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Does mirror matter exist?*

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Abstract

One of the most fascinating ideas coming from particle physics is the concept of mirror matter. Mirror matter is a new form of matter which is predicted to exist if mirror symmetry is respected by nature. At the present time evidence that mirror matter actually exists is in abundance, coming from a range of observations and experiments in astronomy, particle physics, meteoritics and planetary science.

*For a postscript version containing all figures see [http : //www.ph.unimelb.edu.au/~foot/rev.ps](http://www.ph.unimelb.edu.au/~foot/rev.ps)

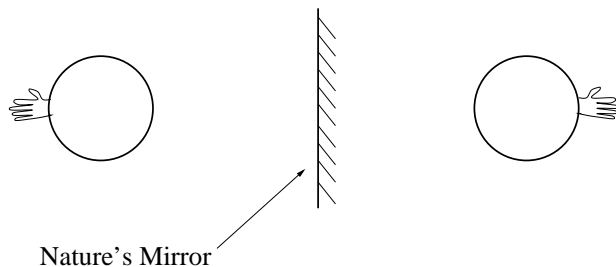
1 Introduction

Prior * to 1957 scientists believed that mirror reflection symmetry was respected by the interactions of the fundamental particles. Why? Perhaps because the other geometrical symmetries such as rotations and translations in space and time were observed to be good symmetries, it seemed natural that mirror reflection symmetry should be a good symmetry too. Furthermore, no experiment up until 1957 had indicated that these symmetries were anything but good symmetries of nature.

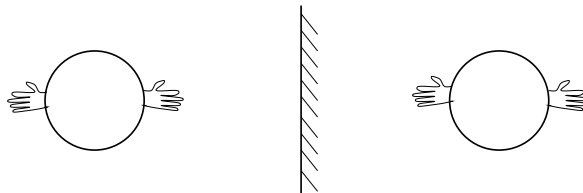
In 1956 Lee and Yang[2] proposed that the interactions of the fundamental particles were not mirror reflection invariant. They suggested that this could explain some known puzzles and proposed some new experiments to directly test the idea. Subsequently Madam C.S.Wu and collaborators dramatically confirmed that the interactions of the known particles were not mirror symmetric, just as Lee and Yang had suspected.

Today, it is widely believed that mirror symmetry is in fact violated in nature. God – it is believed – is left-handed. Actually, though, things are not so clear. What the experiments in 1957 and subsequent experiments have conclusively demonstrated is that the *known* elementary particles behave in a way which is not mirror symmetric. The weak nuclear interaction is the culprit, with the asymmetry being particularly striking for the weakly interacting neutrinos. For example, today we know that neutrinos only spin with one orientation. If one was coming towards you it would be spinning like a left-handed corkscrew. Nobody has ever seen a right-handed neutrino.

The basic geometric point is illustrated in the following diagram:



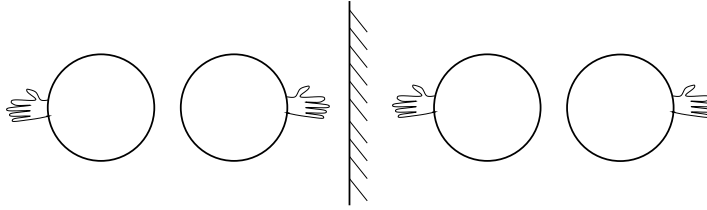
The left-hand side of this figure represents the interactions of the known elementary particles. The forces are mirror symmetric like a perfect sphere, except for the weak interaction, which is represented as a left hand. Also shown is nature's mirror - the vertical line down the middle. Clearly, the reflection is not the same as the original, signifying the fact that the interactions of the *known* particles are not mirror symmetric. If there were a right hand as well as a left hand then mirror symmetry would be unbroken.



*The aim of this article is to provide a fairly non-technical and up to date review of the motivations for mirror matter and the evidence for its existence. For a more detailed and (hopefully) entertaining exposition see the recent book[1].

However, this doesn't correspond to nature since no right-handed weak interactions are seen in experiments (this is precisely what the experiments in 1957 and subsequently have proven).

There are two remaining possibilities: We can either chop the hand off – but this is too drastic and is therefore not shown. It corresponds to having no weak interactions at all, again in disagreement with observations. This last possibility is the most subtle and consists of adding an entire new figure with the hand on the other side. Everything is doubled even the symmetric part, which is clearly mirror symmetric as indicated in the following diagram:



What this figure corresponds to is a complete doubling of the number of particles. For each type of particle, such as electron, proton and photon, there is a mirror twin. Where the ordinary particles favor the left hand, the mirror particles favor the right hand. If such particles exist in nature, then mirror symmetry would be exactly conserved (we denote the mirror particles with a prime).

e	e'
ν	ν'
p	p'
n	n'
\bar{e}	\bar{e}'
$\bar{\nu}$	$\bar{\nu}'$
\bar{p}	\bar{p}'
\bar{n}	\bar{n}'
γ	γ'
W, Z	W', Z'
G	G'

As will be discussed, the mirror particles can exist without violating any known experiment. Thus, the correct statement is that the experiments in 1957 and subsequently have only shown that the interactions of the *known* particles are not mirror symmetric, they have not demonstrated that mirror symmetry is broken in nature.

While many people regard the possible existence of mirror particles as highly speculative, it could also be argued that the assumption of broken mirror symmetry is equally

speculative. Clearly, it is not possible to figure out which path is chosen by nature on the basis of pure thought. What really needs to be done is to understand the experimental implications of the existence of mirror particles and find out whether such things could describe our Universe.

The mirror partners have the same mass as their ordinary counterparts, which is reminiscent of anti-particles. However, there is a crucial difference. Unlike anti-particles, the mirror particles interact with ordinary particles predominately by gravity only. The three non-gravitational forces act on ordinary and mirror particles completely separately [and with opposite handedness: where the ordinary particles are left-handed, the mirror particles are right-handed]. For example, while ordinary photons interact with ordinary matter (which is just the microscopic picture of the electromagnetic force), they *do not* interact with mirror matter*. Similarly, the ‘mirror image’ of this statement must also hold, that is, the mirror photon interacts with mirror matter but does not interact with ordinary matter. The upshot is that we cannot see mirror photons because we are made of ordinary matter. The mirror photons would simply pass right through us without interacting at all!

The mirror symmetry does require though that the mirror photons interact with mirror electrons and mirror protons in exactly the same way in which ordinary photons interact with ordinary electrons and ordinary protons. A direct consequence of this is that a mirror atom made from mirror electrons and a mirror nucleus, composed of mirror protons and mirror neutrons can exist. In fact, mirror matter made from mirror atoms would also exist with exactly the same internal properties as ordinary matter, but would be completely invisible to us! Clearly, if there was a negligible amount of mirror matter in our solar system, we might hardly be aware of its existence at all. Thus, the *apparent* left-right asymmetry of the laws of nature may be due to the preponderance of ordinary matter in our solar system rather than due to a fundamental asymmetry in the laws themselves.

While this is all very interesting, the most remarkable thing of all is that there is now a range of evidence actually supporting the mirror matter theory:

- 1) It predicts the existence of mirror matter in the Universe. Mirror matter would be invisible, making its presence felt by its gravitational effects. Remarkably, there is a large body of evidence for such invisible ‘dark’ matter. There is also specific evidence that mirror stars have been observed from their gravitational effects on the bending of light from background stars.

On the quantum level, small new fundamental interactions connecting ordinary and mirror matter are possible. Various theoretical constraints suggest only a few possible types of interactions: photon-mirror photon kinetic mixing and neutrino-mirror neutrino mass mixing[3, 4]. Such non-gravitational forces are extremely important and open up new ways in which to test the theory:

- 2) Orthopositronium should have a shorter effective lifetime (in a “vacuum” experiment) than predicted due to the effects of photon - mirror photon kinetic mixing[5, 6].
- 3) If there are small mirror matter bodies in our solar system then this would lead to

*Actually, as will be explained in a moment, it is possible for small *new* forces to exist which connect the ordinary and mirror particles together. For the purposes of this introductory paragraph, this possibility is temporarily ignored.

a new class of cosmic impact events when such bodies strike the Earth. Characteristics of such impacts will be the lack of ordinary fragments and other anomalous features. Such impacts will leave mirror matter embedded in the ground which could potentially be extracted and purified (assuming that the small photon-mirror photon kinetic mixing force exists, which is strong enough to oppose the Earth's feeble gravity).

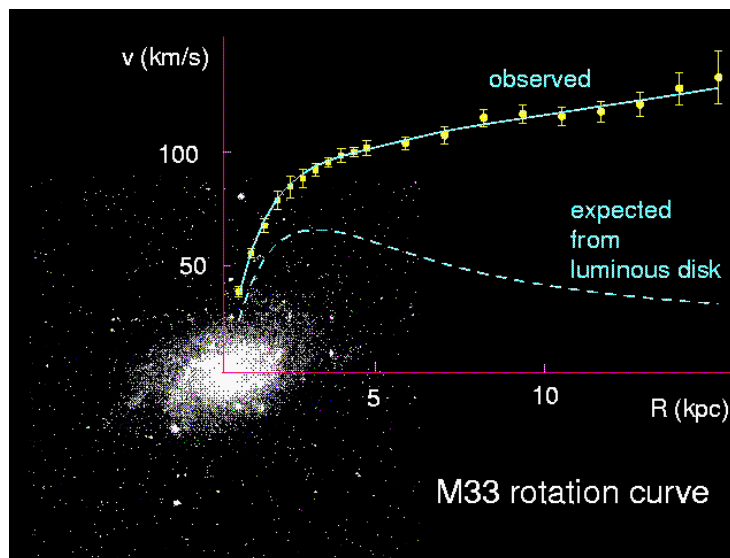
4) If there is some remnant mirror hydrogen gas in our solar system, then spacecraft will experience a drag force and slow down.

5) If neutrinos have mass then oscillations between ordinary and mirror neutrinos can occur. Such effects could show up in neutrino physics experiments.

At the present time there is interesting experimental/observational evidence supporting all five of these predictions. We now describe this evidence in more detail.

2 Implications of the mirror world for cosmology

There is strong evidence for a large amount of dark matter in the Universe. Flat rotation curves of stars in spiral galaxies imply that there must exist invisible halos in galaxies such as our own Milky Way.



The observed orbiting velocities of stars in the spiral galaxy M33 superimposed on its optical image. The horizontal axis is the distance from the center of the galaxy in kiloparsecs. The poor agreement between the expected velocities and the actual ones provides strong evidence for invisible ‘dark matter’. [Credit for this figure belongs to Ref.[7]].

There is also strong evidence that this dark matter must be something exotic: ordinary baryons simply cannot account for it[8]. Mirror baryons are necessarily stable and dark

(because the coupling of mirror matter to ordinary photons is necessarily very small) and are a very natural candidate for the inferred dark matter in the Universe*. This has been argued for some time by Sergei Blinnikov and Maxim Khlopov[9]. In fact dark matter made of mirror matter would have the property of clumping into compact bodies such as mirror stars. This leads naturally to an explanation for the mysterious Massive Astrophysical Compact Halo Objects (or MACHO's) inferred by the MACHO collaboration.

This collaboration has been studying the nature of halo dark matter by using the gravitational microlensing technique. This Australian-American experiment has collected 5.7 years of data and provided statistically strong evidence for dark matter in the form of invisible star sized objects which is what you would expect if there was a significant amount of mirror matter in our galaxy. The MACHO collaboration [10] have done a maximum likelihood analysis which implies a MACHO halo fraction of 20% for a typical halo model with a 95% confidence interval of 8% to 50%. Their most likely MACHO mass is between $0.15M_{\odot}$ and $0.9M_{\odot}$ depending on the halo model. These observations are consistent with a mirror matter halo because the entire halo would not be expected to be in the form of mirror stars. Mirror gas and dust would also be expected because they are a necessary consequence of stellar evolution and should therefore significantly populate the halo.

If mirror matter exists in our galaxy, then binary systems consisting of ordinary and mirror matter should also exist. While systems containing approximately equal amounts of ordinary and mirror matter are unlikely due to e.g. differing rates of collapse for ordinary and mirror matter (due to different initial conditions such as chemical composition, temperature distribution etc), systems containing predominately ordinary matter with a small amount of mirror matter (and vice versa) should exist. Remarkably, there is interesting evidence for the existence of such systems coming from extra-solar planet astronomy.

In the past few years more than 100 "extrasolar" planets have been discovered orbiting nearby stars[11]. They reveal their presence because their gravity tugs periodically on their parent stars leading to observable Doppler shifts. In one case, the planet HD209458b, has been observed to transit its star allowing for an accurate determination of its size and mass. One of the surprising characteristics of the extrasolar planets is that there are a class of large ($\sim M_{Jupiter}$) close-in planets (with a typical orbital radius of $\sim 0.05 A.U.$, that is, about 8 times closer than the orbital radius of Mercury). Ordinary (gas giant) planets are not expected to form close to stars because the high temperatures do not allow them to form. Theories have been invented where they form far from the star where the temperature is much lower, and migrate towards the star.

A fascinating alternative possibility presents itself in the mirror world hypothesis. The close-in planets may be mirror worlds composed predominately of mirror matter[12]. They do not migrate significantly, but actually formed close to the star which is not a problem

*Note that various observations indicate that the amount of dark matter is more than 10 times the amount of ordinary matter in the Universe. This is not a problem for the mirror matter theory because a mirror symmetric microscopic theory does not actually imply equal numbers of ordinary and mirror atoms in the Universe. The point is that the initial conditions need not be mirror symmetric. The Universe could have been created with more mirror matter than ordinary matter; alternatively it is possible that the macroscopic asymmetry was generated during the early evolution of the Universe.

for mirror worlds because they are not significantly heated by the radiation from the star. This hypothesis can explain the opacity of the transiting planet HD209458b because mirror worlds would accrete ordinary matter from the solar wind which accumulates in the gravitational potential of the mirror world. It turns out that the effective radius of ordinary matter depends relatively sensitively on the mass of the planet, so that this mirror world hypothesis can be tested when more transiting planets are discovered.

If this mirror world interpretation of the close-in planets is correct then it is very natural that the dynamical mirror image system of a mirror star with an ordinary planet will also exist. Such a system would appear to ordinary observers as an “isolated” ordinary planet. Remarkably, such “isolated” planets have recently been identified in the σ Orionis star cluster[13]. These planets have estimated mass of $5 - 15M_{Jupiter}$ (planets lighter than this mass range would be too faint to have been detected at present) and appear to be gas giants which do not seem to be associated with any visible star. Given that the σ Orionis cluster is estimated to be less than 5 million years old, the formation of these “isolated” planets must have occurred within this time (which means they can’t orbit faint stellar bodies such as old white dwarfs). Zapatero Osorio et al[13] argue that these findings pose a challenge to conventional theories of planet formation which are unable to explain the existence of numerous isolated planetary mass objects. Thus the existence of these planets is surprising if they are made of ordinary matter, however their existence is natural from the mirror world perspective[14]. Furthermore, if the isolated planets are not isolated but orbit mirror stars then there must exist a periodic Doppler shift detectable on the spectral lines from these planets. This represents a simple way of testing this hypothesis[14].

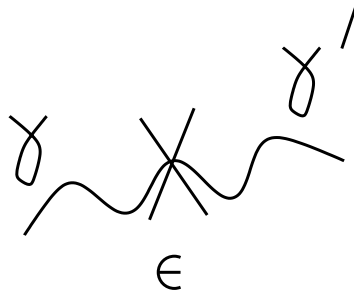
3 Implications of the mirror world for positronium

There are only a few possible ways in which ordinary and mirror matter can interact with each other besides gravity, including: photon - mirror photon kinetic mixing and neutrino - mirror neutrino mass mixing (if neutrinos have mass).

Photon - mirror photon kinetic mixing is described in quantum field theory by the Lagrangian term:

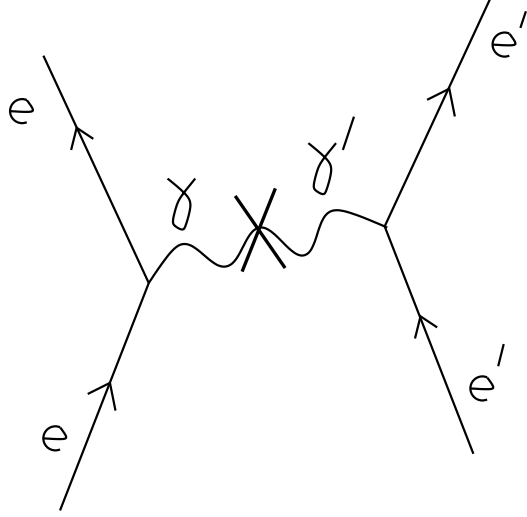
$$\mathcal{L}_{int} = \epsilon F^{\mu\nu} F'_{\mu\nu} \quad (1)$$

where $F^{\mu\nu} \equiv \partial^\mu A^\nu - \partial^\nu A^\mu$ is the usual Field strength tensor, and the F' is the corresponding quantity for mirror photons. It corresponds to a small coupling between ordinary and mirror photons. In the language of Feynman diagrams it is represented by:



In the absence of any photon-mirror photon kinetic mixing interaction, an ordinary elec-

tron cannot interact with a mirror electron because ordinary photons do not interact with mirror electrons (and mirror photons do not interact with ordinary electrons). However, if there is a photon-mirror photon kinetic mixing interaction, then an ordinary electron can interact with a mirror electron:



The net effect of the photon-mirror photon mixing is to make mirror electrons interact slightly with ordinary electrons (and similarly for other charged particles). That is, mirror electrons behave as if they have a tiny ordinary electric charge. The size of the effect depends on the strength of the photon-mirror photon kinetic mixing interaction – which is characterised by the parameter ϵ .

It turns out that the most important experimental implication of photon - mirror photon kinetic mixing is a rather subtle modification of the orthopositronium lifetime[5]. Orthopositronium is the bound state composed of an electron and positron where the spins of both particles are aligned so that the bound state has spin 1. The ground state of orthopositronium (o-Ps) decays predominately into 3 photons. The decay rate has been computed in QED leading to a discrepancy with some of the experimental measurements. Some of the measurements find a faster decay rate than theoretically predicted. This discrepancy has led to a number of experimental searches for exotic decay modes, including a stringent limit on invisible decay modes[15].

The modification of the lifetime predicted in the mirror matter theory occurs because the kinetic mixing of the photon with the mirror photon generates a small off-diagonal orthopositronium mass leading to oscillations between orthopositronium and mirror orthopositronium. The orthopositronium produced in the experiment oscillates into its mirror partner, whose decays into three mirror photons are undetected. This effect only occurs in a vacuum experiment where collisions of the orthopositronium with background particles can be neglected. Collisions with background particles will destroy the quantum coherence necessary for oscillations to occur. Thus, experiments with large collisions rates remain unaffected by kinetic mixing and the lifetime of orthopositronium will be the same as predicted by QED. Experiments in vacuum on the other hand, should show a slight increase in the decay rate, as oscillations into mirror orthopositronium and their subsequent

invisible decays effectively reduce the number of orthopositronium states faster than QED predicts.

The two most accurate experimental results, normalized to the theoretical QED prediction[16] are given in the table below *

Reference	$\Gamma_{oPs}(exp)/\Gamma_{oPs}(theory)$	Method	Γ_{coll}
Ann Arbor[20]	1.0012 ± 0.0002	Vacuum Cavity	$\sim (3 - 10)\Gamma_{oPs}$
Tokyo[19]	1.0000 ± 0.0004	Powder	$\sim 10^4\Gamma_{oPs}$

Thus, we see that the Tokyo experiment agrees with the QED prediction while the Ann Arbor vacuum experiment disagrees at about 5 sigma. These results can be explained in the mirror matter model by observing that the large collision rate of the orthopositronium in the Tokyo experiment will render oscillations of orthopositronium with its mirror counterpart ineffective**, while the larger decay rate obtained in the vacuum cavity experiment can be explained because of the much lower collision rate of orthopositronium in this experiment allows the oscillations of ordinary to mirror orthopositronium to take effect[6]. Clearly, an experiment with a larger cavity should have an even larger effect. Several new experiments are now being done which will test for this effect and either confirm (or refute) the mirror world explanation.

4 Anomalous Earth impact events

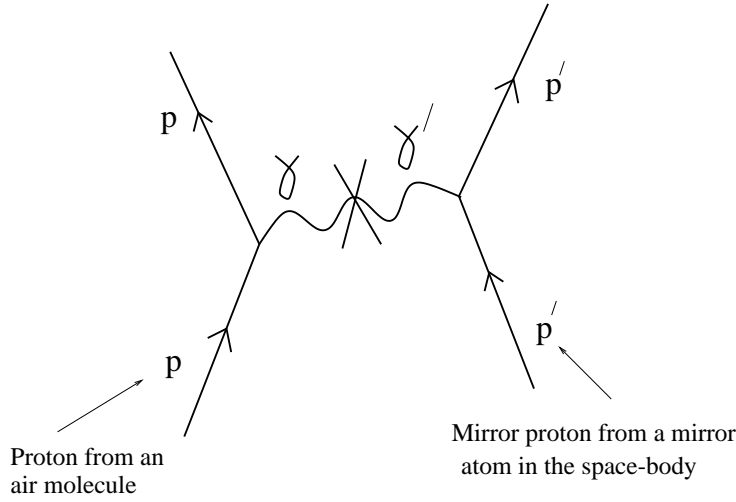
There is not much room for a large amount of mirror matter in our solar system. For example, the amount of mirror matter within the Earth has been constrained to be less than $10^{-3}M_{Earth}$ [21]. However, we don't know enough about the formation of the solar system to be able to exclude the existence 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 possibility***. [Maybe the Oort cloud itself is composed predominately of mirror matter bodies, see section 5].

If such small mirror matter bodies exist 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 matter space-body would simply pass through the Earth and nobody would know about it unless the body was so heavy as to gravitationally affect the motion of the Earth. However, if there is a photon-mirror photon transition force as suggested by the orthopositronium experiments, then the mirror nuclei can interact with the ordinary nuclei, as illustrated on the following page.

*A third experiment with gas[17] also has an anomalously high decay rate, however there appears to be large systematic uncertainties because the orthopositronium is not thermalized in this experiment[18, 19].

**The experimental limit[15] for invisible decay modes also does not exclude this mirror world oscillation mechanism because the collision rate of the orthopositronium was very high in those experiments.

***Large planetary sized bodies are also possible if they are in distant orbits[22] or masquerade as ordinary planets or moons by accreting ordinary matter onto their surfaces.



Scattering of air as it passes through the mirror matter space-body.

In other words, the nuclei of the mirror atoms of the space-body will undergo Rutherford scattering with the nuclei of the atmospheric nitrogen and oxygen atoms. In addition, ionizing interactions can occur (where electrons are removed from the atoms) which can ionize both the mirror atoms of the space-body and also the (ordinary) atmospheric atoms. This would make the mirror matter space-body effectively visible as it plummets to the surface of our planet.

The rate at which the kinetic energy of a space-body composed of mirror matter loses energy through the air depends on a number of factors, including, the strength of the photon-mirror photon transition force (ϵ), the chemical composition of the space-body, its initial velocity and its size and shape. We could estimate the initial velocity of the space-body by observing that the velocity of the Earth around the Sun is about 30 km/s. The space-body should have a similar velocity so that depending on its direction, the relative velocity of the space-body when viewed from Earth would be expected to be between about 11 and 70 km/s *.

It turns out that for $\epsilon \gtrsim 10^{-8}$ (which includes the value $\epsilon \simeq 10^{-6}$ suggested by the orthopositronium experiments) the air molecules typically undergo many collisions within the mirror matter space-body. One important consequence of this is that the air resistance (or atmospheric 'drag force') of the mirror matter space-body is actually roughly the same as if it were made of ordinary matter. The air resistance will 'stop' a space-body in the atmosphere if it is small in size (roughly less than 10 meters in diameter) leaving it with a free fall velocity of ~ 0.3 km/s. On the other hand, for a large body, much bigger than 10 meters in diameter, it will not lose much of its cometic velocity in the atmosphere if it remains intact.

There are important differences between impacting ordinary and mirror matter space-

*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).

bodies. A mirror body would heat up *internally* from the interactions of the atmospheric atoms which would penetrate within the space-body. This is quite unlike that of an ordinary body which would heat up only from the friction on the surface. This means that small mirror matter bodies can have initially low rates of ablation (i.e. surface melting) and therefore be quite dim at high altitudes. If they are made of non-volatile mirror material (such as mirror iron) they can reach the ground without melting and vaporizing in the atmosphere. Remarkably such types of events are actually seen in nature.

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.[23]). 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.[24]. 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. Sound phenomena consisting of sonic booms should also have occurred. Remarkably neither of these two expected phenomena were observed for this event. The authors of Ref.[24] 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. The “crater” had dimensions 29 m \times 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.[24] 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)

Figure Jordan1.jpg

Figure Jordan2.jpg

Pictures of the Jordan impact site[25]

but no ordinary crater. [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[25]. 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 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.

If these anomalous events are due to the impact of a mirror matter space-body, then the implications are extremely important. In particular there should be large pieces of mirror matter still lodged in the ground at the impact sites. The important point is that the small photon-mirror photon transition force should be large enough to oppose the force of gravity*. Clearly an important issue is to develop ways of testing for the presence of mirror matter at these sites. Several ideas have been proposed:

*Technically, there are two quite distinct cases, depending on the sign of ϵ . (The orthopositronium experiments do not provide any information on the sign of ϵ). Either the photon-mirror photon mixing induces a small ordinary electric charge for the mirror electrons ($e\epsilon$) of the same sign as the ordinary electrons, or the sign is opposite. In the first case, the photon-mirror photon mixing force leads to electrostatic *repulsion* between the mirror atoms (of the mirror matter fragment) and the ordinary atoms in the earth. In the alternative case of negative ϵ , there is actually electrostatic *attraction* between ordinary and mirror atoms. In both cases though, the interactions should be strong enough to stop a piece of mirror matter from falling through the Earth. However an important difference between the two cases is that in the first case ($\epsilon > 0$) the repulsion will cause mirror matter fragments to remain on or near the surface, largely unmixed with ordinary matter, while in the second case ($\epsilon < 0$) the mirror matter will penetrate the earth (a few metres perhaps) becoming completely mixed in with ordinary matter, and releasing energy in the process. Maybe this was the cause of the energy release evident at the Jordan impact sites (c.f. above figures).

- *Thermal effects of the mirror matter.* Mirror matter can absorb heat from the surrounding ordinary matter (through the photon-mirror photon kinetic mixing interaction) and radiate it away into invisible mirror photons. This will effectively cool the ordinary matter, an effect which could be measured.
- *The presence of mirror matter fragments embedded in ordinary matter.* Mirror matter, although essentially chemically inert, still has mass. In principle it could be extracted and purified, although the most efficient way of doing this is not yet known.
- *Heavy element bound-states.* Heavy mirror elements can actually form bound-states with ordinary heavy elements (e.g. $Fe - Fe'$, $Fe - Pb'$ etc)[26]. These would appear as anomalously heavy elements which could show up in careful mass spectrometer studies.

Finally, let me also mention that a large mirror matter body may have been responsible for the Tunguska event. For more details of this mirror matter interpretation of the anomalous small meteoritic events and also application to the Tunguska event, See Ref.[27, 1].

Figure tunguska.jpg

Felled trees as seen by Kulik during his 1928 Tunguska expedition.

5 Comets, atmospheric anomalies and pioneer spacecraft

If mirror matter space-bodies do exist in our solar system, then one might expect other scientific implications. In order not to bore the reader too much, I will mention only a few of these things – and only very briefly.

5.1 Are comets made of mirror matter?

Comets are believed to originate from an approximately spherically symmetric cloud extending out about half way to the nearest star. This comet cloud, called the Oort cloud, is reminiscent of the dark halo of our galaxy. Both are largely invisible, are distributed differently to the ‘visible’ matter, and are also hypothetical. Of course, this analogy is very simplistic and should not be taken very seriously. Nevertheless, it is also true that Comets seem to have a number of puzzling features and are not altogether well understood. One interesting feature of comets is that they seem to contain a very dark nucleus, as shown in the picture of comet Halley.

Figure halley.gif

Comet Halley's Nucleus. This picture was taken by the spacecraft Giotto. Contrary to prior expectations, Halley's nucleus is very dark – one of the darkest objects in the solar system. Credit: Halley Multicolour Camera Team, ESA.

Its nucleus has an albedo of only 0.03 making it one of the darkest objects in the solar system – darker even than coal! This has led me to wonder whether the nucleus could be composed predominately of mirror matter. Of course, pure mirror matter would be transparent, but if it contained a small admixture of ordinary matter embedded within, it could appear opaque and dark. If the ordinary matter had a volatile component such as water ice, then this would explain the large head and tail observed when the comet passed close to the sun. Such a picture would also be consistent with observations suggesting that many comets lose a large factor (100-1000) in average brightness after approaching the sun for the first time. If this interpretation is correct, then comets may simply become dimmer and dimmer over time eventually losing all of their volatile ordinary matter component. They may effectively become invisible. Of course, the rate that this occurs may depend on many things such as the proportion of ordinary to mirror matter, the chemical composition, details of the orbit etc.

Interestingly, a recent study[28] has concluded that many old comets must have either become invisible or have somehow disintegrated. The number of cometary remnants (asteroid-like objects) is 100 times less abundant than theoretically expected![28]. Clearly, this seems to support (or at least, encourage) the mirror matter interpretation of the comets. Of course, if many comets are predominately made of mirror matter then this fits in nicely with the mirror matter interpretation of the anomalous small fireballs (and Tunguska event), which was discussed in section 4. It might also be connected with atmospheric anomalies, as will now be discussed.

5.2 Atmospheric anomalies caused by small mirror matter space-bodies?

To explain the anomalous small fireball events we require the mirror matter space-body to survive and hit the ground without completely melting and vaporizing. Detailed studies[27] have shown that this is possible for initial velocities near the minimum (~ 11 km/s) and also for non-volatile mirror matter (such as mirror iron). A mirror space-body composed of volatile material such as mirror water ice would be expected to heat up

enough to completely vaporize in the atmosphere (unless it was very large $\gtrsim 10$ meters in diameter). After vaporizing, the mirror atoms interact with the air atoms by Rutherford scattering. Although initially the mirror matter will heat up the ordinary matter because of its large kinetic energy (since its initial velocity is at least 11 km/s), after a short time, the mirror matter will cool the atmosphere. The mirror atoms will draw in heat from the surrounding ordinary atoms and radiate it away into mirror photons. Since the mirror atoms are not absorbing mirror photons from the environment, heat will be lost from the system. The net effect is a localized rapid cooling of the atmosphere which might lead to the formation of unusual clouds and other strange atmospheric phenomena. Perhaps this might explain the remarkable observations of falling ice blocks[29] and maybe even the observations of atmospheric ‘holes’[30].

5.3 Anomalous acceleration of the Pioneer spacecraft explained?

Another indication for mirror matter in our solar system comes from the Pioneer 10 and 11 spacecraft anomalies. These spacecraft, which are identical in design, were launched in the early 1970’s with Pioneer 10 going to Jupiter and Pioneer 11 going to Saturn. After these planetary rendezvous, the two spacecraft followed orbits to opposite ends of the solar system with roughly the same speed, which is now about 12 km/s. The trajectories of these spacecraft were carefully monitored by a team of scientists from the Jet Propulsion Laboratory and other institutions[31]. The dominant force on the spacecraft is, of course, the gravitational force, but there is also another much smaller force coming from the solar radiation pressure – that is, a force arising from the light striking the surface of the spacecraft. However, the radiation pressure decreases quickly with distance from the sun, and for distances greater than 20 AU it is low enough to allow for a sensitive test for anomalous forces in the solar system. The Pioneer 11 radio system failed in 1990 when it was about 30 AU away from the Sun, while Pioneer 10 is in better shape and is about 70 AU away from the Sun (and still transmitting!).

The Pioneer 10/11 spacecrafts are very sensitive probes of mirror gas and dust in our solar system if the photon-mirror photon transition force exists as suggested by the orthopositronium experiments. Collisions of the spacecraft with mirror particles will lead to a drag force which will slow the spacecraft down. This situation of an ordinary matter body (the spacecraft) propagating through a gas of mirror particles is a sort of ‘mirror image’ of a mirror matter space-body propagating through the atmosphere which was considered in the previous section.

Interestingly, careful and detailed studies[31] of the motion of Pioneer 10 and 11 have revealed that the accelerations of *both* spacecrafts are anomalous and directed roughly towards the Sun, with magnitude, $a_p = (8.7 \pm 1.3) \times 10^{-8} \text{ cm/s}^2$. In other words, the spacecrafts are inexplicably slowing down! Many explanations have been proposed, but all have been found wanting so far. For example, ordinary gas and dust cannot explain it because there are rather stringent constraints on the density of ordinary matter in our solar system coming from its interactions with the sun’s light. However, the constraints on mirror matter in our solar system are much weaker because of its invisibility as far as its interactions with ordinary light is concerned.

If this anomalous acceleration of the spacecraft is due to remnant mirror matter gas or

dust in our solar system, then calculations of Ray Volkas and myself[32] suggest a density of mirror matter in our solar system of about $\approx 4 \times 10^{-19}$ g/cm³. It corresponds to about 200,000 mirror hydrogen atoms (or equivalent) per cubic centimetre. If the mirror gas/dust is spherically distributed with a radius of order 100 AU, then the total mass of mirror matter would be about that of a small planet ($\approx 10^{-6} M_{sun}$) with only about $10^{-8} M_{sun}$ within the orbit of Uranus, which is about two orders of magnitude within present limits. If the configuration is disk-like rather than spherical, then the total mass of mirror matter would obviously be even less. The requirement that the mirror gas/dust be denser than its ordinary counterpart at these distances could be due to the ordinary material having been expelled by solar pressure...

6 Implications of the mirror world for neutrino physics

If neutrinos have mass, then it is possible for ordinary and mirror neutrinos to oscillate into each other. Neutrino oscillations are a well known quantum mechanical effect which arise when the flavour eigenstates are linear combinations of 2 or more mass eigenstates. For example, if the electron and muon neutrinos have mass which mixes the flavour eigenstates, then in general the weak eigenstates are orthogonal combinations of mass eigenstates, i.e.

$$\nu_e = \sin \theta \nu_1 + \cos \theta \nu_2, \quad \nu_\mu = \cos \theta \nu_1 - \sin \theta \nu_2. \quad (2)$$

A standard result is that the oscillation probability for a neutrino of energy E is then

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 L/L_{osc}, \quad (3)$$

where L is the distance from the source and $L_{osc} \equiv 4E/\delta m^2$ is the oscillation length (and natural units have been used, i.e. $c = h/2\pi = 1$). If $\sin^2 2\theta = 1$ then the oscillations have the greatest effect and this is called maximal oscillations.

Anyway, in 1992 Henry Lew, Ray Volkas and I[4] found the remarkable result that the oscillations between ordinary and mirror neutrinos are necessarily maximal which is a direct consequence of the mirror symmetry. One way to see this is to note that if neutrinos mix then the mass eigenstates are non-degenerate and necessarily parity eigenstates if parity is unbroken. Considering the first generation electron neutrino, ν_e and its mirror partner, ν'_e , the parity eigenstates are simply $\nu^\pm = (\nu_e \pm \nu'_e)/\sqrt{2}$ (since parity interchanges the ordinary and the mirror particles) and hence

$$\nu_e = \frac{\nu^+ + \nu^-}{\sqrt{2}}, \quad \nu'_e = \frac{\nu^+ - \nu^-}{\sqrt{2}}. \quad (4)$$

Comparing this with Eq.(2) we see that $\theta = \pi/4$ i.e. $\sin 2\theta = 1$ and hence maximal mixing! Thus, if neutrinos and mirror neutrinos have mass and mix together then the oscillations between the ordinary and mirror neutrinos are necessarily maximal.

This result is extremely interesting in view of the accumulated evidence for neutrino oscillations (for a recent summary, see Ref.[33] and references there-in). Three types of experiments suggest the existence of neutrino oscillations and actually require the existence of at least one new ‘sterile neutrino’ (i.e. non-interacting neutrino such as a

mirror neutrino) maximally mixed with one of the known neutrinos. However, more experimental studies need to be done and are being done, so the situation in neutrino physics will become clearer. Of course, it is possible that there is no detectable mirror world effect for neutrinos, even if mirror matter exists. While the mixing is maximal, the oscillation lengths depend on the details of the neutrino mass physics. In particular, in the limit that the mass mixing between ordinary and mirror neutrinos goes to zero, the effect of the mirror world must also vanish.

7 Conclusion

It is a known fact that almost every plausible symmetry (such as rotational invariance, translational invariance etc) are found to be exact symmetries of the particle interactions. Thus, it would be very strange if the fundamental interactions were not mirror symmetric. It is a very interesting observation that mirror symmetry requires the existence of a new form of matter called ‘mirror matter’, otherwise there is nothing to balance the left-handed nature of the weak force. Even more interesting, is the remarkable evidence that mirror matter actually exists. But, does mirror matter really exist? I’m not sure, but I would very much like to find out. Maybe the answer lies in Jordan or maybe it is blowing in the wind[34]...

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