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Mirror matter and other dark matter models

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Contents

Abstract. **This brief review discusses the role of the mirror matter (MM) model in the context of the dark matter (DM) problem. First proposed in 1966 by Kobzarev, Okun, and Pomeranchuk, MM is the oldest but still viable candidate — admittedly with some modifications — for describing real DM. The difficulties of the standard ΛCDM model with WIMPs (weakly interacting massive particles) are outlined, and situations where mirror matter could be helpful in resolving some of them are identified. Mirror particles are a subclass of a wider set of ADM (asymmetric DM, where DM particles do not annihilate, unlike supersymmetric particles in ΛCDM). References on limits for cross sections of ADM model bosons accreting onto neutron stars are provided. They can be much lower than the experimental limits for WIMPs.**

1. Introduction

A hypothesis of the presence of dark matter (DM) in the Universe (German: Dunkle Materie, DM hereafter) was put forward by Fritz Zwicky in 1933 [1]. In that paper, Zwicky revealed a virial paradox in Coma cluster of galaxies (in the constellation Coma — Coma Berenices) and suggested the presence of 'dunkle Materie' in the cluster. Very soon, just after the paper by Einstein [2] on gravitational lensing (already discussed 12 years earlier by Chwolson [3] for ordinary stars), Zwicky proposed that the presence of DM can be tested by the effect of gravitational lensing [4, 5], which we now call macrolensing.

For investigations of DM, it is very important to study the rotation curves of galaxies, which was also first proposed by Zwicky [6], and soon thereafter the missing mass was found in the M31 (Andromeda) galaxy [7].

But Zwicky's seminal ideas and papers were almost forgotten for half a century, and the rediscovery of DM occurred only decades later, in the 1970s. At that time, this idea was much more popular in the USSR than in the West, where it was accepted only after strong resistance (see the review by Einasto [8]). The problem of hidden or dark mass in galaxies became acute because of the mismatch of direct (kinematic) and indirect (photometric) estimates of the mass of galaxies (and their systems) [9]. The need in DM also became clear after the discovery in X-rays of a huge amount of hot gas (with a temperature of the order of 1 keV) in clusters of galaxies. The hot gas cannot be trapped by the gravity of visible baryons.

Fluctuations of the cosmic microwave background (CMB) tell us that in the recombination epoch, the perturbations of baryonic matter were very small: for the redshift $z = z_{\rm rec} \approx 10^3$, they had a level of $\sim 10^{-5}$. This means that as our epoch was approached, they could grow only as a scale factor, i.e., as $(1 + z_{\rm rec}) \sim 10^3$, and now, at $z = 0$, we would obtain not more than 1% of density fluctuations, which drastically contradicts the observed structure. If DM dominates in gravity, it could have a larger amplitude of perturbations at the time of recombination, and the 'dark matter boost' could lead to structure formation in visible matter (see, e.g., [10]). The DM 'gas' should be nonrelativistic (cold); otherwise, the structure would be smeared. The basic model for DM assumes cold dark matter (CDM).

The technique for investigating DM has been developed not only for gravitational macrolensing but also for 'microlensing' and 'weak lensing' [11–15] (see review [16]).

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2. First dark matter model: the paper by Kobzarev, Okun, Pomeranchuk (1966)

Paper [17] actually suggested the first model for DM. This seminal article by Kobzarev, Okun, and Pomeranchuk was published in 1966, when physicists could not have even known that dark matter would soon become one of the most important questions in cosmology and elementary particle physics. The authors had another motivation: they sought to show how broken *CP*-symmetry can be restored. In that paper, it was shown that if there are 'mirror' particles restoring the *CP* symmetry, they can interact with conventional particles only very weakly. This is exactly what is needed to explain dark matter.

Here are a few detailed quotations from this remarkable article.

The abstract of [17]:

"In connection with the discovery of *CP* violation in the decay $K_2^0 \to 2\pi$, the possibility is discussed that 'mirror' (R) particles exist in addition to ordinary (L) particles. The introduction of these latter particles reestablishes the equivalence of left and right. It is shown that mirror particles cannot interact with ordinary particles strongly, semistrongly, or electromagnetically. Weak interactions between L and R particles are possible, owing to the exchange of neutrinos. L and R particles must have the same gravitational interaction. The possibility of the existence and detection of macroscopic bodies (stars) made up of R-matter is discussed."

The central point in [17] is a proof of the weakness of common electromagnetic interaction of mirror and ordinary particles:

"We start with the case of a common electromagnetic interaction for the two kinds of particles. In this theory there should exist two kinds of π^0-mesons: π_L^0 and π_R^0 ($\pi_R^0 = -CPA\pi_L^0$). In the presence of a common photon, the following transition is possible:

$$\pi_R^0 \rightleftarrows 2\gamma \rightleftarrows \pi_L^0 .$$

This will give rise to two states,

$$\pi_1^0 = \frac{1}{\sqrt{2}}(\pi_R^0 - \pi_L^0)\,, \qquad \pi_2^0 = \frac{1}{\sqrt{2}}(\pi_R^0 + \pi_L^0)\,,$$

where π_1^0 is even under *CPA* (odd under *CA*), and π_2^0 is odd under *CPA* (even under *CA*). We shall assume that the electromagnetic interaction is even under *CPA* and *P*, and thus also under *CA*, but is not necessarily even under *C* [18, 19].[1] By assumption, a γ-(photon) transforms into itself under *CA*. Then the π_1^0 state, which has odd *CA*, cannot decay into two photons, real or virtual, but can decay into three photons. Since the width of such a decay is small, this π_1^0 meson would be long-lived, in contradiction to experiments."

It was also shown in the paper that common strong interaction is impossible. The conclusion was rather pessimistic:

"The main conclusion of the present paper, consisting of the possibility of only a very weak interaction between mirror matter and ordinary matter and that the upper bound for the concentration of mirror matter in the solar system is small, does not add to the attractiveness of the hypothesis of the existence of mirror matter."

[1] Studies cited in the quotations have been added to the list of literature in this paper, and are referred to as such. (*Editor's note*.)

3. Problems that arose after the paper by Kobzarev, Okun, and Pomeranchuk (1966)

In fact, Kobzarev, Okun, and Pomeranchuk [17] suggested the first model for DM, which may contain invisible stars. As noted above, even astronomers, to say nothing about physicists, were aware of the severity of the DM problem. The issue soon became urgent in astronomy, when predictions of supersymmetric particles and axions appeared in physics. Currently, there is a large flow of papers on CDM consisting of WIMPs. Not so much work is published on mirror matter (MM). Nevertheless, the hypothesis of the existence of MM is still attractive in the study of DM.

Below, we briefly discuss some facts about DM and related issues.

3.1 Who introduced the hidden sector into DM?

It is often written that mirror particles were introduced by Lee and Yang in 1956 [20] (see, e.g., a recent paper by Pavšič [21]). Okun himself wrote in his review of 1966 [22] in *Physics–Uspekhi*: "The hypothesis of existence of mirror particles was put forward in paper [20] (see also Lewis Carroll's *Through the Looking-Glass, and What Alice Found There*) and was discussed in detail in [17]."

In reality, Lee and Yang [20] introduced the concept of right-handed protons, but their 'R-matter' was not hidden (!), as some recent papers claim (see, e.g., [23]).

An exact quotation from [20] is as follows:

"... the interaction between them is not necessarily weak. For example, p_R and p_L could interact with the same electromagnetic field and perhaps the same pion field. They could then be separately pair-produced, giving rise to interesting observational possibilities."

Thus, Lee and Yang write explicitly about the possibility of direct electromagnetic and strong interactions between left- and right-handed protons, while Kobzarev, Okun, and Pomeranchuk showed that this is impossible. They demonstrated that the mirror particles 'live' in a hidden sector within which the microphysics is the same as in the visible sector. The terms 'mirror particles' and 'mirror matter' were also first introduced in [17]. We can mention the article of their predecessors, Nishijima and Saffouri [24], who discussed the idea of a 'shadow Universe'. Okun and Pomeranchuk [25, 26] showed that the model of the shadow universe proposed in [24] was in sharp conflict with neutrino experiments. The existence of 'shadow' K_1^0-mesons, which should have high penetrating power, was ruled out by the data obtained in the neutrino experiment at CERN, where no abnormal particles with properties similar to the shadow K_1^0-mesons were revealed behind the protection (25 m of iron).

On other ways of arriving at the concept of MM from various considerations, see [27, 28].

3.2 Literature on MM in recent years

A detailed review of the status of the MM problem as of 2007 is given by Okun in [29]. An optimistic view of the problem is offered by Silagadze [30]. Many papers have been published by Foot (see, e.g., [31, 32]); of the most recent publications, we note [33]. That paper explains how galaxies formed structure, taking the dissipation in MM into account.

An interesting development of the model in terms of fundamental physics is given in the series of papers [34–36].

The model of mirror particles is discussed in [37] in the context of asymmetric DM (ADM); see more about ADM below in Section 3.6.

Ciarcelluti published a review [38] where he discusses the growth of perturbations, CMB, and large-scale structure formation, taking MM into account as DM (see the paper by Berezhiani et al. on this topic [39]).

On astrophysical aspects, in particular on the heating of neutron stars by MM particles [40], see also review [41].

3.3 Possible models for DM

There are many candidates for DM particles, and those discussed in most detail are the following:

- WIMPs: supersymmetric particles (neutralinos for heavy or gravitinos for lighter particles) and their clouds;
- axion-like particles and objects;
- mirror particles and objects; this model is not as popular now as the two above, but it is the oldest of all the proposed models and it is still surprisingly useful.

To date, no reliable signals have been found in underground laboratories aimed at detecting WIMPs. This has stimulated the search for alternatives to WIMPs (see Section 3.6), including MM.

Neutralinos and axions have electromagnetic interactions (on a weak scale). Mirror matter in its pure form is not involved in electromagnetic interactions with ordinary matter (OM) (or in other interactions of the Standard Model). We share only common gravity. Mirror matter has analogues with all 'our' interactions in the mirror sector. In addition to these models of MM, there are options for models with a slightly broken mirror symmetry, which have a weak electromagnetic coupling with OM (see, e.g., [31, 32]). The richness of other opportunities and oscillations is discussed in [42].

We briefly list some predictions about the possible properties of MM in the 'pure' form, without the admixture of electromagnetic interactions or oscillations.

— Basically, MM is able to replace CDM in the cosmological evolution [43–45] if $T_{\rm MM} < 0.3T_{\rm OM}$ in the early Universe.

— MM baryons can form compact objects of stellar masses and sizes.

— Mirror stars should be invisible, but should display the effect of microlensing (see Section 3.4).

— Due to a lower $T_{\rm MM}$, a larger fraction of mirror helium is produced in cosmological nucleosynthesis than in OM helium; hence, stellar evolution is faster, and the proportion of MM intergalactic gas may be lower than in OM.

— There are possibly life and intelligence in MM [29].

3.4 Microlensing: end of the MACHO era?

Invisible stars can be found by the effect of gravitational microlensing, which may be caused by both visible and invisible stars. Those objects are now called MACHOs for massive astrophysical compact halo object. This phenomenon was first discussed in relation to MM by Berezhiani, Dolgov, and Mohapatra [46] and Blinnikov [47].

3.4.1 MACHO, EROS, AGAPE, MEGA, OGLE: contradicting results. The MACHO group [48] has revealed 13–17 microlensing events in the Large Magellanic Cloud (LMC), a significantly higher number than expected from known stars. Not all DM in the halo may be in MACHOs, but only a fraction, usually denoted by f. The MACHO group concluded that compact objects in the mass range $0.15M_\odot < M < 0.9M_\odot$ have a fraction f in the DM halo at the level $0.08 < f < 0.50$ (95% CL).

Bennett [49] concluded (based on the results of the MACHO group) that MACHOs have indeed been found.

The EROS (Expérience pour la Recherche d'Objets Sombres) collaboration has placed only an upper bound on the halo fraction, $f < 0.2$ (95% CL), for objects in this mass range, while EROS-2 [50] gives $f < 0.1$ for $10^{-6}M_\odot < M < 1M_\odot$.

The AGAPE collaboration [51], working on microlensing in the M31 (Andromeda) galaxy, found the MACHO halo fraction in the range $0.2 < f < 0.9$, while the MEGA group marginally conflicts with them, having found the upper bound $f < 0.3$ [52].

A detailed analysis of the controversy among the results of the different groups is given in [53]. Newer results [54] for EROS-2 and OGLE (Optical Gravitational Lensing Experiment) in the direction of the Small Magellanic Cloud claim $f < 0.1$, obtained at a 95% confidence level for the MACHO with a mass of $10^{-2}M_\odot$ and $f < 0.2$ for the MACHO with a mass of $0.5M_\odot$.

Recent data on other aspects of microlensing are discussed in [55].

3.4.2 Destruction of wide pairs of visible stars. Evans and Belokurov [56] criticize some papers in the series "End of MACHO era (1974–2004)". Paper [57], which appeared in this series, asserts that wide pairs of visible stars must be destroyed by invisible MACHOs flying near them. In addition to the criticism in [56], we can point out that it is necessary to consider not only the process of destruction but also the reverse process of creating pairs of visible stars from single individual stars not previously bound by mutual gravitation.

The probability of microlensing [13, 58] is naturally measured by the so-called optical depth τ. Evans and Belokurov [56] confirmed a lower number of compact objects in the direction of the LMC than the number obtained by the MACHO group, i.e., they obtained $\tau < 0.36 \times 10^{-7}$, in agreement with EROS results [50]. Later, a paper by the same Cambridge group [59] was published where, based on the studies of binary stars, arguments in favor of the real existence of MACHOs and against the pessimistic conclusions in [57] were put forward.

The total DM halo mass in the Galaxy cannot be explained by invisible stars; therefore, it is more likely that DM consists of combinations like CDM + MM or WDM + MM, where WDM (warm dark matter) may consist, for example, of sterile neutrinos (with a mass of a few keV) or gravitinos (see, e.g., [60, 61]).

3.5 Constraints on DM particle cross sections from observations of clusters of galaxies

3.5.1 'Bullet' cluster 1E0657-56. The cluster of galaxies 1E0657-56 ('Bullet' cluster) is formed as a result of a collision of two clusters. This is clearly seen in X-ray images. The observations of this cluster give important clues toward the proof of the reality of DM. It is difficult to explain the observations in terms of alternatives to DM like modified gravity (MOND or MG). It is clear that the hot X-ray emitting gas that dominates the baryon mass in the cluster is shifted from the DM distribution in this cluster. The baryon mass is traced by the effect of gravitational lensing and follows the distribution of stars and galaxies (which are effectively a collisionless gravitating gas).

Many physicists tend to use this example as a direct proof of a small cross section of the self-interaction of DM particles. In reality, it proves only what is observed and nothing more: DM behaves like ordinary stars that interact only via gravity and form collisionless matter. But, of course, O-stars are made of strongly and electromagnetically interacting particles. The same may be true of the DM component.

3.5.2 Cluster MACS J0025.4-1222. This cluster is very similar to the Bullet cluster. It is found there that the DM self-interaction cross section satisfies the bound $\sigma/m < 4\ \mathrm{cm}^2\ \mathrm{g}^{-1}$ [62]. For particle masses in the GeV range, this limit is lower than for collisions of ordinary atoms. But this limit would be true for DM particles only if they do not form bound objects! If in DM there is anything like our normal solid bodies, say, ice with a density of about 1 g cm^{-3} with the size r larger than a few cm, then this limit is very well satisfied ($\sigma \propto r^2$, while mass is proportional to r^3).

Hence, if the properties of DM particles are similar to the properties of our particles, and they are able to form stars, planets, asteroids, etc. (e.g., like MM), then all observations of the merging clusters are reproduced. However, we have to squeeze a major fraction of MM particles into those compact objects, not leaving a large fraction in the form of gas as we have in OM in clusters of galaxies, where the O-gas dominates in the baryon component.

3.5.3 DM in the Abell 520 cluster. Dark matter in the Abell 520 cluster is difficult to explain in the CDM model with WIMPs. In contrast to the Bullet cluster, the lensing signal and the X-ray emission here coincide, and are both shifted away from galaxies, indicating that DM is collisional as in the O-gas: "... a mass peak without galaxies cannot be easily explained within the current collisionless dark matter paradigm" [63]. We may reproduce this behavior by leaving a major fraction of DM in the form of gas in MM models. Mirror matter models are richer than the WIMP-based DM models, they "are more flexible and for them the diverse behavior of the dark matter is a natural expectation" [30].

3.6 Difficulties of the CDM model, limits from underground experiments and ADM models

Arguments in favor of the model that is the most popular at the moment — ΛCDM (cold dark matter) — are strong. For example, Sandage [64] already studied the influence of the local group of galaxies on the velocity field. According to current research, clearly visible traces of the DM infall in the local group are found in the distance–speed phase plane [65–67] that are in accordance with the predictions of the ΛCDM model.

Difficulties of the ΛCDM model are discussed by Dolgov in this issue of *Physics–Uspekhi*. In particular, one of the problems is the lack of dwarf satellite galaxies of large galaxies. The CDM model predicts an order of magnitude more satellites of galaxies than observed. The CDM theory predicts, moreover, a singular distribution of matter in the centers of galaxies, with a sharp cusp. It is believed that in reality there is a shallow (cored) profile in the center, although the situation is not yet obvious in observations [69].

Interesting results have been obtained at SAO [70–72] on the voids in the surrounding space, and on the lack of DM near our Local Group of galaxies. This is not easy to understand in the ΛCDM model.

Many other problems in addition to these are discussed in [73]. For example, satellites of our Galaxy and M31 tend to form disk distributions. Contrary to this observation, the CDM model predicts an isotropic random distribution of orbits, while MM can resolve this problem (see the discussion in [74]).

3.6.1 Underground detectors. Currently, there are several working installations aimed at the direct detection of WIMPs, including CDMS (Cryogenic Dark Matter Search), DAMA (DArk MAtter), Xenon, and LUX (Large Underground Xenon dark matter experiment). For a review of the methods, facilities, and other references, see, e.g., [75, 76].

Recent results of the LUX detector [77] give the strongest limits on the DM cross sections. At a confidence level of 90%, the minimum upper limit on the elastic scattering cross section of WIMPs on nucleons is $7.6 \times 10^{-46}\ \mathrm{cm}^2$ at the WIMP mass 33 GeV. This result has overrun all other limits and hints of WIMP detection in other detectors. It is a powerful impetus for the development of models having particles very weakly interacting with ordinary nucleons. MM is exactly such a kind of model.

3.6.2 Asymmetric dark matter. The density of relic WIMPs in the conventional CDM models is explained by freeze-out in the expanding hot universe with a proper choice of their masses and annihilation cross sections [78, 79]. Models of asymmetric dark matter (ADM) are based on a very different assumption: they assume that asymmetry in the density of DM particles and antiparticles is generated in the hot universe, similarly to the baryon–antibaryon asymmetry of ordinary matter [37, 80]. This class also includes MM because mirror baryons should be as asymmetrical to mirror antibaryons as our ordinary baryons are to ordinary antibaryons. In light of the strong constraints obtained in the LUX experiment [77], the MM model becomes attractive, because mirror baryons should not give any signals in underground detectors.

Other options for ADM models are also being explored, for example, the boson ADM is considered in detail in [37, 80, 81]. There are nonzero cross sections, but they may be well below the LUX limits. Strong constraints on the ADM boson are obtained when ADM bosons accreting onto a neutron star are considered, because the maximum mass of a cold boson star is m_{Pl}/m times smaller than the Chandrasekhar limit for fermion stars [82]. Here, m_{Pl} is the Planck mass and m is the particle mass, defining self-gravitation of the star. If the boson mass m is of the order of 1 GeV, the mass limit is 19 orders of magnitude smaller than the mass of the Sun. The accumulation of such a small number of ADM bosons inside a neutron star may lead to black hole formation in its center, which would eventually 'eat' the whole neutron star. This allows obtaining strong limits on the cross section of ADM bosons [81].

A review of different DM models with new physics is given, for example, in [83].

4. Conclusions

There are still several arguments motivating the mirror matter search.

— WIMPs (weakly interacting massive particles) have not yet been discovered.

— Properties of DM particles with respect to clustering on stellar-size and mass scales are unknown.

— Microlensing: there is a lack of normal stars to explain all MACHO events (although the total mass of the DM halo cannot be explained by invisible stars).

— Clusters of galaxies like Abell 520, which are difficult to explain in the pure CDM picture, do exist [30].

— Other difficulties of CDM, which can be resolved in the MM model [74].

— New kinds of mysterious transients, like those reported in [84], may be explained by MM objects [40].

Finally, we can draw several conclusions:

• mirror matter is still a useful model of DM, which shows how rich the world can be structured in the DM sector;

• observations of microlensing are not yet in full agreement, but it is clear that the Milky Way DM halo can contain no more than $\sim 20\%$ of its mass in invisible stars.

• calculations of the perturbation growth at the linear stage based on MM have been carried out: MM can give data on the growth of perturbations in baryonic matter structures [43–45], but this awaits an independent check.

• we cannot use the bounds on cross sections of individual self-interacting DM particles obtained from observations of colliding clusters: such particles can form macroscopic bodies that behave like a collisionless gas.

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