Mirror dark matter discovered?

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Recent astrophysical data indicates that dark matter shows a controversial behaviour in galaxy cluster collisions. In case of the notorious Bullet cluster, dark matter component of the cluster behaves like a collisionless system. However, its behaviour in the Abell 520 cluster indicates a significant self-interaction cross-section. It is hard for the WIMP based dark matter models to reconcile such a diverse behaviour. Mirror dark matter models, on the contrary, are more flexible and for them diverse behaviour of the dark matter is a natural expectation.

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1. Introduction

The evidence of dark matter is compelling at all observed astrophysical scales [1,2]. At that the dark matter reveals itself only through its gravitational interactions. There are no observational facts that indicate existence of any significant interactions between the ordinary and dark matter particles. However, some recent astrophysical observations show that dark matter particles may have significant self-interactions. This is surprising because other observations support the WIMP paradigm that the dark matter is essentially collisionless. The mirror dark matter [3,4,5], first introduced in [6], has a potential to reconcile these seemingly contradictory observational facts. For other attempts to do this, on the base of BEC dark matter, see [7]. Below, after briefly commenting the mirror matter idea, we consider the above mentioned observational facts and argue why, in our opinion, they indicate the existence of the mirror matter as the main dark matter component.
2. Mirror matter

One of characteristic features of our present day increasingly shallow postmodern culture is the existence of a “literature horizon” beyond which many interesting results of the past have fallen. “References familiar to one generation are often less so or unknown to the successive one, an effect which increases with the passage of time” [8].

It is still widely known that in their famous article [9] Lee and Yang revealed “The fact that parity conservation in the weak interactions was believed for so long without experimental support” [10] and hypothesized the possibility of parity non-conservation in the weak interactions. The hypothesis turned out to be true, as the subsequent experiments had shown, and nowadays it is a firmly established fact that our universe is left-handed as far as the weak interactions are concerned.

What is not so widely known is the fact that at the end of the very same paper Lee and Yang indicated how left-right symmetry of the world could be rescued by duplicating the non-symmetric part of our left-handed universe in the mirror.

It is a futile business to establish priority in the genesis of physical ideas. Seldom a good physical idea is already mature at the time of its first appearance and, as a rule, many people participate in its subsequent developments.

In a very postmodern fashion, we can deprive Lee and Yang priority of the mirror matter idea and attribute it, for example, to Lewis Carroll. To paraphrase his Alice Through the Looking Glass, “the mirror particles are something like our particles, only the chiralities go the wrong way . . .” [11].

Jorge Luis Borges, famous Argentine poet, essayist, and short-story writer, with his classic tales of fantasy and dreamworlds, is another candidate to whom the idea of duplication of the world through mirrors could be attributed. Berezinsky and Vilenkin cite [12] somewhat incomplete quote from Borges: “The visible universe is an illusion. Mirrors . . . are hateful because they multiply it”. We found that it appears in the short story of Borges Tlön, Uqbar, Orbis Tertius, written in 1940, and in the complete form has somewhat different accents, going like this: “For one of those gnostics, the visible universe was an illusion or (more precisely) a sophism. Mirrors and fatherhood are abominable because they multiply and disseminate that universe” [13].

However, the most complete and clear explanation of the mirror matter idea is provided by 1946 lithograph print “Magic Mirror” of famous Dutch artist M. C. Escher (see Fig.1). Our world is presented at this lithograph as a left-handed procession of small griffins (winged lions). Griffins are symbols of ordinary particles which participate in the left-handed (V-A) weak
interactions. Interactions between ordinary particles are governed by the
Standard Model gauge group $G = \text{SU}(3) \times \text{SU}(2) \times \text{SU}(1)$ (or by its Grand
Unification or supersymmetric extension). The corresponding gauge bosons
are indicated at the lithograph, perhaps, by a small solid sphere around
which the griffins’ procession goes on. This part of the universe (lithograph)
is clearly not mirror-symmetric (parity is violated in our world). However,
when reflected in the mirror it gives a birth of the mirror partners of every
ordinary particle including the gauge ones. Mirror griffins participate in a
right-handed procession around the mirror copy of the the Standard Model
gauge group $G' = \text{SU}'(3) \times \text{SU}'(2) \times \text{SU}'(1)$. Mirror weak interactions are
right-handed $(V+A)$ and in overall the mirror symmetry of the universe
(lithograph) is restored.

Fig. 1. Mirror matter idea illustrated by M. C. Escher’s lithograph ‘Magic Mirror’.

As we see, the idea of Mirror World was already presented in fiction
literature and art when Lee and Yang gave the beginning of the physical
incarnation of the idea which immediately had fallen beyond the literature
horizon. After a decade, Kobzarev, Okun and Pomeranchuk, influenced by
the Landau’s idea of combined parity and subsequent experimental discovery
of CP-violation, dug out the mirror matter concept from the literature
horizon and gave it the first serious phenomenological consideration \[6\]. This
paper marked the real beginning of the mirror matter story. It was argued
that almost all elementary particles should be duplicated (with possible
exclusion of some neutral particles) and that the mirror particles can not
have common strong and electromagnetic interactions with ordinary particles. The concepts of “Mirror Matter” and corresponding invisible “Mirror World” (after Lewis Carroll’s *Alice Through the Looking Glass*), as complex as our own world, were introduced in this work for the first time and observational effects of the mirror matter were investigated. Some further investigations of possible astrophysical effects of the hidden sector particles followed [14, 15, 16], but the idea was still not far from the literature horizon until it was rediscovered in the modern context of renormalizable gauge theories by Foot, Lew and Volkas [17] and used in the context of neutrino oscillations [18, 19].

Okun’s recent review [20] cites more than 250 references related to the mirror matter idea and we hope that it remains outside the literature horizon. However the idea is still little known to the majority of physicists, oriented at the mainstream.

3. Empirical evidence of dark matter from the bullet cluster

Galaxy clusters are the largest gravitationally constrained structures sitting atop of the hierarchical structure formation in the universe [21, 22]. Because of their size, their matter content resembles the matter content of the Universe with the dark matter as the major mass component (about 85%). Two other main ingredients of a typical cluster are stars which are grouped to form member galaxies (about 5% of the total cluster mass) and very hot (virialized) intergalactic gas (about 10%).

This three components behave differently when two galaxy clusters collide. Note that merger events are typical for hierarchical structure formation and drive the formation of larger systems from the smaller ones. However, at the scale of galaxy clusters mergers are rather rare events. Nevertheless several interesting merger events were observed recently which constitute fascinating laboratories to study dark matter behavior under these titanic collisions. Most dark matter theories predict that self-interaction of the dark matter particles (WIMPs) are very feeble and, therefore, dark matter is collisionless.

Then it is expected that the dark matter components of the colliding clusters do not perturb much each other during the collision allowing them to pass right through. The stars in the member galaxies also form collisionless system because stars are sparse and star collisions are rare. Therefore, during the collision it is expected dark matter to follow the galaxies and these two components of the cluster should stay together even after the collision, while the third component (hot intergalactic gas) having strong electromagnetic self-interaction should lag behind near the collision center and show signs of hydrodynamic disturbances like shock waves formed as a
result of supersonic collisions of gas components of colliding clusters.

This is precisely what is observed in the Bullet Cluster, more formally known as 1E0657-56. Fig. 2 is a composite image of this cluster. The Hubble Space Telescope and Magellan optical image shows cluster’s member galaxies in orange and white. The distribution of hot intergalactic gas is traced by Chandra X-ray observations and is superimposed on the image in pink. The dark matter component of the cluster can not be seen neither in optical nor in X-rays, but it can be revealed by gravitational lensing which leads to the distortion of images of background galaxies. The distribution of the dark matter (unseen concentration of mass) found by gravitational lensing studies is indicated in blue in Fig. 2.

Fig. 2. Dark matter in the Bullet cluster.

We see that the galaxies and the corresponding dark matter clumps stay together and the pink clumps lag behind. Besides, a classic bow-shaped shock wave is clearly seen on the right in the pink image of the smaller cluster hot gas component giving it a bullet-like appearance.

We can conclude, therefore, that the Bullet cluster constitutes the first direct empirical evidence in favor of dark matter [23]. At first sight, all these are good news for WIMP based dark matter models. Especially if we take
into account that the similar behavior was also observed in other merging galaxy clusters CL 0152-1357 [24] and MS 1054-0321 [25]. In latter case the dark matter clumps seem to be offset not only from the corresponding X-ray peaks but also from the galaxy counterparts, as if they were moving ahead of the cluster galaxies. Therefore, in this particular case, the dark matter behaves as effectively more collisionless than the cluster galaxies. Another interesting peculiarity of MS 1054-0321 is that there is no associated X-ray peak in the eastern region where the weak-lensing and luminosity map reveal significant mass concentrations [25]. This maybe indicates that most of the intracluster gas of the eastern clump has been stripped by RAM pressure while passing through the denser regions of the colliding cluster [25].

4. Dark matter in the Abell 520 cluster

Matters are not so simple, however. Observations of another merging galaxy cluster Abell 520 (see Fig.3) seem to be puzzling for WIMP dark matter theories [26].

Fig. 3. Dark matter in the Abell 520 cluster.

As expected, X-ray emission is offset from the galaxy distribution. However, in contrast to the Bullet cluster, the lensing signal and the X-ray emission coincide and lag behind the galaxies indicating that the dark matter is
collisional like the ordinary gases. The inferred estimate on the dark matter self-interaction cross section is well above the upper limit derived for the Bullet cluster and exceeds by many orders the cross section magnitude expected for WIMPs [26].

Certainly, mirror dark matter “is richer than the dark matter of SUSY” [20] and has a better chance to be reconciled with these contradictory astrophysical observations.

It is important to realize that at macroscopic level mirror and ordinary matters are expected to behave differently [27, 28] because the nucleosynthesis bounds demand the mirror sector to have a smaller temperature than the ordinary one and hence a different cosmological evolution.

In particular, mirror stars should be helium dominated and evolve faster than the ordinary ones [29]. Consequently, mirror supernova rate is expected to be larger and star formation more efficient in the mirror sector due to shock waves related to the supernova explosions. As a result, we expect mirror galaxies to contain less gas compared to the ordinary galaxies [29]. Nevertheless some fraction of mirror gas will be inevitably present.

In case of the mirror dark matter, therefore, we expect diverse behavior during galaxy cluster collisions, as diverse as for the ordinary matter. At that a typical cluster of mirror galaxies is expected to be less gas dominated than its ordinary counterpart leading, therefore, to the Bullet cluster like behavior. However, other atypical possibilities like Abell 520 is also not excluded.

5. Further evidence that dark matter behaves like ordinary matter

Could we find other indications that dark matter behaves like ordinary matter forming a diversity of structures? One possible candidate is a remarkable discovery of a ringlike dark matter structure in the galaxy cluster Cl 0024+17 [30]. This galaxy cluster is like the Bullet cluster but viewed along the collision axis at a much later epoch [30]. Fig.4 is a composite image of Cl 0024+17 with reconstructed distribution of the dark matter indicated in blue. A huge dark matter ring of 2.6 million light-years across is clearly seen.

For ordinary matter, ringlike structures are common output of violent collision events both at the scale of galaxies and at the scale of galaxy clusters. For example, Very Large Array radio telescope discovered recently a giant ring-shaped radio-emitting structures of about 6 million light-years across around the galaxy cluster Abell 3376 [31] probably resulting from the megaparsec scale cosmic shock waves associated to the violent collisions of smaller groups of galaxies within the cluster.
A mechanism how ringlike structures can be formed during collisions was suggested by Lynds and Toomre [32] many ears ago. When a compact intruder approaches with a small impact parameter in a nearly head-on collision to a victim galaxy, the stars of this galaxy, assumed to be in circular orbits before the collision, experience inward fall due to extra gravity. As the intruder moves away, extra gravity disappears and perturbed stars rebound outward eventually. At that stars at smaller radii rebound faster and, as a result, stars still moving inward meet rebounders moving outward. The final outcome all of this is a ring-shaped compression wave propagating outward [33, 34].

If the dark matter ring in Cl 0024+17 is created only because of gravitational disturbances during the collision, in the manner of Lynds and Toomre, it is expected the spatial distribution of cluster galaxies to possess the similar ringlike feature. However a detailed dedicated study found no such substructure in the projected two-dimensional galaxy distribution [35]. This indicates that probably dark-matter self-interactions and associated shock waves played an important role in the formation of the observed dark matter ring.
On the other hand, the fact that the ring has not been erased in about 1-2 Gyr after the core impact indicates very small collisional cross-sections of dark matter particles, much smaller than expected for ordinary plasma [30].

The mirror dark matter hypothesis readily explains this seeming contradiction in the behavior of the Cl 0024+17 cluster dark matter. The shock wave propagated in the mirror gas of the cluster leads to the intense burst of mirror star formation transforming the dark matter ring into the effectively collisionless system of mirror galaxies.

This example also indicates how the ordinary and mirror matters could to be separated even at galactic scales: mirror galaxies in the dark matter ring of Cl 0024+17 should be composed predominantly by mirror matter. The existence of purely dark matter galaxies with negligible admixture of ordinary matter, as well as ordinary galaxies without dark matter, can therefore be envisaged. Interestingly, both dark galaxy [36, 37] and ordinary galaxy without dark matter [38] were presumably discovered.

6. Hoag’s object

Fig[5] shows a very interesting ring galaxy, the so called Hoag’s object [39]. Yellow spherical nucleus of old stars is surrounded by a nearly perfect ring of hot blue stars. How this ring was formed is a mystery. Usually ring galaxies are formed by the collision of a small galaxy with a larger disk-shaped galaxy through the Lynds and Toomre density wave mechanism. However, in the case of the Hoag’s object there is no sign of any intruder galaxy nearby.

Curiously, an object is seen inside the Hoag’s object’s image which looks like a another ring galaxy much like to the Hoag’s object itself. Having in mind the estimated minuscule fraction, $10^{-3}$, of Hoag-type galaxies [40], this seems to be an incredible coincidence. Maybe this odd cosmic irony offers a clue about the nature and formation history of the Hoag’s object.

Suppose the intruder galaxy which led to the ring formation was a mirror galaxy. Then we do not expect it to be visible but it should be lurking somewhere there and can reveal itself by its gravitational influence, in particular by gravitational lensing of background galaxies suitably aligned behind it [41, 42].

What if the smaller ring-galaxy-like structure inside the Hoag’s object is the result of the gravitational lens of some distant background galaxy due to the gravitational field of the mirror galaxy?

Note that Hoag himself considered a hypothesis that the ring of the Hoag’s object is a gravitational lensing event caused by the gravity of Hoag’s object’s core [39]. The hypothesis was discarded because it required inordi-
nately high mass for the core of the Hoag’s object, $1.4 \times 10^{13} M_\odot$ \cite{39,43}, while the inferred mass of the Hoag’s object is only $7^{+5}_{-3} \times 10^{11} M_\odot$ \cite{40}.

Nowadays we firmly know that the Hoag’s object’s ring is real, of course, but one cannot be so sure about the much smaller duplicate ring inside. The apparent size of the secondary ring is a factor of twenty smaller than the size of the main ring. The radius of the Einstein ring is proportional to the square root of the lensing mass \cite{42}. Therefore, the required lensing mass which can produce the Einstein ring of the angular size of the secondary ring is $1.4 \times 10^{13} M_\odot/20^2 \approx 3.5 \times 10^{10} M_\odot$, maybe just a correct mass for the putative projectile for the Hoag’s object formation.

7. Conclusions

There is a growing astrophysical evidence of diverse behaviour of dark matter in galaxy cluster collisions. These observations indicate that the mirror dark matter models deserve careful examination and observational verification. If the mirror dark matter were as popular as the SUSY dark
matter, we would say that it is already discovered. However, it would be more fair to conclude that we need more observational evidence to firmly prove this fascinating conjecture.

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REFERENCES

[1] V. Trimble, Existence and Nature of Dark Matter in the Universe, Ann. Rev. Astron. Astrophys. 25, 425 (1987).
[2] G. Bertone, D. Hooper and J. Silk, Particle dark matter: Evidence, candidates and constraints, Phys. Rept. 405, 279 (2005) [arXiv:hep-ph/0404175].
[3] H. M. Hodges, Mirror baryons as the dark matter, Phys. Rev. D 47, 456 (1993).
[4] R. Foot, Mirror matter-type dark matter, Int. J. Mod. Phys. D 13, 2161 (2004) [arXiv:astro-ph/0407623].
[5] Z. Berezhiani, P. Ciarelluti, D. Comelli and F. L. Villante, Structure formation with mirror dark matter: CMB and LSS, Int. J. Mod. Phys. D 14, 107 (2005) [arXiv:astro-ph/0312605].
[6] I. Yu. Kobzarev, L. B. Okun and I. Ya. Pomeranchuk, Sov. J. Nucl. Phys. 3, 837 (1966).
[7] J. W. Lee, S. Lim and D. Choi, BEC dark matter can explain collisions of galaxy clusters, [arXiv:0805.3827] [hep-ph].
[8] R. T. Jantzen, P. Carini and D. Bini, Gravitoelectromagnetism: Just a big word? in Proceedings of the 7th Marcel Grossmann Meeting on General Relativity, edited by R. T. Jantzen and G. M. Keiser (World Scientific, Singapore, 1996), pp.133-152 [arXiv:gr-qc/0105096].
[9] T. D. Lee and C. N. Yang, Question Of Parity Conservation In Weak Interactions, Phys. Rev. 104, 254 (1956).
[10] C. N. Yang, The Law Of Parity Conservation And Other Symmetry Laws Of Physics, in Chen Ning Yang: Selected Papers 1945-1980, with commentary, (Freeman, San Francisco, 1983), pp. 236-246.
[11] Z. Berezhiani, Through the Looking-Glass: Alice’s Adventures in Mirror World, in Ian Kogan Memorial Collection. From Fields to Strings: Circumnavigating Theoretical Physics, Ed. M. Shifman et al. (World Scientific, Singapore, 2005), vol.3, pp.2147-2195 [arXiv:hep-ph/0508233].
[12] V. S. Berezinsky and A. Vilenkin, Ultra high energy neutrinos from hidden-sector topological defects, Phys. Rev. D 62, 083512 (2000).
[13] Jorge Luis Borges, Tlön, Uqbar, Orbis Tertius, in Collected Fictions, translated by Andrew Hurley (Penguin Books, New York, 1998), pp. 68-81.
[14] S. I. Blinnikov and M. Y. Khlopov, On Possible Effects Of Mirror Particles, Sov. J. Nucl. Phys. 36, 472 (1982).
[15] E. W. Kolb, D. Seckel and M. S. Turner, The Shadow World Of Superstring Theories, Nature 314, 415 (1985).
[16] M. Y. Khlopov, G. M. Beskin, N. G. Bochkarev, L. A. Pustilnik and S. A. Pustilnik, Observational physics of a mirror world, Astron. Zh. 68, 42 (1991).
[17] R. Foot, H. Lew and R. R. Volkas, A Model with fundamental improper space-time symmetries, Phys. Lett. B 272, 67 (1991).
[18] R. Foot and R. R. Volkas, Neutrino physics and the mirror world: How exact parity symmetry explains the solar neutrino deficit, the atmospheric neutrino anomaly and the LSND experiment, Phys. Rev. D 52, 6595 (1995).
[19] Z. G. Berezhiani and R. N. Mohapatra, Reconciling present neutrino puzzles: Sterile neutrinos as mirror neutrinos, Phys. Rev. D 52, 6607 (1995).
[20] L. B. Okun, Mirror particles and mirror matter: 50 years of speculations and search, Phys. Usp. 50, 380 (2007) [arXiv:hep-ph/0606202].
[21] G. M. Voit, Tracing cosmic evolution with clusters of galaxies, Rev. Mod. Phys. 77, 207 (2005) [arXiv:astro-ph/0410173].
[22] M. Arnaud. X-ray observations of Clusters of Galaxies, arXiv:astro-ph/0508159.
[23] D. Clowe, M. Bradac, A. H. Gonzalez, M. Markevitch, S. W. Randall, C. Jones and D. Zaritsky, A direct empirical proof of the existence of dark matter, Astrophys. J. 648, L109 (2006) [arXiv:astro-ph/0608407].
[24] M. Jee et al., Weak Lensing Analysis of the z ~ 0.8 cluster CL 0152-1357 with the Advanced Camera for Surveys, Astrophys. J. 618, 46 (2005) [arXiv:astro-ph/0409304].
[25] M. Jee, R. L. White, H. C. Ford, J. P. Blakeslee, G. D. Illingworth, D. A. Coe and K. V. Tran, HST/ACS Weak-Lensing and Chandra X-Ray Studies of the High-Redshift Cluster MS 1054-0321, Astrophys. J. 634, 813 (2005) [arXiv:astro-ph/0508044].
[26] A. Mahdavi, H. Hoekstra, A. Babul, D. D. Balam and P. L. Capak, A Dark Core in Abell 520, Astrophys. J. 668, 806 (2007) [arXiv:0706.3048 [astro-ph]].
[27] Z. Berezhiani, D. Comelli and F. L. Villante, The early mirror universe: Inflation, baryogenesis, nucleosynthesis and dark matter, Phys. Lett. B 503, 362 (2001) [arXiv:hep-ph/0008105].
[28] R. Foot and R. R. Volkas, Spheroidal galactic halos and mirror dark matter, Phys. Rev. D 70, 123508 (2004) [arXiv:astro-ph/0407522].
[29] Z. Berezhiani, S. Cassisi, P. Ciarcia and A. Pietrinferni, Evolutionary and structural properties of mirror star MACHOs, Astropart. Phys. 24, 495 (2006) [arXiv:astro-ph/0507153].
[30] M. J. Jee et al., Discovery of a Ringlike Dark Matter Structure in the Core of the Galaxy Cluster Cl 0024+17, Astrophys. J. 661, 728 (2007) [arXiv:0705.2171 [astro-ph]].
[31] J. Bagchi, F. Durret, G. B. L. Neto and S. Paul, Giant Ringlike Radio Structures Around Galaxy Cluster Abell 3376, Science 314, 791 (2006) [arXiv:astro-ph/0611297].

[32] R. Lynds and A. Toomre, On the interpretation of ring galaxies: the binary ring system II Hz 4, Astrophys. J. 209, 382 (1976).

[33] C. Struck, Galaxy Collisions, Phys. Rept. 321, 1 (1999) [arXiv:astro-ph/9908269].

[34] J. Binney and S. Tremaine, Galactic Dynamics (Princeton University Press, Princeton, 1987), pp. 447-449.

[35] B. Qin, H. Y. Shan and A. Tilquin, Galaxy Distribution as a Probe of the Ring-like Dark Matter Structure in the Galaxy Cluster Cl 0024+17, arXiv:0804.2544 [astro-ph].

[36] R. Minchin et al., A Dark Hydrogen Cloud in the Virgo Cluster, Astrophys. J. 622, L21 (2005) [arXiv:astro-ph/0502312].

[37] R. Minchin et al., 21-cm synthesis observations of VIRGOHI 21 - a possible dark galaxy in the Virgo Cluster, Astrophys. J. 670, 1056 (2007) [arXiv:0706.1586 [astro-ph]].

[38] L. Bratek, J. Jalocha and M. Kutschera, Is dark matter present in NGC4736? An iterative spectral method for finding mass distribution in spiral galaxies, Astrophys. J. 679, 373 (2008) [arXiv:astro-ph/0811113].

[39] A.A. Hoag, A peculiar object in Serpens, Astron. J. 55, 170 (1950).

[40] F. Schweizer, W. K. Ford (Jr.), R. Jederzejewski and R. Giovanelli, The structure and evolution of Hoag’s object, Astrophys. J. 320, 454 (1987).

[41] S. Liebes, Gravitational Lenses, Phys. Rev. 133, B835 (1964).

[42] R. Narayan and M. Bartelmann, Lectures on gravitational lensing, arXiv:astro-ph/9606001.

[43] R. W. O’Connell, J. D. Scargle and W. L. W. Sargent, The Nature of Hoag’s Object, Astrophys. J. 191, 61 (1974).