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ANOMALOUS ISOTOPIC COMPOSITION OF COSMIC RAYS

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ABSTRACT

Recent measurements of non-solar isotopic patterns for the elements neon and (perhaps) magnesium in cosmic rays are interpreted within current models of stellar nucleosynthesis. One possible explanation is that the stars currently responsible for cosmic-ray synthesis in the Galaxy are typically super-metal-rich by a factor of two to three. Other possibilities include the selective acceleration of certain zones or masses of supernovae or the enhancement of ^{22}Ne in the interstellar medium by mass loss from red giant stars and planetary nebulae. Measurements of critical isotopic ratios are suggested to aid in distinguishing among the various possibilities. Some of these explanations place significant constraints on the fraction of cosmic ray nuclei that must be fresh supernova debris and the masses of the supernovae involved.

Subject headings: cosmic rays: abundances, general — nucleosynthesis — stars: supernovae — galaxies: Milky Way

I. INTRODUCTION

Recently new data have become available on the isotopic composition of several intermediate mass nuclei in cosmic rays which when taken at face value suggest a distinctly non-solar pattern at the cosmic-ray source for the elements neon (Fisher et al. 1976; Prezler et al. 1975; Garcia-Munoz, Simpson, and Wefel 1979a; Greiner et al. 1979; Mewaldt et al. 1980a) and perhaps magnesium (Mewaldt et al. 1980a; although see also Dwyer 1978 and Garcia-Munoz, Simpson, and Wefel 1979b). In particular the neutron-rich isotopes of both elements appear to be selectively enhanced compared to the more abundant isotopes having equal numbers of neutrons and protons. The measurements of Mewaldt et al., for example, show ^{22}Ne enhanced relative to ^{20}Ne by a factor 2.7 (+2.6, -1.6) and $^{25}\text{Mg} + ^{26}\text{Mg}$ enhanced relative to ^{24}Mg by a factor 1.8 (+0.8, -0.5) as compared to solar (Cameron 1973) abundances. In this paper we address the question of how such observations can be understood within the context of current theories of stellar nucleosynthesis and what inferences might be drawn concerning the nature of cosmic-ray sources. The nucleosynthesis of neon and magnesium isotopes is briefly reviewed and four possible hypotheses are presented for explaining the observed anomalies. The implications of each hypothesis for the properties of cosmic-ray sources are briefly explored and specific measurements to eliminate or confirm one or more of the models are suggested.

II. SYNTHESIS OF Ne AND Mg

The synthesis in nature of the most abundant isotopes of the elements neon and magnesium, ^{20}Ne and ^{24}Mg , results from a combination of pre-explosive (hydrostatic) carbon burning and explosive neon burning in massive ($M \gtrsim 12 M_{\odot}$) stars that become supernovae (Weaver, Zimmerman, and Woosley 1978; Arnett and Wefel 1978; Woosley and Weaver 1980ab). Substantial nucleosynthesis of the neutron-rich isotopes of magnesium, ^{25}Mg and ^{26}Mg , as well as ^{21}Ne , $^{29,30}\text{Si}$, and a large number of other species also occurs in these same stellar zones (Woosley and Weaver 1980a) although small abundances of these same species could also be byproducts of the s-process (Iben 1975ab; Scalo 1978). The other abundant isotope of neon, ^{22}Ne , as well as the rarer nucleus, ^{18}O , almost certainly owe their existence to the α -capture that occurs upon ^{14}N targets during helium burning

Thus they are produced in amounts that scale linearly with the initial metallicity of the star (essentially all CNO isotopes are converted to ^{14}N by the CNO tricycle prior to helium ignition). Quantitatively, the mass fraction of ^{22}Ne produced during helium burning at sufficiently high temperature that eq. (1) goes to near completion but prior to any (α, n) reactions on ^{22}Ne itself, is given approximately by

$$X(^{22}\text{Ne}) \approx 0.02(Z/Z_{\odot}) \quad (2)$$

where Z is the initial mass fraction of all elements in the star heavier than helium and $Z_{\odot} = 0.018$ is its value in the sun (Cameron 1973).

Although one can assert with considerable confidence that most ^{20}Ne and ^{24}Mg originate in supernova explosions, the location where ^{22}Ne is both produced and ejected is less certain. Not only is ^{22}Ne abundant in the helium layers ejected by a supernova but also in the helium shells of lighter stars that become planetary nebulae or red giants (Scalo 1978; Iben 1975ab). A definitive calculation of the relative importance of the various mass loss mechanisms for the enrichment of the interstellar medium in ^{22}Ne and other heavy isotopes is beyond the scope of the present paper, but it is interesting to note that studies of nucleosynthesis in model $25 M_{\odot}$ Pop I supernovae (Weaver and Woosley 1980a; Woosley and Weaver 1980ab) do show $^{16,17,18}\text{O}$, $^{20,21,22}\text{Ne}$, and $^{24,25,26}\text{Mg}$ all to be produced and ejected in near solar proportions both relative to one another and to a large number of other species in the mass range $12 \leq A \leq 62$. This result suggests but does not prove that all isotopes of oxygen, neon, and magnesium have been produced mostly in Type II supernovae.

III. POSSIBLE EXPLANATIONS FOR NON-SOLAR $^{22}\text{Ne}/^{20}\text{Ne}$

Enhancements in the ratio $^{22}\text{Ne}/^{20}\text{Ne}$ in cosmic rays may arise from several different mechanisms all of which relate either to the disjoint sites of production for the two species or to the metallicity dependence of ^{22}Ne production [eq. (1)]. We will consider here four hypotheses consistent with the observed enhancement of roughly 2.5. While each hypothesis separately offers a valid explanation for the observed $^{22}\text{Ne}/^{20}\text{Ne}$ enhancement none of them is really exclusive of the others and perhaps all occur to some extent. There will, however, presumably be only one dominant effect and it is useful to explore the consequences of each model with an eye towards future measurements that may help to delimit the nature of the cosmic-ray source.

a) Supermetallicity (Model 1)

If that region of the Galaxy now responsible for producing cosmic rays is characterized by a higher fraction of metals than existed in our region of the Galaxy at the time the sun formed, an enhancement in the ratio $^{22}\text{Ne}/^{20}\text{Ne}$ will result since the production of ^{22}Ne scales with metallicity [eq. (2)] while ^{20}Ne production, to first order, is independent of Z (we neglect here minor structural changes that may be caused by variation of metallicity in a massive star as well as any metallicity dependence in the stellar birth function). Additionally, many other isotopic ratios will be systematically affected by increasing Z since the abundance of ^{22}Ne or ^{18}O produced in helium burning determines the neutron excess

$$\eta \equiv \sum (1 - 2Z_i/A_i) X_i \quad (3)$$

for all future burning stages. Here X_i is the mass fraction of the species having nuclear charge Z_i and mass number A_i and the sum extends over all species present. Combining eq. (2) and (3) one has, for a star of initial metallicity Z , a neutron excess following helium burning of

$$\eta \approx 0.002 (Z/Z_\odot). \quad (4)$$

For $3Z_\odot \gtrsim Z > Z_\odot$ subsequent burning phases will have little effect on this value at least for that material destined to produce the intermediate mass elements. Consequently when a massive (Population I) star eventually blows up, ejecting the debris of both its explosive and hydrostatic nuclear processes, this critical parameter will still have a value bearing near linear correlation with the initial (super-) metallicity of the star (such is not the case for metal-deficient Population II stars which are not under discussion here). In Table 1 a summary is presented of the expected modifications of certain key isotopic ratios resulting solely from an increase by a factor of 2.5 of the initial metallicity of the ensemble of nucleosynthesis supernovae. For details of the calculation see Woosley and Weaver (1980a) and Woosley, Arnett, and Clayton (1973). The enhancements of ^{25}Mg , ^{26}Mg , and ^{54}Fe given in Table 1 agree reasonably well with the measurements of Mewaldt et al. (1980ab) who found in cosmic rays ratios of $(^{25}\text{Mg} + ^{26}\text{Mg})/^{24}\text{Mg} = 1.8 (+0.8, -0.5)$ and $^{54}\text{Fe}/^{56}\text{Fe} = 1.6 (+1.8, -0.9)$ times their solar values. Similar enhancements of the neutron-rich isotopes of Si, S, and Ar might also be detectable by future experiments. The enhancement in ^{18}O would probably be undetectable due to its small natural abundance and large spallation contribution in cosmic rays (Shapiro, Silberberg, and Tsao 1975; Stone and Wiedenbeck 1979).

In support of this hypothesis one may note considerable observational evidence for radial gradients in the abundances of nitrogen and oxygen both in our Galaxy (Peimbert, Torres-Peimbert, and Rayo 1978) and in other galaxies (cf. Shields and Searle 1978). If the cosmic rays arriving at earth predominantly originate from a region of the Galaxy considerably more central than the sun's orbit it would not be too surprising to find evidence for supermetallicity in the production sites. Some evidence in fact exists from observations of diffuse gamma and non-thermal radio emission for a central concentration of cosmic-ray sources (Paul, Casse, and Cesarsky 1976; Kniffen, Fichtel, and Thompson 1977; Fichtel, Simpson, and Thompson 1978). Additionally, observations by Solomon, Sanders, and Scoville (1979) suggest the region of galactic radius 4 to 8 kpc to be an area of particularly active star formation. A region where massive stars are being born will also be a region of enhanced supernova activity and cosmic-ray acceleration. Given the short evolutionary time of massive stars, an enhancement in metallicity in the interstellar medium could rapidly, perhaps even during the formation of the Galaxy, translate into enhancements of the neutron-rich isotopes ^{22}Ne , $^{25,26}\text{Mg}$, $^{29,30}\text{Si}$, etc., first in any local intracluster medium and then in the interstellar medium itself, not just in the supernovae condensing out of that medium. To the extent that all interstellar neon was produced by supernovae after the local metallicity arose, both the interstellar composition and the ejecta from a typical supernova would manifest "excesses" of neutron-rich isotopes. Thus in principle any mixture of interstellar medium and fresh supernova debris could give rise to an "anomalous" (to us) cosmic ray composition.

A major difficulty with any such explanation for isotopically anomalous cosmic rays observed at the earth, however, may be the mean diffusion distance for cosmic rays. It will avail us nothing if cosmic rays at 4 to 8 kpc from the galactic center are ^{22}Ne -rich owing to super-metallicity if such cosmic rays never diffuse outwards as far as the sun's orbit. Currently the diffusion distance of galactic cosmic rays is quite uncertain (Owens and Jokipi 1977; Ormes and Freier 1978) but it may be shorter than 1 kpc (Ormes and Freier 1978).

Alternatively, instead of invoking metallicity variations on a galactic dimension (which of necessity leads to assuming large cosmic ray diffusion distances), one might explore the possibility of local heavy-element enhancements. This might manifest itself in two ways. Either the local metallicity of the interstellar medium itself (and hence of the young nearby stars destined to become Type II supernovae) could have increased since the sun's birth, or else there might exist large-scale spatial inhomogeneities in the heavy-element concentration inside the nearby stellar OB-associations thought by some to be active in accelerating cosmic rays (Montmerle 1979). In the latter case a series of supernova explosions in the OB-association would be presumed to substantially contaminate other nearby massive protostars destined to later become supernovae themselves. However, this contamination would have to be at least great enough to increase the heavy-element concentration in this latter generation of supernovae by a factor of two. It seems probably that the actual contamination would in fact be much smaller due to considerable dilution of the supernova ejecta by the substantial intercluster medium (Reeves 1978), but theoretical models have not really adequately addressed this point.

Similarly, theoretical models suggest (but do not prove) that large-scale increases in the (smoothed-out) local metallicity of the interstellar medium have been small since the sun's birth (Tinsley 1977), while actual observations are inconclusive in this regard (McClure and Tinsley 1976).

b) Disjoint Supernova Class (Model 2)

The abundance in cosmic rays may reflect a weighting of the nucleosynthetic components from stars of various masses different from that responsible for solar abundances. For example, as Arnett and Schramm (1973) have pointed out, if each supernova accelerates the same absolute mass of material to cosmic-ray energies, then cosmic-ray abundances might reflect those of the most common supernova, while interstellar abundances, which must be weighted by the total mass ejected from each supernova, would be typical of a somewhat heavier star. Indeed the situation could be even more complicated than these authors suggest. Until our knowledge both of cosmic-ray acceleration mechanisms and supernova models improves considerably, one cannot rule out a very select class of stars for cosmic-ray production, e.g., those that form a pulsar rather than a black hole, those with some critical value of angular momentum or magnetic field configuration, or those that ignite carbon degenerately.

For illustrative purposes we will discuss here the expected nucleosynthesis of neon in non-rotating stars of (constant) main-sequence mass $10 M_{\odot}$, $15 M_{\odot}$, $20 M_{\odot}$ and $25 M_{\odot}$, all of which will probably explode as supernovae, leaving collapsed remnants close to $1.5 M_{\odot}$ (Weaver, Zimmerman, and Woosley 1978; Weaver and Woosley 1980ab; Woosley, Weaver, and Taam 1980; Woosley and Weaver 1980b). In Figure 1 the abundances of ^{18}O , ^{20}Ne and ^{22}Ne are plotted as a function of the Lagrangian mass coordinate for these four stars. Owing to uncertainties in reaction rates and theories of stellar convection each of the abundance curves must be regarded as uncertain in absolute value by about a factor of two, although the distribution with mass coordinate should be qualitatively correct. The plot for the $10 M_{\odot}$ star has been evaluated here following silicon burning in the core (Weaver and Woosley 1980b) but prior to core collapse. We expect such a configuration to be representative of stars in the mass range $8\text{--}12 M_{\odot}$. At this time all but the inner $1.5 M_{\odot}$ of the star is gravitationally unbound, having been previously ejected by a very strong silicon flash. Averaged over the whole star $^{22}\text{Ne}/^{20}\text{Ne} \approx 0.3$. Moreover, the ^{20}Ne in this model is contained in a very thin layer near the core where, unlike ^{22}Ne , it is still tightly bound by gravity. Depending upon the energy of the bounce which must ultimately follow iron core collapse in this star, either all or none of this ^{20}Ne could be ejected. In principle this star could be a source of almost pure ^{22}Ne (although some dilution will of necessity occur because of the small primordial abundance of ^{20}Ne present in the helium layer and hydrogen envelope since the birth of the star). Also present

in the $10 M_{\odot}$ model (but not more massive stars) is a very large overproduction of ^{18}O . In that same region where ^{22}Ne is abundant, ^{18}O has a mass fraction roughly 300 times its solar value. Dilution of the roughly $1 M_{\odot}$ of helium ejecta (see Figure 1) with about $20 M_{\odot}$ of "normal" material, a substantial fraction of which could be the $7.5 M_{\odot}$ hydrogen envelope of the presupernova star itself, will give a ^{22}Ne abundance enhanced by roughly a factor of two and an ^{18}O abundance enhanced by a factor of 15. Although even this large ^{18}O enhancement is still just comparable to the error introduced by uncertain spallation cross sections (Webber, Kish, and Simpson 1979), recent measurements by Guzik et al. (1979) suggest that an ^{18}O anomaly of this magnitude is not present. No ^{25}Mg , ^{26}Mg , or s-process nuclei are produced in the helium shell of this $10 M_{\odot}$ model and such elements should be isotopically normal in cosmic rays from this mass range.

Neon isotopic nucleosynthesis in the $15 M_{\odot}$, $20 M_{\odot}$ and $25 M_{\odot}$ models is also shown in Figure 1, being evaluated in each case at a time near core collapse (Weaver, Zimmerman, and Woosley 1978). Qualitatively these profiles should not be greatly modified during the supernova explosion (Weaver and Woosley 1980a) although part of the inner region of ^{20}Ne will be explosively consumed. At the present time production ratios for $^{22}\text{Ne}/^{20}\text{Ne}$ averaged over the entire $15 M_{\odot}$, $20 M_{\odot}$, and $25 M_{\odot}$ stars are all near 0.033 compared to a solar value of 0.12 (Cameron 1973). Given present uncertainties in convection theories, the considerable error bar associated with the $^{20}\text{Ne}(\alpha, \gamma)^{24}\text{Mg}$ rate (Fowler, Caughlan, and Zimmerman 1975), and the fact that the $^{22}\text{Ne}/^{20}\text{Ne}$ ratio will increase somewhat during the subsequent explosion, this is to be

considered qualitative agreement. Our unpublished calculations in fact show that variation of the $^{20}\text{Ne}(\alpha,\gamma)^{24}\text{Mg}$ rate within its allowed error bar could be the major cause of the remaining overproduction. Apparently the $^{22}\text{Ne}/^{20}\text{Ne}$ ratio is not very sensitive to stellar mass, at least for stars for the mass range $15 M_{\odot}$ to $25 M_{\odot}$, and cosmic rays originating from homogeneous samples of such supernovae need not display any striking neon anomaly.

For stars having main-sequence mass less than about $8 M_{\odot}$ (not illustrated) the qualitative nature of the final evolutionary stages again changes. Such stars develop degenerate carbon-oxygen cores surrounded by a thin, thermally unstable helium burning shell (Iben 1975a). A complicated interplay of helium shell flashes and helium, hydrogen, and surface convective zones can result in the entire hydrogen envelope becoming enhanced in ^{22}Ne and also, depending upon the temperature of the helium flashes, in $^{25,26}\text{Mg}$ and the s-process (Iben 1975b; Scalo 1978). If such stars end their lives as supernovae which for some reason contribute an inordinate proportion of their debris to cosmic rays, overabundance of these same isotopic species could result (Casse 1979).

If all the initial CNO in such a star were converted into ^{22}Ne (certainly a gross upper bound) then dilution with interstellar material having about 65 times the mass of the hydrogen envelope of this supernova would be required to yield a ratio of $^{22}\text{Ne}/^{20}\text{Ne}$ enhanced by a factor of 2.5. A similar enhancement in ^{25}Mg and ^{26}Mg would be possible dependent upon the extent of s-processing that occurred (see Scalo 1978).

c) Inhomogeneous Supernova Remnants (Model 3)

Most modern theories of cosmic-ray acceleration involve processes that occur either in young supernova remnants (Ostriker and Gunn 1969; Scott

and Chevalier 1975; Chevalier, Robertson, and Scott 1976; Eichler 1979) or in supernova shock waves emerging from the surface of the star (Colgate and Petschek 1979) or into the interstellar medium (Blandford and Ostriker 1978). Although scant attention is paid in any of these models to the expected composition accelerated to cosmic-ray energies, one might naively suppose that one is dealing with a simple mixture of two homogeneous fluids, namely supernova debris and interstellar medium (cf Hainebach, Norman, and Schramm 1976). In reality this may not be the case at all! Observations of abundances in the CAS A supernova remnant (Chevalier and Kirshner 1978), for example, show evidence of considerable chemical inhomogeneity even some 300 years following the supernova event. In particular, high concentrations of the products of oxygen burning, such as sulfur and argon, are found in the "fast-moving knots." Given the level of our uncertainty about the time and location of cosmic-ray acceleration, it may well be that the spatial inhomogeneity of the chemical composition of the supernova remnant is preserved in cosmic-ray abundances. If so, then an obvious explanation for an enhanced $^{22}\text{Ne}/^{20}\text{Ne}$ ratio comes from inspection of Figure 1. In all massive stars the synthesis of ^{22}Ne occurs in the helium shell, a region exterior to that where ^{20}Ne is abundant. Moreover the ^{22}Ne -producing region is of considerably greater spatial volume and lower-density than the ^{20}Ne region (see Figures 1 and 2 of Weaver, Zimmerman, and Woosley 1978 for pre-explosive density profiles corresponding to the $15 M_{\odot}$ and $25 M_{\odot}$ stars depicted in Figure 1 here). One finds the lower-density material to be ejected at a higher velocity when the supernova explodes (Weaver and Woosley 1980a). Thus if one proposes an ad hoc acceleration mechanism more active in the outer layers of a supernova, a mechanism sensitive to injection velocity, or perhaps a mechanism that accelerates a constant amount of mass per unit volume, enhancements of

^{18}O and ^{22}Ne follow naturally. Enhancements of other species such as $^{25,26}\text{Mg}$, the s-process, and the products of hydrostatic and explosive carbon, neon, oxygen, and silicon burning may also occur depending on the degree of homogenization following the explosion and the extent of convection prior to explosion.

d) Isotopic Enrichment of the Interstellar Medium (Model 4)

As noted earlier ^{22}Ne , possibly accompanied by $^{25,26}\text{Mg}$ and s-process nuclei, may be synthesized and ejected into the interstellar medium by red giant stars undergoing steady mass loss and by planetary nebulae (Scafo 1978). If so the progressive enrichment of the interstellar medium might produce characteristically non-solar abundances for these isotopes, especially in two regions of disjoint galactic radius or differing supernova rates. Acceleration of matter dominantly comprised of this "anomalous" component could give non-solar isotopic ratios for these elements even if the particular galactic region involved were not super-metal-rich.

Inasmuch as cosmic rays are to be dominantly comprised of this "peculiar" (to that region and time in the Galaxy) interstellar material, little restriction is placed on the cosmic-ray source. In particular the ratio of interstellar material to freshly synthesized nuclides from recent supernova may assume any value so long as it is large. In such a model ^{22}Ne could be superabundant with or without $^{25,26}\text{Mg}$ excesses. Enhancements in ^{18}O and s-process nuclei would probably be undetectable.

IV. S-PROCESS ENHANCEMENTS

Several models described in the previous section offer the possibility of selective s-process enhancements in cosmic rays. Such would be the case if the helium shells of massive stars have been preferentially accelerated (§ IIIc) or if stars lighter than $8 M_{\odot}$ have contributed a disproportionate share of cosmic-ray nuclei either directly as supernovae (§ IIIb) or indirectly by stellar mass loss during their red-giant phase (§ IIId). In these models any substantial excesses of ^{25}Mg and ^{26}Mg are a result of the reactions $^{22}\text{Ne}(\alpha, n) ^{25}\text{Mg}$ and $^{25}\text{Mg}(n, \gamma) ^{26}\text{Mg}$ having occurred and therefore must be accompanied by s-process overproductions of varying degrees (see Scalo 1978). Indeed, excepting the possibility of supermetallicity (§ IIIa), this is the only way such $^{25,26}\text{Mg}$ excesses could exist.

The magnitudes of these s-process enhancements and the feasibility of their detection depend upon (i) the extent to which the reaction $^{22}\text{Ne}(\alpha, n) ^{25}\text{Mg}$ has proceeded and (ii) the "dilution factor," D , for mixing with isotopically normal material from the stellar surface or interstellar medium prior to cosmic-ray acceleration. Table 2 illustrates these effects. The overproduction factor, Θ , has been calculated for a number of isotopes and elements using a parametrized one-zone model of helium burning. Each overproduction factor is defined as the ratio of the abundance in this one zone to its solar (Cameron 1973) mass fraction and has been evaluated for two different values of ^{22}Ne depletion (subscript "A" in the table corresponds to 7% depletion and "B" to 46% depletion).

These particular results were obtained by evolving a composition consisting initially of 98% ^4He and 2% ^{22}Ne by mass with a set of solar seed for isotopes $A \geq 24$ (and no initial abundances below $A = 24$ except ^4He and ^{22}Ne) at a constant temperature, $T = 3.0 \times 10^8$ K, and density, $\rho = 10^3 \text{ g cm}^{-3}$. Reaction

rates were taken from Weigmann, Macklin, and Harvey (1976) for $^{24,25,26}\text{Mg}$; Allen, Gibbons, and Macklin (1971) for ^{28}Si , $^{54,56,57}\text{Fe}$; Allen (1978) for ^{58}Fe ; Beer, Spencer, and Ernst (1974) for ^{59}Co , $^{61,62,64}\text{Ni}$; and Woosley et al. (1978) elsewhere. Similar values to those in Table 2 would be obtained using a more realistic stellar model and other reaction rates (Lamb et al. 1977).

The enhancement factors, E , also given in Table 2, are defined by

$$E = (\Theta + 0)/(1 + 0) \quad (5)$$

and result from the indicated dilution of the helium zone with material having normal (solar) abundances. As indicated previously this material may come from the uncontaminated layers of the presupernova star (if $M \gtrsim 8 M_{\odot}$) or from the interstellar medium. Cases A and B have been chosen to more than span the allowed range of currently observed neon and magnesium isotopic abundances. The range of enhancement factors presented for heavier isotopes and elements should therefore reflect upper and lower bounds to the expected effect (provided of course that the $^{25,26}\text{Mg}$ excess, if any, is not due to supermetallicity; see previous section).

Not surprisingly one sees from Table 2 that the dominant effect occurs in relatively rare neutron-rich isotopes such as ^{36}S , ^{46}Ca , ^{58}Fe , and ^{62}Ni . Unfortunately the difficulty of measuring cosmic-ray abundances for such rare nuclei as well as the possible large spallation contribution probably render such diagnostics useless, at least for the time being. Similarly, s-process excesses of elements heavier than iron would also be difficult to detect. As Table 2 shows, such enhancements will probably amount to no more than a factor of 2 or 3 in elements that are quite rare in cosmic rays (see also Tables 1 and 5 of Lamb et al. 1977 and Figures 1 and 2 of

Scalo 1978 for overproduction factors for still heavier elements). Such elemental abundances are also much more susceptible to chemical fractionation effects (e.g., ionization dependence in the acceleration mechanism) than are isotopic ratios, and the interpretation of any observed elemental anomalies would thus be ambiguous.

We conclude that the relatively small size of the isotopic anomalies observed in cosmic rays for neon and (especially) magnesium demands such large dilution factors for the helium zones (where the neutron-rich isotopes of these elements are actually the most abundant ones) that any s-process overproductions would be undetectable by present techniques except in magnesium itself and perhaps, marginally, in silicon. Any attempt to circumvent these restrictions by burning up the excess ^{26}Mg would require such extreme conditions as to destroy completely any ^{22}Ne , thus defeating the original purpose of the entire procedure.

V. SUMMARY AND PROPOSED MEASUREMENTS

Four possible explanations for the observed isotopic excess of ^{22}Ne in cosmic rays have been discussed. They involve (1) supermetallicity in the cosmic-ray-producing region of the Galaxy; (2) disjoint classes of supernovae for cosmic-ray and solar-system nucleosynthesis; (3) incomplete mixing of supernova debris prior to cosmic-ray acceleration; or (4) selective enhancement of ^{22}Ne and perhaps $^{25,26}\text{Mg}$ and the s-process in the interstellar medium by stellar-mass loss other than supernovae. The implications of and restrictions imposed by each of these hypotheses are summarized in Table 3 and have been discussed in detail in § III.

The allowed dilution factors presented in Table 3 are more restrictive than one might think. For models 2a and 3 a sizable portion of the requisite dilution is provided by the hydrogen envelope of the supernova itself (if the star has not lost that envelope prior to exploding). For example, in the $10 M_{\odot}$ model depicted in Figure 1, $7.5 M_{\odot}$ of hydrogen envelope is ejected containing isotopically normal neon and heavier elements as well as near normal ^{16}O and ^{18}O . This is to be compared to roughly $1 M_{\odot}$ of helium debris bearing the ^{18}O and ^{22}Ne anomalies. Thus, neglecting pre-explosive mass loss, fully 1/3 of the material accelerated into cosmic-ray energy in model 2a must have been part of the original pre-supernova star. Similarly in model 3, a $25 M_{\odot}$ supernova, for example, ejects a helium shell of $2 M_{\odot}$ compared to about $15 M_{\odot}$ of hydrogen envelope isotopically normal in most heavy elements (Weaver, Zimmerman, and Woosley 1978). For a $25 M_{\odot}$ cosmic-ray source, then, at least 10% of the cosmic rays would have originally been part of the pre-supernova star. Mixing from beneath the helium shell would increase this percentage still further. Thus for these two models

the observed ^{22}Ne anomaly has already significantly constrained the cosmic-ray source.

Of highest experimental priority in the future is a more exact determination of the isotopic composition of magnesium at the source. Observations by Mewaldt et al. (1980a) indicate enhancements of $^{25,26}\text{Mg}$ with the solar ratio lying outside a rather substantial error bar. These results are in contrast although not necessarily in disagreement with those of Dwyer (1978); Garcia-Munoz, Simpson, and Wefel (1979b); and Webber, Kish, and Simpson (1979), who conclude a solar ratio for magnesium isotopes at the cosmic-ray source but again with substantial error bars. If it indeed turns out that the element magnesium is enhanced in its neutron-rich isotopes by roughly a factor of two, then supermetallicity of that region of the Galaxy that produces our cosmic rays is a distinct possibility and careful analysis of the isotopes of silicon, sulfur, argon, and iron is mandated. "Normal" isotopic ratios for any of these elements (including magnesium), say within a factor of 50% of the solar value in measurements extrapolated to the source, will rule out the supermetallicity hypothesis. Conversely, isotopic ratios like those of Table 1 for all of these elements, especially for sulfur and argon, will prove its validity. Present measurements of silicon and iron isotopic composition by Mewaldt et al. (1980 ab) give values that are consistent with solar abundances but with error bars such that $^{29,30}\text{Si}$ and ^{54}Fe could be enhanced by a factor of 2 or more. Spallation contributions to the neutron-rich isotopes of silicon, sulfur, and argon are substantial and accurate cross-sections coupled to realistic propagation models will be required in addition to further measurements before definitive statements can be made on the basis of these elements.

None of our other three models makes predictions quite so definitive as the supermetallicity hypothesis and it may be that discrimination among them will not be possible upon the basis of abundance analyses alone. Unfortunately, the abundance in nature of ^{18}O , a potentially important diagnostic, is so small that its practical application in delimiting the cosmic-ray source in all but the most extreme cases is doubtful. Stone and Wiedenbeck (1979) find a spallation contribution to ^{18}O equal to more than 10 times its initial (assumed solar) abundance. A non-ambiguous ^{18}O excess would then have to have an overproduction factor, after dilution and prior to propagation, that was at least comparable to this value. The small (factor of 2 or 3) enhancement of ^{18}O predicted by the supermetallicity hypothesis, for example, would be unobservable. If an ^{18}O abundance equal to more than a few percent of ^{16}O is found to exist it should be regarded as evidence for hypothesis 2a (Table 3), namely that supernovae having mass $8 M_{\odot}$ to $12 M_{\odot}$ with relatively low dilution factors have contributed an inordinately large amount of material to cosmic rays. The upper limits placed on the ^{18}O abundance by Guzik et al. (1979) already come close to ruling out this model.

We note that Casse, Meyer, and Reeves (1979) have also recently reviewed the possible nucleosynthetic implications of a ^{22}Ne excess in cosmic rays. They have (independently) suggested possibilities not too dissimilar from our models 2a and 2b but, in our opinion, were misled into prematurely assigning these models low probability because of: (1) an erroneous misconception that much of the ejected helium layer in a supernova of mass $M \gtrsim 15 M_{\odot}$ must undergo explosive reprocessing as the shock wave passes through (contrary to the results of Weaver and Woosley [1980a]), and (2) a belief that ^{25}Mg and ^{26}Mg are not enriched in cosmic rays

(a result that has yet to be demonstrated by the observations), which disfavored production in lighter stars. Instead, Casse et al. chose as a preferred model the proposition that ^{22}Ne excesses result from explosive hydrogen burning where the ^{22}Ne is produced as a radioactive progenitor, ^{22}Na . We find such a hypothesis to be untenable. The large temperature and densities required (Casse et al. suggest $T \gtrsim 5 \times 10^8 \text{K}$) are not realized in the Type II supernova models of Weaver and Woosley (1980ab). General arguments based upon energetics in fact preclude the existence of these temperatures in a substantial fraction of the hydrogen in any massive star that becomes a supernova while in a red-giant phase (such is the status of all current Type II models). Similarly, compact objects that might become Type I supernovae will probably experience temperatures in the required range only in a minute fraction of their mass (Woosley, Weaver, and Taam 1980). Finally, as Wallace and Woosley (1980) have recently pointed out, the reaction rates governing ^{22}Na destruction [especially $^{22}\text{Na} (p, \gamma) ^{23}\text{Mg}$] in explosive hydrogen burning have been grossly underestimated in the past so that any yield of ^{22}Na calculated in previous parametrized surveys of hot hydrogen burning must be considered an upper bound to the actual production.

TABLE 1
EFFECTS OF A 2.5 FOLD INCREASE IN METALLICITY

Ratio	Increase	Ratio	Increase
$^{18}\text{O}/^{16}\text{O}$	2.5	$^{30}\text{Si}/^{28}\text{Si}$	2.3
$^{22}\text{Ne}/^{20}\text{Ne}$	2.5	$^{34}\text{S}/^{32}\text{S}$	2.3
$^{25}\text{Mg}/^{24}\text{Mg}$	2.4	$^{38}\text{Ar}/^{36}\text{Ar}$	2.3
$^{26}\text{Mg}/^{24}\text{Mg}$	2.1	$^{54}\text{Fe}/^{56}\text{Fe}$	2.3
$^{29}\text{Si}/^{28}\text{Si}$	2.1		

TABLE 2
S-PROCESS OVERABUNDANCES BEFORE AND FOLLOWING DILUTION

Species	$\mathcal{O}_A$	$\mathcal{O}_B$	E_A^a (D=63)	E_B^a (D=36)	Species	$\mathcal{O}_A$	$\mathcal{O}_B$	E_A^a (D=63)	E_B^a (D=36)
^{22}Ne	94	54	2.5	2.5	^{50}Ti	2.7	12	1.0	1.3
^{25}Mg	14	77	1.2	3.1	^{50}Cr	0.4	0.01	1.0	1.0
^{26}Mg	5.5	66	1.1	2.8	^{52}Cr	0.8	0.2	1.0	1.0
^{28}Si	0.9	0.6	1.0	1.0	^{54}Cr	5.1	18	1.1	1.5
^{29}Si	2.7	6.3	1.0	1.1	^{54}Fe	0.5	0.02	1.0	1.0
^{30}Si	3.1	13	1.0	1.3	^{56}Fe	0.7	0.2	1.0	1.0
^{32}S	0.9	0.5	1.0	1.0	^{57}Fe	8.7	4.4	1.1	1.1
^{34}S	1.4	2.0	1.0	1.0	^{58}Fe	29	79	1.4	3.1
^{36}S	17	170	1.3	5.6	^{58}Ni	0.5	0.01	1.0	1.0
^{36}Ar	0.8	0.4	1.0	1.0	^{60}Ni	1.7	12	1.0	1.3
^{38}Ar	1.4	2.7	1.0	1.0	^{62}Ni	2.9	55	1.0	2.5
^{40}Ar	16	230	1.2	7.2	Ni^b	1.0	4.6	1.0	1.1
^{40}Ca	0.9	0.4	1.0	1.0	Zn^b	1.5	20	1.0	1.5
^{42}Ca	1.9	4.0	1.0	1.1	Ge^b	1.7	14	1.0	1.4
^{46}Ca	19	120	1.3	4.2	Se^b	0.8	3.3	1.0	1.1
^{46}Ti	0.6	1.5	1.0	1.0	Kr^b	1.6	3.4	1.0	1.1
^{48}Ti	0.7	0.3	1.0	1.0	Sr^b	1.8	5.4	1.0	1.1

^aThe overproduction ratio observed after the material characterized by superabundance " $\mathcal{O}$ " has been diluted with "D" times its weight in normal (solar) material.

^bElemental overproductions summed over isotopes. Calculated by Howard (1980).

TABLE 3
CONSTRAINTS ON COSMIC-RAY SOURCE MODELS WITH ENHANCED ^{22}Ne

Hypothesis	Additional Enhancements				Ratio of IM to SN Debris	Mass of SN Progenitor $M_{\odot}$
	^{18}O	$^{25,26}\text{Mg}$	$^{29,30}\text{Si}$	$^{34}\text{S}, ^{38}\text{Ar}$		
1) Supermetallicity	Slight ^a	Yes	Yes	Yes	Any value	---
2a) Different Star Mass	Yes	No	No	No	$\sim 20^b$	$8 \lesssim M \lesssim 12$
2b) Different Star Mass	No	Maybe ^c	Slight ^{a,c}	No	< 63	$M \lesssim 8$
3) Inhomogeneous SNR	Slight ^a	Maybe ^c	Slight ^{a,c}	No	$< 63^b$	$M \gtrsim 8$
4) Anomalous IM	No	Maybe ^c	Slight ^{a,c}	No	Large	---

^aEnhancement exists but probably at an unobservable level.

^bIncluded as "interstellar medium (IM)" in models 2a and 3 are the hydrogen-rich envelopes of the presupernova stars themselves. "Supernova (SN) debris" for these two cases refers only to the helium shell masses of recent supernovae. For case 2b the number given includes the hydrogen envelope as "SN Debris."

^cIf there is no $^{25,26}\text{Mg}$ excess then for these cases there will be no $^{29,30}\text{Si}$ excess.

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FIGURE CAPTIONS

Fig. 1 The distribution with Lagrangian mass coordinate of the mass fractions of ^{20}Ne , ^{22}Ne (solid line) and ^{18}O (dashed line) is given for four stars of indicated main-sequence mass at a time near the end of their evolution. The $10 M_{\odot}$ star is evaluated at a time following helium-shell ejection by a degenerate core flash (see text) while the other three stars are evaluated near silicon core ignition. The extent of the helium shell and ratio of the mean isotopes averaged over the entire star are also given for each case.

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