What Are Cosmic Rays Made Of ?

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Cosmic rays are the only samples of matter from beyond the solar system that we can "put our hands on".

The Earth is constantly bombarded by energetic particles: protons, nuclei and electrons of solar, galactic and even extragalactic origin. Bursts of energetic particles emitted by the Sun during flares, arrive at the Earth in bunches, and are generally confined to low energies ($\leq$ 0.1 GeV/nucleon). They are therefore easily distinguished from the comparatively steady flux of cosmic rays of extrasolar origin, which consist predominantly of protons and of entirely stripped heavier nuclei in the 0.1 to 10 GeV/nucleon range. Higher energy particles are also found, with energies up to 10^{11} GeV. In the GeV range electrons are 100 times less numerous than protons.

Here we shall describe the clues to the origin of the cosmic ray nuclei that can be derived from their composition, and especially from their heavy element composition ($Z \geq 3$).

Cosmic Ray Composition As We Observe It

As early as 1948, it was observed that cosmic rays include stripped heavy nuclei and much effort has been devoted ever since to the observation of their elemental composition. After a large number of balloon flights and several satellite-borne experiments over 30 years, this effort culminated in the launch by NASA of the third "High Energy Astronomical Observatory" satellite (HEAO-3) which carried two large cosmic ray telescopes. This operated successfully from September 1979 to June 1981. One instrument, built by a French-Danish team, measured the abundance of all elements between boron and zinc (Z = 5 to 30) with very high precision; the second, built by a consortium of US laboratories, has provided, together with the recent UK satellite Ariel VI, the first comprehensive set of data on the composition of the much rarer cosmic ray nuclei between zinc and uranium (Z = 30 to 92).

Measurements of the isotopic composition of cosmic rays are more difficult to perform although considerable progress has been made in recent years owing to a series of American balloon and satellite experiments searching at energies below 0.5 GeV/nucleon. At higher energies, only indirect methods are at present practicable and these require the reconstruction of the trajectory of each individual incoming particle through the Earth's magnetic field. The French-Danish instrument aboard HEAO-3 for the first time made such analysis possible based on a comprehensive set of data, the treatment of which is at present under way.

An obvious difference in composition between cosmic rays and the ordinary matter to be found in our galactic neighbourhood lies in the ratio of the heavy elements ($Z \geq 3$) to hydrogen and helium: while in galactic matter heavy elements amount to 0.15% by number (1.8% by mass), in cosmic rays they attain 1.5% by number (21% by mass).

But the most striking feature of the observed cosmic ray composition is the high abundance of species that are scarce - sometimes extremely scarce - in galactic matter: deuterium, helium-3, lithium, beryllium, boron and, more generally odd-Z elements.

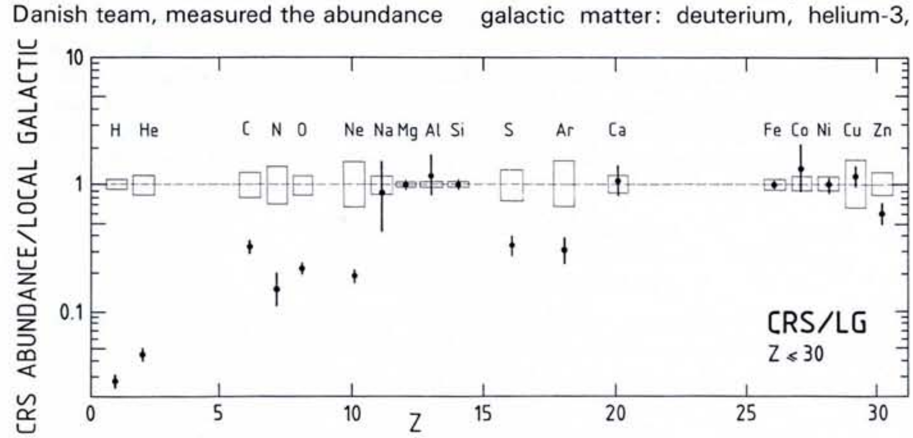

Fig. 1 — Ratios of elemental cosmic ray source (CRS) to local galactic (LG) reference abundances, versus Z, for $Z \leq 30$, normalized to Si. The boxes represent the uncertainties in the local galactic abundances, and the bars those in the cosmic ray source composition as derived mainly from the French-Danish instrument aboard HEAO-3.

This anomaly had been noted early on and readily interpreted as being due to the spallation of cosmic-ray nuclei during their journey in the galaxy from their source to the Earth; in reactions with the nuclei of the interstellar medium, they get broken into lighter nuclei. Whereas a crucial parameter governing the production of ordinary galactic matter by thermonuclear nucleosynthesis in stars is the degree of nuclear stability, it is of little importance in high-energy break up reactions: hence the presence in cosmic-rays of nuclei which are virtually absent everywhere else.

From the measured or interpolated values of spallation cross-sections it is then straightforward to derive simultaneously the amount of matter traversed by cosmic rays between their source and the Earth (several g/cm^2) and the composition they had originally. (At the same time one might note that with the accuracy presently achieved by cosmic-ray measurements, a pressing need for more accelerator cross-section measurements is felt).

Cosmic Ray Source Composition

In the cosmic ray source composition so derived, the pattern of heavy element abundances is reminiscent of that of galactic matter, although some abundance ratios differ by factors of up to 6, as shown in Fig. 1.

As to their isotopic composition however, our knowledge of the source is still quite limited, for two reasons. First, the observations themselves are more difficult; second, for rare isotopes, the few nuclei emitted by the sources are swamped by the numerous nuclei created later by spallation reactions in the interstellar medium. Among the comparatively abundant isotopes, there is at present no hint of very large anomalies in the isotope ratios although the three best-known isotope ratios do show evidence of limited anomalies: $^{22}Ne/^{20}Ne$ is definitely high in cosmic ray sources, by a factor of 3 – 4, while $^{25,26}Mg/^{24}Mg$ and $^{29,30}Si/^{28}Si$ appear to be high by a factor of ~ 1.7 in comparison with galactic matter.

The anomalies in cosmic ray source composition may reflect an acceleration of particles out of sites of current nucleosynthesis. The resulting pattern of abundances should then be directly related to the detailed nuclear properties of the various species. Alternatively, they may reflect any kind of selective process governing the composition of the particular media from which the particles

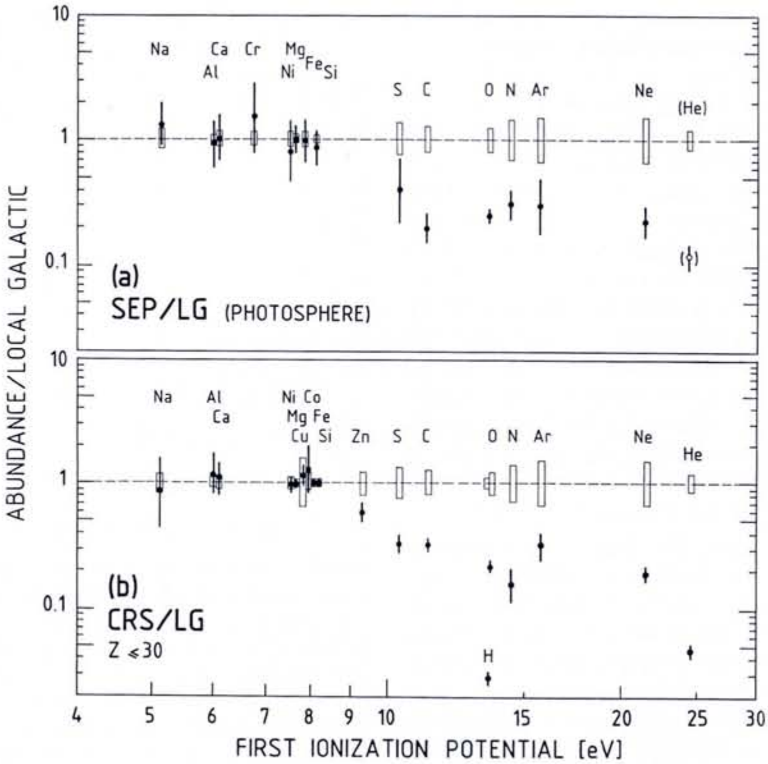

Fig. 2 — Ratios of elemental abundances in (a) solar energetic particles (SEP), and (b) cosmic ray sources (CRS) to local galactic reference abundances, versus first ionization potential, for $Z \leq 30$, normalized to Si (approximately). Boxes and error bars as in Fig. 1.

have been extracted, or operating during the acceleration process itself. Most conceivable selection effects are related to atomic properties. They may strongly discriminate between various elements, but are much less likely to operate between the various isotopes of a particular heavy element. Therefore, while the *elemental* source composition can *a priori* be interpreted in terms of any kind of scenario involving either atomic or nuclear properties, *isotopic* anomalies almost certainly imply specific nucleosynthetic processes.

Special Nucleosynthesis

We shall first try to interpret the anomalies in the elemental cosmic ray source composition, since they are very well known and conspicuous, at least up to zinc ($Z=30$) (Fig. 1). Until recently, the most widespread interpretation was that the bulk of the cosmic ray nuclei were accelerated out of supernova matter as a result of supernovae explosions. As such, the major elemental composition anomalies should correlate with the expected yields of specific nucleosynthetic processes in massive stars, or resemble the expected global yield of a supernova. However, inspection of the cosmic ray source elemental composition, and in particular of the recent results on the elements beyond zinc, does not support this hypothesis at all. Some specific anomalies, such as the low abundances of sulphur and argon relative to neighbouring elements, are particularly difficult to explain in such a framework. We shall see below that the observed isotopic anomalies probably imply that just a small fraction of cosmic rays so originate in sites of current nucleosynthesis.

Seed Particles Emitted By Stellar Flares

The existence of a simple correlation between the elemental abundance anomalies of cosmic ray sources and the first ionization potential was noted several years ago, and has consistently been confirmed by new data. Heavy elements with a first ionization potential higher than ~ 9eV, difficult to ionize, have a tendency to be comparatively underabundant in cosmic ray sources (Figs. 2b and 3), which could be the result of a selection process between neutral and ionized atoms in a dilute warm gas at around 8000 K.

The elemental composition of the energetic particles accelerated by the Sun, although highly variable with time and energy, shows a basic pattern which is remarkably similar to that of cosmic ray sources (Fig. 2). The only clear difference between the two compositions is that in the latter, carbon is twice as abundant. There may also be a more limited oxygen excess. These differences will be discussed below in connection with the ^{22}Ne anomaly.

Although the uncertainties are larger, the same pattern of abundance anomalies are to be found in the thermal gas of the outer solar atmosphere (corona), out of which the solar energetic particles are generally believed to have been extracted, compared with solar surface material (the photosphere which consists of ordinary galactic material) (Fig. 4). The abundance anomalies in solar energetic particles thus do not seem to reflect the effect of acceleration processes beyond thermal energies, but simply the peculiar composition of their native medium. On the whole, the combined observations suggest a selection between thermal neutral and ionized atoms in the feeding of the solar corona. Now, the medium out of which the corona is fed is the underlying chromosphere, whose temperature of about 8000 K is just adequate to bring about the right populations of neutral and ionized atoms (Fig. 4). This gives plausibility to the scenario. But the nature of the processes operating the selection between neutral atoms and ions in the course of the transport of matter from chromosphere to corona remains to be investigated. Thermal diffusion in the extremely steep temperature

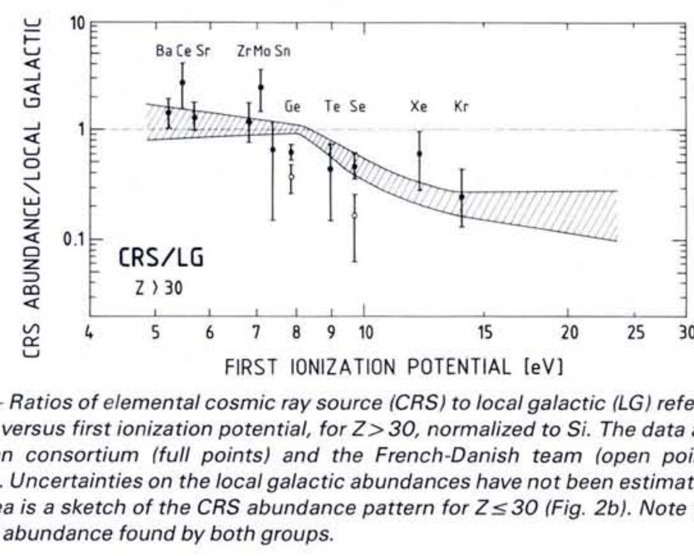

Fig. 3 — Ratios of elemental cosmic ray source (CRS) to local galactic (LG) reference abundances, versus first ionization potential, for $Z>30$, normalized to Si. The data are from the American consortium (full points) and the French-Danish team (open points) aboard HEAO-3. Uncertainties on the local galactic abundances have not been estimated. The hatched area is a sketch of the CRS abundance pattern for $Z \leq 30$ (Fig. 2b). Note the low germanium abundance found by both groups.

gradient between chromosphere and corona (Fig. 4) seems a promising candidate.

All these similarities suggest that the galactic cosmic rays were first extracted out of the outer atmosphere of solar-type stars, most probably in the form of suprathermal "stellar energetic particles" similar to solar energetic particles.

High Energy Acceleration By Supernova Shocks

But the energy of cosmic rays that is observed requires a main acceleration stage that is much more powerful than can be provided by the flaring of ordinary stars. The great dispensers of energy into the interstellar medium are supernova explosions, with stellar winds of massive stars as a close second (about 1/5 as much power available). The supernova explosions result in the formation of shock fronts which continuously sweep the interstellar medium, re-shaping it and maintaining in it a high level of inhomogeneity. Stellar winds also create standing shocks at the point where they merge into the interstellar medium.

The shock environment is turbulent. Particles are scattered almost elastically by magnetic inhomogeneities associated with this turbulence. This scattering is so efficient, the distribution of the particle becomes almost isotropic on both sides of the shock. Macroscopically, each shock crossing results in a head-on encounter between the particle and the shock and leads to a small energy gain for the particle. The efficient scattering ensures that all particles cross the shock many times. Eventually, most particles gain only a factor of a few units in energy, but a few of them are retained for longer times and thus have their energy increased by orders of magnitude.

If many ordinary stars produce suprathermal stellar energetic particles with the right composition, re-acceleration of some of these particles by interstellar shocks can lead to the observed high energy galactic cosmic rays.

Direct Acceleration of Interstellar Gas Particles?

There are however alternative theories. The possiblity has recently been explored that cosmic rays are directly picked out of the thermal interstellar medium material at the passage of a supernova shock. Direct acceleration of a small fraction of the thermal population by a shock front is expected to take place and seems indeed observed in nearby interplanetary shocks and at the Earth bow shock. In the interstellar medium, this process is more likely to happen in the most tenuous and hottest regions, where the temperature reaches a million degrees. In such a medium hydrogen and helium are completely ionized, while the other elements have a mean effective charge Z^* which is smaller than their nuclear charge Z. Out of the thermal population, shock waves accelerate preferentially the elements for which the ratio Z^*/A is small (A = mass number). The underabundance of hydrogen and helium in cosmic rays (Fig. 1) is readily explained by this model, but it is totally unable to account for the discontinuous behaviour of the cosmic ray abundance anomalies as a function of Z (compare, e.g., Ne to Mg and S to Si in Fig. 1).

Moreover, this theory may encounter another obstacle: it is known that in the denser and cooler regions of the interstellar medium, refractory elements are almost entirely condensed into interstellar dust grains; they are therefore highly deficient in the gas phase. It seems quite possible, although not certain, that the refractory cores of these grains do not evaporate even in the hottest regions of the interstellar medium. In this case, cosmic rays extracted directly out of this hot interstellar gas phase should be depleted in refractory elements, contrary to observation. All in all, direct shock acceleration of thermal interstellar gas particles, while physically plausible, does not seem to be the dominant source of the cosmic rays we observe.

Interstellar Dust Grain Destruction Products

Most refractory elements have a low first ionization potential, and tend, as we have seen, to be overabundant in cosmic ray sources (Figs. 2b and 3). It is therefore tempting to link the origin of cosmic rays with the interstellar grain material itself. It has been proposed that the dust grains are accelerated to relativistic velocities, and later on break up. This scenario would yield a cosmic ray component almost entirely devoid of hydrogen, helium and other noble gases. In actual fact, hydrogen and helium, though comparatively somewhat underabundant, are dominant in cosmic rays, and noble gases have normal abundances relative to oxygen.

Another possibility, which now seems more likely, takes advantage of the fact that the interaction length of grains in the interstellar medium is much larger than that of the gas atoms, so that they take a long time to "feel" the passage of a shock. Therefore, just behind the shock, they have a bulk velocity of the order of the shock velocity with respect to the gas. They can thus be destroyed by impinging gas atoms. In this way a new, kinematically distinct gaseous population is produced, composed both of grain material and of ambient particles which have interacted with the grains. This population may then be preferentially picked up by an acceleration mechanism in the shock environment. In this scenario, the relative abundances of hydrogen, helium and oxygen can be understood fairly easily, but complicated and not well known gas processes on grain surfaces have to be invoked to explain the entirely normal abundances of heavier noble gases (Ne, Ar) relative to oxygen (Fig. 2b).

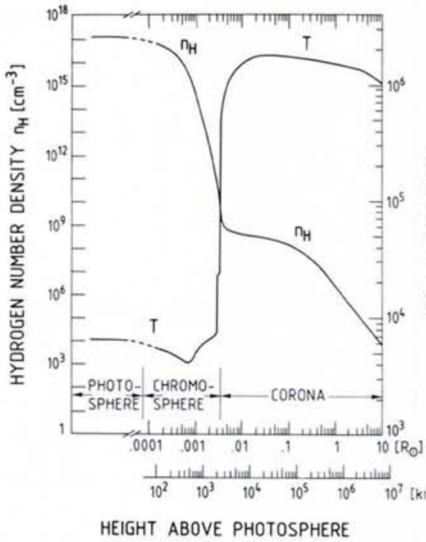

Fig. 4 — Idealized sketch of the outer solar atmosphere, defining the chromosphere and the corona, which are separated by a very thin transition region in which the temperature rises extremely abruptly. Hydrogen density and temperature are plotted against height above photosphere (defined as the depth where the continuum optical depth at 500 nm = 1).

One clue should allow one to discriminate between the interpretations of the cosmic ray abundance anomalies in terms of (i) first ionization potential, and (ii) grain destruction: not all volatile elements have a high first ionization potential. There are exceptions, such as germanium or lead. The recent observations of low Ge/Fe and Pb/Pt ratios by the HEAO-3 satellite seem to favour theories invoking grain destruction (Fig. 3). But the main problem of these grain theories, which remains open, is to account for the similarities in composition between cosmic rays and solar energetic particles (Fig.2).

Isotopic Anomalies and Wolf-Rayet Stars

So much for the elemental composition. The observed isotopic anomalies bring additional pieces to the puzzle. As mentioned above, ^{22}Ne is overabundant by a factor of 3 - 4 and there may also be a smaller overabundance of $^{25,26}Mg$ and $^{29,30}Si$, by factors of ~ 1.7, relative to the dominant isotopes.

We have to look for particular nucleosynthetic sites capable of producing specifically ^{22}Ne. These are related to late stages of the evolution of massive stars. When these stars have consumed all the hydrogen in their centre, they start burning their helium. As far as heavy nuclei are concerned, the quiescent helium-burning results essentially in the copious production of carbon and/or oxygen by fusion of 3 or 4 alpha particles in the centre of the star. At the same time, addition of two alpha particles to the available nitrogen, accompanied by a β-decay, yields a ^{22}Ne overabundance by a factor of ~ 120. The most massive stars that have reached this stage of evolution emit strong winds, which are so powerful that the entire envelope of unprocessed material is expelled. At this stage, the helium-burning material appears at the surface of the star, and is also released into space. Stars having reached this stage are called Wolf-Rayet stars.

If ~ 1/50 of cosmic rays are produced out of Wolf-Rayet star material, the cosmic ray overabundances of both ^{22}Ne and carbon (the latter relative to solar energetic particles) are accounted for. If a smaller fraction of cosmic rays originates from material emitted by Wolf-Rayet stars at slightly later stages of stellar evolution, in which carbon is converted into oxygen, and ^{22}Ne into $^{25,26}Mg$, the observed marginal excesses of these species are explained as well. But the $^{29,30}Si$ excess, if real, does not fit this scenario.

Even later in their evolution, massive stars explode as supernovae. During the explosion itself, chains of high temperature reactions also produce ^{22}Ne, along with many other species. But if explosive reactions were the source of the excess ^{22}Ne, it would be accompanied by many other anomalies, which are not observed.

In Brief

The bulk of the observations suggest that most cosmic rays are suprathermal stellar energetic particles first emitted by stellar flares similar to solar flares, that later are boosted to much higher energies by strong supernova (or stellar wind) shock waves present in the interstellar medium. As such, their peculiar elemental composition, biased according to first ionization potential, reflects that of the outer atmosphere of ordinary stars, just as the similar composition of solar energetic particles apparently samples that of the solar corona. It has indeed been observed that a very wide class of ordinary small mass stars (tyes F to M) possess chromospheres and coronae very similar to those of the Sun, and are the site of flares which resemble those taking place on the Sun. Note also that, if cosmic rays originate in stellar matter, the lack of a deficiency of refractory elements, which are highly depleted in the gas phase of most of the interstellar medium, is readily explained. The ^{22}Ne and C excesses in cosmic rays are accounted for if, in addition to this main component, ~ 1/50 of cosmic rays are made of Wolf-Rayet star material.

But other interpretations are possible. In particular, one should keep in mind that a bias according to first ionization potential can mimic a bias according to volatility. Recent data from the HEAO-3 spacecraft hint that volatility, rather than first ionization potential, may be the relevant parameter. Should these indications be confirmed in the future, then the scenarios regarding cosmic rays as made of grain destruction products would become more appealing.

Third World Academy of Sciences

The Third World Academy of Sciences was formally inaugurated at Trieste on 11 November 1983 with 28 Founding Fellows from 14 different third world countries and 13 Associate Founding Fellows mostly from the USA but with backgrounds in the third world.

The broad aims of the Academy are defined as:

1. To help in providing high-level scientists in developing countries with the conditions necessary for the advancement of their work;
2. To promote individual contacts both within and outside these countries;
3. To help in identifying talent and promoting creativity;
4. To identify experts who can advise on national policy;
5. To encourage research and communication on major third world problems.

The first President of the Academy is Abdus Salam of Pakistan and the first vice-presidents: C. Chagas of Brazil, M.G.K. Menon of India and T.R. Odhiambo of Kenya. The office of the Academy will be at the location of the President and is now at the International Centre for Theoretical Physics in Trieste; M.H.A. Hassan is Executive Secretary.

European Geophysical Society

The European Geophysical Society (EGS) was founded in 1971 with the express purpose of organising regular meetings in Europe which younger geophysicists could attend. The Society is divided into three main sections

I Solid Earth and planets
II Hydrospheres and atmospheres
III Upper atmospheres, ionospheres, magnetospheres and the interplanetary medium.

There is also a Special Interest Group on Planetary Science.

The EGS is run by an elected Council drawn from a broad spread of countries and presently presided over by Professor R. Hide of Bracknell, England. The members, as in the EPS, comprise both individual members and corporate members i.e. societies, academies, institutions and groups. The Society publishes the journal *Annales Geophysicae* and, jointly with the American Geophysical Union, runs the journal *Tectonics*. It also distributes a newsletter to members.

The next annual meeting will be held in Louvain-la-Neuve (Belgium) from 30 July to 3 August 1984. There will be four parallel symposia:

1) Solar Geophysical Indices Revisited
2) First Results from European Geophysics and Solar Experiments on Spacelab
3) Thermosphere/Ionosphere Coupling at High Latitudes and Possible Solar Wind/ Magnetosphere Influence
4) Future Planetary Missions and a workshop on:
Magnetospheric Effects of Seismic Activity (F. Lefeuvre and M.B. Gokhberg)

Proposals for papers are welcome.
Abstracts by 15 April 1984 to:
Dr. P.A. Davies, Ch. of Prog. Comm.,
Dept. of Civil Engineering,
The University, Dundee, DD1 4HN, UK.

Physics as a basic knowledge, as a tool, as a provider of concepts, is involved in the research activities of many borderline fields. It is therefore normal and to be encouraged that EPS develops working contacts with other organisations active on the European scale in these fields. This is particularly true of geophysics, where contacts with, for example, condensed matter physics and atomic and molecular physics as well as with the computing group and general contacts on instrumentation could only be useful to EPS and the European Geophysical Society.

Potential members should contact:
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