Interpreting the Cosmic Ray Composition

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1 Introduction

Detailed composition measurements can be a very powerful means of tracing origins, a fact used regularly by forensic scientists and art historians. One of the main motivating factors for making detailed observations of cosmic rays was always the hope that a unique compositional signature could be found which pointed unambiguously to a particular source. This has proven much harder than expected, but we have now reached a point where it appears possible to begin to decipher the information contained in the compositional data; the key, we have discovered, is to read the data not in isolation, but in the context provided by our general astronomical knowledge and by recent developments in shock acceleration theory (Meyer, Drury and Ellison, 1997, 1998; Ellison, Drury and Meyer, 1997). In our view (not, it is only fair to warn the reader, yet universally accepted) the data show clearly that the Galactic cosmic ray particles originate predominantly from the gas and dust of the general interstellar medium.

2 What is the Composition?

Before attempting to interpret the data it is important to be clear about what exactly we are discussing. The raw measurements are the charge-resolved, and in some cases mass-resolved, differential energy spectra of the cosmic ray nuclei above the Earth’s atmosphere. For instrumental and statistical reasons, good measurements with clean separation of the various species are only easily made for mildly relativistic nuclei. The measurements are affected by solar modulation at energies below a few GeV per nucleon. By correcting for these solar system effects we infer the local Galactic cosmic ray spectra which would be observed in the interstellar medium just outside the heliosphere. However it is clear that these in turn have been influenced, in varying degrees, by spallation nuclear reactions and other interactions during propagation through the interstellar medium. If we attempt to correct for these propagation effects we finally arrive at inferred source spectra. The relative fluxes of the various nuclear species at fixed energy per nucleon (equivalently, at fixed speed or Lorentz factor) in these demodulated and depropagated spectra constitute what is usually called the Galactic Cosmic Ray Source (GCRS) composition.

Quite a number of assumptions have already gone in at this stage. The heliospheric corrections are small above a few GeV per nucleon and probably uncontroversial. However the propagation corrections are clearly dependent on the propagation model used and often implicitly assume that there are distinct acceleration and propagation phases. Particularly with the current interest in so-called “reacceleration” models for propagation, it is not clear that such a sharp separation is justified. It should also be noted that most of the published data have been “de-propagated” using the simple, but clearly unphysical, leaky-box model of Galactic cosmic ray confinement. By talking loosely about “the GCRS composition” without specifying precisely the energy per nucleon or rigidity...
at which the measurements were made we are also implicitly assuming that all the species have virtually identical spectra in energy per nucleon, an assumption which is approximately true for the main nuclear components in the range from 1 GeV to 1 TeV per nucleon (in fact, the data suggests that helium has a slightly flatter spectrum than hydrogen), but is certainly not true of the electrons. It is worth noting that measuring at fixed kinetic energy per nucleon (which is the form traditionally used in experimental work) or fixed momentum per charge (i.e., rigidity, which is often used in theoretical work) gives essentially equal relative abundances for all the heavy nuclei, but different values for the hydrogen abundance relative to the heavies.

3 Nuclear or Atomic Physics?

The obvious first thing to do is to compare the abundance pattern seen in the GCRS to the standard solar system pattern of abundances, which appears to characterise all undifferentiated bodies in the solar system including the sun itself. If corrections are made for the decay of long-lived radioactive nuclides, giving what is sometimes called the primordial solar-system or proto-solar abundance pattern, this appears to be close to the general local Galactic pattern of abundances (in as much as this can be determined); thus it has usually been taken as the base-line "standard" composition. However there is now increasing evidence that, both in the local interstellar medium (ISM) and in the surfaces of young B stars, the abundances of the heavy elements relative to hydrogen are systematically lower than in the sun by factors of order 1.5 to 2 (Snow and Witt, 1996, and references therein). In contrast, the solar system abundances are apparently typical of those in the local F and G type stars (Edvardsson et al, 1993; Andersson and Edvardsson, 1994). Bearing all this in mind we will continue to use the solar system abundances as reference values because they provide a well-determined set of values for all the elements which one might reasonably expect to be relevant to the local ISM, especially as regards the relative abundances of the heavy elements.

The GCRS and solar system abundances are compared in Fig. 1 (see table in Meyer, Drury and Ellison 1998). It is immediately obvious that the GCRS composition is disappointingly normal; all the elements are present, and the general pattern is strikingly similar in both the GCRS and the solar system. However there are some significant differences, in particular Hydrogen is deficient in the GCRS, or the heavy elements are enhanced, by quite large factors relative to the solar system composition. For example iron (Fe) and silicon (Si) are about a factor 30 higher relative to hydrogen in the GCRS than in the solar system and this is a much larger factor than any uncertainty in the measurements. Note that adopting B star abundances would make this even more extreme and increase the overabundance of Fe and Si to between 45 and 60. The challenge is to interpret these slight (relative to the enormous variations between the individual elements), but clearly significant, differences between the two sets of abundances.

Now the heavy elements are known to be produced by nucleosynthesis in stars and, for many elements specifically in supernova explosions, and it has been suspected for a long time that cosmic rays are somehow linked to the supernova phenomenon (this was first suggested in the historic paper of Baade and Zwicky (1934) where they introduced the name supernova, and cogently argued for on energetic grounds by Ginzburg and Syrovatsky (1964) in their influential monograph). It is therefore very natural to seek to interpret the differences between the GCRS and local ISM (or solar system) abundances in terms of biases stemming from the nuclear physics associated with nucleosynthesis, perhaps during the slow core burning phase, but more likely during the rapid explosive phase. This

\[ ^1 \text{One often sees statements that the electron to proton ratio in the cosmic rays is 1 to 30 or 1 to 100. Any such statement is, however, meaningless if one does not specify how the comparison is made. The above applies to comparison at a fixed energy. If, by contrast, one compares at fixed Lorentz gamma factor the electrons are much more abundant than the protons (as pointed out by W Kundt)!} \]
effort was also stimulated by early reports suggesting high GCRS abundances of the ultra-heavy elements including actinides, which are exclusively produced during the supernova explosion.

It is now clear that these attempts to interpret the abundance differences in terms of nucleosynthetic models are unconvincing. For example, Ne is depleted by about a factor 8 relative to Mg, Al and Na although all these elements are thought to be produced by C burning. Similarly S and Ar are depleted by factors of order 4 relative to Si and Ca although these elements are all produced by O and Si burning. No such large anomalies are found in supernova nucleosynthesis calculations, especially for elements produced in the same burning cycle (Woosley and Weaver, 1995; Timmes, Woosley and Weaver, 1995; Arnett, 1995). By contrast, Mg, Al (C burning), Si and Ca (O and Si burning) and Fe and Ni (e-process, i.e., explosive phase) are present in the GCRS in proportions within 20% of the solar values. However Mg, Al, Si and Ca are synthesised in core-collapse type II supernovae while Fe and Ni are predominantly produced in type Ia supernovae and the nucleosynthesis calculations of different supernova models typically yield deviations of these ratios by factors of order 2. In addition the ultra-heavy s-nuclei beyond $A = 90$, which are not produced in any type of supernova, are not underabundant relative to the above elements, or to the r-nuclei, and the general ultra-heavy abundances are not anomalously high. Further, with the exception of $^{22}\text{Ne}/^{20}\text{Ne}$ (and possibly $^{13}\text{C}/^{12}\text{C}$ and $^{18}\text{O}/^{16}\text{O}$) all isotopic ratios are consistent with solar values.

Remarkably, if the data are organised not by nuclear but by atomic properties some, though not all, of the differences can be accounted for. In particular if the ratio of the GCRS abundance to the solar system abundance is plotted against the first ionization potential (FIP) of each element a definite pattern, the so-called FIP effect, is evident (see Fig. 2). There is a large group of low-FIP elements

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2The ultra-heavy elements are usually taken to be those with nuclear charge greater than 28, although the term is used very loosely.
Figure 2: The GCRS to Solar abundance ratios plotted versus FIP. Solid squares denote those elements which can be used to distinguish between FIP and volatility. For detailed discussion see Meyer, Drury and Ellison 1998.
which show a roughly constant and large enhancement of about 30 relative to H. At a FIP of order 10 eV there is a rather sharp break and the elements with larger FIP values show much smaller, but more scattered, enhancements.

Now of course the first ionization potential measures how easy it is to remove one electron from the outermost shell of electrons in the ground state of the neutral atom, and thus correlates strongly with chemistry. For example, elements with easily removed electrons tend to be metallic and chemically very reactive forming stable compounds which readily condense at high temperatures; elements with filled outer shells have very firmly attached electrons and are the inert gases which do not condense except under extreme laboratory conditions. So there exists, by and large, a relationship between the FIP of the various elements and their volatility, which is conveniently measured by the so-called condensation temperature. It has long been known that the GCRS composition data can also be organised in terms of this condensation temperature; refractory (low-FIP) elements tend to be overabundant relative to volatile (high-FIP) ones. Fortunately, there are a few elements which do not follow the general FIP/volatility correlation and which, in principle, allow a distinction to be made between a FIP effect and a volatility effect in the GCRS composition. However these are not the easiest of elements to measure! Such data as is available tends to favour volatility rather than FIP as the better organising parameter (Meyer, Drury and Ellison 1997). However it is clear that neither FIP nor volatility alone completely accounts for the observations. In particular a simple two-step volatility or FIP bias does not account for the low relative abundances of H and He, the two most abundant elements! There must be some additional effect, parameter or process involved.

In Fig. 3 we sort the elements according to their volatility, and then plot their abundance enhancements versus the element mass $A$. This is a very interesting plot. It first shows that the refractory elements are globally enhanced relative to the volatile ones. Among the volatile elements the enhancements of all the inert gases and N appear to follow a smoothly increasing function of the mass (roughly $\propto A^{0.8}$); however, volatile H, C and O lie above this correlation. Among the refractories, by contrast, the enhancements are roughly independent of the mass $A$.

In summary, the empirical evidence is that the GCRS composition is basically similar to that of the local ISM and has not been affected by specific nucleosynthetic processes (with the exception of the $^{22}$Ne and associated $^{12}$C excesses). But it does show clear signs of modification by factors depending on atomic physics or chemistry (an enhancement of low-FIP or, more probably, refractory elements) as well as on the element mass. It is very remarkable that the composition of fully-stripped relativistic nuclei should show traces of atomic physics effects with characteristic energies of only a few electron volts, and this is clearly a significant clue to the cosmic ray origin.

4 The solar coronal FIP effect

The FIP concept received a significant boost when it was discovered that this effect operates in the atmosphere of the sun and biases the composition of the solar corona, solar wind and solar energetic particles. By some not entirely understood mechanism, ionized heavy elements are preferentially lifted from the chromosphere into the corona, giving a coronal composition enhanced relative to the bulk.

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3 The exact definition of the condensation temperature is rather artificial. One imagines starting with a sample of solar composition gas at high temperature and a constant pressure of $10^{-4}$ atm and gradually lowering the temperature. The condensation temperature is the temperature at which 50% of the dominant solid compound formed by each element has condensed out of the gas phase.

4 It is important to note that a tentative similar ordering of the data in terms of a combined FIP and mass effect would not order the data as satisfactorily. Specifically, the non-solar values of the GCRS abundance ratios between elements of similar FIP and mass, but widely different volatilities (Na/Mg, P/S, Ge/Fe, and Pb/Pt), cannot be interpreted in terms of a combined FIP and mass fractionation (Meyer, Drury and Ellison 1998).
Figure 3: The GCRS to solar abundance ratios plotted against element atomic mass number $A$ for four volatility classes.
solar composition in low FIP elements. This biased composition is then also seen in the solar wind and in solar accelerated particles.

This remarkable discovery prompted attempts to relate the origin of cosmic rays to the coronae of cool stars like the sun (Meyer, 1985). However it is certain that even if these stars are the source of the accelerated material, they cannot be the source of the energy needed for the acceleration. The only plausible known source of energy capable of driving the acceleration processes remains the mechanical explosion energy of supernovae. Thus this line of argument requires the dwarf stars to somehow inject large amounts of FIP biased but low energy ions (MeV) into the ISM which are later accelerated to the observed energies by passing supernova shocks.

However there are problems in trying to make any such two-stage model work quantitatively (Epstein, 1981). The basic problem is that sub-relativistic ions suffer quite rapid ionization and Coulomb energy losses in the ISM even allowing for the effect of electron pick-up in screening the nuclear charge (Meyer, 1985). On the other hand, the mean time interval between passages of strong supernova shocks must be long in the general ISM (at least $10^7$ y); otherwise the observed energy dependence of the secondary to primary ratios could not be accounted for. In addition modern shock acceleration theory emphasises that the shock accelerates particles directly out of the “thermal” distribution. Not only is there no need for a separate pre-injected “seed” population: any such population, unless at rather high number density, will tend to be swamped by the ISM particles accelerated directly by the shock.

### 5 SNR acceleration from the ISM

As described elsewhere in this volume [x-refs here] much work has been done on diffusive shock acceleration applied to supernova remnants (SNRs) as a theoretical model for the origin of cosmic rays. However this has mainly concentrated on the spectrum and the total power and, until recently, the question of composition was largely ignored. It has been known for a long time that shocks are intrinsically efficient accelerators and that the resulting nonlinear modifications to shock acceleration (mainly the shock smoothing effect) tend to favour the acceleration of high rigidity over low rigidity species, that is of species with higher mass to charge ratios. At a crude qualitative level this could be said to fit the observed enhancement of heavy elements over hydrogen (e.g., Ellison 1982); however the detailed pattern, and specifically the atomic physics correlations, are not accounted for. In addition it is well known that in most of the ISM the refractory elements are not in the gas-phase but are locked up in the solid state in interstellar dust grains. From UV absorption line studies, for example, it is known that the abundance of Fe in the gas phase is typically only 1% of its total local ISM abundance. If the SNR shock is accelerating ions from the ISM gas phase only, how can Fe be enhanced by a factor of at least 30 relative to hydrogen in the accelerated particles whereas in the gas phase flowing into the shock it is generally depleted by a factor of 100? One could of course suppose that the bulk of the acceleration occurs in a very hot phase of the ISM where the grains are destroyed; however there the characteristic energies are far too high for few eV atomic physics effects to be important.

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5 These constraints would be significantly alleviated if GCR production were located in regions of active star formation containing many young low-mass stars with high levels of surface activity and a few massive stars to provide supernovae, all concentrated within a limited volume.

6 A rough estimate is that the number density of MeV ions would need to be of order $10^{-6}$ that of the background plasma, which in turn would imply an energy density in the putative seed particles comparable to the thermal energy density of the plasma.

7 This is often described as a more efficient acceleration of high rigidity species. However this can be rather misleading. What is meant is that the steady state differential velocity spectra of the higher rigidity species are less rapidly decreasing functions of velocity than those of the low rigidity species at the crucial low velocities close to the shock speed. However the low rigidity species have shorter acceleration time scales and are accelerated more rapidly, albeit to steeper spectra.
The resolution of this problem, and, we believe, the key to interpreting the compositional data, is to recognise that dust grains in the ISM are charged and can therefore be shock accelerated. This is in fact quite an old idea. Epstein (1980) first suggested that charged dust grains could be accelerated, and that ions sputtered off the accelerated grains while the grains were in the upstream region would then be picked up and further accelerated by the shock. With the advances in our understanding of shock acceleration it is now possible to calculate quantitatively and in some detail the process sketched out by Epstein. The full details can be found in Ellison, Drury and Meyer (1997); here we will concentrate on conveying the spirit of the calculations and the results.

The essential idea is to apply the modern theory of shock acceleration consistently to a SNR shock propagating in a dusty ISM. The refractory elements, such as Iron, Magnesium and Silicon, are known to be almost entirely condensed into small dust grains with a range of sizes extending from clusters of a few atoms to a maximum size of about $10^{-7}$ m (this size range is required to fit the UV, optical and IR data). These grains will be charged by a number of processes (secondary electron emission, photoelectric effect, plasma charging etc) to surface potentials of order 10 to 100 V (it is important to note that this is a standard part of ISM grain theory, not an assumption of our model; see, e.g. Spitzer 1978) implying mass to charge ratios for the larger grains of order $10^8$ (and less for the smaller grains). This means that, relative to a shock moving at several hundred kilometers per second, their magnetic rigidity is less than that of a $10^{14}$ eV proton or electron. If the shock is capable of accelerating particles to these energies, the dust grains will inevitably also be scattered across the shock and accelerated.

In fact in the case of at least one remnant, that of the supernova of 1006, there is now direct observational evidence for the acceleration of electrons to these energies from the detection of X-ray synchrotron emission (Koyama et al, 1995) and inverse-Compton gamma-rays (Tanimori et al, 1998). The acceleration of protons to about $10^{14}$ eV, although not yet directly observed, is also required if SNRs are to provide the bulk of the Galactic cosmic ray population up to the “knee” energy. Thus it seems certain that at least some supernova remnant shocks are associated with magnetic field structures capable of scattering particles of rigidities up to $10^{14}$ V. The dust grains will have the same scattering mean free path as the ultra-relativistic protons and electrons of the same rigidity, but a much lower diffusion coefficient because the grain velocity is only of order the shock speed and the diffusion coefficient is, within factors of order unity, just the product of the scattering mean free path and the particle speed.

The conventional picture is that the magnetic field structures themselves are generated by plasma instabilities driven by the accelerated proton pressure gradients in a bootstrap process which drives the mean free path down to a value of order the gyro-radius (Bohm scaling). For the subrelativistic dust grains this means that the effective diffusion coefficient for transport near the shock front rises

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8 At about the same time Cesarsky and Bibring (1981) and Bibring and Cesarsky (1981) also discussed grain sputtering as a source of GCR material; however they did not consider grain acceleration and relied on downstream second order Fermi acceleration to accelerate sputtered ions.

9 As this is a crucial aspect of the model it is worth discussing it in a little detail. The key point is that the trajectory a charged particle follows in a stationary magnetic field is determined only by the rigidity of the particle. Of course the time taken to traverse the trajectory will be different for particles of different velocities, but the path followed is the same for all particles of the same rigidity (and charge sign). Thus, as long as the field varies on time scales longer than the time taken by a particle to traverse the scattering magnetic structures, the scattering mean free path depends only on the rigidity and will be exactly the same for a subrelativistic dust grain and a high energy proton. The time scale for variation in the field will be of order the length scale of the magnetic structure divided by the Alfvén speed, so basically all particles with velocities larger than the Alfvén speed see an essentially static field and will have scattering mean free paths which are determined only by their rigidity. The dust grains enter the downstream region with a velocity of order the shock velocity, and as the shock is super-Alfvénic, this condition is fulfilled for them.
as momentum, or velocity, to the second power (one from the increase in the mean free path and one from that in the speed). Thus as the grains are accelerated from an initial velocity of order the shock speed, the acceleration rate drops rapidly. At the same time the frictional drag on the dust particles resulting from collisions with atoms of the gas increases proportional to velocity. This sets a natural limit to the amount of grain acceleration determined by the balance between acceleration at the shock and frictional losses in the upstream and downstream regions. This process, which was not considered by Epstein, turns out to be crucial because it links the rate of gas collisions with the grain in the upstream region, and hence the amount of ion sputtering, to the acceleration rate of the shock. For any reasonable parameters the grains are only slightly accelerated, by about a factor ten in momentum or velocity, or one hundred in energy (corresponding to about 0.1 MeV per nucleon), but this is enough to produce a small amount of sputtering from the accelerated grains in the region ahead of the shock. We calculate that roughly $10^{-4}$ of the grain material will be sputtered in the upstream region, and give rise to secondary ions with velocities about ten times the shock speed. These ions will be picked up by the interstellar field and swept into the shock, which will then efficiently accelerate them to relativistic energies. Particles that are sputtered downstream from the shock are swept away from the shock and do not get accelerated by it. An important point is that the ions sputtered upstream are produced in association with and close enough to the shock to reach it before they have suffered serious energy losses (as noted above the energy loss times of subrelativistic ions are quite short).

In addition, of course, the same shock will directly accelerate ions out of the gas phase, but because these start down in the thermal distribution at velocities of order the shock speed there will be a strong rigidity dependent bias in the initial phase of the acceleration. Whatever the precise conditions of ionization, this will effectively result in a mass fractionation effect; in particular if, as plausible, we have a UV photoionized gas in which all species have ionization state one or two. Heavier species have larger mean free paths against scattering and thus sample more of the shock compression earlier in their acceleration than the lighter ions. This effect is not easy to model analytically (x-ref Malkov; Berezhko, Yelshin and Ksenofontov, 1996) but has been simulated in Don Ellison’s Monte-Carlo model of shock acceleration for many years. Where it has been possible to compare the Monte Carlo results with observations at the Earth’s bow shock the agreement is generally excellent (eg Ellison, Moebius and Paschmann, 1990).

In terms of their contribution to the bulk composition of GCRs the most important SNR shocks are thought to be those associated with the larger older remnants nearing the end of their Sedov-like phase. The smaller faster shocks associated with young remnants certainly accelerate particles, but they process relatively small amounts of the ISM and the particles they accelerate (except at the highest energies) are trapped inside the remnant and subject to adiabatic losses as the SNR expands. In fact our results turn out not to be very sensitive to the assumed shock speed. We have considered two typical cases, a fast shock of velocity 2000 km s$^{-1}$ and a slower older shock of velocity 400 km s$^{-1}$. For both we have calculated the expected mass fractionation in the acceleration of the volatile element ions using Ellison’s Monte Carlo code and consistently calculated the grain acceleration using the same code. We then used a simple approximation for the sputtering yields to estimate the flux of sputtered energetic ions of refractory elements into the shock, which we then accelerated to relativistic energies, again using the same Monte Carlo code. The results are shown in Fig. 4.

This is a very remarkable plot. We see at once that H, the inert gases and N show a clear mass fractionation effect which is well reproduced by the Monte Carlo code. In fact the agreement is best with the slower shock model, exactly as we expect on physical grounds. The refractory elements, which form the low-FIP group, fall exactly in the region where we predict accelerated sputtered ions from accelerated grains to lie (between the two horizontal lines given to roughly indicate errors in the model). It is important to note that we have not done any fitting to the data in this plot. We have simply taken known physics, a standard dusty ISM composition, and the Monte Carlo shock
COSMIC RAY SOURCE COMPOSITION

Figure 4: Comparison between the Monte Carlo model predictions and the observational data. The dotted and dot-dash lines indicate the mass-dependent fractionation of purely volatile species given by the code for two different shock speeds. The two dashed horizontal lines indicate the enhancement relative to hydrogen of sputtered ions from refractory grains predicted by the slower shock model.
acceleration code and calculated \textit{ab initio} what the composition of the accelerated particles should be at GeV per nucleon energies.

What we have done is to identify \textit{two} distinct routes within the \textit{one} shock acceleration mechanism whereby atoms of interstellar material can reach cosmic ray energies. The first route is the standard shock acceleration picture in which the shock-heated gas-phase ion distribution functions develop tails extending to very high energies and where high mass to charge ratio ions are preferentially accelerated. The second route involves modest acceleration of the interstellar grain population, sputtering of ions from the accelerated grains upstream of the shock, and subsequent acceleration of these sputtered ions at higher energies where the shock acceleration is already quasi-independent of rigidity resulting in little or no species dependent bias. The dynamical coupling between acceleration rate, frictional drag and sputtering links these two routes and shows that the second route, as measured by abundances at GeV energies, is about a factor 30 times as efficient as the first is for protons. This naturally explains the very similar enhancements of all the low-FIP refractory elements which we believe enter the cosmic ray population almost exclusively through the second route, and therefore undergo the crucial first phases of the acceleration, not as individual ions, but as constituents of entire grains. The volatile elements, on the other hand, and in particular the dominant species H and He, enter almost exclusively as gas-phase ions through the first process and are subject to strong mass fractionation as predicted by the Monte Carlo model.

6 Carbon and Oxygen

That exceptions prove rules is a principle going back to the scholastic philosophers; one of the best ways of testing the validity of any general principle is to look closely at the cases where it apparently fails. Clearly the two elements which appear exceptional in our interpretation of the data are carbon and oxygen. Both are clearly above the “volatile” curve, but also well below the “refractory” band. However both these elements are also special in at least two other respects. Firstly, although far from being completely condensed in the ISM, both are known to be important grain constituents. Secondly carbon, and to a lesser extent oxygen, are greatly enhanced in the winds from Wolf-Rayet (WR) stars.

Let us consider first the case of oxygen. The refractory metallic elements such as Mg, Al, Si, Ca and Fe which form grains do so by condensing as oxides (silicate minerals are known from infrared spectroscopy to be one of the main components of interstellar dust). It is generally estimated that this locks some 15% to 20% of the interstellar oxygen up in grains from which it will be preferentially accelerated in the same way as all other grain constituents. Relative to H, fig. shows that O is enhanced by a factor of \( f_O \approx 5 \) whereas the neighbouring (in mass) volatile elements N and Ne are only enhanced by a factor \( f_{\text{vol}} \approx 2 \). However sputtered grain material is enhanced by a factor \( f_{\text{ref}} \approx 20 \) to 25. If a fraction \( x \) of the oxygen is in grains, then the resulting mixture of directly accelerated gas-phase “volatile” oxygen and sputtered “refractory” oxygen will give a net enhancement

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x f_{\text{ref}} + (1 - x) f_{\text{vol}} = f_O \quad \text{so that} \quad x = (f_O - f_{\text{vol}})/(f_{\text{ref}} - f_{\text{vol}}). \tag{1}
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With the above observed values of the enhancement \( f \) factors we get a fraction \( x \) of order 0.15, perfectly consistent with the chemistry of silicate minerals. Recent depletion studies of the ISM suggest, if anything, rather higher fractions of interstellar oxygen in the dust component (Meyer, Jura and Cardelli, 1998), but this is hard to reconcile with the chemistry.

\footnote{In the original sense of \textit{test} as preserved in the saying “the proof of the pudding is in the eating”}

\footnote{Nitrogen is also enhanced in WN-type WR star winds, but only by factors of order 13. In contrast, carbon is enhanced by much larger factors of about 120 in the WC-type star winds. Oxygen can also be enhanced in the much rarer WO-type WR star winds.}
The other element which is known to form a significant interstellar grain component is carbon. Small graphite-like grains have long been a feature of dust models and are apparently required to reproduce the 2175 Å feature in the interstellar extinction curve. Although no generally accepted carrier has yet been identified for the unidentified interstellar absorption features, almost all suggestions involve substantial amounts of carbon. Carbon grains are observed to condense in the atmospheres of carbon stars from which they are ejected by radiation pressure into the ISM. In addition, Greenberg and his colleagues have argued that most interstellar grains acquire “mantles” of refractory organic deposits through condensation of organic compounds in molecular clouds and subsequent UV irradiation. In fact at present there is a “carbon crisis” in that the dust models all require more carbon in the dust than appears to be available (Snow and Witt, 1996; Mathis, 1996; Dwek, 1997). The best current estimates (Cardelli et al, 1996) suggest that the fraction of ISM carbon incorporated into dust grains is between 20% and 60%. The GCRS/solar system enhancement of about 9 relative to H would be compatible with a fraction of about 30% of the interstellar carbon in refractory grains, but in addition we expect a specific carbon excess from WR star nucleosynthesis.

The existence of such a component is indicated by the the one firm isotopic anomaly in the GCRS, the well-established excess of $^{22}\text{Ne}$. This strongly suggests a contribution from material contaminated by the winds from WR stars (van der Hucht and Williams, 1995). This is actually very natural. The most massive supernova progenitor stars are thought to evolve through a WR phase just prior to core collapse. The strong and fast WR wind will blow a circumstellar shell of material enriched in He burning products which will then be traversed by the subsequent SNR shock wave. This rather naturally accounts for a $^{22}\text{Ne}$ excess and must also contribute significant amounts of $^{12}\text{C}$ to the GCRS. In fact a large fraction of the $^{12}\text{C}$ should condense as grains in the C-rich WR star wind so that sputtering of these circumstellar grains may further enhance the importance of this contribution. This may not actually leave much room for a carbon enhancement from “ordinary” ISM grains! As for oxygen, the WR contribution of $^{16}\text{O}$ to the GCRS must be negligible in view of the observed lack of any associated excess of $^{25,26}\text{Mg}$.

7 Conclusion

We have shown that standard shock acceleration applied to an ISM with the bulk composition of the local ISM, but where the refractory elements along with 15% of the oxygen and a significant fraction of the carbon are in dust grains, can replicate all the observed features of the GCRS abundance pattern and do so quantitatively, with the exception of the $^{22}\text{Ne}$ excess. This latter can be rather naturally explained in terms of an additional Wolf-Rayet wind component which must then also contribute to the C excess.

Our interpretation of the compositional data is based solely on calculable physical processes and standard astronomical inputs with essentially no adjustable parameters, yet manages to give a better match to the observations than any other interpretation we are aware of. This, we feel, argues strongly for the basic correctness of the underlying picture which locates the origin of bulk of Galactic cosmic rays in the processing of a dusty ISM by the strong blast waves driven by supernova explosions.

The exciting prospect is that we appear to be able to relate the GCRS composition to important astronomical questions about dust and the ISM. Obviously much more work needs to be done in refining the model (in particular the treatment of sputtering needs to be improved) and this needs to be related to our rapidly increasing knowledge of interstellar abundances and dust properties. However, we may ultimately be able to use cosmic ray composition studies to chemically analyze the interstellar dust!
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References

Andersson, H. & Edvardsson, B. 1994 AA 290 590.
Arnett, D 1995, ARA&A 33 115
Baade, W. & Zwicky, F. 1934, Proc. Nat. Acad. Sci. U. S. 20 254.
Berezhko, E. G., Yelshin, V., & Ksenofontov, L. 1996, Sov. Phys. JETP, 82, 1,
Bibring, J-P. & Cesarsky, C. J. 1981, Proc 17th International Cosmic Ray Conference (Paris) 2 289.
Cesarsky, C. J. & Bibring, J-P. 1981, IAU Sym 94 “Origin of Cosmic Rays” ed G. Setti, G. Spada & A. Wolfendale (Dordrecht: Reidel) 361
Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E. & Tomkin, J. 1993 AA 275 101.
Ellison, D. C., 1982, Ph.D. Thesis, The Catholic University of America.
Ellison, D. C., Drury, L. O’C. & Meyer, J-P. 1997, ApJ 487 197
Ellison, D. C., Moebius, E. & Paschmann, G. 1990 ApJ 352 376
Epstein, R. I. 1980, MNRAS 193 723
Epstein, R. I. 1981, IAU Sym 94 “Origin of Cosmic Rays” ed G. Setti, G. Spada & A. Wolfendale (Dordrecht: Reidel) 109
Ginzburg, V. L. & Syrovatsky, S. I. 1964, “The origin of cosmic rays”, english translation by H. S. H. Massey incorporating revisions by the authors, ed. D. Ter Haar, (Pergamon: Oxford).
van der Hucht, K. A. & Williams, P. M. eds 1995, IAU Symposium 163 Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution (Dordrecht: Kluwer)
Koyama, K. et al 1995 Nature 378 255
Meyer, D. M., Jura, M. & Cardelli, J. A. 1998 ApJ 493 222
Meyer, J-P. 1985, ApJS 57 173.
Meyer, J-P., Drury, L. O’C. & Ellison, D. C. 1997, ApJ 487 182
Meyer, J-P., Drury, L. O’C. & Ellison, D. C. 1998, ACE Workshop, Caltech, Jan. 1997, Space Sci. Rev., in press.
Spitzer, L. Jr., 1978, “Physical Processes in the Interstellar Medium”, (Wiley: New York).
Snow, T. P. & Witt, A. N. 1996 ApJ 468 L65
Tanimori, T., Hayami, Y., Kamei, S., Dazeley, S. A., Edwards, P. G., Gunji, S., Hara, S., Hara, T.,
Holder, J., Kawachi, A., Kifune, T., Kita, R., Konishi, T., Masaike, A., Matsubara, Y., Matsuoka,
T., Mizumoto, Y., Mori, M., Moriya, M., Muraishi, H., Muraki, Y., Naito, T., Nishijima, K., Oda, S.,
Ogio, S., Patterson, J. R., Roberts, M. D., Rowell, G. P., Sakurazawa, K., Sako, T., Sato, Y., Susukita,
R., Suzuki, A., Suzuki, R., Tamura, T., Thornton, G. J., Yanagita, S., Yoshida, T., Yoshikoshi, T.
1998 ApJ 497 L25

Timmes, F. X., Woosley, S. E. & Weaver, T. A. 1995, ApJS 98 617

Woosley, S. E. & Weaver, T. A. 1995, ApJS 101 181