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# Galactic cosmic rays

Our Galaxy is filled with a relativistic gas of high-energy protons, electrons, and heavy nuclei. The interstellar energy density of these cosmic rays is ~1 eV cm$^{-3}$ – comparable to the energy density of the galactic magnetic field and of the thermal energy of the interstellar medium – with an energy spectra that extends to a maximum energy above $10^{20}$ eV. High-energy particles are also an important and distinguishing feature of radio galaxies, quasars, and active galactic nuclei. The direct measurement by space and balloon experiments of their charge and mass composition and energy spectra provide information on the source regions within our Galaxy, on injection and acceleration processes, and offer a steadily increasing understanding of cosmic-ray transport through interstellar space. Observations from radio, gamma-ray, and X-ray astronomy define the distribution of energetic particles throughout our Galaxy and establish their presence in extragalactic sources. The interpretation of these observations by allied scientific disciplines is significantly aided by the detailed study of cosmic rays near Earth while our understanding of the sources and of the distribution of galactic cosmic rays is strongly dependent on the data from these other fields.

Space experiments have played a vital role in the development of cosmic ray astrophysics. These experiments have determined the detailed charge and mass composition of cosmic rays for the elements from hydrogen to nickel ($Z = 1$–$28$) up to energies of ~1 GeV, have mapped the charge distribution of many of the even $Z$ elements to uranium ($Z = 92$) and extended the direct observation of the energy spectra of the more abundant elements up through energies of the order of 10 TeV ($10^{13}$ eV). At high energies ($>100$ TeV), the cosmic-ray intensity is so small that experiments such as large, ground-based air-shower arrays must be used. Throughout the modern era of cosmic rays – defined somewhat arbitrarily as 1946 onward – a vital stimulus has been the guidance and insight from a number of excellent theoretical groups.

Cosmic-ray studies now span an epoch of almost exactly 100 years. In this brief overview we sketch the initial gestation of cosmic-ray astrophysics. A more complete history of the early development of cosmic rays by J. A. Simpson can be found in Chapter 4. At the close of the nineteenth century, scientists using gold-leaf electroscopes to study the conductivity of gases discovered that no matter how carefully they isolated their electroscopes from possible sources of radiation they still discharged at a slow rate. In 1901 two groups investigated this phenomenon, J. Elster and H. Geitel (1901) in Germany, and C. T. R. Wilson (1901) in England. Both groups concluded that some unknown source of ionizing radiation existed. Wilson even suggested that the ionization might be "due to radiation from sources outside our atmosphere, possibly radiation like Röntgen rays or like cathode rays, but of enormously greater penetrating power." A year later two groups in Canada, Ernst Rutherford and H. Lester Cooke (1903) at McGill University, and J. C. McLennan and E. F. Burton (1902), at the University of Toronto showed that 5 cm of lead reduced this mysterious radiation by 30%. An additional 5 tonnes of pig lead failed to further reduce the radiation further.

Nothing significant happened until 1907 when Father Theodore Wulf (1907) of the Institute of Physics of Ignatus College in Valkenburg, Holland, invented a new electroscope. Wulf's electroscope enabled scientists to carry the search for the origin of the mysterious radiation out of the

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laboratory, into the mountains, atop the Eiffel Tower and, ultimately, aloft in balloons. Assuming that the radiation came from the Earth, they expected to find a rapid decrease in the radiation as they moved away from the surface. They did not find the decrease they expected and in some cases there seemed to be evidence that the radiation actually increased. Intrigued by the conflicting results obtained by Wulf and his colleagues, a young Austrian nuclear physicist, Viktor Hess, obtained support from the Austrian Imperial Academy of Sciences and the Royal Austrian Aero Club to conduct a series of balloon flights to study the radiation. Hess obtained a license to pilot balloons in order to reduce the size of the crew and thereby increase the altitude to which he could carry his electroscopes. On 12 August 1912, using the hydrogen-filled *Böhmen*, Hess reached an altitude of 5,350 m. Carrying two hermetically sealed ion chambers, he found that the ionization rate initially decreased, but then at about 1500 m it began to rise, until at 5,000 m it was over twice the surface rate. Hess (1912) concluded that the results of these observations can best be explained by the assumption that radiation of a very high penetrating power from above enters into the atmosphere and partially causes, even at the lower atmospheric layers, ionization in the enclosed instruments.

On a voyage from Amsterdam to Java, Clay (1927) observed a variation in cosmic-ray intensity with latitude with a lower intensity near the equator, thus establishing that before entering the Earth's magnetic field, the bulk of the primary cosmic rays were charged particles. In 1930 Bruno Rossi, using Störmer theory, showed that if the cosmic rays were predominantly of one charge or the other there should be an east–west effect. In the spring of 1933 two American groups, Thomas H. Johnson (1933) of the Bartol Research Foundation and Luis Alvarez and Arthur H. Compton (1933) of the University of Chicago, simultaneously and independently measured the east–west effect. It showed the cosmic radiation to be predominantly positively charged. In a series of balloon flights in the late 1930s, M. Schein and his coworkers (1941) used Geiger counter telescopes interspersed with lead absorbers to determine that most of the primary particles were not electrons, and hence protons were most plausibly the dominant constituent.

In 1948 research groups from the University of Minnesota and the University of Rochester flew nuclear emulsions and cloud chambers on the same high-altitude Skyhook balloon flight (Freier *et al*. 1948) and discovered the presence of heavy nuclei in the primary cosmic radiation. Further studies by many other groups soon established that essentially all of the elements between H and Fe were present in the cosmic radiation near the top of the atmosphere – including an overabundance of the light elements Li, Be, and B. Then in 1950 it was found that a significant fraction of the cosmic radio emission was synchrotron radiation – indicating the presence of highly relativistic electrons throughout our Galaxy including some discrete sources as well as extragalactic sources (Pacholczyk 1970). However, because of their small abundance (~1% of the intensity of cosmic ray nuclei) electrons were not directly detected in the primary cosmic radiation until 1962 (Earl 1962, Vogt and Meyer 1962). These discoveries made it possible to begin constructing realistic models of the origin and interstellar transport of galactic cosmic rays.

As early as 1934, Baade and Zwicky linked the appearance of supernovae with neutron star formation and cosmic-ray generation. Fermi (1949) regarded cosmic rays as a gas of relativistic charged particles moving in interstellar magnetic fields. His paper laid the groundwork for the modern theory of cosmic ray acceleration and transport. The close link between radioastronomy and cosmic rays was conclusively established at the time of the Paris Symposium on Radioastronomy in 1958 (Paris Symposium 1959). This marked the birth of cosmic-ray astrophysics. The basic model of the origin of galactic cosmic rays was developed by Ginzburg and Syrovatskii (1964).

Over the last three decades the continual evolution of cosmic-ray detector systems for space missions have given us a detailed description of galactic cosmic rays and a growing understanding of their source region, acceleration, and transport.

## 1. COSMIC-RAY OBSERVATIONS

The elemental composition of cosmic rays provides information on chemical fractionation in the source region as well as some insight into the nature of this region and of the propagation of cosmic rays in interstellar space. Cosmic-ray isotopes probe more deeply the nature of the source region and the timescales of the injection and initial acceleration. Radioactive isotopes such as $^{10}$Be, $^{26}$Al, and $^{36}$Cl reveal the temporal history of cosmic rays in the disk and halo regions. The variation of the charge and mass composition with energy – their energy spectra – can be related to the acceleration process and to particle transport in the Galaxy. When improved measurements are available at ultra-high energies it should be possible to determine whether these particles are of galactic or extragalactic origin. At the highest energies the cosmic-ray arrival direction may also indicate the approximate direction of the most powerful sources.

Over the past four decades of the space age there has been a remarkable improvement in the ability of cosmic ray experiments to measure the elemental and isotopic composition over a steadily increasing range of charges and energy. Space limitations permit discussion of only the more recent results in a given area.

The most remarkable feature of cosmic rays is their energy spectra (Figure 1). From ~10 GeV to $>10^{20}$ eV these spectra, over some 10 orders of magnitude variation in intensity show a relatively featureless power-law distribution. At energies below a few giga-electronvolts the influence of solar modulation becomes important with significant temporal variations at 1 AU related to the 11- and 22-year solar and heliomagnetic cycles. At energies of less than 40 MeV the oxygen spectra in Figure 1 show the presence of so-called anomalous cosmic rays, discussed in Chapter 4. Those are partially ionized interstellar atoms accelerated at the solar wind termination shock. Near 10 MeV there is a highly variable turn-up in the ion spectrum produced by particles of solar/interplanetary origin although the acceleration up to energies more than tens of giga-electronvolts was registered in some solar flare events.

If the differential intensity in Figure 1 is multiplied by $E^{2.7}$, where $E$ is the particle energy, then the structure in the spectrum becomes more apparent at energies >10 Gev (Figure 2). The spectral slope steepens and the energy is proportional to $E^{-3}$ above $10^{14}$ eV. It decreases back to the form $\sim E^{-2.7}$ above $10^{18}$ eV, and extends to $\sim 3 \times 10^{20}$ eV. The experimental limitation imposed by the current size of air-shower arrays does not allow measurements of the cosmic-ray intensity at energies greater than $3 \times 10^{20}$ eV.

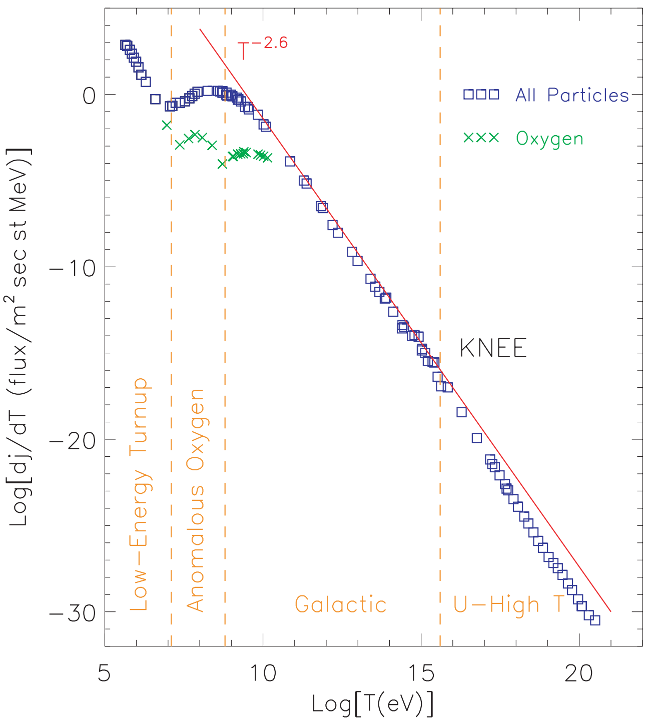


**Figure 1** Energy spectrum of cosmic rays measured at the Earth (Jokipii 1989).

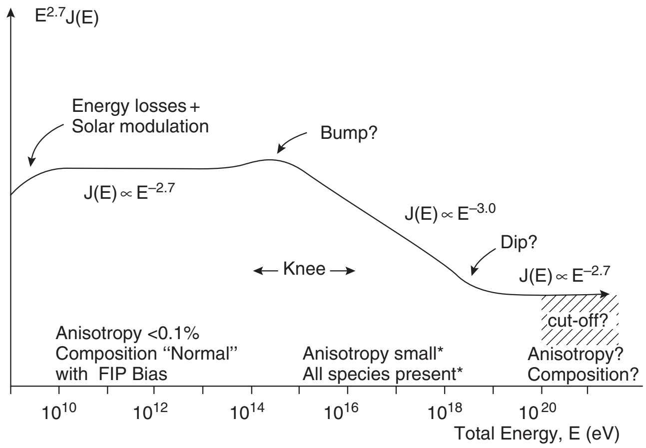


**Figure 2** Schematic representation of cosmic ray spectrum (Axford 1994).

Above 10 TeV the composition is not well known; this is the region where acceleration by supernova shocks becomes difficult. It is generally assumed that the cosmic-ray "knee" at $\sim 10^{15}$ eV may reflect a gradual transition in the composition to particles of increasingly higher charge. At energies $>10^{19}$ eV questions of galactic magnetic confinement lead to the assumption that these particles are of extragalactic origin. At energies above $4 \times 10^{19}$ eV even protons should experience significant deceleration by the 3 K black-body radiation (the Greisen–Zatsepin–Kuzmin effect).

At energies of $10^{12}$–$10^{14}$ eV there are small anisotropies of ~0.1% which are thought to be due to local effects. At this time there are no meaningful anisotropies observed at higher energies except the ultra-high energies $\sim 10^{18}$ eV (see Section 6).

## 1.1 The elemental composition

Over the charge region $Z = 1$–28 (H–Ni), cosmic-ray experiments in space can resolve the individual elements over an extended energy range. A summary of these data (Figure 3) shows the relative abundance of cosmic rays at ~1 AU along with the Solar System abundance (Simpson 1983) for two different energy regimes, 70–280 MeV/nucleon and 1–2 GeV/nucleon. It can be seen that H and He are the dominant elements, constituting some 98% of the cosmic-ray ions, but are still under-abundant in the cosmic rays relative to the Solar System abundance. There is reasonably good agreement between the cosmic-ray and Solar System abundance data for most of the even elements particularly for C, O, Mg, and Fe. The light elements Li, Be and B, and Sc and V in the sub-iron region are greatly over-abundant when compared to the Solar System abundance – a result of nuclear

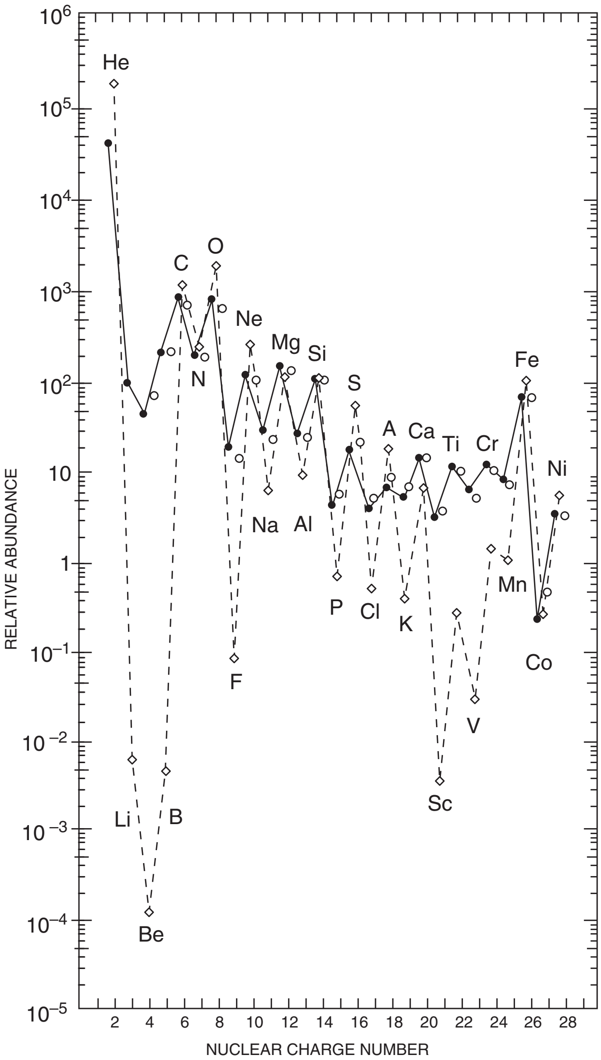


**Figure 3** The relative abundances of H to Ni in cosmic rays, solid line and in the Solar System, dashed line. All abundances normalized at Silicam-100 (Simpson 1983).

spallation in interstellar space by nuclei of higher charge. The secondary nuclei generated by these reactions with the interstellar gas will have essentially the same velocity as the incident primary nuclei and hence the same energy per nucleon. Their energy spectra tend to be steeper than those of the primaries due to energy-dependent escape of the higher-energy primaries from the Galaxy.

It is possible to correct the 1 AU observations for the changes produced by nuclear interactions, ionization energy losses, and escape from the Galaxy in the journey of the energetic nuclei through interstellar space and thus obtain an estimate of the source abundance of these elements. When these source abundances are normalized by their Solar System abundances and plotted against the elements' first ionization potential (FIP), a well-defined fractionation effect is observed (Figure 4). Very similar effects are also present in the relative abundance of the solar coronae, solar wind, and gradual solar energetic particle events.

However, particles with low FIP tend to be chemically active and form stable compounds and structures such as dust grains. Meyer *et al.* (1997) have developed in detail the scenario in which galactic cosmic-ray ions originate predominantly from the gas and dust of the interstellar medium. This model gives a natural explanation of the low abundance of H and He. With the presently available data, it is not possible to choose between FIP and volatility. The maximum energy attainable by the shock acceleration of dust grains is of the order of 0.1 MeV/nucleon, so the "FIP *v.* volatility" argument is really about the injection and initial "energization" processes.

## 1.2 The ultraheavy nuclei ($Z > 30$)

These elements arise from a combination of s-processes (produced in an environment where it is more probable that they undergo beta decay before adding another neutron) and r-processes (produced in a neutron-rich environment where beta decay is less probable). It is expected that r-process elements will dominate in explosive nucleosynthesis such as occurs in supernova explosions. Binns *et al.* (1989) found over the charge range $33 \leq z \leq 60$ that the FIP-corrected observed abundance is similar to that of the Solar System abundance; above $Z > 60$, they found an enhancement of r-process produced nuclei in the source region.

Of particular importance is the actinide region ($Z \geq 88$), where the elements can only be produced via the r-process. These have been studied by an experiment flown on NASA's Long Duration Exposure Facility (LDEF). The experiment consisted of an array of thick, inert, solid-state nuclear track detector stacks – sheets of polycarbonate with a collecting area of $10\,\mathrm{m}^2$. They were exposed in Earth orbit aboard the LDEF for some 69 months. From this exposure Donnelly *et al.* (1999) measured an actinide/subactinide ratio given by

$$\frac{Z \geq 88}{74 \leq Z \leq 87} = 0.0147 \pm 0.003$$

which is consistent within statistical errors with the abundance ratio =0.013 of propagated primordial Solar System material. Notice that the propagated present-day Solar System material would give 0.0077 for this ratio. Donnelly *et al.* (1999) found that the measured abundance is consistent

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