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EXOTIC METEORITIC PHENOMENA: THE TUNGUSKA EVENT AND ANOMALOUS LOW ALTITUDE FIREBALLS — MANIFESTATIONS OF THE MIRROR WORLD?

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There are a number of very puzzling meteoritic events including (a) The Tunguska event. It is the only known example of a low altitude atmospheric explosion. It is also the largest recorded event. Remarkably no fragments or significant chemical traces have ever been recovered. (b) Anomalous low altitude fireballs which (in some cases) have been observed to hit the ground. The absence of fragments is particularly striking in these cases, but this is not the only reason they are anomalous. The other main puzzling feature is the lack of a consistent trajectory: low altitude fireballs, if caused by an ordinary cosmic body penetrating the Earth's atmosphere, should have been extremely luminous at high altitudes. But in these anomalous cases this is (remarkably) not observed to occur! On the other hand, there is strong evidence that most of our galaxy is made from exotic dark material — 'dark matter'. Mirror matter is one well motivated dark matter candidate, since it is dark and stable and it is required to exist if particle interactions are mirror symmetric. If mirror matter is the dark matter, then some amount must exist in our solar system. Although there is not much room for a large amount of mirror matter in the inner solar system, numerous small asteroid sized mirror matter objects are a fascinating possibility because they can potentially collide with the Earth. We demonstrate that the mirror matter theory allows for a simple explanation for the puzzling meteoritic events [both (a) and (b)] if they are due to mirror matter space-bodies. A direct consequence of this explanation is that mirror matter fragments should exist in (or on) the ground at various impact sites. The properties of this potentially recoverable material depend importantly on the sign of the photon–mirror photon kinetic mixing parameter, ε. We argue that the broad characteristics of the anomalous events suggests that ε is probably negative. Strategies for detecting mirror matter in the ground are discussed.

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1. Introduction

One of the most natural candidates for a symmetry of nature is parity symmetry (also called left–right or mirror symmetry). While it is an established experimental fact that parity symmetry appears broken by the interactions of the known elementary particles, this however does not exclude the possible existence of exact unbroken parity symmetry in nature. This is because parity (and also time reversal) can be exactly conserved if a set of mirror particles exist [1,2]. The idea is that for each ordinary particle, such as the photon, electron, proton and neutron, there is a corresponding mirror particle, of exactly the same mass as the ordinary particle[1]. Furthermore, the mirror particles interact with each other in exactly the same way that the ordinary particles do. It follows that the mirror proton is stable for the same reason that the ordinary proton is stable, and that is, the interactions of the mirror particles conserve a mirror baryon number. The mirror particles are not produced (significantly) in laboratory experiments just because they couple very weakly to the ordinary particles. In the modern language of gauge theories, the mirror particles are all singlets under the standard $\mathrm{G} \equiv \mathrm{SU}(3) \otimes \mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{U}(1)_Y$ gauge interactions. Instead the mirror fermions interact with a set of mirror gauge particles, so that the gauge symmetry of the theory is doubled, *i.e.* $\mathrm{G} \otimes \mathrm{G}$ (the ordinary particles are, of course, singlets under the mirror gauge symmetry) [2]. Parity is conserved because the mirror fermions experience $V+A$ (right-handed) mirror weak interactions and the ordinary fermions experience the usual $V-A$ (left-handed) weak interactions. Ordinary and mirror particles interact with each other predominately by gravity only.

At the present time there is a large range of experimental observations supporting the existence of mirror matter, for a review see Ref. [5] (for a more detailed discussion of the case for mirror matter, accessible to the non-specialist, see the recent book [6]). The evidence includes numerous observations suggesting the existence of invisible 'dark matter' in galaxies. Mirror matter is stable and dark and provides a natural candidate for this inferred dark matter [7]. The MACHO observations [8], close-in extrasolar planets [9], isolated planets [10] and even gamma ray bursts [11] may all be mirror world manifestations. On the quantum level, small fundamental interactions connecting ordinary and mirror matter are possible. Theoretical constraints from gauge invariance, renormalizability and mirror symmetry suggest only three possible types of interactions [2,12]: photon–mirror pho-

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[1] The mirror particles only have the same mass as their ordinary counterparts provided that the mirror symmetry is unbroken. It is possible to write down gauge models where the mirror symmetry is broken [3,4], in some cases allowing the mirror particles to have completely arbitrary masses [4], however these scenarios tend to be more complicated and much less well motivated in our view.

ton kinetic mixing, neutrino–mirror neutrino mass mixing and Higgs–mirror Higgs interactions. The main experimental implication of photon–mirror photon kinetic mixing is that it modifies the properties of orthopositronium, leading to a shorter effective lifetime in 'vacuum' experiments [13–15]. A shorter lifetime is in fact seen at the 5 sigma level! [15,16]. Neutrino–mirror neutrino mass mixing implies maximal oscillations for each ordinary neutrino with its mirror partner [12,17]. This provides a simple and predictive explanation for the apparent $\sim 50\%$ solar ν_e flux reduction observed in the solar neutrino experiments (the solar neutrino problem), as well as the observed $\approx 50\%$ reduction in upgoing ν_μ in atmospheric neutrino experiments. [Although it is also true that the mirror world solution to the neutrino physics anomalies is not in perfect agreement with all of the experimental neutrino data at the moment.]

The purpose of the present paper is to make a detailed study of one very explosive implication of the mirror matter theory, and that is, that our solar system contains small asteroid sized mirror matter space bodies which occasionally collide with our planet. In Ref. [5,18] it was proposed that such mirror matter space bodies may have caused the famous 1908 Siberian explosion — the Tunguska event — as well as other smaller, but more frequent events. In the present paper we will examine this idea in more detail. We will show that the mirror matter Space-Body (SB) hypothesis provides a natural framework for a unified explanation for a number of puzzling meteoritic events which do not seem to be naturally associated with an ordinary matter SB, including the 1908 Tunguska event and some anomalous low altitude fireball events.

2. Some puzzling observations

Our solar system contains a large variety of small space bodies (SB) — asteroids and comets — as well as the 9 known planets and the various moons. Although tiny, small SB may be very numerous and may have big implications for life on our planet. The reason is that sometimes they might collide with our planet releasing large amounts of energy in the process. For example, there is interesting evidence that the mass extinction which wiped out the dinosaurs 65 million years ago was caused by the collision of a large asteroid or comet with the Earth. The evidence is in the form of an excess of the rare element iridium in clay samples dating from that time period [19]. Iridium is very rare in the Earth's crust and mantle but much more common in asteroids and comets. There is also evidence for a large meteorite crater also dating from the same time period. It is located in the Yucatan peninsula of Mexico. The estimated size of this asteroid is of order 10 kilometers in diameter with a mass of about 500 billion tons.

More recently, there is evidence that an object of order 50 metres in size collided with the Earth in 1908 causing a very large explosion in the Tunguska river region of Siberia. However, while the impact 65 million years ago left chemical traces (the excess of iridium) as well as a crater, the more recent Tunguska object is somewhat more inconspicuous — and much more puzzling.

2.1. The Tunguska event

In the early morning of June 30th 1908 a powerful explosion occurred in the Tunguska river region of Siberia. The explosion flattened about 2,100 square kilometers of forest in a radial pattern (see figure 1). The energy released in the explosion has been estimated to be the equivalent of roughly 20 megatons of TNT or 1000 atomic bombs. There was also evidence that the inner two hundred square kilometers of trees was burned from above. The broad features of the event suggest a huge explosion in the atmosphere at an altitude of about 5–8 km which produced a downward going spherical shockwave. The spherical shockwave toppled the trees in the radial pattern and the heat from the explosion caused the flash burn of the trees. For a recent review of what is known about the Tunguska event, see Ref. [20].

It is a remarkable fact that after considerable experimental study with more than 40 scientific expeditions to the site, the origin of the Tunguska explosion is still an open question. To explain the forest fall and other features requires a relatively low altitude explosion ($\sim$ 5–8 km height), which suggests that the cosmic body was able to withstand huge pressures without breaking up or completely ablating. Roughly, an ordinary body should break up when the pressure at its surface exceeds its mechanical strength. Furthermore, a large body, like the Tunguska body, would not lose much of its cosmic velocity during its atmospheric flight while it remains intact. Thus, as the body moves closer to the Earth's surface the pressure quickly increases in proportion to the increasing density of the Earth's atmosphere. It has been argued that the necessary low altitude of the explosion, indicated by the broad features of the forest fall, suggests that the body should be mechanically strong of asteroidal composition rather than cometary. However, the break up of a mechanically strong body made of non-volatile material may be expected to lead to multiple explosions and macroscopic fragments (as well as significant chemical traces, such as iridium excess) covering the 'impact region'. Yet, the evidence suggests a single predominant explosion. Furthermore, while there is evidence for subsequent explosions these were very small, and seem to be at much lower altitude. In the words of Vasilyev [21]:

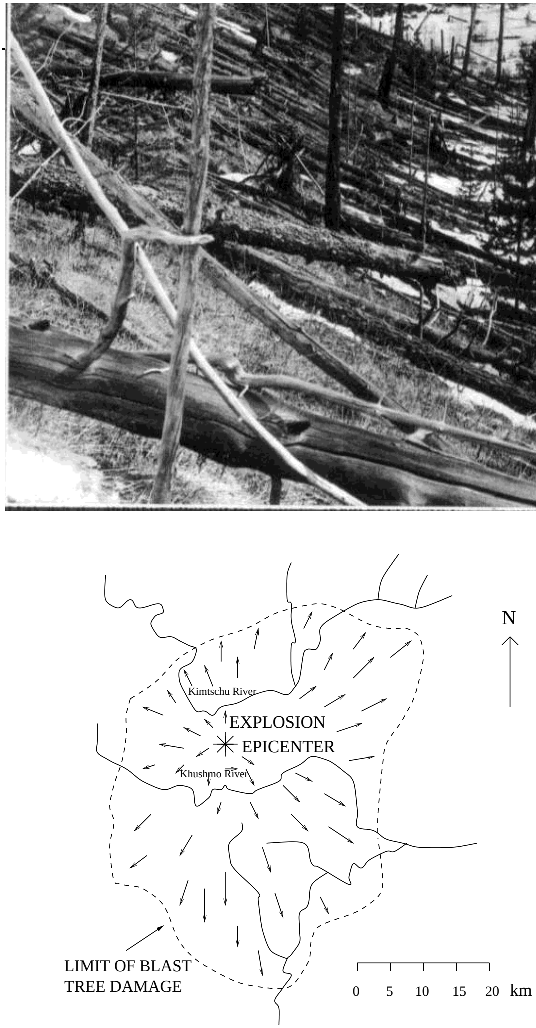

Fig. 1. The forest devastation at Tunguska. The top figure shows the fallen trees on the banks of the Khushmo river as seen by Kulik in 1928. The bottom figure shows the area and orientation of the fallen trees.

‘We may tentatively conclude that along with a great energy release from 5 to 8 kilometers above the Earth, there were a number of low-altitude (maybe even right above the surface) explosions that contributed to the total picture of destruction.

...It should be emphasised that though the patchiness of the effects associated with the Tunguska explosion has been noted in the literature more than once, its origin has not been discussed. This seems to be due to serious difficulties of its interpretation in terms of the existing Tunguska cosmic body models.’

On the other hand, the lack of remnants could point to a body made of volatile material such as ices, which could have completely vaporized in the atmosphere. However, such a body should not have survived to low altitudes before breaking up, especially since comets should impact with relatively high velocities ($v \gtrsim 30$ km/s) because of their elliptical orbits. While it is believed that ices are the main components of comets, it is also known that comets typically contain significant amounts of non-volatile materials as well[2]. Thus, a cometary origin of the Tunguska cosmic body cannot really explain the lack of fragments and chemical traces. In either case, the evidence for lower altitude secondary explosions does suggest that significant pieces of the original body survived the main explosion — but where are the traces?

It is an interesting observational fact that, on smaller scales, there do not seem to be events which exactly mimic the Tunguska example. It is the only known case of a cosmic body exploding at low altitudes in the atmosphere. Yet, there are very puzzling examples of small bodies which have been apparently observed to survive to low altitudes and strike the ground. In a sense they are 'Tunguska-like' because of their lack of fragments and chemical traces (which is even more mysterious because the small bodies have lost their cosmic velocity and strike the ground with relatively low velocities of order 1 km/s). We will discuss some examples of these rather mysterious impact events in Section 2.2 below. More generally fireballs disintegrate or explode at high altitudes ($\gtrsim 30$ km). An example of a high altitude explosion (or 'airburst') is given by the Lugo fireball [23].

On January 19, 1993 a bright fireball crossed the sky of northern Italy, ending with an explosion roughly over the town of Lugo. The energy of the explosion — estimated to be about 14 thousand tons of TNT or one atomic bomb — generated shock waves which were recorded by six local seismic stations. By means of the seismic data, it was possible to calculate the height of the explosion, which was estimated to be approximately 30 km. No fragments were recovered. This event appears to be similar to the Tunguska event, but with about 1000 times smaller in energy release and also the explosion occurred at significantly higher altitude (30 km rather than ~5 km). Literally hundred's of other airburst events have been recorded by the US department of Defense satellite system (with energies in the range of 1–100 thousand tons of TNT). Interestingly, they all appear to airburst

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[2] The puzzling nature of the Tunguska event has also led to suggestions that its origin was purely geophysical (see for example, Ref. [22]). Given the lack of direct material evidence for the standard extraterrestrial explanation (*i.e.* asteroid or comet), such alternative explanations are interesting and possible. However, there were numerous eye witness reports observing the large fireball heading towards Tunguska. It is also true that some details of these reports were contradictory, they nevertheless do support an extraterrestrial explanation for the event (in our opinion).

at high altitudes. The Tunguska explosion appears to be unique for two reasons: It is the *largest* recorded atmospheric explosion and also the *only* known example of a low altitude airburst.

2.2. Some examples of anomalous small fireballs

There are many reported examples of atmospheric phenomena resembling fireballs, which cannot be due to the penetration of an ordinary meteoroid into the atmosphere (for a review of bolides, including discussion of these anomalous events, see Ref. [24]). Below we discuss several examples of this strange class of phenomena.

(i) The Spanish event — January 18, 1994.

On the early morning of 1994 January 18, a very bright luminous object crossed the sky of Santiago de Compostela, Spain. This event has been investigated in detail in Ref. [25]. The eye witnesses observed the object to be low in altitude and velocity (1 to 3 km/s). Yet, an ordinary body penetrating deep into the atmosphere should have been quite large and luminous when it first entered the atmosphere at high altitudes with large cosmic velocity (between 11 and 70 km/s). An ordinary body entering the Earth's atmosphere at these velocities always undergoes significant ablation as the surface of the body melts and vapourises, leading to a rapid diminishing of the bodies size and also high luminosity as the ablated material is heated to high temperature as it dumps its kinetic energy into the surrounding atmosphere. Such a large luminous object would have an estimated brightness which would supersede the brightness of the Sun, observable at distances of at least 500 km [25]. Sound phenomena consisting of sonic booms should also have occurred [25]. Remarkably neither of these two expected phenomena were observed for this event. The authors of Ref. [25] concluded that the object could *not* be a meteoric fireball.

In addition, within a kilometer of the projected end point of the "object's" trajectory a "crater" was later discovered [25]. The "crater" had dimensions 29 m×13 m and 1.5 m deep. At the crater site, full-grown pine trees were thrown downhill over a nearby road. Unfortunately, due to a faulty telephone line on the 17th and 18th of January (the fireball was seen on the 18th) the seismic sensor at the nearby geophysical observatory of Santiago de Compostela was inoperative at the crucial time. After a careful investigation, the authors of Ref. [25] concluded that the crater was most likely associated with the fireball event, but could not definitely exclude the possibility of a landslide.

No meteorite fragments or any other unusual material was discovered at the crater site.

(ii) The Jordan event — April 18, 2001.

On Wednesday 18th April 2001, more than 100 people attending a funeral procession saw a low altitude and low velocity fireball. In fact, the object was observed to break up into two pieces and each piece was observed to hit the ground. The two impact sites were later examined by members of the Jordan Astronomical Society. The impact sites showed evidence of energy release (broken tree, half burnt tree, sheared rocks and burnt ground) but no ordinary crater (see figure 2). [This may have been due, in part, to the hardness of the ground at the impact sites.] No meteorite fragments were recovered despite the highly localized nature of the impact sites and low velocity of impact. For more of the remarkable pictures and more details, see the Jordan Astronomical Society's report [26]. As with the 1994 Spanish event *(i)*, the body was apparently not observed by anyone when it was at high altitudes where it should have been very bright. Overall, this event

Fig. 2. Some pictures of the impact sites (Courtesy of the Jordan Astronomical Society[25]).

seems to be broadly similar to the 1994 spanish event *(i)*. For the same reasons discussed in *(i)* (above) it could not be due to an ordinary meteoric fireball.

(iii) The Poland event — January 14, 1993.

Another anomalous event, similar to the Spanish and Jordan cases was observed in Poland, January 14, 1993 [24, 27]. Again, a low altitude, low velocity ($v \sim 1$ km/s) body was observed. In this particular case there was evidence of an enormous electrical discharge at the 'impact site', which destroyed most of the electrical appliances in nearby houses.

There are many other similar examples, some of which have been described by Ol'khovatov in Ref. [22].

2.3. Other anomalous events — speedy meteors

In standard theory, light produced by a meteoroid during its interaction with the Earth's atmosphere is caused by the ablation process: The surface of the meteoroid melts and vapourises due to the extreme heating of its surface by the interactions with the atmosphere, leading to emission lines as the atoms in the surrounding vapour de-excite. However, observations [28] of the Leonid meteors have shown that radiation from these extremely speedy meteors (entering the Earth's atmosphere at about 71 km/s) starts at an extremely high altitude, up to 200 km in height. At these high altitudes the atmosphere is so sparse that the ablation process should not be occurring at all: there is simply not enough air molecules to heat and evaporate an entering meteoroid — yet radiation exists because it is observed in rather great detail [28].

Clearly, the observations 2.1 and 2.2 [and maybe even 2.3] indicate that there are many strange happenings a foot. These largely unexplained phenomena do provide motivation to examine the fantastic possibility that they may be manifestations of the mirror world.

3. The interactions of a mirror matter space-body with the atmosphere

There is not much room for a large amount of mirror matter in our solar system. For example, the amount of mirror matter within the Earth has been constrained to be less than $10^{-3} M_{\mathrm{Earth}}$ [29]. However, we do not know enough about the formation of the solar system to be able to exclude the existence of a large number of Space Bodies (SB) made of mirror matter if they are small like comets and asteroids. The total mass of asteroids in the asteroid belt is estimated to be only about 0.05% of the mass of the Earth. A similar or even greater number of mirror bodies, perhaps orbiting in a different plane or even spherically distributed like the Oort cloud is a fascinating and potentially explosive possibility[3] if they collide with the Earth. The possibility that such collisions occur and may be responsible for the 1908 Siberian explosion (Tunguska event) has been speculated in Ref. [5,18]. The purpose of this paper is to study this fascinating possibility in detail.

If such small mirror bodies exist in our solar system and happen to collide with the Earth, what would be the consequences? If the only force connecting mirror matter with ordinary matter is gravity, then the consequences would be minimal. The mirror SB would simply pass through the Earth and nobody would know about it unless it was so heavy as to gravitationally affect the motion of the Earth. While we know that ordinary and mirror matter do not interact with each other via any of the *known* non-gravitational forces, it is possible that new interactions exist which couple the two sectors together. In Ref. [2,12], all such interactions consistent with gauge invariance, mirror symmetry and renormalizability were identified, namely, photon–mirror photon kinetic mixing, Higgs–mirror Higgs interactions and via ordinary neutrino–mirror neutrino mass mixing (if neutrinos have mass). While Higgs–mirror Higgs interactions will be tested if or when the Higgs particle is discovered, there is currently strong evidence for photon–mirror photon kinetic mixing [15] and also ordinary neutrino–mirror neutrino mass mixing [12,17]. Of most importance though for this paper is the photon–mirror photon kinetic mixing interaction.

In field theory, photon–mirror photon kinetic mixing is described by the interaction

$$\mathcal{L} = \frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu}, \tag{1}$$

where $F^{\mu\nu}$ ($F'_{\mu\nu}$) is the field strength tensor for electromagnetism (mirror electromagnetism). This type of Lagrangian term is gauge invariant and renormalizable and can exist at tree level [2,31] or may be induced radiatively in models without U(1) gauge symmetries (such as grand unified theories) [13,32,33]. One effect of ordinary photon–mirror photon kinetic mixing is to give the mirror charged particles a small electric charge [2,13,32]. That is, they couple to ordinary photons with electric charge εe.

The most important experimental implication of photon–mirror photon kinetic mixing is that it modifies the properties of orthopositronium [13]. This effect arises due to radiative off-diagonal contributions to the orthopositronium, mirror orthopositronium mass matrix. This means that orthopositronium oscillates into its mirror partner. Decays of mirror or-

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[3] Large planetary sized bodies are also possible if they are in distant orbits [30] or masquerade as ordinary planets or moons by accreting ordinary matter onto their surfaces [6].

thopositronium are not detected experimentally which effectively increases the observed decay rate [13]. Because collisions of orthopositronium destroy the quantum coherence, this mirror world effect is most important for experiments which are designed such that the collision rate of the orthopositronium is low [14]. The only accurate experiment sensitive to the mirror world effect is the Ann Arbour vacuum cavity experiment [16]. This experiment obtained a decay rate of $\Gamma_{\rm oPs} = 7.0482 \pm 0.0016\ \mu{\rm s}^{-1}$. Normalizing this measured value with the recent theoretical value of $7.0399\ \mu{\rm s}^{-1}$ [34] gives

$$\frac{\Gamma_{\rm oPs}({\rm exp})}{\Gamma_{\rm oPs}({\rm theory})} = 1.0012 \pm 0.00023\,, \tag{2}$$

which is a five sigma discrepancy with theory. It suggests a value $|\varepsilon| \simeq 10^{-6}$ for the photon–mirror photon kinetic mixing [15]. Taken at face value this experiment is strong evidence for the existence of mirror matter and hence parity symmetry. It is ironic that the last time something important was discovered in high energy physics with a table top experiment was in 1957 where it was demonstrated that the ordinary particles by themselves appear to violate parity symmetry.

Of course, this vacuum cavity experiment must be carefully checked by another experiment to make sure that mirror matter really exists. Actually this is quite easy to do. With the largest cavity used in the experiment of Ref. [16] the orthopositronium typically collided with the cavity walls 3 times before decaying. If the experiment was repeated with a larger cavity then the mirror world effect would be larger because the decohering effect of collisions would be reduced. For example if a cavity 3 times larger could be used (which means that the orthopositronium would typically collide with the walls just once before decaying) then the mirror world would predict an effect roughly 3 times larger.

There are several important implications of photon–mirror photon kinetic mixing with the relatively large value of $|\varepsilon| \simeq 10^{-6}$, some of which have been discussed previously [18, 35, 36]. One very interesting effect is that it allows mirror matter space-bodies to interact with the Earth's atmosphere. Imagine that a mirror SB of velocity v is entering the Earth's atmosphere and plummeting towards the ground. The mirror SB is constantly bombarded by the atmosphere in front of it, initially with the velocity, v. Previous work [18] has shown that the air molecules lose their relative forward momentum after travelling only a distance of a few centimeters within the mirror SB. The collision process is dominated by Rutherford scattering of the atmospheric nuclei (of atomic number $Z \sim 7$) off the mirror SB nuclei (with mirror atomic number Z') of effective electric charge $\varepsilon Z' e$. The Feynman diagram for the scattering process is shown in figure 3.

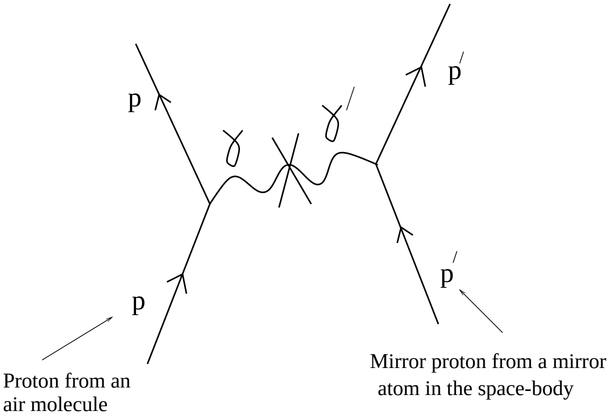

Fig. 3. Rutherford scattering of the mirror nuclei off the atmospheric nuclei. The scattering is only possible because of the photon–mirror photon kinetic mixing, indicated by the cross (X) in this diagram.

The interaction cross section is simply the standard Rutherford formula (modified for small angle scattering by the screening effects of the atomic electrons at the Bohr radius, $r_0 \approx 10^{-8}$ cm) [37] suppressed by a factor ε^2:

$$\frac{d\sigma_{\mathrm{coll}}}{d\Omega} = \frac{4M_A^2 \varepsilon^2 e^4 Z^2 Z'^2}{(4M_A^2 v^2 \sin^2 \frac{\theta}{2} + 1/r_0^2)^2}\,, \tag{3}$$

where M_A is the mass of the air molecules[4].

Anyway, the Rutherford scattering causes the ordinary air molecules to lose their forward momentum within the mirror space-body (assuming that $|\varepsilon| \approx 10^{-6}$ as suggested by the experiments on orthopositronium [15]). It follows that the air resistance of a mirror SB is roughly the same as an ordinary SB assuming the same trajectory, velocity, mass and size and that the body remains intact. The (kinetic) energy loss rate of the body through the atmosphere is then

$$\frac{dE}{dx} = \frac{-C_d \rho_{\mathrm{atm}} S v^2}{2}\,, \tag{4}$$

where ρ_{atm} is the mass density of the air, v the speed, $S = \pi R^2$ the cross sectional area and R the effective radius of the mirror SB. C_d is an order

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[4] Ordinarily, the Rutherford formula only applies (for standard ordinary matter scattering) at high velocity ($v \gtrsim 1000$ km/s) because the Born approximation, from which it can be derived, is only valid for weak potentials and high incident energies (see *e.g.* Ref. [37]). In the case of ordinary-mirror matter scattering — that we are considering — the potential is suppressed by a factor of $\varepsilon \sim 10^{-6}$, which means that the Rutherford scattering formula is applicable even for very low velocities such as $v \sim 1$ km/s.

of unity drag force coefficient depending on the shape (and velocity) of the body. In Eq. (4) the distance variable x is the distance travelled.

Equation (4) is a standard result but we will derive it anyway. Specifically, an on-coming air molecule which interacts with the mirror SB and surrounding compressed air loses its relative momentum, thereby slowing down the body. Conservation of momentum tell us that the change in the SB velocity is then:

$$\delta v = -\frac{M_A}{M_{\rm SB}} v. \tag{5}$$

Multiplying this by the number of air molecules [of number density $n(h)$] encountered after moving a distance dx, we have

$$\begin{aligned} dv &= -\frac{M_A}{M_{\rm SB}} v n(h) S dx \\ &= -\frac{\rho_{\rm atm} v S dx}{M_{\rm SB}}. \end{aligned} \tag{6}$$

Note that this equation is equivalent to Eq. (4) with $C_d = 2$. The factor C_d arises because, in general, not all air molecules in the path of the body will lose their relative momentum to the body; it is a complicated aerodynamic and hydrodynamic problem, which depends on the shape, speed and trajectory of the body. Solving Eq. (6), we find an exponentially decaying velocity:

$$v = v_i {\rm e}^{-x/D} \tag{7}$$

where v_i is the initial velocity of the SB and

$$D = \frac{x}{\int^x \frac{\rho_{\rm atm} S}{M_{\rm SB}} dx} \tag{8}$$

For an air density of $\bar{\rho}_{\rm air} \approx 10^{-3}\ g/{\rm cm}^3$,

$$D \sim 10 \left(\frac{R}{5 \text{ meters}}\right) \left(\frac{\rho_{\rm SB}}{1\ g/{\rm cm}^3}\right) \text{ km}. \tag{9}$$

In general, one must also take into account the effect of mass loss or 'ablation'. For an ordinary matter body, the air molecules do not penetrate the body, but merely strike the surface and bounce off. The energy is therefore dissipated right at the surface which causes it to rapidly melt and vapourise. This means that R typically decreases quite rapidly for an ordinary matter body. For a mirror matter SB, some of the energy is dissipated within the body by Rutherford scattering of the ordinary air molecules with the mirror atoms of the SB and also by collisions of the air molecules with other air molecules. Furthermore the heating of the surrounding air as well as the air trapped within the body should provide an efficient means of transporting the heat. The air can transfer heat from the surface regions of the mirror SB to the rest of the body. As a crude approximation, we can assume that the entire mirror matter SB, as well as a significant fraction of air molecules within and surrounding the SB are heated to a common temperature T_b. We call this the 'isothermal approximation'. Anyway, the important point is that in the mirror matter case, the energy imparted to the SB is dissipated within it, rather than just at its surface. Instead of rapid surface melting, the SB initially has very low ablation (relative to the case of an ordinary SB). The kinetic energy of the impacting air molecules is dumped into the mirror SB and surrounding air, and rapidly thermalized within it.

Broadly speaking two things can happen depending on the chemical composition of the SB and also on its initial velocity and trajectory: If the temperature of the mirror SB and surrounding air reaches the melting point of the body, then the entire body will break up and melt and subsequently vapourise. On the other hand, if the temperature remains below the melting point, then the body should remain intact. Note that once a SB breaks up into small pieces it rapidly dumps its kinetic energy into the atmosphere since its effective surface area rapidly increases, which also rapidly increases the atmospheric drag force.

For a body that remains intact, there are two interesting limiting cases. For large bodies with size much greater than 10 metres, the atmospheric drag force is not large enough to significantly slow the body down during its atmospheric flight, while for small bodies less than about 10 metres in size, they typically lose most of their cosmic velocity in the atmosphere. We will examine each of these limiting cases in turn, starting with the most dramatic case of large bodies such as the Tunguska SB.

4. Heating of a large mirror space-body penetrating the Earth's atmosphere

In this section, we shall examine the case of a large mirror SB entering the Earth's atmosphere. For large space-bodies, $R \gg 10$ metres, the atmospheric drag force does not slow them down much [*cf.* Eq. (9)], which means that we can treat their velocity as being approximately constant during their atmospheric passage. For a SB in an independent orbit around the Sun, the velocity at which the body strikes the atmosphere (as seen from the Earth) is in the range[5]:

$$11 \text{ km/s} \lesssim v \lesssim 70 \text{ km/s}. \tag{10}$$

A pure mirror SB entering the Earth atmosphere would have an extremely low initial temperature, only a few degrees above absolute zero. However, its temperature rapidly begins to rise during its atmospheric passage as the kinetic energy of the on-coming atmospheric molecules (in the rest frame of the SB) are dumped into the SB and the surrounding co-moving compressed air. If the atmosphere was infinite in extent, the temperature would eventually rise high enough so that the body melts, in which case it would rapidly dump its kinetic energy into the atmosphere because the effective surface area of the body rapidly increases when it breaks apart. The net effect would be an atmospheric explosion. There is evidence that such atmospheric explosions actually occur, and the Tunguska event is one well studied example.

This mechanism has been discussed qualitatively in Ref. [18], and we wish now to examine it quantitatively. Could it reasonably be expected to occur given what is known about the Tunguska event? To answer this question we must first estimate the rate at which energy is dumped into the mirror SB as it propagates through the atmosphere.

We start with a simple model for the Earth's atmosphere. We assume that it is composed of molecules of mass $M_A \approx 30 M_p$ (M_p is the proton mass), with number density profile:

$$n(h) = n_0 \exp\left(-\frac{h}{h_0}\right), \tag{11}$$

where $M_A n_0 \simeq 1.2 \times 10^{-3}$ g/cm^3 is the air mass density at sea-level, and $h_0 \approx 8$ km is the scale height. Eq. (11), which can be derived from hydrostatic equilibrium, is approximately valid for $h \lesssim 25$ km. Above that height, the density actually falls off more rapidly then given by Eq. (11), but we will nevertheless use this equation since it is a good enough approximation for the things which we calculate.

The parameters defining the mirror SB's trajectory are illustrated in figure 4. Its trajectory is directed towards a point on the ground O'. Consider an instantaneous point P, located at a vertical height $x_d \cos\theta$ above the ground, where the distance $O'P$ is x_d. In the frame of the SB, on-coming air molecules strike the body and/or surrounding compressed air (both outside

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[5] The minimum velocity of a space-body as viewed from Earth is not zero because of the effect of the local gravity of the Earth. It turns out that the minimum velocity of a space-body is about 11 km/s, for a body in an independent orbit around the Sun (and a little less if there happened to be a body in orbit around the Earth).

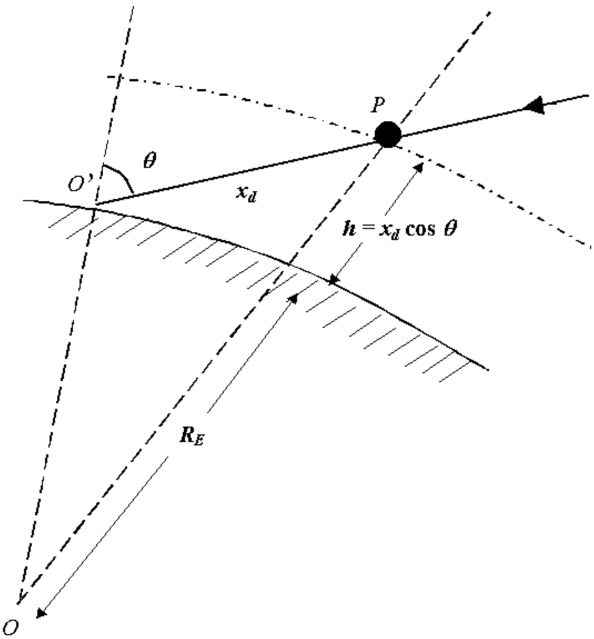

Fig. 4. Trajectory of a SB entering the Earth's atmosphere, taken to be approximately a straight path. All the length scales involved, x, h are all very small compared to $R_{\rm E}$, allowing the curvature of the Earth be ignored.

and within the mirror body), eventually losing most of their kinetic energy ($M_A v^2/2$) after many collisions. Their kinetic energy is converted primarily into thermal energy, heating the body and surrounding compressed air.

To estimate the amount of energy dumped into the mirror SB and surrounding compressed air from the interaction of it with the atmosphere, consider an infinitesimal distance dx (at the point P). As a simple approximation, let us assume that all the air molecules in the volume Sdx are swept up by the on-coming SB and surrounding air. This approximation is similar to the one leading to Eq. (6) where detailed hydrodynamic and aerodynamic effects are ignored (equivalent to setting $C_d = 2$). In this approximation, the energy, $d\varepsilon$, dumped into the mirror SB and surrounding compressed air is simply given by the number of air molecules in the volume Sdx multiplied by their average energy (with respect to the rest frame of the SB):

$$d\varepsilon = n(h)\frac{1}{2}M_A v^2 S dx. \tag{12}$$

This means that the total energy dumped into the space-body (and surrounding highly compressed co-moving air) during its passage from far away up until the point P is simply:

$$\varepsilon(x_d) = \int\limits_{x_d}^{\infty} n_0 \mathrm{exp}\left(\frac{-x\cos\theta}{h_0}\right)\frac{1}{2}M_A v^2 S dx\,. \tag{13}$$

We are most interested in working out the energy going into just the mirror SB, rather than both SB and surrounding compressed air. Actually this is another difficult hydrodynamic problem. The air trapped within the body and in front of it is highly compressed. The total number of air molecules moving with the SB could be of the same order as the total number of mirror molecules within the SB. With our isothermal assumption, we can lump this hydrodynamic uncertainty into a single factor, f_a, which is just the fraction of SB molecules to air molecules co-moving with the SB ($N_{\rm air}$):

$$f_a = \frac{N_{\rm SB}}{N_{\rm SB} + N_{\rm air}}. \tag{14}$$

Here $N_{\rm SB}$ is the number of mirror molecules comprising the SB. If these molecules have mass $M_{A'}$ (for example, $M_{A'} \simeq 18M_P$ for mirror H_2O ice) then $N_{\rm SB} = M_{\rm SB}/M_{A'}$. Essentially f_a is the the proportion of the kinetic energy of the on-coming air molecules transferred into heating the mirror SB. The energy dumped into the SB is then

$$\varepsilon_{\rm SB}(x_d) \;=\; f_a \varepsilon(x_d). \tag{15}$$

In addition to the factor f_a, there are other hydrodynamic uncertainties coming from the flow of air around the body. We assumed that every air molecule in the path of the body would be swept up by the body, however real life is always more complicated. In general we must model the flow of air around the body — a difficult hydrodynamical problem... . So, we must introduce another hydrodynamic uncertainty, f_b. Actually, we will combine all of our hydrodynamic uncertainties (f_a and f_b) into a single factor f. We will later take $f \sim 0.1$, but this is quite uncertain. A useful quantity is the energy gained per molecule of the space-body, $\tilde{\varepsilon}_{\rm SB} = \varepsilon_{\rm SB}(x_d)/N_{\rm SB}$. Evaluating this quantity, we find:

$$\begin{aligned}\tilde{\varepsilon}_{\rm SB} &= \frac{3fn_0v^2M_AM_{A'}h_0 \exp\left(\frac{-x_d\cos\theta}{h_0}\right)}{8\rho_{\rm SB}R\cos\theta}, \\ &\simeq \frac{5f}{\cos\theta}\left(\frac{M_{A'}}{18M_P}\right)\left(\frac{100\ {\rm m}}{R}\right)\left(\frac{1{\rm g/cm}^3}{\rho_{\rm SB}}\right)\left(\frac{v}{30\ {\rm km/s}}\right)^2 \exp\left(\frac{-x_d\cos\theta}{h_0}\right)\ {\rm eV},\end{aligned} \tag{16}$$

where M_P is the proton mass and R is the effective radius of the mirror SB.

If we know the energy dumped into the SB, $\varepsilon_{\rm SB}(x_d)$, we can estimate the temperature gained by the SB if we know the specific heat of the body. Recall that specific heat is just the energy required to raise the temperature of a body by 1 degree. Actually we are particularly interested in the energy required to heat the body from a temperature near absolute zero until it melts. For this we must integrate the specific heat from near absolute zero to the melting temperature, and also add on the heat of fusion, which is the energy required to effect the phase transition. This total energy — which we label ε_m — obviously depends sensitively on the type of material. While we do not have any direct empirical guidance about the likely chemical compositions of mirror SB, we can be guided by the compositions of ordinary matter SB — the asteroids and comets. An important observation though is that while icy ordinary matter bodies (comets) have only a relatively short lifespan in the inner solar system because they would have been melted by the Sun (and therefore can only exist in elliptical orbits), mirror space-bodies made of mirror ices could be plentiful in the inner solar system (in circular orbits) and might be expected to dominate over non-volatile substances. In the table below, we estimate this quantity for a few plausible space-body materials.

TABLE I

The physical properties [38] of some cited minerals in common meteorites [39].

Mineral (A')	$\rho_{\rm SB}$ (g/cm^3)	T_m (K)	Q_1 (kJ/mol)	L_F (kJ/mol)	ε_m eV/molecule
Ammonia Ice, NH_3 (17)	0.8	195	4.2	5.7	0.1
Methane Ice, CH_4 (16)	0.5	91	2.6	0.9	0.04
Ice, H_2O (18)	0.9	273	6	6	0.12
Cristobalite, SiO_2 (60)	2.2	1996	120	9.6	1.4
Enstatite, $MgSiO_3$ (104)	3.9	1850	200	75 ± 21	2.8
Forsterite, Mg_2SiO_4 (140)	3.2	2171	360	71 ± 21	4.5
Fe (56)	7.9	1809	62	13.8	0.8
Magnetite, Fe_3O_4 (232)	5.2	1870	360	138	4.1
Troilite, FeS (88)	4.7	1463	88	31	1.2
Nickel (59)	8.9	1728	53	17	0.7

A' denotes mirror atom's relative molecular weight;
T_m denotes melting point of A';
Q_1 denotes total heat absorbed by A' to raise its temperature from 0°K to its melting point;
L_F denotes heat of fusion (from solid phase to liquid phase);
$\varepsilon_m = Q_1 + L_F$, and we have changed to the convenient units of eV per molecule.

Assuming that no fragmentation occurs (prior to melting), then a large mirror SB would melt above the ground provided that $\tilde{\varepsilon}_{\rm SB}\ (x_d = 0) > \varepsilon_m$. Solving this condition for the SB velocity, v, we find:

$$v \gtrsim 10\sqrt{\left(\frac{\cos\theta}{0.5}\right)\left(\frac{0.1}{f}\right)\left(\frac{R}{100\ \rm m}\right)\left(\frac{18M_P}{M_{A'}}\right)\left(\frac{\rho_{\rm SB}}{1\ {\rm g/cm}^3}\right)\left(\frac{\varepsilon_m}{0.1\ \rm eV}\right)}\ \ {\rm km/s}. \tag{17}$$

We emphasise that this equation was derived assuming that the body's velocity, v, is approximately constant. This is roughly the case for a large body ($R \gg 10$ metres) because it is not slowed down much by the atmospheric drag force [*cf.* Eq. (9)]. Observe that Eq. (17) suggests that a large ($R \sim 100$ m) mirror SB made of mirror ices would typically melt at some point in the atmosphere (only for $R \gg 100$ m could a mirror icy body survive to hit the ground). Once it melts, the effect of the pressure of the atmosphere on the liquid body would cause it to disperse dramatically, increasing its effective surface area. This greatly increases the atmospheric drag force, causing the body to rapidly release its kinetic energy into the atmosphere, leading in essence, to an atmospheric explosion.

On the other hand, a large mirror rocky body could survive to hit the ground intact; only if its velocity was relatively large ($\gtrsim 50$ km/s) would it melt in the atmosphere. Of course, our estimation might be too simplistic to allow us to draw very rigorous conclusions. Nevertheless, the mirror matter hypothesis does seem to provide a nice explanation for the main features of the Tunguska event: the low altitude explosion, absence of ordinary fragments, and no chemical traces. Let us now take a closer look.

The SB would melt at a height $h = x_d \cos\theta$ above the ground if $\tilde{\varepsilon}_{\rm SB}$ $(x_d) = \varepsilon_m$. Solving this condition for the height, h, we find

$$h = h_0 \ln\left[\left(\frac{v}{10\ {\rm km/s}}\right)^2\left(\frac{1{\rm g/cm}^3}{\rho_{\rm SB}}\right)\left(\frac{100\ \rm m}{R}\right)\left(\frac{f}{0.1}\right)\left(\frac{0.5}{\cos\theta}\right)\left(\frac{M_{A'}}{18M_P}\right)\left(\frac{0.1\ \rm eV}{\varepsilon_m}\right)\right]. \tag{18}$$

Focussing our attention onto the Tunguska event, which is characterized by $M_{\rm SB} \sim 10^8 - 10^9$ kg ($\Rightarrow R \sim 40$ m for mirror ice and 20 m for mirror iron), $\cos\theta \sim 0.5$, and the height of the atmospheric explosion is $h \sim h_0$. In this case we find that

$$\begin{aligned} v &\sim 12\ {\rm km/s}\ \ \text{for mirror ice,}\\ v &\sim 40\ {\rm km/s}\ \ \text{for mirror iron.} \end{aligned} \tag{19}$$

Recall the range of expected velocities of the SB is 11 km/s $< v <$ 70 km/s. Thus, it seems that both mirror ices and mirror non-volatile material may plausibly explain the Tunguska event.

An interesting observation is that if large mirror SB are predominately made of mirror ices, then Eq. (18) suggests that smaller such bodies should explode at higher altitudes because of their smaller R values. Roughly speaking, the energy gained per molecule (in a large SB) is proportional to the area swept out divided by the number of SB molecules (*i.e.* $\propto S/V \propto 1/R$). That is, the energy gained per molecule is inverserly proportional to the body's size. Thus, smaller bodies should heat up faster. Furthermore, the energy gained also depends on the body's velocity, but the characteristics of the Tunguska event suggest a mirror body near the minimum value possible, 11 km/s [see Eq. (19)]. SB with higher velocities, which are possible, would also lead to higher altitude explosions. Thus, the unique low altitude explosion associated with the Tunguska event seems to have a simple explanation in this mirror matter interpretation. Smaller mirror SB of Tunguska chemical composition should always melt and thereby explode higher up in the atmosphere. This feature is in accordance with the observations of airburst events discussed in part II.

To conclude this section, let us mention that there are many puzzling features of the Tunguska event which we have yet to address here. For example, the origin of the optical anomalies, including abnormal sky-glows and unprecedented bright noctilucent clouds [6]. The most puzzling aspect of which is that they seem to appear a few days *before* the Tunguska event (for a review, see *e.g.* [20]). We make no claims that the mirror matter space-body hypothesis definitely explains all of the observed effects; our main task is to see if it can explain the main characteristics of the event (the low altitude atmospheric explosion, absence of fragments and chemical traces, visual sightings of the bolide). We suggest that the broad features of a SB made of mirror matter are indeed consistent with the main features of the Tunguska event. Further work needs to be done to see to what extent it can explain the other reported features.

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[6] These optical anomalies are in addition to the visual sightings of the bolide on June 30, 1908. The visual sightings could be explained in the mirror SB hypothesis because part of the kinetic energy of the SB is transferred to the air, which is eventually converted into ordinary heat and light as the high velocity air molecules (at least 11 km/s) eventually interact with (more distant) surrounding 'stationary' air.

5. Heating of a small mirror space-body penetrating the Earth's atmosphere

In this section we will examine the case of a small mirror SB entering the Earth's atmosphere. For small bodies, $R \lesssim 10$ metres, the atmospheric drag force effectively "stops" the body in the atmosphere — it loses its cosmic velocity and would reach the Earth's surface with only a relatively low impact velocity in the range 0.1 km/s $\lesssim v_{\rm impact} \lesssim 3$ km/s (providing of course that it does not melt or break up on the way down).

Because the velocity is not constant in this case, we must combine Eq. (12) with Eq. (6):

$$\begin{aligned} d\varepsilon &= n(h)\frac{1}{2}M_A v^2 S dx \\ dv &= -\frac{M_A}{M_{\rm SB}} v n(h) S dx. \end{aligned} \tag{20}$$

That is,

$$d\varepsilon = -\frac{vM_{\rm SB}}{2}dv. \tag{21}$$

Thus, if the body loses most of its cosmic velocity in the atmosphere, then integrating the above equation (and putting in the hydrodynamic factor, f), we find:

$$\varepsilon_{\rm SB} \approx f M_{\rm SB} v^2/4. \tag{22}$$

Here v is the initial velocity of the SB.

The above equation for the energy transferred to heating the SB can also be conveniently expressed in terms of heat energy per molecule, $\tilde{\varepsilon}_{\rm SB} \equiv \varepsilon_{\rm SB}/N_{\rm SB}$:

$$\begin{aligned} \tilde{\varepsilon}_{\rm SB} &= f M_{A'} v^2/4 \\ &\simeq f\left(\frac{M_{A'}}{18M_P}\right)\left(\frac{v}{11\ {\rm km/s}}\right)^2 5\ {\rm eV}. \end{aligned} \tag{23}$$

Clearly, the only small mirror space-bodies which can survive to strike the ground without completely melting must have relatively high values for ε_m and relatively low initial velocities near the minimum ~ 11 km/s. In the following table we compare $\tilde{\varepsilon}_{\rm SB}$ with ε_m for some plausible mirror SB materials.

TABLE II

Comparison between ε_m and $\tilde{\varepsilon}_{\rm SB}$ for a small mirror SB ($R \lesssim 10$ metres).

Mineral	$\tilde{\varepsilon}_{\rm SB}$ (eV per molecule)	ε_m (eV per molecule)
H_2O & NH_3 Ice	$0.5\left(\frac{f}{0.1}\right)\left(\frac{v}{11km/s}\right)^2$	0.1
CH_4 Ice	$0.5\left(\frac{f}{0.1}\right)\left(\frac{v}{11km/s}\right)^2$	0.04
Cristobalite, SiO_2	$1.5\left(\frac{f}{0.1}\right)\left(\frac{v}{11km/s}\right)^2$	1.4
Enstatite, $MgSiO_3$	$2.5\left(\frac{f}{0.1}\right)\left(\frac{v}{11km/s}\right)^2$	2.8
Forsterite, Mg_2SiO_4	$3.5\left(\frac{f}{0.1}\right)\left(\frac{v}{11km/s}\right)^2$	4.5
Fe	$1.5\left(\frac{f}{0.1}\right)\left(\frac{v}{11km/s}\right)^2$	0.8
Magnetite, Fe_3O_4	$7\left(\frac{f}{0.1}\right)\left(\frac{v}{11km/s}\right)^2$	4.1
Troilite, FeS	$2\left(\frac{f}{0.1}\right)\left(\frac{v}{11km/s}\right)^2$	1.2
Nickel	$1.5\left(\frac{f}{0.1}\right)\left(\frac{v}{11km/s}\right)^2$	0.7

As this table shows, a small mirror SB can potentially reach the Earth's surface without melting provided that $f \lesssim 0.1$ if they are made of typical non-volatile materials (and $f \lesssim 0.02$ if the are made of ices). While values of f as low as ~ 0.1 are presumably possible[7], values as low as 0.02 seem less likely. This means that a small mirror matter SB can possibly survive to hit the Earth's surface provided that it is made of a non-volatile composition such as mirror rocky silicate materials or mirror iron materials.

Can such a small mirror matter SB be responsible for the observed anomalous events discussed in Section 2.2? Recall that an ordinary matter SB explanation of these events suffers from two main difficulties. First, any low altitude ordinary body must have had a large highly luminous parent body. Second, a body having survived to low altitudes, losing its cosmic velocity, should have left recoverable fragments. Remarkably both of these difficulties evaporate in the mirror matter interpretation.

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[7] Roughly speaking Eq. (23) also applies to ordinary matter bodies which lose their cosmic velocity in the atmosphere; parts of which certainly do sometimes survive without completely melting. In addition to meteorite falls, there are also well documented space debris, such as parts of satellite (*e.g.* Skylab debris). Satellite parts enter the Earth's atmosphere at about 8 km/s, just below the minimum velocity of SB's.

First, the lack of ordinary fragments is easily explained if the SB is made of mirror matter. One might expect recoverable mirror matter fragments, but these might have escaped notice (especially if ε is negative, as we will explain in the next section).

Second, low altitude mirror SB need not have been large and highly luminous at high altitudes. Ablation should occur at a much lower rate for a mirror SB because the pressure of the atmosphere is dissipated within the body (rather than just at its surface as would be the case for an ordinary matter body entering the atmosphere). More importantly, air can be trapped *within* the body and can transport the heat away from the surface regions. The mechanism for producing ordinary light from a mirror SB is therefore completely different to an ordinary matter body. For a mirror SB, we can identify three basic mechanisms for producing ordinary light:

- Interactions with the air through ionizing collisions (where electrons are removed from the atoms) and excitations of the air molecules.
- The potential build up of ordinary electric charge as a consequence of these ionizing collisions which can trap ionized air molecules within the body. This build up of charge can lead to electrical discharges [40]. Note that this trapping of air cannot occur if the SB is made of ordinary matter.
- Heating of any ordinary matter fragments (if they exist!) within the mirror matter space-body, which subsequently radiates ordinary light.

The first two of these mechanisms listed above are actually most important for very speedy (mirror) meteoroids (as we will explain in a moment) but nevertheless may still play a role even if the velocity is near the minimum ~ 11 km/s as we suspect to be the case for the anomalous low altitude fireballs (such as the 2001 Jordan event and the 1994 Spanish event). A small mirror matter body can thereby be relatively dim at high altitudes (especially if it is of low velocity, $v \sim 11$ km/s). As it moves through the atmosphere it slows down due to the atmospheric drag force. The kinetic energy of the body is converted into the heating of the whole body and the surrounding compressed air both outside and *within* the body. Any ordinary matter fragments within the body will also heat up and emit ordinary light, but the body need not be extremely bright at high altitudes. The heating of the whole body could make the body act like a heat reservoir, perhaps allowing trapped air and ordinary matter fragments to emit some ordinary light even at low altitudes where it is moving relatively slowly (especially as our estimates in table II suggest that the body will be heated to near melting temperature which is typically $\gtrsim 1800\ K$ for plausible non-volatile mirror SB materials).

Let us briefly expand upon the effect of ionizing collisions and the potential build up of ordinary charge within the SB due to trapped ionized air molecules. This mechanism is most important at very high altitudes ($\gtrsim$ 100 km), since impacting air molecules can strike the mirror SB with their full velocity. At lower altitudes compressed air develops within and in front of the body which can shield the mirror SB from direct impacts at cosmic velocity. Note that this mechanism is also most important for SB entering the atmosphere with high velocity. The impacting air atoms have energy,

$$E = \frac{1}{2}M_A v^2 \approx 70 \left(\frac{v}{30 \text{ km/s}}\right)^2 \text{ eV}. \tag{24}$$

For a high velocity SB, $v \sim 70$ km/s, the energy of the impacting air atoms is sufficiently high for ionizing collisions to occur. For ordinary SB, the probability of ionizing collisions at these velocities is quite low [41], however for mirror SB energy loss due to ionizing collisions can potentially be comparable to Rutherford scattering. This might explain the anomalously high altitude beginnings of the observed light from certain speedy meteors [40]. It might also explain the release of electrical energy in some anomalous events such as the 1993 Polish event briefly mentioned in Section 2.2, because ionizing collisions should lead to a build-up of ordinary electric charge within the mirror SB from trapped ionized air molecules.

Of course, if the body is made (predominately) of mirror matter and does survive to hit the ground, it would not leave any significant ordinary matter fragments. This obviously simply explains the other mysterious feature of the anomalous small fireball events — the lack of ordinary fragments (despite the fact that the body was actually observed to hit the ground at low velocities). An important consequence of the mirror matter interpretation of the anomalous small fireball events is that mirror matter should exist in solid form (if they are indeed due to non-volatile mirror matter material[8]) and may therefore be potentially recoverable from these impact sites as we will explain in the following section.

6. Finding mirror matter in/on the ground and the sign of ε

The photon–mirror photon kinetic mixing induces small ordinary electric charges for the mirror electron and mirror proton. A very important issue though is the effective sign of this induced ordinary electric charge (the

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[8] Transfer of heat from the air to the mirror body would quickly melt any volatile mirror matter components (if they are on the Earth's surface), even if it could survive to hit the ground.

orthopositronium experiments are only sensitive to $|\varepsilon|$, they do not provide any information on the sign of ε). There are basically two physically distinct possibilities: The induced charge is either of the same sign or opposite, that is, either the mirror electrons repel ordinary electrons, or they attract them. In the case where ordinary and mirror electrons have ordinary charge of the same sign, the ordinary and mirror matter would repel each other. In this case, a fragment of mirror matter could remain on the Earth's surface, largely unmixed with ordinary matter. In the case where the mirror electrons have a tiny ordinary electric charge of the opposite sign to the ordinary electrons, the mirror atoms attract the ordinary ones. In this case it would be energetically favourable for mirror matter to be completely immersed in ordinary matter, releasing energy in the process.

In the first case, the maximum repulsive force at the mirror matter — ordinary matter boundary can be crudely estimated to be of order[9]:

$$\begin{aligned} F^{\text{electrostatic}}_{\text{maximum}} &\sim N^{\text{surface}}_{\text{atoms}} \frac{\varepsilon Z_1 Z_2 e^2}{r^2_{\text{bohr}}} \\ &\sim (N_{\text{SB}})^{2/3} \frac{\varepsilon Z_1 Z_2 e^2}{r^2_{\text{bohr}}}, \end{aligned} \tag{25}$$

where $N^{\text{surface}}_{\text{atoms}}$ is the number of surface atoms [which is related to the total number of atoms, N_{SB} by, $N^{\text{surface}}_{\text{atoms}} \sim (N_{\text{SB}})^{2/3}$] and Z_1 (Z_2) is the atomic number of the ordinary (mirror) nuclei. The electrostatic force opposes the force of gravity, so a mirror rock can be supported on the Earth's surface provided that $F^{\text{electrostatic}}_{\text{maximum}} > F^{\text{gravity}}$. F^{gravity} is simply given by

$$\begin{aligned} F^{\text{gravity}} &= g M_{\text{rock}} \\ &= g M_{A'} N_{\text{SB}}, \end{aligned} \tag{26}$$

where $g \simeq 9.8$ m/s^2 is the acceleration of gravity at the Earth's surface. Thus, we find:

$$\frac{F^{\text{gravity}}}{F^{\text{electrostatic}}_{\text{maximum}}} \sim \frac{g M_{A'} r^2_{\text{bohr}} (N_{\text{SB}})^{1/3}}{\varepsilon Z_1 Z_2 e^2}. \tag{27}$$

For a macroscopic sized body, N_{SB} is of order the Avagadro's number, N_A. Putting in the numbers we find:

$$\frac{F^{\text{gravity}}}{F^{\text{electrostatic}}_{\text{maximum}}} \sim 10^{-6} \left(\frac{10^{-6}}{\varepsilon}\right) \left(\frac{N_{\text{SB}}}{N_A}\right)^{1/3}, \tag{28}$$

---

[9] This equation completely neglects the shielding effect of electrons which means it is probably an over estimate (by an order of magnitude or two) of the maximum electrostatic repulsive force. Nevertheless, it is perhaps good enough for our purposes.

where we have taken $Z_1 \sim Z_2 \sim 10$ and $M_{A'} \sim 20 M_P$. Clearly, in this case where the induced ordinary electric charge of mirror particles are of the same sign as their ordinary counterparts, mirror matter bodies can be supported against gravity if $\varepsilon \sim 10^{-6}$ as suggested by experiments on orthopositronium [15]. If they impact with the Earth at low velocity then one might expect mirror fragments to exist right on the ground at the impact sites (or perhaps partly embedded in the ground).

Of course, a pure mirror rock or fragment would be invisible, but one could still touch it and pick it up (if $\varepsilon \sim 10^{-6}$). If it contained embedded ordinary matter, then it would then be visible but surely of unusual appearance. Of course, the fact that no such mirror rocks have been found may be due to their scarcity. The oldest terrestrial age of an iron meteorite that has been recovered on Earth (in Tamarugal in the Atacama desert, Chile) is 1.5 million years [42]. This represents a crude upper estimate for the typical time that an extraterrestrial body could remain and be found on the Earth's surface before it is buried by tectonic movements of the Earth's crust. The actual rate of anomalous low altitude bolide events across the entire Earth should be roughly 10–100 times the observed event rate (since they are only observed in populated regions). Thus, since Jordan-like events are observed to occur roughly on a yearly basis[10], one might expect them to occur on the planet roughly once every few weeks. Each event might leave small rocks and fragments over an area of about 1 m^2. Thus, the total area covered by mirror rocks and fragments integrated over the last million years is roughly expected to be less than of order 10^7–10^8 m^2 (or between 10–100 square kilometers) — a very small fraction of the Earth's surface. Nevertheless, the odds of finding a mirror matter rock could be greatly improved if one were to carefully search the 'impact sites', such as the one in Jordan and the one in Spain. Nevertheless, the fact that no strange invisible rocks have been recovered suggests perhaps that the induced ordinary electric charge of mirror particles is of *opposite* sign as their ordinary counterparts. In this case things are more interesting but somewhat more complicated.

If ordinary and mirror matter attracts each other, as it would do if say ε is negative (or if one had a piece of mirror anti-matter and ε were positive) then a fragment of mirror matter should become completely immersed in the ground (or at least the bulk of it). In the process energy will be released, but exactly how much is a non-trivial solid state problem.

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[10] In this estimate, we use the smaller Jordan-type events discussed in Section 2.2, rather than large Tunguska-type atmospheric explosions (Section 2.1), because the former seem to be more likely to leave large non-volatile fragments ('miror rocks') which should be easier to find then small fragments which might be left after atmospheric explosions.

In the realistic case of materials of varying density and composition, a mirror body should be expected to come to rest within the Earth, probably only just below the surface ($\sim$ meters).

Thus, irrespective of the sign of ε, mirror matter should be found in the impact sites — either on the ground or buried beneath the surface — if the anomalous low altitude fire balls are indeed caused by mirror SB. In some cases (*e.g.* the 2001 Jordan event) these sites are highly localised and easily accessible. One could collect samples of earth underneath the impact site and try to search for the presence of mirror matter fragments in the sample. Although chemically inert, mirror matter still has mass so its presence can be inferred by its weight. If one could count the number of ordinary atoms (and their mass) in the sample, maybe by using a mass spectrometer, then the presence of invisible gravitating matter could be inferred.

Another complementary way to test for mirror matter is by searching for its thermal effects on the ordinary matter surroundings. Consider the case where there is indeed mirror matter embedded in the ground. The mirror matter will be heated up by the interactions with the ordinary atoms. However, the mirror matter will thermally radiate mirror photons (which quickly escape) providing a cooling mechanism. Heat will be replaced from the ordinary matter surroundings which will become cooler as a result.

To make this quantitative, consider a spherical mirror body of radius R' surrounded by a much larger volume of ordinary matter. In this case, the energy lost per unit time to mirror radiation is given by the Stefan–Boltzmann law:

$$Q_{\rm rad} = \sigma T'^4 A', \tag{29}$$

where T' is the surface temperature of the mirror body and A' is its surface area. As energy escapes, this causes a temperature gradient in the surrounding ordinary matter as it thermally conducts heat to replace the energy lost. If we consider a shell of radius R surrounding the mirror body ($R > R'$) then the heat crossing this surface per unit time is given by:

$$Q = -\kappa \frac{\partial T}{\partial R} A, \tag{30}$$

where κ is the coefficient of thermal conductivity, and $A = 4\pi R^2$. Thus, equating the thermal energy transported to replace the energy escaping (as mirror radiation), we find:

$$\frac{\partial T}{\partial R} = \frac{-\sigma T'^4 R'^2}{\kappa R^2}. \tag{31}$$

This means that the change in temperature of the ordinary matter surrounding a mirror matter body at a distance R, $\delta T(R)$, is given by:

$$
\begin{aligned}
\delta T(R) &= \frac{-\sigma T'^4 R'^2}{\kappa R} \\
&\approx \left(\frac{T'}{270\ \mathrm{K}}\right)^4 \left(\frac{R'}{5\ \mathrm{cm}}\right)^2 \left(\frac{50\ \mathrm{cm}}{R}\right)\ \mathrm{K},
\end{aligned} \tag{32}
$$

where we have taken $\kappa = 0.004$ cal/K.s.cm, which is the average value in the Earth's crust. [Of course, the actual value of κ is the one valid at the particular impact site.] Clearly, an important but non-trivial solid state problem is to figure out the rate at which heat can be transferred from the surrounding ordinary matter into the mirror matter object, *i.e.* what is T'? If there were perfect thermal conduction between the mirror matter and surrounding ordinary matter, then $T' = T(R')$. However, because the thermal conduction is not perfect (and must go to zero as $\varepsilon \to 0$), it follows that $T' < T(R')$. It is possible that T' could be significantly less than $T(R')$; more work needs to be done to find out. However, if T' is not so small (it should be largest for mirror matter bodies with $\varepsilon < 0$ and large mirror thermal conductivity, such as mirror iron or nickel, because they can draw in heat from the surrounding ordinary matter throughout their volume) then Eq. (32) suggests that mirror matter fragments can leave a significant imprint on the temperature profile of the surrounding ordinary matter. Thus, we may be able to infer the presence of mirror matter in the ground simply by measuring the temperature of the Earth at various depths[11].

7. Conclusion

One of the most fascinating ideas coming from particle physics is the concept of mirror matter. Mirror symmetry — perhaps the most natural candidate for a symmetry of nature — requires a new form of matter, called 'mirror matter', to exist. The properties of mirror matter make it an ideal candidate to explain the inferred dark matter of the Universe. In addition, the mirror matter theory predicts maximal neutrino oscillations and a shorter effective orthopositronium lifetime — both effects which have been seen in experiments.

If mirror matter really does exist, then some amount should be out there in our solar system. While there is not much room for a large proportion of mirror matter in the inner solar system, it is conceivable that numerous small (asteroid sized) mirror matter space-bodies might exist. In fact, it is

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[11] It may be worth looking at satellite infrared temperature maps of the Tunguska region to see if there is any discernable temperature anomaly.

possible that many of the observed fireballs are in fact caused by the entry into the Earth's atmosphere of such mirror matter space-bodies [12]. We have shown that the interaction of a mirror matter space-body with the Earth's atmosphere seems to provide a very simple explanation for the Tunguska event as well as the more puzzling low altitude fireball events (such as the 1994 Spanish event and 2001 Jordan event discussed in Section 2.2).

Our analysis assumes that the photon–mirror photon kinetic mixing interaction exists, which is supported by experiments on orthopositronium. This fundamental interaction provides the mechanism causing the mirror space-body to release its kinetic energy in the atmosphere thereby making its effects 'observable'. Thus, one way to test the Tunguska mirror space-body hypothesis is to repeat the orthopositronium experiments. If mirror matter really exists and there is a significant photon–mirror photon interaction ($\varepsilon > 10^{-9}$), then this must show up if careful and sensitive experiments on orthopositronium are done.

A more dramatic way to test the mirror space-body hypothesis is to start digging! If these events are due to the impact of a mirror matter space-body, then an important implication is that mirror matter should exist on (or in) the ground at these impact sites. We have argued that the characteristics of mirror matter fragments on the Earth's surface depend rather crucially on the effective sign of the photon–mirror photon kinetic mixing parameter, ε, with the evident lack of surface fragments at various 'impact sites' suggesting that $\varepsilon < 0$. In this case, mirror matter should exist embedded in the ground at the various 'impact sites' and can potentially be extracted.

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[12] Interestingly, recent studies using the Sloan digital sky survey data have found [43,44] that the number of ordinary space-bodies (greater than 1 km in size) seems to be significantly less ($\sim$ 3 times) than expected from crater rates on the moon [45]. While both ordinary and mirror matter space-bodies would leave craters on the moon (assuming $\varepsilon \sim 10^{-6}$), mirror space-bodies may be invisible (or very dark) if they contain negligible amount of ordinary matter. Thus, large mirror space-bodies may have escaped direct observation, but their presence may have been hinted by the measured lunar crater rate.

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