COSMIC RAYS INTERACTIONS AND THE ABUNDANCES OF THE CHEMICAL ELEMENTS *

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(Received October 9, 1996)

Our Galaxy is the largest nuclear interaction experiment which we know, because of the interaction between cosmic ray particles and the interstellar material. Cosmic rays are particles, which have been accelerated in the Galaxy or in extragalactic space. Cosmic rays come as protons, electrons, heavier nuclei, and their antiparticles. Up to energies up to some tens of TeV of particle energy it is possible to derive chemical abundances of cosmic rays. It has been proposed that cosmic ray particles can be attributed to three main sites of origin and acceleration, a) supernova shocks in the interstellar medium, b) supernova shocks in a stellar wind of the predecessor star, and c) powerful radio galaxies. This proposal leads to quantitative tests, which are encouraging sofar. Quantitative models for transport and interaction appear to be consistent with the data. Li, Be, B are secondary in cosmic rays, as are many of the odd-Z elements, as well as the sub-Fe elements. At very low energies, cosmic ray particles are subject to ionization losses, which produce a steep low energy cutoff; all particles belown the cutoff are moved into the thermal material population, and the particles above it remain as cosmic rays. This then changes the chemical abundances in the interstellar medium, and is a dominant process for many isotopes of Li, Be, B. With a quantitative theory for the origin of cosmic rays proposed, it appears worthwhile to search for yet better spallation cross sections, especially near threshold. With such an improved set of cross sections, the theory of the interstellar medium and its chemical abundances, both in thermal and in energetic particles, could be taken a large step forward.

PACS numbers: 13.85. Tp

* Presented at the "Meson 96" Workshop, Cracow, Poland, May 10–14, 1996.

1. Introduction

Before we can use our Galaxy as a tool for the interaction of cosmic rays and thermal material, we need to understand the origin of cosmic rays. The origin of cosmic rays is still a question [39, 45, 28, 29, 34, 38, 5] which is not finally answered; however, already some time ago Cocconi [22] argued convincingly that the very high energy cosmic rays must originate outside our Galactic disk, since their Larmor motion could not be contained. While the questions about the subtleties of cosmic ray acceleration provide ample material for discussion, the debate about the origin of cosmic rays of moderate energy has reached a consensus, that they are produced in the shockwaves of supernova explosions [3, 69, 32, 33, 46, 23, 15, 4, 42, 35, 36], be it into the interstellar medium, or into a stellar wind [74, 70, 7]. However, the origin of the cosmic rays of the highest energy has remained under dispute. Many of the relevant issues here have been dealt with in the excellent review by Hillas [40] and in the book by Berezinsky *et al.*, [5].

Here we are concerned with the interactions of cosmic rays in the Galaxy, and so we will adopt the picture that indeed the cosmic ray particles originate in the shocks of supernova explosions.

Using this concept (see, *e.g.* the review by Ginzburg [36], we will describe recent advances in our theoretical attempt to formulate a quantitative theory for the cosmic rays in the Galaxy. The interaction between energetic particles and the interstellar medium has long been of interest [63, 76]. We observe consequences of such interaction, such as gamma ray emission in lines or in continuum, as well as abundances of some elements and isotopes (see, the comprehensive review by Reeves [64] and by Bloemen [17]). A recent example of a new measurement of the Boron isotope ratio, together with a summary of relevant references, has been given in [27]. The detection of gamma ray lines, presumably from excited nuclei after nuclear collisions between energetic particles and interstellar medium nuclei (predicted a long time ago by Meneguzzi & Reeves [48], and Ramaty *et al.* [55]), from the Orion complex [16] has aroused the interest of many [18, 19, 52, 20, 73]. Especially the group around R. Ramaty has contributed to the discussion, based on their experience with energetic particle interactions in the solar activity regions [55–62]. The situation has possibly improved, as we will try to demonstrate, since we have now a quantitative proposal to account for the origin of cosmic rays, and while many of the aspects of this proposal remain to be worked out and verified, it may provide a useful basis for further investigations. Therefore here we will try to demonstrate that it will be worthwile to obtain better cross sections for many of these interactions, so that these interactions may become a quantitative tool in the future.

The structure of this review is as follows: First we briefly summarize the recent proposal to account for the origin of cosmic rays; then we describe some aspects of injection of cosmic rays, and their electromagnetic interaction with the interstellar medium gas; then we go through the arguments for the various interaction sites, near the source and far from the source; for the latter argument we go through the concept of trapping and leakage from interstellar clouds in some detail, since it is new. Finally we draw some conclusions and stress the importance of better cross sections.

2. A quantitative proposal for the origin of galactic cosmic rays

Cosmic rays arrive at earth with energies from several hundred MeV/particle to $3 \cdot 10^{20}$ eV; their spectrum is at GeV energies close to $E^{-2.75}$, and at higher energies close to $E^{-2.65}$ below a knee at $\approx 5 \cdot 10^{15}$ eV, where the spectrum turns down to about $E^{-3.1}$, to flatten out again near $3 \cdot 10^{18}$ eV, called the ankle (*e.g.* [47, 49, 82]). The chemical composition is roughly similar to that of the interstellar medium, with reduced hydrogen and helium relative to silicon, and with the same general enhancement of elements of low first ionization potential as we find in solar energetic particles. The low energy end of the observed spectrum is cut off due to interaction with the solar wind. There is reason to believe that in interstellar space the cosmic ray spectrum extends far below what we can observe at Earth.

In the newly proposed theory (starting with [7]) the origin of the cosmic rays below $3 \cdot 10^{18}$ eV is traced to the shockwaves caused by supernovae exploding either into the interstellar medium, or into the predecessor stellar wind, following some rather classical ideas; the new element is a premise on the particle transport in the shock region, inspired by the observations of the radio polarization in supernova remnants, and the actual motion of radio features, as well as the size of the observed X-ray and radio supernova remnant shells [12]: These data suggest a strongly turbulent interaction region rather than a smooth shock wave, consistent with several arguments which have demonstrated that cosmic ray influenced shocks are unstable (see the references and detailed discussion of this point in [12]). This premise is the *principle of the smallest dominant scale*, which follows work by Prandtl [53] and von Karman & Howarth [43]: Applied to supernova shock shells, this principle leads to a large length scale associated with fast convective shock turbulence, and therefore to a specific model of the transport of particles in the shock region. In the construction of a transport coefficient for energetic particles, then this scale is used, and thus determines, *e.g.*, the time which a particle spends on either side of a shock; this time scale is in turn important for losses, which a particle experiences, as well as energy gains by drifts in the electric fields, seen in the moving shock frame, and thus determines the spectrum of the final particle spectrum. A large scale then gives an appreciable adiabatic energy loss during the expansion of the shock, and leads to a steepening of the predicted spectrum as compared to the plane-parallel shock case.

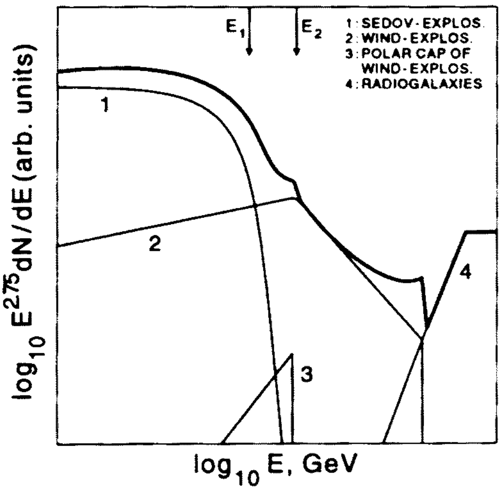

Fig. 1. A schematic picture of the three different source sites and their respective contributions; the polar cap contribution arises from the polar region of the acceleration in wind-supernovae (adapted from [71]).

The proposal leads to quantitative predictions for *(i)* the spectra both below and above the knee of the cosmic ray spectrum near $5 \cdot 10^{15}$ eV, where the spectrum turns downwards, *(ii)* the particle energies of the knee and the various cutoffs, as well as *(iii)* the chemical composition. We have been able to subject these predictions [6, 7, 54] to a variety of tests in various publications and reviewed them as well; the latest overviews of these developments are [9, 12, 13]. We continue to perform further tests using ever more detailed and newer data.

2.1. Summary of the predictions for nuclei

The proposal is that three sites of origin account for the cosmic rays observed, *(i)* supernova explosions into the interstellar medium, ISM-SN, *(ii)* supernova explosions into the stellar wind of the predecessor star, wind-SN, and *(iii)* radio galaxy hot spots. Here the cosmic rays attributed to supernova-shocks in stellar winds, wind-SN, produce an important contribution at all energies up to $3 \cdot 10^9$ GeV.

Particle energies go up to $100Z$ TeV for ISM-SN, and to $100Z$ PeV with a bend at $600Z$ TeV for wind-SN. Radiogalaxy hot spots go up to near or slightly beyond 100 EeV at the source. These numerical values are estimates with uncertainties of surely larger than a factor of 2, since they derive from an estimated strength of the magnetic field, and estimated values of the effective shock velocity (see above).

The spectra are predicted to be $E^{-2.75\pm0.04}$ for ISM-SN, and $E^{-2.67+0.02\pm0.02}$ for wind-SN below the knee, and $E^{-3.07+0.07\pm0.07}$ for wind-SM above the knee, and $E^{-2.0}$ at injection for radiogalaxy hot spots. The polar cap of the wind-SN contributes an $E^{-2.33}$ component (allowing for leakage from the Galaxy), which, however, contributes significantly only near and below the knee, if at all. These spectra are for nuclei and are corrected for leakage from the galaxy.

The chemical abundances are near normal for the injection from ISM-SN, and are strongly enriched for the contributions from wind-SN. At the knee the spectrum bends downwards at a given rigidity, and so the heavier elements bend downwards at higher energy per particle. Thus beyond the knee the medium nuclear mass elements dominate all the way to the switchover to the extragalactic component, which is, once again, mostly Hydrogen and Helium, corresponding to what is expected to contribute from the interstellear medium of a radiogalaxy, as well as from any intergalactic contribution mixed in [8]. This continuous mix in the chemical composition at the knee already renders the overall knee feature in a spectrum in energy per particle unavoidably quite smooth, a tendency which can only partially be offset by the possible polar cap contribution, since that component also is strongest at a given rigidity ; this term refers to the factor occurring in the expression for the Larmor radius for any energetic particle, and stands for pc/Z, the momentum multiplied by the speed of light, divided by the charge; thus nuclei at the same rigidity have the same Larmor radius in their gyromotion in a magnetic field.

These predictions can be compared at some detail with data, and we have given adequate comparisons in previous work; a summary of sake of the predictions is given in Table I, adapted from [10]:

TABLE I

Spectral indices for hydrogen, helium and heavier nuclei.

Experiment	Energy Range (p)	element range	sp.index	....
Predicted				
	below knee	H	2.75 ± 0.04	
Webber [75]	1–50 GeV	H + He	2.70 ± 0.05	
LEAP [67]	10–100 GeV	H	2.74 ± 0.02	
JACEE [1]	<40 TeV	H	2.64 ± 0.12	
JACEE [1]	>40 TeV	H	3.22 ± 0.28	
Sokol [41]	>5 TeV	H	2.85 ± 0.14	
Ryan *et al.* [66]	50–2000 GeV	H	2.75 ± 0.03	
MSU [81]	10–200 TeV	H	3.14 ± 0.08	
JACEE [2, 1]	50–200 TeV	H	2.77 ± 0.06	
Japan [44]	8–50 TeV	H	2.82 ± 0.13	
predicted				
	below knee	He,..,Fe	$2.67 + 0.02$	± 0.02
LEAP [67]	10–100 GeV	He	2.68 ± 0.03	
RICH [24]	100–1000 GV	He	2.64 ± 0.09	
Ryan *et al.* [66]	50–2000 GeV	He	2.77 ± 0.05	
Sokol [41]	>5 TeV	He	2.64 ± 0.12	
JACEE [2, 1]	50–200 TeV	He	2.67 ± 0.08	
Japan [44]	8–50 TeV	He	2.75 ± 0.15	
Akeno [49]	$< 5\,10^{15}$ eV		2.62 ± 0.12	
Akeno [71]	below knee	all	2.66 +syst.	
predicted				
	above knee		$3.07 + 0.07$	± 0.07
HP [47]	$< 0.4\,10^{18}$ eV		3.01 ± 0.02	
HP [47]	0.4–4 10^{18} eV		3.14 ± 0.06	
FE [14]	2–4 10^{17} eV		3.07 ± 0.01	
Akeno [71]	above knee	all	3.07 +syst.	
Akeno [49]	5 10^{15} eV–6 10^{17} eV		3.02 ± 0.03	
FE [14]	2 10^{17}–4 10^{19} eV		3.18 ± 0.01	
Akeno [49]	$6\,10^{17}$–$7\,10^{18}$ eV		3.18 ± 0.08	

The cutoffs in the three source components and their chemical abundances can be checked using vertical and slanted airshowers, and are all consistent to within 20 % with prediction [71]. Here we note also that the cosmic ray spectra of the various chemical elements and electrons can be studied separately, and all are consistent with the predictions in the GeV to TeV range [77, 78]. This is the range of interest here.

3. Injection of cosmic ray nuclei

For the elements He,..C, O,.. Fe the the injection law can be written as

$$N(p) \sim p^{-2.67}\, dp\,, \tag{1}$$

which extends all the way down to non-relativistic energies. This means that with $p = A\, m_p\, c\, \gamma\, \beta$, where A is the atomic weight of the nucleus considered, and γ and β the Lorentz-factor and velocity in units of the velocity of light c, the spectrum at sub-relativistic energies can be written as

$$\sim \beta^{-2.67}\, d\beta\,. \tag{2}$$

The energy loss in interactions with electrons, bound or unbound in a shell around a nucleus of the thermal matter can be written as

$$\frac{d\beta}{dt} \sim \frac{n_e, n_{\rm H}}{\beta^2}\, Z^2, \tag{3}$$

where n_e and $\rm n_H$ are the densities of free electrons, and neutral Hydrogen atoms, respectively, and Z is the charge of the energetic nucleus losing energy. This simple behaviour is valid only for suprathermal energies and sub-relativistic speeds.

After traversal of thermal matter for some time τ the interaction results in a low energy cutoff of the distribution of energetic nuclei, and a law of

$$\sim \beta^2\, d\beta \tag{4}$$

below the cutoff, and the original law above the cutoff. The cutoff energy is given by

$$\beta_{\rm crit} \sim \{Z^2\,(n_e, n_{\rm H})\tau\}^{1/3}. \tag{5}$$

All the particles which are lost to the energetic particle spectrum below the cutoff are shifted in phase space to the thermal particles, and can modify the chemical abundances there. This effect is especially important in the case that the chemical abundances in energetic particles are very different from those in the interstellar medium, and this is the case for some elements, such as Li, Be, B.

The column density along the twisted and scattering path of a charged particle in a highly chaotic magnetic field configuration is referred to as *grammage*, and this grammage is the relevant quantitity to discuss cosmic ray interactions. This grammage can be inserted into the above expression, and then leads to estimates of the cutoff energies near 100 MeV.

4. Spallation of cosmic ray nuclei

Cosmic ray nuclei can be broken up in collisions with thermal matter; this process is called spallation. Obviously, there is a corresponding interaction between energetic protons, and thermal material comprising heavier nuclei such as Carbon.

There are several sites, which can be distinguished, where spallation is relevant (see, *e.g.*, the recent work in this area [30, 25, 31, 26, 68]):

First of all, the massive stars, which explode as supernovae after going through an evolutionary phase accompanied by heavy mass loss, usually have a molecular cloud shell. When the central star explodes, it gives rise to a powerful shock wave, which races through the wind, and then smashes into the shell ([52]); since the shock is loaded with energetic particles, these particles then spallate in the shell. From the abundance of sub-Fe elements one can estimate that the grammage in this shell is of order $1\mathrm{g/cm}^2$ [79, 80], consistent with the data from radio and millimeter observations. This apparently is the dominant process at higher energy to account for the abundances in cosmic rays for most odd-Z elements, for the sub-Fe elements, and for some Li, Be, and B isotopes.

In this case the spectrum of the secondary particles N_s is the same as the primary particles N_p:

$$N_\mathrm{s} \sim N_\mathrm{p}\,. \tag{6}$$

Next is the interaction in clouds, and here we have to distinguish between the energy range for which the particles move diffusively through a cloud, and the higher energy range, where they move unencumbered through the cloud material. It is this latter approximation which is commonly used in the literature.

The secondary particles are then created in the clouds, and diffuse out of the galaxy, and so their creation equation can be written as

$$\frac{dN_\mathrm{s}}{dt} = \frac{N_\mathrm{p}}{\tau_\mathrm{s}} - \frac{N_\mathrm{s}}{\tau_\mathrm{L,gal}}, \tag{7}$$

where τ_s is the spallation time scale, and $\tau_\mathrm{L,gal}$ is the time scale for diffusion out from the disk of the Galaxy. There is a fair amount of evidence that this latter diffusive transport can be derived from a Kolmogorov spectrum of interstellar turbulence [65, 37]. The evidence for such a law of turbulence in the ISM has been discussed extensively in [11]. The solution to this equation is in the stationary case

$$N_\mathrm{s} = N_\mathrm{p}\,\frac{\tau_\mathrm{L,gal}}{\tau_\mathrm{s}}, \tag{8}$$

which translates to an energy dependence of the ratio of secondary to primary isotopes and elements of

$$\frac{N_s}{N_p} \sim E^{-1/3}, \tag{9}$$

in the case of a Kolmogorov spectrum; here we have also neglected for didactic simplicity the energy dependence of the spallation. The ratio of secondary to primary nuclei has been used in the past to argue that in fact the spectrum of interstellar turbulence is *not* a Kolmogorov law. Since the B/C ratio gives an energy dependence of close to $E^{-0.6}$ [25, 31, 26], a Kolmogorov law did not seem to be consistent with the data.

However, this line of argument is *only* true, if the cloud interaction is stationary; on the other hand we do know that interstellar clouds have their own temporal evolution, and so we need to check what happens when clouds form and dissipate again, *e.g.* by heating from newly formed stars. The decisive difference to the argument above arises, when we consider the formation of clouds, and we will proceed to do this in the next Section.

5. The capture of cosmic rays in clouds

Here we wish to explore the following concept: The interstellar medium is forming large molecular clouds out of its small fragments and warmer parts, by gravitational instability. Gravitational instability sets in, as soon as the time scale for free-free collapse is shorter than the time scale for any pressure signal to propagate through the cloud. This means that the collapse also needs to be faster than the Alfvén velocity. As a consequence, cosmic rays are trapped upon the formation of a gravitationally bound system, such as a large molecular cloud, since cosmic rays cannot stream faster than the Alfvén velocity.

Trapped cosmic rays can get out of the cloud by diffusion; diffusion is a good approximation only as long as the mean free path for scattering by magnetic irregularities is significantly shorter than the size of the cloud. This entails an upper particle energy limit for the diffusion approximation.

Consider then a particle population of cosmic rays $N_{p,1}(E,t)$ trapped in a cloud, where the index 1 stands for *inside*:

$$\frac{d\,N_{\mathrm{p},1}}{d\,t} = -\frac{N_{p,1}}{\tau_{\mathrm{L,cl}}} \tag{10}$$

with

$$\tau_{\mathrm{L,cl}} = \tau_{\mathrm{L,cl,0}}\,(\frac{E}{E_0})^{-1/3}. \tag{11}$$

This energy dependence follows from the concept that small scale turbulence in media, which are magnetic and partially ionized, can be approximated by a Kolmogorov law.

The solution is clearly

$$N_{\rm p,1} \; = \; N_{\rm p,1,0}(E) \exp(-\frac{t}{\tau_{\rm L,cl}}) \,. \tag{12}$$

The particle population outside the cloud, but coming from inside, is then given by

$$\frac{d\,N_{\rm p,2}}{d\,t} \; = \; +\frac{N_{\rm p,1}}{\tau_{\rm L,cl}} \tag{13}$$

which translates to

$$N_{\rm p,2} \; = \; N_{\rm p,1,0}(E)\{1 - \exp(-\frac{t(E/E_0)^{1/3}}{\tau_{\rm L,cl,0}}\} \,. \tag{14}$$

Secondaries are produced in nucleus-nucleus collisons inside the cloud, and so their production equation reads

$$\frac{d\,N_{\rm s,1}}{d\,t} \; = \; \frac{N_{\rm p,1}}{\tau_{\rm s}} \; - \; \frac{N_{\rm s,1}}{\tau_{\rm L,cl}} \,. \tag{15}$$

The solution is

$$N_{\rm s,1}(E) \; = \; N_{\rm p,1,0}(E)\,\frac{t}{\tau_{\rm s}} \exp(-\frac{t}{\tau_{\rm L,cl}}) \,. \tag{16}$$

The secondaries outside the cloud are just those produced inside and leaking out, and so we have the relation

$$\frac{d\,N_{\rm s,2}}{d\,t} \; = \; +\frac{N_{\rm s,1}}{\tau_{\rm L,cl}} \,. \tag{17}$$

The solution to this differential equation is then

$$N_{\rm s,2}(E) \; = \; \frac{N_{\rm p,1,0}(E)}{\tau_{\rm s}}\,\tau_{\rm L,cl} \int_0^x x' e^{-x'} dx' \,. \tag{18}$$

This entails for *long times* then

$$N_{\rm s,2}(E) \; = \; \frac{N_{\rm p,1,0}(E)}{\tau_{\rm s}}\,\tau_{\rm L,cl,0}\,(\frac{E}{E_0})^{-1/3} \,. \tag{19}$$

Therefore, the secondary particles, injected into the interstellar medium outside the original cloud, have a spectrum which is steeper than the primary particles by 1/3. Or, given that the primary particles are well approximated by a spectrum of $E^{-8/3}$, the secondary particles at injection have a spectrum of E^{-3}.

Now, considering then also the leakage from the Galaxy generalizes this results and gives the equilibrium spectrum for secondaries:

$$\frac{d\,N_{\rm s,2}}{d\,t} = +\frac{N_{\rm s,1}}{\tau_{\rm L,cl}} - \frac{N_{\rm s,2}}{\tau_{\rm L,gal}}\,, \tag{20}$$

where $\tau_{\rm L,gal}$ is the leakage time from the Galaxy, and is also taken to follow from a Kolmogorov law, and so has the same energy dependence as the time scale for leaking from a cloud. The arguments for such a law have been summarized above.

The solution then is

$$N_{\rm s,2} = \frac{N_{\rm p,1,0}(E)}{\tau_{\rm s}}\,\tau_{\rm L,cl}\exp(-\frac{t}{\tau_{\rm L,gal}})\,(1-\tau_{\rm L,cl}/\tau_{\rm L,gal})^{-2}\int\limits_0^x x' e^{-x'} dx'\,, \tag{21}$$

where

$$x = t\,(\frac{1}{\tau_{\rm L,cl}} - \frac{1}{\tau_{\rm L,gal}})\,. \tag{22}$$

Without loss of generality we can assume at first that $\tau_{\rm L,cl} < \tau_{\rm L,gal}$, when the integral converges; in the opposite case a brief calculation confirms also the convergence.

The next step is to assume that we are at present at no particular time; for each individual source this corresponds of $N_{\rm s,2}$ to an integration over past injection time to give $N^{\star}_{\rm s,2}$; the sum over many sources no longer changes the spectrum, but only the normalization. This then means the further integral gives already the proper energy dependence

$$N^{\star}_{\rm s,2} = \frac{N_{\rm p,1,0}(E)}{\tau_{\rm s}}\,\tau_{\rm L,cl}(E)\,\tau_{\rm L,gal}(E)\,(1-\tau_{\rm L,cl}/\tau_{\rm L,gal})^{-2}\,I(t)\,, \tag{23}$$

where

$$I(t) = \int\limits_0^{x} {}^{"}\exp(-x')\,dx' \int\limits_0^{x} s e^{-s} ds\,, \tag{24}$$

where

$$x" = t/\tau_{\rm L,gal}, x = x'\,\tau_{\rm L,gal}\,(1/\tau_{\rm L,cl} - 1/\tau_{\rm L,gal})\,. \tag{25}$$

The energy dependence of the secondaries, as compared to the primaries is then clearly

$$N_{s,2}/N_{p,1} \sim E^{-2/3}, \tag{26}$$

with our modelling of the interstellar and intracloud turbulence with a Kolmogorov spectrum.

This is in accord with the observations, such as by Engelmann *et al.* [26]. This is in contrast to the usual finding that a *stationary* leaky box gives a ratio of secondary to primaries $\sim E^{-1/3}$, if we use a Kolmogorov spectrum for turbulence.

Therefore, considering the non-stationarity of the normal interstellar medium, we can readily explain the ratio of secondaries to primaries, and at the same time use a spectrum of turbulence which is consistent with all other observational evidence.

Translating this result into the language common in the literature, this means that escape length as measured in gm/cm^2 and escape time can no longer used synonymously. The escape time is given by $\tau_{L,gal}$, and is proportional to $E^{-1/3}$ in the relativistic range of particle energies. The escape length as a means to describe interaction has three different regimes, and the one relevant in the GeV/nucleon range is, as before, about $E^{-0.6}$, and here, in our simplistic model, $\sim E^{-2/3}$.

In the following we adopt the primary cosmic ray for nuclei such as He and higher in mass spectrum of E^{-2} and the Kolmogorov law of turbulence, giving an energy dependence of a diffusive time of $E^{-1/3}$. Therefore, the energy dependence of the secondary to primary ratio has three simple domains, which can be summarized as follows:

- The spallation in the molecular cloud shell around the massive star leads to a ratio of secondary to primary nuclei as a function of energy in the interstellar medium observable of

$$N_s/N_p \sim \text{const}. \tag{27}$$

- The spallation in the energy range where trapping occurs for cosmic ray nuclei leads to

$$N_s/N_p \sim E^{-2/3}. \tag{28}$$

- And the higher energy range when the interaction is no longer diffusive, we return to the canonical solution, which in our case gives

$$N_s/N_p \sim E^{-1/3}. \tag{29}$$

A comparison with the data suggests that we discern only regime 1 and 2, and that regime 3 is never a dominant contributor. The data suggest that the switch between regime 1 and 2 occurs near an energy per nucleon of about 20 GeV/n. To repeat, the spallation is described this way, and the escape time corresponds to a $E^{-1/3}$ law.

6. Chemical abundances

The origin of the chemical elements and their isotopes can be traced to three main source sites (see [63, 64]):

- The big bang nucleosynthesis accounts readily for H, ^{4}He, ^{2}H, ^{3}He, and ^{7}Li. Deuterium, after some excitement about absorption lines in quasars, seems to be now in agreement given the first measurements in a neighboring galaxy [21]. Thus big bang nucleosynthesis does seem to give a coherent picture of a universe, where only a small fraction of the critical density is made up of normal baryons.
- Stellar interiors and stellar envelopes provide clearly most heavy elements, spewed into interstellar space in supernova explosions.
- The interactions of cosmic rays with thermal matter can explain a number of features both in the abundance distribution of thermal matter, as well as in the distribution of cosmic rays: First, the even-odd-Z distribution is dissimilar between the interstellar medium and the higher energy cosmic rays, with spallation providing a higher abundance for the odd-Z elements of cosmic rays. Second, the sub-Fe elements in the cosmic rays are also due to spallation. And finally, most isotopes of the elements Li, Be, and B are provided by cosmic ray interaction bot in the interstellar medium and in the cosmic rays.

One test [50] is the effect of ionization losses on the low energy protons, which provide also an ionization and heating source in molecular clouds; it is an important test for the entire concept that the cutoff in the proton spectrum due to such losses, also is consistent with the cutoff in the spallation product spectrum required to explain the abundances of Li, Be, and B in the interstellar medium. This is the case.

There is a large amount of work yet to be done, to test the detailed concept proposed, in order to account for the chemical abundances in some detail, for the abundances of radioactive isotopes, and for accurate isotope ratios. This will provide stringent tests for this theory as for any other, and may yet disprove it.

7. Outlook

Given that a quantitative theory is beginning to show the promise of an explanation for the origin of cosmic rays, it may be worthwile to obtain much better cross sections for the cosmic ray interactions, especially near the critical threshold for any reaction. This would then allow to not only provide a qualitative explanation of the various abundances, but also to actually use them to study both cosmic rays and the interstellar medium.

The report is based on much work by my present and former graduate students, mostly here Alina Donea, Torsten Ensslin, Karl Mannheim, Heino Falcke, Wolfram Krülls, Jörg Rachen, and Yiping Wang, as well as that resulting from my interactions and collaborations with Venya Berezinsky, Jim Cronin, Tom Gaisser, Gopal-Krishna, Hyesung Kang, Phil Kronberg, Jeremy Lloyd-Evans, Horst Machner, Matthew Malkan, Hinrich Meyer, Motohiko Nagano, Ray Protheroe, Reuven Ramaty, Wolfgang Rhode, Marcia and George Rieke, Dongsu Ryu, Eun-Suk Seo, Todor Stanev, Alan Watson, and Barbara Wiebel-Sooth. I thank them all and apologize for any errors and omissions which surely remain.

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