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CONSTANCY OF THE He TO MEDIUM NUCLEI RATIO IN THE SOLAR COSMIC RAYS

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Constancy of the He to Medium Nuclei Ratio
in the Solar Cosmic Rays

(A Reply to A Statistical Study of Solar Protons,
Alphas, and $Z \geq 3$ Nuclei in 1967-68
by Armstrong and Krimigis)

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Introduction

The constancy of the relative abundances of the multiply charged nuclei of the same charge-to-mass ratio above about 20 MeV/nucleon in solar cosmic ray events has been a concept which has developed from detailed experimental measurements on charge and energy spectra, and has been tested several times in a number of events (Fichtel and Guss, 1961; Biswas et al., 1962; Biswas et al., 1963; Biswas et al., 1966; Durgaprasad et al., 1968; Bertsch et al., 1969). It has been indicated previously (e.g. Biswas et al., 1962; Fichtel and McDonald, 1967; Durgaprasad et al., 1968) that the energetic solar nuclei coming from the sun with charges ranging from that of helium through at least 16 appear to be in good agreement with the composition of the solar surface, where comparisons can be made.

Recently, on the basis of data obtained at low energies with a single-element solid state detector, Armstrong and Krimigis (1971) have questioned the constancy of the helium to medium nuclei ratio, and the justification for using it to estimate the solar helium abundance. Specifically, their conclusion is based on several measurements of the ratio of helium nuclei in one channel corresponding to an energy interval from 0.5 to 2.5 MeV/nucleon to heavier nuclei in another single channel, which they indicate corresponds to an energy/nucleon interval of 0.56 to 9.5 MeV/nucleon for carbon, 0.51 to 14 MeV/nucleon for nitrogen, and 0.47 to 19 MeV/nucleon for oxygen. The interval also corresponds to wider ranges of energy/nucleon for heavier elements which will be considered in detail in the next section of this paper. The ratio of these two channels, P4/P3, for different events is found to be variable and generally lower than the consistent 58 ± 5 value for the helium to medium (C,N,O) ratio at higher energies **where** each species is measured in the same energy/nucleon interval.

In spite of the different energy/nucleon intervals of the P4/P3 measurements and the fact that nuclei other than medium nuclei are included, Armstrong and Krimigis speak of the difference as an "apparent discrepancy" and use this together with solar wind data as an argument for questioning the concept of combining solar spectroscopic and solar cosmic-ray data for nuclei of the same charge-to-mass ratio to obtain a hydrogen to helium ratio for the sun. It is the intent of this paper to show that this is not a valid criticism, and that, although the limited information provided by the Armstrong and Krimigis detector makes interpretation difficult, the observed P4/P3 ratios, in fact, fall in a range that would be expected if the conditions existing at higher energies remain valid at lower energies.

Analysis and Discussion

P4 and P3 of the Armstrong and Krimigis experiment are related to pulse height thresholds in a single solid state detector. Assuming the channel sensitive to heavy nuclei is not enhanced by pile-up or splash events (There is no anticoincidence cup around this detector.), the higher channel, P3, corresponds to various energy/nucleon intervals for the different heavy nuclei and the second highest, P4, to the energy/nucleon interval for helium nuclei mentioned in the Introduction, together with very minor contributions from the heavy nuclei. Since there are no individual charge measurements in the experiment, and there are no energy spectral measurements for helium or medium nuclei, a charge and energy/nucleon spectrum must be assumed before P4/P3 can be interpreted. For the charge spectrum, we shall assume that the composition is the same as that measured at higher energies (The most recent summary is in Bertsch et al., 1971; it is essentially the same as that in Durgaprasad et al., 1968, and Bertsch et al., 1969.), which agrees with the solar spectroscopic measurements - the fundamental difference from the Armstrong and Krimigis paper being that nuclei heavier than oxygen will not be ignored here. The spectral shape will first be assumed to be of the form

$$J\ (>E) \sim E^{-a} \qquad (1)$$

since this form seems to be as good a representation as any in the low energy region (e.g., Lanzerotti, 1969), at least late in solar particle events. In the non-relativistic region being discussed here this shape is equivalent to a power law spectrum in rigidity for particles of the same charge to mass ratio. For the moment, "a" of Equation (1) will be left as a variable, although its value will be discussed later.

Table I lists the relative abundances of the more abundant solar cosmic rays together with the energy/nucleon interval in which the nucleus would be detected in the Armstrong and Krimigis detector (Armstrong and Krimigis, 1968, and Krimigis and Armstrong, 1966). For the heavier elements not considered by these authors, the energy interval was deduced from the description of their detector and the range energy curves given by Northcliffe and Schilling (1970). The energy/nucleon intervals determined in this manner for He, C, N, and O nuclei agree with those quoted by Armstrong and Krimigis. For the energy spectral shape mentioned in the last paragraph, P4/P3 becomes

$$\frac{P4}{P3} = \frac{n_\alpha \left(E_{1\alpha}^{-a} - E_{2\alpha}^{-a}\right)}{\sum_{z=3}^{26} n_z \left(E_{1z}^{-a} - E_{2z}^{-a}\right)} \qquad (2)$$

It is worth noting at this point that the P4/P3 ratio is sensitive to uncertainties in threshold setting, especially for steep spectra. Assuming, however, that the experimenters do know the threshold precisely, P4/P3 can be calculated as a function of "a". The results of this calculation are shown in Fig. 1. In Fig. 2, the results of a similar calculation wherein the spectral shape

$$J(>E) \sim \exp(-E/E_0)$$

was assumed are given. In both cases, P4/P3 values range from about 10 to 40 for values of "a" and "E_0" that might be expected. Notice that P4/P3 is smaller for steep spectra (large "a" and small "E_0") and for flat spectra than for intermediate spectra. The former result is due to the large contribution of nuclei heavier than oxygen at low energies, and the latter is due primarily to the contribution of C, N, and O nuclei in the higher part of the energy/nucleon interval available to them. This range of values is in good agreement with the P4/P3 data presented by Armstrong and Krimigis (1971). Thus there seems at present to be no discrepancy with the higher energy data.

With regard to the values of "a" and "E_0", very little is known about the spectral shape of helium nuclei at these low energies and essentially nothing about the medium nuclei energy spectral shape. Armstrong and Krimigis have tried to use their proton measurement as an indication of what the helium spectra might be. In addition to the difficulty of the proton spectra being known to be different from the heavier nuclei, the Armstrong and Krimigis measurements discussed in their paper are ambiguous because they are based on only two pulse height levels and thereby involve nested energy intervals. These data in general allow two solutions for any assumed one parameter spectral shape function, one steep and one flat, and cannot distinguish between spectral shape functions. The analysis here would suggest that a rather wide range of spectral values is being seen for the helium and medium nuclei data as would be expected both from the low energy proton data

(Bryant et al., 1962; Fichtel and McDonald, 1967; Lanzerotti et al., 1969; Simnett, 1971) and the higher energy helium and medium nuclei data referenced earlier. If the spectra should be steep as Armstrong and Krimigis suggest, Figs. 1 and 2 show clearly that it is still necessary to know how steep and what the spectral shape is before P4/P3 can be predicted for a specific case.

Even though the results of the Armstrong and Krimigis experiment, when interpreted more fully, are seen to be completely consistent with the higher energy solar cosmic ray particle measurements a word of caution should be added about using very low energy data for composition considerations. As has been emphasized from the earliest papers on solar cosmic ray composition (e.g. Biswas et al., 1962) and subsequent ones, the solar cosmic ray composition can be expected to reflect that of the source only for those nuclei whose charge-to-mass ratios are the same, since both velocity and rigidity effects enter into the propagation phase of the solar particles, and probably at least the latter stages of the acceleration process. Particles with different charge-to-mass ratios are known to have different energy/nucleon (or velocity) spectra and varying ratios during an event, as shown by measurements on protons and helium nuclei (e.g. Biswas and Fichtel, 1965).

Ions of any given velocity will attain an equilibrium average charge state after passage through very small amounts of material ($<5 \times 10^{-5}$ g/cm^2 for C and O). At $\sim$1 MeV/nucleon the dominant charge state for oxygen will be O^{+6} giving a mass-to-charge ratio of 2.7 (Heckman et al., 1963); helium at the same energy/nucleon will be fully stripped of electrons. There is also the possibility that these lowest energy nuclei may not be fully ionized because they are a part of a hot thermal distribution at the source. Thus, before consideration is given to comparing solar cosmic ray composition below a few MeV/nucleon to solar abundances, it is essential, at a minimum, to know that the energy/nucleon spectra of helium and medium nuclei are the same, as one possible indication that the medium nuclei are, or have remained, fully ionized.

The variation in the helium to medium ratio in the solar wind was also mentioned by Armstrong and Krimigis. The solar wind is a hot plasma being convected outward from the sun and is in effect an extension of the corona. Theoretically, substantial variations are expected in the ratio of heavy elements to hydrogen or helium in the solar wind because a heavy element excess tends to build up in the corona to varying degrees depending on solar conditions at any given time. As a compensating effect, heavy elements do not escape from the corona as readily. Over a very long time average, the solar wind composition may reflect that of the photosphere under the concept that the solar wind ultimately is a net flow of material from the photosphere; however, even if this is true, and it may not be, substantial variations in the solar wind helium to medium ratio on a short time scale are to be expected and, indeed, have been observed. Data from the Vela 3 satellite shows that not only are there large variations in the helium to hydrogen ratio over periods of the order of months, but also a general increase in the long time average value over the period of two years (Robbins et al., 1970). At present, data to provide a long term average over a continuous period for heavier elements do not exist; so the solar wind abundance cannot be considered relevant to the present problem of photospheric composition at this time (Hundhausen, 1970; Brandt, 1966).

Summary

In the previous section, it was shown that the P4/P3 values measured by Armstrong and Krimigis are not inconsistent with the solar cosmic ray composition measured at higher energies. In fact, the P4/P3 measurements are in the expected range when it is assumed that the composition of the solar cosmic rays multicharged nuclei are the same as at higher energies and all the energy/nucleon spectra of the particles with the same charge-to-mass ratio are the same. These conclusions were seen to result basically from the fact that the P3 channel records all heavy nuclei with energy bands which are increasingly wide as the nuclear charge increases and that the energy intervals for heavy nuclei are much wider than that of helium nuclei. The lower energy/nucleon threshold for heavier nuclei is important for steep spectra and the differing widths of the energy bands are important for flat spectra. A word of caution was also added about using very low energy MeV/nucleon measurements for composition purposes, even when the bare nuclei themselves have the same charge-to-mass ratios, until the energy spectra of at least two multiply-charged species are measured, since these nuclei may not be fully ionized.

Table I

Relative Abundances of Solar Cosmic Ray Nuclei in the Same Energy/Nucleon Interval Above 20 MeV/Nucleon, And Energy/Nucleon Intervals of the Armstrong and Krimigis Detector

Detector	Nucleus	n_z[*]	E_1	E_2
P_4	He	103	.54	2.5
P_3	C	.56	.58	9.5
	N	.19	.51	14
	O	1.0	.46	19
	Ne	.16	.40	45
	Mg	.056	.35	70
	Si	.028	.31	105
	S	.008	.28	155
	Fe	.011	.175	∞

[*] Bertsch, et al. (1971); Durgaprasad, et al. (1968); and Bertsch, et al. (1969).

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Figure Captions

Fig. 1. Variation of the P4/P3 measure of solar particle composition on Explorer 35 (see text) as a function of spectral index "a" assuming spectra of the form $J(> E) \sim E^{-a}$ for all multiply-charged nuclei and the relative abundances shown in Table I. The P4/P3 ratio becomes strongly shape dependent for steep (large a) and flat (small a) spectra owing to the effects of the different energy/nucleon regions sampled for different nuclear species. The predicted ratios are in reasonably good agreement with those measured by Armstrong and Krimigis (1971) for typical solar particle spectra.

Fig. 2 Variations of the P4/P3 measure of solar particle composition on Explorer 35 (see text) as a function of the spectral parameter E_o assuming spectra of the form $J(> E) \sim \exp(-E/E_o)$ for all multiply-charged nuclei and the relative abundances shown in Table I. The P4/P3 ratio becomes strongly shape dependent for steep (small E_o) and flat (large E_o) spectra owing to the effects of the different energy/nucleon regions sampled for different nuclear species. These predicted ratios are in reasonably good agreement with those measured by Armstrong and Krimigis (1971) for typical solar particle spectra.

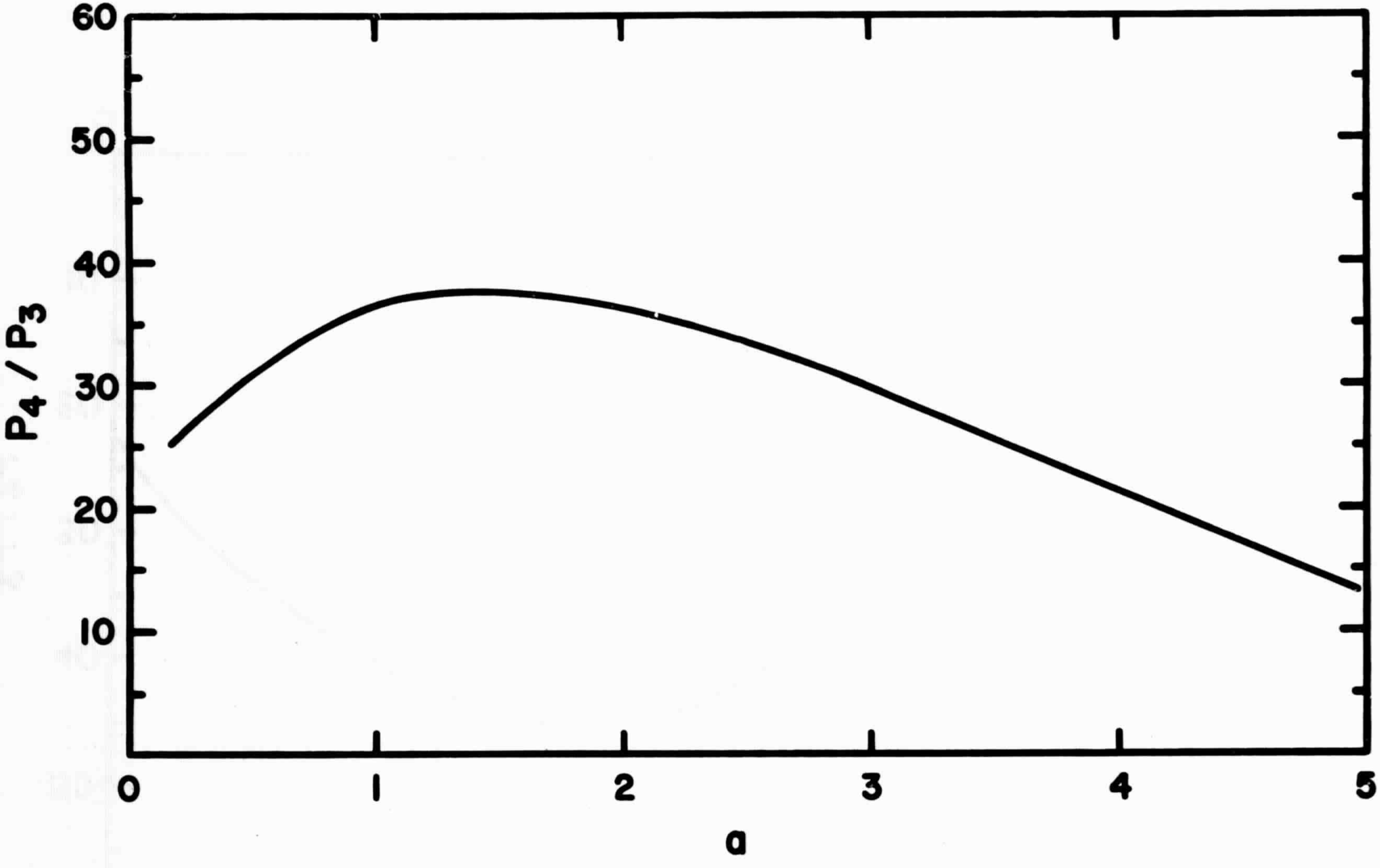

FIG. 1

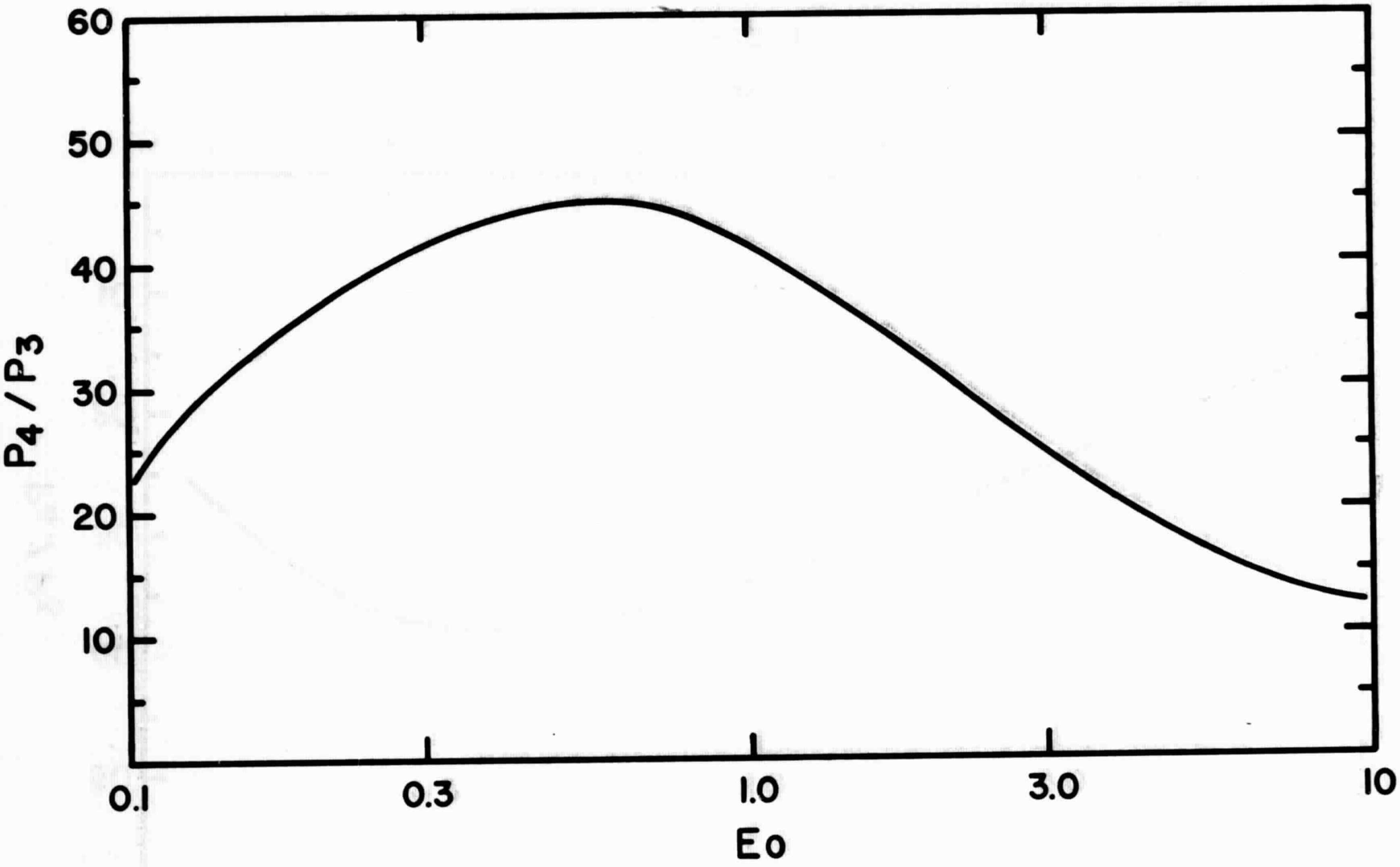

FIG. 2