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3. COSMIC RAYS: PARTICLE ASTRONOMY

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Cosmic-ray particles provide a probe for investigating the interstallar medium and high-energy processes in astrophysics. There have been noteworthy advances in cosmic-ray research during the last three years, subsequent to the publication of several comprehensive reviews, e.g., those of Hayakawa (**1**) and Meyer (**2**) giving overviews of the field, Daniel and Stephens (**3**) on cosmic-ray electrons, Parker (**4**) on the dynamics of the cosmic-ray gas in the galaxy, and Shapiro and Silberberg (**5**) on cosmic-ray nuclei. The present brief summary of recent highlights has perforce omitted many significant developments. Details of recent research appear in the 500 papers (**6, 7**) presented at the 12th International Conference on Cosmic Rays held in Hobart, Tasmania in August, 1971.

Observations of cosmic-ray nuclei: elemental and isotopic composition

Charge resolution and the statistics of events have improved so that abundances of the elements from hydrogen to iron are now fairly well known (**5, 8–13**), and the isotopic composition of hydrogen and helium has been measured (**14**). On the other hand, the study of isotopic abundances for elements heavier than helium has barely begun (**15, 16**). New measurements have markedly improved our knowledge of some abundances, e.g., those of nickel and chromium.

There is a striking difference between the composition of cosmic rays and the general abundances (**17**) of elements and isotopes: the cosmic rays are greatly enriched in the fragmentation products of heavier nuclei. Examples of such fragmentation products are ^{2}H, ^{3}He, Li, Be, B and elements with atomic numbers 17–25. The abundances of these nuclei imply that cosmic rays have passed through 4 to 5 g cm^{-2} of material before reaching Earth (**13, 18**). Hence the cosmic rays seen to be confined for considerable times by galactic magnetic fields before leaking into intergalactic space.

Recent experiments (**10, 19**), unlike some older ones, indicate that the fraction of fragmentation products is nearly independent of energy between 0·1 and 30 GeV/a.m.u. (**13**). However, subsequent observations (**11, 12**) suggest that cosmic rays of higher energy ($30 \lesssim E \lesssim 100$ GeV/a.m.u.) contain fewer fragmentation products: this higher energy component may have leaked out of the galaxy more readily. Further confirmation of these findings is essential; it would elucidate the nature of the hydromagnetic mechanisms that help to confine the galactic cosmic rays.

Nuclear interactions with the interstellar gas

As mentioned above, the cosmic rays we detect near Earth have traversed nearly 5 g cm^{-2} of material from the time of their initial production. As a result, about half of the nuclei between C and

Fe have fragmented into lighter ones during their journey from sources to Earth. In order to interpret the observed abundances (which comprise both original and secondary nuclei), we must know the nuclear breakup cross sections. Only a few of the latter have been measured – mainly for certain radioactive products – but semi-empirical relations have been developed recently for calculating the unmeasured ones (**20**). Newly achieved relativistic beams of heavy ions at particle accelerators show promise of yielding cross-section estimates for the stable product nuclei as well; very few of these are known.

Composition at the cosmic-ray sources

The composition of cosmic rays at their sources has been calculated (**5**) from that observed locally by making appropriate corrections for the fragmentation products. The principal results have been confirmed (**10, 21**), and the calculations have been extended to nuclei heavier than iron (**22**). When this source composition is compared with that of the sun, the relative abundances of nuclides having atomic numbers $Z > 10$ are found to be similar. However, the elements C, N, O and Ne are underabundant in the cosmic rays by a factor of 3 or 4, and H and He by a factor of ~ 20.

There are two alternative explanations for these differences: (a) The cosmic rays are accelerated by shock waves acting on the interstellar gas surrounding the sources – a gas whose composition resembles that of the solar photosphere. However, injection into the cosmic ray beam depends on the first ionization potential; this discriminates against atoms with a high ionization potential (**23, 24**). (b) The composition of cosmic rays springs from a nucleogenesis similar to that of supernova ejecta, i.e., it is enriched in the elements formed in helium-burning, in explosive C, O and Si burning, and in elements formed in the *r-process*. Detailed studies of the composition will distinguish between the two explanations; e.g., confirmation of a high abundance (**25**) for the shortlived trans-uranic nuclei Np, Pu and Cm would favor alternative (B).

Sources of cosmic rays

Various theories of cosmic ray origin have been briefly reviewed (**5**), e.g., hydrodynamical acceleration during supernova explosions, and acceleration in supernova remnants, either close to pulsars or in the expanding shells. It has recently been proposed (**26**) that electromagnetic waves from a pulsar interact with the supernova nebula and filaments during the first ten years after the explosion. After the first year, the particles will be accelerated to energies of about 1 to 300 GeV, and have a spectral index $-2{\cdot}5$. There is also a recent theory (**27**) of cosmic ray acceleration by white dwarfs; one difficulty is that too few of these stars have sufficiently high magnetic fields (**28**).

Cosmic-ray confinement in the galaxy: isotropy

The confinement time of cosmic rays in the galaxy can be determined from the abundance of long-lived radioactive nuclides like ^{10}Be. The half-life of the latter was recently reevaluated to be $1{\cdot}6 \times 10^6$ years (**29**). Recent experimental data on the ratio Be/B (**9, 11, 12, 30**) favor the survival (**13**) of most of the ^{10}Be produced by fragmentation of heavier nuclei. Preliminary, scanty data on isotopic resolution (**16**) of Be also suggest survival. Calculations by the NRL group point toward a confinement time of the order of 2×10^6 years or less, but the uncertainties in nuclear cross sections are still so large, that a value of 6×10^6 years is only 1 standard deviation from the best-fit estimate. In view of the new ^{10}Be lifetime and estimates of cosmic-ray 'age', it now appears likely that at sufficiently high energies a substantial fraction of the nuclides ^{26}Al, ^{36}Cl, ^{53}Mn, ^{54}Mn, ^{242}Pu and ^{248}Cm could also survice. Eventually, studies of cosmic-ray confinement will help determine the mean density of matter in the regions where they are stored.

At energies $\gtrsim 10^{11}$ eV, the cosmic rays arrive isotropically (**31**) within $1{\cdot}5 \times 10^{-4}$. This implies, for cosmic rays of intragalactic origin, a thorough mixing by interstellar magnetic fields and hydromagnetic waves. The propagation of cosmic rays in the galaxy, the pressure they exert on its magnetic fields, and their leakage from the galaxy have been discussed by Parker (**4**). Other recent studies (**32**, **33**) on cosmic-ray scattering by hydromagnetic waves suggest that at energies above 100 GeV there is less scattering and easier leakage.

Examination of the relative abundances of cosmic-ray fragmentation products has shown that the distribution of cosmic-ray path lengths resembles an exponential function (**5**). Particle leakage from the galaxy suppresses the longer path lengths. Recently a theoretical model resembling an exponential distribution (but having a flatter tail) has been proposed (**34**). It is based on one-dimensional diffusion of cosmic rays along interstellar magnetic field lines and on a three-dimensional random walk of these field lines.

Nuclei heavier than nickel

These heavy nuclei are exceedingly rare: the abundance relative to protons of all cosmic-ray nuclei with $Z > 30$ is $\approx 10^{-6}$. Yet, with large-area detectors consisting of emulsions and plastics, a few hundred nuclei have been recorded and analyzed by research groups in Bristol, Schenectady, St. Louis, and Berkeley. (See ref. **25** for a recent review.) The experimental data appear to have abundance peaks for elements expected to be formed in the *r*-process. About three transuranic nuclei have been reported, but the presence of nuclei with $Z > 100$ has not yet been established.

Electrons

We have seen that the *composition* of the nuclear component tells us of its transformations in the interstellar environment. Similarly, the *energy spectrum* of cosmic-ray electrons is affected by the magnetic and radiation fields of the galaxy. Interactions with the former fields result in synchrotron losses, while Compton collisions with the microwave and other electromagnetic radiations also degrade the electron energies. Together these should lead to a steepening of the electron spectrum at the high-energy end. Recent experimental data are consistent with a differential power law having an exponent $\gamma = 2{\cdot}8 \pm 0{\cdot}2$ up to 1000 GeV; however, a steepening of the exponent by about 0·5 beyond 100 GeV cannot be excluded (**35**). This would set an upper limit of a couple of million years to the galactic confinement time of electrons.

Between $\sim 0{\cdot}5$ and $\lesssim 10$ GeV the intensity of cosmic-ray positrons is of the order of one-tenth of electrons (**2**). They are generated in the galaxy by cosmic-ray collisions with the interstellar gas, via pion production and π-μ-e decay. Recent studies (**35**) have clarified the problem of solar modulation of electrons with energies $\lesssim 1$ GeV.

Antiparticles, neutrinos, exotic particles

Rather stringent upper limits have been set on antihelium nuclei (**36**, **37**): $J(\overline{\mathrm{He}})/J(\mathrm{He}) < 2 \times 10^{-4}$. From this one can conclude that if extragalactic cosmic rays consisted equally of matter and antimatter, then $\lesssim 0{\cdot}04\%$ of the arriving cosmic-ray flux is extragalactic; or, if $\gtrsim 1\%$ of the observed cosmic rays are extragalactic, then at least 98% of the extragalactic component consists of 'ordinary' matter (**37**, **13**).

High-energy neutrinos are detected with muon detectors placed deep underground. The number of observed events is similar to that expected from the production of neutrinos in the atmosphere; the flux of extraterrestrial neutrinos is still unknown, and upper limits have been set for neutrinos associated with Weber's "pulses of gravitational radiation". However, the studies have yielded useful information for high-energy physics (**38**, **39**): cross sections for neutrino interactions at high energies, and lower limits to the mass of the intermediate boson.

The search for quarks has yielded only upper limits, the lowest reported flux (**40**) being $< 3 \times 10^{-11}$ $\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$. For charged tachyons, an upper limit of $1{\cdot}5 \times 10^{-5}$ has been reported (**41**) relative to the number of electrons in extensive air showers.

The highest particle energies: air showers

Extensive air showers (EAS) with total energies exceeding 10^{20} eV, have been observed, and ascribed to single primary particles (**42**). In fact, an event attributed to a particle of 4×10^{21} eV has been reported (**43**). However, the validity of this high value is controversial. For the *largest* EAS there is as yet no sure prescription for estimating the energy from the particle number and other properties of the shower.

In the energy domain above 10^{17} eV the flattening of the spectrum – the so-called 'ankle' – formerly thought to set in at $\sim 4 \times 10^{17}$ eV has tended to fade away with the accumulation of additional data (**44**).

Whether ultra-high energy events ($> 10^{16}$ eV) are due to particles originating inside our galaxy (**45, 46**) is uncertain.* It has not been convincingly shown that the galactic magnetic fields could confine protons of such energies, much less make them isotropic.† Yet EAS with energies $> 10^{17}$ eV exhibit a rather uniform distribution of arrival directions, suggesting an extragalactic origin. From distant galaxies, however, the extreme particle energies $< 10^{20}$ eV might not survive, but instead be degraded by inelastic collision with the 3 K blackbody radiation (**46**). It has been speculated that the highest energy cosmic ray showers might be initiated by neutrinos (**48**).

Valuable information on ultra-high-energy nuclear interactions has come from studies of air-showers and of cosmic-ray 'jets'. Secondary particles having transverse momenta up to 30 GeV/c have been reported in EAS interactions (**42**). The data on high-energy jets has been exploited to investigate whether Feynman's theory of scaling is applicable. Firm conclusions are difficult, because statistics are low and the intra-nuclear cascade distorts the data on nucleon-nucleus interactions. The *p-p* interactions observed at the Echo Lake facility (**49**) do not suffer from this difficulty, but they occur at lower energies.

Composition of solar flare particles

Well below the characteristic energies ($\gtrsim 10^9$ eV) of the so-called galactic cosmic rays are those of energetic particles from the sun. Nuclei emitted from several solar flares with energies of ≈ 2 to 60 MeV, and ranging from hydrogen to iron (**50–53**) have generally displayed abundances resembling those deduced from analysis of solar optical spectra. However, one group (**51**) has found an increasing relative abundance of heavy nuclei – an order of magnitude more Si and Fe nuclei than reported in ref. (**50**). The disparate observations are not necessarily inconsistent: it has been suggested that the heavy particles injected in flares are not fully ionized; if so, they have higher rigidities and can leak out of the confinement region more readily. The degree of ionization during injection, and the rigidity thresholds are considered to vary from flare to flare.

Solar modulation of cosmic rays

Solar modulation restricts the interpretation of low-energy data on 'galactic' cosmic rays, particularly below ≈ 200 MeV. It has been shown (**54**) that even at solar minimum, most of the particles at, e.g., 50 MeV/a.m.u. must have had energies ≈ 150 MeV/a.m.u. upon entering the solar system. This adiabatic energy loss in the interplanetary regions also explains two puzzling observations – the apparent suppression of ionization-loss effects, and the approximate energy-independence of cosmic ray abundance ratios down to low energies (**13, 14**). Below several hundred MeV/a.m.u., the energy spectrum of cosmic rays in interstellar space and the degree of solar modulation are unknown: e.g., two recent estimates of the local interstellar proton intensity at 30 MeV (**18, 55**) differ by a factor of 50. The cosmic-ray source spectrum in ref. (**18**) conforms to a power law in total energy/a.m.u. ($\approx^{-\gamma}$) with $\gamma = 2{\cdot}6$, while in ref. (**55**), it follows a power law in rigidity, $R^{-2{\cdot}6}$ for $R > 1{\cdot}5$ GV, and $R^{-1{\cdot}6}$ at low rigidities.

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* Indeed, this question has not been settled (**47**) even for cosmic rays having $< 10^{16}$ eV.

† For complex nuclei such as Fe, a *total* energy of 10^{16} eV would correspond to a lesser rigidity, as the energy per *nucleon* is lower; such nuclei would therefore be contained more readily than protons.

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