Knee-deep in cosmic rays

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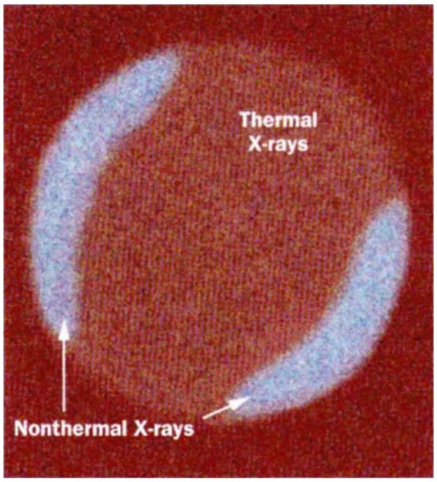
Cosmic rays — the electrons and ions of relativistic velocities that bombard the Earth from all directions — were first observed in experiments with balloon-borne electroscopes over 80 years ago. The problem of their origin has attracted some of the great minds of twentieth-century physics, most famously Enrico Fermi[1]. The general view[2] is that the vast bulk of cosmic-ray ions and electrons, up to energies of about 10^{15} eV (1,000 TeV), are accelerated in the shock waves of supernova remnants, in a process that is a descendant of Fermi's original idea. But direct evidence for particles of these enormous energies in supernova remnants has been lacking. Now Koyama *et al.*[3], as they describe on page 255 of this issue, have evidence for the presence of electrons with energies over 100 TeV in at least one such remnant, that of the supernova known from historical records in AD 1006.

Cosmic rays are detected at the Earth by satellites, balloons and ground-based air-shower detectors. Their energies are observed to range from below 1 GeV, where they disappear into the solar wind, up to the astonishing energy of over 10^{20} eV, or around 10 joules. The highest-energy events are detected at the Earth's surface as huge sprays of debris resulting from collisions by unknown particles with air molecules at the top of the atmosphere. The spectrum is close to a power law in energy over most of this range, with an index of about -2.7 below 1,000 TeV, where a slight steepening occurs (the 'knee') to an index of about -3.1. Cosmic-ray electrons are observed up to about 1,000 GeV. Above this energy, the electron flux, already lower than that of ions by about a factor of a hundred, drops off more steeply and becomes lost in a background of proton-induced events.

It is generally thought that Galactic sources, most likely interstellar shock waves from supernovae, produce the cosmic rays up to the 'knee', whereas some other process, perhaps extragalactic, is responsible for the more energetic component. (Pulsars do produce extremely energetic electrons, but are not thought likely to account for a significant fraction of Galactic cosmic rays.) In the process of diffusive (Fermi) shock acceleration[2], energetic particles move upstream of the shock, scatter from magnetic turbulence convected in with the incoming flow and acquire extra energy. Some of them return downstream and are again reflected from downstream turbulence, again gaining energy. The cycle can repeat indefinitely, until particles are lost downstream or reach energies at which the required resonant scattering waves are absent.

For cosmic rays below the 'knee', supernova remnants make handy culprits; they result from highly energetic (10^{44} joule) explosions which are regularly observed in galaxies like our own (although none has been observed in the Milky Way since Kepler's supernova of 1604). Their shock waves expand into the interstellar medium for up to 100,000 years, reaching sizes of tens to hundreds of light years. Supernova remnants are associated with strong radio synchrotron emission from relativistic electrons, providing direct evidence for the production of electrons with energies at least into the 1–10 GeV range. But it is a large extrapolation from this evidence to the conclusion that the remnants can provide the entire Galactic component of all cosmic rays — it's a long way from 10 GeV to 1,000 TeV. There is as yet no firm evidence for the acceleration of ions in supernova shock waves, and an early estimate[4] of the maximum energies that could be produced by shock acceleration suggested that the 'knee' could not in fact be reached.



Outline of the X-ray morphology of supernova remnant 1006. The brightest regions, and those now shown to have nonthermal spectra, are the opposing blue arcs, whereas the remainder of the remnant shows fainter, less energetic thermal emission.

In addition to being potential cosmic-ray factories, supernova remnants are bright thermal X-ray sources, their spectra revealing the elemental abundances of the stars that produced them. Whilst studying one such object, the galactic remnant of the supernova of AD 1006, Koyama *et al.*[3] have found a convincing resolution to a long-standing puzzle. Unlike other remnants of historical supernovae, this had been found to have an X-ray spectrum devoid of individual spectral lines, with a continuum shape much better represented by a power law than by the expected exponential cut-off from thermal bremsstrahlung. Although early suggestions were made that the X-rays might be synchrotron emission from highly energetic electrons[5], the discovery of weak oxygen lines below 1 keV seemed to favour a thermal origin, and complex thermal models were produced[6] which managed to suppress line emission.

Koyama *et al.* find, however, that the power-law spectrum is alive and well in the bright opposing limbs of the object, shown in blue (more energetic photons) in the figure. Their observations, made with the Japanese ASCA X-ray satellite, show that spectra from the fainter areas of the limbs, and from the centre, are normal and line-dominated. Koyama *et al.* conclude that the thermal model cannot explain the emission from the bright areas, and that the most likely origin here is synchrotron emission from electrons. The emitted photon energy is linked to the electrons' energy by the magnetic field strength, estimated to be 10^{-5} gauss, requiring that the radiating electrons range in energy to 100 TeV and above — within a factor of 10 of the 'knee'.

Confirmation of the nonthermal nature of the X-ray emission is a large step towards the confirmation of supernova remnants as the source of Galactic cosmic rays below 1,000 TeV. The putative process of shock acceleration operates differently for electrons and ions of low energies, but at higher energies such that both ions and electrons are relativistic, the processes by which they produce, and scatter from, magnetohydrodynamic waves are identical. Thus the evidence that electrons find the appropriate conditions to attain energies over 100 TeV strongly suggests that those conditions are accessible to ions as well.

Confirmation of the nonthermal nature of the emission from supernova 1006 could be made when we have observations at higher energies, such as should be possible from the X-ray Timing Explorer scheduled to be launched this month. But already, the direct demonstration that supernova remnants have the wherewithal to produce 100 TeV particles has gone far towards solving at least part of the mystery of cosmic rays. ☐

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