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U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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Initial Observations of Geomagnetically Trapped Alpha Particles at the Equator

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**Space
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While the population of energetic protons trapped in the earth's radiation belt has been investigated in considerable detail, only a few experiments have been designed to search for heavy particles. We present in this report the first observations of alpha particle fluxes and pitch angle distributions at high altitudes ($3.1 \le L \le 5.2$) near the geomagnetic equatorial plane.

Included in the scientific payload of the S^3-A satellite is a Heavy Ion Telescope which measures the fluxes of ions with $Z \ge 2$. This telescope consists of two surface barrier solid state detectors of thickness 3.4 and 100 microrns (μ). The properties of such thin detectors, including the S^3-A 3.4μ unit, are discussed in detail by Wilken and Fritz [1972]. This telescope uniquely identifies the presence of alpha particles ($Z = 2$) and two groups of heavier ions, $3 \le Z \le 5$ and $6 \le Z \le 8$.

Energetic, geomagnetically trapped nuclei with $Z \ge 2$ were observed first by Krimigis and Van Allen [1967] using the low altitude satellite Injun 4. These trapped nuclei were assumed to be alpha particles and their intensities and spatial distributions at low altitudes were determined. These results were confirmed and extended by Fritz and Krimigis [1969] using the low altitude satellite OGO-4 and by Paulikas, Blake and Freden [1968] [also Blake and Paulikas, 1970, 1972] using the low altitude satellites 1966-70A, 1968-26B, and 1969-25C. The results of most of these measurements have been summarized by Krimigis [1970]. The basic parameter of interest has been the measurement of the ratio of the flux of α-particles, $j_\alpha(E)$, to the flux of protons, $j_p(E/4)$ compared on the basis of equal energy/nucleon. Measurements of this ratio range from $\sim 10^{-4}$ to $\sim 2 \times 10^{-3}$ which is much lower than the same ratio determined in the solar wind of $\sim 10^{-2}$ to 10^{-1}.

The origin of these trapped nuclei in the radiation belts is still unknown. These particles may come from the solar wind or they may come from the upper atmosphere of the earth [Axford, 1970]. A third possibility has been presented by Van Allen and Randall [1971] that energetic solar protons and alpha particles are directly injected into the magnetosphere although a number of authors argue that this must be a very inefficient process [Krimigis, 1970; Williams and Heuring, 1971; Blake and Paulikas, 1972].

Cornwall [1971, 1972] has examined some of these possible sources from the standpoint of magnetic and electrostatic diffusion. He presents arguments whereby certain magnetospheric acceleration and diffusion mechanisms can be differentiated from a knowledge of the various heavier ion fluxes. Theoretical studies of the distribution and charge composition of alpha particles and heavier ions on closed field lines yield methods of differentiating not only the origin, transport, and loss processes for heavy ions but for protons as well [Tverskoy, 1964, 1965, 1969, 1971; Dungey et al., 1965; Falthammer, 1965, 1966, 1968; Nakada and Mead, 1965; Hess, 1966; Haerendal, 1968]. A common feature of theories which use the solar wind as a source and magnetic fluctuations to diffuse the particles into the magnetosphere is that the solar wind ratio of j_α/j_p should be preserved when losses are neglected.

A notable fact in the literature concerning the Z ≥ 2 ions is that while all theoretical work has been restricted to the geomagnetic equatorial plane, all experimental measurements to date have been made using low altitude satellites at the high latitude end of the magnetic field line. Tverskoy [1969] recognized the difficulty in making comparisons between the two sets of work by stating that "it is obviously quite desirable to investigate the α-particle belt near the equatorial plane". The following data describe the near equatorial alpha particle distribution from 3.1 to 5.2 earth radii.

There are four α-particle channels in the experiment, labeled $\Delta\alpha 1 - \Delta\alpha 4$, two of which ($\Delta\alpha 3$ and $\Delta\alpha 4$) uniquely identify He ions through a $\frac{dE}{dx}$ and E coincidence technique. Due to initial operational considerations, attention is restricted herein to the $\Delta\alpha 2$ channel which responds to α-particles with energies between 0.91 MeV and 2.00 MeV and heavier ions but is insentitive to protons. The experiment was set up in such a way as to have adequate dynamic range to measure an α-particle flux a few time 10^{-4} that of the proton flux at the same energy/nucleon and for a satellite spin period of ~16 seconds. Neither of these conditions were met with the result that a severe overflow condition occurs in the low duty cycle mode which samples the alpha channels once every 147 seconds.

All channels sensitive to ions with Z ≥ 2 (except $\Delta\alpha 1$) are outputted through non-resetting seven bit accumulators on low duty cycle spacecraft analog sub-com fixed format channels. It is possible on a special basis to sample these channels at a maximum rate of once every 2.29 seconds in the Accelerated Sub-Com Mode (ASM) of spacecraft operation at the expense of the rest of the data. On January 6, 1972, six five minute segments of data were recorded in the ASM mode during an outbound portion of the S^3 orbit.

In figure 1 the five minute segment associated with the highest observed counting rate is presented. In the top portion of the figure the "raw" data are presented for the $\Delta\alpha 2$ channel. The spin period of the satellite at that particular time was 8.91 seconds [Longanecker and Hoffman, 1972]. With this spin period and an accumulation time of 2.29 seconds, each data point in figure 1 represents a detector response integrated over 92.72° in particle pitch angle. Restricting one's attention to only every second point in the sequence, a consistent pattern of a lower envelope is observed. By careful study and analysis of the "raw" data sequence and by adding multiples of 128 (7 bit accumulator overflow condition) to data points, the data sequence at the bottom of figure 1 is produced. Note that there is an increasing linear slope to the data sequence and that there is a distinct "beating" pattern superimposed on the sequence. The linear slope is due to the radial dependence in the alpha particle intensity being measured. The "beating" effect is the result of the sample period (2.29 seconds) being close to but not equal to an integral fraction of the satellite spin period (8.91 seconds) which determines pitch angle distribution sampling.

It is possible to get a qualitative picture of the alpha particle pitch angle distribution by examining figure 1. Since each data point is

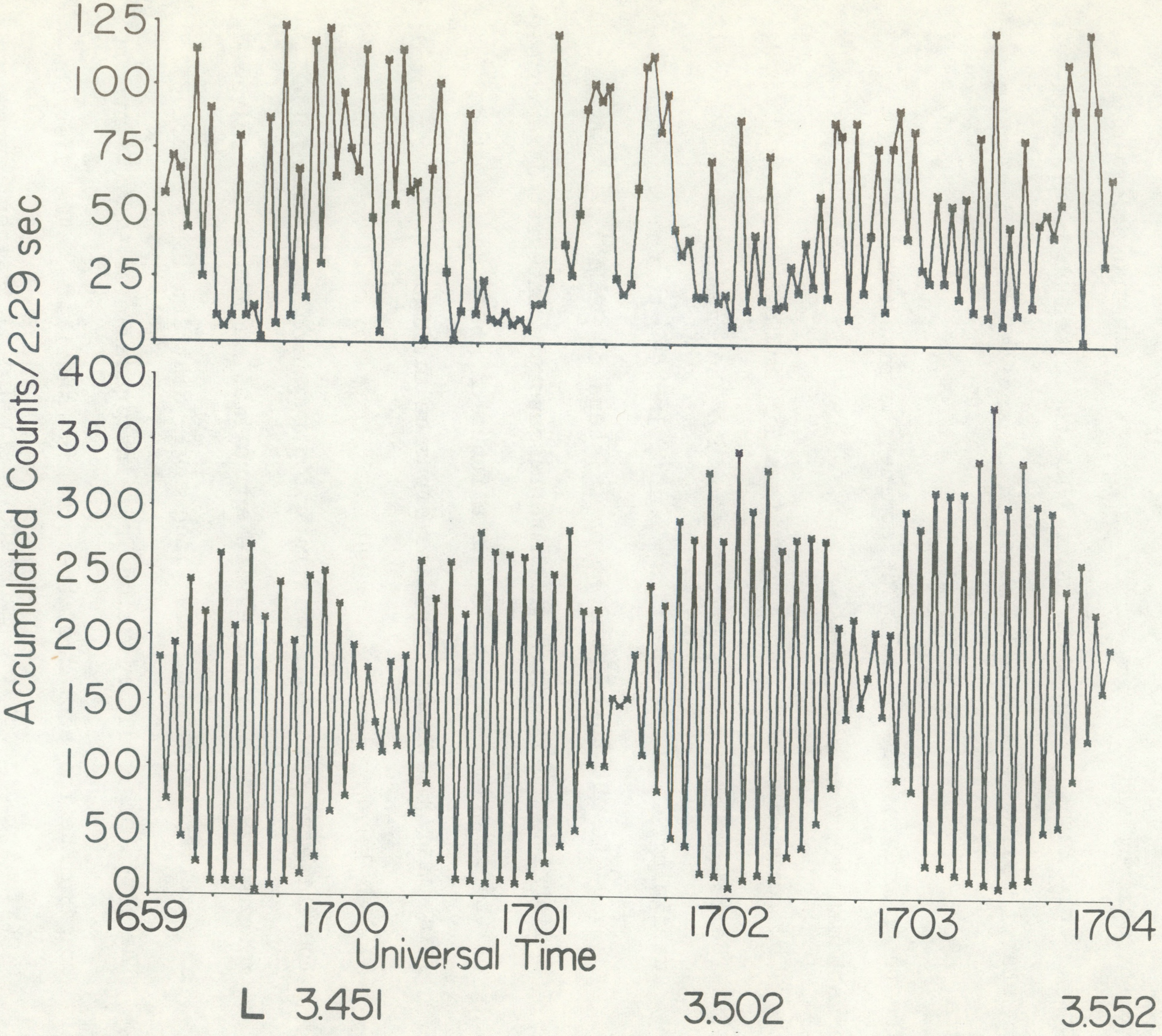

Figure 1. A 5-minute segment of data recorded by the $\Delta\alpha 2$ channel near $L = 3.5$ on January 6, 1972. The "raw" data are presented in the top portion of the figure and the "corrected" data are presented in the bottom portion. Each point represents the integrated response of the detector over 92.72° in particle pitch angle.

an integration over a pitch angle interval of 92.72°, there are pitch angle intervals of ±45° (assumed to be along the field line) where a relatively small particle flux exists. Note also that the difference between the maximum and minimum values is greater than two orders of magnitude. This leads to the conclusion that the pitch angle distribution is sharply peaked (assumed to be at pitch angles perpendicular to the local $\vec{B}$).

The procedure used to actually determine the pitch angle distribution mathematically is as follows:

1) The point sequence is desloped in a linear fashion.
2) The points are then placed in a modulo 360° grouping by assigning 92.72° to the first point, 185.44° to the second, 278.16° to the third, and so on in steps of 92.72°.
3) A distribution function which represents the integrated response of the detector over 92.72° as a function 360° is generated. This distribution for the data sequence of figure 1 is presented in figure 2.
4) The integrated response distribution function is then unfolded mathematically in a successive approximation method to arrive at a representation of the pitch angle distribution (figure 3).
5) The pitch angle distribution is reintegrated over 92.72° intervals to simulate the action of the spinning satellite. The distribution function described in 3 above (figure 2) is then reproduced and compared to the data distribution function.

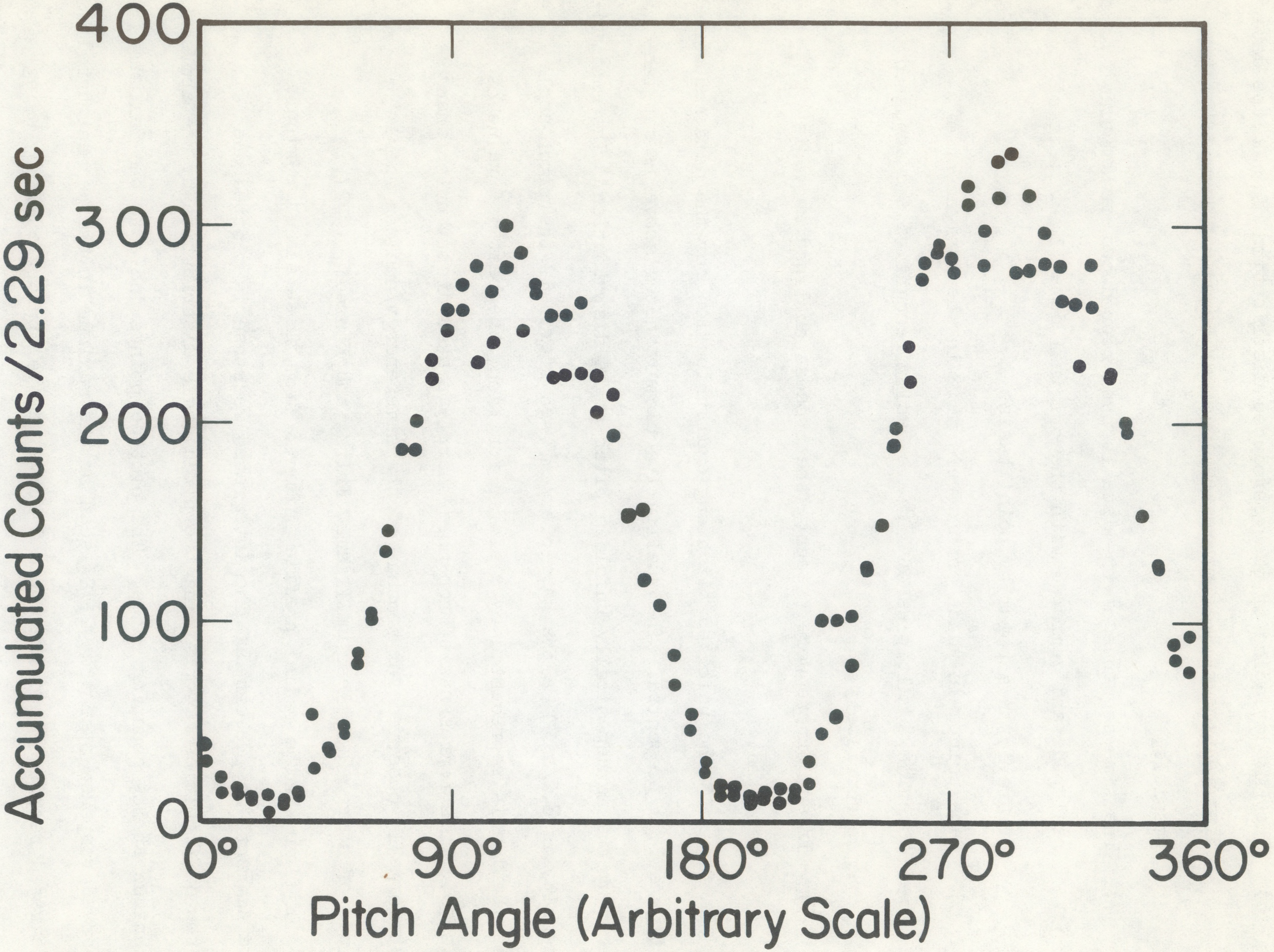

Figure 2. A distribution function for the data sequence of figure 1 in a modulo 360° grouping. Pitch angle scale is arbitrary.

6) The RMS deviation of the reproduced distribution of 5 to the data distribution of 3 is minimized in order to obtain the best fit possible.

7) The time sequence of the data is then reproduced mathematically, resloped, and compared with the original data (lower part of figure 1) on a point by point basis.

8) Data points in which errors were made in the assignment of "overflow" multiples of 128 are easily recognized and adjusted appropriately.

9) If any errors were present, the process outlined above is repeated.

In figure 3 the unfolded pitch angle distribution for the data sequence of figure 1 is presented. The qualitative picture noted above is substantiated by the mathematically unfolded pitch angle distribution. The maximum intensity is 8.2×10^5 alpha particles/cm^2 sec ster. If the pitch angle distribution is represented by a $\sin^n \theta$ function, the best fit value of n is ≈ 8. This represents a much more sharply peaked distribution than that normally observed for protons of the same energy/nucleon where values of n are ~ 2 or less [Williams, Fritz, and Konradi, 1972].

In figure 4 the radial profile inferred from these six five-minute data segments is presented. The integrated response is plotted due to the difficulties of obtaining the pitch angle distribution by the above technique at low counting rates. The plotted points indicate the maximum observed response over the 92.72° scan or the maximum in the reconstructed integrated response function (Item 5 above) as is appropriate. By using

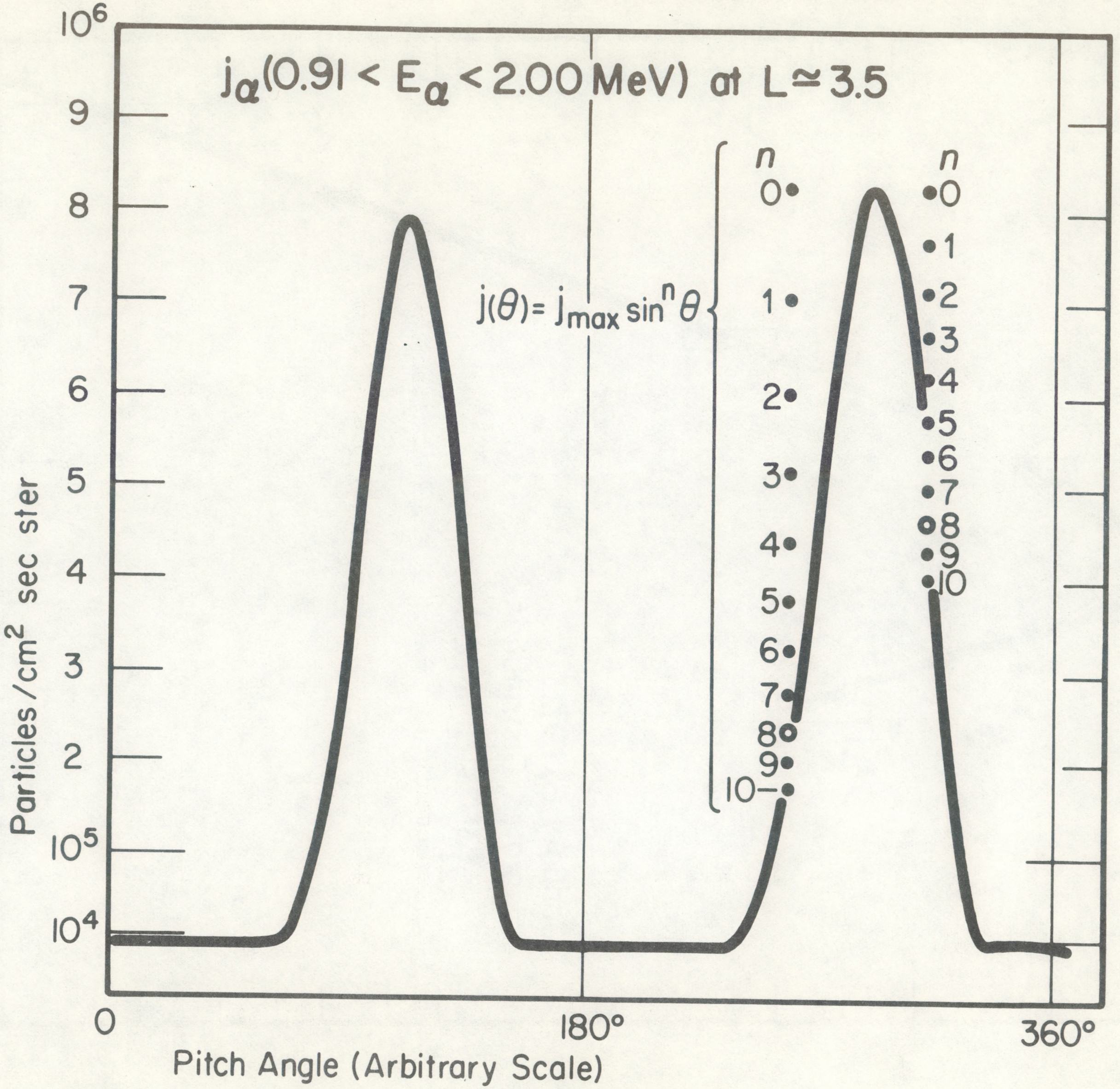

Figure 3. The pitch angle distribution for $j_\alpha(0.91 < E_\alpha < 2.00$ MeV) at $L = 3.5$. The distribution is mathematically unfolded from the distribution function of figure 2 by the technique of successive approximation to achieve a pitch angle distribution which reproduces the distribution function of figure 2.

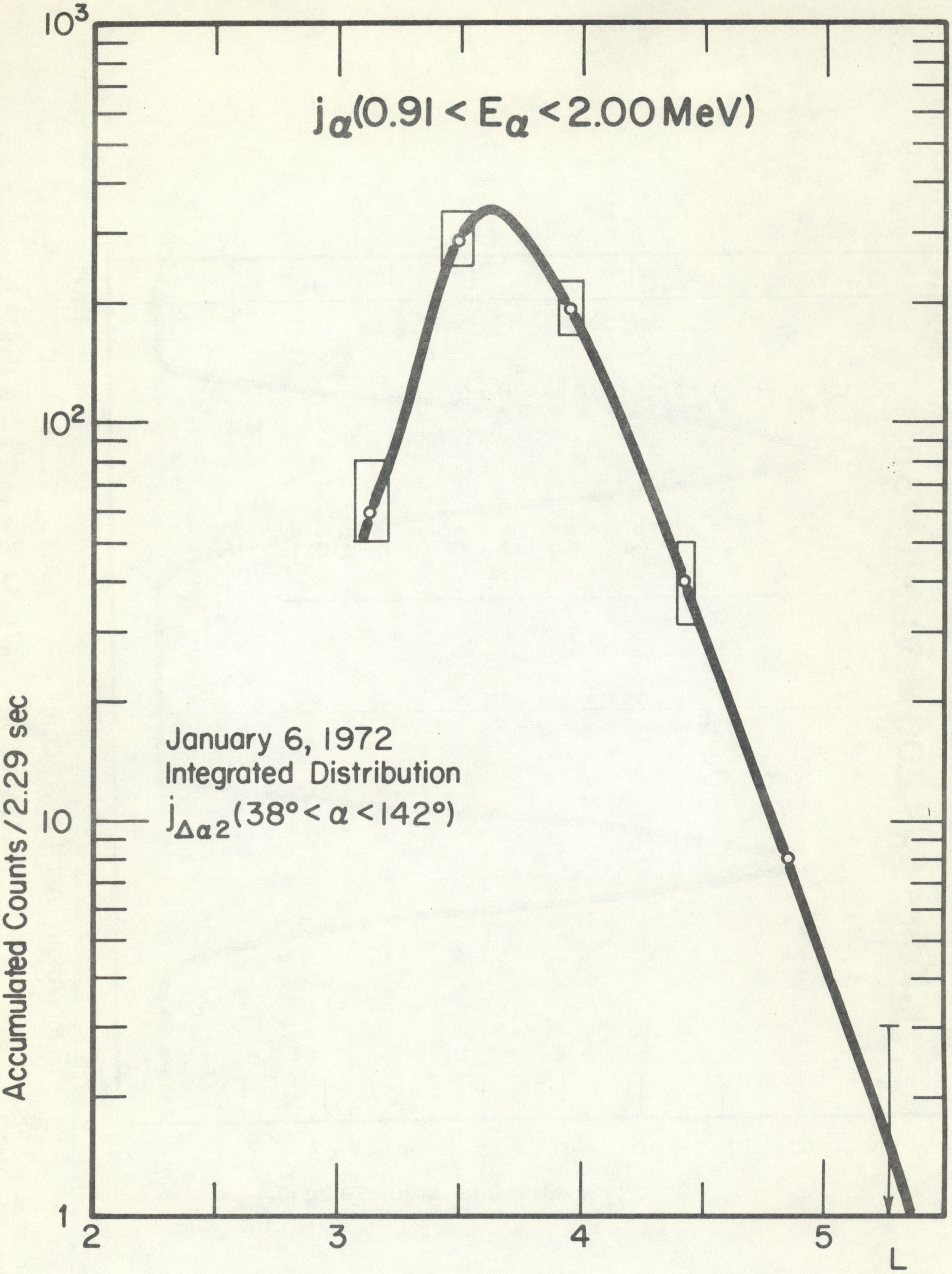

Figure 4. The radial profile of $j_\alpha(0.91 < E_\alpha < 2.00$ *MeV) inferred from the response of the* $\Delta\alpha 2$ *channel.*

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both the points and the slopes, the radial profile curve is produced.

It is possible to calculate the value of the ratio, j_α/j_p, as a function of L for the four lowest altitude intervals using the simultaneously determined proton energy spectrum. These results compared on the basis of equal energy/nucleon are presented in Table 1. The values of j_α/j_p are in the 1 to 2% range which is close to values of the same ratio measured in the solar wind. The quoted values of the proton flux in Table 1 may be larger than the actual value due to the nature of the proton passbands measuring the higher energy protons [Smith and Hoffman, 1972] particularly at the higher altitude where the proton spectrum is steepest. This effect when removed from the proton spectrum should increase the values of j_α/j_p presented in Table 1.

The measurements at the equatorial plane of the j_α/j_p ratio, the intensity, and the pitch angle distribution for α-particles in the energy range of .225 to .50 MeV/nucleon are all greatly different from that expected on the basis of the low altitude measurements noted previously, but there is no apparent disagreement between the two sets of measurements at the present time [J. B. Blake, D. Hovestadt, and S. M. Krimigis, private communication, April, 1972].

Our conclusion (which needs further verification) is that theories which diffuse particles from the solar wind may be adequate to explain conditions at the equatorial plane. This in turn implies that processes responsible for transporting particles along field lines (e.g., pitch angle diffusion) are more effective for protons than for α-particles thus giving rise to the small ratios of j_α/j_p of 10^{-3} to 10^{-4} observed at the low altitude end of the field line.

It is emphasized that the measurements made herein are from one data channel recorded on January 6, 1972 and may or may not be representative. An onboard program has been written and loaded into the S^3 data system which samples the $\Delta\alpha 1$ channel $[j_\alpha(0.59<E_\alpha<0.91\ \mathrm{MeV})]$ up to 128 times per satellite spin period. Preliminary results from the analysis of this data appear to substantiate the results presented here.

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TABLE 1

L (earth radii)	3.13	3.50	3.95	4.42
$j_\alpha(0.91 < E_\alpha < 2.00$ MeV)*	1.7×10^5	8.2×10^5	6.5×10^5	1.2×10^5
$j_p(225 < E_p < 500$ keV)*	2.1×10^7	4.9×10^7	3.4×10^7	1.5×10^7
$\frac{j_\alpha}{j_p}$	0.8%	1.7%	1.9%	0.8%

*in units of particles/cm^2 sec ster.

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