Have mirror micrometeorites been detected?

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Slow-moving ($v \sim 15$ km/s) ‘dark matter particles’ have allegedly been discovered in a recent experiment. We explore the possibility that these slow moving dark matter particles are small mirror matter dust particles originating from our solar system. Ways of further testing our hypothesis, including the possibility of observing these dust particles in cryogenic detectors such as NAUTILUS, are also discussed.

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Drobyshevski et al\cite{1, 2} have been searching for slow-moving (\(v \sim 30 \text{ km/s}\)) dark matter objects and have obtained some interesting positive results. While they have interpreted their results in terms of Planckian mass objects with electric charge \(\sim 10e\) (daemon hypothesis), we will suggest an alternative interpretation in this note.

Their idea is very novel and straightforward. Dark matter could consist of massive particles with interactions strong enough to be captured by our solar system (or perhaps be a component of the gas cloud from which our solar system was formed). In this case such particles would have a velocity (relative to the Earth) of order 30 km/s. If its interactions are weak enough and/or the dark matter particles are heavy enough then such particles will not be stopped in the Earth’s atmosphere and can enter the Earth’s surface with a velocity of order 30 km/s. If such particles interact electromagnetically, then they may appear as a sort of cosmic ray, yet potentially distinguishable from ordinary cosmic rays because of their low velocity. Thus, one needs to design a suitable detector capable of searching for such slow-moving dark matter objects.

The detector devised by Drobyshevski et al is very simple. It consists of a tinned iron box containing two transparent polystyrene plates arranged horizontally one above the other separated by a distance of 7 cm. Each plate is coated on the downside with a layer of scintillator, ZnS (Ag) powder, with photomultiplier tubes at each end (i.e. the top and bottom). See Ref. \cite{1, 2} for more details. The passage of a charged particle through each of these plates or the tin walls can potentially be detected by the photomultiplier tubes. The time difference between the pulses from the top and bottom photomultiplier tubes (\(\Delta t\)) will allow a determination of the velocity of the particle through their detector. A positive (negative) \(\Delta t\) corresponds to the upper photomultiplier tubes being triggered before (after) the lower photomultiplier tubes. Background from cosmic rays and other conceivable backgrounds should occur equally for positive and negative \(\Delta t\) bins (Drobyshevski et al use bins of duration \(\Delta t = 20\mu s\)). This can be exploited by defining an up-down asymmetry, \(R_n\), \((n = 1, 2, 3, \ldots)\) defined by

\[
R_n = \frac{N(-20n \mu s < \Delta t < -20(n-1) \mu s)}{N(20(n-1) \mu s < \Delta t < 20n \mu s)}
\]  

Clearly in the absence of exotic slow moving particles one expects \(R_n\) to equal 1 (for each value of \(n\)). Any statistically significant deviation from unity would be an interesting signal for such new particles, with velocity of order \(L/\Delta t\) (where \(L\) is the size of their tin box). According to Ref.\cite{1}, there is a statistically significant anomaly occurring for \(R_2\) (see figure 2 of Ref.\cite{1}):

\[
R_2 = 0.3 \pm 0.15
\]  

However, the total number of events was statistically small, roughly 70 events (in the 20 \(\mu s < |\Delta t| < 40 \mu s\) bins) during a 700 hour exposure\cite{4}, and is as yet unconfirmed by any other experiment. Some interesting hints for a seasonal variation were also claimed\cite{1, 2}.

Taken at face value these results represent intriguing evidence for a flux of slow moving (\(v \sim L/\Delta t \sim 10-15 \text{ km/s}\)) long lived massive particles, with fairly large penetrating ability and which interact sufficiently to produce an observable burst of photons. One possible, more specific interpretation of the experimental
Table 1: Predicted effects of the mirror world.

| Observed phenomena/prediction                      | Observations consistent with prediction? | Preferred $\varepsilon$ range |
|---------------------------------------------------|------------------------------------------|-------------------------------|
| Dark matter [21]                                   | Y                                        |                               |
| Microlensing by mirror stars [13]                 | Y                                        |                               |
| Mirror planets orbiting stars [14]                | Y                                        |                               |
| Ordinary planets orbiting mirror stars [16]       | Y                                        |                               |
| Orthopositronium-mirror orthopositronium oscillations [18] | ?[20] | $|\varepsilon| \lesssim 10^{-6}$ |
| Pioneer spacecraft anomaly [15, 12]                | Y [9]                                    | $|\varepsilon| \gtrsim 10^{-9}$ |
| Lack of small craters on asteroids [12]           | Y [17]                                   | $10^{-6} \gtrsim |\varepsilon| \gtrsim 10^{-9}$ |
| Anomalous meteoritic events [10, 12]              | Y [11]                                   | $|\varepsilon| \gtrsim 10^{-9}$ |

Another possibility is that this experiment has observed the impacts of mirror dust particles, i.e. mirror micrometeorites, as we will shortly explain.

Mirror matter is predicted to exist if nature exhibits an exact unbroken mirror symmetry (for reviews and more complete set of references, see Ref. [3]). For each type of the ordinary particle (electron, quark, photon etc) there is a mirror partner (mirror electron, mirror quark, mirror photon etc), of the same mass. The two sets of particles form parallel sectors each with gauge symmetry $G$ (where $G = SU(3) \otimes SU(2) \otimes U(1)$ in the simplest case) so that the full gauge group is $G \otimes G$. The unbroken mirror symmetry maps $x \rightarrow -x$ as well as ordinary particles into mirror particles. Exact unbroken time reversal symmetry also exists, with standard CPT identified as the product of exact T and exact P [4].

Ordinary and mirror particles can interact with each other by gravity and via the photon-mirror photon kinetic mixing interaction\(^2\), the effect of which is to give mirror charged particles a small effective ordinary electric charge $\varepsilon e$ [4, 7]. Interestingly, the existence of photon-mirror photon kinetic mixing allows mirror matter to explain a number of puzzling observations, including the pioneer spacecraft anomaly [8, 9], anomalous meteorite events [10, 11] and the unexpectedly low number of small craters on the asteroid 433 Eros [12, 17]. It turns out that these explanations and other constraints [20, 19] suggest that $\varepsilon$ is in the range

$$10^{-9} \lesssim |\varepsilon| \lesssim 10^{-6}. \tag{3}$$

In table 1 we have summarized the observational effects of the mirror world for $\varepsilon$ in this range.

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\(^2\)Given the constraints of gauge invariance, renomalizability and mirror symmetry it turns out [4] that the only allowed non-gravitational interactions connecting the ordinary particles with the mirror particles are via photon-mirror photons kinetic mixing, $L = \frac{i}{2} F^{\mu\nu} F_{\mu\nu}^{\prime}$, where $F^{\mu\nu}$ ($F_{\mu\nu}^{\prime}$) is the field strength tensor for electromagnetism (mirror electromagnetism) and via a Higgs-mirror Higgs quartic interaction, $L = \lambda \phi \phi^\dagger \phi^{\prime}$. If neutrinos have mass, then ordinary - mirror neutrino oscillations may also occur [5, 6].
The properties of mirror matter space-bodies (SB) impacting on the Earth’s atmosphere has been studied in some detail in Ref.[12, 10]. Things depend (mainly) on the following parameters: the velocity of the SB ($v$), the direction of its trajectory ($\cos \theta$), the SB diameter ($D_{SB}$), and the value of the fundamental parameter $\epsilon$. (Of course, while the parameters $v, \cos \theta, D_{SB}$, can all have different values, depending on each event, $\epsilon$ can only have one value which is fixed in nature, like the fine structure constant).

While previous work[10, 12] focussed on the impacts of fairly large objects ($\gtrsim 1$ meter) which can potentially explain various anomalous impact events (such as the Jordan event, tunguska event etc[11]), the possible effects of small dust particle impacts on Earth was not specifically explored. In fact, the number of small mirror dust particles could potentially be quite large as collisions of large ($\gtrsim 1$ meter) mirror space bodies with themselves and ordinary bodies will generate them within our solar system. Thus, such small particles are potentially important because the number of such impacts on Earth should be much greater than the impacts of larger bodies. Furthermore, small dust particles can potentially retain their cosmic velocity impacting on the Earth’s surface with velocity of $11 \text{ km/s} \lesssim v \lesssim 70 \text{ km/s}$. 3.

The condition that small mirror dust particles pass through the atmosphere without losing their velocity is that (from Eq.22 of Ref.[12])

$$|\epsilon| \lesssim 2 \times 10^{-7} \sqrt{\cos \theta (v_i/30 \text{ km/s})^2}$$

where $v_i$ is the initial velocity relative to the Earth. Thus, since $v_i \lesssim 70 \text{ km/s}$ (for solar system objects), it follows that such cosmic velocity impacts can begin to occur for $|\epsilon| \lesssim 10^{-6}$.

At low velocities ($v \lesssim 70 \text{ km/s}$) the energy loss is dominated by Rutherford scattering. An important secondary process is bremsstrahlung, where a real photon is emitted when the ordinary nucleus (of electric charge $Ze$ and mass $M_A$) scatters off a mirror nucleus (of effective ordinary electric charge $\epsilon Z' e$ and mass $M_A'$). The kinetic energy of a mirror iron nucleus (taking the case of a mirror iron dust particle for definiteness) moving at a velocity $v$ is:

$$E_{\text{kin}} = \frac{1}{2} M_{Fe} v^2 \approx 260 \left(\frac{v}{30 \text{ km/s}}\right)^2 eV$$

Clearly, there is sufficient energy to produce optical and UV photons via the bremsstrahlung process.

In the case where $M_A \ll M_A'$, and for photon energies ($k$) much less than

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3The minimum impact velocity, 11 km/s, is equivalent to the escape velocity for a particle on Earth, while the upper limit of about 70 km/s assumes that the particle is bound within the solar system.

4Unfortunately Ref.[12] (and Ref.[10]) contains an error in the Rutherford cross section formula used ($\epsilon^2 e^4 \rightarrow e^\ast e^\ast$). This means that the $\epsilon$ ranges in Ref.[12] should increase by roughly one order of magnitude.

5Note that even in the case where $M_A \sim M_A'$, the cross section will be of the same order of magnitude.
The cross section is given by

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\text{brem}} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{elastic}} \frac{2Z^2\alpha}{\pi} \frac{4}{3} v^2 \sin^2 \frac{\theta}{2} \ln \frac{k_{\text{max}}}{k_{\text{min}}} \tag{6}
\]

where the elastic cross section is given by

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\text{elastic}} = \frac{4M_A^2\alpha^2 Z^2 Z'^2}{(4M_A^2 v^2 \sin^2 \frac{\theta}{2} + \frac{1}{r_0^2})^2} \tag{7}
\]

where \(r_0 \sim 10^{-9} \text{ cm}\) is the radius at which the screening effects of the atomic electrons becomes effective. The total bremsstrahlung cross section can easily be evaluated by integrating Eq. (6),

\[
\sigma_{\text{brem}} = \frac{16\alpha^3 Z^4 Z'^2}{3M_A^2v^2} \ln(r_0 M_A v) \ln \frac{k_{\text{max}}}{k_{\text{min}}} \tag{8}
\]

Taking \(k_{\text{min}} \sim 1 \text{ eV}\) and \(k_{\text{max}} \sim 50 \text{ eV}\), we find:

\[
\sigma_{\text{brem}} \approx 3 \times 10^{-32} \left( \frac{\epsilon}{10^{-7}} \right)^2 \left( \frac{Z}{26} \right)^4 \left( \frac{Z'}{26} \right)^2 \left( \frac{50 M_P}{M_A} \right)^2 \left( \frac{10 \text{ km/s}}{v} \right)^2 \text{ cm}^2 \tag{9}
\]

For the passage of a mirror iron nucleus through ordinary matter of atomic number density, \(n \sim 10^{23}/\text{cm}^3\), the mirror iron nucleus would have to travel an average distance of \(L = 1/(n \sigma) \sim 10^9 \text{ cm}\) before a bremsstrahlung process, producing a photon in the energy range \(1 \text{ eV} \lesssim k \lesssim k_{\text{max}} \sim 50 \text{ eV}\), occurs. However, a mirror dust particle contains, e.g. \(10^{14}\) such mirror nuclei, so that \(10^5\) photons (or more for larger dust particles) can be produced when such a dust particle passes through 1 cm of ordinary matter.

The importance of this is that these photons can be detected in a photomultiplier tube, and could thereby explain the interesting experimental results of Drobyshevski et al.\cite{1,2}. In this interpretation, the excess of down-going events occurs because of the passage of a mirror matter dust particle impacting with velocity \(v \sim 10 \text{ km/s}\). The dust particle produces optical and UV photons via the bremsstrahlung process upon passing through the detector. Hard elastic scattering in the scintillator, may also produce an observable signal (depending on their threshold, efficiency etc).\footnote{The seasonal dependence of the flux, if real, might be due to the Earth passing through a mirror matter dust stream, in much the same way that the Earth passes through ordinary meteor streams. For example, twice each year, in May and October we pass through the meteor stream from Halley’s comet. Perhaps there is a mirror meteor dust stream which we pass through in August and February?}

The flux estimated by Drobyshevski et al is \(f \sim 10^{-5} \text{ m}^{-2}\text{s}^{-1}\). This implies a solar system number density of order \(n = f/v \sim 10^{-15} \text{ cm}^{-3}\) or one mirror dust particle per cubic kilometer of the solar system, which seems plausible. Such a tiny density of solar system mirror dust particles may have been generated by

\footnote{Unless stated otherwise, we use natural units, \(h = c = 1\).}

\footnote{Note that the cross section, above, is valid assuming that the particles are point particles. For our application, we have the scattering of nuclei (of size \(R_N\)). In general we need to add in a Form factor, but this effect is only important when the momentum transfer is greater than \(1/R_N \gtrsim 10 \text{ MeV}\). Given that we are concerned with solar system dust particles, with relatively low velocity, \(v \lesssim 70 \text{ km/s}\), the momentum transfer is always low enough so that we can treat the atomic nuclei as point particles.}
random collisions of larger mirror space bodies. Drobyshevski et al. found an excess in the 10-15 km/s velocity region. This is close to the minimum value expected, which might indicate a flux of particles moving in roughly circular orbits, near Earth’s orbit. However, the bremsstrahlung cross section favours low velocities, since, from Eq. (9), \( \sigma_{\text{brem}} \propto 1/v^2 \). This feature, together with the relatively low statistics collected so far, suggests that the distribution of mirror dust particles might extend to higher velocities, potentially up to the maximum (\( v \approx 70 \) km/s) for solar system particles.

The specific explanation presented here can be distinguished from the daemon hypothesis in a number of ways. Perhaps the best way to do this would be to use an up-down symmetric detector. The reason is that daemons are so heavy and compact that they can penetrate the entire diameter of the Earth without losing a significant proportion of their energy. This means that the up-going daemon flux should be the same as the down-going daemon flux. [In contrast, the mirror dust particles stop in the Earth after a distance of \( L \sim 10(10^{-7}/\epsilon)(v_i/30 \text{ km/s})^4 \) meters for \( \epsilon \sim 10^{-7} \) [12, 6]. Note that even though an up-down asymmetry was obtained in the experiment, the detector was not up-down symmetric, which could allow the daemon hypothesis to potentially explain the results [1]. Further experimental work, with an up-down symmetric detector should help distinguish the daemon hypothesis from the mirror matter one.

The bremsstrahlung process, although important because it generates easily detectable eV photons, is not the only way of detecting mirror matter dust particles. Most of the kinetic energy of the dust particle is dissipated not via the bremsstrahlung process but via Rutherford scattering. Let us now estimate the rate at which the kinetic energy of a mirror dust particle is dissipated into heat and vibration energy via Rutherford scattering. The rate of energy loss is simply the product of the collision rate, the (forward) momentum lost per collision and the total number of atoms in the mirror dust particle (\( N \)), which is easily evaluated to be

\[
\frac{dE_{\text{elastic}}}{dx} = -2N \left( \frac{M_A}{M_M} \right) \int \frac{d\sigma}{d\Omega} \rho v^2 \sin \frac{\theta_s}{2} d\Omega
\]

\[
\approx \frac{4\pi N Z^2 Z'^2 e^2 \alpha^2}{M_A M_M v^2} \ln(M_A v_0)
\]

\[
\sim \left( \frac{N}{10^{15}} \right) \left( \frac{\epsilon}{10^{-7}} \right)^2 \left( \frac{30 \text{ km/s}}{v} \right)^2 300 \text{ TeV/cm} \quad (10)
\]

where \( v \) (assumed to be \( \geq 1 \) km/s in the above calculation) is the velocity of the dust particle and \( \rho \) is the mass density of ordinary matter medium which the dust particle is moving through.

Eq. (10) can be compared with the energy loss due to the bremsstrahlung process,

\[
\frac{dE_{\text{brem}}}{dx} = N n \sigma_{\text{brem}} \langle k_\gamma \rangle
\]

\[
\sim \left( \frac{N}{10^{15}} \right) \left( \frac{\epsilon}{10^{-7}} \right)^2 \left( \frac{30 \text{ km/s}}{v} \right)^2 \left( \frac{\langle k_\gamma \rangle}{10 \text{ eV}} \right) \text{ MeV/cm} \quad (11)
\]

where \( \langle k_\gamma \rangle \) is the mean energy of the bremsstrahlung photons emitted (of order 10 eV). In fact, if one looks at the ratio, \( (dE_{\text{brem}}/dx)/(dE_{\text{elastic}}/dx) \), then the
dependence on $\epsilon, N, v$ cancels, leaving

$$
\frac{dE_{\text{brem}}/dx}{dE_{\text{elastic}}/dx} = \frac{4Z^2\alpha A'}{3\pi M^2} \ln \frac{k_{\text{max}}}{k_{\text{min}}} \langle k_\gamma \rangle \\
\sim 10^{-9}
$$

(12)

The heat and vibration energy generated in ordinary matter due to the passage of mirror matter dust particles can potentially be observed in sensitive cryogenic detectors, such as the NAUTILUS gravitational wave detector[25]. NAUTILUS consists of an aluminum 2300 Kg bar cooled to 0.1 Kelvin. In addition, there is a cosmic ray detector system. Although designed to search for gravitational waves, NAUTILUS seems to be capable of detecting mirror matter - type dark matter via detection of the energy deposited in the bar via the elastic collisions $(dE/dx)_{\text{elastic}}$, and potentially sensitive to $(dE/dx)_{\text{brem}}$ in the cosmic ray detector. Interestingly, this collaboration has found anomalously large energy depositing events in the bar which feature a paradoxically low electromagnetic component in the cosmic ray detector[26]. It seems to be possible that these anomalous events are associated with the passage of a mirror dust particle, but it may also be due to some unexpected property of aluminum[27]. Nevertheless it is interesting that the dark matter interpretation of the St. Petersburg and NAUTILUS experiments yield flux estimates which are roughly comparable:

$$
f_{\text{drob}} \sim 10^{-5} \text{ m}^{-2}\text{s}^{-1}
$$

$$
f_{\text{Nautilus}} \sim 2 \times 10^{-6} \text{ m}^{-2}\text{s}^{-1}
$$

(13)

The difference might be due to the detection thresholds being different for the two experiments.

In conclusion, we have shown that mirror matter dust particles impacting with the Earth might appear as a sort of ‘anomalous cosmic ray’. The anomalous features include a) it is slow-moving ($\sim 30$ km/s) and b) the energy loss is dominated by elastic collisions. Interestingly, there is evidence for particles with these anomalous features coming from two existing experiments. Further work and further experimental observations should clarify this interesting situation.

Acknowledgements: The authors would like to thank E. Drobyshhevski, for helpful correspondence regarding his experiment and Z. Silagadze for his comments on the paper.

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As shown in Ref. [18], photon-mirror photon kinetic mixing induces a small off-diagonal mass which mixes orthopositronium and mirror-orthopositronium. This mass term causes oscillations of orthopositronium into mirror-orthopositronium, effectively leading to a faster (apparent) decay rate for orthopositronium, since the decays of the mirror state are not observed. This effect could explain the anomalously high decay rate observed in the 1990 orthopositronium vacuum cavity experiment [J. S. Nico et al., Phys. Rev. Lett. 65, 1344 (1990)], provided that $|\epsilon| \approx 10^{-6}$ [19]. However, a new vacuum cavity experiment was recently carried out by R. S. Vallery et al [Phys. Rev. Lett. 90, 203402 (2003)] where the anomaly is absent. The negative result of the latter experiment, suggests that $|\epsilon| \lesssim 10^{-6}$.

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