

COSMIC RAYS, NUCLEAR GAMMA RAYS AND THE ORIGIN OF THE LIGHT ELEMENTS

The origin of cosmic rays has been a major mystery in astrophysics for nearly a century.¹ However, any lingering doubt about whether the bulk of the cosmic rays (those with energies below about 10^{15} eV) are Galactic or extragalactic has been removed in the 1990s in favor of a Galactic origin. The question has been settled by gamma-ray observations made by the Energetic

Gamma Ray Experiment Telescope on the Compton Gamma Ray Observatory. The EGRET observations showed that the cosmic-ray energy density in a nearby galaxy—the Small Magellanic Cloud—is much lower than that found locally in our own Galaxy and is thus inconsistent with a uniform extragalactic density.² This discovery, of course, does not preclude an extragalactic origin for the very highest energy cosmic rays, which are observed above about 10^{19} eV. (See PHYSICS TODAY, January 1998, page 31.) The power of about 10^{41} ergs/s required to maintain the cosmic rays throughout the Galaxy is most likely supplied by supernovae (figure 1). With a Galactic supernova rate of roughly three per century, the required energy per supernova is about 10^{50} ergs, which is about 10% of the kinetic energy of the expanding supernova ejecta. Shock acceleration in the supernova blast wave driven by the ejecta could impart such a proportion of the available kinetic energy to cosmic rays.¹

Although the source of the energy in cosmic rays thus appears to be well understood, the source of the particles that become cosmic rays is still a matter of debate. It is not clear whether the bulk of these energetic nuclei are accelerated from interstellar gas and dust, from preaccelerated particles originating in stellar coronae or from fresh supernova ejecta before they mix into the interstellar medium.

In addition to providing a direct sample of cosmic matter with implications for the processes of nucleosynthesis, cosmic rays also play a major role in the Galactic nucleosynthesis of the light elements—lithium, beryllium and boron—which are largely bypassed in the major processes of nucleosynthesis in stars. Hubert Reeves, William Fowler and Fred Hoyle showed in 1970 that Galactic

Recent observations of Li, Be and B abundances in halo stars formed in the early Galaxy shed new light on the source of cosmic rays, suggesting acceleration from the ejecta of supernovae.

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cosmic rays interacting with the ambient interstellar medium on a timescale comparable to the age of the Galaxy could have produced most of these light elements. It is the elements' extremely low abundances ($< 10^{-5}$) relative to their carbon and oxygen progenitors that make this spallogenic origin viable. In fact, of all stable elements and isotopes, only for lithium, beryllium and boron

does cosmic-ray spallation play a major role. Even though not all the ${}^7\text{Li}$ and ${}^{11}\text{B}$ are produced by cosmic rays, ${}^6\text{Li}$, ${}^9\text{Be}$ and ${}^{10}\text{B}$ are almost certainly the sole products of cosmic-ray interactions.

Studies of the origins of both the light elements and cosmic rays have recently acquired a whole new dimension, as a result of the extensive observations of light-element abundances in halo stars formed early in the history of the Galaxy. These observations,³ at optical and ultraviolet wavelengths, have greatly expanded the timescale of cosmic-ray studies, from the 10 million year mean age of contemporary cosmic rays to the 10 billion year age of the Galaxy. The fact that the early Galaxy was almost totally devoid of carbon and heavier elements (it contained mostly hydrogen and helium produced in the Big Bang) has very important implications for the origin of both early and contemporary cosmic rays.

Origin of lithium, beryllium and boron

Figure 2 shows lithium and beryllium abundances relative to hydrogen for stars of various ages, as a function of their iron abundance. Figure 3 shows boron abundances relative to beryllium. The stellar metallicity $[\text{Fe}/\text{H}]$, defined as the logarithm of the iron-to-hydrogen abundance ratio, increases with time, reflecting the accumulating production of supernova nucleosynthesis, and thus provides a convenient (albeit nonlinear) representation of elapsed time since the formation of the Galaxy. Studies of Galactic chemical evolution have provided information on the age-metallicity relation.⁴ The halo phase of the Galaxy, for which $[\text{Fe}/\text{H}]$ is less than about -1 (that is, the period when the average iron abundance of the Galaxy was less than 10% of the solar value), corresponds to a period of about a billion years preceding the formation of the Galactic disk. Light-element abundances have been measured for stars whose iron abundance is as low as one-thousandth of that of the Sun. Such observations are very challenging because the spectral lines of these rare elements are very weak and are usually blended with interfering lines from other, more abundant elements.³ The

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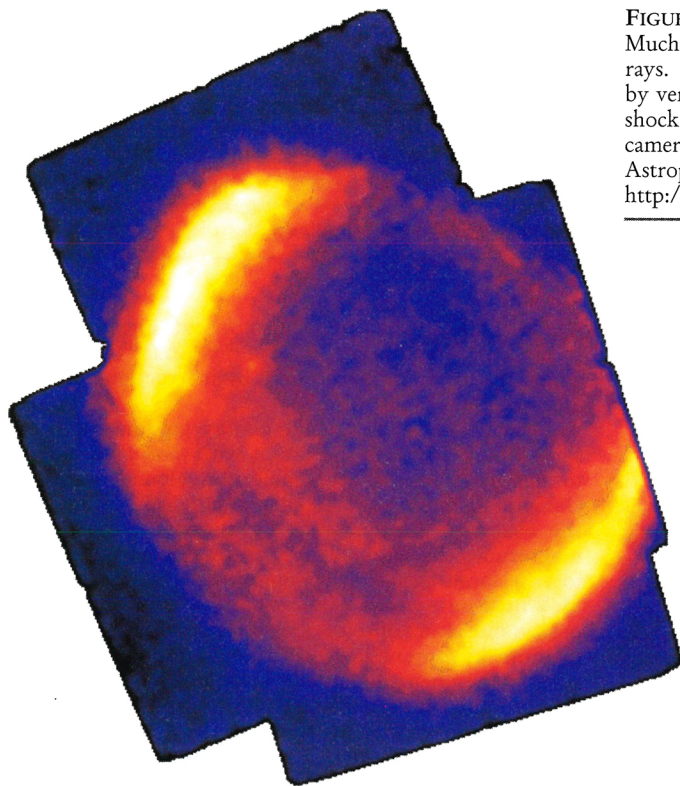


FIGURE 1. SUPERNOVA REMNANT SN1006 seen in x rays. Much evidence points to supernovae as the source of cosmic rays. The bright regions show synchrotron emission produced by very-high-energy electrons accelerated by the supernova shock. The data were taken with the charge-coupled device cameras aboard the Advanced Satellite for Cosmology and Astrophysics. More details can be found at the Web site <http://lheawww.gsfc.nasa.gov/users/evg/images/sn1006.html>.

average iron yield per core-collapse supernova, strongly suggests that beryllium production is due to such supernovae, with an essentially constant beryllium yield per supernova.

As already mentioned, a variety of processes produce lithium, and neutrino-induced spallation reactions on carbon in Type II supernovae can contribute to ^{11}B production.⁶ But the only viable process⁵ for producing the Galactic beryllium is spallation of interstellar carbon, nitrogen and oxygen by cosmic-ray protons and alpha particles and the spallation of cosmic ray C, N and O in collisions with interstellar hydrogen and helium. This strong relationship of beryllium production to cosmic rays, coupled with the essentially constant beryllium production per core collapse supernova required by the data for the entire history of Galactic evolution, has major implications for the origin of cosmic rays. It rules out the acceleration of cosmic rays, or at least the beryllium-producing cosmic rays,

out of the interstellar medium, because in that case the composition of cosmic rays would evolve in proportion to that of the interstellar medium, and the beryllium yield per supernova would increase as the interstellar abundances of carbon and oxygen increase—conditions that are contrary to observations.

Energetics

Independent evidence against cosmic-ray acceleration purely out of the interstellar medium is provided by energetics. The constant Be/Fe abundance ratio of 1.4×10^{-6} (figure 3), combined with the average iron yield of 0.1 solar masses per core collapse supernova, requires that on average each such supernova produce about 2×10^{-8} solar masses of beryllium. Calculations of beryllium production by cosmic rays of varying compositions and energy spectra yield the cosmic-ray energy that an average core-collapse supernova must supply to produce the required beryllium.⁷ As can be seen in figure 4, if all of the cosmic rays were accelerated from the interstellar medium and interacted in the interstellar medium (the upper curves), then an unacceptably large amount of energy—namely, about 10^{53} ergs, or two orders of magnitude more than the total energy in supernova ejecta—would be needed per supernova to produce the observed Be/Fe abundance ratio at the lowest metallicities. Thus, a scenario in which all the cosmic rays are accelerated out of the interstellar medium can clearly be ruled out.

The simplest solution is that the shock from each supernova accelerates cosmic rays from its own ejecta. (See the box on page 34.) In this case, it is reasonable to assume that, on average, the cosmic-ray sources at all metallicities have the same composition and the same energy spectrum as those of current-epoch (contemporary) cosmic rays. Beryllium production in the early Galaxy is

observations therefore require large telescopes and very efficient, high-resolution detectors. Although the lithium and beryllium lines can be observed from the ground, the boron lines require observations from space.

The flat portion of the lithium evolution, usually referred to as the Spite plateau (after the original work of François and Monique Spite in 1982), is generally believed to represent the lithium abundance resulting from nucleosynthesis in the Big Bang.⁵ The subsequent increase in the Li/H ratio is due to nucleosynthesis in a variety of Galactic objects, including Type II supernovae, novae and giant stars, as well as to production by cosmic rays.

Unlike the lithium abundance, the beryllium abundance (figure 2) has no obvious flat portion. The approximately linear evolution of beryllium is equivalent to an essentially constant Be/Fe abundance ratio up to [Fe/H] of about -1 (figure 3). For this entire period of early Galactic evolution, the bulk of the iron is thought to be produced in Type II and Type Ib supernovae.⁴ These core-collapse supernovae result from massive (more than about 10 solar masses) stellar progenitors that explode to leave compact remnants—neutron stars or black holes. They produce, on average, about 0.1 solar masses of iron per supernova, independent of the epoch of Galactic evolution (that is, the metallicity) in which their stellar progenitors were born.⁶ The decrease in the Be/Fe ratio seen in figure 3 at later times (that is, for [Fe/H] > -1) most likely results from additional iron production in Type Ia supernovae.⁴ These supernovae account for about half of the iron made in the later phases of Galactic evolution, but they do not eject much carbon and oxygen, the progenitors of beryllium. Thus, the observed Be/Fe abundance ratio over the entire history of Galactic evolution, coupled with the theoretically derived constancy of the

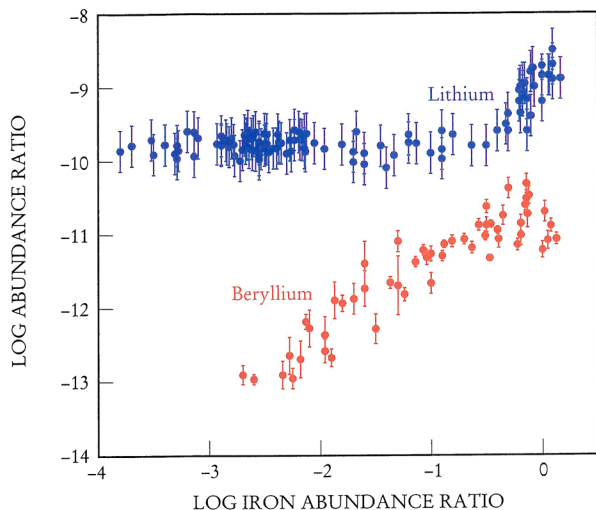


FIGURE 2. LITHIUM AND BERYLLIUM abundances for stars of various ages as a function of their iron abundances. The vertical axis is the logarithm of these light-element abundances (by number of nuclei) relative to hydrogen. The horizontal axis is metallicity $[\text{Fe}/\text{H}]$ defined as $\log(\text{Fe}/\text{H}) - \log(\text{Fe}/\text{H})_{\text{solar}}$, where Fe/H is the iron abundance relative to hydrogen and $(\text{Fe}/\text{H})_{\text{solar}} = 3 \times 10^{-5}$ is the photospheric iron abundance. The iron abundance is a convenient (albeit nonlinear) representation of elapsed time since the formation of the Galaxy. The Solar System was formed at $[\text{Fe}/\text{H}] = 0$. (Data from compilations by Martin Lemoine and Keith Olive.)

then mostly due to fast carbon and oxygen interacting with ambient hydrogen and helium, the yield of the inverse reactions due to fast protons and α particles being very low because of the low carbon and oxygen abundances of the ambient interstellar medium.³ The cosmic-ray source curves in figure 4 give the required energy in cosmic rays per supernova for this scenario. This energy of about 10^{50} ergs is now practically independent of metallicity and is essentially the same as that derived for current-epoch cosmic rays.

Another, more complex scenario invokes a separate low-energy cosmic-ray component, accelerated from fresh nucleosynthetic matter, to produce the bulk of the Galactic beryllium. The existence of such a component would allow the acceleration of the standard cosmic rays out of the interstellar medium at all epochs of Galactic evolution, including the current one. Before considering this option, we briefly discuss the boron data, which have important implications for neutrino nucleosynthesis in supernovae.

Observations of boron abundance made with the Hubble Space Telescope show (figure 3) that the B/Be abundance ratio also remains essentially constant, implying a common origin for these two elements.³ It has often been mentioned⁵ that there is a problem with a pure cosmic-ray origin for boron: Its isotopic ratio, $^{11}\text{B}/^{10}\text{B} = 4.05 (\pm 0.2)$ measured in meteorites and $^{11}\text{B}/^{10}\text{B} = 3.4 (+1.3, -0.6)$ in the interstellar medium,⁸ exceeds the calculated ratio of 2–2.5 for production by Galactic cosmic rays.⁷ But the required additional ^{11}B production could be due to ^{12}C spallation by neutrinos in core-collapse supernovae.⁶ As the spallation processes induced by both the neutrinos and cosmic rays are related to such supernovae, the constancy of the B/Be ratio is ensured. The neutrinos mostly make ^{11}B and not ^{10}B , because their temperature is not high enough for interactions above the higher threshold energy for ^{10}B production. The required ^{11}B production per Type II supernova, about $2\text{--}7 \times 10^{-7}$ solar masses,⁷ is consistent with the supernova calculations.⁶

Nuclear line emission from Orion

The possible existence of a distinct low-energy component of cosmic rays, not observable in the inner Solar System because of interference from the Sun, is a topic of major interest for cosmic-ray research. The detection by the Imaging Compton Telescope on the Compton Gamma Ray Observatory of MeV gamma rays from the Orion molecular cloud complex provided evidence for the existence of such cosmic rays.⁹ The observed spectrum in the 3–7 MeV

region exhibits structure (figure 5) that appears to be due to nuclear deexcitation lines of ^{12}C and ^{16}O . Such line emission can be produced only by interactions of accelerated particles.

Orion's emission of high-energy gamma rays, as observed by EGRET, is consistent with pion production due to the irradiation of the molecular clouds by standard Galactic cosmic rays.² As such cosmic rays underproduce the observed line emission by at least three orders of magnitude, the gamma-ray line production must be due to very large fluxes of low-energy cosmic rays (up to 100 MeV/nucleon), whose origin is still a mystery. They deposit a minimum of a few times 10^{38} ergs into the ambient medium in conjunction with the gamma-ray line production.¹⁰ The phenomenon is probably relatively short lived, because this huge deposited power leads, in only about 10^5 years, to an energy equal to the total ejecta kinetic energy of a supernova.

Carbon and oxygen deexcitation lines have been observed in many solar flares, but there are very significant differences between the Orion and solar spectra (figure 5). The lines from Orion appear much broader, suggesting that they come primarily from accelerated carbon and oxygen interacting with ambient hydrogen and helium, rather than accelerated protons and alpha particles interacting with the ambient carbon and oxygen. This requires a strong enhancement of the accelerated carbon and oxygen abundances. The Orion upper limit on the 1–2 MeV emission,⁹ where solar flare spectra show many lines from neon, magnesium, silicon and iron, also requires the enrichment of the accelerated carbon and oxygen relative to these heavier elements.¹⁰

The suppression of both the neon-to-iron and the proton and alpha particle abundances relative to carbon and oxygen could be understood if the seed particles that are accelerated come from the winds of Wolf-Rayet stars.^{10,11} These stars¹ have optical spectra dominated by emission lines of helium, carbon, nitrogen and oxygen. The weakness of their hydrogen lines is caused by mass loss of the progenitor star. While the transfer of the hydrogen envelope to a binary companion is a possible mechanism for Wolf-Rayet star formation, the dominant process appears to be mass loss due to radiation-driven winds in massive stars. The strong winds, by removing the stellar envelopes, reveal the products of nucleosynthesis and thus become enriched in carbon and oxygen relative to hydrogen and helium, and also relative to heavier elements, which are synthesized deeper in the star and during the subsequent supernova explosion. These carbon- and oxygen-enriched winds may then be accelerated to higher energies by the supernova shock, as well as by shocks and turbulence in the bubble created by the winds of the Wolf-Rayet stars and other massive stars.¹²

Soon after the Compton telescope discovery, it was suggested that Orion-like low-energy cosmic rays could make a significant contribution to the total Galactic light-

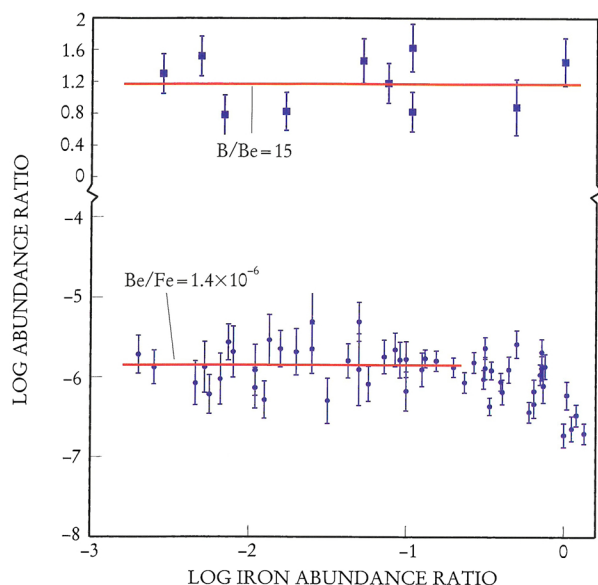


FIGURE 3. ABUNDANCE RATIOS. Top: boron-to-beryllium abundance ratio.³ Bottom: beryllium-to-iron abundance ratio derived from the data shown in figure 1. The logarithmic representation of the abundances on both the vertical and horizontal axes is defined in the figure 2 caption.

element inventory.¹³ An attractive feature of these low-energy cosmic rays was their ability to yield a higher $^{11}\text{B}/^{10}\text{B}$ ratio than that produced by the standard Galactic cosmic rays.¹⁰ It could account for the meteoritic observations discussed above, but, as we already noted, the excess ^{11}B could also result from neutrino interactions in supernovae.⁶

In addition, because the low-energy cosmic rays in Orion are strongly enriched with carbon and oxygen (as a consequence of the acceleration of the nucleosynthetic products in the winds of Wolf-Rayet stars before their mixing into the interstellar medium), one could expect that they could provide an explanation for the observed constancy of the Be/Fe abundance ratio as a function of metallicity. However, even though Wolf-Rayet stars could be the dominant injection source in Orion, they probably were not a major source of beryllium-producing carbon and oxygen in the early Galaxy because the generation of the Wolf-Rayet winds depends on metallicity. Specifically, both evolutionary calculations and observations of the Large and Small Magellanic Clouds showed that the lower the metallicity of the environment, the fewer the Wolf-Rayet stars produced.¹⁴ As iron production in core-collapse supernovae is independent of the metallicity of the progenitor stars, this relation implies an increasing Be/Fe production ratio, contrary to the observations.

Origin of cosmic rays

Thus, while the early Galactic beryllium data strongly suggest production by cosmic rays originating from supernovae accelerating their own ejecta, the most popular models for the source of cosmic rays posit acceleration out of the ambient interstellar medium.¹⁵ These models are based on the inferred composition of the cosmic-ray source material. This composition is significantly modified by nuclear spallation during cosmic-ray propagation in the Galaxy,^{1,15} but the average source composition of the most abundant elements can be well determined. Figure 6

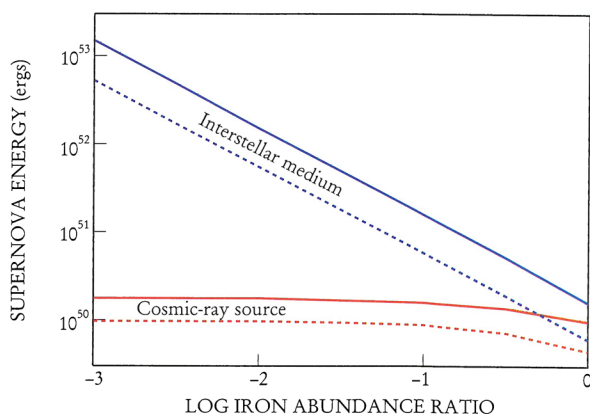


FIGURE 4. ENERGY IN COSMIC RAYS required to produce 2×10^{-8} solar masses of beryllium, the yield per average core-collapse supernova that is required to account for the data. The horizontal axis represents the metallicity (defined in the figure 2 caption) of the ambient medium. The interstellar medium curves are for cosmic rays with composition identical to that of the ambient medium. The cosmic-ray source curves are for cosmic rays with composition identical to that of the current-epoch cosmic-ray source. The solid and dashed curves represent two cosmic-ray transport models, corresponding respectively to a finite (10 g/cm^2) and infinite mean cosmic-ray escape path from the Galaxy. The finite escape path is consistent with the current-epoch cosmic-ray data,¹⁵ and the infinite escape path corresponds to the limiting "closed Galaxy" case in which the cosmic rays are trapped in the Galaxy until they are either stopped by Coulomb collisions or destroyed by nuclear reactions. Although the closed-Galaxy case may be applicable to the early Galaxy, it is not efficient enough energetically to allow beryllium production by cosmic rays accelerated out of the interstellar medium.

shows these cosmic-ray source abundances relative to Solar System abundances as a function of their atomic mass number.¹⁶ We see that there is a strong enhancement of the abundances of the highly refractory elements relative to those that are highly volatile. Alternatively, the enrichments may reflect a correlation with first-ionization potentials, because the highly refractory elements also have low first-ionization potentials, while the highly volatile elements have high first-ionization potentials. Carbon and oxygen are enriched as well, but not as much as the highly refractory elements.

The correlation with first-ionization potentials led to the suggestion that cosmic-ray source material originates in the atmospheres of stars. Based on the fact that the abundances of elements with low first-ionization potentials are enhanced in the solar corona and in solar energetic particles, it was suggested that similar shock acceleration on low-mass, cool stars could provide a particle injection source for acceleration by supernova shocks in the interstellar medium.¹⁷ The correlation with volatility led to a model in which the refractory enrichments are the result of preferential acceleration of the erosion products of refractory interstellar grains that have been preaccelerated to energies of about 100 keV/nucleon by supernova shocks.¹⁶ Because of their suprathermal energies, the sputtered ions from these grains are preferentially accelerated relative to the volatile elements, which are accelerated from thermal energies in the ambient interstellar gas.

For carbon and oxygen, it has been suggested¹⁶ that the bulk of these elements is accelerated from the winds

Cosmic Rays: Interstellar Matter or Supernova Ejecta?

Acceleration from supernova ejecta has long been an appealing scenario for the origin of cosmic rays. But several arguments have been raised that appear to argue against this possibility. The most important of these are:

▷ The enrichment of the cosmic-ray source abundances relative to solar abundances in refractory (or low first-ionization potential) elements relative to volatile (high-potential) elements. If these enrichments are due to first-ionization potential selection, they would argue against the supernova ejecta because the conditions for such selection (temperatures on the order of 10^4 K) exist in the atmospheres of stars but not in supernova environments. If the enrichments are due to selection according to volatility, preacceleration of interstellar grains could occur in the supernova environment. The grains could be interstellar—that is, produced prior to the supernova explosion.¹⁶ Alternatively, they could be produced as fresh condensates in the expanding supernova ejecta.¹⁸

▷ The similarity of the cosmic-ray source and solar abundance for the refractory elements. Even though this suggests that the source is interstellar matter, it is not an argument against acceleration of supernova ejecta, because supernovae are the primary sources of these elements in the Galaxy.⁴ However, in the supernova origin scenario, the various types of supernovae should contribute to cosmic rays in the same proportions as they do for the Galactic abundances.

▷ Ultraheavy cosmic-ray nuclei. The enrichment of r-process (nucleosynthesis by means of rapid neutron capture) nuclei such as platinum in cosmic rays supports the supernova origin. (The r-process is thought to occur in supernovae just above the newly formed neutron star.) The fact that s-process (slow neutron capture) nucleosynthesis elements such as strontium and barium are present in cosmic rays but not produced in supernova explosions is invoked against the supernova origin. However, s-process elements are made in the cores of stars, including the stellar progenitors of supernovae, and are ejected in supernova explosions. Overabundances of strontium and barium relative to iron have been observed in SN1987A.¹⁸

▷ The time between nucleosynthesis and acceleration. K-capture isotope decays are prevented if the atoms are accelerated on timescales shorter than their lifetimes. (An accelerated atom is stripped of electrons, preventing K capture). Abundances of such isotopes and their decay products can provide information on the time between nucleosynthesis and acceleration. Consider the cosmic-ray system $^{59}\text{Ni}/^{59}\text{Co}$ ($^{59}\text{Ni} \rightarrow ^{59}\text{Co}$, $\tau = 1.1 \times 10^5$ years).¹⁵ If ^{59}Ni decayed, acceleration must have occurred several tens of thousands of years after nucleosynthesis, ruling out acceleration of the ejecta before mixing into the interstellar medium. However, the contribution of ^{59}Ni decays amounts to only about one-third of the total ^{59}Co , the rest coming from nucleosynthesis in the explosion⁶ and spallation during propagation. Uncertainties in nucleosynthesis theory, in the spallation cross sections and in the cosmic-ray data (about 30%) still prevent it from being possible to determine the fate of ^{59}Ni .

of Wolf-Rayet stars, a scenario that is motivated by the strong cosmic-ray enrichment¹⁵ in ^{22}Ne , which is also overabundant in these stars. On the other hand, carbon and oxygen enrichments relative to the volatiles are expected, because a significant part of the carbon and oxygen is locked in grains. The fraction of the oxygen in highly refractory oxides—primarily Al_2O_3 , MgSiO_3 , CaO and Fe_3O_4 —is sufficient to account for the observed oxygen

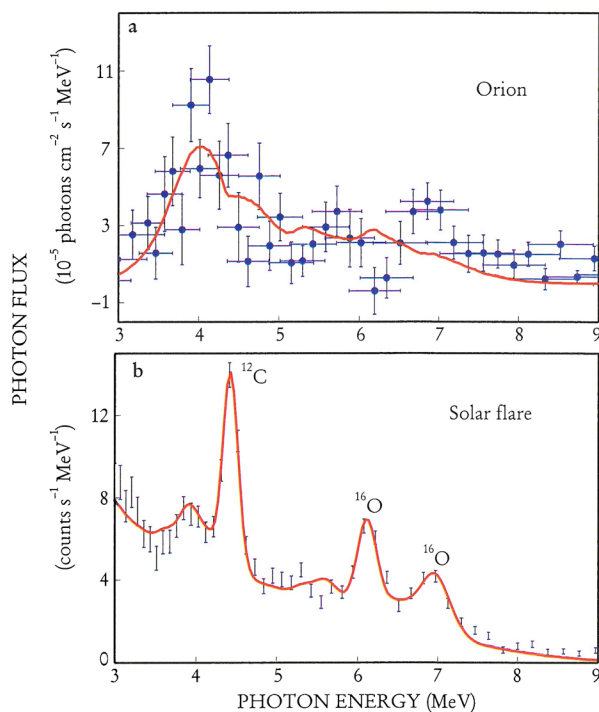


FIGURE 5. NUCLEAR GAMMA-RAY LINE EMISSION from Orion⁹ (a) and from the Sun (b). The data in a are from the Imaging Compton Telescope on the Compton Gamma Ray Observatory. The solid curve is a calculated spectrum (see Kozlovsky *et al.* in reference 10) that takes into account the anisotropy of gamma-ray emission from individual nuclei and incorporates an anisotropic interaction probability for the accelerated particles. The spectrum in b is from a 4 June 1991 solar flare, observed by the Oriented Scintillation Spectroscopy Experiment on the Compton observatory (Ronald Murphy and his coworkers did the data analysis). The relatively narrow lines in the solar spectrum at 4.44, 6.13 and about 7 MeV are due to proton and alpha particle interactions with ambient ^{12}C and ^{16}O .

enrichment. Carbon can also form refractory graphite grains, as observed in the Type II supernova SN1987A.¹⁸

As the cosmic rays in both the first ionization potential and volatility-correlated models are accelerated interstellar matter, they would produce insignificant amounts of beryllium and boron in the early Galaxy and thus require a separate cosmic-ray component accelerated out of fresh nucleosynthetic matter at all epochs of Galactic evolution. As already mentioned, the low-energy cosmic rays discovered in Orion with the Compton telescope indicate the presence of a separate component, but the Wolf-Rayet winds, which are likely sources of these cosmic rays, cannot lead to cosmic rays capable of accounting for the constant Be/Fe abundance ratio in the early Galaxy, because the formation of Wolf-Rayet stars is metallicity dependent.¹⁴ For the same reason, Galactic cosmic-ray carbon and oxygen originating from Wolf-Rayet stars, with the rest of the cosmic rays being accelerated out of the interstellar medium, also do not solve the problem.

What then are the arguments—and how strong are they—against supernovae accelerating their own ejecta? They are summarized in the box at the left. We see that the possibility of cosmic rays being accelerated from supernova ejecta is still wide open.

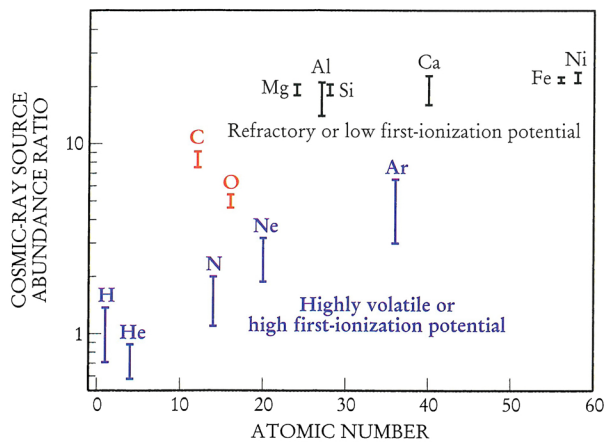


FIGURE 6. GALACTIC COSMIC-RAY SOURCE ABUNDANCES relative to Solar System abundances, shown as a function of atomic number.¹⁶ The highly refractory elements (magnesium, aluminum, silicon, calcium, iron, nickel) will condense into grains, which play an important role in the explanation of the observed enrichments. The fact that the refractories also have low first-ionization potentials could provide another explanation for the enrichments, in analogy with the solar corona.¹⁷ Carbon and oxygen are highly volatile, particularly in the form of carbon monoxide. However, both carbon and oxygen could be present in refractory grains, mostly graphite and oxides.

Where things stand

We have seen how the recent atomic spectroscopy observations of light-element abundances in old halo stars have brought exciting new insights to the question of the origin of cosmic rays, a problem that traditionally has been investigated by local cosmic-ray observations. Where do these observations leave us? As noted above, the light-element abundances, especially that of beryllium, require a critical reexamination of prevailing theories of cosmic-ray origin. The cosmic rays in the early Galaxy, or at least their carbon and oxygen, must have been accelerated from freshly nucleosynthesized matter rather than from the then extremely metal poor interstellar medium. It is still not clear, however, whether the contemporary cosmic rays are also accelerated from such fresh matter or from the interstellar medium. If accelerated from the interstellar medium, a separate component accelerated from fresh nucleosynthetic matter at all epochs of Galactic evolution would be needed, but there is no evidence for such cosmic rays from local measurements. Nuclear spectroscopic observations of the Orion molecular cloud complex have revealed the existence of large fluxes of low-energy cosmic rays, probably accelerated from enriched nucleosynthetic matter in the winds of Wolf-Rayet stars.

Many challenging questions remain concerning the origin of these low-energy cosmic rays and their role in light-element production. However, the simplest scenario for the origin of the beryllium and the bulk of the boron is production by cosmic rays from sources that at all epochs of Galactic evolution have approximately the same composition and energy spectrum as those of the Galactic cosmic rays observed locally. This scenario suggests that the bulk of the carbon and heavier elements in the Galactic cosmic rays are accelerated from supernova ejecta.

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