Astrochemical Aspects of the Origin of Cosmic Rays

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Based on analysis of the observed results concerning the chemical composition of galactic cosmic rays, a serious question has been put forward as to whether most of these cosmic rays have been directly produced by supernova explosions in the interstellar space. It is currently thought that the observed relative overabundances of the elements in these cosmic rays, as compared to those found in the solar atmosphere, are determined by taking into account some effects related to their dependence on the first ionization potentials of those elements. Furthermore, some similarity between the chemical composition of galactic cosmic rays and carbonaceous chondrites has been claimed.

It is, therefore, necessary to search anew for some physical quantity explaining these two properties observed in the source composition of galactic cosmic rays. In this paper, the condensation temperature for each of the elements contained in these cosmic rays is shown to be causally related to the formation of their source composition. In fact, the observed relative overabundances of many elements found in galactic cosmic rays are dependent on the temperature for each of these elements, which is usually less than $10^4$ K. This may mean that the elements to be found in the source regions of those cosmic rays must have passed at least once through a stage in which their temperature was as low as just mentioned before they were accelerated into cosmic rays.

1. Introduction

It is now known that the chemical composition of galactic cosmic rays found in their source regions is similar to that of the solar atmosphere, although elements whose first ionization potentials in their atomic states are relatively low are comparatively overabundant in the former as compared to the latter (e.g., Simpson, 1983; Israel, 1986). It has been thought that this aspect of cosmic ray composition may reflect the physical state prevailing throughout the source regions of these cosmic rays, since the ionization states of various atoms are usually estimated by their temperatures in those regions in thermal equilibrium. Since the first ionization potentials for elements which are relatively overabundant in the chemical composition of galactic cosmic rays as compared to that of the solar atmosphere are normally lower than 10 ev, they become easily ionized by losing orbiting electrons in their outer shells as the result of their interaction with other atoms and free
electrons. Therefore, it follows that they are more effectively accelerated as compared to atoms whose first ionization potentials are relatively higher. The observed overabundances of elements with relatively low first ionization potentials have thus been interpreted this way, because it seems that most of these elements are in partially ionized states in the source regions, and so more efficiently accelerated to become such high energy particles as those identified as galactic cosmic rays. The acceleration of these particles may occur as a result of their interaction with shock waves propagating outward from the sites of supernova explosions through interstellar space, since those elements, being partially ionized, seem to be accidentally drifting in space near the sites of such explosions.

In addition to the overabundant nature of such elements with relatively lower first ionization potentials, the observed data on the relative abundances of isotopic elements such as Ne, Mg and Si play some important role in the search for the properties of the source regions of galactic cosmic rays. Furthermore, several trace elements such as $^{26}$Al, $^{44}$Ti, $^{49}$V, $^{55}$Fe and others may give us a clue to understand the behavior of the elements before they encounter shock waves as mentioned earlier, and also their propagation in interstellar space after they are released from the source regions. In particular, the existence of the isotopes as $^{22}$Ti, $^{44}$V, $^{55}$Fe and $^{59}$Co in galactic cosmic rays have been rarely found up to now, despite the fact that several research groups have tried to detect them for the last several years by analysing the extensive records available from their satellite observations (e.g., MEWALDT, 1981; SIMPSON, 1983). This negative result suggests that cosmic ray particles have never been accelerated from particles in the expanding gas clouds released from supernova explosions. This may further mean that the clouds released from these explosions later usually pass through a phase in which their temperature is approximately equal to $10^6$ K or less for a few years, after they cool down while drifting in interstellar space.

In this paper, the observed results on the chemical composition of galactic cosmic rays will be first reviewed with the aim of looking for some appropriate cause of the observed nature of the chemical composition of galactic cosmic rays. In comparison to the first ionization potential for each of the elements, it will then be shown that the condensation temperature is better fitted to interpreting the observed overabundances of some elements in the chemical composition of galactic cosmic rays in their sources, as compared to that of the solar atmosphere. The physical state of the birthplace of galactic cosmic rays and its possible relation to the interstellar matter released from supernova explosions will be discussed.

2. Chemical Composition of Galactic Cosmic Rays

Detailed knowledge of the chemical composition of galactic cosmic rays can give us a clue in the search for the physical processes associated with the acceleration and propagation of these cosmic rays and the physical nature of their birth place in the Galaxy and beyond. Using the observed data on their composition currently available, many attempts have been made, therefore, to interpret by what mecha-
nism the observed composition of these cosmic rays has been generated in galactic space. One of them has taken into account the relative overabundances of some elements in the chemical composition of galactic cosmic rays in reference to that of the solar atmosphere, which seems to be determined by the first ionization potentials (FIP's) of the elements (HAVNES, 1972; KRISTANSSON, 1972).

When we plot the source composition of galactic cosmic rays estimated from their observed composition near the earth's orbit, being relative to that of the solar atmosphere, as a function of FIP's for the elements, we obtain the result as shown in Fig. 1. This shows that, though relative to the chemical composition of the solar atmosphere, this source composition is highly dependent on these FIP's (BINNS et al., 1985). This result thus seems to suggest that the source composition of galactic cosmic rays is causally determined by the ionization states of the elements contained in the source regions where these cosmic rays are generated. Such an idea was put forward some years ago, and predicted that the kinetic temperature of the source matter to be accelerated to cosmic rays must be no more than $10^6$ K (e.g., CASSÉ and GORET, 1978).

Since elements with relatively high first ionization potentials are usually volatile, there is some possibility that such elements would have been already

![Graph showing the ratio of relative abundances of cosmic rays to solar atmosphere as a function of first ionization potential.](image)

Fig. 1. The ratio of the relative abundances of galactic cosmic rays in their sources to those of the solar atmosphere as plotted for the first ionization potentials of the elements (BINNS et al., 1985).
excluded from the source regions of galactic cosmic rays before their acceleration begins. In order to examine if this possibility is acceptable in our interpretation of the formation about the source composition of galactic cosmic rays during their acceleration, it also seems better to consider the relation between the chemical compositions of galactic cosmic rays at their sources and of carbonaceous chondrites classified as C-2 since this relation may give us some clues in looking for possible source regions of these cosmic rays in the interstellar space. This relation, which was first obtained by Binns et al. (1985), is summarized in Fig. 2, and can be clearly seen to be very similar to the result shown in Fig. 1.

Since most volatile elements have been more effectively lost from these chondrites as compared to C1 chondrites, whose chemical composition is almost the same as that of the solar atmosphere (Wood, 1979), the difference between the two results shown in Figs. 1 and 2 is well reflected in several volatile elements, whose FIP's are relatively higher than those of non-volatile elements classified as refractory and siderophile.

Many refractory and siderophile elements are usually weakly volatile, as is well known from the geochemical point of view. Therefore, the fact that the most of these

![Graph](image)

Fig. 2. The ratio of the relative abundances of galactic cosmic rays in their sources to those of carbonaceous C2 chondrites as plotted for the first ionization potentials of the elements (Binns et al., 1985).
elements appear to be relatively overabundant in galactic cosmic rays as compared to the chemical compositions of both the solar atmosphere and C1 chondrites, necessarily leads to the suggestion that these elements are relatively more abundant in the source regions of these cosmic rays. Thus, the source composition of these cosmic rays may have originally been different from the chemical composition of the matter found in the solar system and of the proto-solar nebula; the former may have been more abundant in these elements than the latter.

To examine whether the suggestion just mentioned is acceptable or not, it seems reasonable to refer to the interstellar depletion of elements relative to the chemical abundances of the sun, because these depletions can be used to estimate how much of each element is concentrated in making dust and grains in interstellar space. An example of such depletion of many elements is shown in Fig. 3, which gives the relative magnitude of the depletion for each element as estimated from the spectral characteristics of the star, zeta-Ophiuchi (e.g., SNOW, WEILER and OEGERLE, 1979). In this figure, the condensation temperature for each element is adopted to plot the magnitudes of these depletions, since this temperature is thought to be a good measure for expressing the case with which each element is adsorbed by the interstellar grains or dust. Furthermore, it is thought that this temperature can also give us a clue for studying the formation processes of our solar system.

First, the condensation temperature for each element is here referred to examine whether or not the interstellar depletions of various elements are causally

![Fig. 3. Interstellar depletions of the elements relative to the chemical abundances of the solar atmosphere (SNOW et al., 1979).](image-url)
related to the observed characteristics of the source composition of galactic cosmic rays. Taking the data about these depletions into account, the relative abundances in these cosmic rays have been obtained, as shown in Figs. 4 and 5, in comparison with the chemical compositions of both the solar atmosphere and carbonaceous C2 chondrites. It is clear from these two figures that volatile elements such as C, O, Ar, N, S and others are much less abundant in the source composition of these cosmic rays than in either the solar atmosphere or carbonaceous C2 chondrites. The interstellar depletions of both refractory and siderophile elements are highly dispersed, despite the fact that their relative quantities remain almost constant and nearly equal to unity, as clearly seen in Figs. 4 and 5. These results thus seem to indicate that the source composition of galactic cosmic rays may have been dependent on the chemical properties of the elements found in them.

In order to see whether or not there is some causal relation between these elements' chemical properties and the origin of the source composition of galactic cosmic rays, the relative quantities of these cosmic rays have been estimated as a function of the elements' condensation temperatures in reference to the chemical composition of the solar atmosphere. The data on these temperatures have been picked up from Snow et al. (1979) and Wasson (1985). Figure 6 clearly indicates that the relative overabundance of the elements in galactic cosmic rays as compared to the amounts in the solar atmosphere are usually seen in elements whose condensation temperatures are relatively higher than about 800 K. This result suggests that less-volatile elements, such as refractory and siderophile ones, must

![Graph showing the ratio of relative abundances of galactic cosmic rays to those of the solar atmosphere as a function of the interstellar depletions.](image)

**Fig. 4.** The ratio of the relative abundances of galactic cosmic rays in their sources to those of the solar atmosphere as a function of the interstellar depletions.
Fig. 5. The ratio of the relative abundances of galactic cosmic rays in their sources to those of C2 chondrites as a function of the interstellar depletions.

Fig. 6. A relation between the source composition of galactic cosmic rays relative to the chemical composition of the solar atmosphere and the condensation temperature of the elements.
have been relatively more abundantly condensed in the regions where the source composition of galactic cosmic rays were formed in interstellar space.

To examine in more detail whether or not these elements have definitely been condensed in such regions, those elements plotted in Fig. 6 have been selected in accordance with their specific refractory, siderophile, less- and highly-volatile properties. The result thus obtained is shown in Fig. 7, and it may give us some clue as to how the source composition of galactic cosmic rays has possibly been formed in interstellar space. Only refractory and siderophile elements are overabundant in the source composition of galactic cosmic rays. In this figure, though refractory, all of the lanthanoid elements detected in these cosmic rays are marked with a special symbol, because their behavior in cosmic rays seems to be vitally important in pursuing the mechanism for their condensation in the regions where cosmic rays have been generated, though complicated it may be (Sakurai, 1985).

The result shown in Fig. 7 further suggests that, in contrast to less- and non-volatile elements, volatile elements have been quite effectively excluded from the source regions of galactic cosmic rays. Furthermore, some possible cause for the relative overabundances of the latter elements in galactic cosmic rays as compared to the solar atmosphere must be deeply connected with the condensation temperature of each element which prevailed in their source regions. Hence, the kinetic temperature of the matter, either in gas form or grains, in these regions should be very low, as low as $10^3$ K or less, before it is energized to become possible candidates for the source matter of galactic cosmic rays. This seems to mean that galactic cosmic rays have originally accelerated from elements whose temperature was

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**Fig. 7.** The relative overabundances of the elements in the source composition of galactic cosmic rays to those of the solar atmosphere as viewed from the chemical properties of the elements.
initially as low as $10^3$ K. Thus, these elements must have been only partially ionized in the initial stage during which the particle acceleration took place somewhere in the source regions of galactic cosmic rays, although it is highly probable that most volatile elements remain neutral or have already been squeezed out of these regions. As the next step, it therefore seems necessary to examine the physical state of the regions where galactic cosmic rays may have been generated; the possible acceleration mechanism of these cosmic rays would become clearer for further research.

3. Physical State of the Regions Where Cosmic Rays Are Born

Through examination of the first ionization potential dependence of the elements found in galactic cosmic rays in relative abundance to those of the solar atmosphere, as shown in Fig. 1, it has been deduced that the elements to be accelerated into cosmic ray energy are mostly partially ionized before the beginning of their acceleration in the source regions (e.g., Cassé and Goret, 1978; Binns et al., 1981). Furthermore, the kinetic temperature of these elements has also been deduced to be as low as $10^6$ K in these regions. This suggests that galactic cosmic rays have never been generated in the gases expanding from supernova explosions, since the temperature of these gases is estimated to be as high as to $10^8$ K or more, so that most of the elements contained within them must be fully ionized. As considered by Cassé and Goret (1978), for instance, it is therefore impossible to interpret the results as shown in Figs. 1 and 2. Of course, it is also difficult to explain the results shown in Figs. 6 and 7, since they indicate that the elements, both non- and less-volatile, may have been effectively concentrated in the source regions of galactic cosmic rays.

As shown in Fig. 7, refractory, less-volatile and siderophile elements are usually overabundant in the chemical composition of galactic cosmic rays in about equal proportions as in the solar atmosphere. Although they are plotted separately from refractory elements in Fig. 7, lanthanoids are also classified as refractory, since their behavior is especially interesting in the study of the formation of the chemical composition of galactic cosmic rays (Sakurai, 1985). The condensation temperature for each of these elements is relatively higher than that of any volatile element, so that the source matter, a part of which is to be accelerated to cosmic rays, may be identified as interstellar matter whose temperature is as low as $10^3$ K, drifting in interstellar space.

In order to search for such source matter in interstellar space, it would be reasonable to refer to the relative abundances of the isotopes Ne, Mg and Si in galactic cosmic rays, as shown in Fig. 8. From the relatively large quantities of neutron-rich isotopes in these elements, it follows that the source matter to be partly accelerated to cosmic ray energy must have been originally supplied from the matter ejected from supernova explosions into interstellar space (Wannier, 1980). Since some radioactive elements such as $^{44}$Ti, $^{49}$V, $^{55}$Fe and $^{57}$Co, whose half-lives are relatively short (see Table 1), are always absent from the observed results on the isotopic abundances in cosmic rays, it seems that galactic cosmic rays have never
Fig. 8. Relative abundances among the isotopes as Ne, Mg and Si (Miyake, 1981).

Table 1. Decay lives of isotopes synthesized in the r-process.

(a) Isotopes to be beta-decayed

<table>
<thead>
<tr>
<th></th>
<th>Decay Life</th>
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<tbody>
<tr>
<td>26Al</td>
<td>$7.2 \times 10^7$ yrs</td>
</tr>
<tr>
<td>36Ar</td>
<td>1.8 sec</td>
</tr>
<tr>
<td>37Cl</td>
<td>$3.1 \times 10^7$ yrs</td>
</tr>
<tr>
<td>54Mn</td>
<td>$3.7 \times 10^7$ yrs</td>
</tr>
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(b) Isotopes to be decayed by K-electron capture

<table>
<thead>
<tr>
<th></th>
<th>Decay Life</th>
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<tbody>
<tr>
<td>48Ca</td>
<td>$1.1 \times 10^2$ yrs</td>
</tr>
<tr>
<td>45Ti</td>
<td>48.3 yrs</td>
</tr>
<tr>
<td>53V</td>
<td>330 days</td>
</tr>
<tr>
<td>51Cr</td>
<td>27.8 days</td>
</tr>
<tr>
<td>56Fe</td>
<td>2.60 yrs</td>
</tr>
<tr>
<td>59Co</td>
<td>27.0 days</td>
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been directly accelerated from matter ejected from supernovae immediately after their explosions. In other words, before the beginning of the acceleration of cosmic rays, this matter seems to have existed for a few years at least after these explosions. This length of time is enough for those radioactive elements to be lost as the result of decay while cooling down in interstellar space, as well as time enough for that matter to be cooled down to $10^3$ K or less while being in motion in space.

Binns et al. (1985) have shown from Figs. 1 and 2 that the chemical composition of galactic cosmic rays is better fitted to that of carbonaceous C2 chondrites as compared to that of the solar atmosphere. Since the Allende meteorite is known as the typical sample of C3 chondrites, its overall chemical composition has been compared to that of the solar atmosphere (e.g., Wood, 1979; Wasson, 1985). The relative abundances for the Allende meteorite as compared to those of the solar atmosphere are shown in Fig. 9, in which both of these are normalized with respect to Si = $10^6$ as always. It is remarkable that the results in this figure are very similar to that in Fig. 7, except for some volatile elements, since they have already been lost from this meteorite while aging since its formation. This result just shown clearly supports the hypothesis put forth by Binns et al. (1985), who have shown that the chemical composition of galactic cosmic rays at their sources is similar to that of C2 chondrites. As suggested earlier by Sakurai (1985), our results show more conclusively that the source composition of these cosmic rays must have been formed by making use of a portion of the matter whose composition is nearly the same as that of the proto-solar nebula, since the Allende meteorite is now thought as a debris of this nebula formed almost 4.6 billion years ago.

Taking the results shown in this paper into account, it is proposed that galactic cosmic rays have been generated from matter which passed through a low-temperature stage at least once, while drifting in interstellar space as debris from supernova explosions. It seems that non- and less-volatile elements have been concentrated into the matter which eventually became partly accelerated to galactic cosmic rays.

The ratio of the concentration of these elements in the source material of galactic cosmic rays relative to that in the Allende meteorite is therefore estimated by comparing the results shown in Fig. 7 with those for this meteorite (Fig. 9). As shown in Fig. 10, this ratio is always higher than unity in regards to all of the elements ever observed in both galactic cosmic rays and this meteorite. Furthermore, this ratio tends to be larger with a decrease in the condensation temperature for the elements. This means that volatile elements are relatively less efficiently concentrated in the source material of galactic cosmic rays as compared to C3 chondrites like the Allende meteorite. Therefore, it may be said that the source material just cited consists of interstellar gas clouds still containing enough volatile elements which could be identified as the material which later becomes dust or grains, whose chemical composition is almost the same as C2 or C3 chondrites after being cooled enough.
Fig. 9. The ratio of the relative abundances in the Allende meteorite to those of the solar atmosphere.

Fig. 10. The ratio of the chemical composition of cosmic ray sources to that of the Allende meteorite plotted as a function of the condensation temperature of elements.
4. Supernovae as Cosmic Ray Sources

As has been cited earlier in this paper, the observations of several isotopes in galactic cosmic rays as listed in Table 1 are crucial to disclose the physical processes which may have taken place in the source matter of cosmic rays shortly after its release from supernova explosions into the interstellar space. In spite of the extensive effort of several groups, the isotopes which decay by K-electron capture have never been detected up to now; no evidence has been found for the existence of such isotopes as $^{44}$Ti, $^{49}$V, $^{55}$Fe and $^{57}$Co (MEWALDT et al., 1980; MEYER, 1981). These observational results strongly suggest that, after they were synthesized during the r-process taking place within hot ionized clouds expanding out of the sites of supernova explosions, these elements have completely decayed as a result of K-electron capture before reaching the nearby-space of the earth. These results would also indicate that these elements must have cooled down quite enough for them to be capable of combining with interstellar electrons during the few years they were in motion through space after being released from supernova explosions. Taking such an idea into account, we can explain the fact that their existence has never been detected.

The absence of those elements which decay by K-electron capture, summarized in Table 1, therefore suggests that the acceleration of galactic cosmic rays starts at least a few years after the source matter for cosmic rays has been released from supernova explosions. At present, some evidence to support this idea is accumulating, based on the radio observations of supernova explosions and their after-effects (BROWN and MARSCHER, 1978; MORFILL and DRURY, 1981; WEILER et al., 1986). According to these observations, high energy electrons responsible for radio emissions may have been produced a few years after supernova explosions, since there has been no evidence of strong radio emissions within the couple of years immediately after these explosions (e.g., MORFILL and DRURY, 1981; WEILER et al., 1986). These observations also suggest that, a few years after supernova explosions, the acceleration of those electrons begins, simultaneously with that of the nuclear components which will become a part of galactic cosmic rays.

The results shown in Figs. 6, 7 and 9 may give us a clue to estimate to what temperature the cosmic ray source matter is cooled down within a few years after being released from supernova explosions. Relatively higher concentrations of both non- and less-volatile elements suggest that these materials may have sometimes been cooled to temperatures as low as 800 K. This temperature is lower by a factor of $10^3$ than that proposed earlier by CASSE and GORET (1978) and SAKURAI (1981). For instance; but the observed similarity between the chemical compositions of galactic cosmic rays and of carbonaceous C3 chondrites such as the Allende meteorite is good evidence to support the idea that those materials cited above may have passed through a stage with temperature as low as $10^3$ K or less.

While drifting in the interstellar space, those cosmic source materials may occasionally encounter shock waves expanding out of the sites of supernova
explosions and become partially ionized. Then, various elements partially ionized within these materials may be quickly accelerated into cosmic ray energy by some mechanism as the Fermi process, as the result of their interaction with those shock waves (e.g., CESARSKY, 1980). Such processes would occur repeatedly in the interstellar space and produce most of the galactic cosmic rays currently observed in space near the earth.

5. Remarks on Future Research

It has been shown that the chemical composition of galactic cosmic rays seems to be dependent on the condensation temperature of each element. Relative to the chemical composition of the solar atmosphere, the quantities of the elements contained in cosmic rays tend to become higher with the increase of this temperature, as shown in Figs. 6 and 7. This tendency seems to reflect upon the chemical properties of the elements that are closely related to their condensation temperatures.

Taking into account the chemical composition of galactic cosmic rays, as summarized in section 2, some consideration has been given to the formation of the source composition of these cosmic rays and its possible relation to the elements in interstellar space, being associated with their relative depletion from the chemical composition of the solar atmosphere. The fact that the chemical composition of galactic cosmic rays at their sources is similar to that of carbonaceous C2 and C3 chondrites such as the Allende meteorite seems to be powerful evidence that these cosmic rays are accelerated from the matter which has passed through a phase of low temperature, as low as 800 K, while drifting in the interstellar space after being released from supernova explosions. Such matter may also be identified as that released from novae and partly observed as planetary nebular matter.

In order to confirm whether or not galactic cosmic rays have been generated from the matter mentioned above, it is necessary to make detailed observations on volatile elements found in these cosmic rays and to compare them with data on those contained in carbonaceous C1 and C2 chondrites. Furthermore, confirmatory data are also necessary for various isotopes up to the elements of the iron group, since these may give us a clue for understanding the physical processes in the source matter of cosmic rays in the interstellar space.

As shown in this paper, however, the most important result is that the source composition of galactic cosmic rays has certainly been formed from interstellar matter whose composition is almost the same as that of carbonaceous C2 and C3 chondrites such as the Allende meteorite (SAKURAI, 1985). Whatever it may be, it is urgently necessary to search for the formation mechanism of the source composition of galactic cosmic rays from matter like the debris of the proto-solar nebula or circumstellar dust ejected from stellar explosions such as nova phenomena.
REFERENCES


