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SOLAR-STELLAR OUTER ATMOSPHERES AND ENERGETIC PARTICLES, AND GALACTIC COSMIC RAYS

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CONTENTS

ABSTRACT

The heavy element compositions of the solar corona, solar wind (SW), solar energetic particles (SEP, "mass-unbiased baseline"; Paper I) and galactic cosmic-ray sources (GCRS) are remarkably similar. They all show the same pattern as compared to standard local galactic (or solar photospheric) composition: an underabundance of heavy elements with first ionization potential (FIP) $\gtrsim 9$ eV relative to elements with lower FIP, by factors of ~ 4–6. Only C is clearly more abundant in GCR sources than in SEP (by a factor of ~ 2–3), as well as possibly O.

The correlation of the solar coronal composition with FIP suggests an ion-neutral separation during the rise of matter out of the underlying chromosphere, which is cool enough to contain neutrals (possibly due to thermal diffusion at the base of the transition region or in spicules).

The similar abundance patterns found in SW, SEP, and GCRS suggest that they were all extracted from solar-stellar coronae, their composition reflecting to first order that of their birthplate. Note that all later type main-sequence stars of type F–M do possess coronae, transition regions, and chromospheres, with chromospheric temperatures remarkably similar to that of the Sun.

Actually, consideration of the GCRS composition *by itself* (lack of depletion of the refractory elements; correlation with FIP; lack of correlation with specific nucleosynthetic cycles) leads independently to the conclusion that most GCRs did not originate in the ISM gas, but most likely in unevolved star surface material.

But one-step acceleration to high energy, directly out of stellar coronal or wind material meets with difficulties. GCRs are therefore interpreted in a two-step acceleration scenario: most GCRs should be MeV-stellar energetic particles first "injected" by flares out of the coronae of unevolved later type stars (F–M), which were later on reaccelerated to high energy (GeV) by strong interstellar shock waves (SNR, or OB star wind terminal shock). Note that the flares of very active stars (young stars; binary dMe stars) seem qualitatively very similar to those of the Sun.

Besides, coulomb energy losses on "injected" MeV particles prior to high energy acceleration are not expected to alter significantly their composition, when the pickup of electrons is properly taken into account. The problem of the energetics of the injection is, however, still open.

All the above statements apply to the bulk of the GCR heavy nuclei. The fact that, together with ^{22}Ne, precisely C is in excess in GCRs strongly suggests that a small fraction ($\sim 2\%$) of the GCR heavy nuclei originate in He-burning zones (perhaps in Wolf-Rayet stars). The possible O and ^{25,26}Mg excesses could be interpreted in the same context.

Subject headings: cosmic rays: abundances — nucleosynthesis — stars: atmospheres — Sun: abundances — Sun: atmosphere — Sun: flares

I. INTRODUCTION

The composition of solar energetic particles (SEP; ~ 1–50 MeV per nucleon [MeV/n]) is highly variable and, hence, is difficult to interpret. However, it was noted by several authors that the various observed SEP compositions seemed to be influenced by first ionization potential (FIP), thus bearing some similarity with the galactic cosmic-ray source (GCRS) composition (Mogro-Campero and Simpson 1972*a*, *b*; Webber 1975, 1982*a*; Nevatia, Durgaprasad, and Biswas 1977; McGuire, Von Rosenvinge, and McDonald 1979; Cook *et al.* 1979; Cook, Stone, and Vogt 1980; Mewaldt 1980). In a preceding paper (Meyer 1985; hereafter Paper I) we have shown more precisely that all the spacecraft observations of SEP heavy element[1] composition in non ^{3}He-rich events point toward the existence of an *ever-present baseline SEP composition*, which differs from that of the photosphere by a simple selection effect according to FIP. The heavy element composition at any particular time and energy then seems to result from the distortion of *this* baseline composition by additional highly variable biases, which are always *monotonic* in mass or Z (see also McGuire, Von Rosenvinge, and McDonald 1979; Cook *et al.* 1979; Cook, Stone, and Vogt 1980; Mewaldt 1980). These biases seem at least partly related to the mass/charge ratio of the SEP ions, thus probably reflecting the variable conditions for their acceleration or coronal and interplanetary propagation, or both (Paper I). Our concern in the present paper is not these additional variable biases, but the interpretation of the ever-present baseline composition, which has been dubbed in Paper I "mass-unbiased (m.u.) baseline" composition of SEP.

The situation that the SEP heavy element composition is basically governed by FIP seems at first very strange, especially if interpreted in terms of a selection effect taking place when particles are being accelerated. It implies some selection between ions and neutrals in a gas that must be cool enough to contain neutral atoms, i.e., at $\sim 10^4$ K, while density considerations, supported by the measurement of charge states in SEP, indicate that SEP are accelerated in the corona, a medium at $\sim 10^6$ K!

To try to disentangle the problem, we first undertake in §§ II*a*, *b*, *c* a systematic comparative study of the composition of three media in the outer solar atmosphere: solar corona, solar wind (SW), and SEP (m.u. baseline). Substantiating earlier suggestions by Cook, Stone, and Vogt (1980), Mewaldt (1980), Veck and Parkinson (1981), and Webber (1982*a*), we conclude that the heavy element compositions of these three media are identical within errors, each of them showing the imprint of a bias according to FIP when compared to photospheric (or "local galactic" [LG]) composition (§§ II*e*, *f*).

Since SW and SEP are extracted from the solar corona, this finding leads us to interpret the SW and SEP baseline compositions, not in terms of selective acceleration processes, but in terms of a selective feeding of the solar corona itself from the underlying chromosphere, which does have the required temperature of $\sim 10^4$ K: thermal chromospheric heavy ions ought to rise into the corona more easily than neutral heavy atoms (§ III*a*). The structure of the abundance pattern versus FIP actually supports this view (§ III*b*). Physical processes possibly capable of producing such a selection between chromospheric heavy neutrals and ions are mentioned in § III*c*.

In a totally different context, a very similar correlation of heavy element abundances with FIP has been found a few years ago in the composition of galactic cosmic-ray sources (GCRS; ~ 1–100 GeV/n) (e.g., Cassé and Goret 1978; Mewaldt 1981) (§ II*d*). Again the heavy element compositions of GCRS and SEP (m.u. baseline) are found to be almost identical within errors, with the very significant exception of carbon, which is twice as abundant in GCRS, and possibly of oxygen (§§ II*e*, *f*).

This high degree of similarity between the heavy element composition biases in suprathermal *and especially thermal*

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[1] Throughout this paper, we shall consider essentially the heavy elements, not H and He. Of course, H and He are always dominant both in terms of number of nuclei and of energy content. But we shall see that they generally behave differently from heavier elements (§ II; note [8]), perhaps *because* they are dominant, and/or because they are much lighter, or because of the unique A/Z ratio of H. In any case, there are always many different possible interpretations of the behavior of H and He. On the contrary, differences in behavior of *trace* heavy elements between themselves yield much more specific clues as to their origin. Any attempt at interpretation of heavy element abundances can also be rather reliably checked, in view of the large number of elements that have to fit into the assumed pattern.

media of the outer solar atmosphere and in the GCRS may be extremely significant and fruitful. It may permit a link to be forged between two fields which were heretoforth disconnected.

In this light, we investigate in § IV the possible origins of the material constituting the GCRs. In § IV*a* we show that, *by itself*, the GCRS composition strongly suggests that the origin of most of the GCR material is ordinary unevolved star surface material. This conclusion is, of course, strongly supported by the similarity with solar coronal and SEP compositions (§ IV*b*). This similarity further suggests that the origin of the GCRS heavy element composition might ultimately be the selective transport of thermal matter from stellar chromospheres into stellar coronae. Other arguments strongly suggest that GCR particles were not directly accelerated out of stellar coronal material, but rather first "injected" by stellar flares as MeV stellar energetic particles before being boosted up to GCR energies by more powerful accelerators (§ IV*b*). Again, this interpretation is supported by the structure of the GCRS abundance pattern versus FIP (§ IV*c*).

In § IV*d* we investigate which stellar populations are possible injectors for the bulk of GCRs, both in terms of the existence of solar-like chromospheres and coronae and of stellar surface activity. We find that main-sequence (or possibly pre-main-sequence) later type stars of type F to M ought to be the dominant injectors. Finally, we show in § IV*e* that, contrary to the conclusion of recent studies by Eichler (1980) and Epstein (1980*a*), energy loss during traversal of matter at low energy by the "injected" particles should not significantly alter their composition.

Section V is devoted to showing that the presence, along with the ^{22}Ne excess, of a C excess in the GCRS (relative to SEP) is a signature that the ^{22}Ne excess originates in a small admixture of quiescent He-burning material to the dominant ordinary stellar surface material in the matter to be accelerated to GCR energies. The possible ^{25,26}Mg and O excesses could be understood in the same context.

In § VI we summarize our conclusions and suggest future lines of research to test their validity. Preliminary results of this study have been presented in Meyer (1981*a*, *b*).

II. ABUNDANCES IN THE SOLAR CORONA, SOLAR WIND, SOLAR ENERGETIC PARTICLES, AND GALACTIC COSMIC-RAY SOURCES

a) *Abundances in the Solar Corona*

i) *Description of the Available Observations*

A number of spectroscopic studies have been devoted to determining elemental abundances in the solar "corona." Hereafter the word "corona" will denote both the very thin "transition region" with its steep temperature gradient (from 3×10^4 to 10^6 K) and the widely extended "upper corona" with roughly constant temperature ($1-2\times10^6$ K). Ordinary quiet corona, coronal holes, and transient features such as cool prominences ($\sim$ 6000–12,000 K) and hot active regions ($2.5-13\times10^6$ K) have been investigated by the various authors.

Since H, being entirely ionized, has no lines in the corona, most abundance studies do not give any "absolute" abundances, relative to H. Only abundance ratios between heavies are obtained, which we have normalized to Si whenever possible (see Table 1, note a). There are only two exceptions, both of which are discussed below: the studies by Heasley and Milkey (1978) on He/H, and by Veck and Parkinson (1981) on Si, S, Ar, and Ca/H.

Since the corona is optically thin, coronal studies are free from the problem of radiation transfer. The oscillator strengths for the highly ionized atoms of the hot corona, although inaccessible to laboratory measurements, can be rather reliably calculated (central field dominant). But the uncertainties in the calculation of the ionization equilibrium, in conditions very far from LTE, seriously limit the accuracy of the abundances obtained.

In particular, the abundances deduced from observations of forbidden lines (between sublevels of the same multiplet) of highly excited atoms in the visible wavelengths (see, e.g., Pottasch 1964; Nikolsky, Gulyaev, and Nikolskaya 1971; De Bœr, Olthof, and Pottasch 1972; Magnant-Crifo 1974; Mason 1975) are often considered quite unreliable because (i) the upper sublevel is largely populated by cascade from higher levels, and these cascades cannot be accurately calculated owing to resonances and wavelength coincidences, and (ii) radiative excitation is important, while the radiation field is poorly known. The abundances obtained indeed scatter very much (Withbroe 1976). They will not be considered here.

The situation is more favorable for the resonance lines of highly ionized species, which have recently been observed in the extreme ultraviolet (EUV) and X-ray ranges. The excitation is direct and purely collisional, and the principal coronal parameter of importance is the electron density, which is reasonably well known. The abundances are not extremely sensitive to temperature. The main errors are those associated with the collisional excitation cross sections and the oscillator strengths (typically a factor of 2). In addition, the calibration of the observing instruments often limits the accuracy of the derived abundances.

The available EUV and X-ray data are presented in Table 1, which gives for each study the range of wavelengths and the coronal medium which is being investigated, as well as the number of attached electrons of the ions used for the abundance determination (for a few key elements). These data can be divided into three groups.

First, *the EUV observations of the transition region* (Dupree 1972; Malinovsky and Heroux 1973; data reanalysis by Jordan 1976, 1977; Mariska 1978, 1980; Meyer and Nussbaumer 1979). These observations give access to the intermediate levels of ionization prevailing in the comparatively cool transition region (largely Li-like ions), whose atomic parameters can be reasonably well calculated. The main difficulty in these studies lies in that a region with extremely steep temperature gradient is being investigated. However, several degrees of ionization of various elements are often observed simultaneously, which permits self-consistent reconstitutions of the temperature profile allowing reasonable abundance determinations.

Second, we have two off-limb *EUV-observations of the upper corona or active regions* (Flower and Nussbaumer 1975; Withbroe 1975). Abundances are derived from observed Li-like ions, which are *not* dominant in the hot media under consideration.

TABLE 1

CORONAL ABUNDANCES

Authors	Heasley and Milkey 1978[a,b]	Dupree 1972[c]	Malinovsky and Heroux 1973[c]	Jordan 1976, 1977[c]	Mariska 1980[d]	Mariska 1978	Meyer and Nussbaumer 1979[a,e]	Flower and Nussbaumer 1975[a]	Withbroe 1975
Wavelengths, experiment, and remarks	visible ground based	EUV *OSO 4*	EUV rocket	EUV reanalysis of Dupree and Malinovsky and Heroux	EUV *Skylab* many media investigated	EUV *Skylab*	EUV *OSO 6* study of diffusion	EUV *OSO 6* off-limb observations of nondominant ions	EUV *OSO 6* off-limb observations of nondominant ions
Observed medium	prominences	transition region	transition region	transition region	● quiet transition region ● coronal hole ● prominence ● active region (cool)	transition region (coronal hole)	transition region	upper corona	cool active region
Ion states used (number of attached electrons) O	...	3–6	4,5	3–6	(4,5),6	3	3,5	3	3
Ne	...	3–8	3–5	3–8	...	3	...	3	3
Mg	...	3–5	3–6	3–6	...	3	3	3	3
Si	...	3,11–13	5–9	3,5–13	11	3	...	...	3
Fe	...	11	9,12–19	9,11–19	...	...	...	...	11
H	$\equiv 2.55\times10^6$ [a]	...	...	...	...	...	...	...	...
He	$[2.55\times10^5]$	...	...	...	...	...	...	...	...
C	...	[1000.][k]	...	[615.][k]	...	...	...	...	...
N	...	[430.][k]	...	[145.][k]	[170.][l]	...	...	...	140.
O	...	[1700.][k]	[980.][k]	[1540.][k]	605.	660.	475. 1200. } [e]	[380. (2.)][m]	[660.][m]
Ne	...	79.	[250.][k]	200.	...	84.	...	50. (1.75)	51.
Na	...	[5.4]	...	...	...	...	...	...	5.8
Mg	...	85.	[145.][k]	125.	...	95.	≡ 95.[a]	≡ 95.[a]	...
Al	...	[10.]	...	...	...	7.0	...	...	5.6
Si[a]	...	≡ 100.	≡ 100.	≡ 100.	≡ 100.	≡ 100.	...	...	≡ 100.
S	...	58.	14.	33. (1.50)	...	...	...	...	...
Ar	...	...	...	...	...	...	...	...	...
Ca	...	...	...	...	...	...	...	...	...
Fe	...	[56.]	55.	100.	...	...	...	...	...
Ni	...	...	2.7	4.0	...	...	...	...	...

TABLE 1—*Continued*

Authors	McKenzie *et al.* 1978[a,f]	Acton, Catura, and Joki 1975[a,f,g]	Walker, Rugge, and Weiss 1974*a*, *b*, *c*[h]	Rugge and Walker 1976[a,f,h]	Parkinson 1977[f,h]	Parkinson 1977[f,i]	Veck and Parkinson 1981[j]	Adopted "Coronal"
Wavelengths, Experiment, and Remarks	X rocket	X rocket	X *OVI-10* and *17* model-dependent analysis	X reanalysis of Walker, Rugge, and Weiss	X reanalysis of Walker, Rugge, and Weiss	X rocket good calibration	X *OSO 8* good calibration study of H	…
Observed Medium	quiet upper corona	quiet upper corona warm active regions	warm active regions	warm active regions	warm active regions	warm active regions	hot active regions	…
Ion states used (number of attached electrons) O	2	1	1,2	…	1	1	…	…
Ne	…	2	1,2	1	1,2	1,2	…	…
Mg	…	…	1,2	2	1,2	1,2	…	…
Si	…	…	1,2	…	2	2	1,2	…
Fe	…	…	10	…	10	10	…	…
H	…	…	…	…	…	…	2.55×10^6 (1.4)	2.55×10^6 (1.4)
He	…	…	…	…	…	…	…	0.25×10^6 (3.0)
C	…	…	…	…	…	…	…	600. (3.0)
N	87.	…	260.	…	…	…	…	100. (1.7)
O	≡ 630.[a]	≡ 630.[a]	2000.	…	1100.	625. (1.70)	…	630. (1.6)
Ne	…	108. (1.50)	155.	135. (1.30)	120.	95. (1.50)	…	90. (1.6)
Na	…	…	4.9	…	…	7.9 (1.60)	…	7. (1.7)
Mg	…	…	86.	≡ 95.[a]	86.	98. (1.35)	…	95. (1.3)
Al	…	…	7.1	…	…	…	…	7. (1.7)
Si[a]	…	…	≡ 100.	…	≡ 100.	≡ 100. (1.35)	≡ 100. (1.65)	≡ 100. (1.3)
S	…	…	26.	…	…	…	19.2(1.45)	22. (1.7)
Ar	…	…	[17.][n]	…	…	…	5.4(1.75)	5.4 (1.8)
Ca	…	…	…	…	…	…	7.5(1.55)	7.5 (1.5)
Fe	…	…	75.	…	107.	101. (1.40)	…	100. (1.5)
Ni	…	…	…	…	…	5.8 (1.70)	…	5.5 (1.7)

NOTES TO TABLE 1

Error factors ("within a factor of ...") are in parentheses. When not given, the error is typically a factor of ~ 2. Highly questionable values are in brackets.

[a] Whenever possible, abundances are normalized to Si ≡ 100. When Si is not observed, a secondary standard is used, to which we assess the "adopted coronal" abundance value (last column) derived from other measurements relative to Si.

[b] Heasley and Milkey's 1978 analysis on He/H in a prominence is based on observations by Landman and Illing 1976, 1977. It has been later criticized by Landman and Mongillo 1979. The quoted error (±25%) corresponds only to that on the He D_3 line measurement, while major systematic errors may affect the derived He abundance. There are still two major observational difficulties: the conversion of line-emission measures to absolute intensities, and the low spatial resolution of the available data. In the modeling of the prominence, a major problem is posed by our poor knowledge of the radiation field which illuminates the plasma and may control the ionization equilibrium (Heasley and Milkey 1978). Further, the observed $\mathrm{H}\alpha/\mathrm{H}\beta$ ratio differs from that of Heasley and Milkey's 1978 modeling, and the observed Doppler widths in the sheath of the prominence make the assumption of a common H and He emission region quite questionable (Landman and Mongillo 1979). We conclude that this He abundance determination is very questionable. We shall assign it an error factor of ~ 3.

[c] Jordan 1976, 1977 has reanalyzed the data of Dupree 1972, Malinovsky and Heroux 1973, and Burton *et al.* 1971, with her own set of atomic data and a refined calculation of the contribution of the various temperature ranges to line formation.

[d] Mariska's 1980 study consists in 11 abundance measurements performed in distinct directions toward the quiet transition region, a coronal hole, an active region, and a prominence (i.e., toward regions with widely different electrons densities, emission measures, turbulent mass motions, and heights above the limb). The abundances found are remarkably homogeneous (standard deviation of the spread on O/Si: 0.2 dex = a factor of 1.6), and no systematic differences are found between measured abundances in the various media investigated. This homogeneity both gives us confidence that the model used in deriving the abundances is adequate and that diffusion effects are not very important. Note also that Mariska does not measure the C abundance: the C III line intensity serves in determining the density, and the C IV lines lie in a temperature range where the temperature profile is too poorly known to be of any use.

[e] Meyer and Nussbaumer 1979 study the possible effect of diffusion on the derived abundances in the transition region (see § II*a* [ii]). If diffusion is unimportant, their data imply O = 475, while, with a fully developed diffusion, they would imply O = 1200.

[f] Analysis of line intensity ratios between couples of H-, He-, or Ne-like ions of different elements, which are dominant in the *same* (*wide*) range of temperatures. The derived elemental abundance ratios should therefore be quite insensitive of the temperature structure of the medium.

[g] See also Parkinson 1977.

[h] Walker, Rugge, and Weiss's 1974*a*, *b*, *c* original analysis is quite model dependent. Their data have been reanalyzed in a less model-dependent way by Rugge and Walker 1976 and Parkinson 1977 (see note f).

[i] The abundances of Parkinson 1977 are based on the data of Parkinson 1975. The instrument used is better calibrated than that of Walker *et al.* 1974*a*, *b*, *c*. It is also more collimated to see *only* the active region, and thus avoid line blendings from the general coronal background. The error estimate is ours. It includes the uncertainty related to the relevant range of temperatures and a 25% uncertainty on the oscillator strengths.

[j] Veck and Parkinson's 1981 study is the first one to derive *absolute abundances relative to* H. They are based on observed line to continuum ratios, thanks to the graphite crystal spectrometer on board *OSO 8*, which is the first one to observe reliably both X-ray lines and continuum simultaneously. In addition, only H- and He-like ions are used. Note the strikingly "normal" Si/H ratio (in the local galactic standard, $\mathrm{H} = 2.71 \times 10^6$ for Si ≡ 100).

[k] Dupree's 1972 data on oxygen yield an inaccurate abundance, since the oxygen "lines lie in a region where the shape of the emission measure distribution is changing rapidly with temperature" (Jordan 1976). Carbon and nitrogen are actually not easier to put to scale (Dupree's Fig. 3). In Malinovsky and Heroux's 1973 analysis, oxygen also cannot be properly put to scale with other elements, since the two available oxygen ionization stages sample the emission measure curve in a temperature range where no other ions are observed (their Fig. 2). Note also that significant fractions of the emission of the Li-like ions O^{+5}, Ne^{+7}, Mg^{+9} may originate from the higher corona, resulting in a possible overestimate of the abundances of these elements (Flower and Nussbaumer 1975).

[l] Mariska's 1980 N abundance derived from the N IV and N V lines is twice as high as that derived from the N III line, for which the atomic physics is, however, quite uncertain. We adopt tentatively the abundance derived from N IV, N V, which is, however, derived from a medium in which the electron density has not been determined and is somewhat dependent on the more or less well-known temperature structure of the medium.

[m] Flower and Nussbaumer's 1975 and Withbroe's 1975 values for O are derived from observations of O^{+5}, which is formed mainly by dielectronic recombination of the much more abundant O^{+6}. The resulting O abundances are highly sensitive to the dielectric recombination and collisional ionization rates (Flower 1977).

[n] Walker, Rugge, and Weiss's 1974*a*, *b*, *c* determination of the Ar abundance is based on one resonance line of Ar^{+16}. The line is weak above background, and the quoted error on the equivalent width (30%) is probably optimistic. Further, the temperature distribution of the coronal emission measure is poorly determined at the high temperatures where Ar^{+16} is dominant ($> 5 \times 10^7$ K). If the amount of matter at $T \approx 10^7$ K is underestimated, the derived Ar abundance may be too high, possibly by a factor as high as ~ 4 (Flower 1977).

Third, we have the *X-ray observations of the upper corona and mostly of active regions* (McKenzie *et al.* 1978; Acton, Catura, and Joki 1975; Walker, Rugge, and Weiss 1974*a*, *b*, *c*; Rugge and Walker 1976; Parkinson 1977; Veck and Parkinson 1981). They have access to H- and He-like ions (Ne-like for Fe and Ni). There are two nice points about these studies: first, the atomic parameters can be particularly well calculated for the simple H- and He-like structures, and, second, these ions are dominant over quite wide ranges of temperatures. Actually all these studies (except the original analysis of Walker, Rugge, and Weiss 1974*a*, *b*, *c*, and Veck and Parkinson 1981) consist of analysis of line intensity ratios between couples of ions of different elements, which are dominant in about the same (wide) range of temperatures. The derived abundances should be quite insensitive to the temperature structure of the medium under investigation (see, in particular, Parkinson 1977). Note also that the calibration of Parkinson's (1977) detector is more precise than that of Walker, Rugge, and Weiss (1974*a*, *b*, *c*) (see Parkinson 1975).

The last of these studies, by Veck and Parkinson (1981), deserves special attention. Veck and Parkinson's instrument is the first one to observe reliably both X-ray lines and continuum simultaneously in very hot active regions ($T \approx 7$–13×10^6 K). At these high temperatures the continuum is dominated by free-free and free-bound processes of hydrogen, allowing *for the first time* absolute abundance measurements of heavies (lines) with respect to H (continuum). Thus, H can be placed on our scale $\mathrm{Si} \equiv 100$ (Table 1), the Si/H ratio being found essentially equal to photospheric.

Finally, a word concerning the He/H ratio. There is only one modern estimate, by Heasley and Milkey (1978), based on optical observations in prominences (6000–12,000 K). This determination is discussed in some detail in note b of Table 1. The estimated ratio $\mathrm{He/H} = 0.10$ should still be considered to be very uncertain.

ii) *Adopted Coronal Abundances, and Discussion Thereof*

The last column of Table 1 gives our adopted "coronal abundances," with our estimated error factor. For the reasons given above, more weight has been given in this assessment to the X-ray studies of H-, He-, and Ne-like ions (especially those of Parkinson 1977 and Veck and Parkinson 1981, who used well-calibrated instruments). In Tables 2 and 3, these "coronal abundances" are compared with the standard "local galactic" ones (LG), which are believed to be our best estimate of the composition of the solar photosphere (see Paper I and references therein).

To better illustrate the situation, we have plotted in Figure 1 a few key abundance ratios as measured (often quite directly) by the various authors, together with our adopted "coronal" ratios and with the LG ratios. The most instructive ratio is O/Mg. Its LG value is highly reliable (O and Mg are very well measured in the solar photosphere; see Lambert 1978; Lambert and Luck 1978; Holweger 1979; and Mg is very well known in meteorites, too). In the corona, the measurements are numerous, and they converge well, but around a value ~ 3 times below LG. It must be stressed at this point that, while systematic errors related to atomic physics and ionization equilibrium calculation may affect each of the individual determinations, the wide variety of physical conditions (electron densities, temperatures, temperature gradients, *observed degrees of ionization*) involved in the various abundance analyses would make it highly unlikely that all systematic errors (if any) go in the same direction. Particularly impressive is, for example, the agreement, within a factor of ~ 1.5, between the 11 O/Mg ratios derived from Mariska's (1980) observations of O^{+2} and Si^{+3} around 70,000 K in media as different as the quiet transition region, coronal holes, prominences, and active regions, as well as the agreement between all these ratios and that found, for example, by Parkinson (1977) from observations of H- and He-like O^{+7} and Mg^{+10} around 2–5×10^6 K in hot active regions (Fig. 1). So the difference between the LG and coronal O/Mg ratios, repeatedly found in all analysis, cannot be due to a common systematic error. It also tells us that the composition of the corona is quite homogeneous, from the lower part of the transition region (at $T = 70{,}000$ K, Mariska 1980) to the upper corona, and for quiet as well as perturbed coronae (coronal holes, prominences, active regions).

Another point to be considered is the so-called "diffusion," i.e., differential motions of the various ions under the influence of gravity, thermal diffusion in the steep temperature gradient of the transition region, and thermal motions (Chapman 1958; Delache 1967; Nakada 1969; Tworkowski 1975; Shine, Gerola, and Linsky 1975; Meyer and Nussbaumer 1979; Roussel-Dupré 1980, 1981, 1982; Geiss 1982). Diffusion may be important or not, depending on whether it is erased by turbulent motions or not. As far as abundances are concerned, diffusion, if important, modifies the distribution in space of each ionic species, which has in practice two consequences: (i) it may cause real variations in space of the *total elemental* abundances, and (ii) it may affect the models to be used for *deriving* the *elemental* abundances from the observed *ionic* abundances. An interesting assessment of this second effect has been performed by Meyer and Nussbaumer (1979): they have shown that taking into account a fully developed diffusion would modify the derived O/Mg ratio in the transition region from $\sim$ LG/4 to LG/2 (Fig. 1). But, of course, diffusion effects will be highly dependent upon the local physical conditions; hence, the homogeneity of the O/Mg ratios obtained in very different coronal media from the lower transition region ($T = 70{,}000$ K) upward strongly suggest that in these regions diffusion effects are unimportant and do not invalidate the derived elemental abundances.

Returning to Figure 1, the various determinations of Ne/Mg in the corona strongly suggest a value lower than LG,[2] exactly like that for O/Mg. Actually the two effects cancel out remarkably well in the O/Ne ratio, which shows no evidence for any deviation from LG. The more limited data on Mg/Si and Fe/Si do not suggest any anomaly, but S/Si tends to be low, especially according to the recent study of Veck and Parkinson (1981).

These features of Figure 1 (low O/Mg, Ne/Mg, S/Si; normal O/Ne, Mg/Si, Fe/Si) are suggestive of a selection effect according to FIP, as was also remarked by Veck and

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[2] Concerning the determination of the local galactic Ne/Mg ratio see Paper I and references therein.

TABLE 2

ABUNDANCES IN VARIOUS MEDIA

Element	Local Galactic (LG)		Solar Corona		Solar Wind (SW)		SEP (m.u. baseline)		GCRS	
H	2.71×10^6	(1.10)	2.55×10^6	(1.40)	$1.43\ \times10^6$	(1.30)	...		$0.077\ \times10^6$	(1.12)[a]
He	0.26×10^6	(1.25)	0.25×10^6	(3.00)	0.056×10^6	(1.30)	[0.038×10^6	(1.27)][b]	0.0118×10^6	(1.07)
C	1260.	(1.26)	600.	(3.00)	...	...	290.	(1.30)	420.	(1.08)
N	225.	(1.41)	100.	(1.70)	...	...	81.	(1.33)	34.	(1.34)
O	2250.	(1.25)	630.	(1.60)	650.	(1.50)	650.	(1.13)	505.	(1.04)
F	0.093	(1.60)	...	...	...	...	...	...	< 2.5	
Ne	325.	(1.50)	90.	(1.60)	100.	(1.40)	84.	(1.32)	62.	(1.14)[c]
Na	5.5	(1.18)	7.	(1.70)	...	...	8.5	(1.47)	4.6	(1.90)
Mg.......	105.	(1.03)	95.	(1.30)	...	...	123.	(1.28)	105.	(1.06)[c]
Al	8.4	(1.05)	7.	(1.70)	...	...	8.9	(1.55)	10.2	(1.45)
Si	≡100.	(1.03)	≡100.	(1.30)	≡100.	(3.00)	≡100.	(1.37)	≡100.	(1.06)[c]
P	0.94	(1.24)	...	...	...	...	...	...	< 2.5	
S	43.	(1.35)	22.	(1.70)	...	...	20.	(1.80)	14.1	(1.20)
Cl........	0.47	(1.60)	...	...	...	...	...	...	<1.6	
Ar	10.7	(1.50)	5.4	(1.80)	2.6	(1.50)	3.8	(1.70)	3.2	(1.30)
K	0.34	(1.41)	...	...	...	...	...	...	<1.9	
Ca	6.2	(1.14)	7.5	(1.60)	...	...	7.6	(1.55)	6.8	(1.34)
Sc........	0.0035	(1.15)	...	...	...	...	...	...	< 0.8	
Ti........	0.27	(1.16)	...	...	...	...	...	...	< 2.4	
V	0.026	(1.21)	...	...	...	...	...	...	<1.1	
Cr	1.29	(1.10)	...	...	...	...	2.25	(1.90)	< 2.9	
Mn.......	0.77	(1.24)	...	...	...	...	...	...	< 3.7	
Fe	88.	(1.07)	100.	(1.50)	57.	(2.00)	99.	(1.47)	91.	(1.06)
Co	0.21	(1.15)	...	...	...	...	...	...	0.28	(1.55)
Ni	4.8	(1.13)	5.5	(1.70)	...	...	4.5	(1.75)	4.7	(1.17)
Cu	0.052	(1.60)	...	...	...	...	...	...	0.060	(1.20)
Zn	0.098	(1.22)	...	...	...	...	...	...	0.058	(1.20)

NOTES.—Error factors ("within a factor of...") are in parentheses. Entries are discussed in §§ II*a*, *b*, *c*, *d*, and normalized to Si.

[a] Based on the H/He ratio at a given rigidity.

[b] Not really significant, since the m.u. baseline SEP abundance of He cannot be property defined (Paper I).

[c] If a hypothetical specific component enriched in ^{22}Ne, ^{25,26}Mg, and ^{29,30}Si is being subtracted (§ V*a*), the figures for "normal" Ne, Mg, and Si decrease down to 47, 93, and 95, respectively.

Parkinson (1981) on the basis of their data alone. To check this idea, we plot in Figure 2*a* the adopted coronal/LG ratios (Table 3) for all observed elements versus FIP. Relative to Si, there is no indication of any anomaly for all metals, i.e., elements with FIP < 9 eV (hereafter denoted "low-FIP" elements). For elements heavier than He with FIP > 9 eV ("high-FIP" elements), there is a clear underabundance for O, N, and Ne, and a probable one for S and Ar.[3] Carbon shows the same trend, but is very poorly measured in the corona. So, FIP seems to order the data: the observations in the corona are consistent with an underabundance by a factor of ~ 3 of all elements (heavier than He) with 10 eV < FIP < 22 eV with respect to those with FIP < 9 eV. Particularly striking is the apparent constancy of the depletion factor between O (13.6 eV) and Ne (21.6 eV).

Hydrogen does not fit within this pattern, which seems to describe the relative abundances of heavy elements: although it is a "high-FIP" element, its abundance seems normal with respect to the "low-FIP" metals, rather than to the "high-FIP" heavies. Note that the H abundance with respect to heavies has been determined by a single experiment (Veck and Parkinson 1981). Although this determination seems dependable, it should certainly be repeated. As for helium, it might behave like H, but its abundance determination is too poor for any conclusion to be drawn.

b) *Abundances in the Solar Wind* (*SW*)

Most solar wind (SW) elemental abundance determinations have been recently reviewed by Geiss (1982). Two techniques have been used: (i) electro-static analyzers, which yield He, O, Si, and Fe abundances relative to H (Bame *et al.* 1975, 1977, 1979; Grünwaldt 1976; Neugebauer 1981); and (ii) the foil collection technique which yields the noble gas ratios He/Ne/Ar (Geiss *et al.* 1970, 1972; Cerutti 1974). The two sets of data can be merged via He. In addition, the new plasma composition experiment on board *ISEE 3* has recently yielded a much improved O/Ne ratio (Kunz *et al.* 1983).

The abundances of Fe and especially of Si, which are quite variable, are rather poorly determined since the interpretation of the electrostatic analyzer data depends quite critically upon the ionization model for the SW and upon the abundances of neighboring elements (Bame *et al.* 1975). The noble gas ratios are much better known.

The He/H ratio in the SW (on the average 4±1%) is distinctly low as compared to the probable photospheric ratio

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[3] A recent interpretation by Antonucci *et al.* (1984) of solar flare X-ray spectra obtained by the *Solar Maximum Mission* also suggests an Ar/Ca ratio ~ 2.5 times lower than LG.

TABLE 3

ABUNDANCE RATIOS

Element	Corona/LG		SW/LG		SEP m.u.b./LG		GCRS/LG		GCRS/SEP m.u.b.	
H	0.94	(1.40)[a]	0.53	(1.30)	...	...	0.028	(1.15)[b]	...	...
He	0.96	(3.10)[a]	0.21	(1.40)	[0.14	(1.40)][c]	0.045	(1.25)	[0.31	(1.30)][c]
C	0.48	(3.10)	...	...	0.23	(1.40)	0.33	(1.30)	1.45	(1.30)
N	0.44	(1.90)	...	...	0.36	(1.55)	0.15	(1.57)	0.42	(1.50)
O	0.28	(1.70)	0.29	(1.60)	0.29	(1.30)	0.22	(1.25)	0.78	(1.15)
Ne	0.28	(1.85)	0.31	(1.70)	0.26	(1.65)	0.19	(1.55)[d]	0.74	(1.35)[d]
Na	1.27	(1.75)	...	...	1.54	(1.50)	0.84	(1.95)	0.54	(2.15)
Mg	0.90	(1.30)	...	...	1.17	(1.30)	1.00	(1.07)[d]	0.85	(1.30)[d]
Al	0.83	(1.70)	...	...	1.06	(1.55)	1.21	(1.45)	1.15	(1.80)
Si	≡1.00	(1.30)	≡1.00	(3.00)	≡1.00	(1.35)	≡1.00	(1.07)[d]	≡1.00	(1.40)[d]
S	0.51	(1.85)	...	...	0.46	(1.95)	0.33	(1.40)	0.71	(1.85)
Ar	0.50	(2.05)	0.24	(1.80)	0.35	(1.95)	0.30	(1.60)	0.84	(1.80)
Ca	1.21	(1.65)	...	...	1.23	(1.55)	1.10	(1.40)	0.89	(1.70)
Cr	...	...	...	...	1.73	(1.90)	....	...	...	...
Fe	1.14	(1.50)	0.65	(2.00)	1.13	(1.50)	1.03	(1.10)	0.92	(1.50)
Co	...	...	...	...	...	...	1.33	(1.60)	...	...
Ni	1.15	(1.70)	...	...	0.94	(1.80)	0.98	(1.20)	1.04	(1.80)
Cu	...	...	...	...	...	...	1.15	(1.65)	...	...
Zn	...	...	...	...	...	...	0.59	(1.30)	...	...

NOTES.—Error factors ("within a factor of ..."), which are the quadratic sum of the errors on the numerator and the denominator, are in parentheses. Entries are derived from Table 2, and normalized to Si. They are discussed in § II and depicted in Figs. 2, 3*a*, and 4 (although with a different normalization more adequate to visualize the phenomena, and with the errors on numerator and denominator presented separately in Fig. 2).

[a] Derived from a single measurement (§ II*a*).

[b] Based on the GCRS H/He ratio at a given rigidity (§ II*d*).

[c] Not really significant, since the m.u. baseline SEP abundance of He cannot be properly defined (Paper I).

[d] If a hypothetical specific component enriched in ^{22}Ne, ^{25,26}Mg, and ^{29,30}Si is being subtracted from the GCRS values (§ V*a*), the figures for "normal" Ne, Mg, and Si decrease down to:

	GCRS/LG	GCRS/SEP
Ne ...	0.145	0.56
Mg ...	0.89	0.76
Si	0.95	0.95

(taken equal to the LG value, ~10±2%). But He-enriched SW (up to ~40%) is often observed associated with solar flares (Bame *et al.* 1979). As a result, the long-term average ratio varies systematically from ~3% near solar minimum to ~5% around solar maximum (Ogilvie and Hirshberg 1974; Feldman *et al.* 1978; Neugebauer 1981). In contrast, remarkably constant ratios He/H = 4.8±0.5% are observed in fast SW streamers associated with coronal holes (Bame *et al.* 1977).

The time averaged SW abundances, based on Geiss (1982) and Kunz *et al.* (1983), are presented in Table 2, and the resulting overabundances with respect to LG (Table 3) are plotted versus FIP in Figure 2*b*. While the abundances of the low-FIP elements Si and Fe, which serve for the normalization, are quite poorly determined, the data as they stand still suggest the same underabundance of high-FIP relative to low-FIP heavy elements as observed in the corona. But, again, it is the low-FIP elements that seem to have normal abundances relative to H.

c) *Abundances in Solar Energetic Particles* (*SEP*)

It has been shown in Paper I that *all* the highly variable SEP compositions observed aboard spacecraft in non ^{3}He-rich events seem to result, at least to first order, from variable but always monotonic mass (or Z)-dependent biases, acting upon an ever-present basic composition pattern whose composition differs from that of the photosphere (LG) by a simple bias according to FIP. It is this basic pattern, the "mass-unbiased (m.u.) baseline" SEP composition, that has been entered in Tables 2 and 3 and has been plotted in Figure 2*c*.

This ordering works for all elements between C and Ni, but not for He whose m.u. baseline abundance cannot be properly defined since, like H, it does not behave like heavier elements in SEP (Paper I). On Figure 2*c*, He is therefore plotted for completeness only.

The "average SEP composition," obtained by Cook *et al.* (1979) and Cook, Stone, and Vogt (1980) based on four flare observations, is very similar to the m.u. baseline composition.

As judged from the behavior of six key elements, the same composition pattern is found in the fairly constant composition of very intense events (Mason *et al.* 1980; Zwickl *et al.* 1978). The same basic pattern seems present in quiet-time energetic particles (presumably of solar origin; Klecker *et al.* 1977; Webber and Cummings 1983). The composition of corotating energetic particle streams (presumably accelerated out of the SW), while possibly suggesting a similar trend, shows some distinctly different features (Gloeckler *et al.* 1979; Gloeckler 1979; McDonald 1981) (see Fig. 7 of Paper I).

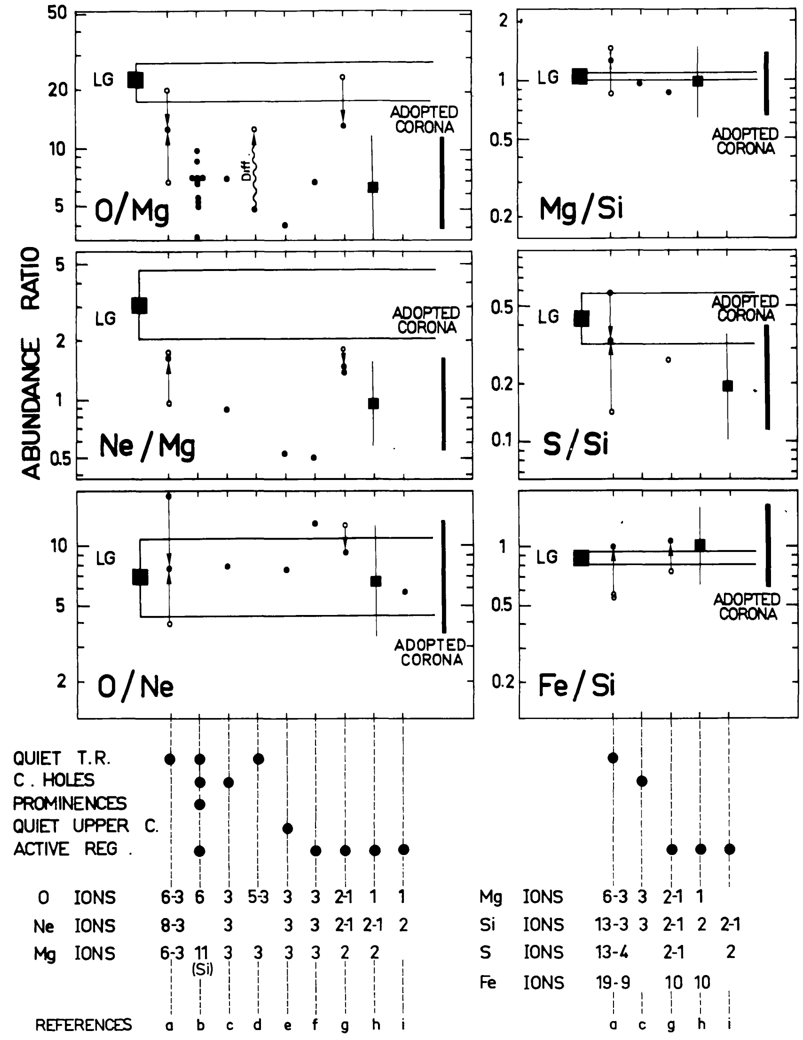

FIG. 1.—A few key abundance ratios observed by various authors in the solar corona, compared to their local galactic value (LG) (see Table 1). For each particular study are given, *along one and the same vertical line*, from bottom to top: its reference, the number of attached electrons in the ions used for the abundance determination, the investigated coronal medium, and the various observed abundance ratios. We also give the "adopted" coronal abundance ratios (Table 1). Errors (typically factors of ~ 2–3) are not indicated, except for Parkinson's (1977) and Veck and Parkinson's (1981) studies, in which they are more precisely known. Open circles with arrows toward a filled circle indicate improved reanalysis of the same data by different authors (Table 1). The study of O/Mg by Meyer and Nussbaumer (1975) investigates the effect of a possible fully developed diffusion on the O/Mg ratio to be derived from the observations (see § II*a*[ii]). Mariska's (1980) numerous O/Mg ratios are derived from their measured O/Si values assuming Mg/Si = 0.95 (adopted coronal value; Table 1).

References: *a*, Dupree (1972), Malinovsky and Heroux (1973), Jordan (1976, 1977); *b*, Mariska (1980); *c*, Mariska (1978); *d*, Meyer and Nussbaumer (1979); *e*, Flower and Nussbaumer (1975); *f*, Withbroe (1975); *g*, Walker, Rugge, and Weiss (1974*a*, *b*, *c*), Rugge and Walker (1976), Parkinson 1977; *h*, Parkinson (1977); *i*, Acton, Catura, and Joki (1975); *j*, Veck and Parkinson (1981).

d) *Abundances in Galactic Cosmic-Ray Sources* (*GCRS*)

The GCRS elemental abundances up to Zn are given in Table 2, and the corresponding overabundances with respect to LG (Table 3) are plotted versus FIP in Figure 2*d*. This figure shows the well-known trend of GCRS overabundances to correlate with FIP (e.g., Cassé and Goret 1978). For heavy elements, we used the source values derived from the high energy elemental data of the isotope spectrometer on board the *HEAO 3* spacecraft (Goret *et al.* 1981; Koch-Miramond 1981; updated by Koch-Miramond *et al.* 1983 for Ar). These heavy element source abundances are in general agreement with those derived from earlier balloon data or low energy satellite data (e.g., Webber 1982*a*; Dwyer *et al.* 1981) except for one element, nitrogen. Helium is taken from Webber (1982*a*), and H is derived from the H/He ratio at a given rigidity (Webber and Lezniak 1974; Webber 1981*a*).

With respect to nitrogen, we have a contradiction between lower values of the GCRS N/O ratio ~ (4 ± 1)% derived from the low energy observations (Preszler *et al.* 1975; Wiedenbeck *et al.* 1979; Guzik 1981; Mewaldt *et al.* 1981*a*, *b*; Webber 1981*b*, 1982*b*, 1983*b*), and values ~ (7 ± 2)% derived from the high energy observations, both elemental and isotopic (Lezniak and Webber 1978; Dwyer 1978; Webber 1982*a*,

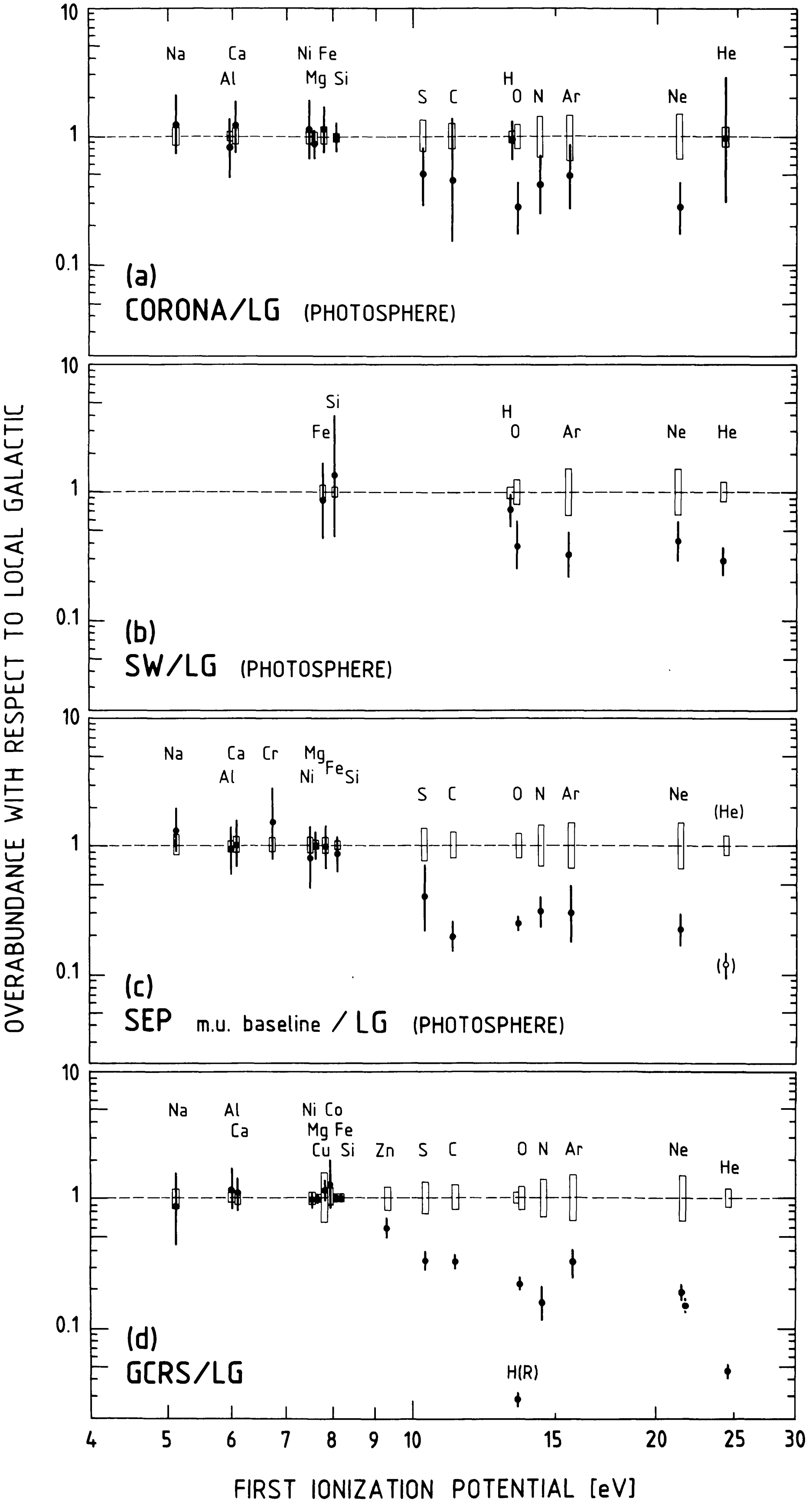

FIG. 2.—Overabundances of elements in (*a*) solar corona, (*b*) solar wind (SW), (*c*) solar energetic particles (SEP), and (*d*) galactic cosmic-ray sources (GCRS) with respect to local galactic (LG) composition vs. first ionization potential (FIP) (Tables 2 and 3; §§ II*a*, *b*, *c*, *d*). Boxes represent the uncertainty on the LG composition, which is also considered as our best estimate of the composition of the solar photosphere (Paper I). Each plot is normalized to the weighted average of the overabundances of the elements with FIP < 9 eV (low-FIP elements, Na–Si). In the SEP plot, the mass-unbiased baseline composition derived in Paper I is given. The point for He is not really significant since the m.u. baseline SEP abundance of He cannot be properly defined (Paper I). In the GCRS plot, hydrogen is derived from the H/He ratio observed at a given rigidity. We have indicated as a dashed bar the overabundance of "normal" Ne if a specific ^{22}Ne-rich component is being subtracted (§ V). The effect of similar subtractions of a neutron-rich component on Mg and Si (§ V) would be smaller. For the sake of clarity, it has not been plotted (but see Fig. 4*b*).

1983*a*, *b*; Koch-Miramond *et al.* 1983; Byrnak *et al.* 1983*a*; Soutoul *et al.* 1983; Goret *et al.* 1981, 1983). Following the discussion in the Appendix, we shall tentatively adopt the high energy source value N/O = (7 ± 2)% in the present work. But it should be clear that the GCRS N/O ratio is an absolutely crucial clue to models of GCR origin. Should this ratio lie positively below ~ 6% (as would be the case if the low energy value turned out to be exact), then N would be definitely underabundant with respect to almost all other high-FIP elements, and the entire framework in which we shall interpret the GCRS composition would have to be deeply revised (§§ II*e*, IV).

For Ne, we have also indicated as a dashed bar in Figure 2*d* the overabundance of "normal" Ne if a specific ^{22}Ne-rich component is being subtracted (§ V). Similar subtraction of specific neutron-rich components of Mg and Si would have smaller effects. For the sake of clarity, their effect has been plotted only in Figure 4*b*.

We have not plotted in Figure 2*d* the GCRS overabundances of elements beyond Zn since, inspite of dramatic recent improvements, the observational situation is still much less ripe for these high charges. The present data from three recent experiments aboard the *HEAO 3* and *Ariel 6* spacecrafts would by and large fit into the pattern of Figure 2*d* (Israel *et al.* 1983; Fixsen *et al.* 1983; Fowler *et al.* 1983; Byrnak *et al.* 1983b). However, these data yield surprisingly low Ge/Fe and Pb/Pt ratios, which suggest that volatility, rather than FIP, might be the parameter governing the GCRS composition, and that GCRs could be grain destruction products (Cesarsky and Bibring 1980; Epstein 1980*b*; Bibring and Cesarsky 1981) (see discussion in note [20]). But before such conclusions can be drawn, the cosmic-ray data have to be confirmed and the uncertainties of the abundances of reference used for the relevant *volatile* elements (predominantly determined from meteorites) precisely assessed.

e) *Comparison between Abundances in Solar Corona, SW, SEP, and GCRS*

Figure 2 shows that, for elements heavier than He, the compositions found everywhere in the solar corona, in the SW, in SEP (m.u. baseline)[4] and in GCRS all exhibit very similar patterns: a simple bias according to FIP with respect to LG (or photospheric) composition. While in the corona this pattern is but strongly suggested by the behavior of a few key elements, and while the observations of the SW are too poor to give more than a weak indication of the same behavior, in SEP the pattern seems quite well established.[5] The similarity between the three compositions in the solar environment, of course, gives us more confidence in their reality. In GCRS, the pattern is also very conspicuous.

To make comparisons more precise, we plot in Figure 3 the ratio of the SEP (m.u. baseline) abundances to those in the photosphere (LG), corona and SW. For all elements heavier than He (He is not understood in SEP, Paper I) the observations are consistent, within the large error bars, with identical coronal, SW, and SEP (m.u. baseline) compositions.

Similarly, Figure 4 shows the GCRS/LG and GCRS/SEP (m.u. baseline) abundance rations (Table 3). Here the data show more *conclusively* that, when scaled to the SEP (m.u. baseline) abundances, the clear-cut correlation of the GCRS abundances with FIP *to first order* disappears: the GCRS and SEP (m.u. baseline) compositions are to first order identical for elements heavier than He, with the notable exception of C which is about twice as abundant in GCRS as in SEP.

In a more tentative approach, one can try to interpret the data on the GCRS/SEP ratio to a higher level of precision. While the fit of the data in Figure 4*b* by a single horizontal line (*dashed*) for all heavy elements but C is by and large acceptable, it can only marginally account simultaneously for the data (i) on Mg, Si, Fe, and even O, and (ii) on N and "normal" Ne (i.e., after subtraction of the excess ^{22}Ne). Actually, the various high-FIP elements show some scatter in Figure 4*b*. Putting aside inaccurately determined S and Ar, their behavior can be interpreted, *either* in terms of overabundances of C and O in GCRS relative to a baseline defined by N and "normal" Ne, *or* in terms of an underabundance of N and "normal" Ne and an overabundance of C relative, for example, to O. We choose the former interpretation, for two reasons. *First*, the first-order similarity between the GCRS and SEP composition evidently suggests that the two compositions are to first order governed by similar phenomena. In this context, it is *much easier to explain an overabundance of specific elements* in GCRS, which can always be produced by admixture of a minor component highly enriched in these elements, *than an underabundance* that would require suppression of specific elements or abandoning the whole scheme and accepting that the similarity between the GCRS and SEP compositions (Figs. 2*c*,2*d*) be fortuitous. *Second*, we have already a clear-cut overabundance of C, and an associated overabundance of O is easily conceivable (§ V).

We therefore *tentatively* propose to interpret more precisely the data on the GCRS/SEP (m.u. baseline) ratio in terms of the dotted line in Figure 4*b*. This interpretation implies that the underabundance of high-FIP elements relative to low-FIP elements be larger by a factor of ~ 1.5 in GCRS than in SEP (underabundance factor in SEP ≈ 4, in GCRS ≈ 6). It further implies that, in addition to C, which is now overabundant by a factor of ~ 3, O is also in excess in GCRS relative to SEP, by a smaller factor of ~ 1.5. These overabundances of C and possibly O in GCRS will be interpreted in § V in connection with the Ne and Mg neutron-rich isotope excesses.

Note that this entire interpretation of the data depends critically on our adopting the GCRS N/O ratio derived from the high energy observations (§ II*d*; Appendix). If this ratio lay below ~ 6%, as seemingly implied by the lower energy observations, N would be definitely underabundant in GCRS relative to Ar and Ne and all other elements (as compared to LG and to SEP). The *bulk* of the GCRS material then

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[4] The same seems true for the remarkably constant composition of very intense events and for quiet-time energetic particles, but not entirely for corotating energetic particle streams (§ II*c*; Fig. 7 of Paper I).

[5] Although extracting the m.u. baseline SEP composition out of the SEP observations has required a nontrivial procedure (Paper I). But the basic pattern is actually conspicuous even in the raw SEP data (Fig. 3 of Paper I).

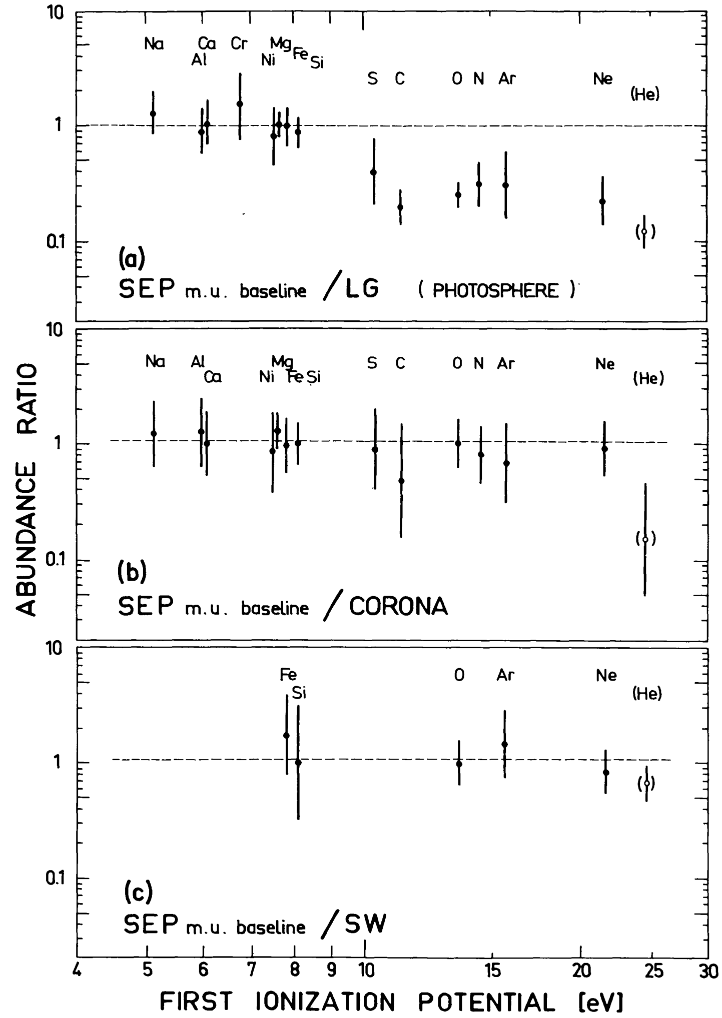

FIG. 3.—Ratios of SEP (m.u. baseline) abundances to (*a*) LG, (*b*) coronal, and (*c*) SW abundances vs. FIP, as derived from Figs. 2*a*–2*c* and Tables 2 and 3 (§ II*e*). See Fig. 2 legend. Errors are the quadratic sum of the errors on both terms. Plot (*a*) is normalized to the weighted average of the abundance ratios for the low-FIP elements (Na–Si). Plots (*b*) and (*c*) are normalized to Si, and the horizontal lines are only meant to guide the eye and show that the two sets of abundances are identical within errors. The points for He are not really significant since its m.u. baseline abundance cannot be properly defined (Paper I).

probably ought to originate in a medium specifically depleted in N.

f) The Structure of the Ubiquitous Abundance Pattern versus First Ionization Potential (FIP)

The structure of the supposedly common pattern of heavy element overabundances apparent in the four panels of Figure 2 deserves some attention (see also Figs. 3*a* and 4*a*, in which the LG errors have been combined with the SEP and GCRS errors). All elements with $5 < \mathrm{FIP} \lesssim 8.5$ eV (hereafter low-FIP elements) have between themselves abundance ratios consistent with normal LG. High-FIP elements with $10 \lesssim \mathrm{FIP} \lesssim 22$ eV are all underabundant with respect to low-FIP elements by factors of ~ 4 to 6, which might be slightly larger for GCRS (~ 6) than in the solar environment populations (~ 4) (Fig. 4*b*; § II*e*). High-FIP heavy elements have also remarkably normal abundance ratios between themselves, independent of FIP. This behavior is already apparent when only elements between C (or even S) and Ar are considered. But the key element is Ne. It is quite striking that, *in all four populations,* Ne *(FIP = 21.6* eV*) is not significantly more depleted than* N *(14.5* eV*),* O *(13.6* eV*) or even* C *(11.2* eV*)*[6] (Fig. 2). Even taking into account the uncertainty on the LG abundance of Ne, this conclusion is particularly inescapable for SEP (Fig. 3*a*). In GCRS, only a comparatively small depletion of Ne relative to N or O is *possible* (Fig. 4*a*), even when a specific ^{22}Ne-rich component has been subtracted (§ V).

In the intermediate range of FIPs ($8.5 \lesssim \mathrm{FIP} \lesssim 10$ eV) we lack data for the solar environment. But in GCRS, Zn does exhibit an intermediate degree of depletion. The depletion of S might also be intermediate in the various populations.

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[6] This is not quite true for C in GCRS. For the expected excess of ^{12}C (and possibly ^{16}O) associated with the ^{22}Ne and ^{25,26}Mg excesses in GCRS, see § V.

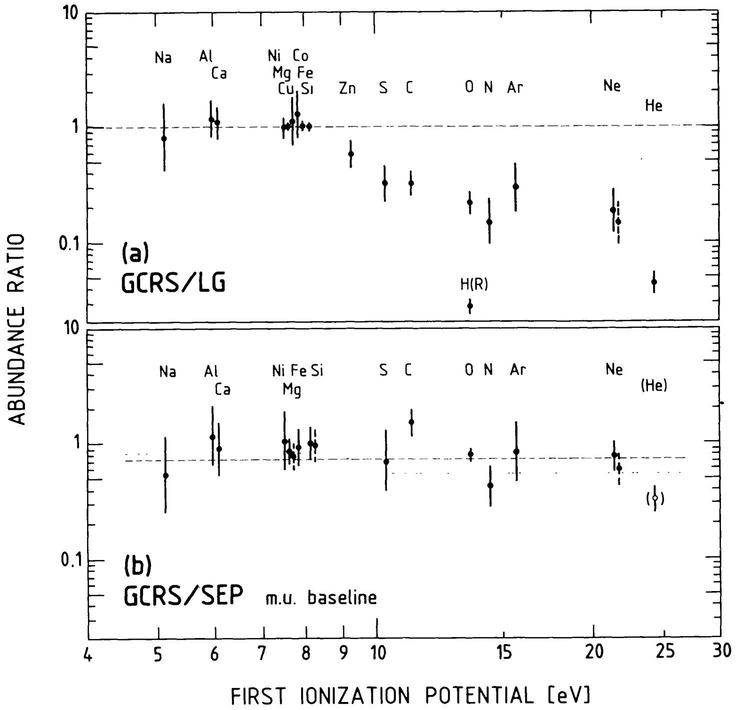

FIG. 4.—Ratios of GCRS abundance to (*a*) LG and (*b*) SEP (m.u. baseline) abundances vs. FIP, as derived from Figs. 2*c*, 2*d* and Tables 2 and 3 (§ II*e*). See Fig. 2 legend. Errors are the quadratic sum of the errors on both terms. Plot (*a*) is normalized to the weighted average of the abundance ratios for low-FIP elements (Na–Si). Plot (*b*) is normalized to Si. Its point for He is not really significant since the m.u. baseline SEP abundance cannot be properly defined (Paper I). We have indicated as dashed bars the abundance ratios for "normal" Ne, Mg, and Si if specific neutron-rich components are being subtracted (shown only for Ne in [*a*], for the sake of clarity) (§ V). Both lines in (*b*) are only meant to guide the eye: the dashed horizontal line shows that the two sets of abundances are to first order identical within errors, except for C; the dotted line tentatively suggests a slightly different behavior that would fit better the Mg, Si, Fe, and the N and "normal" Ne data; it would imply that high-FIP elements are slightly more underabundant in GCRS than in SEP, and that the C excess in GCRS is accompanied by a slight O excess (§ II*e*).

This near constancy of overabundances over wide ranges of FIP may suggest a two-plateau structure, with a narrow intermediate region in between: one plateau for low-FIP elements (5–8.5 eV), and another one for high-FIP elements (~ 10–22 eV), underabundant by a factor of 4 to 6 with respect to the former. The two plateaus may have slight negative slopes, although the high-FIP plateau seems remarkably flat, at least in SEP. But one would certainly have to stretch the data on SEP and GCRS to fit them with a single straight line for all securely measured heavy elements.[7],[8]

III. DISCUSSION OF THE SOLAR ENVIRONMENT

a) *Basic Conclusions*

The heavy element compositions of the apparently homogeneous solar corona, of SW, and of SEP (m.u. baseline), while different from photospheric composition (bias according to FIP), are identical within errors (§ II*e*; Figs. 2 and 3). Since SW and SEP are most probably both extracted from the coronal reservoir,[9] this fact strongly suggests a single basic phenomenon: *a bias according to FIP of the composition of the solar corona, with respect to photosphere. The compositions of SW and SEP (m.u. baseline) then simply reflect, at least to first order, that of their birthplace, the corona.*

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[7] Changing the logarithmic scale for the abscissae (FIP) into a linear one (Mewaldt 1981) would not help in fitting the data with a single straight line!

[8] We insist that all this discussion is concerned only with heavy elements, not with H and He. Hydrogen does not behave like other high-FIP elements in the solar corona and SW, and very conspicuously so in GCRS (Figs. 2*a*,2*b*,2*d*) (in SEP the H abundance is not easy to define, and we have not attempted to do it). The behavior of He in the corona is not clear (Fig. 2*a*), but in SEP its variations with time do not fit into the pattern followed by all heavier elements (§ III of Paper I). As for GCRS, one could formally interpret the pattern of high-FIP elements (Figs. 2*d* or 4*a*), *either* as a decreasing slope joining the points for O and N to the He point, with H, Ne, and Ar being anomalous, *or* as a roughly flat plateau from O up to Ne, with H and He being anomalous. We choose the second interpretation, first, by analogy with SEP where Ne and Ar behave normally and He does not and, second, since, like H, He is by far more abundant and lighter than all other elements.

[9] It is generally accepted that SEP are accelerated in the solar corona, in particular since it would be difficult to accelerate the particles in the much higher densities prevailing in the underlying chromosphere and photosphere. The lack of observable effects of energy loss and spallation in SEP actually shows that very little matter has been traversed after acceleration (< 0.004 g cm^{-2}; McGuire, Von Rosenvinge, and McDonald 1979; Cook *et al.* 1979; Mason, Gloeckler, and Hovestadt 1983). These views are strongly confirmed by the observed ionization states in SEP, which are principally those of the ordinary corona (Gloeckler *et al.* 1976, 1981; Sciambi *et al.* 1977; Hovestadt *et al.* 1981, 1983; Ma Sung, Gloeckler, and Hovestadt 1981; Hovestadt, Klecker, and Gloeckler 1982; see discussion in Paper I, § III*b*).

There is a strong additional argument supporting this view: in SEP, ratios such as Mg/O or (Mg + Si)/(C + N + O + Ne) are observed to be (*i*) *definitely different from the photospheric value*, *and* (*ii*) *remarkably constant from observation to observation* (at a level within 25% of 4 times the photospheric value in all but the few "Fe-richest" observations; Fig. 3 of Paper I). It would seem very odd that an acceleration process could produce abundance distortions by a factor of 4 that are constant to within 25%. If, however, the SEP abundance anomaly just reflects that of the coronal reservoir, its constancy simply implies that the abundance ratios we consider are generally not altered by the acceleration process itself (see § III*b* of Paper I).

So, the basic problem is to explain the composition of the solar corona. How can abundances in the solar corona, a medium at ~10^6 K, be biased according to FIP, i.e., reflect some selection between ions and neutrals? The answer probably lies in the way the corona is being fed. *The corona is indeed fed by transport of thermal matter from the chromospheric reservoir (including spicules), which does have the right temperatures (~5000–10,000* K*) for FIP to govern ionization, and in which some elements are indeed predominantly neutral.*

These considerations suggest that the basic phenomenon behind the ubiquitous bias of abundances according to FIP in the solar environment is *that ionized heavies rise ~4 times*[10] *more efficiently than neutral ones from chromosphere to corona.*

If one accepts the single, but seemingly good, measurement of the H abundance in the corona (Veck and Parkinson 1981; § II*a*), one can state more precisely: *ionized heavies in the chromosphere seem to fully follow the dominant* H *gas* (*which is itself predominantly neutral*) *in its rise into the corona*, *while neutral heavies are to a large extent left behind*. As for He, its behavior is not known, since its abundance in the corona is poorly measured (§ II*a*); it cannot either be simply derived from the SEP data (§ II*c*); only the SW value is well known (§ II*b*), but it may be influenced by other factors (see, e.g., Neugebauer 1981, Geiss 1982).

As concerns energetic particles (SEP), we note that neutrals, of course, cannot be accelerated. This scenario is therefore a *two-step scenario*, *in which the shaping of the composition and the energization occur at two different stages*: (i) out of some cool medium at ~8000 K (the chromosphere), *some reservoir is filled* (the corona) with an efficiency ~4 times lower for neutral than for ionized heavies; and (ii) all elements in this reservoir (corona, at 10^6 K), are ionized and *accelerated* (with alterations in composition which are only monotonic functions of mass; see § III of Paper I).

These simple views will be confirmed by the following analysis of the structure of the overabundance pattern versus FIP (§ III*b*).

b) *Interpretation of the Structure of the Coronal*, *SW*, *and SEP Abundance Pattern versus FIP*

This interpretation of the coronal, SW, and SEP abundances in terms of a selection between ionized and neutral heavies during the transport of thermal matter from chromosphere to corona is particularily attractive since, as we shall now show, it explains at once the otherwise puzzling two-plateau structure of the overabundance pattern versus FIP (Figs. 2*a*–2*c*; § II*f*).

The following discussion will necessarily be only qualitative, because of a lack of adequate ionization calculations for the chromosphere, properly taking into account photoionization, charge exchange reactions, and the comparatively high density of the medium in relevant equilibrium and possibly nonequilibrium (spicules, loops) situations. By analogy with various coronal-type ionization calculations (Jordan 1969; Jacobs *et al.* 1977, 1979, 1980; Jain and Narain 1978; Cassé and Goret 1978; Shull and Van Steenberg 1982; Arnaud and Rothenflug 1984), which, however, do not properly apply to the chromosphere, we shall accept the idea that, at some temperature around ~8000–10,000 K elements with FIP $\lesssim 8$ eV are ~100% ionized, and that the ionized fraction falls steeply for elements with higher FIP to be ~0 for FIPs above some ~10 eV. Note that the main temperature plateau in the chromosphere lies at a temperature of 6000–7000 K (Vernazza, Avrett, and Loeser 1981), a temperature not too different from the above roughly estimated temperature of ~8000–10,000 K.

Let us now consider the pattern of Figures 2*a*–2*c*. The interpretation of the low-FIP plateau is straightforward: these elements are all ~100% ionized in the selection medium, presumably some region in the chromosphere. (If this plateau has a slight negative slope, it simply implies that the elements with FIP ~8 eV are not quite 100% ionized there.)

The interpretation of the high-FIP plateau is much more instructive. *That heavy elements with FIPs as different as ~10–14 and ~22* eV *behave alike can be best understood if they are all either ~100% ionized or ~100% neutral in the medium from which they have been extracted*. With this idea in mind, we now explore two possible lines of thought:

1. *The abundance pattern is interpreted as simply reflecting ionized fractions in gaseous media*. This assumption implies the following: out of some original gaseous reservoir, a new population (corona, SW, SEP) is "selected" by the picking out of the same fraction η_i of all ionized heavy atoms and of none of the neutrals: $\eta_n = 0$. This assumption is quite natural if one considers populations of energetic particles (SEP, GCR) with the idea that in the electromagnetic energization process *only ions* get accelerated, so that energization and total elimination of neutral atoms quite naturally take place in one and the same step. (This was the view taken by Cassé and Goret 1978 for GCRs). But when one considers the feeding of a medium (the corona) with thermal particles, a total exclusion of the neutrals from the transport process ($\eta_n = 0$) would probably require very specific physical conditions.

Actually, if one nevertheless wants to interpret the abundance pattern of Figures 2*a*–2*c* as reflecting ionized fractions in a gas, one runs into difficulties. The entire pattern of Figures 2*a*–2*c* can indeed be accounted for, neither by a gas at a single temperature, nor by any *monotonic* distribution of gas temperatures. Actually, any monotonic temperature distribution which accounts simultaneously for an ionization of most of the Ni, Mg, Fe, Si and of ~25% of Ne will yield

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[10] This factor of ~4 is the factor separating the two plateaus in Fig. 2*c*. In Figs. 2*a*,2*b* it is much less precisely defined.

ionized fractions of O and especially of $C \gg 25\%$, which conflicts with the pattern shown in Figure 3*a*.[11]

Only a *bimodal* distribution of temperatures could simply account for the data. Physically, it would mean that the particles originate in two media: first, a hot medium (> 25,000 K) in which all heavy elements are ~100% ionized, and from which the high-FIP elements are extracted (together with the corresponding quantity of low-FIP elements, if they are not locked in grains[12]); and, second, a cool medium (~ 8000–10,000 K, and grain-free) which provides the excess low-FIP elements. But very little material at intermediate temperatures (10,000–25,000 K) is allowed. This model is sketched in Figure 5*a*.

In the context of the upper chromosphere and transition region, we may find these two media, one at ~ 8000–10,000 K (the chromospheric plateau lies at 6000–7000 K, and it gets warmer toward its top), and one above 25,000 K (the bulk of the transition region), with very little matter in between in view of the very steep temperature gradient in the transition region.[13] But observations show that the composition (O/Si ratio) is already biased at very low altitude within the narrow transition region, at T ~ 70,000 K (Mariska 1980; § II*a*). This leaves very little room (between the layers where $T = 25{,}000$ K and where $T = 70{,}000$ K) for the "hot" component to be extracted and the selective rise of ions to take place. So, this explanation of the coronal heavy element composition in terms of a rise of ions only, out of a mixture of "cool" and "hot" materials in the chromosphere and transition region (or spicules) is not appealing.[14] Especially so since, in addition, the relevant medium is highly turbulent, and the assumption that neutral heavies do not at all rise into the corona ($\eta_n = 0$) is not too plausible.

2. *The abundance pattern is no longer supposed simply to reflect ionized fractions in gases*. Since assuming the pattern simply reflects ionized fractions does not seem convenient, we now relax this hypothesis and are free to introduce neutrals, which are fed into the corona with an efficiency $\eta_n \neq 0$. In a roughly uniform medium at T ~ 8000 K (as can be found in the upper chromosphere) in which the low-FIP elements are all ~100% ionized, the high-FIP elements are all *~ 100% neutral*. The presence of a broad high-FIP plateau is therefore readily understood if a selection takes place between ionized and neutral heavies *in a single medium*, at ~ 8000 K, the chromosphere: neutral heavies ought to rise from chromosphere to corona ~ 4 times less efficiently than ionized ones ($\eta_n/\eta_i \approx 0.25$, from Figs. 2*a*–2*c*). This model is sketched in Figure 5*b*. SW and SEP are later extracted out of the corona. It is the scenario proposed in the preceding § III*a*.[15]

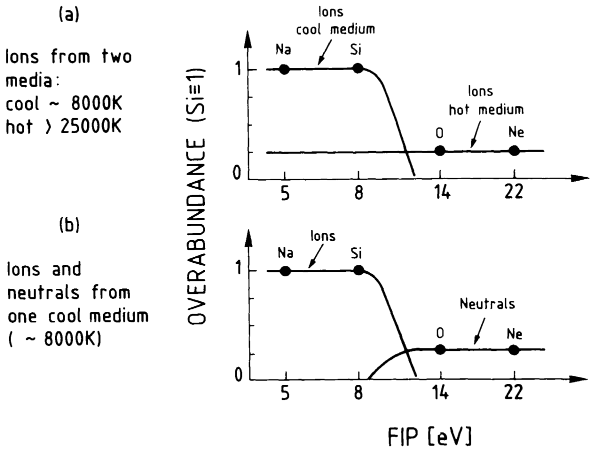

FIG. 5.—Sketch of the two possible interpretations of the two-plateau structure of the ubiquitous abundance pattern vs. FIP (Fig. 2). See discussion in §§ II*b* and IV*c*.

c) Possible Mechanisms for an Ion-Neutral Separation in the Transfer of Matter from Chromosphere to Corona

A mechanism is needed (i) that selects between ionized and neutral heavies, by letting ions rise from chromosphere to corona ~ 4 times more efficiently than neutrals, (ii) that does *not* select between the various heavy ions, nor between the various heavy neutrals, and (iii) in which it is the ionized heavies that follow the predominantly neutral H gas (if Veck and Parkinson's 1981 measurement is correct; § II*a*). No further constraint can be given by the He data, which are still too poor (§ II*a*).

The mechanism may produce either a preferential rise of ions or a preferential downfall of neutrals in the continuous exchange of matter back and forth between chromosphere and corona. In any case, it must work, either within spicules, or at a very low altitude at the base of the transition region (TR) since (i) it must work before the neutrals get ionized, and (ii) the composition is observed to have already fully reached its typical coronal character (bias against FIP) in various media in the TR with temperatures as low as 70,000 K (Mariska 1980).

The mechanism must be extremely efficient, in view of the highly turbulent character of the medium in which it takes place, which will strongly tend to erase any gradient in composition. However, the role of the magnetic field may be important in stabilizing part of the material.

So, which mechanisms can be considered? The specific situation we have here is, of course, the huge simultaneous density and temperature gradients, in which thermal diffusion may be extremely efficient (Chapman 1958; Delache 1967;

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[11] For GCRS, Cassé and Goret (1978) and Arnaud and Cassé (1984) have proposed to apply additional biases proportional to $(A/Z^*)^\alpha$, where Z^* is the charge of the ion in the weakly ionized plasma (see § IV*c*). One cannot totally exclude that the coronal-SW-SEP abundance pattern may be accounted for by some combination of adequate monotonic temperature distribution and selection effects proportional to $(A/Z^*)^\alpha$, where Z^* is the charge of the ion in either chromospheric or coronal plasmas. See also note 26.

[12] Elements highly locked in grains are essentially low-FIP elements (Meyer 1981*c*).

[13] Spicules and loops also consist in low temperature regions embedded in very hot material (e.g., Beckers 1972; Athay 1981; Foukal 1975, 1976, 1978; Raymond and Foukal 1982; Priest 1978).

[14] The observation of typically ~10% of He^+ in SEP (and sometimes much more in very small events; Gloeckler *et al.* 1981; Hovestadt *et al.* 1981, 1983) is not relevant here. These particles do not tell us anything about the filling process of the corona.

[15] For the behavior of H and He, see also § III*a*.

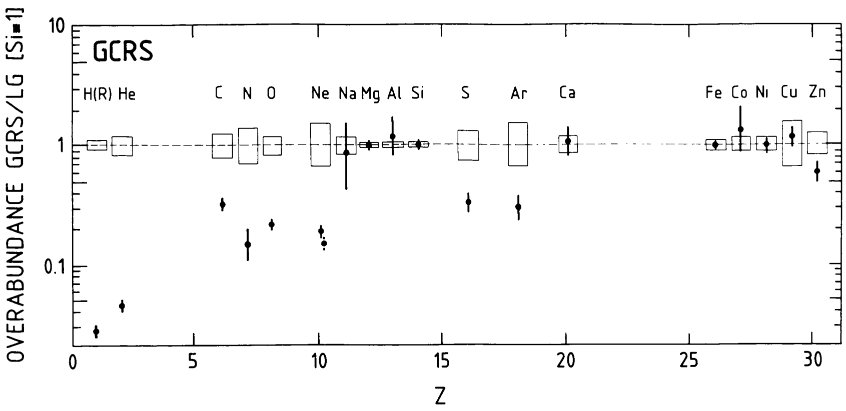

FIG. 6.—Overabundances of elements in GCRS with respect to LG composition vs. Z (Tables 2 and 3; § II*d*). Boxes represent the uncertainty of the LG composition. Normalized to Si. See Fig. 2 legend.

Nakada 1969; Tworkowski 1975; Shine, Gerola, and Linsky 1975; Meyer and Nussbaumer 1979; Roussel-Dupré 1980, 1981, 1982; Geiss 1982). Thermal diffusion is particularly attractive in view of the very large difference in behavior between the thermal diffusion coefficients for neutrals and for ions. Geiss (1982) has attempted to explain in this context the low abundance of He in the SW (see also the discussion in Michaud *et al.* 1983).

Convection governed by electric or magnetic fields could also be considered, provided heavy neutrals are not fully dragged along.

Veck and Parkinson (1981) have also suggested ambipolar diffusion.

IV. DISCUSSION OF GALACTIC COSMIC RAYS (GCR)[16]

a) *From Where Can GCR Nuclei Have Been Extracted?*

The composition of galactic cosmic-ray sources (GCRS), shown versus Z and FIP in Figures 6 and 2*d* (see also Fig. 4*a*), is by itself very instructive. In the present section, we shall discuss it *regardless of any similarity with SEP composition* (which will be considered in the subsequent § IV*b*).

i) *Ordering in Terms of FIP*

The GCRS composition anomalies are quite limited. The plot versus Z (Fig. 6) shows that, while most metallic elements have remarkably normal relative abundances, a sharp discontinuity appears between Ne and Na, and that, in addition, S and Ar form a sharp dip between Si and Ca. But the abundances of 16 heavy elements are smoothly ordered in terms of a single parameter, FIP (Figs. 2*d* or 4*a*).[17] This suggests some selection effect related to ionization in a cool plasma ($\sim 10^4$ K; Cassé and Goret 1978) that will be discussed more precisely in § IV*c*. Whatever the exact mechanism, the ordering parameter, FIP, is related to atomic, *not* to nuclear physics.

This fact strongly suggests that the main features of the GCRS composition are *not* to be explained in terms of specific nucleosynthetic processes, but that *most* GCR particles originate from a medium with ordinary composition ("solar mix") as far as nucleosynthetic history is concerned.

ii) *Difficulties with In Situ Nucleosynthesis*

An examination of the main features of the GCRS composition versus Z (Fig. 6) in terms of nucleosynthetic processes confirms this view.

The approximately normal H/He ratio indeed does not suggest a predominance of material processed by H burning (although the abundances of H and He among energetic particles are difficult to interpret). This is confirmed by the lack of a N overabundance with respect to C and O, showing that *most* particles do not originate in material just processed by the CNO cycle. The *bulk* of the accelerated material did not either originate in a He-burning layer, since in this case one would expect a very low N/(C+O) ratio, and *very large* C, ^{22}Ne, and possibly O enhancements with respect to heavier elements (see § V, and Fig. 9). Further, the ratios Na/Mg/Al/Si/Ca/Fe/Co/Ni are remarkably normal: there is definitely no systematic enhancement of products of a specific advanced nucleosynthetic cycle (C burning producing Ne, Na, Mg, Al; O and Si burning producing Si, S, Ar, Ca; equilibrium process producing Fe, Co, Ni) with respect to other ones. The difficulty in explaining in terms of nucleosynthesis the low S and Ar abundances with respect to Si and Ca has been pointed out by Meyer, Cassé, and Reeves (1979) (while these abundances are readily interpreted in terms of FIP). Neither do the recent data on elements beyond zinc show evidence for a systematic enhancement of *r*- or *s*-process products (Binns *et al.* 1982, 1983; Stone *et al.* 1983; Fixsen *et al.* 1983; Israel *et al.* 1983; Fowler *et al.* 1983).

Existing global models of supernova nucleosynthesis (Weaver and Woosley 1980; Woosley and Weaver 1982) are actually unable to fit the GCRS heavy element composition, as pointed out by Cassé (1981). In Figure 7 we compare the GCRS composition to the calculated outcome of 15 and 25 $M_\odot$ supernovae. For 15 $M_\odot$, the relative abundances of a surprisingly large number of elements (including H and He)

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[16] This entire discussion requires our adopted GCRS N/O ratio to be correct (§§ II*d*, *e*; Appendix). Were this ratio actually lower than $\sim 6\%$, our analysis would have to be revised considerably (§ II*e*).

[17] We recall that we interpret this pattern as ordering all heavy elements, but not H and He. See note 8.

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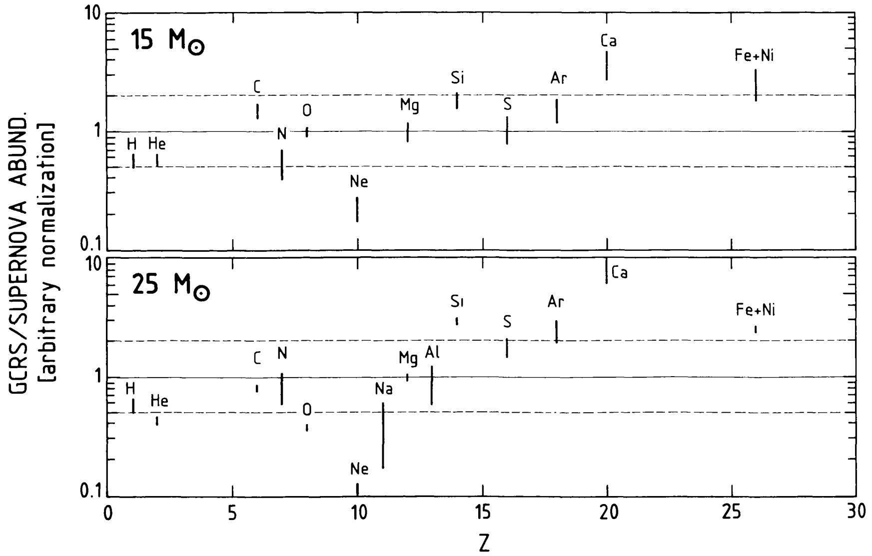

FIG. 7.—Ratios of abundances in GCRS to calculated abundances yielded by model supernova explosions. *Top*: 15 $M_\odot$ model by Weaver and Woosley (1980); *bottom*: 25 $M_\odot$ model by Woosley and Weaver (1982). The normalization is arbitrary, chosen to have as many elements as possible close to 1. Dashed lines at 0.5 and 2 have been drawn to guide the eye.

can be accounted for within a factor of ~ 2, but with a few key elements far off: (Fe + Ni), and especially Ne and Ca.[18] At least the fact that the GCRS Ca abundance cannot be accounted for is not accidental, but has deep physical grounds.[19] As for the 25 $M_\odot$ model, it does not at all fit the GCRS composition. The recent calculations of presupernova abundances by Arnett and Thielemann (1983) using updated $^{12}\mathrm{C}(\alpha, \gamma)^{16}\mathrm{O}$ reaction rates (Kettner *et al.* 1982), while leading to an improved fit of the LG composition, do *not* yield an improved fit of the GCRS composition (see, e.g., the Mg/O, Ne ratios).

We conclude that, *if some in situ nucleosynthesis affects the GCRS composition* (and it will have to, in view of the ^{22}Ne excess; see § V), *it can be only via a minor component strongly enriched in specific nuclear species, highly diluted in solar-type material.*

iii) *The Need for a Grain-free Source Medium, and Difficulties with the Hot Interstellar Medium*

Refractory elements which are locked in grains, and hence are virtually absent in almost all of the interstellar medium (ISM) gas phases, are not at all depleted in GCRS (Cassé, Goret, and Cesarsky 1975; Meyer, Cassé, and Reeves 1979).[20] This remark permits us to exclude the ordinary cold (100 K) and warm (10^4 K) ISM phases as media from which GCRs can have been extracted.[21] In the ISM, we see only three

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[18] One can see from Fig. 7 that a GCRS N abundance twice lower than we adopted (§§ II*d*, *e*; Appendix) could not better be accounted for by the calculated outcome of a 15 $M_\odot$ supernova than by our models involving the outer atmosphere of unevolved stars.

[19] In the quasi-equilibrium O and Si burning which takes place in Weaver and Woosley's model supernovae, most of the material reaches only rather low temperatures, so that low abundances of S and Ar relative to Si are obtained. This is why the low GCRS S/Si and Ar/Si ratios are roughly fitted. But, since the productions of S, Ar, and Ca are *coupled* in quasi-equilibrium (which is indeed reached; see Woosley, Arnett, and Clayton 1973), the simultaneous production of a low Ca/Si ratio cannot be avoided (Bodansky, Clayton, and Fowler 1968; Woosley, Arnett, and Clayton 1973; Meyer, Cassé, and Reeves 1979). But the Ca/Si ratio is normal in GCRS! In a hotter explosion that would fit the standard Ca/Si ratio, the S/Si and Ar/Si ratios would certainly also be higher and would no longer be consistent with their low values in GCRS.

[20] Actually the refractory elements locked in grains are even enhanced in GCRS relative to the volatile ISM gas-phase elements: indeed low-FIP elements are generally refractory and high-FIP elements volatile (e.g., Meyer 1981*c*), so that the correlation of GCRS abundances with FIP (Fig. 2*d*) can as well be interpreted as a correlation with volatility. This has led Cesarsky and Bibring (1980) and Epstein (1980*b*) to propose that GCRs might be largely grain destruction products (see also Tarafdar and Apparao 1981). The main difficulty with this hypothesis is that it does not explain the similarity between GCRS, SEP, and solar coronal compositions (unless most heavy elements in the solar coronal gas are interplanetary grain destruction products). Another specific challenge is to explain the noble gas abundances, and in particular the normal Ne/O ratio (Bibring and Cesarsky 1981). There exists, in fact, an observational test which should permit us to choose between FIP and volatility as the governing parameter: the abundances of the few low-FIP elements that are nevertheless volatile (Meyer 1981*c*). The recent observation of surprisingly low Ge/Fe and Pb/Pt ratios seems to favor volatility (Israel *et al.* 1983; Fixsen *et al.* 1983; Fowler *et al.* 1983; Byrnak *et al.* 1983*b*). These data still have to be confirmed. In addition, caution is in order as long as we do not know better *to within which accuracy* the abundances of *volatile* elements measured in Type I carbonaceous chondrites, commonly used as a sole source of reference abundances for such heavy elements, are representative of those of the solar system (Meyer 1979; Anders and Ebihara 1982).

[21] Refractory elements (Ca, Ti, Si, Fe), which are depleted by several orders of magnitude in the cold H I gas (100 K), are indeed observed to be still depleted by factors of ~ 20 in the gas phase of the warm neutral ISM at 10^4 K (Hobbs 1975, 1976; Stokes 1978; York 1983). In the gas phase of H II regions and planetary nebulae, refractory elements also seem depleted by factors of $\gtrsim 10$ (Olthof and Pottasch 1975; Shields 1975, 1978*a*, *b*; Garstang, Robb, and Rountree 1978; Nussbaumer and Storey 1978; Perinotto and Patriarchi 1980; Péquignot and Stasinska 1980; Aller *et al.* 1981; Kindl, Nussbaumer, and Schild 1982; York 1983). But there it is not clear whether the grains survive the environment or are rapidly ejected from the warm region by radiation pressure.

media in which the grain material may have returned to the gas phase: (i) *The high velocity clouds* (e.g., Shull, York, and Hobbs 1977; Shull 1977, 1978; Cowie 1978), which are not plausible sites for cosmic-ray birth. (ii) The presumably pervasive *hot interstellar medium* at $\sim 10^6$ K (HIM; e.g., McKee and Ostriker 1977), in which there is evidence from X-ray observations that grains might be sometimes thoroughly destroyed (Draine and Salpeter 1979*a*; Hayakawa *et al.* 1978; Inoue *et al.* 1980; Arnaud *et al.* 1981; Rothenflug, Rocchia, and Arnaud 1981; Schnopper *et al.* 1982; Arnaud, Rothenflug, and Rocchia 1984; Rothenflug *et al.* 1984; Rocchia *et al.* 1984). But, even assuming the HIM gas phase has a fully normal LG composition, how could a correlation of GCR abundances in FIP originate in such a medium at $\sim 10^6$ K?[22] In particular, models assuming that most GCR particles have been accelerated directly out of the HIM thermal gas (Eichler 1979; Ellison 1981*a*, *b*; Ellison, Jones, and Eichler 1981; Eichler and Hainebach 1981), while accounting for the low GCRS abundances of H and He, have not succeeded in producing the sharp upward and downward discontinuities in the GCRS heavy element overabundance pattern versus Z (Fig. 6) or versus A/Z^* (A/Z^* is always a smooth and, for $T \gtrsim 0.3 \times 10^6$ K, monotonic function of Z as shown in Fig. 11 of Paper I; Z^* is the average effective charge in the hot plasma) (Cesarsky, Rothenflug, and Cassé 1981; Ellison 1981*a*; Cassé 1983). (iii) *A supernovae remnant* (*SNR*) *shock wave*: an SNR shock wave entering a cool material may destroy its grains (Shull 1977, 1978; Cowie 1978; Barlow 1978*a*, *b*; Draine and Salpeter 1979*b*; Hollenbach and McKee 1979), but the strong shock waves that may accelerate GCRs are preceded by an ionizing precursor (Hollenbach and McKee 1979; McKee and Hollenbach 1980), so that, again, one cannot expect a correlation of GCRS abundances with FIP.

iv) *Conclusions from GCRS Composition Alone*

It seems very difficult to find in the ISM adequate sites for extraction of GCR particles, in which (i) the refractory elements are not locked in grains, and (ii) the temperature is low enough for FIP to govern the ionization (i.e., for some elements to remain largely neutral). The obvious alternative source material, not depeleted in refractory elements, is *stellar matter*. These considerations, together with the lack of correlation of the major abundance anomalies with expectations from specific nucleosynthetic processes, suggest that *the vast majority of GCR nuclei must have been extracted from the surface of ordinary*, *unevolved stars*.

b) *Similarity to SEP Composition*, *and Three Phase Scenario for the Genesis of GCRs*

The strong similarity between the GCRS and the SEP (*m.u. baseline*), *solar coronal*, *and SW compositions* (§ II*e*; Figs. 2–4) *very strongly supports the above conclusion*.[23] (The composition of SEP is certainly not shaped by in situ nucleosynthesis!). On the Sun, the SW and SEP (m.u. baseline) compositions most probably reflect that of the corona (§ III*a*). *The similar GCRS composition therefore suggests that GCRs were ultimately extracted out of stellar coronal material.* Now, there are two ways by which coronal material can be turned into GCRs:

1. One way is *direct high-energy acceleration of thermal stellar coronal or wind material*. As will be shown in § IV*d* on composition arguments, the main providers of GCR material should *not* be massive OB stars, but later type F–M stars. High energy acceleration by the stellar flares themselves can probably be excluded on energetic grounds (Mullan 1979; Gorenstein 1981). One must therefore consider more powerful *external* agents acting directly on the coronal or wind gas, such as supernova shock waves, or massive star wind terminal shocks. *But the acceleration mechanism would have to work specifically within the wind cavity of the stars*, *prior to any dilution of the wind material with external ISM gas*. This scenario is not realistic in view of the small dimensions of the later type star wind cavities ($\lesssim 10^{-3}$ pc) as compared to the scale of the strong shock waves in the ISM (1–10 pc).

2. The other possibility is *a later reacceleration of MeV stellar energetic particles* "*injected*" *out of coronal matter* (two-step acceleration). Injecting at MeV energies permits us *to single out a kinematically distinct population of particles with* "*frozen-in*" *stellar coronal composition*, *which may spread in the ISM while keeping its identity*. These particles are then available for further acceleration by a passing strong shock wave. Stellar flares, similar to solar flares, would then be the principal "injectors" of GCR nuclei.

By analogy with the situation on the Sun, we therefore propose the following scenario. The genesis of the *bulk* of the GCR population implies *three separate phases*, *the first of which is responsible for its heavy element composition*, *and the latter two for its energization*: (i) *a selective rise of thermal heavy ions relative to neutrals from stellar chromospheres into stellar coronae* yields stellar coronal heavy element compositions biased according to FIP (as on the Sun); (ii) once in the corona, all atoms get ionized, and some of them are later accelerated to MeV energies or "*injected*" *by stellar flares* (as on the Sun); (iii) *a small fraction* of these injected MeV particles are later on taken over by *more powerful accelerators* such as SNR or massive star stellar wind shock waves, which boost them up to GeV energies. The two energization phases, on average, must not substantially alter the heavy element composition inherited from the stellar coronal material.[24]

The high energy acceleration phase *can* proceed by the currently proposed shock wave acceleration mechanisms acting within the HIM, in which the required highly diffusive waves can develop without being damped by collisions with neutrals (e.g., Krimsky 1977; Axford, Leer, and Skadron 1977; Bell 1978*a*, *b*; Blandford and Ostriker 1978; Axford 1981).

We insist that, while *direct* acceleration of particles out of the high energy tail of the HIM *thermal* plasma ought to be possible and is indeed observed at the Earth's bow shock, it is

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[22] We leave aside the possibility that the general ISM might be enriched by a factor of ~ 6 (the factor separating the two plateaus in Figs. 2*d* and 4*a*) in low-FIP, refractory elements, in the same way the solar corona probably is (§ II*a*; Figs. 2*a*–2*c*). It is, in particular, not suggested by the X-ray observations of the HIM composition mentioned above.

[23] The differences, the excess of C and possibly of O (§ II*e*), will be interpreted in § V in connection with the ^{22}Ne and ^{25,26}Mg excesses in terms of a *minor* fraction of the GCR material originating in He-burning zones.

[24] In SEP it is indeed found that a median (hence plausibly an average) SEP composition would not be very different from the m.u. baseline (i.e., presumably coronal) composition (see § III and Figs. 1, 4, 5, 8 of Paper I).

expected to work much *less efficiently* than the acceleration of preinjected suprathermal particles (Eichler 1979; Eichler and Hainebach 1981; Ellison 1981*a*, *b*; Ellison, Jones, and Eichler 1981). We feel that the discontinuous and nonmonotonic character of the GCRS heavy element composition anomalies versus *Z* (Fig. 6) simply tells us that the more efficient acceleration of preinjected suprathermal particles *in actual fact* dominates among the observed GCRs (§ IV*a*(iii); Cesarsky, Rothenflug, and Cassé 1981; Ellison 1981*a*; Cassé 1983).

Our scenario will be further supported by the following analysis of the structure of the GCRS overabundance pattern versus FIP (§ IV*c*).

c) *Interpretation of the Structure of the GCRS Abundance Pattern versus FIP*

The discussion of § III*b* on the shape of the overabundance pattern versus FIP in the solar corona, SW, and SEP can apply as well to the very similar GCRS pattern (§ II*f*; Figs. 2*d* and 4*a*).[25] Here also the fact that Ne is not much more depleted than N, O, and even S relative to Si prevents the composition to be interpreted as representing ionized fractions in a gas at a single temperature or with any *monotonic* distribution of temperatures (à la Cassé and Goret 1978).[26] If this composition directly reflects ionized fractions, only a *bimodal* distribution of gas temperatures can be invoked (Fig. 5*a*), such as a cool medium at $\sim 10^4$ K (*grain free*, hence probably late-type star material; § IV*a*), plus a hot medium above 2.5×10^4 K in which all elements are $\sim$ *100% ionized* (e.g., the HIM at 10^6 K, or O star surface material), with essentially no cosmic rays originating in media at intermediate temperatures. Such a solution would seem quite ad hoc.

Otherwise we are left with the second hypothesis, adopted for the solar environment in § III*b*: all high-FIP elements behave alike because the origin of the GCRS composition pattern lies in a *partial* selection between ions and neutrals out of *one* medium at $\sim 10^4$K in which all high-FIP elements are $\sim$ *100% neutral* (Fig. 5*b*). If the scenario of the preceding § IV*b* is correct, this situation applies, and the fact that Ne is not much more depleted than N, O, and S in GCRS is readily explained.

d) *GCR Injection and Stellar Chromospheres, Coronae, and Surface Activity*

i) *The Need for Solar-like Chromosphere and Corona*

If one accepts (i) that the solar coronal composition is governed by the ionization equilibrium in the chromosphere and by the transport of neutral and ionized matter through the transition region (TR), (ii) that the SEP (m.u. baseline) composition reflects this solar coronal composition, and (iii) that the similarity between SEP and GCRS compositions is not fortuitous, then a link is established between GCRS composition and the physics of *stellar* chromospheres, TRs, and coronae. Concerning the stellar outer atmospheres, these considerations suggest that the chromospheric and TR phenomena that lead to a composition bias in the corona of our Sun may be general phenomena operative on many stars.

Concerning cosmic rays, the problem is posed of which kinds of stars possess chromospheres, TRs, and coronae sufficiently similar to those of the Sun to be acceptable injectors for GCRs. X-ray and UV observations by the *Einstein* and *IUE* observatories show that the main sequence (and some of the giant) stars of types F–M do have coronae, as well as adequate chromospheres and TRs, *with chromospheric temperatures very similar to those of the Sun* (Linsky and Haisch 1979; Haisch and Linsky 1980; Linsky 1980, 1981, 1982; Vaiana *et al.* 1981; Vaiana 1981; Ayres *et al.* 1981; Stern *et al.* 1981; Stern 1982; Zolcinski *et al.* 1982*a*, *b*; Haisch and Simon 1982). For massive O and B stars, in which highly active coronae and winds are seen in X-rays, one does not know whether chromospheres and TRs exist or not: they are *not* observed, but existing UV emission lines may be not visible against the strong background photospheric UV flux (Linsky 1981, 1982). Note however that, since this photospheric UV flux leaves essentially no neutral H in the atmosphere of these stars, *there is most probably no cooling agent available to permit formation of a cool chromospheric plateau in O and B stars* (Linsky 1980, 1981). And even if such a cool plateau did exist, which ionization equilibrium would prevail for heavy elements in the presence of this same ionizing photospheric UV flux? Probably one very different from that of the solar chromosphere. Type A stars are in an intermediate position. But they are generally very quiet, so that very little energy is available to heat the outer atmosphere. However, faint coronae are observed on some of them (Linsky 1981; Stern *et al.* 1981). Finally, observations of T Tauri stars indicate the presence of active, dense chromospheres, but coronae are not observed, and may be present or not (possibly blown off by the stellar winds) (Walter and Kuhi 1981; Imhoff and Giampapa 1982).

ii) *Stellar Surface Activity*

Another parameter of importance for the determination of the injectors of GCRs is the surface activity of stars.[27] One

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[25] See note 8.

[26] A recent updating of Cassé and Goret's (1978) ionization calculations by Arnaud and Cassé (1984) confirms that monotonic temperature distributions which fit simultaneously the (Ni, Mg, Fe, Si) group and Ne yield S, C, O, N abundances which are too high. If an additional bias proportional to $(A/Z^*)^{0.8}$ adjusted as to account for the GCRS H/O ratio is invoked, the calculated yields for the lighter elements are decreased (Z^* is the charge of the ion, ~ 1–2 in the weakly ionized plasmas under consideration). Thus, a marginal fit of the (Ni, Mg, Fe, Si), (C, O, N), and (Ne) groups becomes possible within the limits of the error bars. But the low abundance of S as compared to Si can definitely not be accounted for. Neither can the He/H ratio be well fitted in this context.

[27] Fundamentally, the cause for both heating of a hot corona and surface activity (flares, winds, particle acceleration) on a star is the same: emergence of nonradiative energy out of the stellar surface (Linsky 1981; Vaiana 1981). The source for this energy is probably very different for OB stars and for F–M stars. For OB stars, the observed hot coronae and huge winds are not entirely understood. The strong correlation of the X-ray luminosity and wind intensity with stellar luminosity suggests that a fraction of the photospheric radiation itself is being converted into mechanical energy (Cassinelli 1979; Pallavicini *et al.* 1981; Vaiana 1981; Lucy and White 1980; Lucy 1982*a*, *b*). Alternatively, the relaxation of primordial magnetic fields in the short-lived OB stars can be another source of surface energy (Vaiana 1981). Solar-like F–K stars are better understood: the source of the energy is probably disordered magnetic fields generated by the dynamo process near the surface of the star (Linsky 1981). The effectiveness of the process depends on the rotation speed and on the depth of the outer convective zone.

can consider ordinary, weakly active stars like the Sun as possible GCR injectors. But it is, of course, tempting to consider objects with much higher surface activity. The detection of these objects has recently made huge progress, thanks to the X-ray investigations by the *Einstein Observatory*. The X-ray luminosity of a star is indeed a good indicator of its coronal activity, although discriminating between quiescent hot coronal emission and flaring activity is not always trivial.

OB stars have a very high surface activity, resulting in both very high X-ray emission and huge (presumably radiation driven) stellar winds (e.g., Cassinelli 1979; Vaiana 1981; Linsky 1981). But we have just shown that, for probable lack of a cool chromosphere, they are not attractive candidates to account for the GCRS composition.

For later type main-sequence stars, it is observed that (i) the X-ray luminosities do *not* tend to decrease from G to M stars, and (ii) for any particular spectral type, the observed X-ray luminosities span a very broad range (three orders of magnitude) (Vaiana *et al.* 1981; Vaiana 1981). The data suggest that a high surface activity requires (i) a high rotation speed, and (ii) as deep as possible an outer convective zone (e.g., Pallavicini *et al.* 1981; Vaiana 1981; Linsky 1981; Stern 1982). Entirely radiative A stars are very inactive. A high rotation speed generally cannot persist throughout the life of a star, except in close binaries, and binarity is the probable cause for the high flaring activity of old stars such as a numerous dMe main-sequence stars and the RC CVn–type slightly evolved stars (Kahn *et al.* 1979; Johnson 1981; Gorenstein 1981; Walter and Bowyer 1981; Kahler *et al.* 1982; Haisch *et al.* 1983). But most stars were first born with a high angular momentum, and this is why *young* stars are much more active than most slowed-down mature stars, and especially red giants (for Hyades, see Stern *et al.* 1981; Stern and Zolcinski 1982; Stern, Underwood, and Antiochos 1983). In particular, pre–main-sequence T Tauri stars, both very rapidly rotating and highly convective, are extremely active as observed in the optical (Worden *et al.* 1981) and, especially, X-ray ranges (Gahm 1980; Feigelson and De Campli 1981; Vaiana 1981; Stern 1982; Montmerle *et al.* 1983; Feigelson 1984).[28]

One very noticeable conclusion from the above studies is that *the physical characteristics* (temperatures, densities, time history, X-ray surface emissivity and energy spectrum, X-ray/visible luminosity ratio) *of active regions and flares on very active late-type stars (including T Tauri stars) seem very similar to those of solar active regions and flares*. The essential difference seems to lie only in the fraction of the stellar surface occupied by active regions, which is always minute on the Sun ($< 2\%$) and can reach several tens of percent on very active stars (Gorenstein 1981; Zolcinski *et al.* 1982*a*, *b*; Stern 1982; Ayres *et al.* 1982; Kahler *et al.* 1982; Montmerle *et al.* 1983; Feigelson 1984).

iii) *Conclusion and Discussion*

We conclude: to account for the GCRS composition (and for its similarity with SEP and solar coronal composition) we have required that the injecting stars possess a cool chromosphere similar to that of the Sun, a TR, and something resembling a corona. Massive OB stars probably do not meet this requirement because they lack a chromosphere, while all main-sequence and pre–main-sequence later type stars of type F–M do, with chromospheric temperatures remarkably similar to that of the Sun.[29] Among these stars, some are flaring much more actively than the Sun, but the physical conditions in their flares seem remarkably similar to those prevailing in solar flares. Only the fraction of the stellar surface that is active is much larger. The very actively flaring stars can be divided into two groups: (i) a very young population, associated with sites of current or recent star formation (T Tauri, young cluster stars), and (ii) an old population in which activity has probably been maintained because of binarity, such as dMe stars (and RS CVn red subgiants).

Now, how can we understand that low-mass stars, rather than the highly active OB stars, are apparently the dominant injectors of GCRs, or at least of those GCRs we observe? It may seem odd: OB stars are indeed not only very active, but, due to their short lifetime, they are in addition systematically located near strong shocks presumably capable of accelerating injected particles to the GeV range: first, the shock waves from the SNRs resulting from the explosion of nearby massive stars formed out of the same parent cloud (e.g., Reeves 1978), and, second, the terminal shock of their own wind (whose capability of being reached by their own suprathermal particles is being debated, as discussed below; Cassé and Paul 1980; Völk and Forman 1982; Cesarsky and Montmerle 1983).

Several reasons for the predominance of much less massive injecting stars can be suggested, leading to as many future directions of research. The first factor is the small number of OB stars, as compared both with the number of later type stars newly formed within the same OB association (which are also very active during their T Tauri and early main-sequence lifetime, before total disruption of the association) and with the number of old, field later type stars. In particular, active dMe stars are extremely numerous and are likely to be the principal progenitors of suprathermal particles in the galaxy (Gorenstein 1981). Second, the cavity formed by the wind of the OB stars is orders of magnitude larger than that of later type stars. Therefore, adiabatic losses for particles injected near the surface of the star ought to be much more prohibitive than those experienced by particles injected close to later type stars (Völk and Forman 1982; Cassé 1981). However, continuous reacceleration within the turbulent wind cavity might compensate for the adiabatic energy losses in OB stellar cavities (Lucy and White 1980; Lucy 1982*a*, *b*; Cesarsky and Montmerle 1983). Third, because of their short lifetime, O and earlier type B stars lie always within or very near their parent molecular cloud complex, i.e., in very dense, opaque regions. In addition, any energetic particles will be very efficiently trapped in their associated H II region (Montmerle 1981; Montmerle and Cesarsky 1981*a*, *b*; Cesarsky and Montmerle 1983). Therefore, OB stars may inject energetic particles, which may be reaccelerated to the GeV range by nearby strong shocks, but as a result of the huge amount of matter

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[28] Accretion has also been considered as a possible cause of the surface activity of T Tauri stars (e.g., Vaiana 1981). But the similarity between flares on T Tauri stars and on the Sun does not plead in favor of this hypothesis.

[29] For red giants the situation is not entirely clear.

surrounding them, the particles may never get out, except possibly in the form of protons and antiprotons (Cowsik and Gaisser 1981; Cesarsky and Montmerle 1981; Lagage and Cesarsky 1984). In this case, we have not a source of GCRs (at least of heavy nuclei), but a very efficient γ-ray source. This may be the situation in the "SNOBs" largely correlated with the *COS B* gamma-ray sources (Montmerle 1979), and more particularly in the Carina nebula (Cesarsky and Montmerle 1983). The same problem might apply for T Tauri stars as GCR injectors.

e) *Two-Stage Acceleration and Propagation at Low Energy*

The two-stage acceleration scenario of § IV*b* implies some propagation of injected particles in the MeV range, before further acceleration to the GeV range. At these low energies, coulomb energy losses are very efficient in braking the particles, while nuclear interactions are totally negligible.[30] We do not know how much matter is traversed at this stage. But the ranges for thermalization are so short that we must consider the extreme case in which particles are reaccelerated out of *a "pool" of suprathermal particles in equilibrium against coulomb losses* (on a galactic kpc scale or on a much more local scale—say, an active region).

Eichler (1980) and Epstein (1980*a*) have argued that acceleration of GCRs out of such a pool of suprathermal particles could be excluded, essentially on two grounds: (i) energetics, and (ii) systematic distortions of the heavy element composition during the propagation at low energy. We shall first discuss this second point.

i) *Distortion of the Composition during Propagation at Low Energy?*

On the basis of coulomb losses proportional to Z^2/A, Eichler (1980) and Epstein (1980*a*) conclude that heavier elements would be systematically depleted with respect to lighter ones, contrary to observation (Fig. 6).

But this statement overlooks *the pickup of electrons by low-energy heavy nuclei*, which modifies drastically the rates of energy loss relevant for the injected particles ($\propto Z^{*2}/A$ instead of Z^2/A, where Z^* is the effective charge of the ion and Z is its nuclear charge) (see also Havnès 1982). Figure 8 compares the stopping ranges R of all elements in neutral hydrogen[31] to that of Si, for various initial energies (after Northcliffe and Schilling 1970). The curve labeled "∞" describes the ranges at high energy, where $R \propto A/Z^2$. The important conclusion from this figure is that, *for any injection energy between* ~ *0.01 and* ~ *2.5* MeV/n, *the stopping ranges of all elements between* C *and* Fe *are within 30% of that of* Si.[32] Therefore, the *relative* abundances of these heavy nuclei among injected low-energy particles should not be seriously affected by traversal of any amount of matter prior to acceleration to high energy.

Beyond Fe, the ranges tend to increase by small factors, up to ~ 2. Incidentally, this increase might possibly account for the recent data on ultraheavy nuclei (Israel 1981; Mewaldt 1981; Fixsen *et al.* 1983; Fowler *et al.* 1983), which might imply a source (Pt + Pb)/Fe ratio 2 times higher than expected on the basis of current models (Mewaldt 1981; Tsao *et al.* 1983). However, these data do *not* suggest an enhancement in the Sn-Te-Xe-Ba region ($Z = 50$–58), which would be expected on the basis of Figure 8 (Mewaldt 1981; Stone *et al.* 1983).

We conclude that two-step acceleration models *cannot* be rejected on the grounds of the effect of coulomb losses at low energies on composition (provided the majority of the particles are injected below ~ 2.5 MeV/n, a very plausible hypothesis indeed in view of the observed SEP spectra). As far as composition is concerned, the particles accelerated to high energy may have been extracted out of a pool of suprathermal particles in equilibrium against coulomb losses.

ii) *Energetics of the Injection*

Of course, suprathermal particles injected below ~ 2.5 MeV/n lose their energy at a very high rate and are very rapidly thermalized. The probability of meeting a strong shock wave capable of high-energy acceleration prior to thermalization is therefore low, and the energy requirement from flaring

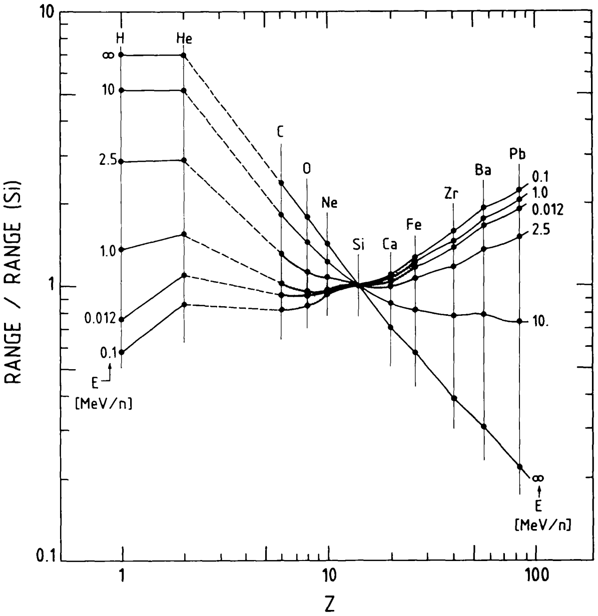

FIG. 8.—Ratio of the stopping range R (coulomb energy loss) of all elements to that of Si for various injection energies E in neutral hydrogen (after Northcliffe and Schilling 1970). The curve labeled "∞" corresponds to ranges $R \propto A/Z^2$ as is the case at high energy, and the strong departures from this curve for low injection energies are due to pickup of electrons resulting in an effective charge Z^* lower than the nuclear charge Z. One may note that at low enough energies, R even tends to *increase* with increasing charge and that the ranges relative to Si do *not* behave monotonically with energy in the 1.0–0.1–0.01 MeV/n range: there is a broad extremum in the 0.1–0.3 MeV/n region. The shaded area is meant to point out that the ranges of all elements between C and Fe are within 30% of that of Si for all injection energies between 0.012 and 2.5 MeV/n.

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[30] The low-energy stopping ranges are much shorter than the nuclear interaction lengths. In addition, most particles will have energies below the threshold for nuclear interactions.

[31] Similar calculations should be made for ionized hydrogen. But we expect the results obtained for neutral H to remain qualitatively valid for ionized H as well.

[32] This statement will remain true for a certain range of injection energies below 0.01 MeV/n (see Fig. 8), which is only the lower bound of Northcliffe and Schilling's (1970) study.

stars is accordingly high (Eichler 1980; Epstein 1980*a*). This question of energetics is far-reaching and lies beyond the scope of the present paper. We shall restrict ourselves to a few qualitative remarks:

1. The energy requirements may be difficult to meet if cosmic rays are to originate principally in a pool of suprathermal particles filling the entire galactic disk, some of which are accelerated to high energy whenever a random strong supernova shock wave is passing by (see, e.g., Axford 1981). In such a context the main injectors would probably be dMe stars, as judged from their X-ray emission (e.g., Gorenstein 1981).

2. OB associations may be much more favorable sites. There, indeed, a large number of later type stars are being formed within a small volume, together with a few short-lived massive stars. The former have a very high surface activity owing to their youth and should emit lots of suprathermal particles (§ IV*d*), while the latter provide stellar wind and supernova shock waves within their few 10^6 yr lifetime (Reeves 1978). So, possible injectors and high energy accelerators are closely linked in space and time (e.g., Montmerle 1979, 1981; Cesarsky and Montmerle 1983).

3. The energy at which most particles are injected, which has been requested above to lie below ~ 2.5 MeV/n, can be very low. Energies as low as ~ 0.01–0.10 MeV/n are sufficient for suprathermal particles to be accelerated much more efficiently than the thermal gas[33] (Ellison 1981*a*; Ellison, Jones, and Eichler 1981).

4. The time for thermalization is inversely proportional to the density of the medium in which the suprathermal particles propagate. If t is the time for a Si ion to be decelerated down to 0.01 MeV/n in a neutral medium of density n_{H}, the product $n_{\mathrm{H}}t$ amounts to ~ 0.027, 0.017, 0.011, and 0.008 cm^{-3} Myr for initial energies of 2.5, 0.50, 0.10, and 0.05 MeV/n, respectively (based on Northcliffe and Schilling 1970; note that the time for thermalization decreases only very slowly with decreasing initial energy). Particles propagating in dense clouds ($n_{\mathrm{H}} \approx 100\ \mathrm{cm}^{-3}$) are thermalized within ~ 100–1000 yr. The most favorable case is that of particles propagating exclusively in the dilute HIM ($n_{\mathrm{H}} \approx 3 \times 10^{-3}\ \mathrm{cm}^{-3}$), which is also the best candidate medium for a high-energy acceleration (§ IV*b*): there the thermalization times should be of the order of several times 10^6 years.[34]

5. OB associations, considered above as favorable source sites, are systematically linked with dense clouds in which suprathermal particles are thermalized in less than 1000 yr! So, only the "happy few" suprathermal particles that happen not to encounter the surrounding dense clouds at all have a significant chance of being reaccelerated to high energies. The question is "how few are the happy few?"

To answer this question a very complete modeling of OB associations is required, including the history of star formation, the rate of suprathermal particle emission by newly born low mass stars (T Tauri and young main-sequence stars; § IV*d*), the spatial distribution of the low-mass stars, massive stars, dense clouds, and dilute media, the development of stellar wind cavities and supernova shock waves, the confinement of suprathermal and high energy particles, and the X- and γ-ray emissions (à la Montmerle 1979, 1981; Cesarsky and Montmerle 1983). In this context, it may be noted that ionized media tend to confine energetic particles (Montmerle 1981), which might help suprathermal particles first emitted in the HIM not to traverse any neutral, dense medium at all. It may also be of importance that in dense cloud complexes later type stars (the injectors) seem to form continuously (Cohen and Kuhi 1979), while there are indications that OB stars may form only late in the game, when the complex is close to being dispersed (Doom, De Greve, and De Loore 1984). Reacceleration of suprathermal particles emitted by young later type stars having migrated into the dilute HIM just nearby the cloud complex may also be considered.

6. Constraints on the low-energy particle populations may also be obtained from the degree of ionization of clouds (to the extent that they are penetrated; Cesarsky and Völk 1978; Morfill 1982), nuclear gamma rays, and light element formation.

V. A COUPLED C AND ^{22}Ne EXCESS IN GALACTIC COSMIC RAYS

a) *General*

The value of $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$ ratio in the solar system is at present a matter of controversy. The directly measured SW value is 0.073 ± 0.002, which is apparently quite stable (Geiss 1973; Bochsler and Geiss 1976). Ne-B, which is presumably SW implanted in meteorites and lunar samples, yields a similar ratio, 0.080 ± 0.001 (Black 1972*a*, *b*, 1983; Podosek 1978). The directly measured SEP value is 0.120 ± 0.030 between 8 and 50 MeV/n (Mewaldt *et al.* 1979; Mewaldt, Spalding, and Stone 1983; Dietrich and Simpson 1979). The various data on Ne-C, which is presumably ~1 MeV/n SEP implanted in meteorites and lunar samples, suggest a ratio 0.086 ± 0.004 which lies near the lower bound of the larger error bar for directly measured SEP (Black 1972*a*, *b*, 1983; Podosek 1978; Venkatesan, Nautiyal, and Rao 1981; Venkatesan *et al.* 1983; Nautiyal *et al.* 1983; Wieler *et al.* 1983). While the interpretation of the implanted Ne-B and Ne-C ratios may always be subject to discussion (Podosek 1978; Black 1983), there is a clear difference between the directly measured SW and SEP $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$ ratios.

It has been argued that the SW value ought to be more representative of the Sun, in view of the relatively limited and reproducible biases in the SW elemental composition (§ II*b*, Fig. 2*b*), as compared to the huge variations of, for example, the Fe/O ratio in SEP (Fig. 1 of Paper I). But Dietrich and Simpson (1979), Mewaldt (1980), and Mewaldt, Spalding, and Stone (1983) have shown that the existing SEP data show no trend for a systematic dependence of the $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$ ratio on Fe/O, or on time and energy within a particular flare (see, however, Wieler *et al.* 1983, or Black 1983). A strong argument in favor of the SEP value being representative of the solar system is that the C, N, O, and especially the Mg isotope ratios in SEP have been found consistent with the terrestrial-

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[33] As discussed in § IV*a*, this condition is imposed by the fact that the accelerated particle compositions that can plausibly be derived from the HIM thermal gas do not match the observed GCRS composition.

[34] This is only an order of magnitude estimate, since the above values of the product $n_{\mathrm{H}}t$ have been calculated for a neutral medium.

meteoritic values, to within 30% for Mg. This makes a significant mass fractionation among Ne isotopes in SEP quite unlikely (Mewaldt *et al.* 1981*c*, *d*; Dietrich and Simpson 1981; Mewaldt, Spalding, and Stone 1983).[35] We shall therefore adopt here as a reference $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$ ratio a compromise between the directly measured SEP value and the marginally consistent, more precise, but also more ambiguous implanted SEP value (Ne-C): $^{22}\mathrm{Ne}/^{20}\mathrm{Ne} \approx 0.110\ (+0.040, -0.030)$. If the lower SW value turned out to be the correct one, the GCRS $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$ excess to be discussed below would be even larger.

As for the GCRS $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$ ratio, everybody agrees that it lies around 0.400 ± 0.100, i.e., ~ 3.5 times higher than the adopted solar system value. The GCRS $^{25,26}\mathrm{Mg}/^{24}\mathrm{Mg}$ and $^{29,30}\mathrm{Si}/^{28}\mathrm{Si}$ ratios are probably also higher than the solar system values, but by a smaller factor of order of ~ 1.7 (Fisher *et al.* 1976; Garcia-Munoz, Simpson, and Wefel 1979*a*, *b*; Dwyer and Meyer 1979; Freier, Young, and Waddington 1980; Young *et al.* 1981; Mewaldt *et al.* 1980, 1981*a*; Wiedenbeck and Greiner 1981*a*, *b*, *c*; Juliusson *et al.* 1981; Koch-Miramond 1981; Webber 1982*b*; reviewed by Mewaldt 1981).

What is the cause for the difference in Ne isotope ratio between GCRS and solar system? The hypothesis that the solar system value might be not relevant for the present-day local galactic medium, because of either galactic evolution or strong anomalies of the solar system abundances with respect to the average local medium (Olive and Schramm 1982), can probably be excluded (Audouze *et al.* 1981; Cassé 1981, 1983).

So, we are left with the more classical hypothesis that the $^{22}\mathrm{Ne}$ excess gives us evidence that GCRs contain newly synthesized matter. But we have shown in §§ IV*a*, *b* that the conspicuous characteristics of the bulk GCRS (and SEP!) elemental composition indicate that *most* GCR heavy nuclei were extracted from reservoirs with a normal "solar mix" basic composition, disturbed only by atomic selection effects. Therefore, *the* $^{22}\mathrm{Ne}$ *excess can only be due to a minor processed component*, *highly enriched in* $^{22}\mathrm{Ne}$, *highly diluted in solar-type material* in which only atomic selection effects are at work. In this situation indeed, only those species highly enriched in the minor component will stand out in the bulk composition (and in particular any *under*abundance in the minor component will be invisible).[36]

Now, there are essentially two nuclear processes capable of synthesizing significant quantities of $^{22}\mathrm{Ne}$ (Arnould and Norgaard 1978, 1981*a*, *b*; Cassé, Meyer and Reeves 1979; Woosley and Weaver 1981):

i) $^{20}\mathrm{Ne} + 2p \rightarrow {}^{22}\mathrm{Na} \rightarrow {}^{22}\mathrm{Ne}$ (via β-decays) in explosive H burning (above references; Wallace and Woosley 1981). This process is a plausible source for the Ne-E in meteorites (Arnould and Norgaard 1978, 1981*a*). This origin for the cosmic-ray $^{22}\mathrm{Ne}$, which we favored in Cassé, Meyer, and Reeves (1979) because the explosion itself spreads out the $^{22}\mathrm{Na}$ formed, now meets with difficulties. First, only small $^{22}\mathrm{Ne}$ enhancement factors can be reached, allowing only uncomfortably low dilution factors (~ 6) for the newly processed material. In addition, the temperatures required for $^{22}\mathrm{Na}$ synthesis are indeed expected *not* to be reached in the explosion of a Type II supernova (Arnould *et al.* 1980; Woosley and Weaver 1981). Only novae, and possibly Type I supernovae, might be favorable sites. Finally, $^{22}\mathrm{Na}$ might be destroyed by p-capture much more rapidly than previously estimated (Wallace and Woosley 1981).

ii) $^{14}\mathrm{N} + 2\alpha \rightarrow {}^{22}\mathrm{Ne}$ (via β-decay and $^{18}\mathrm{O}$), which occurs at the onset of ordinary, quiescent He burning in high- and possibly intermediate-mass stars (and in thermally pulsing red giants) (above references, and references therein). In this very common situation, *all* the $^{14}\mathrm{N}$ present when He burning sets in (i.e., all the original CNO in massive stars) is readily transformed into $^{22}\mathrm{Ne}$ and remains in this form throughout the $3\alpha \rightarrow {}^{12}\mathrm{C}$ phase. In sufficiently massive stars, $^{22}\mathrm{Ne}$ gets later on destroyed into $^{25,26}\mathrm{Mg}$, while $^{12}\mathrm{C}$ is being turned into $^{16}\mathrm{O}$. This process has two nice features: first, the $^{22}\mathrm{Ne}$ enhancement is large in the He burning zone, so that a high degree of dilution of the "newly cooked" material with ordinary material is possible. Second, it explains at once the C excess in GCRS as compared to SEP (Fig. 4*b*, § II*e*). A realistic site in which pure He-burning material could be brought into interstellar space may be provided by Wolf-Rayet stars (Cassé and Paul 1982). In § V*b* we discuss this $^{22}\mathrm{Ne}$ synthesis during He burning.

b) $^{12}\mathrm{C}$ *and* $^{22}\mathrm{Ne}$ *Production in* He-*burning Material*

We shall show that interpreting the $^{22}\mathrm{Ne}$ excess in GCRS in terms of a small fraction of the GCR material originating in He-burning zones of massive stars (highly diluted in material with normal, "solar mix" nuclear history) leads to the firm prediction that *one* other species, $^{12}\mathrm{C}$, should be overabundant in GCRS, by a factor of up to a few units ($^{18}\mathrm{O}$ may also have an associated excess, which is highly model dependent). The fact that, together with $^{22}\mathrm{Ne}$, specifically $^{12}\mathrm{C}$ is unambiguously in excess in GCRS (when compared to SEP; see Fig. 4*b* and § II*e*) can thus be regarded as a fairly model-independent signature of the above scenario. The possible excess of $^{25,26}\mathrm{Mg}$ and $^{16}\mathrm{O}$ could be understood in the same framework.

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[35] Two remarks apply at this point: *first*, Mullan (1983) has proposed that a selective preacceleration of SEP in collapsing magnetic neutral sheets might in some cases lead to an enhancement of $^{22}\mathrm{Ne}$ specifically. But we have shown in Paper I (Appendix C, § III) that this scenario should not be relevant for the genesis of SEP since it does not account for the observations of the *elemental* composition of SEP. *Second*, the directly measured SEP value agrees well with the so-called "planetary" Ne-A ratio $^{22}\mathrm{Ne}/^{20}\mathrm{Ne} = 0.122 \pm 0.006$, which has often been taken as a cosmic standard (Cameron 1982). This agreement is, however, no support to the SEP ratio. It is even rather embarrassing, since Ne-A has every reason to be abnormal because it has been observed to be intimately associated, in the same host phase, with the grossly anomalous Xe component "CCF Xe" (e.g., Anders 1981).

[36] So the hypothesis put forward by Woosley and Weaver (1981) that GRCs might be *undiluted* material ejected by supernovae in the inner part of the Galaxy (where the metallicity is higher than in the solar neighbourhood, so that a higher $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$ is produced, but by a small factor only) is not only very demanding from the point of view of GCR propagation, but also inadequate in explaining the elemental composition of GCR (as well as the fact that the $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$ ratio is much more enhanced than the $^{25,26}\mathrm{Mg}/^{24}\mathrm{Mg}$ and $^{29,30}\mathrm{Si}/^{28}\mathrm{Si}$ ratios) (§ IV*a*; Audouze *et al.* 1981; Cassé 1981, 1983; Mewaldt 1983).

A typical temporal evolution of abundances during the standard, quiescent He-burning is shown for illustrative purpose in Figure 9, for the case of a 15 $M_\odot$ star (scaled from Gallino and Masani 1979). The top plot shows mass fractions, and the bottom one the corresponding enhancement factors with respect to LG abundances within the He-burning zone. Except for the time scale, the picture would be very similar for stars of other masses, provided that they are massive enough for ^{18}O to be destroyed rapidly after its formation (i.e., probably $\gtrsim 12$ $M_\odot$; Thielemann and Arnould 1979; Arnould 1981), and small enough for ^{12}C not to be readily turned into ^{16}O, a condition still fulfilled in many massive Wolf-Rayet stars (e.g., Maeder 1983*a*; Prantzos and Arnould 1983).[37]

At the very onset of He-burning, *all* the ^{14}N present is readily converted into ^{18}O, which is in turn rapidly converted into ^{22}Ne. In sufficiently massive stars this ^{22}Ne will eventually be converted into ^{25,26}Mg, but only at a later stage: during most of the He-burning phase, all the original ^{14}N in the He-burning layer is in the form of ^{22}Ne. Meanwhile, the ^{12}C content slowly builds up by 3α process, long before ^{16}O production by burning of ^{12}C seriously sets in. So, if matter is ejected from a He-burning zone, it will be enriched in ^{22}Ne, and possibly in ^{12}C.

Now, in massive stars having undergone complete CNO cycle, the ^{14}N present at the onset of He-burning phase is all the original CNO. Assuming standard LG initial abundances (Table 2; on the scale Si ≡ 100 by number, $\mathrm{CNO_{LG}} = 3735$ and $^{22}\mathrm{Ne_{LG}} = 325 \times 0.11/1.11 = 32$), conversion of all this ^{14}N into ^{22}Ne leads to a ^{22}Ne overabundance by a factor of $3735/32 \approx 120$. To yield the observed GCRS overabundance factor of ~ 3.5, this component must be diluted with a component with standard $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$ by a factor of $120/(3.5-1) \approx 50$ (Meyer 1981*b*). This factor has been plotted in Figure 9, bottom.[38] Introducing the uncertainties on the various abundance ratios leading to this figure, the probable range for the dilution factor extends from ~ 25 to ~ 100.

Which accompanying anomalies should one expect in GCRS? With a large dilution of ~ 50, all overabundances by factors $\ll 50$ in the He-burning layer (in particular, that of ^{4}He, and *a fortiori* all underabundances) will never be visible in the GCRS composition. Therefore, only two other anomalies are to be expected from the ^{22}Ne-rich zone. First of all, ^{12}C is overabundant by factors comparable to ^{22}Ne during most of the He-burning phase. The maximal possible ^{12}C overabundance, obtained if all the initial H and He have been converted into ^{12}C, is $(\mathrm{H_{LG}}/4 + \mathrm{He_{LG}})/3\mathrm{C_{LG}} = (2.71/4 + 0.26) \times 10^6/(3 \times 1260) = 250$. With a dilution by a factor of 50, one gets a maximal possible GCRS ^{12}C excess of $1 + 250/50 \approx 6$ (in the case of Fig. 9, the maximum ^{12}C overabundance reached is ~ 190, i.e., a factor of ~ 5 after dilution, because some of the ^{12}C is burnt into ^{16}O before He is exhausted). Roughly, the ^{12}C content rises linearly throughout the He-burning phase, and a simpleminded time averaging over this phase in the case of Figure 9 yields an average ^{12}C overabundance factor of ~ 75, i.e., $1 + 75/50 = 2.5$ in the GCRS after dilution (Meyer 1981*b*). So, the observed C overabundance factor of ~ 2–3 in GCRS as compared to SEP (Fig. 4*b*; recall that C/O is "normal" in SEP) is right in the expected range.

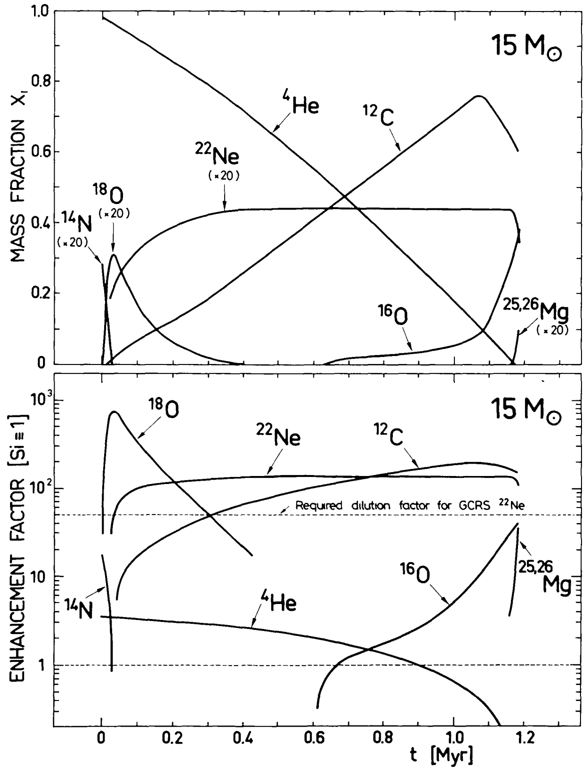

FIG. 9.—Time evolution of abundances in standard quiescent He burning for a 15 $M_\odot$ star (scaled down from Gallino and Massini 1979 for adequate LG initial abundances). *Top*: mass fractions X_i. *Bottom*: enhancement factors with respect to LG abundances, normalized to Si (which is not affected by He burning). The dilution factor of ~ 50 required to account for the GCRS ^{22}Ne excess is also indicated (§ V*b*).

We insist that the above conclusions that He-burning zone material (i) yields the observed GCRS ^{22}Ne excess if diluted in ~ 50 times as much "normal" material and (ii) yields simultaneously a comparable ^{12}C excess are ***highly model independent*** since it rests only on ratios of initial abundances in the star (standard LG). The only requirements are that ^{18}O be rapidly turned into ^{22}Ne (Thielemann and Arnould 1979; Arnould 1981), and that the bulk of ^{12}C be not turned into ^{16}O before exhaustion of ^{4}He and destruction of ^{22}Ne (Maeder 1983*a*; Prantzos and Arnould 1983).

The other possible directly coupled anomaly concerns ^{18}O. Here everything one can say becomes highly model dependent. The lack of a very large ^{18}O excess in GCRS (Wiedenbeck and Greiner 1981*c*; Webber 1982*b*; Mewaldt 1981) should permit one to set a limit to the amount of matter originating from He-burning zones in low-mass stars which do not rapidly burn their ^{18}O (Thielemann and Arnould 1979). In the case of a massive 15 $M_\odot$ star illustrated in Figure 9, if a zone in which He burning just started recently is ejected, ^{18}O overabundances by factors up to 720 can be present, leading

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[37] Using the new, higher, cross sections for $^{12}\mathrm{C} + {}^4\mathrm{He} \rightarrow {}^{16}\mathrm{O}$ of Kettner *et al.* (1982), Prantzos and Arnould (1983) have shown that in a 32 $M_\odot$ WC Wolf-Rayet star (corresponding to an initial mass of ~ 75 $M_\odot$), ^{12}C is still dominant during most of the time in which ^{22}Ne is enhanced.

[38] Time averaging over the ^{22}Ne content throughout the He-burning phase in the illustrative case of Fig. 9 would not yield a significantly different dilution factor.

to excesses by factors up to $1+720/50 \approx 15$ after dilution. But such large excesses do not last long. Again, a simpleminded time averaging over the He-burning period leads to an excess by a factor of ~ 2.5 after dilution, which is not in conflict with the present upper limit on the ^{18}O excess in GCRS (a factor of ~ 4; Wiedenbeck and Greiner 1981*c*; Webber 1982*b*; Mewaldt 1981). Note that more massive stars will produce even more short-lived ^{18}O peaks.

The question now arises: in which astrophysical site can we get matter out of a He-burning zone into space, without explosively reprocessing it, and without mixing it with products of fresh nucleosynthesis in other layers, that would conceivably bring other major composition anomalies (§ IV*a* [ii])? Cassé and Paul (1982), followed by Maeder (1983*b*), have proposed that WC-type Wolf-Rayet stars might be a suitable site from which *pure* He-burning material could be expelled into space: these very massive stars have indeed been peeled off by huge stellar winds deeply enough for the He-burning material to appear at their surface, and these same winds are efficient in dispersing the He-burning material, and possibly in accelerating it to MeV "injection" energies. The terminal shock of the wind might also further accelerate the particles to the GeV range (Cassé and Paul 1980). Whether this in situ acceleration scheme will work or will be cancelled by adiabatic energy losses within the huge wind cavity is at present controversial (see § IV*d* [iii]; Völk and Forman 1982; Cassé 1981; Cesarsky and Montmerle 1983). If adiabatic losses do kill the "injected" particles, one will have to have recourse to other, nearby "injectors" and high energy accelerators (SNR) to boost up some of the material spread out by the Wolf-Rayet star winds (§ IV*d* [iii]).

c) *Anomalies from Related Burning Stages*

If confirmed, the possible slight excesses of ^{25,26}Mg (§ V*a*) and of ^{16}O (Fig. 4*b*; § II*e*), which are direct burning products of ^{22}Ne and ^{12}C, may indicate that some slightly more processed material is also present in GCRS, possibly originating in the surface of WO-type Wolf-Rayet stars (Maeder 1983*a*, *b*; Prantzos and Arnould 1983; Prantzos, Arnould, and Cassé 1983). But the explanation of the comparable ^{29,30}Si excess (§ V*a*) at present does not seem possible in the same context (Prantzos and Arnould 1983). Limited galactic evolution effects might play a role here (Cassé 1981, 1983).

In the above discussion we have not considered the effect *of atomic* selection effects on the predicted overabundances of the "newly cooked" nuclides after dilution of the "processed" component. Of course, we cannot take in consideration all conceivable selection effects that might possibly affect the processed component (and it has been implicitly accepted above that no atomic selection effect distorts the C/Ne ratio in the processed component). But it should be kept in mind that in the main component in which the processed material is thought to be diluted, high-FIP C, O, and Ne are deficient by factors of ~ 6 relative to low-FIP Mg and Si. If the processed component happened *not* to be affected by the same bias, the "processed" Mg and Si atoms from a given zone would be diluted in ~ 6 times as many "normal" atoms of the same element as the corresponding "processed" C, O, and Ne atoms. This situation is likely to occur if GCRs are reaccelerated stellar energetic particles (§§ IV*a*, *b*) and if the origin of the "processed" material is indeed very hot Wolf-Rayet Stars, which are most likely devoid of chromospheres (§ IV*d* [i]).

On the other hand, the lack of a ^{14}N excess in GCRS (Fig. 4) may seem disturbing in the present context, since it appears plausible that some material originating in less processed zones (H burning by the CNO cycle, e.g., from the surface of WN-type Wolf-Rayet stars) should be present in GCRS as well. However, the N excess produced in the CNO cycle can reach only a factor of $\mathrm{CNO_{LG}/N_{LG}} = 3735/225 \approx 17$ (as compared to 120 for ^{22}Ne, and on the average ~ 75 for ^{12}C during the He-burning stage). Therefore, a factor of dilution of the H-burning material comparable to that required for the He-burning material (~ 50) would be sufficient to wipe off the N excess.

d) *The Mass Fraction of* He-*burning Material in GCRS*

It is useful to state more precisely what the requirement of a dilution factor of 50 for the ^{22}Ne and C rich He-burning material means. Strictly speaking, this factor of 1/50 is the ratio of the amount of ^{20}Ne originating in He-burning material to the amount of ^{20}Ne from the "normal," dominant component of GCRs. Here ^{20}Ne is a prototype of the species whose abundances are *not* affected by nucleosynthesis in the He-burning zone, i.e., which represent the same fraction of the total mass in the He-burning zone as in ordinary material. Therefore, if there had been no atomic selection effects in either of the cosmic-ray components, the dilution factor of 50 for ^{20}Ne would have simply implied that 2% of the total *mass* of GCRs originates in He-burning zones.

But, of course, there are atomic selection effects at work, which are well known for the dominant component of GCRs (Figs. 2*d* or 4*a*) and may be anybody's guess for the He-burning GCR component. To discuss their effect, we first consider the global mass budget in ordinary LG and in He-burning material: by mass, H, He, and heavier elements amount to, respectively, 70%, 28%, and 2% in ordinary matter, and to 0%, $\sim 50\%$, and $\sim 50\%$ (essentially C and some O) in He-burning zones (averaged over the duration of the He-burning period; Fig. 9, *top*). In both types of media, the mass fraction of ^{20}Ne is the same, $\sim 0.15\%$. Now, in the dominant GCR component, H and He are depleted by factors of ~ 4–6 relative to ^{20}Ne and other high-FIP elements (Fig. 4*a*), so that the mass fraction of ^{20}Ne in either ordinary LG or He-burning material is ~ 4 times smaller than in the dominant GCR component.

So, *if* for instance *no* atomic selection effect whatsoever takes place in the GCR He-burning component, injection of 2% of the GCR ^{20}Ne will correspond to a fraction of $\sim 8\%$ of the GCR mass originating in the He-burning material. *If* in the He-burning component He is depleted relative to Ne by the same factor as in the main component, this figure drops to $\sim 5\%$ of the GCR mass. Possible limited atomic selection effects *between heavy elements* in the He-burning component are unimportant as concerns this global mass budget (as long as they do not affect the C/O/Ne ratios).

VI. SUMMARY AND REQUIRED FUTURE WORK

a) *Summary*

We have shown the following:

1. The heavy element compositions of the solar corona, solar wind (SW), solar energetic particles (SEP; mass-unbiased baseline, Paper I), and galactic cosmic-ray sources (GCRS) are extremely similar (Fig. 2, § II). They all show the same basic pattern: an underabundance of all heavy elements with first ionization potential (FIP) $\gtrsim 9$ eV with respect to elements with FIP $\lesssim 9$ eV, by factors of ~ 4 (SEP) to ~ 6 (GCRS). (The constancy of this depletion factor for all heavy elements with FIP between ~ 9 and 22 eV is quite striking, especially in SEP).

2. There is one clear-cut exception to this similarity: C is 2–3 times as abundant in GCRS as in SEP. Oxygen may also be slightly more abundant in GCRS (by a factor of ~ 1.5) (Fig. 4*b*).

3. In the solar environment, the similarity between the coronal, SW, and SEP (m.u. baseline) abundances, as well as the constancy of anomalous abundance ratios such as Mg/O in SEP, strongly suggests that the SW and SEP (m.u. baseline) compositions primarily reflect the composition of the medium they have been extracted from, the corona, rather than a specific selection related to acceleration (§ III).

4. The Coronal heavy element composition itself seems to imply a selective rise of ionized relative to neutral heavies from the underlying cool chromosphere or from spicules: heavy ions must rise ~ 4 times as efficiently as heavy neutrals. It is probably the *ionized* heavies that behave like the (predominantly neutral) hydrogen gas (§ III).

5. *The bulk* of the GCR nuclei are most likely reaccelerated stellar energetic particles similar to solar energetic particles, originating in the coronae of ordinary, unevolved later type stars (type F–M). A plausible scenario would be that (i) a selective transport of ions and neutrals from cool stellar chromospheres to coronae yields stellar coronal compositions biased according to FIP, (ii) particles out of these coronae are accelerated to MeV energies ("injected") by stellar flares, and (iii) at a later stage some of these MeV particles are accelerated to GeV energies by strong shock waves, most plausibly in the hot interstellar medium (HIM). On the average, the two acceleration phases must not distort the original coronal composition (§ IV).

This scenario is, of course, very strongly suggested by the similarity between GCRS, SEP, SW, and solar coronal compositions.

But inspection of the sole GCRS composition is *by itself* sufficient to lead to the conclusion that most GCRs must originate in ordinary unevolved star surface material since (i) the GCRS major abundance anomalies are not correlated at all with expectations from specific nucleosynthetic processes, and (ii) it is very difficult to find an environment in the interstellar medium in which refractory elements are not locked in grains, and in which at the same time the temperature is low enough (and hot ionizing radiations weak enough) for FIP to play a role (§ IV*a*).

Low-mass stars ought to be the dominant injectors because they possess a corona, a transition region, and especially a chromosphere whose temperature is very similar to that of the solar chromosphere, independent of their spectral type from F to M. Meanwhile, massive O and B stars are too hot to maintain a chromosphere in which neutrals would survive. While massive stars certainly show more surface activity, low-mass stars are much more numerous, and they can also be very active in their youth, as well as throughout their lifetime if they are part of a binary system. The energetic particles emitted by massive stars may also not survive adiabatic energy loss in their huge wind cavities, nor traversal of associated dense clouds (§§ IV*d*, IV*e*[ii]).

One-step acceleration to high energy of most GCRs directly out of stellar coronal or wind material would not conflict with the GCRS composition, but is not plausible because it would require the high-energy acceleration mechanisms to be at work *specifically* within the stellar wind cavities of later type stars. One-step acceleration of most particles directly out of the HIM material, while accounting for the low H and He abundances in GCRS, would conflict with the discontinuous and nonmonotonic character of the GCRS composition anomalies when plotted versus Z or A/Z^* (unless the entire HIM has a solar coronal type composition, which is not suggested by the recent X-ray observations) (§ IV*a* [iii]).

6. So, via SEP and GCRS compositions, a link can possibly be established between the physics of solar and stellar chromospheres and coronae. GCRs might be direct probes of stellar coronal matter.

7. We have made no attempt to account for the low GCRS abundances of H and He relative to heavier species. In our view the behavior of these *light*, *dominant* elements may be controlled by different processes than those governing the *relative* abundances of the various *heavier*, *trace* elements. It should be noted that in SEP, the only accelerated population in which we have access to the behavior of the composition as a function of *time*, H and He generally do *not* follow the ordered pattern of the time variations of the heavier element abundances (§ III of Paper I; see also note [8]).

8. The GCRS N/O ratio, which is still a matter of debate, is a crucial clue to GCR origin (§ II*d*, *e* and Appendix). Our above interpretation would have to be considerably revised if this ratio turned out to be definitely lower than $\sim 6\%$. The shaping of the composition of the bulk of the GCR heavy nuclei by FIP and the similarity with the SEP composition would then break down, and GCRs would then have to originate in a medium specifically depleted in N.

9. Our analysis would also break down if the recent indications from elements heavier than zinc (Ge/Fe and Pb/Pt ratios) suggesting that volatility rather than FIP might be the parameter governing the GCRS abundances were confirmed (see note [20]). In this case GCRs would probably have to be grain destruction products, and the similarity with solar coronal and SEP compositions would be fortuitous.

10. The heavy element composition (from C to Fe) of low energy "injected" particles is not expected to be significantly distorted by any amount of coulomb energy loss during their interstellar propagation (at least in a neutral medium), pro-

vided most particles are injected below ~ 2.5 MeV/n (and down to at least 0.01 MeV/n). This is the result of pickup of electrons by low-energy ions. Therefore, two-stage acceleration scenarios can be acceptable from the point of view of composition (§ IV*e*).

11. The fact that, together with ^{22}Ne, specifically C is in excess by a factor 2–3 in GCRS relative to SEP is an unambiguous signature that a *small fraction* of GCRs (~ 1/50) originate in quiescent He burning zones (in which specifically ^{22}Ne and ^{12}C remain highly enriched for a long time; Fig. 9). A smaller contribution of slightly more processed material could account for the possible excesses of ^{24,25}Mg and ^{16}O (which are direct burning products of ^{22}Ne and ^{12}C). But a ^{29,30}Si excess does not seem easy to account for in this context (§ V).

b) *Future Work*

Several lines of future work should be pursued to check the validity of the ideas put forward in the present paper:

1. Development of detailed ionization models for the solar chromosphere and spicules.

2. Study of possible mechanisms for a selective transport of ionized and neutral heavies and of hydrogen from solar chromosphere to corona (see § III*c*). Thermal diffusion in extremely steep temperature gradients at the base of the transition region or in spicules may have to be considered.

3. Pursuit of coronal composition measurements, especially of those relating heavy element abundances to hydrogen.

4. Settling the key GCRS N/O ratio, which would require (i) further precise systematic measurements of the spallation cross sections for formation of B, ^{14}N, ^{15}N out of ^{12}C and ^{16}O over a wide energy range, and (ii) additional measurements of the B/C, N/O, ^{14}N/O, and ^{15}N/O ratios in GCRs at various energies, but especially at very high energies where the secondary component is smaller.

5. Further study of the few key elements, most of them low-FIP volatiles, which allow to distinguish between FIP and volatility as the parameter governing the GCRS composition. Except for Na, these elements are all heavier than Ni. The best indicators are Na, Ga, Ge, Rb, Ag, In, Sn, Cs, Pb (Meyer 1981*c*). Additional information might be obtained also from Cu, Zn, As, Cd, Fe, Os, Ir, Pt. Required are (i), of course, more GCR abundance measurements beyond Zn, (ii) improvement of the spallation cross sections, especially for the production of Na, and (iii) an evaluation of the uncertainty on the (LG) reference abundances, largely from meteoritic sources, for the volatile elements.

6. Further X-ray determinations of the composition of the hot interstellar medium, which would be important to exclude it definitely—or not—as a possible medium out of which GCRs could have been extracted.

7. Study of the coulomb losses of low-energy injected particles in ionized media and calculation of times for thermalization rather than stopping ranges as we have done here.

8. Investigation of the energetics and other constraints on injected low-energy particle populations, in the contexts both of the general ISM and of OB associations (sources: dMe or young F–M stars; time for thermalization vs. frequency of meeting a strong SNR or OB star wind shock wave capable of high-energy reacceleration; confinement of low- and high-energy particles in ionized and neutral media of OB associations; ionization of clouds; light element and nuclear γ-ray production).

9. Continued UV, X-ray, and radio observations of both the quiet outer stellar atmosphere and the flaring activity of the various types of main-sequence as well as pre–main-sequence stars, essential to help specify the injecting stars.

10. For suprathermal particles emitted by OB and Wolf-Rayet stars, investigation of the competition between adiabatic energy losses in the huge wind cavity and possible reaccelerations.

11. Further measurements of both the ^{25,26}Mg and ^{29,30}Si formation cross sections and abundances in GCRs, to confirm —or not—their excess in GCRS.

12. Studies of coupled ^{12}C, ^{16}O, ^{22}Ne, ^{25,26}Mg, and ^{29,30}Si nucleosynthesis in the He-burning phase, especially in Wolf-Rayet stars in which the He-burning products are directly ejected into space. One should, in particular, investigate whether a ^{29,30}Si excess can or not be accounted for in this context.

I am indebted to a large number of colleagues, in particular at Saclay and at Goddard (High Energy Astrophysics Laboratory, where part of this work has been done), for discussions which all have had an impact on this paper. More specifically, extensive discussions with David Flower, John Parkinson, and Thierry Montmerle on coronal abundance determinations and on stellar surface activity have been essential. I am in addition particularly indebted to Jean-Jacques Engelmann, Michel Cassé, and Pierre-Olivier Lagage, who have patiently read and criticized the various versions of the manuscript. I would also like to thank the anonymous referee, whose pertinent remarks have often led to significant improvements of the manuscript.

APPENDIX

THE N/O RATIO AT THE GCR SOURCES

There is, at present, an as yet unresolved contradiction between the low GCR *source* N/O ≈ ^{14}N/O ratio ≈ (4 ± 1)% derived from *low-energy* observations (60–500 MeV/n) and the higher ratios ~ (7 ± 2)% derived from the *high-energy* observations (0.8 to 25 GeV/n).

Observations of both the *elemental* N/O ratio and the more sensitive *isotopic* ^{14}N/O ratio near Earth are being used in these determinations. While there is a good continuity in the elemental N/O ratio observed at the various energies (e.g., Webber 1983*a*, *b*), there is an uncomfortably sharp apparent drop between the isotopic ^{14}N/O ratios observed in the high-energy and in the low-energy ranges. The low-energy isotope data, the result of direct observation of the isotopes by counters with good mass resolution, are very difficult to question (Preszler *et al.* 1975; Wiedenbeck *et al.* 1979; Guzik 1981; Mewaldt *et al.* 1981*a*, *b*;

Webber 1981*b*, 1982*b*, 1983*b*). But the high-energy isotope data, although obtained by the much more indirect geomagnetic method, are also not easy to question in view of the self-consistent masses obtained for the neighboring elements C and O, and of the convergent N mean masses obtained by different modes of analysis of the *HEAO 3* data in four different energy intervals (Byrnak *et al.* 1983*a*; Soutoul *et al.* 1983; Goret *et al.* 1983; see also Dwyer 1978).

The interpretation of the data depends critically on the cross sections for production of secondary ^{14,15}N (e.g., Guzik 1981; Mewaldt 1981), which were, until recently, measured only at high energy (2 GeV/n, Lindstrom *et al.* 1975), so that it was hoped that the discrepancy could be due to an overestimated ^{14}N production cross section at low energy. But the recent cross section measurements by Webber *et al.* (1983) show that this should not be the case.

On the other hand, the amount of matter traversed, and, hence, the secondary contribution to N or ^{14}N and its associated uncertainty, becomes smaller at high energy above a few GeV/n than in the low-energy range (e.g., Goret *et al.* 1981). It is also better determined. At low energy, indeed, uncertainties on the model for solar modulation might also interfere in the interpretation of the data (amount of interplanetary deceleration, and of preferential penetration of the heavier ^{15}N and ^{11}B isotopes).

So, *at high energy*, meaningful estimates of the source N/O ratio can be obtained separately from observations of both the elemental N/O ratio (Lezniak and Webber 1978; Goret *et al.* 1981; Webber 1982*a*, 1983*a*, *b*; Koch-Miramond *et al.* 1983) and the isotopic ^{14}N/O ratio (Dwyer 1978; Byrnak *et al.* 1983*a*; Soutoul *et al.* 1983; Goret *et al.* 1983). Consistent values are obtained, ~ $(7 \pm 2)\%$, the error including the uncertainties on the cross sections for formation of ^{14,15}N and on the B tracer. Also, *the purely secondary-to-primary ratios* ^{15}N/O *and* B/C *can be fitted simultaneously* (Perron 1983).

Meanwhile, *at low energy*, only the observed isotopic ^{14}N/O ratio can yield a meaningful source ratio. Most data suggest $\mathrm{N/O} \approx 4 \pm 1\%$ at the source (Preszler *et al.* 1975; Wiedenbeck *et al.* 1979; Mewaldt *et al.* 1981*a*, *b*; Webber 1981*b*, 1982*b*, 1983*b*; review in Mewaldt 1981), although Guzik (1981) obtained a source ratio of 7%. But, *unlike at high energy*, *one does not succeed in fitting simultaneously both tracer ratios* ^{15}N/O *and* B/C *with realistic estimates of the cross sections based on the existing measurements* (Perron 1983; for a somewhat different view, see Webber 1983*b*). Note that the calculated (B/C)/(^{15}N/O) ratio is almost independent of the models for interstellar propagation and solar modulation; it depends only on the cross sections.

In view of the self-consistent picture we get from the data on ^{14}N, ^{15}N, total N, and B at high energy, of the lower and better determined secondary contribution, and of the absence of possible problems with solar modulation at high energy, we shall tentatively adopt the N/O source ratio $(7 \pm 2)\%$ derived from the high energy data.[39]

But the contradiction between the two sets of data is still not understood. One possible way out, accounting for the low-energy observations in terms of a reacceleration of cosmic-ray nuclei *after* fragmentation, has been recently suggested by Silberberg *et al.* (1983). But the matter will be really settled only when a program of systematic, self-consistent accelerator measurements of the cross sections for $^{12}\mathrm{C} \rightarrow \mathrm{B}$ and $^{16}\mathrm{O} \rightarrow {}^{14,15}\mathrm{N}$ over a wide range of energies has been carried through.

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[39] Of course, the source ^{14}N/O or ^{15}N/O ratios might also change with energy. We shall disregard this bold hypothesis as long as absolutely compelling evidence does not force us to adopt it.

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(Continued from Cover 4)

"Line Identifications, Line Strengths, and Continuum Flux Measurements in the Ultraviolet Spectrum of Arcturus." KENNETH G. CARPENTER, ROBERT F. WING, AND ROBERT E. STENCEL.

The ultraviolet spectrum of Arcturus has been observed at high resolution (~ 0.2 Å) with the *IUE* satellite. Line identifications, mean absolute "continuum" flux measurements, integrated absolute emission-line fluxes, and measurements of selected absorption-line strengths are presented for the 2250–2930 Å region. In the 1150–2000 Å region, identifications are given primarily on the basis of low-resolution spectra. Chromospheric emission lines have been identified with low-excitation species including H I, C I, C II, O I, Mg I, Mg II, Al II, Si I, Si II, S I, and Fe II; there is no evidence for lines of C IV, N V, or other species requiring high temperatures. A search for molecular absorption features in the 2500–2930 Å interval has led to several tentative identifications, but only OH could be established as definitely present. Iron lines strongly dominate the identifications in the 2250–2930 Å region, Fe II accounting for ~ 86% of the emission features and Fe I for 43% of the identified absorption features.

"Catalog of CO Observations of Galaxies." FRANCES VERTER.

This paper includes all observations of CO isotopes in external galaxies up to spring 1984. Listed for each galaxy are (general) morphological type, apparent magnitude, diameter, recession velocity, H I content, (CO) antenna temperatures of detections and upper limits, detected and extrapolated integrated emission, and distribution of emission in mapped galaxies. For each reference the telescopes used, the features examined, the portion of the galaxy observed, and the uncertainties in the data are given. Calibration and notation conventions are discussed, and conversion factors are given.