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THE ELEMENTAL AND ISOTOPIC COMPOSITION OF GALACTIC COSMIC RAY NUCLEI

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1. Introduction

Galactic cosmic rays represent a directly accessible sample of matter that originates outside the solar system. The elemental and isotopic composition of this sample of high-energy matter contains a record of nucleosynthesis in other regions of the galaxy, and of subsequent nuclear and electromagnetic interactions that have altered its composition. There have recently been significant new advances in reading this record, brought about in large part by the launch of new high-resolution instrumentation. In particular, measurements of the abundances of individual elements have now been extended into the upper 2/3 of the periodic table, and the individual isotopes of a number of heavy cosmic ray nuclei have recently been resolved. As a result, we can now specify the composition of cosmic ray source material in much greater detail.

The primary focus of this report is recent progress in addressing the following question: In what ways is the composition of the matter that gets accelerated to be cosmic rays similar to, or different from, the composition of solar system matter? The answers to this question are providing important new quantitative clues to the origin and evolution of this high-energy sample of matter from the galaxy. The report is divided into three main sections, covering the composition of: 1) elements with nuclear charge $Z \lesssim 28$; 2) ultraheavy ($Z \gtrsim 30$) nuclei; and 3) cosmic ray isotopes. Each section summarizes observational advances, theoretical implications, and progress that can be expected within the next few years. I have limited the discussion to the energy region (~30 MeV/nucleon to ~100 GeV/nucleon), where direct measurements of individual elements or isotopes are presently possible. Following the report is a bibliography, as well as references to other work cited in the text.

Because the purpose of this report is to summarize U.S. contributions to this topic over the last four years (1979-1982), I will not report on important contributions that have recently been made outside of this country, although in many cases non-U.S. work will be cited in the context of the topics discussed.

2. The Elemental Composition of Cosmic Ray Nuclei from Helium through Nickel

With improvements in the resolution and collecting power of both satellite and balloon-borne instruments, the cosmic ray (CR) abundances of all the elements from H to Ni (atomic number Z=1 to 28) have now been measured. Comprehensive observations of individual elements have now been carried out from ~0.1 to ~20 GeV/nucleon, while some of the more abundant elements have been measured up to ~100 GeV/nucleon.

In order to relate the measured composition to the cosmic ray source (CRS) composition, it is necessary to correct for high-energy fragmentation reactions that occur with the interstellar gas, in which "primary" CR nuclei, accelerated at the source, produce lighter "secondary" CR nuclei. This requires a "cosmic ray propagation" calculation (see, e.g., Reames, 1974) which takes into account the fragmentation cross sections, radioactive decay, ionization energy loss, and the mean free path for the escape of cosmic rays from the confining influence of the galactic magnetic field. The escape mean free path (λ) is obtained by determining the amount of material necessary (6 to 7 g/cm^2) to produce the observed abundance of secondary elements such as Li, Be, and B (assumed to be absent in the source). Also taken into account in the above procedure are solar modulation effects. Using such calculations, the secondary contribution to each element (or isotope) can be subtracted to obtain the source composition.

Source Abundances of Cosmic Ray Elements

In the energy range from ~0.1 to ~2 GeV/nucleon, three studies, two by the Chicago group (Dwyer and Meyer, 1981; Dwyer et al., 1981) and one by the New Hampshire group (Webber, 1982b) have recently obtained improved source abundances for a wide range of elements through Ni. At higher energies (~1 to ~20 GeV/nucleon), the French-Danish experiment on HEAO-3 has reported a similar study (Koch-Miramond, 1981).

A comparison of the source abundances for the more abundant elements from these four studies shows that they agree to within ~20% (Mewaldt, 1981). This implies that to a good approximation the source composition is independent of energy/nucleon (however, see also Dwyer et al., 1981), as concluded by Koch-Miramond (1981). In addition, measurements extending up to ~100 GeV/nucleon (see, e.g., Simon et al., 1980; Chappell and Webber, 1981) are consistent with the source composition determined at lower energies. Thus there appears to be a reasonably well-defined CRS composition that can reproduce measurements over ~3 decades in energy.

Table 1 summarizes average source abundances for elements from He to Ni, based mainly on the 0.2 to 2 GeV/nucleon data discussed above, but also including other inputs as indicated. The uncertainties in the table include propagation uncertainties, and also take into account differences between the results of the various studies. Note that there are now at least 15 elements with $Z \lesssim 28$ that are known to be present in significant quantity in the cosmic ray source. With the possible exception of Li, Be, and B, the other ele-

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Table 1. Comparison of Cosmic Ray Source and Solar System Elemental Compositions

Z	Element	Cosmic Ray Source[a]	Solar System[b]
2	He	11500 ± 1000	1.8×10^5
6	C	465 ± 40	1110
7	N	20 ± 10[c]	231
8	O	525 ± 50	1840
10	Ne	62 ± 5	260
11	Na	9 ± 3	6.0
12	Mg	110 ± 7	106
13	Al	14 ± 3	8.5
14	Si	100	100
16	S	14 ± 3	50
18	Ar	4 ± 2[d]	10.6
20	Ca	7 ± 2[e]	6.25
26	Fe	92 ± 12	90
28	Ni	4.8 ± 0.6[f]	4.8

[a] Based mainly on 0.1-2 GeV/Nucleon data from Dwyer et al.(1981) and Webber (1982b), with other inputs as noted

[b] Cameron (1981).

[c] Based also on isotope data (Section 4.)

[d] See also Webber (1981b).

[e] See Tarle et al.(1979b); Young et al. (1981); Webber (1981b).

[f] See Binns et al.(1981), Minagawa (1981).

ments are undoubtedly also present, but because of greater fragmentation contributions to these rarer species, it can presently be said with confidence only that their source abundance is less than a few per cent of that of Si.

Comparison with the Solar System Composition

During the past decade it has become evident that differences in the CRS and solar system (SS) elemental abundances are correlated with first ionization potential (I), or some related atomic parameter (see, e.g., Cassé and Goret, 1978). With improved source abundances, and additional elements, this pattern has now become clearer. Figure 1 shows the ratio of the CRS to SS abundance for 21 elements, including recent results for even-Z nuclei with 30≲Z≲42 from HEAO-3 (Binns et al., 1981; Israel, 1981; see also Section 3). Note the striking extent to which I organizes the data: for I < 8 eV the ratio CRS/SS is approximately one or somewhat greater, while elements with I > 8 eV are noticeably depleted in the CR source with respect to the solar system. While the functional form of this correlation is not yet clear (both exponential, and two plateaus have been suggested), there will clearly be some elements that are exceptions to any choice.

The SS abundances used throughout this report (for both elements and isotopes) are from the recent compilation by Cameron (1981), based on a combination of meteoritic, terrestrial, and solar measurements. Although the extent to which this compilation represents the composition of the Sun is not well known, it serves as a useful standard for comparison. Figure 1 includes only the CRS uncertainties, but there are also uncertainties in the SS abundances. In a compilation similar to Cameron's, Meyer (1979) estimates uncertainties for some elements as large as ~50% (Ne, Ar); for others ~30% (C, N, O, S); and for the remaining elements with Z<30 less than ~20%. Thus, significant errors in the SS abundances are not likely to be the cause of the correlation in Figure 1 (however, see Webber, 1982b).

A second interesting comparison, shown in Figure 2, is the ratio of the CRS abundances to average solar energetic particle (SEP) abundances from measurements of nuclei accelerated in large solar flares. This comparison has also become better defined recently because of improvements in both the CRS and SEP abundances (see the report by R. E. McGuire in this volume). The fact that this ratio is ~1 for most elements implies that the SEP/SS ratio also depends on I (see Webber, 1975; Cook et al., 1980), and suggests that whatever atomic (or other) selection effects have produced the pattern in Figure 1 have also affected the source or acceleration of SEP nuclei (Mogro-Campero and Simpson, 1972; Webber, 1975).

While the overall picture that emerges from Figure 2 is one of similarity, there are also important exceptions. These exceptions are more evident when nearby elements are compared, in which case the uncertainties (due largely to systematic flare to flare variations in the SEP

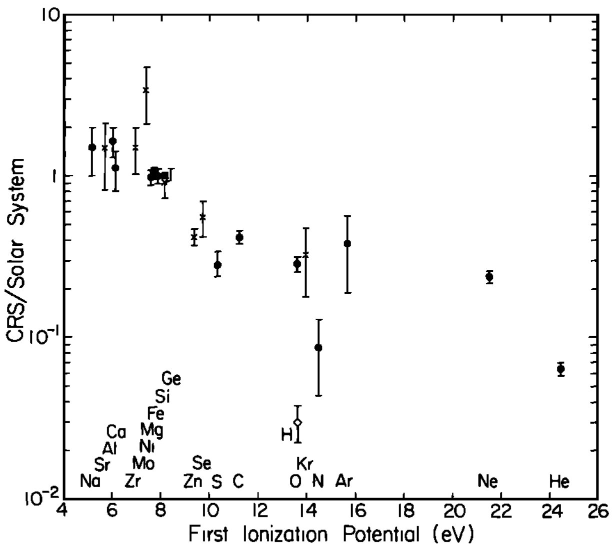

Figure 1. Ratio of cosmic ray source (CRS) to solar system abundance for 21 elements (assuming Si=1; solid square). The CRS data is from Table 1 for Z≲28 (solid dots) and from Israel (1981) for Z≳30 (x's). These two data sets are normalized at Fe. A 20% uncertainty in the Z≳32 normalization to Fe (Binns et al., 1981) has been included. The H point (diamond) is based on Webber and Lezniak (1974).

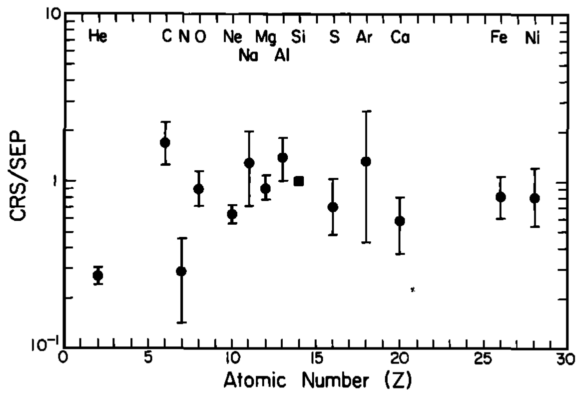

Figure 2. The CRS/SEP ratio vs. atomic number, normalized at Si. The CRS abundances are from Table 1, while the SEP abundances are flare-average data from Cook et al. (1980) and Cook (1981). The uncertainties include flare to flare variations in the SEP abundances relative to Si.

abundances relative to Si) are considerably reduced. for the CRS, C:N:O ≈ 0.9:0.03:1 (see Table 1) while for SEPs, C:N:O ≈ 0.5:0.12:1 (Cook et al., 1980), and thus C is overabundant and N depleted (see also Section 4) in the CRS composition. He, and to a lesser extent Ne, are also depleted. Although such differences may be important clues to the nucleosynthesis of CRS material (see, e.g., Webber, 1982b), Figures 1 and 2 suggest that atomic rather than nuclear processes are mainly responsible for the difference between the CRS and SS (as well as the SEP and SS) compositions.

Interpretation of the Element Composition

While there is insufficient space in this report to adequately discuss theories for the origin and acceleration of cosmic rays, I will attempt to give an idea of the kinds of models that are currently being discussed. For further information see Cassé (1981).

There are now a number of reasons to believe that cosmic rays are accelerated by shock waves from supernovae (see, e.g., Blandford and Ostriker, 1980; Axford, 1981). However, within the context of such acceleration models (or others) there are several possible sources for the material that gets accelerated, including: (a) a sample of the interstellar medium; (b) fresh supernova ejecta (e.g., Colgate and Petshek, 1979; Wefel, 1980); (c) matter lost from other stellar objects (e.g., Montmerle, 1979); (d) interstellar grains (e.g., Tarafdar and Apparao, 1981); and finally, (e) mixtures of the above; in particular, mixtures of freshly synthesized and interstellar medium (ISM) material (e.g., Hainebach et al., 1976). While all of these possibilities can (with other assumptions) account to some extent for the general trend of the CRS elemental abundances, they all encounter difficulties with at least some of the details.

A second important question is the extent to which the source composition has been altered, either prior to, or during acceleration to high energies. Shock acceleration models can produce enhancements that vary with the mass A divided by the effective charge Z^* of the ion. (see, e.g., Eichler and Hainebach, 1982). For a source of solar composition this A/Z^* dependence can produce a general overabundance of heavier elements, as observed, but many individual elements remain unexplained (see, e.g. Cesarsky et al., 1981). Figure 1 is often assumed to be evidence of "preferential acceleration" in which I or some closely related atomic property has been instrumental in selecting CR (and also SEP) ions for acceleration. It has proven difficult, however, to incorporate this idea into acceleration models in a natural manner (see, e.g., Cassé and Goret, 1978).

Another possibility is that atomic selection effects occur prior to CR acceleration, as may be the case on the Sun, where it appears that the coronal composition (which SEPs presumably sample) differs from that of the photosphere (Cook et al., 1980; J. P. Meyer, 1981). Thus the similarity of the CRS and SEP compositions might be consistent with the suggestion that cosmic rays represent material ejected from stellar coronae by flares or stellar winds (e.g., Montmerle, 1979; Cassé and Paul, 1980).

While the CRS elemental abundances appear to reflect mainly the atomic properties of the elements, there is now clear evidence from CR isotope studies (see Section 4) that the nucleosynthesis of CRS material has differed from that of SS material. This has led to suggestions of new models (see Section 4) and placed new constraints on the models described above. In particular, there is renewed interest in sources that contain at least some freshly synthesized material.

Future Prospects for Cosmic Ray Element Studies

During the next few years we can expect that instruments on Voyagers 1 and 2, and on ISEE-3, will have accumulated sufficient data to determine improved abundances for some of the rarer elements with $Z \lesssim 30$. These studies, and those from HEAO-3 at higher energies, should extend the list of elements for which definite source abundances can be determined. Note, however, that in many cases, the accuracy of the cross sections, and not the observations, is the limiting factor in such studies. Thus, in an increasing number of instances (see also Section 4), a lack of nuclear physics measurements is limiting progress in astrophysics.

I expect that the most exciting new observations over the next few years may come from the University of Chicago experiment to be launched on Spacelab 2 in 1984. This experiment will measure nuclei from Li to Fe with ~50 to >2000 GeV/nucleon, an energy regime virtually unexplored to date.

It is known from measurements of various "secondary/primary" ratios that at energies above ~2 GeV/nucleon cosmic rays have passed through less material. This is usually interpreted as energy-dependent confinement to the galaxy with a mean path length (λ) that decreases from ~7 g/cm^2 at ~2 GeV/nucleon to only 1 or 2 g/cm^2 at ~100 GeV/nucleon (see, e.g., Protheroe et al., 1981). Thus very high energy cosmic rays are a more "pure" sample of the source composition. Among other things, Spacelab 2 should determine whether λ continues to decrease above 100 GeV/nucleon, and whether the composition of the "primaries" changes at very high energies.

3. Ultra-Heavy (Z>30) Cosmic Ray Nuclei

Although nuclei with Z>30 comprise ~2/3 of the periodic table, their combined abundance in nature and in cosmic rays is only $\sim 10^{-4}$ of that of Fe. While this rarity makes them difficult to measure, these so called ultra-heavy (UH) nuclei are of particular interest because they can provide important new tests of cosmic ray origin and propagation models.

UH nuclei are thought to be synthesized predominantly by the so-called r (rapid) and s (slow) neutron-capture processes, each of which results in a characteristic elemental abundance distribution (see. e.g., Clayton, 1968). Thus, in SS material, some UH elements are predominantly due to the r-process, or to the s-process, while others contain roughly equal contributions from both processes. Since it would not be surprising if cosmic rays contained a non-solar mix of r- and s-process material, a determination of the contribution of these processes to CR nuclei would provide important clues to the origin and evolution of CRS material. For example, earlier studies (see, e.g., Shirk and Price, 1978) have concluded that r-process nuclei dominate cosmic rays with Z>70, as might be expected for a supernova origin.

Prior to 1979, UH cosmic ray nuclei were studied mainly using plastic track-detectors and nuclear emulsions. These detectors had the necessary collecting power, but their charge resolution was several charge units wide, so that only groups of adjacent elements could be studied. During 1979 the first electronic UH detectors were launched into space on Ariel-6 and HEAO-3. These instruments provided improved charge resolution, and covered a wider range of elements (Z ≈ 20 to Z ≈ 120). The HEAO instrument allows individual UH elements to be studied for the first time with reasonable statistical accuracy. To date even-Z nuclei through Z=56 have been resolved. With further analysis and instrument calibrations, it is expected that even-Z elements through Z=82 can be identified.

Cosmic Ray Nuclei with 30<Z<42

Using a portion of the HEAO-3 data, Binns et al (1981; see also Israel, 1981) determined the source abundances of the even-Z nuclei with $30 \lesssim Z \lesssim 42$ and, as shown in Figure 1, found the same general dependence on I as for lighter elements. In addition, Binns et al. concluded that their results were inconsistent with a CRS composition dominated by r-process nucleosynthesis, and more nearly comparable to a source with SS composition.

Cameron (1982) has recently re-analyzed the r- and s-process contributions to SS nuclei with Z≥32. Comparing his abundance distributions (combined with I dependence) with the latest HEAO results for even-Z nuclei with $32 \lesssim Z \lesssim 42$, it is more difficult to distinguish between possible source compositions of r-process, s-process, or SS material. There are several reasons for this difficulty. First of all, for each of the even-Z elements with $32 \lesssim Z \lesssim 42$, the relative r- and s-process contributions are similar, and it is therefore difficult to find definitive tests of either an r- or s-process signature. Secondly, some elements expected to be depleted in the r-process (e.g., $_{38}$Sr) are enhanced by the I-dependence, the exact form of which is uncertain. Finally, since the solar system r-process contributions are all small (<25%) for these six even-Z elements, their magnitudes are not accurately determined. As a result, it appears to me that with the available CR data, it is not presently possible to rule out a source dominated by either r-process or s-process nucleosynthesis for this charge region.

Other tests of this question might be applied, however, when more refined HEAO (or other) data become available for this charge region. A characteristic of the Cameron (1982) abundances is that the relative abundance of the odd-Z elements is ~10 times greater in the r-process than in the s-process. If it is possible to determine (or place meaningful limits on) the source abundances of odd-Z elements such as $_{35}$Br, $_{37}$Rb, $_{39}$Y, they are especially sensitive to r-process contributions. In addition, enhanced source abundances of the even-Z elements $42 \lesssim Z \lesssim 48$ would be indicative of r-process nucleosynthesis. Unfortunately, the very elements with sizable r-process contributions are in general somewhat rarer, and therefore more sensitive to secondary contributions from interstellar fragmentation. It should also be kept in mind that other nucleosynthesis processes may also contribute to this charge region (Wefel et al., 1981).

Nuclei with 50<Z<83

More definitive tests of nucleosynthesis can be made using the elements with $50 \lesssim Z \lesssim 56$ and $76 \lesssim Z \lesssim 83$ (see, e.g., Blake and Margolis, 1981, 1982; Brewster et al., 1983; Tsao et al., 1981). For $50 \lesssim Z \lesssim 56$ the elements $_{50}$Sn and $_{56}$Ba are dominated by the s-process, while $_{52}$Te and $_{54}$Xe are dominated by the r-process. Preliminary HEAO results indicate that r-process nucleosynthesis does not dominate this charge region (Israel, 1981; see also Tsao et al., 1981).

For nuclei with Z>70, the r-process produces mainly $76 \lesssim Z \lesssim 78$ (including $_{78}$Pt), while the s-process produces mainly $80 \lesssim Z \lesssim 83$ (including $_{82}$Pb). Studies to date (e.g., Shirk and Price, 1978; Fowler et al., 1981) have concluded that this charge region is dominated by Pt rather than Pb, thus favoring an r-process source. It has also been reported that there is an overabundance of Z>74 nuclei with respect to $50 \lesssim Z \lesssim 56$ nuclei (Fowler et al., 1981). HEAO measurements in this charge region (not yet reported) will be important because they should have inherently better charge resolution, and also an absolute calibration of the charge scale through accelerator calibrations with Z ≈ 80 nuclei.

The Abundance of Cosmic Ray Actinides

Included in the actinide group are the long-lived radioactive elements $_{90}$Th, $_{92}$U, $_{93}$Np, $_{94}$Pu, and $_{96}$Cm, which might survive in significant quantities in cosmic rays. The importance of the

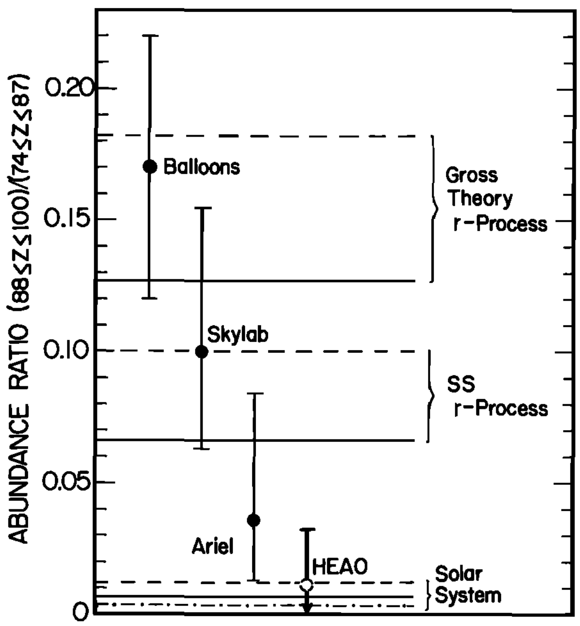

Figure 3. Comparison of observed cosmic ray "actinide"/"Pt-Pb" ratios with predicted values (from Binns et al., 1982). Data points: Balloons (Fowler et al., 1977); Skylab (Shirk and Price, 1978); Ariel (Fowler et al., 1981); HEAO (Binns et al., 1982). Theoretical lines: solid and dashed (Blake et al., 1978), where the dashed lines in each case include corrections due to first ionization potential. Dot-dashed line (Brewster et al., 1983) is for a source composition like the solar system today, rather than at the time of its formation.

actinides is two-fold: 1) they are made only in the r-process; and 2) several of the radioactive species might serve as "clocks" to estimate various CR time scales (see, e.g., Margolis et al., 1979).

Several studies (e.g., Fowler et al., 1977; Shirk and Price, 1978) have concluded that CR actinides are overabundant by a factor of ~10 or more when compared to SS material, suggesting that the cosmic ray source is enriched in the products of r-process nucleosynthesis. The HEAO experiment, however, finds a significantly lower actinide abundance than in earlier studies (Binns et al., 1982).

For normalization purposes, it is conventional to use the $(89 \lesssim Z \lesssim 100)/(74 \lesssim Z \lesssim 87)$ abundance ratio, commonly referred to as the "actinide" to "platinum-lead" ratio. Note that $84 \lesssim Z \lesssim 89$ nuclei are all short-lived, so there should be a noticeable gap between the Pt-Pb and actinide groups. The HEAO experiment observed at most 1 "actinide" event, compared to 101 Pt-Pb nuclei, giving an upper limit of 0.03 for this ratio. Figure 3 shows that this new result is inconsistent with the earlier results from balloon-borne detectors and from Skylab. The HEAO result is consistent with the recent Ariel-6 measurement, but sets a much more stringent upper limit on the CR actinide abundance.

Binns et al., (1982) point out that the HEAO-3 experiment has better charge resolution than the other measurements, and suggest that their lower actinide abundance most likely results from a reduction in the spillover from the Pt-Pb region. Except for the actinides, the various measurements of other groups of elements are in relatively good agreement (see, e.g., the comparison in Mewaldt, 1981).

Figure 3 also includes calculated ratios, based on various assumed source compositions. The HEAO result is the first that is clearly inconsistent with a source composed only of freshly synthesized r-process material. Thus, while the earlier results indirectly favored a supernova origin, the HEAO actinide result is consistent with a SS composition, and thus with models in which cosmic rays are a sample of ISM material. However, other possibilities also remain, including a source with a non-solar mix of r- and s-process material, such as the s-process enhancement suggested by the model of Olive and Schramm (1982). Another possibility is an "aged" r-process source (non-freshly synthesized material), for example, the r-process part of the present-day SS composition.

It now appears that such possibilities can, at present, be best tested with lower-Z elements such as the Pt-Pb region. To further explore the actinide region and its interesting possibilities will require an experiment with at least an order of magnitude greater collecting power, combined with good charge resolution.

Interstellar Propagation of UH Nuclei

Because UH nuclei have relatively short interaction mean free paths (1 to 2 g/cm^2 of H) they can provide sensitive tests of CR propagation models. Although there have been several calculations of UH propagation in the galaxy, there has so far been only limited comparison with UH observations. I expect some of the following problems to be addressed within the next year or so.

The basic question is whether UH observations are consistent with conventional models devised for lower-Z nuclei, or whether new models are required. Preliminary comparisons (Mewaldt; 1981, Brewster et al., 1983) suggest that more fragmentation has occurred than expected from the conventional "leaky-box" model, in which there is an exponential distribution of CR path lengths whose mean is $\lambda \cong 7$ g/cm^2. Thus, "truncated" path length distributions (deficient in path lengths < 1 g/cm^2) suggested for lighter nuclei, might agree better with UH observations (Blake and Margolis, 1981; Brewster et al., 1983; Protheroe and Ormes, 1981). Protheroe and Ormes (1981) suggest that there should be considerable energy dependence observed in various secondary/primary ratios, which should be looked for in the data. Finally, now that the LBL Bevalac can accelerate relativistic nuclei heavier than Fe, significant improvement in UH cross sections is possible.

These and other problems have implications not only for propagation models, but also for source abundance determinations for many "primary" UH nuclei. The ultimate tests of propagation models will come when abundances of individual elements (even-Z, if not odd-Z) are available over a broad charge range.

UH Summary

Although only the first results from the new electronic UH detectors have as yet been reported, it is already clear that atomic selection effects continue to be important, at least through Z=40, and probably throughout the charge spectrum. Unambiguous evidence for differences in the nucleosynthesis of UH cosmic rays and SS material is, however, proving to be more elusive than suggested by earlier observations. While the HEAO results presently available are, in general, consistent with SS abundances, the range of possibilities is still large. If there are significant anomalies in the CRS composition of UH cosmic rays, I expect that they will become evident when the composition of the Pt-Pb region is better determined, as suggested by earlier results.

4. Cosmic Ray Isotopes

Although it is only recently that high-resolution measurements of CR isotopes became experimentally possible, they have already altered our views of both CR origin and propagation. This is because cosmic ray isotopes contain a new kind of information - a detailed record of their nuclear history, including their synthesis in stars and subsequent high-energy nuclear interactions with the interstellar gas. The CR element distribution, in contrast, appears to be determined largely by atomic interactions, and it reflects only very weakly the rare isotopic species that carry the most significant nuclear information.

Recent progress in measuring CR isotopes has been due in large part to the launch of two high-resolution isotope spectrometers on ISEE-3 (built by U. C. Berkeley and by Caltech); the first space experiments specifically designed to measure the isotopic composition of heavy CR nuclei. Figure 4 shows examples of the ISEE data, where it can be seen that all the isotopes

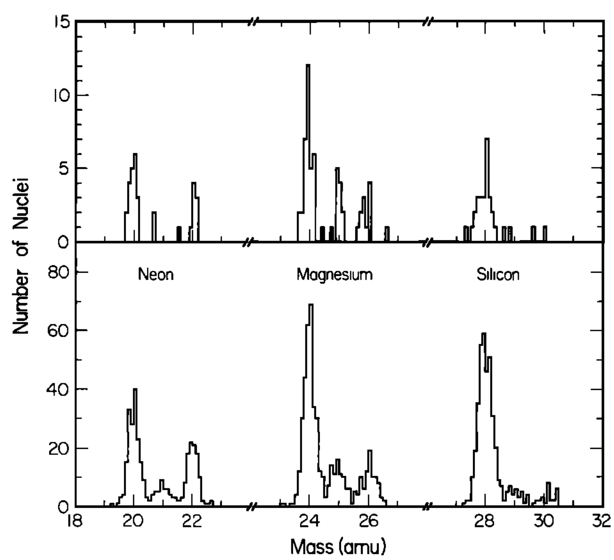

Figure 4. Measured mass distributions for CR Ne, Mg, and Si isotopes from the Caltech (top) and Berkeley (bottom) experiments on ISEE-3.

are individually resolved with an rms mass resolution ≅ 0.2 amu. There have also been noticeable improvements in the mass resolution of recent balloon measurements.

Source Abundances of Cosmic Ray Isotopes

As with cosmic ray elements, the accuracy with which isotope source abundances can be determined depends on the magnitude of the fragmentation contribution to the measured abundance (Stone and Wiedenbeck, 1980). There are 25 to 30 isotopes with Z<30 where this secondary contribution is <50% (see Adams et al., 1981) and propagation corrections are relatively minor, including several elements where two or more isotopes can be studied (e.g., Ne, Mg, Si, Fe, and Ni). In other interesting cases (e.g., ^{13}C, ^{14}N, ^{18}O) propagation corrections presently limit the source abundance accuracy.

We consider first elements where only one of the isotopes has a presently-measurable primary contribution; even here isotope measurements can improve determinations of the source composition. Thus three groups (Tarlé et al., 1979b; Young et al., 1980; Webber, 1981b) have found the ^{40}Ca/Fe source ratio to be ~0.06 to 0.09 by combining isotope measurements with the fact that more than 90% of the arriving ^{40}Ca is of primary origin. Ca is an important element for determining if the CRS/SS ratio (Figure 1) continues to increase for I < 7 eV (Tarlé et al., 1979b). Similarly, Webber (1981b) has determined the ^{36}A/Fe source ratio. Another important source ratio is ^{14}N/O, discussed below.

The Nitrogen Abundance in the Cosmic Ray Source

The significance of the CRS ^{14}N abundance was pointed out by Silberberg et al., (1975; see also Hainebach et al., 1976) who concluded that a depletion of N would favor models where the source material resembles supernova ejecta rather than a sample of the ISM. This abundance is best determined by N isotope studies which measure the CR ^{15}N/N ratio and use ^{15}N as a tracer of the fragmentation contribution to the observed ^{14}N (assuming ^{15}N has negligible source abundance as in the solar system where ^{15}N/N = 0.004).

Although earlier CR ^{15}N/N measurements ranged from ~0.4 to ~0.6, three new experiments with unambiguous isotope separation (Wiedenbeck et al., 1979; Mewaldt et al., 1981; Webber, 1982a) give a weighted average of ^{15}N/N = 0.56±.02, a value close to that expected from fragmentation alone (~0.6; Guzik, 1981), implying that most of the observed ^{14}N is of secondary origin. The resulting source abundance is ^{14}N/O = 0.03±.02, using cross sections (and their uncertainties) from Guzik (1981).

For SS material, Cameron's (1981) tabulation gives ^{14}N/O = 0.125, consistent with recent coronal, photospheric, and SEP measurements, while ^{14}N/O ≅ 0.10 in the local ISM (Hawley, 1978). Thus it appears that ^{14}N is depleted by at least a factor of two with respect to the solar system and local ISM, which argues against present models in which a majority of cosmic rays originate from typical ISM material (Silberberg et al., 1975; Mewaldt et al., 1981), and favors a supernova origin (Hainebach et al., 1976)

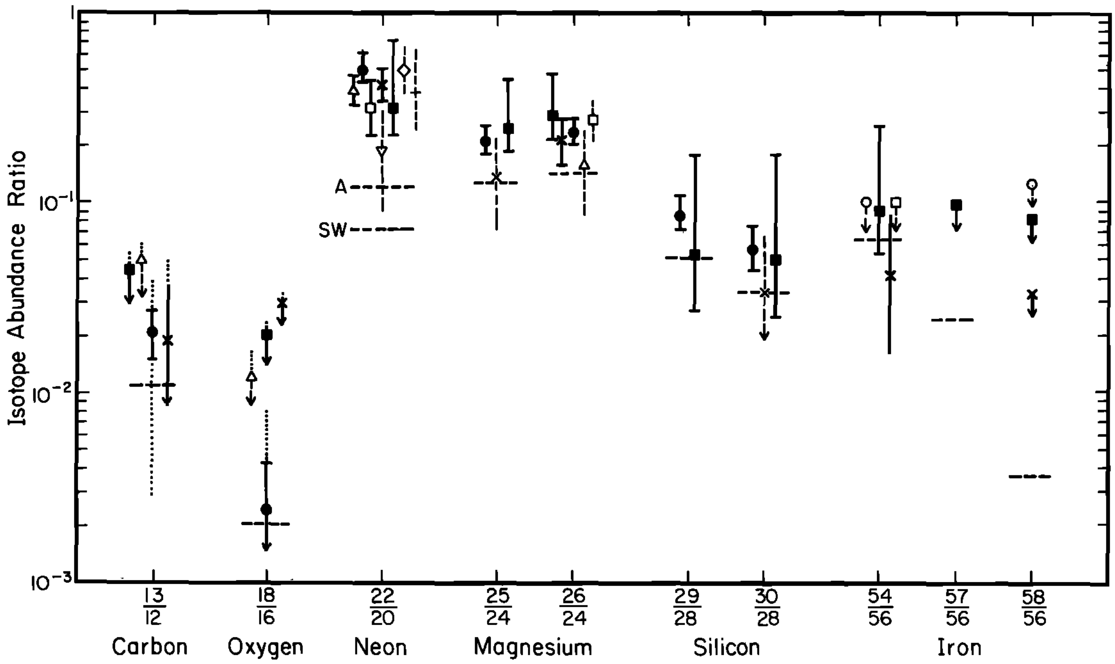

Figure 5. Comparison of selected cosmic ray source (CRS) measurements with solar system measurements for various isotope abundance ratios. The SS values (horizontal dashed lines), including neon-A (A), are from Cameron (1981), except for solar wind neon (SW). CRS measurements based on "unresolved" data (see text) are shown with dashed vertical error bars. Dotted extensions to the C and O error bars indicate propagation uncertainties (Wiedenbeck and Greiner, 1981c). Satellite data: ● Wiedenbeck and Greiner (1981a, 1981b); ■ Mewaldt et al. (1980a, 1980b, 1981); △ Garcia-Munoz et al. (1979c, 1979d), and Guzik (1981); + Koch-Miramond (1981). Balloon data: O Tarlé et al. (1979a); ▽ Dwyer (1978), and Dwyer and Meyer (1979); □ Freier et al. (1980), and Young et al. (1981); ◇ Maehl et al. (1975); × Webber (1981, 1982a).

It should be pointed out that measurements of the elemental N abundance suggest a somewhat larger source abundance (N/O ≈ 0.05 to 0.09; see e.g., Dwyer et al., 1981; Webber, 1982; and Goret et al., 1981). In addition, the N production cross sections are not well known (Guzik, 1981). It is likely that the cross sections will be directly measured in the next year or two. In the meantime, CR nitrogen remains a controversial topic (see also Guzik, 1981; Mewaldt, 1981; Goret et al., 1981; and Cassé, 1981).

Source Abundances of Neutron-Rich Isotopes

The most important new result from recent CR isotope measurements has been the discovery of enhancements in the source abundances of various neutron-rich isotopes. In these cases it is possible to deal with isotope abundance ratios of the same element (e.g., $^{22}Ne/^{20}Ne$) without possible complications introduced by atomic selection effects.

Prior to the last few years CR isotope experiments had succeeded in demonstrating that both CRS and SS material are dominated by the same isotopes (e.g., the "alpha-particle nuclei" ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, and ^{28}Si). In addition, two groups had reported measurements that implied a significantly greater CRS $^{22}Ne/^{20}Ne$ ratio than in the solar system (Maehl et al., 1975, Preszler et al., 1975). There was not, however, general agreement on whether the isotopic composition of CRS and SS matter differed.

Since 1978, several groups have confirmed the CRS $^{22}Ne/^{20}Ne$ enhancement (Garcia-Munoz et al., 1979c; Mewaldt et al., 1980a; Wiedenbeck and Greiner, 1981b; see also Figure 5), and significant enhancements have also been reported in the neutron-rich isotopes of Mg (Mewaldt et al., 1980a; Freier et al., 1980; Wiedenbeck and Greiner, 1981b), and also Si (Wiedenbeck and Greiner, 1981a).

Figure 5 summarizes selected determinations of ten CRS isotopic ratios relative to the SS abundances of Cameron (1981). To aid the reader, a distinction has been made between "resolved" and "unresolved" isotope measurements, based on whether the mass resolution achieved is sufficient to cause a "valley" between adjacent isotopes (Stone, 1973). If so, (e.g., Figure 4), it is likely that statistical uncertainties dominate. For "unresolved" measurements it is possible that undetermined systematic uncertainties not reflected in the quoted error bars may be important, and thus greater weight should be given to "resolved" measurements.

As Figure 5 indicates, there is now general agreement that the CRS ^{22}Ne abundance is several times greater than in the solar system. [Note that $^{22}Ne/^{20}Ne$ in the Sun is controversial (see, e.g., Podosek, 1978); the two most likely choices are the meteoritic component neon-A ($^{22}Ne/^{20}Ne$ = 0.122), or solar wind neon ($^{22}Ne/^{20}Ne$ = 0.073)]. There also appears to be general agreement that ^{25}Mg and ^{26}Mg are overabundant, but by a lesser amount than ^{22}Ne. For Si, there is only one

Table 2. Comparison of Cosmic Ray Source and Solar System Isotopic Composition

Abundance Ratio	Enhancement Factor[b] (CRS/SS)
$^{13}C/^{12}C$	≤ 4
$^{18}O/^{16}O$	≤ 4
$^{22}Ne/^{20}Ne$	$3.5 \pm .6$ or 5.8 ± 1.0[a]
$^{25}Mg/^{24}Mg$	$1.6\ ^{+.4}_{-.3}$
$^{26}Mg/^{24}Mg$	$1.6 \pm .25$
$^{29}Si/^{28}Si$	$1.6\ ^{+.5}_{-.3}$
$^{30}Si/^{28}Si$	$1.6\ ^{+.5}_{-.4}$
$^{54}Fe/^{56}Fe$	≤ 1.7
$^{58}Fe/^{56}Fe$	≤ 10

[a]Depending on whether neon-A or solar wind neon is used as a standard.
[b]Uncertainties indicated include propagation uncertainties.

measurement that combines high resolution with good statistics, which finds that ^{29}Si and ^{30}Si are also enhanced (Wiedenbeck and Greiner, 1981a).

The isotopes ^{13}C and ^{18}O are less abundant than those considered above. Although a ^{13}C enhancement is possible, in this case (as for ^{18}O) propagation uncertainties dominate (mainly cross section uncertainties), and preclude a definite conclusion (Wiedenbeck and Greiner, 1981a). Cross section measurements might resolve the important ^{13}C question.

While there has been considerable progress in measuring the Fe isotopes, and it is now established that ^{56}Fe is the dominant CR Fe isotope, the present measurements of the other Fe isotopes still allow for significant differences from solar abundances.

Table 2 (see also Figure 6) summarizes CRS isotope enhancement factors, based on a weighted mean of the "resolved" measurements in Figure 5. Note that in each of the five cases where the enhancement (or depletion) factor is known to ~50% accuracy or better, a difference between the CRS and SS compositions has been found. Thus CR isotope anomalies appear so far to be the rule rather than the exception.

In the ISM, anomalies have been detected in the C, N, and O isotopes (see, e.g., Wannier, 1980). It is interesting that the ISM and CRS anomalies are of similar magnitude (e.g., ^{13}C is enhanced by a factor of ~1.5 in the galactic plane and ~3 in the galactic center; Wannier, 1980). By comparison, isotopic anomalies in SS material are typically ~100 times smaller (Lee, 1979). While there are as yet no elements where a direct comparison between CR and ISM results is possible, the best candidates appear to be C (assuming accurate measurement of the ^{13}C production cross sections) and Si (Wiedenbeck and Greiner 1981a; Penzias, 1981).

Interpretation of Cosmic Ray Isotope Anomalies

The differences in the isotopic composition of CRS and SS matter imply that cosmic rays have had a different nucleosynthesis history than the matter immediately around us. This discovery has stimulated several proposed explanations (for further discussion, see Casse, 1981; and Wefel, 1982a, 1982b).

Since neutron-rich isotopes are "second-generation" nucleosynthesis products, their abundance in the galaxy should gradually increase with time (Arnett, 1971). Woosley and Weaver (1981) point out that the yield of many neutron-rich isotopes produced in massive stars is proportional to the initial "metallicity", i.e., the fraction of heavy elements (Z>2) in the material that formed the star. They suggest, therefore, that the excess of neutron-rich isotopes might result if cosmic rays originate in regions of the galaxy that are metal-rich compared to the solar system, possibly because cosmic rays are younger (age ~10^7 years; Wiedenbeck and Greiner, 1980) than the solar system (age ~5×10^9 years), or because of inhomogeneities in the galactic metal distribution. Woosley and Weaver make quantitative predictions relating a number of isotopic ratios (see Figure 6).

The "supermetallicity" model is consistent with the nearly equal enhancements observed for the four neutron-rich Mg and Si isotopes (for an ~80% metallicity increase), but fails to explain the large ^{22}Ne enhancement. This might suggest the need for an additional source of ^{22}Ne. However, since Ne has several distinct isotopic components in the solar system, it is possible that neither neon-A or solar wind Ne is representative of the ISM from which the solar system formed.

A number of models, proposed to explain the ^{22}Ne overabundance, suggest that cosmic rays may include contributions from a limited class of stellar objects (or stellar zones within these objects) that are rich in ^{22}Ne. Among the possibilities suggested are: explosive hydrogen burning in novae or supernovae (Cassé et al., 1979;

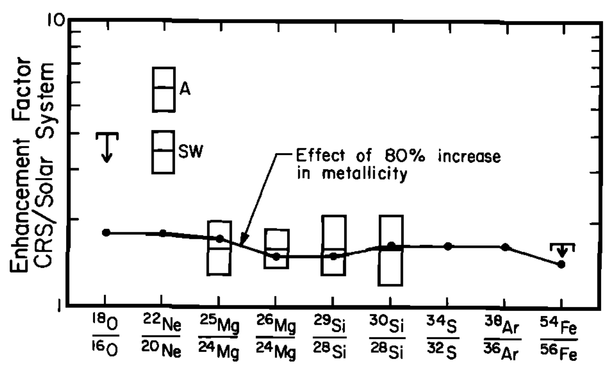

Figure 6. Measured and calculated enhancement factors for nine isotope abundance ratios. The CRS measurements (boxes) are from Table 1, where both neon-A (A) and solar wind neon (SW) have been used as a SS standard. The uncertainties indicated include worst-case propagation uncertainties (Wiedenbeck and Greiner, 1981c). Calculated enhancements (solid dots) are derived from Woosley and Weaver (1981) assuming a metallicity 80% greater than that of the solar system.

Audouze et al., 1980); low-mass supernovae (Cassé et al., 1980; Woosley and Weaver, 1981); and various possibilities that enhance the yield of He-burning products (Casse et al., 1979; Woosley and Weaver, 1981; Arnould and Norgaard, 1981), including Wolf-Rayet stars (Cassé and Paul, 1982). It is not yet clear, however, if such sources could account for the observed Mg and Si isotope anomalies.

An interesting alternative point of view has been proposed by Olive and Schramm (1982). Their scenario assumes that the solar system formed after the first few supernova (SN) explosions within an OB association (a region of active star formation containing many O and B type stars). These SN added an excess of α-particle nuclei and r-process nuclei to the proto-solar nebula, as well as material that led to isotope anomalies in meteorites. Later, less massive SN contributed most of the ^{22}Ne and s-process nuclei to the local ISM after the solar system formed. In this model, cosmic rays could be representative of the ISM, while the solar system (used as our standard) would be anomalous because of the addition of material just prior to its formation. Tests of this model include ^{13}C and s-process enhancements in cosmic rays. Thus CR measurements might shed light on the events associated with the formation of the solar system.

Future Prospects for Cosmic Ray Isotope Studies

Our knowledge of the isotopic composition of CRS material is still very limited. Only for the Ne, Mg, and Si isotopes have the source abundances been determined to an accuracy of ~30% or better, and in each case they have been found to differ. It is clearly important to extend these measurements to other elements to see if this pattern continues. In particular, Fe and Ni both have several isotopes sensitive to nucleosynthesis conditions. Another important quantity for discriminating between CR origin models is the time-delay between nucleosynthesis and acceleration. This might be obtained from measurements of various electron-capture isotopes in cosmic rays (see, e.g., Adams et al., 1981).

During the next few years we can expect progress from further analysis of existing satellite data, and from new balloon experiments. However, to extend determinations of the CRS isotopic composition to many of the important rare isotopes, and to "read" the most interesting CR "clocks", will require instruments with mass resolution as good or better than the ISEE instruments, but with 1 to 2 orders of magnitude greater collecting power. The next high-resolution isotope spectrometer to go into space (built by the University of Chicago and collaborators) will be launched on the ESA Solar Polar Mission, scheduled for 1986. This instrument should collect about a factor of 10 more data than the ISEE instruments, and determine the source composition of the more abundant isotopes. Beyond that, the technology is now available to build a high-resolution spectrometer that could improve on the ISEE data base by a factor of >100, and determine the source abundances of even rarer isotopes.

5. Concluding Remarks

The past four years have been marked by significant advances in the precision of cosmic ray composition measurements. It is clear from these new observations that the differences between cosmic ray and solar system matter result from a superposition of effects, including atomic, nucleosynthesis, and propagation processes. Until the last decade, only the nuclear and electromagnetic interactions occurring during CR propagation in the galaxy could be clearly identified. However, CR element studies have now provided clear evidence that atomic selection effects are important, at least through Z=40, and probably throughout the periodic table. As little as four years ago, many would not have included nucleosynthesis differences on the list of processes that have shaped the CR composition - this new dimension is now required by the clear evidence that the isotopic composition of CR material differs from that of SS material.

The improved observations now available have inspired a number of new suggestions as to how and where CR nucleosynthesis, acceleration, and propagation takes place, and it is possible that all the essential pieces to the cosmic ray origin puzzle are now on the table. It remains, however, to identify which of the many available pieces fit together, and to interlock these into a complete picture.

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U.S. NATIONAL REPORT TO INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS 1979-1982

THE COMPOSITION, PROPAGATION AND ACCELERATION OF ENERGETIC SOLAR PARTICLES: A REVIEW OF UNITED STATES RESEARCH 1979-1982

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We study solar energetic particles in an effort to better understand physical processes which occur at the Sun and in the heliosphere, but improvements in our understanding of the physics of these processes should have broader implications in more general astrophysical problems. Among the questions of greatest interest are: (1) what is the basic elemental and isotopic composition of the solar atmosphere, to what extent is this composition reflected in observed energetic solar particles and how do these abundances relate to or influence our understanding of universal and galactic cosmic ray abundances; (2) by what mechanisms, under what conditions and where does the acceleration of solar energetic particles take place; (3) what are the mechanisms by which energetic particles are transported and/or stored in the vicinity of the Sun; (4) how can we describe the escape from the Sun and subsequent transport of charged solar particles through interplanetary space and how can we relate that description to measurable properties of the medium through which they travel?

Each of the above points raises numerous and difficult subsidiary questions. But probably the primary obstacle to direct study of these problems is that the various processes and mechanisms are almost inextricably interwoven observationally (Wibberenz, 1979). All measurements that we make of particles in space (e.g., composition, time evolution of intensities and anisotropies, energy spectra) are influenced both by the nature of the original particle acceleration and by the propagation of these particles from the acceleration site to the observing instruments.

It is the intent of this review to cover major developments in American research related to solar energetic particles, both observational and theoretical, during the last four years (late 1978 to late 1982). The organization of this review is divided into three major sections, loosely defined on the basis of (1) time independent measurements (e.g., solar event-averaged elemental, isotopic and charge state composition, electron and ion spectra), (2) time dependent measurements (e.g., intensity and anisotropy versus time, at multiple energies and for multiple species) subdivided into the topics of interplanetary propagation and coronal transport/storage, and (3) the question of the injection and primary acceleration mechanisms. To some extent, this choice of organization mirrors the organization of the 1978 reviews but the material covered here together was then the subject of two separate reviews, one on composition (Gloeckler, 1979a) and one on solar particle transport and acceleration (Van Hollebeke, 1979).

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Composition and Spectra

It is particularly in the area of solar energetic particle composition (elemental, isotopic, and the distribution of charge states) that there has been substantial progress in solar particle research over the last four years. This progress is primarily the result of improved instrumentation available at a time of higher solar activity.

The subject of elemental and isotopic abundances has been recently reviewed by Mewaldt (1980) and the reader is referred to this review for additional detail, as well as the review by Gloeckler (1979a) for earlier references. Recent studies of basic elemental solar particle composition include Dietrich and Simpson (1978), McGuire et al. (1979a, 1981b), Cook et al. (1979, 1980), Mason et al. (1979a, 1979b, 1980) and Reames and von Rosenvinge (1981). These analyses cover a combined energy range from 1 to