The following article was accepted for publication in the Macmillan Encyclopedia of Physics in 1996. It presents a general introduction to the field of cosmic rays.

Cosmic Rays

R. A. Mewaldt

California Institute of Technology

Cosmic rays are high energy charged particles, originating in outer space, that travel at nearly the speed of light and strike the Earth from all directions. Most cosmic rays are the nuclei of atoms, ranging from the lightest to the heaviest elements in the periodic table. Cosmic rays also include high energy electrons, positrons, and other subatomic particles. The term "cosmic rays" usually refers to galactic cosmic rays, which originate in sources outside the solar system, distributed throughout our Milky Way galaxy. However, this term has also come to include other classes of energetic particles in space, including nuclei and electrons accelerated in association with energetic events on the Sun (called solar energetic particles), and particles accelerated in interplanetary space.

Discovery and Early Research: Cosmic rays were discovered in 1912 by Victor Hess, when he found that an electroscope discharged more rapidly as he ascended in a balloon. He attributed this to a source of radiation entering the atmosphere from above, and in 1936 was awarded the Nobel prize for his discovery. For some time it was believed that the radiation was electromagnetic in nature (hence the name cosmic "rays"), and some textbooks still incorrectly include cosmic rays as part of the electromagnetic spectrum. However, during the 1930's it was found that cosmic rays must be electrically charged because they are affected by the Earth's magnetic field.

From the 1930s to the 1950s, before man-made particle accelerators reached very high energies, cosmic rays served as a source of particles for high energy physics investigations, and led to the discovery of subatomic particles that included the positron and muon. Although these applications continue, since the dawn of the space age the main focus of cosmic ray research has been directed towards astrophysical investigations of where cosmic rays originate, how they get accelerated to such high velocities, what role they play in the dynamics of the Galaxy, and what their composition tells us about matter from outside the solar system. To measure cosmic rays directly, before they have been slowed down and broken up by the atmosphere, research is carried out by instruments carried on spacecraft and high altitude balloons, using particle detectors similar to those used in nuclear and high energy physics experiments.

Cosmic Ray Energies and Acceleration: The energy of cosmic rays is usually measured in units of MeV, for mega-electron volts, or GeV, for giga-electron volts. (One electron volt is the energy gained when an electron is accelerated through a potential difference of 1 volt). Most galactic cosmic rays have energies between 100 MeV (corresponding to a velocity for protons of 43% of the speed of light) and 10 GeV (corresponding to 99.6% of the speed of light). The number of cosmic rays with energies beyond 1 GeV decreases by about a factor of 50 for every factor of 10 increase in energy. Over a wide energy range the number of particles per m^2 per steradian per second with energy greater than E (measured in GeV) is given approximately by $N(>E) = k(E + 1)^{-a}$, where $k \sim 5000$ per m^2 per steradian per second and $a \sim 1.6$. The highest energy cosmic rays measured to date have had more than 10^{20} eV, equivalent to the kinetic energy of a baseball traveling at approximately 100 mph!

It is believed that most galactic cosmic rays derive their energy from supernova explosions, which occur approximately once every 50 years in our Galaxy. To maintain the observed intensity of cosmic rays over millions of years requires that a few percent of the more than 10^{51} ergs released in a typical supernova explosion be converted to cosmic rays. There is considerable evidence that cosmic rays are accelerated as the shock waves from these explosions travel through the surrounding interstellar gas. The energy contributed to the Galaxy by cosmic rays (about 1 eV per cm^3) is about equal to that contained in galactic magnetic fields, and in the thermal energy of the gas that pervades the space between the stars.

Cosmic Ray Composition: Cosmic rays include essentially all of the elements in the periodic table; about 89% of the nuclei are hydrogen (protons), 10% helium, and about 1% heavier elements. The common heavier elements (such as carbon, oxygen, magnesium, silicon, and iron) are present in about the same relative abundances as in the solar system, but there are important differences in elemental and isotopic composition that provide information on the origin and history of galactic cosmic rays. For example there is a significant overabundance of the rare elements Li, Be, and B produced when heavier cosmic rays such as carbon, nitrogen, and oxygen fragment into lighter nuclei during collisions with the interstellar gas. The isotope ^{22}Ne is also overabundant, showing that the nucleosynthesis of cosmic rays and solar system material have differed. Electrons constitute about 1% of galactic cosmic rays. It is not known why electrons are apparently less efficiently accelerated than nuclei.

Cosmic Rays in the Galaxy: Because cosmic rays are electrically charged they are deflected by magnetic fields, and their directions have been randomized, making it impossible to tell where they originated. However, cosmic rays in other regions of the Galaxy can be traced by the electromagnetic radiation they produce. Supernova remnants such as the Crab Nebula are known to be a source of cosmic rays from the radio synchrotron radiation emitted by cosmic ray electrons spiraling in the magnetic fields of the remnant. In addition, observations of high energy (10 MeV - 1000 MeV) gamma rays resulting from cosmic ray collisions with interstellar gas show that most cosmic rays are confined to the disk of the Galaxy, presumably by its magnetic field. Similar collisions of cosmic ray nuclei produce lighter nuclear fragments, including radioactive isotopes such as ^{10}Be, which has a half-life of 1.6 million years. The measured amount of ^{10}Be in cosmic rays implies that, on average, cosmic rays spend about 10 million years in the Galaxy before escaping into inter-galactic space.

Very High Energy Cosmic Rays: When high energy cosmic rays undergo collisions with atoms of the upper atmosphere, they produce a cascade of "secondary" particles that shower down through the atmosphere to the Earth's surface. Secondary cosmic rays include pions (which quickly decay to produce muons, neutrinos and gamma rays), as well as electrons and positrons produced by muon decay and gamma ray interactions with atmospheric atoms. The number of particles reaching the Earth's surface is related to the energy of the cosmic ray that struck the upper atmosphere. Cosmic rays with energies beyond 10^{14} eV are studied with large "air shower" arrays of detectors distributed over many square kilometers that sample the particles produced. The frequency of air showers ranges from about 100 per m^2 per year for energies $>10^{15}$ eV to only about 1 per km^2 per century for energies beyond 10^{20} eV. Cosmic ray interaction products such as neutrinos are also studied by large detectors placed deep in underground mines or under water.

Most secondary cosmic rays reaching the Earth's surface are muons, with an average intensity of about 100 per m^2 per second. Although thousands of cosmic rays pass through our bodies every minute, the resulting radiation levels are relatively low, corresponding, at sea level, to only a few percent of the natural background radiation. However, the greater intensity of cosmic rays in outer space is a potential radiation hazard for astronauts, especially when the Sun is active, and interplanetary space may suddenly be filled with solar energetic particles. Cosmic rays are also a hazard to electronic instrumentation in space; impacts of heavily-ionizing cosmic ray nuclei can cause computer memory bits to "flip" or small microcircuits to fail.

Cosmic Rays in the Solar System: Just as cosmic rays are deflected by the magnetic fields in interstellar space, they are also affected by the interplanetary magnetic field embedded in the solar wind (the plasma of ions and electrons blowing from the solar corona at about 400 km/sec), and therefore have difficulty reaching the inner solar system. Spacecraft venturing out towards the boundary of the solar system they have found that the intensity of galactic comic rays increases with distance from the Sun. As solar activity varies over the 11 year solar cycle the intensity of cosmic rays at Earth also varies, in anti-correlation with the sunspot number.

The Sun is also a sporadic source of cosmic ray nuclei and electrons that are accelerated by shock waves traveling through the corona, and by magnetic energy released in solar flares. During such occurrences the intensity of energetic particles in space can increase by a factor of $10^2$to 10^6 for hours to days. Such solar particle events are much more frequent during the active phase of the solar cycle. The maximum energy reached in solar particle events is typically 10 to 100 MeV, occasionally reaching 1 GeV (roughly once a year) to 10 GeV (roughly once a decade). Solar energetic particles can be used to measure the elemental and isotopic composition of the Sun, thereby complementing spectroscopic studies of solar material.

A third component of cosmic rays, comprised of only those elements that are difficult to ionize, including He, N, O, Ne, and Ar, was given the name "anomalous cosmic rays" because of its unusual composition. Anomalous cosmic rays originate from electrically-neutral interstellar particles that have entered the solar system unaffected by the magnetic field of the solar wind, been ionized, and then accelerated at the shock wave formed when the solar wind slows as a result of plowing into the interstellar gas, presently thought to occur somewhere between 75 and 100 AU from the Sun (one AU is the distance from the Sun to the Earth). Thus, it is possible that the Voyager 1 spacecraft, which should reach 100 AU by 2007, will have the opportunity to observe an example of cosmic ray acceleration directly.

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