LOOKING FOR COSMIC AN

by MAURICE BOURQUIN and GORDON FRASER

WHEN IT BLASTED OFF from NASA's Kennedy Space Center on June 2, 1998, the Space Shuttle Discovery carried the three-ton Alpha Magnetic Spectrometer (AMS), the first major particle physics experiment ever to go into orbit around Earth.

Despite its excitement and glamor, the 10-day flight of the Alpha Magnetic Spectrometer aboard the Space Shuttle was only a taste of bigger things to come. Although all AMS detector systems were up and working, the mission was a trial run to provide operational experience before deploying AMS on the International Space Station in the first years of the new millennium. This milestone mission could reveal the first evidence for nuclear cosmic antimatter, a major step towards resolving a long-standing puzzle about the apparent absence of antimatter in a Universe created in a Big Bang which supposedly produced matter and antimatter in equal amounts.

Stars and other powerful cosmic engines continuously blast out streams of high energy particles. These particles crash into nuclei in the upper atmosphere, producing showers of secondary debris which rain down from the sky as cosmic rays. To see the primary cosmic particles, messengers from distant parts of the Universe, detectors have to be flown high up into the atmosphere in balloons, or above the atmosphere in satellites. The largest pieces of antimatter seen in cosmic rays so far are antiprotons. Cosmic rays appear to contain no antinuclei, suggesting that their sources contain no nuclear antimatter.

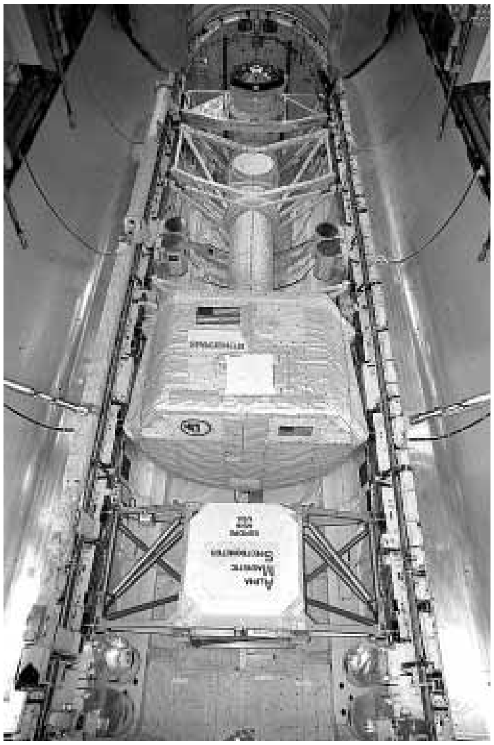
TIMATTER

Space Shuttle astronauts at CERN. Left to right are Mission Pilot Commander Dominic Gorie, Mission Specialist Franklin Chang-Diaz, Commander Wendy Lawrence, Mission Specialist Janet Kavandi, co-author Maurice Bourquin of the University of Geneva, and Mission Commander Colonel Charles Precourt.

This apparent absence of cosmic antimatter has been underlined in a careful appraisal of the implications of a balanced matter-antimatter Universe by Andy Cohen of Boston University, Alvaro de Rújula of CERN, and Sheldon Glashow of Harvard, published in 1998 in the *Astrophysical Journal*. They look at the consequences of matter and antimatter confined in separate and distinct domains.

Such a balanced Universe should have produced matter-antimatter encounters wherever and whenever the boundaries of the matter and antimatter domains touched. In such encounters, the separate pieces of matter and antimatter mutually annihilate to form bursts of energy in the same (but time-reversed) way that energy can create equal amounts of matter and antimatter. In the Universe, this matter-antimatter annihilation would provide a source of high energy cosmic radiation—gamma rays.

As the Universe expands, these annihilation radiation relics cool, giving a diffuse cosmic gamma ray background. But detailed calculations by Cohen, de Rújula and Glashow show that any such effect would be larger than currently observed gamma ray signals, such as those from the EGRET telescope aboard NASA's Compton Gamma Ray Observatory. Today's very low gamma background reveals no evidence for such annihilation processes ever having taken place on a large scale.



The AMS module installed in the Space Shuttle's payload bay. Above is the Spacehab module with supplies and logistics for the Russian Mir space station. This Discovery mission was the last of nine such dockings with Mir.

Detecting cosmic antimatter would be a new Copernican revolution, calling for a reappraisal of our picture of the Universe. However because of the limited sensitivity of the experiments, the existence of antimatter somewhere in the Universe cannot be completely ruled out. In the absence of any sighting, improving the limits on how much antimatter could exist and where it could be helps determine the fundamental parameters of particle theory and its cosmological implications.

AN ANTIMATTER EXPERIMENT IN SPACE

On its own, antimatter should behave like ordinary matter, with antiprotons and antineutrons forming antinuclei, and then attracting orbital positrons to form anti-atoms. Paul Dirac, the spiritual father of antimatter, pointed out that the spectra from atoms of antimatter should be no different from those of ordinary atoms, and antimatter stars would shine in the same way as ordinary ones. How then can antimatter be detected?

The only direct way is to look for stray particles of antimatter, just as Carl Anderson did in 1932 when he saw cosmic ray tracks bending the "wrong" way in a magnetic field and so discovered the anti-electron, better known as the positron. However any primordial cosmic antinuclei would be quickly mopped up by the earth's atmosphere. To see them means sending a magnetic detector into space.

In 1994 Samuel Ting of Massachusetts Institute of Technology presented an imaginative proposal to NASA. His Alpha Magnetic Spectrometer would be a space-borne equivalent of Anderson's historic experiment. Instead of using a cloud chamber to track cosmic particles, it would use sophisticated semiconductor technology.

Ting built up a diverse, skilled team of scientists from the United States, China, Russia, Taiwan, Germany, Italy, Switzerland, and other European countries. The experiment brings a novel symbiosis of space-borne and particle physics research.

Particle physicists are skilled at designing and building detectors to record particle reactions under controlled laboratory conditions. For AMS, the interactions would instead be supplied by Nature. However for AMS, the conditions are very different, calling for new solutions. As well as the size, weight, and electric power restrictions of a space-borne experiment, the detector has to respect stringent crew safety requirements and be compatible with delicate space shuttle systems (even in an airplane the use of electronic equipment by passengers is restricted!). AMS instrumentation has to withstand the huge forces when the space shuttle blasts off and lands, where accelerations reach 15 G and noise vibration levels attain 150 decibels. In flight, the detector has to withstand large temperature swings, high radiation levels and the intense vacuum of outer space. This was new territory for particle physicists used to the relative calm of their terrestrial laboratories. Instead of being on hand in a nearby control room, they would have to monitor their detector from the remote ground station, with an astronaut mission specialist as their space-borne representative.

A VERY SPECIAL DETECTOR

The AMS detector contains the usual components of a particle physics experiment—a central spectrometer with a magnet to bend the particle trajectories and tracking to record the paths of particles, particle identification capability, data acquisition systems to filter, compress, and record the information, and monitoring and control systems, as well as communications with the mother craft. Almost all these functions required special attention for a space environment.

To provide these capabilities, AMS uses a cylindrical permanent magnet, a set of six silicon tracking planes with double-sided readout, a time-of-flight measurement system with two pairs of scintillator arrays and an aerogel Cerenkov counter. An anticoincidence counter system around the tracker helps distinguish particles passing inside the detector from those interacting in the surrounding material.

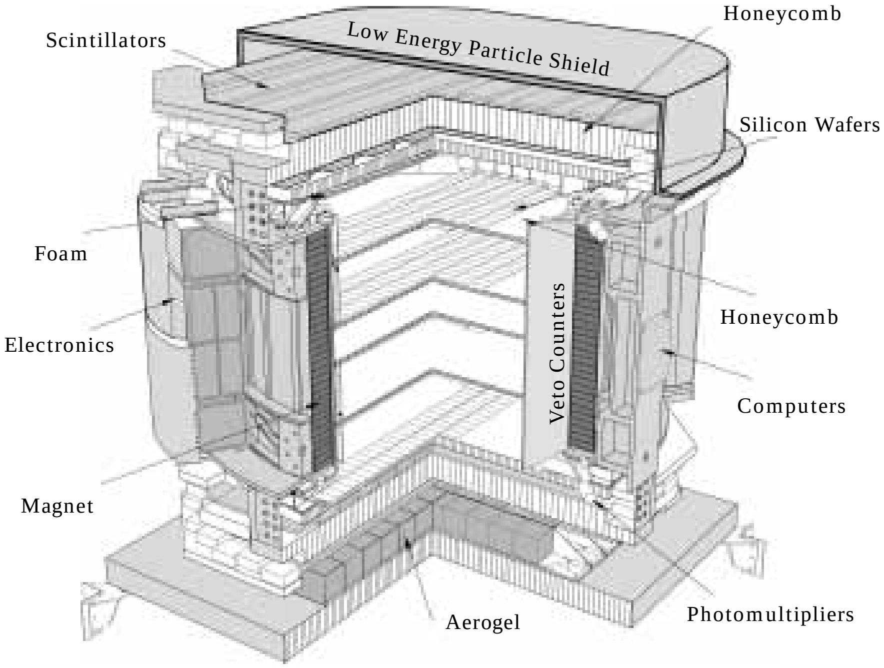
These components are assembled on an aluminum barrel structure, 1.14 m in diameter and 0.80 m in height, supporting the permanent magnet. The outside of the barrel carries electronic crates for the power supplies, trigger systems, data acquisition systems, monitoring and orbiter communication interfaces.

A charged antiparticle passing through the detector bends the "wrong" way in the magnetic field. However full identification comes from measuring the particle's momentum (from the exact curvature of its trajectory), its velocity (measured by the time-of-flight system) and its energy losses by ionization in the tracker and scintillators.

The magnet uses a neodymium-iron-boron alloy to optimize its field-to-weight ratio. The ferromagnetic material is shaped into 6000 small blocks (about 1 kg each) glued together into prismatic bars with suitably oriented magnetization. In the magnet aperture, the highly uniform magnetic field is of the order of 0.1 tesla. With such a magnetic field, the flux leakage has to be very small to safeguard the overall operation of the spacecraft. The magnet was built and space qualified using carefully chosen components and with stringent acceleration and vibration tests in China.

The core of the detector, the particle tracker, is based on the Silicon Microvertex Detector of the L3 experiment at CERN's LEP electron-positron collider, but most modules

Cutaway view of the AMS detector as flown on the Space Shuttle in June 1998. To track cosmic particles, the interior of the AMS detector contains semiconductor technology developed and perfected for the L3 experiment at CERN. As well as pinpointing cosmic tracks with micron precision, this instrumentation has to endure the extreme vibration and noise levels during the launch and landing of the Space Shuttle. Only half the silicon sensors were installed for this flight, thus providing valuable experience before deploying AMS on the International Space Station in the first years of the new millennium.

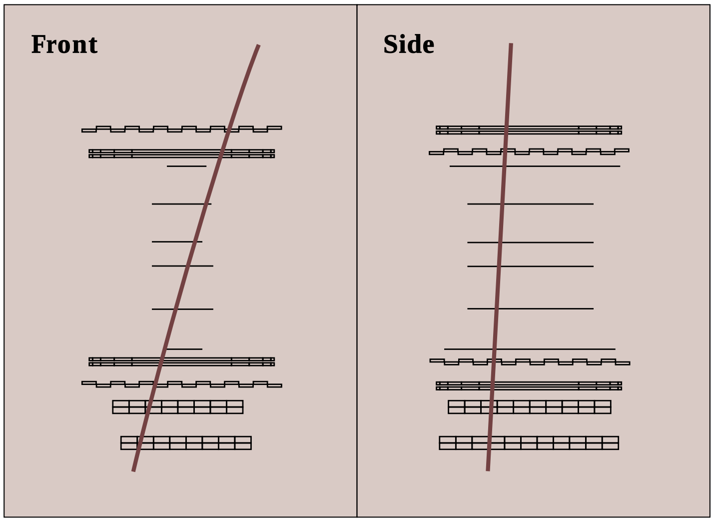


are much longer. These detector elements using arrays of high purity silicon wafers were developed to pinpoint particle tracks and so detect the decay products of very short-lived charged particles, which even when moving almost at the speed of light travel only a fraction of a millimeter before decaying.

The AMS tracker is made of 41×72 mm double-sided silicon sensors, 300 microns thick. The arrangement gives measurements in three dimensions. Charged particles can be pinpointed down to 10 microns. The modules are mounted on disk-shaped honeycomb supports. The front-end readout electronics uses hybrid circuits mounted perpendicular to the module planes. Cooling bars conduct the heat produced to the magnet. Flat ribbons of coaxial cables take the signals to the analog to digital converters and other data processing circuits in the outside crates.

The time-of-flight system uses four planes of scintillators, two above and two below the magnet. It has three tasks: to trigger the detector by selecting single particles traversing the spectrometer; to measure their velocity and distinguish between upward and downward particles; and to perform four independent ionization measurements to separate particles carrying different electric charges. When the two independent measurements provided by the four planes are combined, the time-of-flight measurement is about 100 ps.

A candidate cosmic antiproton recorded by the AMS tracker.



The threshold Cerenkov counter below the spectrometer uses a radiating medium made of 8 cm thick aerogel blocks optically connected to photomultipliers. The blocks are arranged in two layers of 8×10 and 8×11 matrices. As low energy protons and antiprotons do not produce Cerenkov light, they can easily be distinguished from positrons and electrons.

The anticoincidence counter system rejects sprays of neutrons and protons coming from comic ray interactions in the magnet body or in the detector material. This rejection considerably reduces background in the other systems and allows much more sensitive measurements. The system consists of a cylindrical wall of 16 plastic scintillators between the tracker and the internal face of the magnet.

For the space station mission, the silicon tracker has to be augmented to reach a total area of about 6 square meters, and additional detectors have to be built.

Space qualification tests on the state-of-the-art detector were carried out in specially-equipped space laboratories. After final assembly at the Swiss Federal Technical Polytechnic (ETH) in Zurich, the initial version of the AMS detector was shipped to the US for final integration aboard the space shuttle.

Discovery's flight crew brought the space shuttle into land on schedule June 12, 1998. Although the orbiter's high speed data transmission link to earth failed during the flight, this did not affect actual AMS data taking: all data were safely recorded on board. Resourceful NASA communications specialists and the astronauts were also able to patch through some data via a link normally reserved for video pictures, and this 10 percent sample showed that the detector performed flawlessly. The valuable 100 million-event trawl of physics from outer space is being carefully analyzed.

Before publishing their final results, AMS scientists have to calibrate all their detectors with benchmark particle beams, including helium and carbon ions. This is being done at particle accelerators at GSI, Germany and CERN.

Is cosmic antimatter out there? Is it further away than we can currently see? As the curtain goes up on 21st century research, answers could soon be within reach. As Cohen, de Rújula and Glashow conclude in their milestone paper, "The detection of antinuclei among cosmic rays would shatter our current understanding of cosmology."