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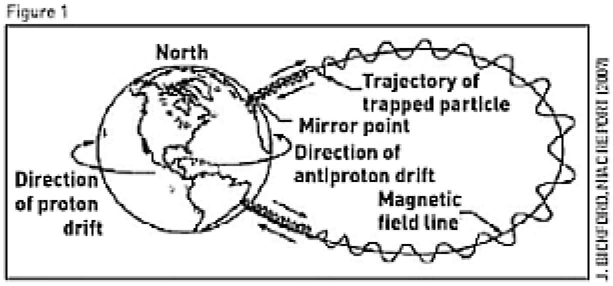
Antimatter belt

R. RAMACHANDRAN

Antimatter technology has enormous potential because of the huge amount of energy released during the annihilation process.

Figure 1



MOTION OF A charged particle trapped in a magnetic field.

Figure 2

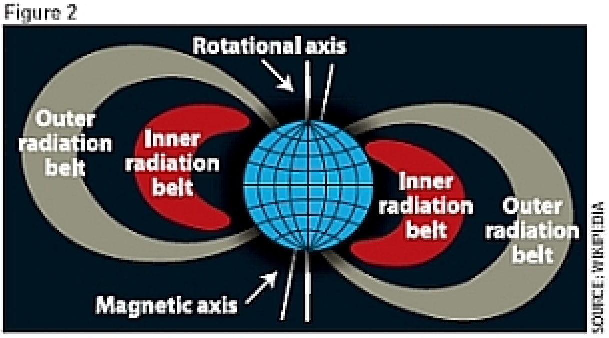
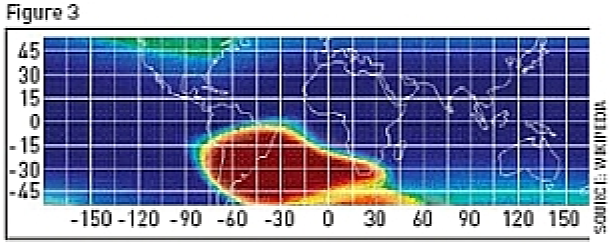


Figure 3



THE SOUTH ATLANTIC Anomaly (in red), as measured by the ROSAT X-ray satellite, is a dip in the earth's magnetic field that allows cosmic rays and charged particles to reach lower into the atmosphere.

ONE of the biggest mysteries of science is the lack of antimatter in the universe. Antimatter is the counterpart of matter, which we are familiar with, and according to the laws of physics the two are identical except for the electric charges (and the other quantum attributes that fundamental particles are endowed with), which are opposite. That is, every fundamental particle has an antiparticle but with the opposite electric charge. The positron is the antiparticle of the electron and the antiproton is the antiparticle of the proton. The photon has no charge and hence is its own antiparticle, but the antineutron is different from the neutron even though it has no charge because it has a magnetic moment that is opposite to that of the neutron. More precisely, since protons and neutrons are made of quarks, which are charged particles, while a neutron is made of quarks, an antineutron is made of antiquarks. When a particle and an antiparticle meet, they annihilate each other and give out enormous energy according to Einstein's $E = mc^2$ equation.

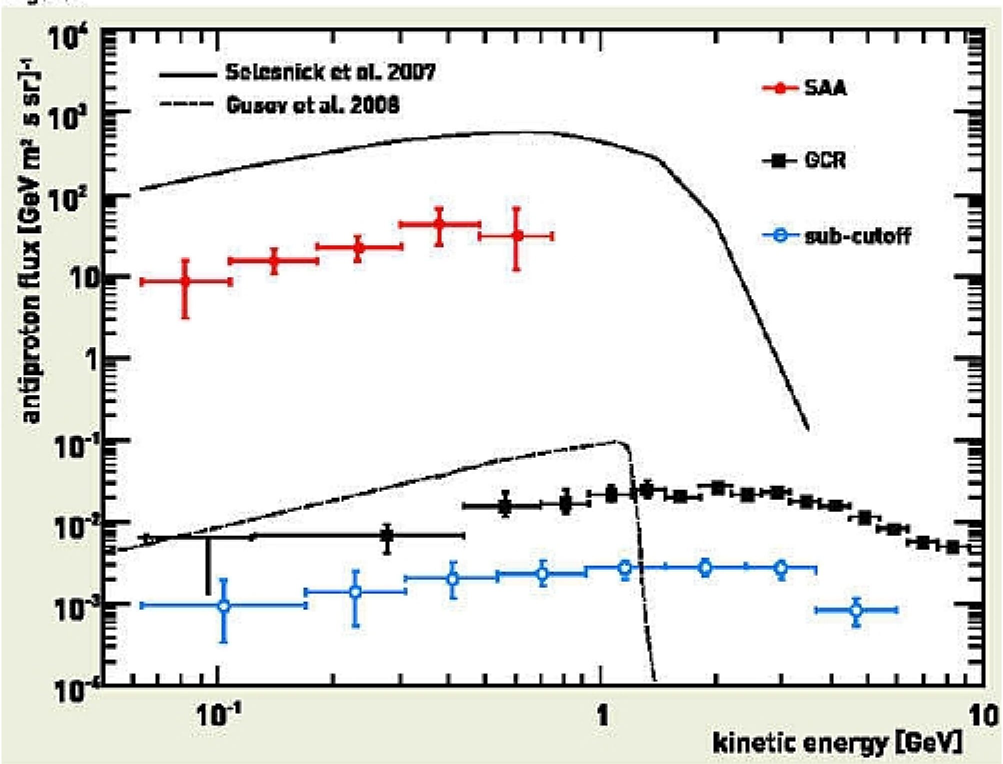
If the laws of physics as we know them today are correct, at the Big Bang, matter and antimatter should have been created in equal amounts. However, the world as we see it seems to be made only of matter; antimatter, for some reason not yet understood, seems to have disappeared. One of the objectives of present-day cosmic ray experiments is to search for this primary (primordial) antimatter to understand the observed matter-antimatter asymmetry in the universe. So far, none of such experiments has found any evidence for primary antimatter. A new experiment to search for antimatter, the AMS (Anti Matter Spectrometer), was launched during the last trip of the space shuttle.

Currently, antimatter can be created only in high-energy accelerators, such as the ones at Fermilab in the United States and at CERN (European Organisation for Nuclear Research) in Switzerland, which are used to produce a controllable supply of antiparticles for physics research. The method used is basically the reverse of annihilation, where the high energy delivered in accelerators results in the production of particle-antiparticle pairs, which can then be separated by applying suitable magnetic fields because particles and antiparticles behave in opposite ways in a magnetic field. In November 2010, experiments at CERN succeeded in producing and trapping large quantities of anti-hydrogen atoms.

High-energy galactic cosmic rays (GCR) produce antimatter in nature in the same manner. They bombard planetary atmospheres and interstellar medium to generate antiparticles naturally through “pair production”, and these are called “secondary production” antiparticles. The existence of such secondary production antiprotons, with energies up to tens of giga electronvolt (GeV) in the normal background of ionising radiation, have been established by high-altitude balloon measurements and other space-based instruments. Also, the results of all the experiments launched to date to detect primary antimatter are consistent with secondary production. But the flux of such a natural source of antiprotons in the GCR background in space is very low. However, magnetic fields surrounding planets can generate much larger fluxes of antiprotons by the interaction of these cosmic ray particles with the planetary atmospheres and magnetic fields.

It is known that because of the force exerted by magnetic fields on moving charged particles – the Lorentz force – normal charged particles (electrons, protons, and so on) from cosmic rays, in particular solar wind, are bent around the earth's magnetic field and get trapped as they are forced to move along magnetic field lines (Figure 1). The magnetic field around the earth has “mirror points”, where the field lines come together and the spirals get tightened. This causes the charged particles to execute a spiralling motion back and forth, bouncing between the earth's North and South Poles and forming a torus-shaped radiation belt around the earth. This is the so-called van Allen radiation belt (Figure 2). The belt actually has two components: the outer belt, which consists of energetic electrons and lies at an altitude of thousands of kilometres above the earth's surface, and the inner belt, which consists of a combination of protons and electrons and is at an altitude of a few hundred to about 2,000 km.

Figure 4



SAA: South Atlantic Anomaly; GCR: Galactic cosmic ray

Source: Paper of O. Adriani et al. on PAMELA results published in The Astrophysical Journal Letters (August 2011)

The belts pose a radiation hazard to satellites and their components, which must be adequately shielded if their orbits cause them to spend a considerable time in the belts. In particular, the radiation belt has a region called the South Atlantic Anomaly (SAA) where the inner radiation belt comes closest to the earth's surface. The SAA region has a higher flux of charged particles than other regions of the belt and exposes orbiting satellites to higher-than-usual levels of radiation. The SAA occurs because of the non-concentricity of the earth and its magnetic dipole, and the SAA is the region where the earth's magnetic field happens to be the weakest (Figure 3).

During each orbit, a satellite passes through the anomaly, and this exposes it to several minutes of strong radiation because of the trapped protons in the magnetosphere, which have energies of about 10 million electronvolts (MeV) and strike passing spacecraft at the rate of about 3,000/cm^2/second. Usually all the detectors on-board satellites are powered down during their passage through the SAA. For example, the Hubble Space Telescope, which passes through the SAA 10 times every day and spends about 15 per cent of its time in this hostile zone, does not take any observations during this period. Passing through the SAA is believed to be what caused the first failures of the satellites of the Globalstar Network.

Like normal charged particles, it is natural to expect GCR-generated secondary antiparticles to also get trapped by the earth's geomagnetic field and accumulate in the belt in much the same way. Indeed, many theoretical studies have predicted the existence of a significant flux of antiprotons confined to the earth's magnetosphere. The particles will accumulate until they are removed owing to annihilation or ionisation losses. But new ones get generated to maintain a quasi-steady flux trapped in the geomagnetic field. However, a couple of experiments launched in the 1990s aboard the Russian Salyut-7 and MIR orbital stations, which looked for antiprotons with energies under 150 MeV, could only set upper limits on the trapped antiproton-proton ratio (at a few thousandths level) in the magnetosphere. An experiment, PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics), aboard the Russian satellite Resurs-DK1, which was launched on June 15, 2006, by the Soyuz rocket, has for the first time detected these secondary production antiprotons trapped in the inner radiation belt. The results of the experiment have been published in the latest issue of The Astrophysical Journal Letters.

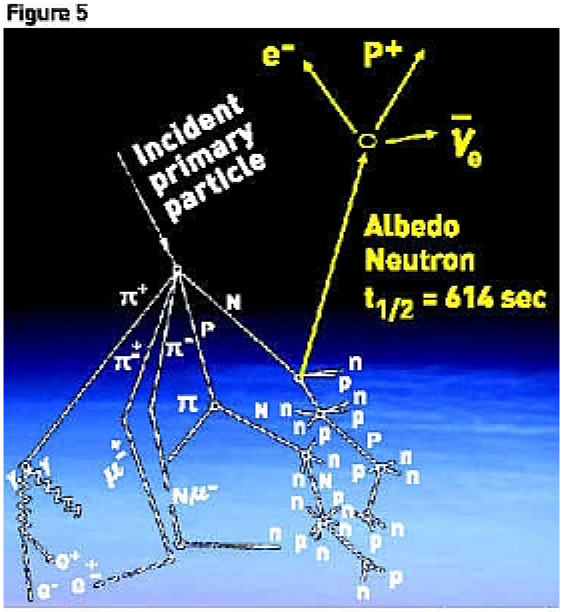
The investigations under the PAMELA mission are aimed at addressing the most compelling issues facing astrophysics and cosmology: the nature of the dark matter that pervades the universe, the apparent absence of cosmological antimatter, and the origin and evolution of matter in the galaxy. This international collaboration mission is chiefly funded by the INFN (Instituto Nazionale di Fisica Nucleare, or the Italian Institute for Nuclear Physics) and the ASI (Agenzia Spaziale Italiana, or the Italian Space Agency) and includes scientists from Germany, Russia and Sweden.

The satellite has an orbit inclination of 70° and an altitude of 350-610 km, which, according to the authors, allows PAMELA to perform very detailed measurements of cosmic rays in different regions of the earth's magnetosphere, in particular the SAA through which the satellite passes. PAMELA is a powerful particle identifier and uses a permanent magnet spectrometer with a variety of specialised detectors capable of measuring with unprecedented precision and sensitivity the abundance and energy spectra of cosmic ray electrons, positrons, antiprotons and light nuclei over a very large range of energy, from 50 MeV to hundreds of GeV, depending on the species. In particular, PAMELA is optimised to identify the small component of cosmic ray antiparticles, according to the authors of the paper.

"Since launch," the paper says, "PAMELA has collected an unprecedented number of antiprotons and positrons." The PAMELA group has, in fact, obtained significantly improved data on cosmic ray antiproton spectrum and antiproton-to-proton ratio in the 60 MeV-180 GeV energy range, which agree with models with pure secondary production of antiprotons due to the interaction of GCR with the interstellar medium. The magnetospheric antiproton flux is, however, expected to be significantly larger than the GCR-generated flux because of the trapping in the earth's "magnetic bottle".

Specifically, the PAMELA antiproton experiment analysed the data gathered during the first 850 days of its mission, between July 2006 and December 2008, and obtained the energy spectrum of the geomagnetically trapped antiprotons in the SAA region in the kinetic energy range of 60-750 MeV by restricting the antiproton selection to radial distances corresponding to the SAA. These antiprotons have to be picked from the background of a larger flux of protons in the SAA, and the instrument, which is basically a magnetic spectrometer that separates detected particles by their charge and momenta, is said to be able to do this reliably. In addition, the instrument has to discriminate between electrons and similarly charged antiprotons, and this selection is done on the basis of the annihilation signatures of the detected antiprotons with matter inside the instrument's calorimeter. Further, the propagation of each antiproton candidate was checked using simulation models that traced the trajectories through the magnetosphere. All identified antiprotons, according to the paper, “were found to spiral around field lines, bounce between mirror points, and also perform a slow longitudinal drift around the earth”, as they should (Figure 1).

Figure 5



Cosmic Ray Albedo Neutron Decay (CRAND)
Source: J. Bickford, NIAC Report (2007)

The data show that the flux of these geomagnetically trapped antiprotons exceeds the GCR secondary antiproton flux by four orders of magnitude, which, as the authors of the paper say, constitutes the most abundant source of antiprotons near the earth (Figure 4). Actually, the PAMELA team detected 28 antiprotons within the kinetic energy range 60-750 MeV in the SAA region, and this number is converted to flux values using a trapped antiproton model. A comparison of the SAA-trapped antiproton flux with that of secondary production antiprotons in the sub-cutoff region just outside the SAA shows a threefold increase.

“I think the significance of the present result is in understanding the flux of secondary antiprotons near the earth's environs, which is a severe background in the quest for primary antimatter,” said B.S. Acharya of the Tata Institute of Fundamental Research, Mumbai. “This result helps [us] to understand the background of secondary anti-protons as well as to model earth's magnetosphere. The discovery of primary antimatter itself will indeed be a very significant step. The AMS experiment may help resolve this issue, but we have to wait for a few years for its data,” he added.

Asked whether the measured flux represented a steady state value, Alessandro Bruno, of the INFN, Bari, and a member of the PAMELA group, said through e-mail: “In principle, if there were no losses due to interaction, the antiprotons would be trapped for ever. But because there are losses due to interactions and diffusion effects, the trapping time depends on particle energy.

Trapped antiprotons can be lost in the interactions with atmospheric constituents, especially at low altitudes where the annihilation becomes the main loss mechanism. Above altitudes of several hundreds of kilometres, the loss rate is significantly lower, allowing a relatively large supply of antiprotons to be produced. In addition, the geomagnetic field generates a bottle to stably hold particles, which get accumulated until ionisation losses and nuclear interactions remove them. The trapped particles are slowly transported via radial diffusion in the magnetosphere, until a quasi-static balance between the source and loss functions is ultimately reached. Due to this process, the resulting magnetically confined flux significantly exceeds the atmospheric flux outside belts and that of the galactic antiprotons in the earth's proximity by some orders of magnitude."

One could ask whether antiproton-proton annihilation events can be detected by the emitted gamma ray signatures using some space-based instrument. "Although positron/electron annihilations produce easily identifiable gamma rays," pointed out James Bickford of Draper Laboratory, Cambridge, Massachusetts, U.S., in an e-mail response, "the best way to see the antiproton belt is directly with a mass spectrometer. The AMS sensor just installed on the space station should be able to get some good statistics on the belt in the coming months and years." Bickford is the author of the two reports on "Extraction of Antiparticles Concentrated in Planetary Magnetic Fields" that he produced for the NASA Institute for Advanced Concepts (NIAC).

It is interesting to note that even though PAMELA is capable of detecting higher-energy particles the experiment had put an energy cut-off at 750 MeV. To a query on this, Bruno said, "The observed 28 antiprotons are limited to that energy range. Data will be improved with the addition of the data sample acquired by PAMELA after Dec 2008." He, however, added: "Particles remain trapped when their gyro-radius is small compared with the curvature of the field lines. Particles with large gyro-radii are likely to be absorbed by the atmosphere. Since the particle gyro-radius scales with energy, there is a high-energy limit of the trapped particle spectrum."

From the data, however, it is difficult to give an estimate of the total number of antiprotons trapped in the SAA region alone and in the entire radiation belt since the experiment explored only a portion of the inner radiation belt, the SAA region, and the spacecraft orbit is limited to altitudes between 350 km and 600 km, whereas the antiproton radiation belt is expected to extend up to thousands of kilometres, Bruno pointed out. However, according to Bickford's estimates, the total trapped antiproton mass is about 160 nanograms, with a replenishment rate of 2 nanograms/year.

There are actually four distinct processes that can result in the concentration of antiprotons in and around planetary magnetic fields. These have been investigated in detail by Bickford. His studies also looked at ways of harvesting antiprotons for potential applications. Of these four processes, the two most important ones are (1) Cosmic Ray Albedo Antineutron Decay (CRANbarD) and (2) Direct pair production and trapping of antiprotons in the exosphere.

As Bickford has described, in the van Allen belt, the GCR flux interacts with the earth's upper atmosphere to release free neutrons with a half-life of just over 10 minutes. A fraction of these free neutrons travel back (albedo) and escape from the atmosphere and decay in the earth's magnetosphere into protons (plus electrons and antineutrinos). High-energy protons (>30 MeV) in the belt are formed primarily by such decays (Figure 5). This process is called CRAND (Cosmic Ray Albedo Neutron Decay). The interaction of GCR is also expected to produce antineutrons through pair production (in reactions such as proton + proton proton + proton + neutron + antineutron (n-bar)). Just as neutrons, these antineutrons, too, can get backscattered after interacting with the atmosphere and subsequently decay to produce antiprotons (plus positrons and neutrinos).

Table 1

Fuel energy densities		
Fuel	Energy density (joules/kg)	Notes
Battery	7.2×10^5	Lithium ion
Chemical	1.4×10^7	LO_2 / LH_2
Fission	8.2×10^{13}	U^{235}
Fusion	3.4×10^{14}	DT
Antimatter	9.0×10^{16}	$E=mc^2$

DT: Deuterium/tritium

Source: J. Bickford, NIAC Report (2007)

However, computer modelling by Bickford suggests that the ratio of albedo antineutrons to albedo neutrons, which is energy dependent, ranges between one-hundred thousandth and one-billionth. This analogous process, referred to as CRANbarD, acts as a source of antiparticles in the radiation belt around the earth. The only difference is that the negatively charged antiprotons will spiral and drift in the opposite direction compared with the positively charged protons.

Antiprotons can also be produced directly by pair production in the exosphere, the second significant process. However, as Bickford points out, there is a fine balance between the generation and loss processes in this case. Unlike the albedo antineutrons, which can travel fairly freely through the magnetosphere to decay deep in the radiation belts, antiprotons produced directly by pair production are trapped immediately after production where loss rates are high, resulting in negligible trapped flux from this direct mechanism. So the main contribution to the stable antiproton energy spectrum comes from the CRANbarD mechanism whose flux is predicted to be several orders of magnitude more than the antiproton flux from the direct proton-antiproton pair production in the exosphere. However, even this antiproton flux is not very high because of the inefficiency of the antineutron backscatter process, points out Bickford, but, according to the PAMELA paper, model predictions differ a great deal because of the uncertainties in the CRANbarD process (Figure 4). According to Bickford, the data are relatively consistent with the models.

As mentioned earlier, Bickford's studies were done towards a futuristic vision of using antiparticles for a variety of applications. One such science fiction-like application uses tens of nanograms to micrograms of antiprotons to catalyse nuclear reactions and propel spacecraft to velocities up to 100 km/s. This is, to quote his report, “well beyond the capability of traditional chemical propellants and opens up new exciting options for space exploration. Larger supplies of antiprotons would eventually enable spacecraft capable of relativistic velocities.”

The enormous potential of antimatter technology is because of the huge amount of energy released during the annihilation process. The antimatter annihilation is about two to three orders of magnitude more efficient than nuclear reactions and nearly 10 orders of magnitude more efficient than chemical propellants used in spacecraft such as the space shuttle. The annihilation of 1 kg of antimatter releases the energy equivalent of 30 million barrels of oil (Table 1). However, the main limiting factor in realising this has been the production and storage of antiprotons. Antiparticle trapping is an extremely inefficient process since at present it relies on extracting them from subatomic collisions in accelerators. A small portion of this can be magnetically confined and focussed to separate out the antiprotons, which are decelerated and placed in a confinement ring for use in subsequent experiments. According to Bickford, the worldwide output is currently in the low nanogram a year range at an estimated cost of up to $160 trillion a gram with additional overheads for infrastructure and personnel.

Summary of natural antiproton sources in the solar system

Table 2

Source		Notes
 Galactic Cosmic Rays (GCR)	**Peak flux** $3\ m^{-2}\ s^{-1}$ **Trapped supply** Not applicable **Fill rate** Not applicable	Antiprotons are generated when the GCR flux interacts with the 5-7 g/cm^2 of material that it encounters as it travels through the interstellar medium. This creates a pervasive flux that has been well characterised by balloon and space-based measurements. About 1 kg/sec enters the solar system, but only a few grams reach the earth's magnetosphere each year. The influence of the earth's magnetic field may locally increase the flux levels by a factor of five near the magnetic poles.
 Earth's magnetosphere	**Peak flux** $4{,}000\ m^{-2}\ s^{-1}$ **Trapped supply** 160 ng **Fill rate** 2 ng/yr	Albedo antineutrons generated from GCR interactions with the atmosphere decay to produce antiprotons, which can be trapped by the planet's magnetic field. Their diffuse nature enables an antiproton belt analogous to the protons in the van Allen radiation belt to form.
 Mar's surface	**Peak flux** $30\ m^{-2}\ s^{-1}$ **Trapped supply** Not applicable **Fill rate** Not applicable	The GCR proton flux passing through the average atmospheric thickness of 65 g/cm^2 will generate the maximum antiproton flux near the surface. The magnitude is roughly equivalent to 10 times the GCR antiproton background flux.
 Jupiter's magnetosphere	**Peak flux** $10\ m^{-2}\ s^{-1}$ **Trapped supply** 6 µg **Fill rate** 7 µg/yr	Antiprotons are primarily formed from the interaction of the GCR flux with the atmosphere of Jupiter to produce antineutrons via pair production. A portion of the antineutron flux decays into antiprotons, which are then trapped in the planet's magnetic field. The strong magnetic field of the planet assists in the trapping of the particles but also shields the atmosphere from much of the GCR source flux.
 Saturn's magnetosphere	**Peak flux** $70\ m^{-2}\ s^{-1}$ **Trapped supply** 10 µg **Fill rate** 240 µg/yr	Saturn is similar to Jupiter, but the source strength is increased substantially because of the rings surrounding the planet. The belt is far more efficient at generating antineutrons, which can decay in the trapping region of the planet since the generated particles do not have to go through a secondary scattering reaction like the atmospheric albedo source.
 Uranus' magnetosphere	**Peak flux** $320\ m^{-2}\ s^{-1}$ **Trapped supply** 1.4 µg **Fill rate** 0.9 µg/yr	Primarily formed from the interaction of the GCR flux with the planetary atmosphere to produce antineutrons via pair production. A portion of the antineutron flux decays into antiprotons, which are then trapped in the planet's magnetic field.
 Neptune's magnetosphere	**Peak flux** $600\ m^{-2}\ s^{-1}$ **Trapped supply** 2 µg **Fill rate** 0.9 µg/yr	Primarily formed from the interaction of the GCR flux with the planetary atmosphere to produce antineutrons via pair production. A portion of the antineutron flux decays into antiprotons, which are then trapped in the planet's magnetic field.
 Sun	**Peak flux** $<0.02\ m^{-2}\ s^{-1}$ **Trapped supply** Not applicable **Fill rate** Not applicable	GCR interactions with the solar atmosphere produce albedo antineutrons via pair production, which escape and decay into antiprotons. Nearly 6 g/yr is produced by the sun though the flux is less than $10^{-6}\ m^{-2}s^{-1}$ at 1 A.U. Approximately 100 ng/yr will impinge on the earth's magnetosphere though only a small fraction ($\sim10^{-3}$) will be trapped for any length of time.
 Comet tails	**Peak flux** $<10^{-6}\ m^{-2}\ s^{-1}$ **Trapped supply** Not applicable **Fill rate** Not applicable	The GCR flux interacts with comet material to generate antiprotons through pair production. Only very small fluxes are produced because of the low density of the tail.

Source: J. Bickford, NIAC Report (2007)

So, can the GCR-created secondary antiprotons accumulated in planetary magnetospheres provide good sources of antimatter that can be harvested for potential use? “There are enough antiprotons in theory,” said Bickford, “but you'd really need to go to Saturn to get a large supply that can be replenished. The earth supply is enough for a mission or two but takes a very long time to refill. Saturn, on the other hand, has a very large supply that could support an exploration programme” (Table 2). Clearly, while antimatter propulsion may be somewhat distant at present, it is no longer in the realm of science fiction.

But more pertinently, from the perspective of the immediate potential additional threat to aircraft and spacecraft passing through the radiation belt because of the high-energy radiation released by the annihilation of antiprotons in the belt, and the probable need for additional shielding, Bickford said, “We looked at this – although there is a minor increase in the radiation levels from the annihilation – it probably isn't elevated enough to justify additional protection. The difference should be within existing design margins.”

URL: http://www.hindu.com/fline/fl2818/stories/20110909281810200.htm