Can we really rule out the existence of antistars?

Luigi Foschini
Institute TeSRE – CNR, Via Gobetti 101, I–40129, Bologna(Italy)
email: foschini@tesre.bo.cnr.it

Abstract
The existence of large domains of antimatter is still an open question. Some space mission and experiments in the near future are expected to give reasonable answer to that question. Meanwhile, we can try to search for other signatures of the presence of antimatter. This paper presents a discussion about possible effects of the close encounter of stars and antistars. It is known that the accretion power can be higher in presence of antimatter, because of high-energy photons generated in annihilation, which result in a smaller radiation pressure. Therefore, the Eddington luminosity can reach higher values. Calculations of the gamma-ray flux above 100 MeV, and comparison with recent data from satellites, show a good agreement for certain sources. So, let’s play some science-fiction!

1 Introduction

During last decades, high-energy astrophysics has dramatically changed, with the discovery of powerful gamma-ray sources. Gamma-ray bursts (GRB) represent one of the most fascinating mysteries of the nature. Since their accidental discovery, in the late 1960s (Klebesadel et al. [1973]), they puzzled astrophysicists both for their enormous amount of energy released (about $10^{51} - 10^{54}$ erg in a few seconds) and for their “inner engine”, hidden from direct observations. This started soon a plethora of theories, involving supernovae, neutron stars, antimatter effects, black holes, and more and more exotic options (for a review see Piran [1997], [1999], Rees [2000]).
GRB are not the only source in the universe with large energy release; for example, another exciting mystery is represented by active galactic nuclei (AGN). They are found to produce much more luminosity than a typical galaxy, even $10^4$ times, in a tiny volume, less than 1 pc$^3$ (for a review, Krolik [1999]).

It is worth noting that the energy release is too large to be due to nuclear reactions and, if we want to avoid introducing new physics, we can use only two sources of energy: gravitation and matter–antimatter annihilation. Actual theories consider gravitation as the main mechanism driving these high–energy astrophysical sources, while matter–antimatter annihilation has been neglected mainly because we have not detected macroscopic bodies made of antimatter in the Solar System and its neighbourhood. Moreover, a well detailed review by Steigman ([1971]) showed that there is no experimental evidence of the existence of large amount of antimatter in the universe. But according to Steigman himself: “On the other hand, failure to construct consistent, symmetric cosmologies may indicate either a lack of antimatter or a lack of imagination”.

Indeed, although experimental particle physics has showed the symmetry between particles and antiparticles – the creation of matter must occurs simultaneously with the creation of antimatter –, it can be unsatisfactory that current cosmologies consider a universe made of matter only. First attempts to construct a symmetric cosmology were done by Klein and Alfvén during fifties and sixties (see Alfvén [1965]). Later on, this argument was widely debated – literature includes diametrically opposed points of view –, but there are no sufficient data to select among several theories (Cohen et al. [1998]). It is quite difficult to show the existence of antimatter in the universe, but it is also difficult to show why we have a universe made of matter only (Stecker [1978]).

The recent developments of astrophysical technologies allowed the discovery of several gamma–ray sources and it is time to ask ourselves if new discoveries and measurements can overcome past objections to antimatter theories.

Among various theories, Alfvén ([1979]) proposed an annihilation model for the energy source of quasi–stellar objects. It is a detailed paper and we refer the reader to it, but there are some features that Alfvén did not take into account and here we would like to examine them, in order to extend, improve, and update the Alfvén theory. Particularly, in this paper we investigate some ideas about the close encounter of stars and antistars in order
to search possible signatures of antimatter. The notes exposed here do not want to propose a “universal” theory for astrophysical gamma–rays sources. However, some (not all) gamma sources might be due to the close encounter of stars and antistars and related phenomena.

2 Matter or antimatter, that is the problem

The main source of information about cosmic bodies is the electromagnetic radiation they emit. However, photons are not subjected to CPT symmetry. The interaction of antimatter with magnetic fields is different from the interaction of matter, but the effects (Zeeman; Faraday rotation) depend also on the sign of the magnetic field, and therefore we cannot get any conclusions on the kind of matter.

The best way to show the evidence of an antistar is surely the detection of antinuclei with \( Z > 2 \). This was the purpose of the Alpha Magnetic Spectrometer (AMS), that was flown on the space shuttle in June 1998: first results indicate no antihelium flux and pose an upper limit on the ratio of antihelium to helium (Alcaraz et al. [1999]). Best results should be available with a second experiment, that will have a sensitivity in antihelium search of \( 10^{-9} \).

Another method was suggested by Cramer and Braithwaite ([1977]). They noted that the polarization of photons generated in fusion processes of stars is different according to that there is matter or antimatter. While stars of matter emit right–circularly polarized photons, antistars emit photons which are left–circularly polarized.

Another way is to detect the products of annihilation: neutrinos, \( \gamma \)-rays, and relativistic electron–positron pairs. A typical decay scheme for nucleon–antinucleon annihilation is (Steigman [1976]):

\[
N + \bar{N} \rightarrow \begin{cases} 
\pi^0 \rightarrow \gamma + \gamma \\
\pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu)
\end{cases}
\]

and:

\[
\mu^\pm \rightarrow e^\pm + \nu_\mu (\bar{\nu}_\mu) + \nu_e (\bar{\nu}_e)
\]

The spectra are in the range from several tens to several hundreds of MeV, and with a peak around 100 MeV and a median energy around 250–300 MeV.
This is the most frequent annihilation process for free nucleons. The generation of “protonium” (something similar to positronium, but with protons and antiprotons) with following annihilation, has a rate that is about $10^{-5}$ times smaller than the process described above. Direct annihilation (that is $p + \bar{p} \rightarrow \gamma + \gamma$) is quite rare, with a rate about $10^{-7}$ times smaller (Steigman [1976]).

The annihilation of electrons and positrons gave two photons with energy of 511 keV. Under certain environmental conditions, specifically with gas temperature lower than about $5 \cdot 10^5$ K (Guessoum et al. [1991]), positronium can take place by mean of radiative recombination. After some fraction of seconds, the particle and the antiparticle annihilate with the production of two or three photons, according to the state: two photons for the singlet and three photons for the triplet. In this case, the spectrum presents a continuum spectrum in the low energy side of the 511 keV line. If the gas temperature is higher than $5 \cdot 10^5$ K, the annihilation takes place directly without the formation of positronium; therefore we have only the 0.511 MeV line.

For example, OSSE observations of both galactic 511 keV line emission and the three photon continuum components of the electron–positron annihilation radiation showed the presence of a galactic region with positronium (Kinzer et al. [1996], Purcell et al. [1997]). Therefore, the gas temperature in the galactic centre is lower than $5 \cdot 10^5$ K.

About half of the energy released in annihilation is carried away by neutrinos, and some authors proposed to search there signatures for antimatter (see Steigman [1976], Barnes et al. [1987]). However, it is well known how difficult is to detect netutrinos.

Actually there are still large uncertainties in measurements: the INTEGRAL satellite, for example, that will be launched on April 2002, will provide for the first time fine gamma–ray spectroscopy. In this situation, there are still several questions without answers of reasonable certainty and the antimatter in the universe cannot be completely ruled out. So we can speculate about possible signatures of its presence.

### 3 Evaporation and ejection from a cluster

Khlopov ([1998]) showed that it is possible that there were isolated domains of antimatter, but they should be larger than a globular cluster. Antistars can escape from an anticluster in two ways (Binney and Tremaine [1987]):
ejection, that is the antistar gains the escape speed by a single close encounter with another antistar in the cluster; evaporation, that is a gradual increase of the speed from several distant encounters. The first case is negligible, when compared to the second one, but the rate of evaporation is more complicated to calculate. A crude estimation is given in Binney and Tremaine ([1987]), that put $t_{ev} \approx 100t_{rh}$, where $t_{rh}$ is the mean relaxation time. This means that during a time $t_{ev}$ a significant fraction of stars leave the cluster. For typical globular cluster $t_{rh}$ is in the range between $3 \cdot 10^7$ to $2 \cdot 10^{10}$ years (Meylan and Heggie [1997]).

Globular clusters date back to the formation of galaxies and they are located within a large roughly spherical halo around galaxies. As known, if there were isolated domains of antimatter, they could have survived in globular clusters (Khlopov [1998]). If a cluster of antistars survived near a galaxy of matter, then it is possible that an antistar evaporates from the cluster and goes into the galaxy, causing the annihilation and gamma–ray emission. The tidal forces of the galaxy can increase the evaporation rate and once in the galactic nucleus, there is a high probability of binary formation by tidal capture and stellar merging or collision (Lee and Ostriker [1986]).

Under these conditions, a fraction of close encounters could be between stars and antistars. This value depends on the mass fraction of antimatter domains relative to the total baryon mass, which in turn is strongly model dependent. For the sake of the simplicity, let us suppose that, at least, one globular cluster near a galaxy was made of antimatter. We consider a mean total number of globular cluster for each galaxy of about $2 \cdot 10^2$. In addition, we have to evaluate the rate of evaporation through escaping stars, that in its simplest form can be written as (Binney and Tremaine [1987]):

$$\frac{dN}{dt} = -\frac{N}{t_{ev}}$$  \hspace{1cm} (1)

If we assume $N = 10^6$ and consider a time interval of one year, we obtain, in the best case, that $N \approx 3 \cdot 10^{-4}$ star for each year and for each cluster. The rate of evaporation of an antistar from an anticluster is then $1.5 \cdot 10^{-6} \text{ yr}^{-1}$. We remind that we assumed that at least one globular cluster near a galaxy was made of antimatter.

It is worth noting that the rate of escape from a cluster is a function of star mass (see Meylan and Heggie [1997]) and values obtained here are strongly dependent on simplifying assumptions. Numerical models are required to give better results; here we want only to give a rough evaluation.
The next step is then to study what happens during the close encounter of a star and an antistar.

4 Close encounters

Close encounters can lead to tidal capture and, in certain cases, also to collisions and merging. These processes are driven by gravity and therefore there is no difference when we are dealing with stars or antistars.

Let us consider the mass transfer in a binary system of a star and an antistar, which involves the accretion power. The standard model explains the radiation emission by using the gravitation as a source of energy: the kinetic energy of the infalling matter is converted into radiation. There are two ways to do the mass transfer: stellar wind or accretion disk due to Roche–lobe overflow (see Frank et al. [1995]). When antimatter is present, we have additional energy release from annihilation.

The main effect of this additional energy is to change the Eddington luminosity, that is found by balancing the inward gravitational force and the outward radiation pressure, deriving from the conversion of kinetic energy and from annihilation. The standard formula of Eddington luminosity is:

\[ L_{\text{Edd}} = \frac{4\pi GM m_p c}{\sigma_T} \approx 1.3 \cdot 10^{38} \frac{M}{M_\odot} \text{ erg/s} \]  

(2)

where \( G \) is the gravitation constant, \( M \) is the mass of the accreting star, \( m_p \) is the mass of the proton, and \( \sigma_T \) is the Thompson cross section:

\[ \sigma_T = \frac{8\pi}{3} r_e^2 \]  

(3)

with \( r_e \) the electromagnetic radius of the electron.

For luminosities greater than \( L_{\text{Edd}} \) the radiation pressure stops the accretion process, because it exceeds the inward gravitational force.

When dealing with accretion processes between a star and an antistar, the radiation pressure becomes very important. Photons produced by annihilation of electron–positron pairs have energy of 511 keV, that is the upper limit of validity of the Thompson cross section. Annihilation of heavier particles produce photons with energy \( \hbar \omega \) greater than \( m_e c^2 \), as seen in the above section. Therefore, we must use proper quantum relativistic cross section, that is given by Klein–Nishina formula (see, for example, Longair [1997]):
\[
\sigma_{\text{KN}} = \frac{\pi r_e^2}{\epsilon} \cdot \left\{ \ln(2\epsilon + 1) \left[ 1 - \frac{2(\epsilon + 1)}{\epsilon^2} \right] + \frac{\epsilon + 8}{2\epsilon} - \frac{1}{2(2\epsilon + 1)^2} \right\} \tag{4}
\]

where \( \epsilon = \hbar \omega / m_e c^2 \). Therefore, in Eq. (2), the Thompson cross section must be replaced by Klein–Nishina formula, while all other quantities remain unchanged. When \( \epsilon \gg 1 \), in the ultrarelativistic case, Eq. (4) becomes:

\[
\sigma_{\text{KN}} = \frac{\pi r_e^2}{\epsilon} (\ln 2\epsilon + \frac{1}{2}) \tag{5}
\]

For photons produced in proton–antiproton annihilation, we have \( \epsilon \approx 391 \) (for 200 MeV photon), which results in \( \sigma_{\text{KN}} \approx 4.6 \cdot 10^{-31} \text{ m}^2 \). Therefore, the Eddington limit of matter–antimatter case:

\[
L_{\text{am}} \approx 2 \cdot 10^{40} \frac{M}{M_\odot} \text{ erg/s} \tag{6}
\]

Eq. (6) shows that in the case of accretion power from a close encounter of a star and an antistar, the balance of radiation pressure and gravitational force occurs at higher luminosities, owing to smaller cross section for high–energy photons produced by annihilation of protons and antiprotons. The new limit can be higher when we deal with direct annihilation \((p + \bar{p} \rightarrow \gamma + \gamma)\) or with heavier nuclei. For example, the direct annihilation of helium leads to:

\[
L_{\text{am}} \approx 2.5 \cdot 10^{41} \frac{M}{M_\odot} \text{ erg/s} \tag{7}
\]

When photon energy is greater than \( 2m_e c^2 \), pair production can take place in the field of a nucleus. The pair production is not possible in free space, because of the conservation of momentum and energy. In matter and antimatter environment, nuclei annihilate among themselves, and therefore they cannot help in the pair production.

However, the role of the nucleus in balancing energy and momentum, can be replaced by another photon with lower energy. The electron–positron pair can be created in a head–on collision of a photon with energy \( \epsilon_1 \) with another photon with lower energy (see Longair [1997]):

\[
\epsilon_2 \geq \frac{m_e^2 c^4}{\epsilon_1} \tag{8}
\]
For 300 MeV photons, it is necessary to have 1 keV photons, which are present in accretion processes; therefore 300 MeV photons can be absorbed from the environment. Higher-energy photons require a lower energy photons, up to the Microwave Background Radiation for photons of $4 \cdot 10^{14}$ eV.

It is worth noting that also the decay of $\mu^\pm$ create electron–positron pairs. These particles interact with the magnetic field of the stars and emit synchrotron radiation (Alfvén [1979]). The energy released cannot be larger than $m_e c^2/3$ and the frequency spectrum depends on the geometry and the intensity of the magnetic field. Moreover, $e^+e^-$ pairs can eventually generate X-rays by inverse Compton scattering of starlight (Carlqvist and Laurent [1976]).

5 Collisions and merging

As the annihilation is a surface process (a few mean free paths thick), the release of energy due to annihilation is not large enough to affect the kinematics of the collision (Alfvén [1979]). Massive stars can collide and release energy of surface annihilation in a few seconds, as a gamma–ray burst.

One of the first theory invoked to explain the origin of cosmic gamma–ray bursts was the collision of asteroids and comets of antimatter with stars of matter (Sofia and Van Horn [1974], Sofia and Wilson [1976]). Here we propose another version of that theory, specifically the collision of a star and an antistar.

There are already some theories that explain gamma–ray emission from merging of massive stars (Eichler et al. [1989], Narayan et al. [1992]), but they have an upper limit in the energy released (up to $10^{53}$ erg) and they have to use beaming effects, or other, in order to explain higher values for energy.

In the case of collision of a star with an antistar, the energy released derives from annihilation. Therefore, it depends simply on the total amount of matter and antimatter, does not need of any particular effects, and has virtually no upper limit.

A crude estimation of an order of magnitude shows that the total mass (of matter and antimatter) required to generate a GRB of $E = 10^{54}$ erg is:

$$m_{\text{tot}} = \frac{E}{c^2} \approx 1.1 \cdot 10^{33} \text{ g}$$

(9)
that is equal to about 0.56 solar masses; \( c \) is the speed of light in vacuum. The collision time is of the order of some milliseconds and this can be compatible with very short GRB (see Cline et al. [1999], Krennrich et al. [2000]).

Once the merging is occurred, then the new star has a particular behaviour, because of the mixing of matter and antimatter. Such a star has already been studied, even though with no reference to such a case, by Unno and Fujimoto ([1974]). They found that a very massive star (\( 10^7 \) solar masses or higher) made of matter and antimatter can release \( 10^{61} \) erg of energy in \( 10^5 - 10^6 \) yr, with a luminosity of \( 10^{47} \) erg/s. These data are comparable with that of QSO.

The existence of a correlation between QSO and GRB was already invoked by Sillanpää ([1995]) and Schartel et al. ([1997]). In our case, the correlation can be explained so that the GRB is the “first light” of a future QSO, even though it is still unknown how this type of system can evolve.

6 Some examples

Steigman ([1976]) wrote his paper in 1976. Later on, Allen ([1981]) analysed again the constraints on annihilation in active galaxies and used more recent data (in 1981). Today we have even more recent data, so we can do another evaluation of order of magnitudes.

In his calculations for photon flux above 100 MeV, Steigman ([1976]) noted that for every erg of energy going in electron-positron pairs, there are roughly \( 10^4 \) photons with energy above 100 MeV. Steigman found a relationship between the observed flux and the gamma–ray flux:

\[
S_\gamma [\text{photons cm}^{-2}\text{s}^{-1}] \approx 10^4 S_{\text{obs}} [\text{erg cm}^{-2}\text{s}^{-1}] \tag{10}
\]

Allen ([1981]) noted that it is better to use as reference the flux at radio frequencies, because non thermal optical emission need not to be synchrotron radiation (we remind that an annihilation source is also a strong synchrotron source; see Sect. 4). Therefore, Eq. (10) should be changed in the more suitable:

\[
S_\gamma [\text{photons cm}^{-2}\text{s}^{-1}] \approx 10^4 S_{\text{radio}} [\text{erg cm}^{-2}\text{s}^{-1}] \tag{11}
\]

We can therefore set up a new table of selected strong radio sources, calculate the expected gamma–ray flux above 100 MeV, and compare with data available in literature (see Tab. II).
Table 1: Selected examples of sources with strong synchrotron emission and comparison with gamma–ray flux above 100 MeV (calculated and observed).

| Source | \( S_{\text{radio}} \) at 1 GHz* | \( S_\gamma \) Calc. | \( S_\gamma \) Obs. | Notes |
|--------|-------------------------------|----------------|----------------|------|
| 3C273  | \( 5 \cdot 10^{-13} \)         | \( 5 \cdot 10^{-9} \) | \( 1 \cdot 10^{-7} \) | a    |
| Cen A  | \( 2 \cdot 10^{-11} \)         | \( 2 \cdot 10^{-7} \) | \( 1 \cdot 10^{-7} \) | a    |
| Crab   | \( 1 \cdot 10^{-11} \)         | \( 1 \cdot 10^{-7} \) | \( 7 \cdot 10^{-6} \) | b    |
| Cyg A  | \( 2 \cdot 10^{-11} \)         | \( 2 \cdot 10^{-7} \) | \( 2 \cdot 10^{-7} \) | a    |
| M87    | \( 3 \cdot 10^{-12} \)         | \( 3 \cdot 10^{-8} \) | \( 4 \cdot 10^{-8} \) | a    |
| Sgr A  | \( 2 \cdot 10^{-11} \)         | \( 2 \cdot 10^{-7} \) | \( 1 \cdot 10^{-6} \) | c    |

* From Zombeck ([1990]).

a Fichtel et al. ([1994]).

b Range 50 MeV – 10 GeV (EGRET). Macomb and Gehrels ([1993]).

c Closest \( \gamma \)-ray source: 2EGJ1746–2852. Macomb and Gehrels ([1993]).

It is possible to see that more recent data show some cases of interest (Cen A, Cyg A, M87), but it is worth noting that these sources must be studied and observed with greatest details before to claim that they are powered by matter–antimatter annihilation. However, these calculation show that recent data renew the annihilation hypothesis as inner engine for certain sources. Perhaps future \( \gamma \)-ray astrophysics satellites can give more reliable constraints, allowing a precise choice.

7 Conclusions

Although the existence of stars made of antimatter is still doubtful, we can search for other signatures of the presence of antimatter in the universe. This paper showed that the Eddington luminosity in the presence of an antistar can be substantially higher. The high–energy photons created by annihilation of nuclei have a small cross section for their interaction with electrons and then the effect of radiation pressure in balancing the gravitational force is smaller than in standard conditions.

However, a source with luminosity higher than the standard Eddington...
limit is not sufficient to claim for the presence of antimatter. It is necessary to detect several other features, such as a strong synchrotron radiation, neutrinos, and high-energy photons. We have shown that more recent data have, for some sources, a good agreement with the calculated flux from annihilation.

These results must be taken *cum grano salis* and more results are expected from the new generation of gamma-ray astrophysics satellites. It is not possible to claim for the discovery of large amount of antimatter in the universe, but it is time to renew this type of research.

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