtrsim 3 r_i^2 M_{pl} \ .$$

The major shadow conclusions are: 1) shadow matter is hard to detect - no present observation rules out the existence of mirror shadow matter. 2) Primordial nucleosynthesis does rule out mirror symmetry. 3) The shadow world could have been inflated away, and hence be exponentially uninteresting, although it is possible to imagine inflationary scenarios where the inflaton decays gravitationally into normal and shadow matter. 4) The fate of massive shadow states may be of cosmological interest, and if any of the limits are saturated, massive shadow states could make an important contribution to the present mass density of the Universe.

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References

1. For a general review, see M. Green, Nature 314, 409 (1985).

2. D. Gross, J. A. Harvey, E. Martinec and R. Rohm, Phys. Rev. Lett. 54, 503 (1985).

3. For a more detailed treatment of the shadow world, see E. W. Kolb, D. Seckel and M. S. Turner, Nature 314, 415 (1985).

4. Here, we assume that the shadow matter is self interacting, *i.e.*, that $n_S\sigma|v| > H$, where n_S is the density of shadow matter and $\sigma|v|$ is the interaction cross section of shadow matter with shadow matter.

5. Ya. B. Zel'dovich and I. Novikov, *Relativistic Astrophysics Volume 2* (University of Chicago Press, 1983).

6. P. J. E. Peebles, *The Large-Scale Structure of the Universe* (Princeton University Press, 1980).

7. The shadow matter would not respond to a seismic shock produced by ordinary matter.

8. The g_{eff} limit is usually presented as a limit on the number of neutrinos. For the detailed calculations, see Y. Yang, M. S. Turner, G. Steigman, D. N. Schramm, and K. A. Olive, Ap. J. 281, 493 (1984).

9. P. Candelas, G. Horowitz, A. Strominger and E. Witten, "Vacuum Configurations for Superstrings" preprint 1985.

10. Even in the mirror Universe case, inflation can in general occur at different epochs due to the random nature of the commencement of inflation.

11. S. Wolfram, Phys. Lett. 82B, 313 (1979); G. Steigman, Ann. Rev. Nucl. Part. Phys. 29, 313 (1979).