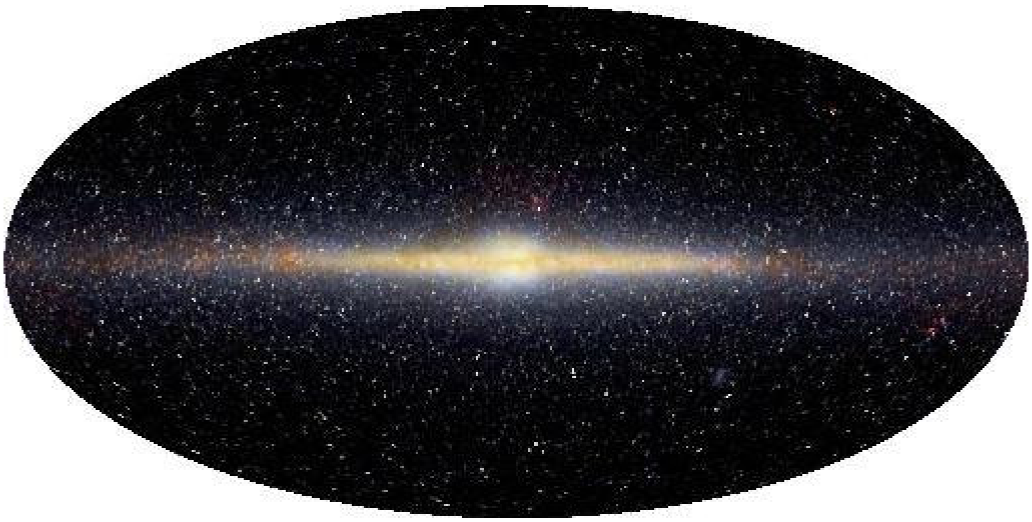
The Cloud in the Galactic Halo:



http://map.gsfc.nasa.gov/html/milky_way.html

Changing Ideas About the Center of Our Galaxy

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Abstract

The discovery of an antimatter cloud in an isolated region of the galactic halo in the mid-1990's shows evidence of positron-electron annihilation. Because there are no known sources of positrons in this region of the galaxy, scientists must develop theories to explain the production and transport of these positrons. This paper examines the discovery of the antimatter cloud and describes several major theories that have emerged to explain its presence. The cloud could have been caused by a massive black hole. Another theory involves long-term supernova activity that produces heavy elements that beta decay and create positrons. A third theory involves one or several starbursts in the galactic past. In the end, more observation will be required to obtain a full explanation for the antimatter cloud's existence. The European Space Agency plans to launch a new observatory in the near future that will make such observational work possible.

Introduction

In 1997, after years of research, a group of astronomers announced the identification of a cloud above the galactic center region that shows evidence of positrons colliding with electrons. This cloud was unexpected by the astronomical community and has caused astronomers to reexamine their ideas about what has been and is going on in the center of our galaxy and galaxies similar to ours. The purpose of this paper is to explain what the cloud is, how astronomers detected it, and how scientists are trying to explain its existence.

Background: Antimatter

In the late 1920′s, a physicist named Paul Dirac created a set of equations that would describe the behavior of the electron and also obey the laws of quantum mechanics and special relativity. In these equations, two results were possible for the energy of the electron, one positive and one negative. Rather than disregarding the negative results, Dirac recognized a fundamental symmetry of matter in the equations. In 1929, he theorized that a complement, or antielectron, must exist for the electron. By 1931, he had predicted that this antielectron must be an as-yet undiscovered particle having the same mass and spin as the electron but a positive charge. If they came into close proximity, the electron and antielectron would annihilate one another, and the reaction would release energy. Dirac also predicted the existence of an antiproton, which would have the same mass and spin as the proton but would be negatively charged.

In 1932, Carl Anderson first discovered the antielectron, or positron, while detecting cosmic rays with Robert Millikan at Caltech. Anderson′s work involved measuring the momentum and charge of cosmic particles by observing their paths as they passed through a cloud chamber while being bent by a magnetic field. Some of the paths that Anderson observed were identical to an electron's path but were bent in the opposite direction. Not knowing of Dirac′s prediction, Anderson concluded that the particles that followed these paths had the same mass as the electrons but were oppositely charged. When Anderson combined his discovery with Dirac′s theory, he was able to detect electron-positron creation from cosmic rays, for which he received the 1936 Nobel Prize.[1]

Today we understand that every known subatomic particle has a corresponding antiparticle. All antiparticles have identical mass and spin as but opposite charge to their corresponding particles. When a particle and its corresponding antiparticle come into close proximity they annihilate, converting all of their rest energy into photons. The most common antiparticle is the positron, the corresponding antiparticle of the electron.

One of the several ways that positrons are created occurs during a form of radioactive decay called beta plus (β^+) decay, when a proton decays into a neutron and positron. The following equation[2] illustrates β^+ decay in which an isotope of copper decays into an isotope of nickel while emitting a positron (e^+) and a neutrino (v):

$$^{64}\text{Cu} \rightarrow {}^{64}\text{Ni} + e^+ + v$$

Certain isotopes, such as ^{22}Na, ^{26}Al, ^{44}Sc, and ^{56}Co, undergo this type of decay.

Another type of positron formation is called pair production, which can occur near black holes. In this process, matter spiraling into the black hole becomes so hot that it emits high-energy photons. These photons interact with each other in the extremely high gravitational field near the black hole and spontaneously produce pairs of positrons and electrons that stream away from the black hole in two high-energy, anti-parallel jets.[3] These jets are moving too fast for positron-electron (e^+-e^-) annihilation to occur. Eventually the jets will move slowly enough for the positrons and electrons to annihilate.

A positron and an electron can interact in several ways. If they collide head-on, they annihilate and produce two gamma ray photons, each having an energy of 511 keV. If a positron and an electron get close but do not collide, they can orbit each other. This motion creates an unstable atom called positronium, which is like a hydrogen atom with the proton replaced by a positron. The e^+-e^- pair in positronium eventually annihilate each other, producing either two photons with energies of 511 keV or three photons with energies less than 511 keV [4]. Detecting gamma rays with energies of 511 keV is evidence for e^+-e^- annihilation, and it is the only method we have to detect the existence of positrons in space.

Using Gamma Rays to Explore the Universe

Gamma rays are useful because they allow astronomers to detect matter in parts of the universe where other frequencies of radiation are blocked by debris and dust. Unfortunately gamma rays react with matter in the earth′s atmosphere, and therefore detectors located at the earth′s surface cannot detect most gamma radiation originating in space. Gamma rays more energetic than 10MeV can make the trip through the atmosphere and be detected on Earth's surface, but only with special detectors on mountaintops. However, astronomers had to wait until detectors could be placed above the earth′s atmosphere before most gamma radiation emitted from space could be detected.

In April 1974, a balloon was sent into the upper atmosphere, and the detector that it housed measured gamma rays in the 20-12,000 keV range. Several intense energy lines were observed at the center of our galaxy, including a 511 keV line.[5] Such energy lines can be used to identify certain processes in the same way that atomic spectra identify electronic energy transitions. In this manner, the 511 keV line indicated e^+-e^- annihilation in the direction of the Milky Way's center.[6] Large-scale e^+-e^- annihilation in this region came as somewhat of a surprise, but theories were soon modified to include greater formation of positrons in the galactic center region. Unfortunately, equipment capable of making high-resolution mapping or clear distinctions in frequency was not feasible in the 1970's. Therefore the specific locations of e^+-e^- annihilation relative to the galactic center could not be ascertained.[7] For the next fifteen years, few experiments were done to further this research, as the launching of balloons was expensive and balloons could only remain in the atmosphere to collect data for a limited time. Detection equipment that could remain above the atmosphere and take long-term and more precise measurements was needed.

Launched in 1991, the Compton Gamma Ray Observatory (CGRO) satellite was launched into Earth′s orbit to study gamma ray emission from space (see Fig. 1 below). The CGRO carries four instruments that perform a variety of observations[8]. One of these instruments, the Oriented Scintillation Spectrometer Experiment (OSSE), was especially designed for detecting gamma rays over the energy range of 0.05 B 10 MeV, which includes the radiation released during e^+-e^-

annihilation. OSSE was able to take more precise and numerous measurements of gamma ray emissions.

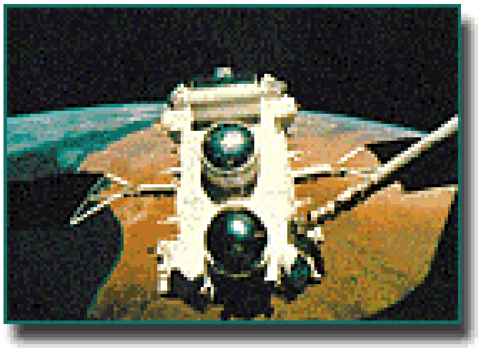

Fig. 1 Top View of Compton Gamma Ray Observatory during deployment.

http://spacelink.nasa.gov/NASA.Projects/Space.Science/Universe/Compton.Gamma.Ray.Observatory.CGRO/.index.html

Cloud of Positron-Electron Annihilation Above the Galactic Plane

William Purcell of Northwestern University, together with a team of astronomers, used OSSE to look for evidence of positrons through the detection of e^+-e^- annihilation. Purcell's team of astronomers was not able to make significant observations overnight. OSSE can only record one small chunk of sky at a time, so through innumerable tedious observations and overlapping snapshots they were able to obtain enough valid data to pinpoint more precisely the location of the e^+-e^- annihilation. It took more than five years for Purcell's team and other astronomers to piece together the map. Upon completion Purcell concluded that there is a vast cloud containing positrons that hovers above the galactic plane, where the OSSE detected an abundance of 511 keV gamma rays.[9] "This certainly is surprising," says Purcell. "It poses more questions than we have answers."[10] The CGRO map shows that the high-altitude radiation cloud connects to the radiation at the galactic center (see Fig. 2 below). Although its resolution is limited, this map suggests that the gamma ray emission is coming from a stream of matter and antimatter rising from the galactic center. Some sort of activity "is building up and breaking open a hole in the plane of our galaxy and pouring gas into the galactic halo," speculates Charles Dermer of the Naval Research Laboratory (NRL).[11]

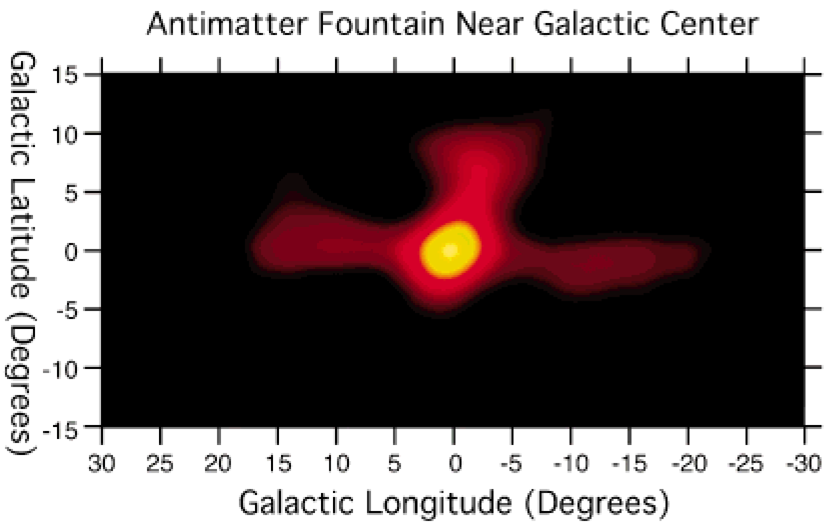

Fig. 2 CGRO map of 0.511 MeV gamma rays surrounding the galactic plane.
The cloud protruding above the center has yet to be fully explained.

http://cossc.gsfc.nasa.gov/cossc/osse

To explain the cause of this antimatter plume, scientists have had to examine old theories and revise them to satisfy the new data and observations. Because there are no known sources of positrons in the newly observed region of the galaxy, scientists must develop theories to explain the production and transport these positrons.

Theories Explaining the Cloud: Black Holes

One possible explanation of the e^+-e^- annihilation cloud is the existence of one or more black holes near the center of the galaxy. As previously explained, scientists believe that positrons and electrons are created when photons are pulled into the high gravitational field surrounding a black hole. It is widely held by astronomers that there is a super-massive black hole at the galactic center, estimated at about 1 million solar masses (M_{υ}). Edison Liang from Rice University suggests that at least six black holes close to the galactic center produce e^+-e^- streams, which are blown far from the galactic halo by hot interstellar winds.[12]

Recent observations have lead many scientists to reject the theory that black holes cause the production of the positrons above the galactic center. These positrons and electrons would be ejected in two anti-parallel streams above and below the galactic plane, and a complimentary cloud below the galactic plane has not been detected. Also, the velocities of the ejected positrons and electrons would have a spread up to 0.9c, and thus the photons produced would be expected to have an energy distribution with a significant component higher than 0.511 MeV, which has not been observed.[13]

Supernova Theory

Another theory that attempts to explain the existence of the positron cloud postulates the birth of a large cluster of stars at the heart of the galaxy between 100,000 and 1,000,000 years ago. When the massive stars in this cluster died, a host of spectacular explosions, called supernovae, resulted. A supernova results when a star exceeding 8 $M_{\odot}$ dies.[14] The star's core rapidly heats and collapses, sending a shock wave to the outer layer of the star. When the shock wave reaches the star's surface it releases 10^{46} joules of energy. Part of this energy is manifested as light, and part of it ejects most of the star's matter into space at speeds of several thousand kilometers per second.[15]

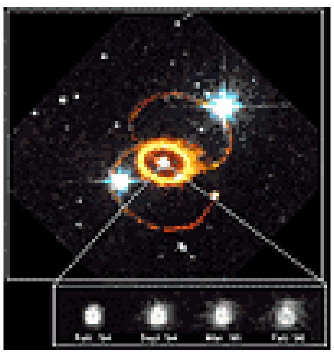

Fig. 3 Remnant of Supernova 1987A

http://oposite.stsci.edu/pubinfo/novaesupernovae.html

Supernovae leave debris that can be observed many thousands of years after the explosion. During a supernova, the star's material gets compressed so much by the shock wave that thermonuclear reactions produce nearly all of the known elements. Radioactive isotopes of these elements later undergo β^+ decay, releasing both positrons and gamma ray radiation that is characteristic of the decaying isotope. Supernova remnants consist of a wall of gas that moves away from the dead star at supersonic speeds. This matter collides with other atoms in interstellar space and causes them to radiate electromagnetic radiation[16], which serves as evidence of the existence of a past supernova event.

Astronomers have observed evidence for the existence of the bubble of rapidly expanding gas that would have been released by a supernova in the galactic plane. Chimneys of hot gas escaping from the galactic plane have been observed, and glimpses of the galactic center have revealed hints of turmoil there. Radio emissions suggest the flow of gas streaming in the general direction of the positron cloud, and x-ray emissions suggest ionized gas that has been heated to temperatures that are indicative of supernovae.[17]

Another piece of evidence supporting the supernova theory is the observation of 1.809 MeV radiation emanating from the direction of the galactic center, which corresponds in energy to the radiation emitted when radioactive aluminum-26 (^{26}Al) decays. Supernovae produce this radioactive isotope, and therefore its existence in the galactic center suggests past supernovae. The half-life of ^{26}Al is only 720,000 years, and since we can still observe radiation emitted by ^{26}Al, the proposed supernovae must have been relatively recent. However, another possible source of this 1.809 MeV radiation is the Scorpius-Centaurus association of stars, which has blown a huge bubble of gas close to the solar system.[18]

The supernova theory offers an explanation for the perpendicular orientation of the positron cloud above the plane of the Milky Way. The bubble of gaseous matter released during supernovae would have expanded into the least dense portion of the surrounding interstellar medium, which is oriented perpendicular to the galactic plane.[19] Scientists postulate that slight asymmetries in the initial supernovae explosions caused the gas to expand above, rather than below, the plane of the galaxy. The rapidly moving gas bubble would be expected to sweep the positrons in this direction as well.[20]

The supernova theory still leaves several unanswered questions. Although there are plenty of stars close to the Milky Way's core that are massive enough to produce supernovae, it would take the occurrence of a supernova once every century for many thousands of years to explain the vast quantity of positrons that have been observed.[21] Such behavior is not presently observed in our galaxy, so the supernova theory implies that the center of the Milky Way used to be much more violent than it is today. This theory also does not explain what allowed the positrons to migrate so far from their source before annihilating.

Starburst Theory

The most favored theory postulates that the antimatter cloud above the galactic plane resulted from a nuclear starburst, which is a sudden spurt of star formation that takes place near the core of a galaxy. When stars are created in this manner, relatively quickly and in great number, they produce strong stellar winds. As the more massive stars in the starburst region age, many of them exhaust their hydrogen resources at approximately the same time, are torn apart by the battling pressures inside, and explode in supernovae of Type II (supernovae of massive stars). The supernovae plethora spews out gases rich in radioactive nuclei that are carried along by the stellar winds of the starburst region, and some of these nuclei decay to produce positrons that can be transported great distances before annihilating.

The gases emitted by these supernovae move at high speeds and hit the cooler background interstellar dust and gas, heating it to millions of degrees. This ejected gas forms a bubble-like region, with the cooler gas and dust at the edges slowing the bubble's rate of expansion. Normally the bubble expands above and below the galactic plane, but asymmetries can cause it to favor one side. The inner portion of the bubble continues to expand but the outer area is significantly slowed by the interstellar gas. This process creates a zone of turbulence. At this stage, the bubble can be seen from Earth. If this zone of turbulence is energetic enough, the bubble can blow a hole in the galaxy's disk and project parts of the bubble's shell into the galactic halo. Material can be spewed up to thousands of light-years away from the shell's origin. This bubble phenomenon has been observed in the galaxy NGC 3079 (refer to Fig. 4 below) and many scientists believe it to be the same driving force behind the one-sidedness of the stream of positron annihilation emerging from our galaxy's center.[22 23]

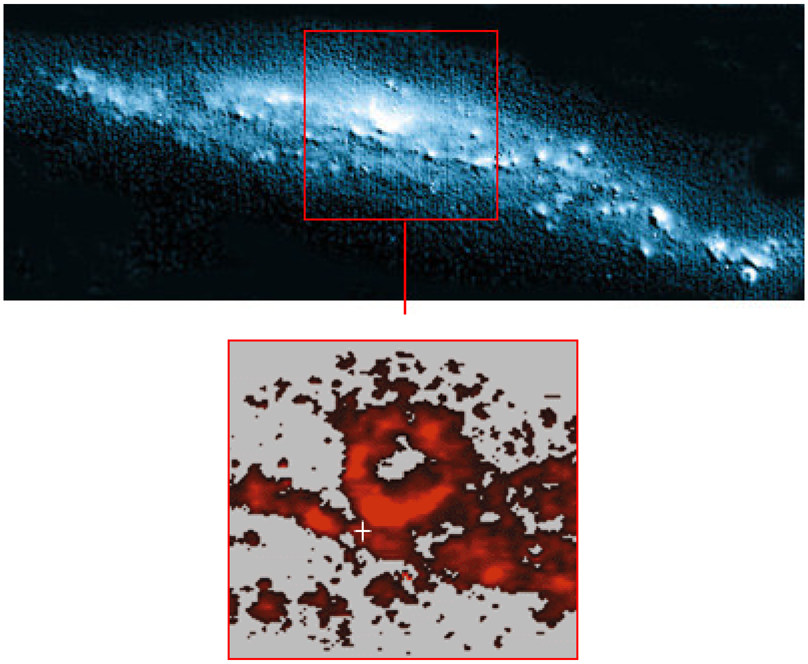

Fig. 4 STARBURST, a sudden pulse of star formation, may be responsible for the activity of NGC 3079 (*side*) even though the galaxy has a black hole at its center. A close-up view of the area near the nucleus (*white cross*) reveals the outlines of an enormous bubble that has been blown into the interstellar medium by the heat of the stars forming at the galaxy's center.

http://www.sciam.com/specialissues/0

Dermer and Skibo published a journal in September of 1997 naming a starburst episode within the inner regions of our galaxy as the culprit behind the observed e^+-e^- annihilation. They explained that the site of initial pressure release, corresponding to the original supernovae and star formation region, was a major factor in the one-sidedness that pushed hot, positron-electron-laden gas into the halo. As the fast-moving positrons moved away from the initial pressure release site, they lost kinetic energy and annihilated in the gas flow, but sometimes traveled far above the galactic disk before annihilating. Dermer and Skibo calculated the high-latitude annihilation patterns and found that they agreed with the observed distance of the antimatter cloud from the galactic plane, which is some of the best evidence in favor of the starburst theory.[24]

A starburst generates a great deal of its high-energy radiation from supernova-spewed material that collides with the surrounding interstellar gas and dust, which in turn cannot produce radiation above the x-ray range. This condition is a difficulty for the starburst theory because much of the energy released during the starburst must go into x-ray production, while only a fraction of the energy goes into creating radioactive nuclei, and hence, 0.511 MeV gamma rays. Therefore, a very massive starburst is needed to produce the quantity of gamma rays that we observe.[25] [26]

Whether or not the starburst theory can stand on its own two feet is a very controversial issue between astronomers. Roberto Terlevich of the Royal Greenwich Observatory and his collaborators are collecting the most recent research to discover whether starbursts can work on their own in transporting the hot gas over great distances. He and Jorge Melnick proposed the existence of unusual stars named "warmers" that have temperatures larger than 100,000 degrees and enormous stellar winds. These stars should occur in regions where previous supernovae produced heavy chemical elements and then underwent starburst activity and produced the warmers. Terlevich and his colleagues believe their model works for certain active galaxies and that starbursts alone can be fully responsible for the large outpourings of gas.[27]

Rapid star formation and the resulting bubbles have recently been observed in other galaxies through the resolution power of the Hubble telescope. Astronomers hope to find more galactic bubble examples as they search for a better grasp on this not-yet-understood occurrence.

Conclusion:

The Celebrated launch of the International Gamma-Ray Astrophysics Laboratory: INTEGRAL

How will astronomers be able to distinguish which of these theories, if any, best explains the presence of this cloud emitting 511 keV gamma rays? The ESA (European Space Agency) has designed a satellite for gamma ray detection, INTEGRAL, which will be launched in 2001. The new modules included onboard this satellite will be immensely helpful in fine-tuning the current image of the galactic center and the annihilation fountain protruding from it. INTEGRAL will focus on galactic structure, the galactic center, and stellar nucleosynthesis (radioactive nuclei produced by supernovae), not to mention many other areas of research. Through the use of a germanium spectrometer and other improved features, INTEGRAL will be able to distinguish between point sources and will accurately locate and identify gamma-ray emitting objects. Detecting line-forming (stable energy and wavelength emitting) processes such as nuclear excitation, radioactivity, and positron annihilation also place it well above the capabilities of the CGRO. Its resolving power will be nothing short of phenomenal. Lower resolution spectrometers, such as the modules SIGMA, OSSE, and COMPTEL that make up the CGRO, lack sufficient energy resolution to adequately resolve spectral lines. There is no doubt that the launching of this satellite will lead to new fundamental discoveries in the field of gamma ray astronomy. Perhaps it will provide the observations needed to give us the key to understanding the source of the antimatter cloud in the galactic halo.[28]

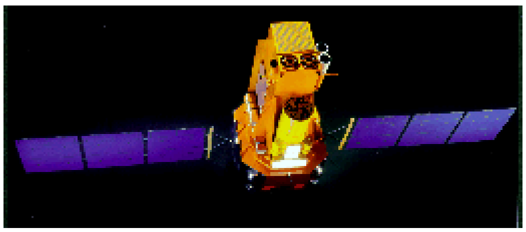

Fig. 5 Computer generated image of the INTEGRAL *(side)*. Once launched, it is expected to become the revolutionizing factor in furthering gamma-ray astronomy.

http://sci.esa.int/integral/

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