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<p>-It has recently been recognized that single intensely-ionizing particles can cause soft upsets in microelectronic components used in spacecraft. These particles can be heavy ions in galactic cosmic rays or heavy ions accelerated in solar flares. When the upsets are due to the trapped radiation, they are thought to result from nuclear interactions initiated by trapped protons. In this report, we have investigated whether there are sufficient numbers of heavy ions trapped in the Van Allen belts to be the dominant cause of soft upsets.</p> <p>(Continues)</p>		

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20. ABSTRACT (Continued)

We conclude, based on the scanty data available, that the contribution from upsets caused by trapped heavy ions is likely to be important at least under some conditions. We also found that we could not rule out the possibility that trapped heavy ions may cause upset rates that are orders of magnitude larger than those predicted from the trapped proton population.

## CONTENTS

1.0 INTRODUCTION .....	1
2.0 EXPERIMENTAL MEASUREMENTS .....	1
3.0 THE LIMIT OF STABLE TRAPPING .....	5
4.0 THEORETICAL ESTIMATES OF THE HELIUM TO PROTON RATIO .....	7
5.0 THEORETICAL CALCULATIONS OF THE OXYGEN/PROTON RATIO .....	9
6.0 COMPARISON OF SKYLAB RESULTS WITH PROTON SPECTRA .....	9
7.0 TRANSIENT ENHANCEMENT IN THE HEAVY ION FLUX .....	16
8.0 THE RELATIVE IMPORTANCE OF TRAPPED HEAVY IONS IN SINGLE-EVENT INDUCED UPSETS .....	18
9.0 CONCLUSIONS .....	19
10.0 ACKNOWLEDGEMENTS .....	25
REFERENCES .....	26



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## **DO TRAPPED HEAVY IONS CAUSE SOFT UPSETS ON SPACECRAFT?**

### **1.0 Introduction**

It has recently been discovered that single intensely-ionizing particles can cause soft upsets, i.e., changes in the logical state of digital micro-circuits (Binder et al., 1975). Laboratory tests have shown that such particles can also cause memory circuits to latch up in one state and can even permanently damage the circuit elements (see Pickel and Blanford, 1980). Such effects result from particles that lose energy rapidly when passing through the semiconductor material. This energy generates a burst of electrical charge that interferes with normal circuit functions. In most commercially-available circuits only helium nuclei (mostly alpha particles) or the nuclei of heavier elements lose energy rapidly enough to produce these effects. Hydrogen nuclei (protons, mostly) and neutrons can only produce such effects by causing nuclear reactions (within the sensitive micro-circuit elements) that have heavier ions as products (see Petersen, 1981). Only one proton in  $\sim 10^6$  will produce such a reaction while traversing a circuit element, resulting in a soft upset. By contrast, most heavy ions passing through the critical circuit element will produce soft upsets.

Heavy ions are therefore responsible for soft upsets even though they are minor constituents of the natural energetic particle radiation. Heavy ions cause the soft upsets produced by cosmic rays and solar flare particles. Only the trapped radiation may be so poor in heavy ions that protons dominate as the cause of soft upsets (Adams et al., 1981).

In a recent report on this subject, Adams et al. (1981) reviewed the data base on trapped alpha particles and heavy ions. These authors concluded that the data base on these trapped particles was too scanty to permit the construction of a model that could be relied on to predict their fluxes. Since a credible worst-case model would have been very severe, these authors suggested a model based on existing data which assumes that conditions are never worse than those that have been reported. This assures the designer that his spacecraft is likely to experience an environment as severe as the one described by the model. The authors pointed out that it is possible that the environment in other parts of the magnetosphere, and at other times, may be far more hostile than that described by the model.

This report extends the review of trapped heavy ion data and extrapolates experimental measurements, using data at lower energies, to explore the importance of trapped heavy ions for single-event effects on space-borne microelectronics.

### **2.0 Experimental Measurements**

Electronic components in satellites are located inside the skin with at least 25 mils of aluminum shielding from the environment. Protons and helium nuclei must have energies of at least 10 MeV/u to penetrate the spacecraft skin and reach the electronics. Heavier ions require somewhat more energy. For the purposes of this report, we will only consider particles with energies above 10 MeV/u.

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Figure 2.1 shows various measurements of the alpha particle to proton ( $\alpha/p$ ) ratio. There have been two reported measurements of helium nuclei, normalized to protons, with energies above 10 MeV/u. The first was reported by Rubin et al. (1977) for  $1.8 < L < 2.6$  at low altitude, well off the geomagnetic equator ( $L$  is the McIlwain  $L$  parameter, see McIlwain, 1961). The second measurement has been reported by Panasyuk et al. (1977). These authors report an  $\alpha/p$  ratio of  $\sim 10^{-3}$  at the same energy per nucleon and in a range of  $L$ -values which makes their results consistent with those of Rubin et al. Below  $L = 1.85$ , Panasyuk et al. measured an  $\alpha/p$  ratio that increases to  $\sim 10^{-2}$  at  $L = 1.68$  for  $5 \leq E \leq 15$  MeV/u near the geomagnetic equator (not shown in Fig. 2.1). This does not seem to be inconsistent with the upper limit of  $6 \times 10^{-3}$  reported by Naugle and Kniffen (1961) in the range  $1.45 \leq L \leq 1.85$ , since their measurement was well off the equator. Based on work at lower energies (see Fennell and Blake, 1976), we should expect  $\alpha/p$  to be lower at positions well off the geomagnetic equator. The results mentioned above are also compared with those of Blake et al. (1973) and Fennell et al. (1974) at lower energies.

Additional upper limits have been reported by Heckman and Armstrong (1962) and Freden and White (1960) at low altitudes. Fenton (1967) reported  $\alpha/p \leq 7 \times 10^{-4}$  in the energy range  $26 \leq E \leq 85$  MeV/u and  $1.6 \leq L \leq 3.3$ . He used a very small subset of his data (2 hours out of six months) which had been selected to be free of pulse pile-up. It is possible that this selection criterion biased the experiment against alpha particles.

We have been unable to find a single report of trapped  $\alpha$  particles observed conclusively at an energy above 10 MeV/u. Based on the proton and alpha particle pitch-angle distributions reported at lower energies by Fennell and Blake (1976) we should assume that the  $\alpha/p$  ratio is also strongly dependent on pitch angle at the higher energies considered here. This leads us to expect that  $\alpha/p$  will be much larger near the geomagnetic equator than at lower altitudes. The upper limit reported by Rubin et al. at 15 MeV/u must be taken to apply only to low altitude locations well off the geomagnetic equator. We must instead rely on the upper limit reported by Fenton as the best information on equatorially mirroring  $\alpha$  particles above 10 MeV/u.

The report by Panasyuk et al. of  $\alpha/p = 10^{-2}$  at  $L = 1.68$  for  $5 \leq E \leq 15$  MeV/u range, when combined with the upper limit of Fenton at higher energies, may be evidence that the  $\alpha/p$  ratio decreases with increasing energy. Additional measurements will be needed to confirm this.

There are also two reported measurements of heavier nuclei. Neither of these measurements was accompanied by simultaneous proton measurements, so only the heavy ion fluxes are available. The first measurement was reported by Mogro-Campero and Simpson (1970). These results are presented in Fig. 2.2, taken from Mogro-Campero (1972). They cover the range  $3 \leq L \leq 5$  and are average fluxes over the energy range  $13 \leq E \leq 33$  MeV/u for carbon, nitrogen, and oxygen nuclei, combined. These measurements were made near the geomagnetic equatorial plane for particles with equatorial pitch angles greater than  $45^\circ$ .

The second measurements were first reported by Chan and Price (1975) and Biswas et al. (1975a) from the same experiment. The final results for oxygen nuclei, taken from Chan (1976) and Biswas and Durgaprasad (1980), are

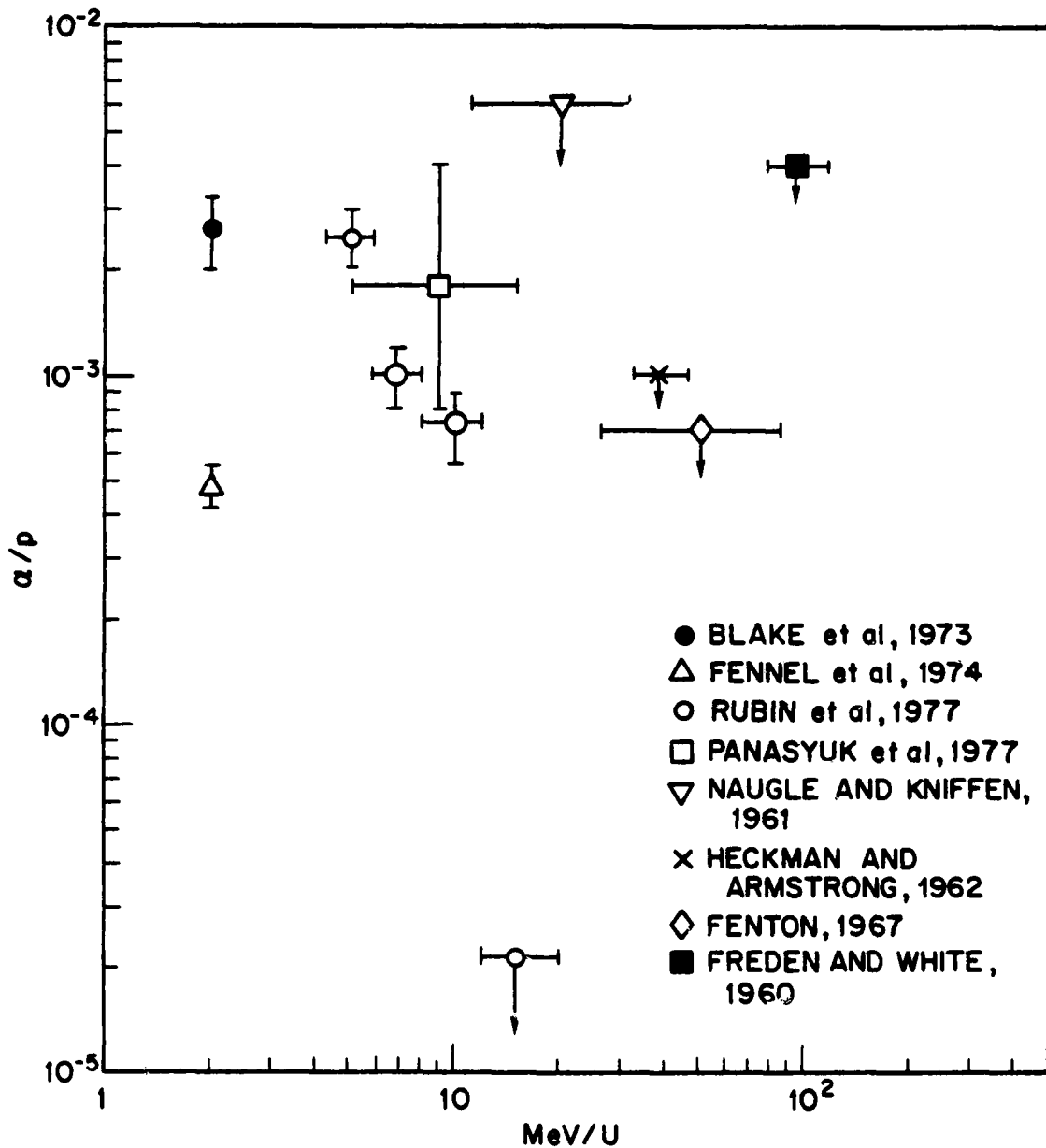


Figure 2.1

Measurements of the helium to proton ( $\alpha/p$ ) ratio in the trapped radiation as a function of energy. This figure compares measurements on different L shells in the range  $1.2 < L < 2.7$ . The measurements of Blake et al. (1973) are at high altitudes near the geomagnetic equator. The measurements of Fennel et al., Panasyuk et al., and Fenton et al. are the combined results at a variety of altitudes and the remaining measurements are at low altitudes.

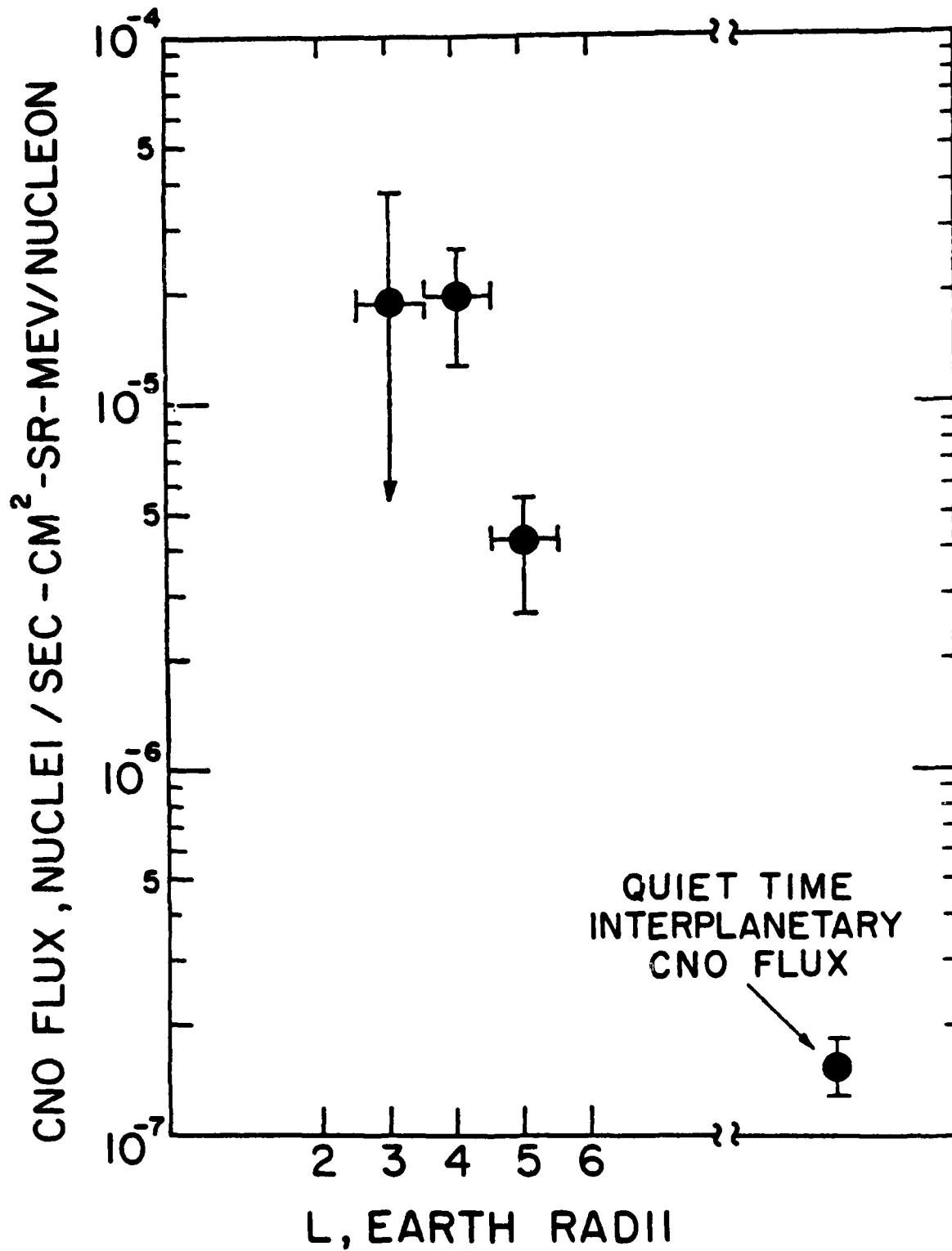


Figure 2.2

Trapped CNO fluxes (taken from Mogro-Campero, 1972).

shown in Fig. 2.3. Biswas et al. (1975b) also reported observations of heavier nuclei up to chromium. All these measurements were made with the same detector stack flown on Skylab which was in a 420 km altitude, 50° inclination, circular orbit. The experiment produced an integral measurement around the Skylab orbit, so the authors were unable to show that the particles were trapped in the radiation belt. Assuming the particles were trapped, they would have been collected in the South Atlantic anomaly between L values of 1.4 and 1.7. Since Skylab spent only a small part of its orbit time in the anomaly, the flux shown in Fig. 2.3 should be scaled up by a factor of ~ 72.

These are all the available measurements on heavy ions above 10 MeV/u. The upper limits reported by Freden and White (1960), Heckman and Armstrong (1962) and Naugle and Kniffen (1961) all apply equally to ions heavier than helium at low altitudes. They can therefore be compared with the results reported by Chan and Price (1975) and Biswas et al. (1975a,b). By comparing these measurements with the trapped proton flux expected on the Skylab orbit (using the model of Sawyer and Vette, 1976) we find an oxygen/proton (O/p) ratio of ~  $3 \times 10^{-4}$  at the same energy per nucleon. This result is below the upper limits set by the earlier research, at similar altitudes, cited above.

These are all the results, to our knowledge, on the heavy ion flux above 10 MeV/u and they are hardly adequate to develop a model of the trapped heavy ion flux that could be used to assess the importance of trapped heavy ions for the soft upset problem.

We will turn next to some general theoretical considerations for guidance.

### 3.0 The Limit of Stable Trapping

Only particles that conserve the first adiabatic invariant of trapped particle motion will remain trapped in the magnetosphere. There is an upper energy limit above which particles will no longer remain trapped.

According to the Alfvén criterion, the first adiabatic invariant is well conserved when  $\rho |\nabla B|/B \ll 1$ , where  $\rho$  is the ion gyroradius and  $\nabla B$  is the gradient of the magnetic field. The gyroradius may be written

$$\rho = \frac{A(E^2 + 2Em_0)^{1/2} \sin \alpha_0}{qcB},$$

where A is the atomic mass, E is the energy/nucleon,  $m_0$  is the rest mass of one nucleon (931 MeV), q is the charge,  $\alpha_0$  is the equatorial pitch angle, c is the speed of light, and B is the magnetic field intensity.

To find the energy at which orbits begin to become unstable, we assumed the particles were fully-ionized and we calculated  $\rho$  for various values of E using a dipole model of the earth's field (see Roederer, 1970). Particles with energies higher than that giving the ratio  $\rho |\nabla B|/B < 0.1$  were assumed to be unstably trapped. We found the energy limit of stable trapping as a function of equatorial pitch angle for various L values. The results are shown in Fig. 3.1 for nuclei with  $A/Z = 2$ . Using  $\rho |\nabla B|/B \leq 0.1$  as the limit

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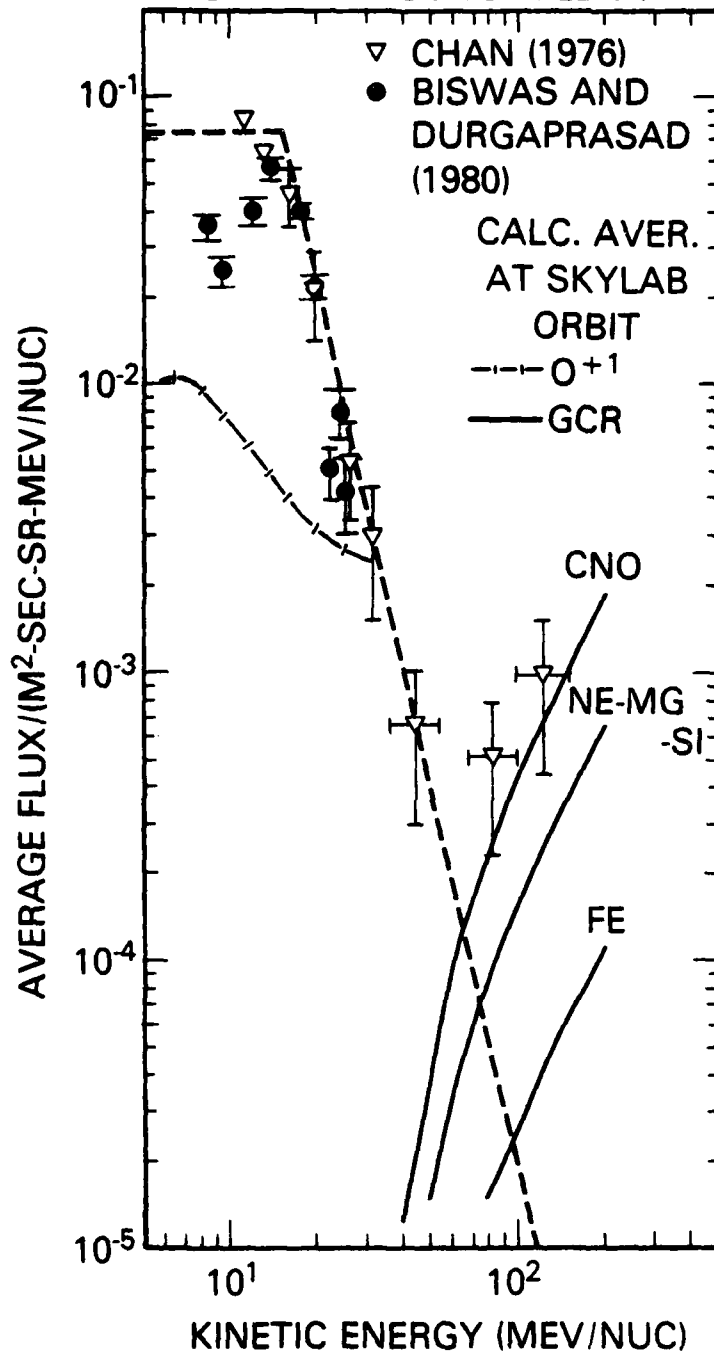


Figure 2.3

Skylab results as reported by Chan (1976) and Biswas and Durgaprasad (1980). The data show the measured oxygen flux. The dashed curve is an analytic fit to these data (see Adams et al., 1981). The solid curves show the orbit-averaged cosmic ray spectra for various elements as they should have been seen at Skylab. The dash-bar curve is the oxygen spectrum to be expected at Skylab if the low energy oxygen flux is singly ionized in the interplanetary medium.

of stable trapping, we find that none of Mogro-Campero's data (1972) is stably trapped. The Alfvén criterion, however, gives only a rough estimate of the limit of stable trapping. Had we used a criterion of  $\rho|\nabla B|/B < 0.4$ , then all of Mogro-Campero's data would have been within the limit of stable trapping.

From the results in Fig. 3.1, it is clear that heavy ions can be stably trapped at energies well above 10 MeV/u out to  $L = 3.5$ . At  $L < 2$ , heavy ions can be trapped up to energies capable of penetrating any reasonable amount of spacecraft shielding. This is, however, only a rough limit on the energies at which heavy ions could be trapped. Next we review some theoretical estimates of what the helium and heavy ion composition might actually be.

#### 4.0 Theoretical Estimates of the Helium to Proton Ratio

Fritz and Spjeldvik (1979) have shown that at low energies ( $\sim 2$  MeV/u), and during magnetically quiet periods, the measured ratio of equatorially mirroring helium flux to proton flux is well described by radial diffusion theory, with the appropriate choice of radial diffusion coefficients. At the same energy per nucleon, they find  $\alpha/p$  ratios of  $\sim 5 \times 10^{-4}$  at  $\sim 1$  MeV/u. A more extensive set of radial diffusion calculations for helium have been reported by Spjeldvik and Fritz (1978a). These authors present estimates of the equatorially mirroring  $\alpha$  flux at selected  $L$  values of 2.0 and larger, and for energies up to 250 MeV/u. We have compared these calculated fluxes with equatorially-mirroring proton fluxes at the same energies per nucleon, using the results of Fritz and Spjeldvik (1979) and Sawyer and Vette (1976). We found an  $\alpha/p$  ratio of  $\sim 3 \times 10^{-4}$  at 10 MeV/u for  $L = 2.5$ . This ratio increased to  $6 \times 10^{-4}$  at 25 MeV/u and to  $\sim 10^{-3}$  over 100 MeV/u. These results are consistent with the upper limits (see Fig. 2.1) for equatorial flux ratios, but are a factor of  $\sim 3$  lower than the results of Panasyuk et al. (1977) in the  $5 < E < 15$  MeV/u range at  $L = 2.5$ . The quiet-time flux levels, estimated by radial diffusion theory, are very sensitive to the choice of diffusion coefficient and the boundary conditions, especially at  $L$  values as low as 2.5. Fluxes at  $L = 2.5$  can change by an order of magnitude depending on these choices.

Spjeldvik and Fritz (1978a) also calculated  $\alpha$  fluxes at  $L = 2.0$ . Here the  $\alpha/p$  ratio appears to be generally lower than at  $L = 2.5$ , in strong disagreement with the results of Panasyuk et al. which show an increase between  $L = 2.5$  and  $L = 2.0$ . We found no theoretical calculations of the  $\alpha$  flux in the interesting region below  $L = 2$ .

Based on the discussion above, we can say that: 1) Calculated  $\alpha$  fluxes are likely to provide unreliable predictions owing to the dependence of the results on the unknown value of the radial diffusion coefficient and the unknown boundary conditions; and 2) The  $L$  value dependence of the calculated  $\alpha/p$  ratio appears to be inconsistent with the results reported by Panasyuk et al. (1977).

There seems to be no accurate means of predicting the quiet-time  $\alpha/p$  ratio on theoretical grounds and no experimental data on the ratio above 15 MeV/u. We can, however, say that there are no results known to us that rule out  $\alpha/p$  ratios of  $\sim 10^{-3}$  at the high energies of interest here.

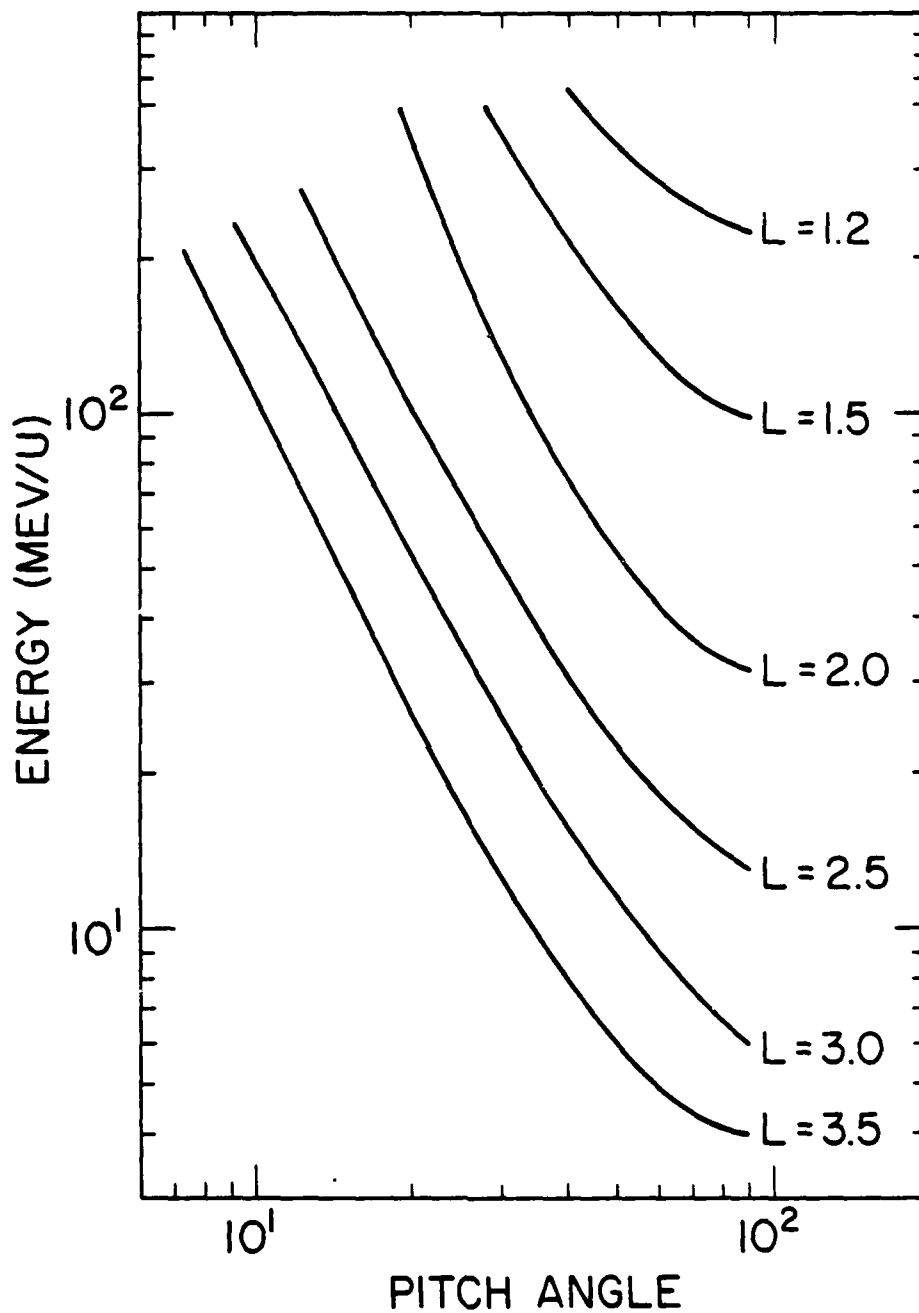


Figure 3.1

The energy limit for stable trapping of oxygen nuclei as determined by the Alfvén criterion. Results are presented as a function of equatorial pitch angle for various L values.

Based on the results of Petersen (1981), it appears that upsets caused directly by  $\alpha$  particles may become a major contributor to the total upset rate of an  $\alpha/p$  ratio of  $\sim 10^{-5}$ . This is 2 orders of magnitude lower than present experimental upper limits or theoretical predictions for the equatorial  $\alpha/p$  ratio. We therefore cannot exclude the possibility that  $\alpha$  particles contribute directly to the soft upset rate, at least near the geomagnetic equator. However, based on the results of Rubin et al., it appears that trapped helium may not contribute to the soft upset rate on low altitude satellites even in polar orbit.

### 5.0 Theoretical Calculations of the Oxygen/Proton Ratio

Spjeldvik and Fritz (1978b) have used radial diffusion theory to obtain theoretical estimates of the equatorially mirroring oxygen flux during quiet times at various L values. Their results extend only to 6 MeV/u and they considered charge states only up to  $O^{+6}$ . Most oxygen ions above  $\sim 4$  MeV/u will be in charge state 7 or higher. Above 10 MeV/u most oxygen ions will be fully stripped of their electrons. Nevertheless, we compared their results for a magnetic radial diffusion subcoefficient of  $10^{-8} R_E/\text{day}$  with equatorially mirroring protons at the same energies per nucleon and same L values, using the data from Fritz and Spjeldvik (1979) for protons. These results are presented in Fig. 5.1. For energies over 0.7 MeV/u, these ratios are only lower limits because oxygen charge states above +6 were not considered.

Next we compared the proton flux with the data of Mogro-Campero (1972) for CNO nuclei. In order to make the comparison, we fit the proton spectra of Fritz and Spjeldvik (1979) to a power law in energy and integrated between 13 and 33 MeV/u. The result was then averaged over pitch angle,  $\alpha > 45^\circ$ , using a  $\sin^5\alpha$  distribution and compared with Mogro-Campero's data. The two resulting data points are shown in Fig. 5.1.

These results show that the O/p ratio is well above the value of  $10^{-6}$ , which is the approximate threshold for heavy ions to become an important cause of soft upsets. At  $L = 4$  the ratio seems to continue to rise from low energies out to the 13 to 33 MeV/u energy interval, reaching a value of  $\sim 10^{-1}$ . The measurements at  $L = 3$  suggest that the O/p ratio turns over and declines at higher energies. Whatever the O/p ratio at  $L \geq 3$ , the proton and heavier ion fluxes at these L values are falling rapidly with increasing energy and are much lower than they are closer to the earth (Adams et al., 1981). The limits of stable trapping at these L values assure us that the trapped ion energies will be relatively low for particles with large pitch angles. The soft upset problem is potentially more serious at lower L values.

### 6.0 Comparison of Skylab Results with Proton Spectra

The results of the Skylab experiment were discussed briefly in Section 2.0 and presented in Fig. 2.3. A direct comparison of the orbit-averaged oxygen flux in the Skylab experiment with the orbit-averaged proton flux (from the AP8MIN model of Sawyer and Vette, 1976) at the same energy per nucleon gives an O/p ratio of  $\sim 10^{-4}$ .

As mentioned in Section 2.0, it was not possible for the experimenters to show that the particles seen in the Skylab experiment were trapped. If

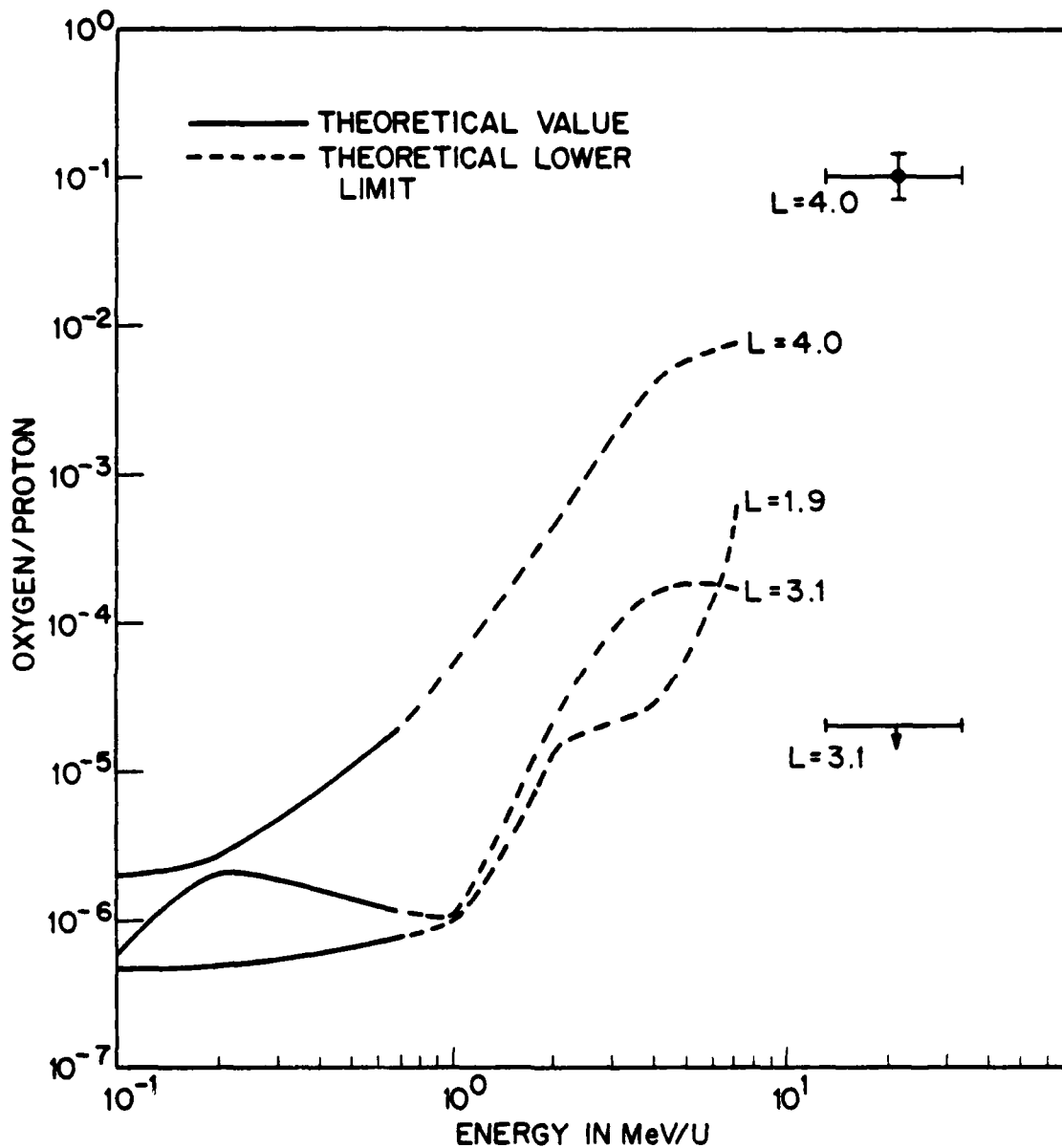


Figure 5.1

The oxygen/proton (O/p) ratio based on the theoretical estimates of Spjeldvik and Fritz (1978b). Because the theoretical work considered oxygen charge states only up to + 6, we treat the results as a lower limit above 0.7 MeV/u. Also shown for comparison are the results of Mogro-Campero (1972).

they were trapped, the omnidirectional flux in the South Atlantic anomaly would be ~ 72 times greater than the average shown in Fig. 2.3. The real question, though, is what O/p ratio would we expect near the geomagnetic equator if the Skylab oxygen nuclei were trapped. To find out, we must choose an appropriate equatorial pitch angle distribution for the extrapolation.

Unfortunately, the only data on heavy ion pitch angle distributions is at lower energies. This data is consistent with a radial diffusion transport mechanism, but it is not clear that this same mechanism is responsible for the oxygen nuclei observed outside Skylab.

The pitch angle distribution depends on the assumed source. Blake and Friesen (1977) have discussed the possibility that these oxygen nuclei come from the anomalous component (see Adams et al., 1981) which they assumed to be singly-ionized. If this were the case, the pitch angle distribution would be peaked near edge of the loss cone and the flux at higher altitudes would be similar to that observed at Skylab. Pitch-angle diffusion could alter this picture somewhat, but generally their model would lead to a flat pitch angle distribution.

Another possible source of energetic heavy ions in the inner magnetosphere is cosmic ray splash albedo. These are galactic cosmic rays that have grazed the atmosphere and lost enough energy to be contained by the earth's magnetic field. Such particles are always initially confined on incomplete drift shells and would be expected to re-enter the atmosphere. Such a particle could become stably trapped only if it were pitch-angle scattered in such a way as to raise its mirror points; because of the stability of the inner magnetosphere, we will assume that this mechanism is an unimportant source of trapped heavy ions.

Apart from the unusual mechanisms mentioned above, only radial diffusion from the boundary of the stable trapping region (at  $L = 7$ ) can account for the presence of heavy ions in the inner magnetosphere. This mechanism seems to correctly account for the observed helium and heavy ion fluxes at lower energies. At the energies of interest here, radial diffusion should be less efficient because the ions being transported are near the limit of stable trapping. Using the criteria we employed in section 3.0, we would expect equatorially mirroring  $O^{+6}$  ions to start becoming unstable at  $E = 0.156$  MeV/u at  $L = 6.6$ . Assuming that the first adiabatic invariant is conserved, these same ions would have energies of 5.5 MeV/u at  $L = 2$  and 25 MeV/u at  $L = 1.2$ . Above these energies we would expect radial diffusion to become increasingly inefficient. Hovestadt et al. (1978) have reported steeply falling carbon and oxygen spectra in the 0.5 to 1.0 MeV/u range at  $L = 3.1$  and the absence of iron ions above 0.2 MeV/u at quiet times. As the authors have pointed out, their results are consistent with the breakdown in the radial diffusion mechanism discussed above.

This limitation of the radial diffusion process may be partly overcome by the rapid radial diffusion that occurs during magnetic storms. We would expect energetic ions to be transported into the inner magnetosphere more efficiently at those times.

From the above discussion, we conclude that the mechanism responsible for the heavy ions observed on Skylab is difficult to determine and may not be the same radial diffusion mechanism responsible for heavy ions at lower energies. It is therefore with this caveat in mind that we proceed to use pitch angle distribution derived from observations of trapped heavy ions at lower energies.

Fennell and Blake (1976) have reviewed the low energy  $\alpha$  particle data and shown that a consistent set of measurements exists which demonstrates that the  $\alpha$  particle pitch-angle distribution is more sharply peaked at  $90^\circ$  than the corresponding proton pitch angle distribution. This results in a pitch-angle dependent  $\alpha/p$  ratio, varying from  $\sim 10^{-2}$  at  $90^\circ$  pitch angle to  $\sim 10^{-4}$  for the smallest pitch angles allowed. Hovestadt et al. (1981) report even more steeply peaked pitch angle distributions for low energy carbon and oxygen nuclei based on measurements they made with the ULEZEQ experiment on the ISEE-1 satellite. They find that the pitch angle distribution obeys the functional form  $\sin^n \alpha_0$ , where  $\alpha_0$  is the equatorial pitch angle and  $n$  is an adjustable parameter. Hovestadt et al. report that the value of  $n$  increases with ion atomic number and ion energy. For the 0.5 to 0.7 MeV/u energy range they report  $n = 11.1$  for helium,  $n = 17.4$  for carbon and  $n = 22.3$  for oxygen. Their measurement of  $n$  for helium is consistent with the results of other investigators.

It is not clear whether the pitch angle distribution law,  $\sin^n \alpha_0$ , applies for  $\alpha_0 < 50^\circ$  with the same  $n$  that fits for  $\alpha_0 > 50^\circ$ . In the case of helium, Blake et al. (1973) observed that the pitch angle distribution broadens (smaller  $n$ ) for  $\alpha_0 < 50^\circ$ . Hovestadt et al. found that a single value of  $n$  correctly described the pitch angle distributions of carbon and oxygen ions for  $90^\circ \geq \alpha_0 \geq 39^\circ$ . Below  $39^\circ$ , the flux levels appeared to exceed the prediction, suggesting a smaller  $n$  value is appropriate for  $\alpha_0 < 39^\circ$ . According to the analysis of Chan (1976), the Skylab oxygen nuclei would probably have been collected between  $L = 1.4$  and  $L = 1.7$  giving them equatorial pitch angles in the range  $24.4^\circ \leq \alpha_0 \leq 41.9^\circ$ . Because the pitch angles sampled do not range too much below  $39^\circ$ , we have assumed that the simple  $\sin^n \alpha_0$  law correctly describes the pitch angle distribution. For  $n$ , we have chosen the value 15. This is somewhat smaller than the values reported by Hovestadt et al. Since the trend is for  $n$  to increase with energy, we might have been justified in choosing a much larger value for  $n$ , but because of the uncertainty in this sort of extrapolation, we have chosen to be conservative. Also, we did not assume  $n$  was energy-dependent, increasing with energy as it does at lower energies. This leads to a softer energy spectrum than may actually exist.

The differential flux shown in Fig. 2.3 was obtained by simply dividing the number of events in each energy interval by the geometry factor appropriate to that energy interval and the 72-day exposure time. Each flux value was multiplied by a factor of 2 to correct for occultation by the earth. Here we approximate the spectrum in Fig. 2.3 using the analytic fit of Adams et al. (1981), which is shown as a dashed curve in the figure. To convert these results to omnidirectional trapped flux, we divide by 2, assuming that the heavy ion flux gradient at the Skylab orbit was small over a particle gyroradius. Next we multiply by  $4\pi$  to obtain oxygen nuclei/m<sup>2</sup> sec MeV/u. Skylab spent only a small part of its time in the South Atlantic anomaly. Using the map of trapped  $\alpha$  particles at the Skylab orbit, calculated by Chan (1976), we estimate trapped particles were collected in

1.4 per cent of the total exposure time. So we multiply the omnidirectional flux by 72 to obtain the omnidirectional flux that would have been observed during South Atlantic anomaly passes, had all the particles been collected in such passes. This procedure assumes that the particles recorded over the entire Skylab exposure were uniformly distributed in position and arrival direction in the detectors. This point was examined by Chan (1976), who showed that the arrival directions of the particles were anisotropic. The effect of this anisotropy on our interpretation is to cause us to underestimate the trapped flux by perhaps a factor of 2.

Following Roederer (1970), the observed omnidirectional flux, at a field line point,  $B_p$ , is given by,

$$J(B_p) = 4\pi \frac{B_p}{B_0} \int_{(1-B_0/B_p)^{1/2}}^{(1-B_0/B_E)^{1/2}} j_0 (1-u^2)^{n/2} \frac{u du}{\left[1 - \frac{B_0}{B_p} (1-u^2)\right]^{1/2}}$$

where  $B_0$ ,  $B_p$ , and  $B_E$  are magnetic field intensities at the equator, the Skylab orbit, and the top of the atmosphere, respectively, all on the same magnetic field shell. The variable of integration is  $\cos \alpha_0$ , where  $\alpha_0$  is the equatorial pitch angle and  $n$  is just the power of the pitch angle distribution law (i.e.  $n = 15$ ).  $j_0$  is the equatorially mirroring flux on the field line. We have solved the equation for this quantity and used it to obtain the omnidirectional flux at the equator, i.e.

$$J_0 = 4\pi \int_0^{(1-B_0/B_E)^{1/2}} j_0 (1-u^2)^{n/2} du .$$

The resulting equatorial flux is shown in Figure 6.1. The rapid fall off of the spectrum above 15 MeV/u is the result of not using the energy dependent  $n$  suggested by the results of Hovestadt et al. (1981). Using the expression for the energy dependence of  $n$  suggested by Fritz and Spjeldvik (1980) would result in higher oxygen intensities at all energies.

Finally, we compare the spectrum in Fig. 6.1 with the AP8MIN model proton flux (Sawyer and Vette, 1976). The resulting O/p ratio at the equator is shown in Fig. 6.2 and is appropriate to  $L = 1.7$  at the equator. These results were obtained by fitting the integral proton spectra at  $L = 1.5$  and  $2.0$  with power laws in the appropriate energy range. The power law was then interpolated to  $L = 1.7$  and differentiated to obtain a differential energy spectrum for protons at  $L = 1.7$  and  $B/B_0 = 1$ . This power law spectrum was then divided into the results shown in Fig. 6.1 to obtain the results shown in Fig. 6.2. Quite different energy dependent ratios would have resulted from a smaller choice of  $L$  value for the comparison, or from the use of a different and/or energy dependent  $n$  value for the heavy ion pitch angle distribution. In every case, O/p would be much greater than  $10^{-6}$  and, for much larger choices of  $n$ , would have exceeded unity at the lowest energy considered.

If the particles observed in Skylab were trapped and if they have a pitch angle distribution at all like that of lower energy heavy ions, we must conclude that the Skylab result implies that heavy ions will be the dominant cause of soft upsets in much of the inner magnetosphere. However,

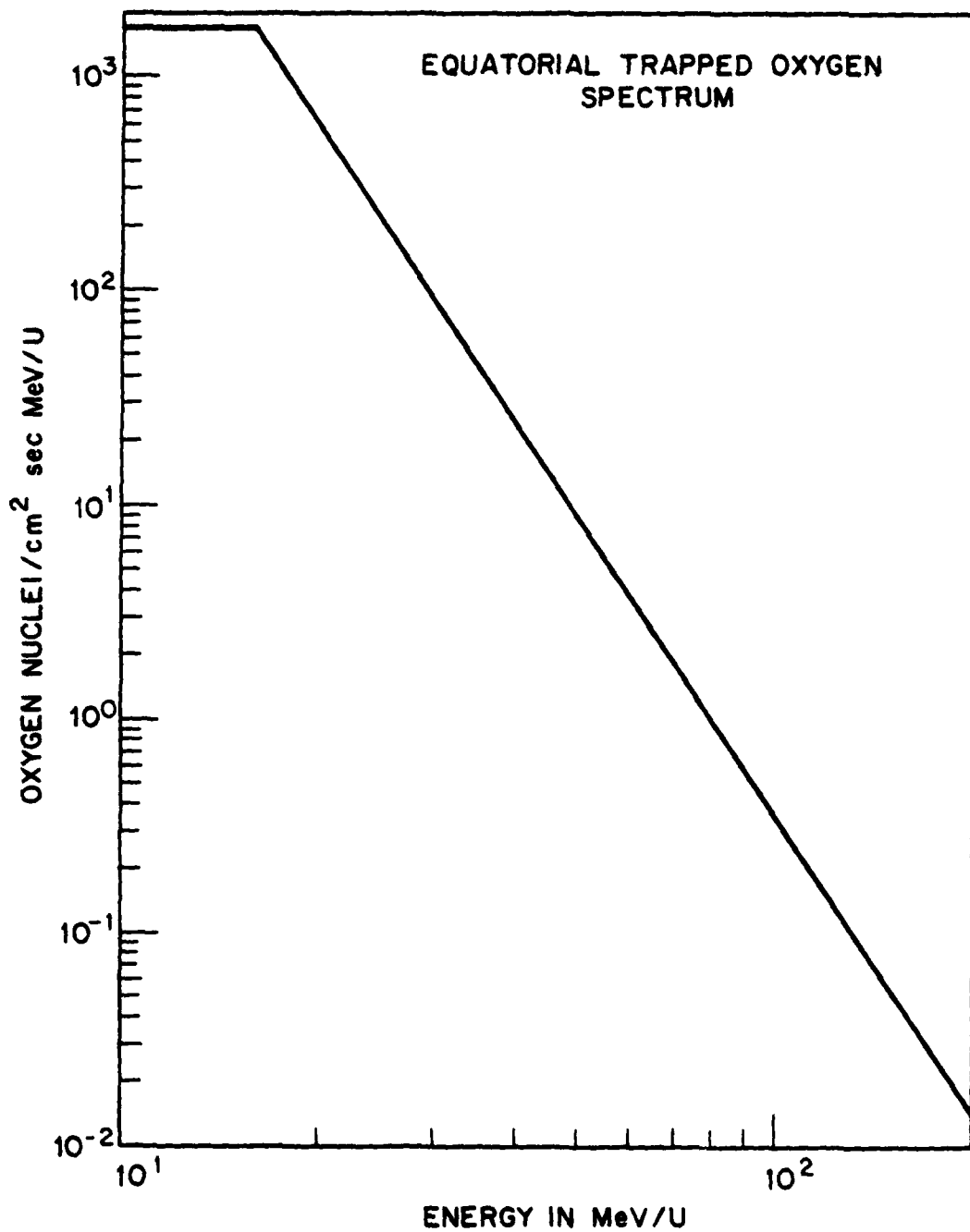


Figure 6.1

The differential energy spectrum of trapped oxygen nuclei at  $L = 1.7$  and at the geomagnetic equator. This is the omnidirectional equatorial flux as inferred from the Skylab results.

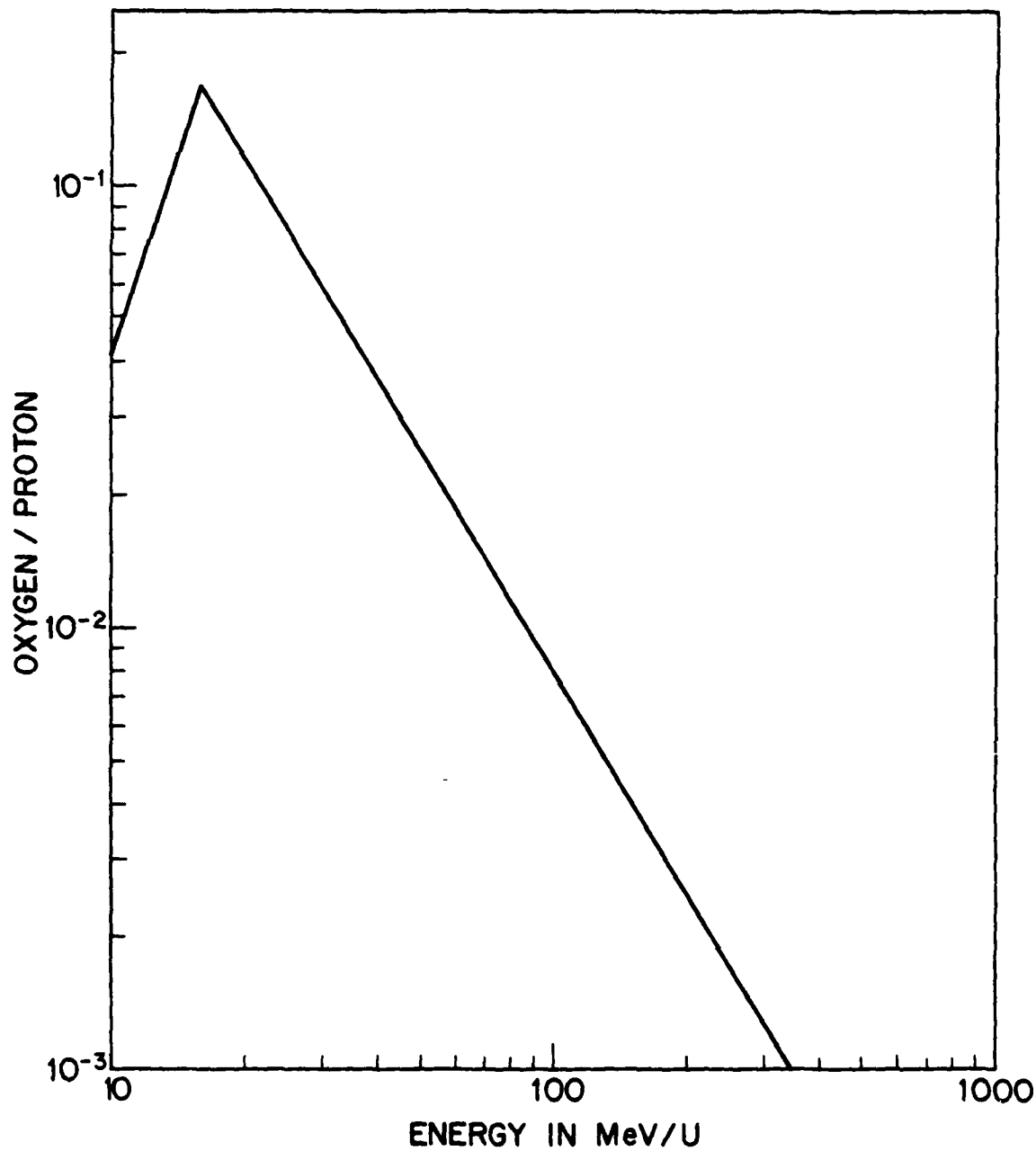


Figure 6.2

The oxygen/proton (O/p) ratio at the same energy per nucleon. This curve was obtained by comparing the results in Fig. 6.1 with the results of Sawyer and Vette (1976).

if the Skylab oxygen nuclei have a much flatter pitch angle distribution, protons could still be the dominant cause of soft upsets near the geomagnetic equator.

## 7.0 Transient Enhancement in the Heavy Ion Flux

In addition to the stable component of trapped heavy ions in the radiation belts, there are large transient increases in the heavy ion population in association with large magnetic storms. The first observation of such an increase was reported by Van Allen and Randall (1971), who reported a large increase of the 1-8 MeV/u  $\alpha$  particle flux in the outer zone. There have been published reports of similar events by Verzariu (1973), Scholer et al. (1979), and Mogro-Campero and Simpson (1970).

Spjeldvik and Fritz (1981a, b, c) have reported that large fluxes of heavy ions at  $\sim 1$  MeV were injected deep in the magnetosphere following the large solar flares of August, 1972. These heavy ions were trapped for a period of weeks to months after the storm's end. Since no increase in proton flux was observed, the CNO/p ratio was observed to increase dramatically ( $\sim 10^3$ ) at  $L = 2.5$ , while the  $\alpha/p$  ratio increased by  $\sim 20$ , and the  $(Z > 9)/p$  ratio increased more than  $10^3$  at the same  $L$  values.

Spjeldvik and Fritz also show that the heavy ion flux can be expected to decay much less rapidly at higher energies, see Fig. 7.1. This is because the charge loss time in the geocorona is much longer at higher energies, as is the coulomb energy loss time. This leaves diffusion time as the only significant mechanism limiting the lifetime of trapped particles. As can be seen from Fig. 7.1, at  $L = 2.5$  trapping lifetimes for the higher energy particles considered here would be  $\geq 16$  years!

This leads us to suggest that there may be no equilibrium population of trapped heavy ions at high energies. With such long trapping lifetimes in the quiet magnetosphere, we would expect heavy ions to remain trapped until the magnetosphere is once again disturbed by a magnetic storm. Such a storm could either increase or decrease the trapped heavy ion population.

In section 6.0, we discussed the inefficiency of radial diffusion at high energies. During magnetic storms, radial diffusion occurs more rapidly so that higher energy heavy ions can be more effectively transported into the inner magnetosphere. The reports of flux increases following magnetic storms, discussed above, are thought to be the result of such rapid radial diffusion.

The results reported above are all at  $L \geq 2.5$ . At lower  $L$  values the magnetosphere is less disturbed by magnetic storms. Bostrom et al. (1971) report only a  $\sim 10\%$  decrease in the 25 - 100 MeV proton flux at  $1.8 \leq L < 2$  due to the May 1976 magnetic storm. These authors report a larger effect for  $L > 2$ . Parsignault et al. (1981) have recently reviewed the 55 MeV proton data at low altitude. They report that the proton flux varies by a factor of  $\sim 5$  over the period 1964 - 1978. These authors find that this variation can be explained by the interactions of the trapped protons with the upper atmosphere, whose scale height varies with the solar cycle.

Farley and Walt (1971) examined the adequacy of the known source and loss processes to populate the inner magnetosphere with protons. These

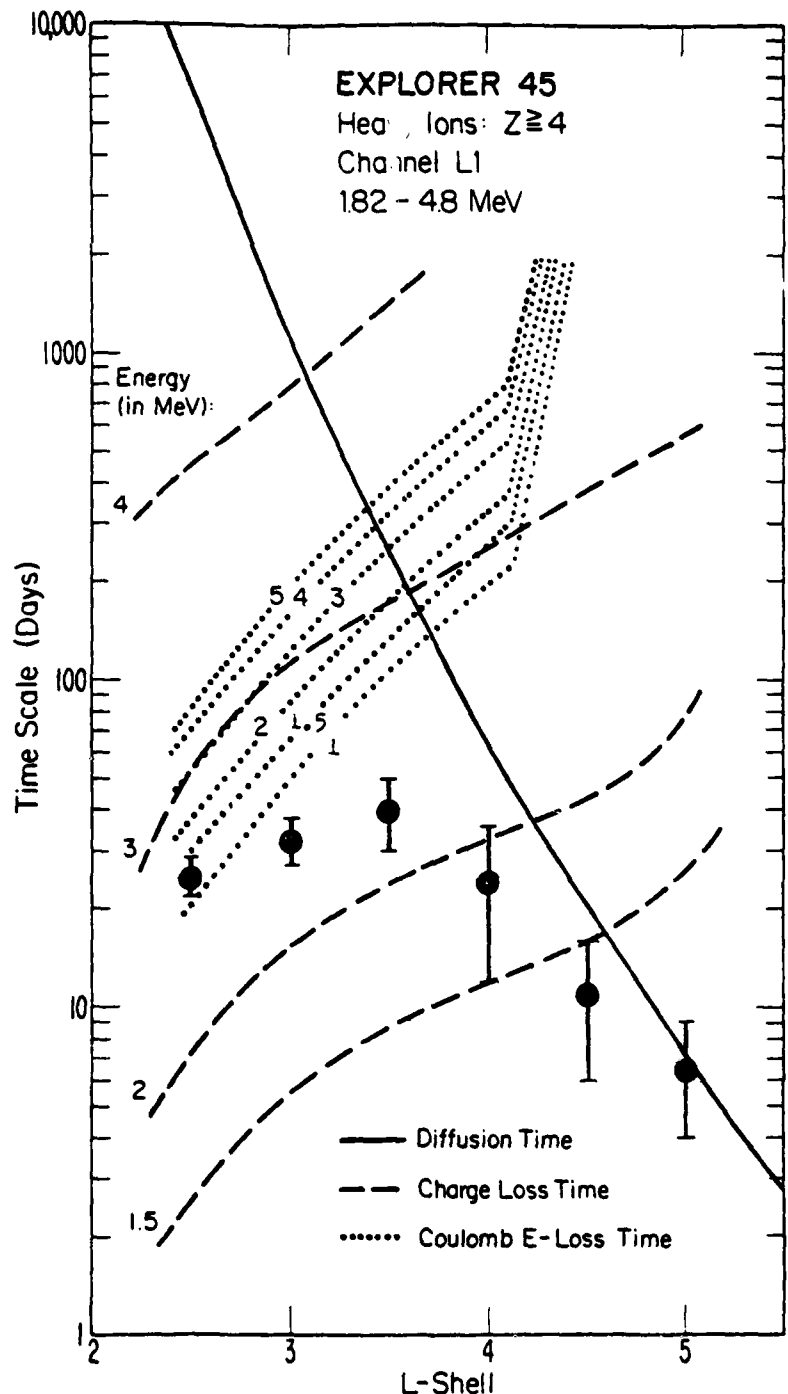


Figure 7.1

Trapping lifetime for equatorially mirroring  $Z \geq 4$  nuclei against various loss mechanisms as a function of ion total energy. The data points are measured trapping lifetimes for low energy heavy ions (taken from Spjeldvik and Fritz, 1981b). For the energies we are considering here, trapping lifetimes are limited only by the diffusion time above  $L = 2.5$ . Below this  $L$  value, Coulomb E losses may limit the trapping lifetimes for the lowest energies we have considered.

authors found that most protons having a first adiabatic invariant below 1400 MeV/gauss have diffused in from the outer boundary of the stable trapping region ( $L \sim 7$ ). In the range  $1.15 < L < 1.7$ , such protons, have energies of 100-200 MeV. Farley and Walt also found that protons at these energies had residence times of  $\sim 100$  years. This slow decay in the particle flux is presumably balanced by small increases following magnetic storms.

From this discussion, we can conclude that the importance of the trapped heavy ion contribution to soft upsets is likely to be greater in the period following a large magnetic storm, at least at  $L > 2$ . Storm-time radial diffusion probably transports heavy ions to the inner magnetosphere ( $L < 2$ ) in small increments over many years. This mechanism should be effective up to tens and possibly hundreds of MeV/u.

### 3.0 The Relative Importance of Trapped Heavy Ions in Single-Event Induced

#### Upsets

Up to now, we have used the rule of thumb that one heavy ion in  $\sim 10^6$  protons should be the level at which heavy ions begin to contribute to soft upsets. In fact, this is an oversimplification. Below the nuclear reaction thresholds of 10 to 50 MeV, protons do not produce upsets except by direct ionization, and then only in very sensitive devices. By contrast, heavy ions are their most ionizing below 10 MeV/u and may become so lightly ionizing at high energies that they can no longer produce upsets. Clearly, a more careful examination is required.

In this section we compare the soft upset rates to be expected from trapped protons, cosmic rays, and trapped heavy ions.

To estimate the upset rates due to trapped protons, we use the methods of Petersen (1981). The trapped proton fluxes are obtained from Sawyer and Vette (1976). Upsets due to cosmic rays are estimated from integral LET spectra calculated by the method described in Adams et al. (1982). The cosmic ray fluxes are obtained from Adams et al. (1981) and are modulated for the geomagnetic cutoff using the results of Heinrich and Spill (1979).

Soft upsets due to trapped heavy ions are also estimated using LET spectra computed from the trapped heavy ion spectra shown in figures 2.3 and 6.1 assuming a normal solar flare composition (Adams et al., 1981).

All the particle spectra used to compute upsets were first transmitted through aluminum shielding, allowing for the effects of the energy loss on these spectra.

The upsets are compared for a model microcircuit which has an effective cross sectional area of 400 square micrometers. It is further assumed that every particle striking the microcircuit will have a path length of 20 micrometers within the sensitive volume of the device. Products of nuclear reactions are also assumed to have up to 20 micrometers of path length available in the sensitive volume to deposit their energy. This simple device model allows LET spectra to be scaled to obtain upset rate spectra. The scale factors are  $4.343 \times 10^{-4}$  upsets/bit.day per (particle. $m^2$ .ster.sec) and 1290 electrons per (MeV/gram/cm $^2$ ).

First let us compare these components for the environment actually observed on Skylab. Skylab was in a 225 n.mi. by 50° inclination circular orbit. The geomagnetic cutoff transmission function of Heinrich and Spill (1979) for 50° had to be extrapolated in altitude from 223 km to 420 km using Stormer theory (see Adams et al., 1981, section 5.0). The orbit-averaged results are shown in Fig. 8.1 for 25 mils of aluminum shielding. In this case, the heavy ion flux actually observed is always the dominant cause of soft upsets. Figure 8.2 shows that by increasing the shielding to 100 mils, the low energy heavy ion contribution can be largely removed.

Next we compare the instantaneous upset rates for  $L = 1.7$  at the geomagnetic equator using the extrapolated results of section 6.0. We compare the upsets resulting from the trapped heavy ion spectrum shown in Fig. 6.1, the cosmic ray spectra above a cutoff of 5.5 GV (which is appropriate for  $L = 1.7$ ) and equatorial trapped protons at  $L = 1.7$ . Figures 8.3 and 8.4 show the resulting upset rates as a function of device sensitivity for 25 mils and 100 mils of shielding respectively. These are the instantaneous rates a satellite would experience when passing through the equatorial plane at  $L = 1.7$ . The trapped proton flux here is about the most intense to be found in the magnetosphere, yet the upset rate due to trapped heavy ions is overwhelmingly dominant and extends to far less sensitive devices than are affected by protons.

As can be seen in Petersen (1981) the important thresholds for the fission reactions of protons on silicon are ~ 40 MeV. This insures that the heavy ions observed by Mogro-Campero (1972) at  $L = 4$  and 5 will dominate trapped protons as a cause of soft upsets. Although Mogro-Campero reported no spectral data, the limits of stable trapping at these  $L$  values should insure that upset rates can be reduced to the cosmic ray background levels by adequate shielding, a few hundred mils should prove sufficient.

The upper limit reported by Mogro-Campero at  $L = 3$  combined with the steeply falling proton spectrum at this  $L$  value suggests that here, too, heavy ions may be the dominant cause of soft upsets for lightly shielded devices.

In Figs. 8.1 through 8.4, we did not extend the device sensitivity down to the level where stopping  $\alpha$ -particles can produce upsets. This is because there are no unambiguous measurements of trapped  $\alpha$ -fluxes above 10 MeV/u. As shown in section 4.0, the present upper limits on the  $\alpha/p$  ratio suggest that, for more sensitive devices, trapped  $\alpha$  particles may be the dominant cause of soft upsets in much of the magnetosphere.

We wish to stress again that the conclusions drawn from figures 8.3 and 8.4 are dependent on the correct choice of pitch angle distribution in section 6.0.

## 9.0 Conclusions

Using the Alfvén criterion for the limit of stable trapping, we have determined that heavy nuclei will be stably trapped in the inner magnetosphere up to energies of ~ 400 MeV/u, an energy more than adequate to penetrate the shielding of any spacecraft. The question is whether such

## SKYLAB ORBIT

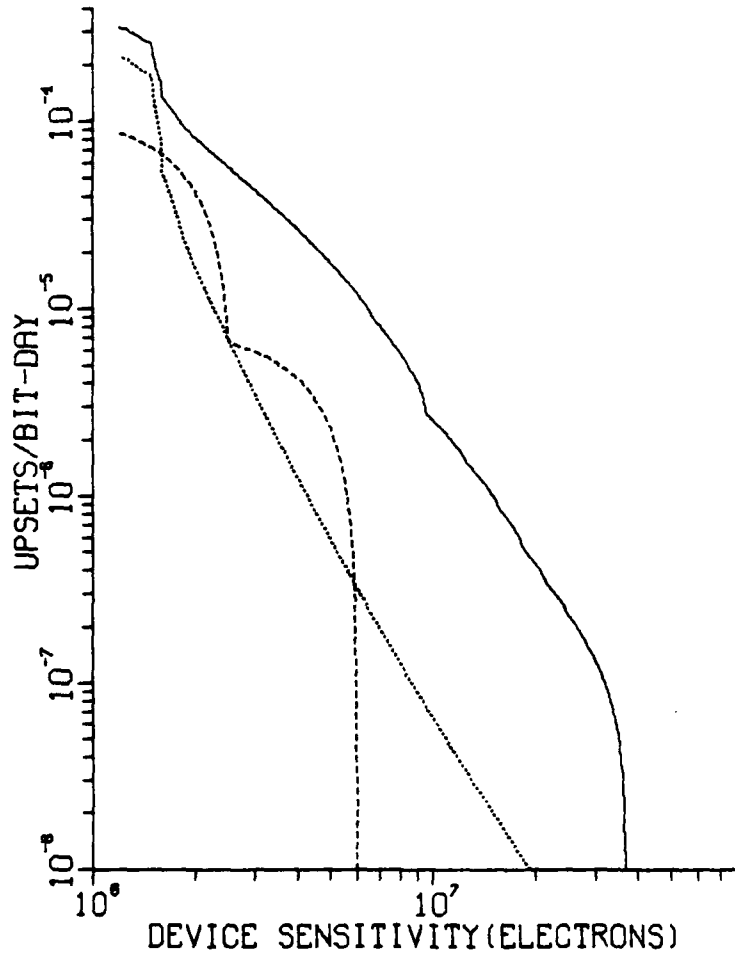


Figure 8.1

A comparison of predicted soft upset rates as a function of device sensitivity. The dotted curve is for upsets due to galactic cosmic rays; the dashed curve is for upsets due to protons (following the methods of Petersen, 1981); and the solid curve is for the upsets due to the heavy ion spectrum actually observed outside Skylab (see Fig. 2.3). These results are orbit-averaged for Skylab, which was in a 420 km by 50° inclination circular orbit. All the spectra were transmitted through 25 mils of aluminum shielding before the upset rates were estimated.

SKYLAB ORBIT

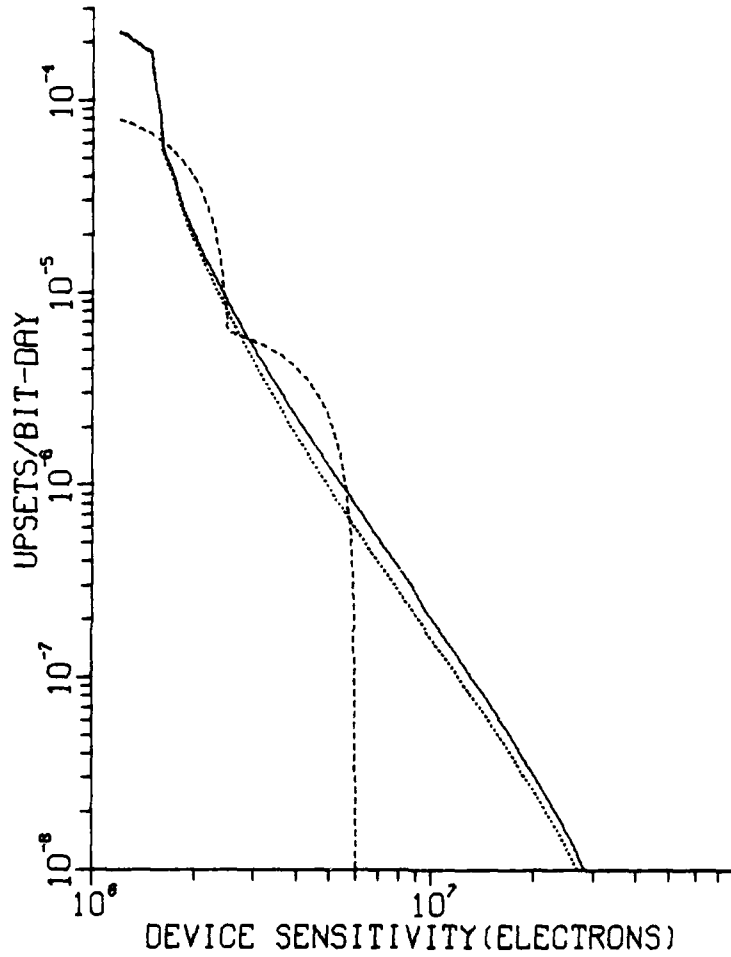


Figure 8.2

The same as Fig. 8.1, but behind 100 mils of aluminum instead of 25 mils.

# GEOMAGNETIC EQUATOR

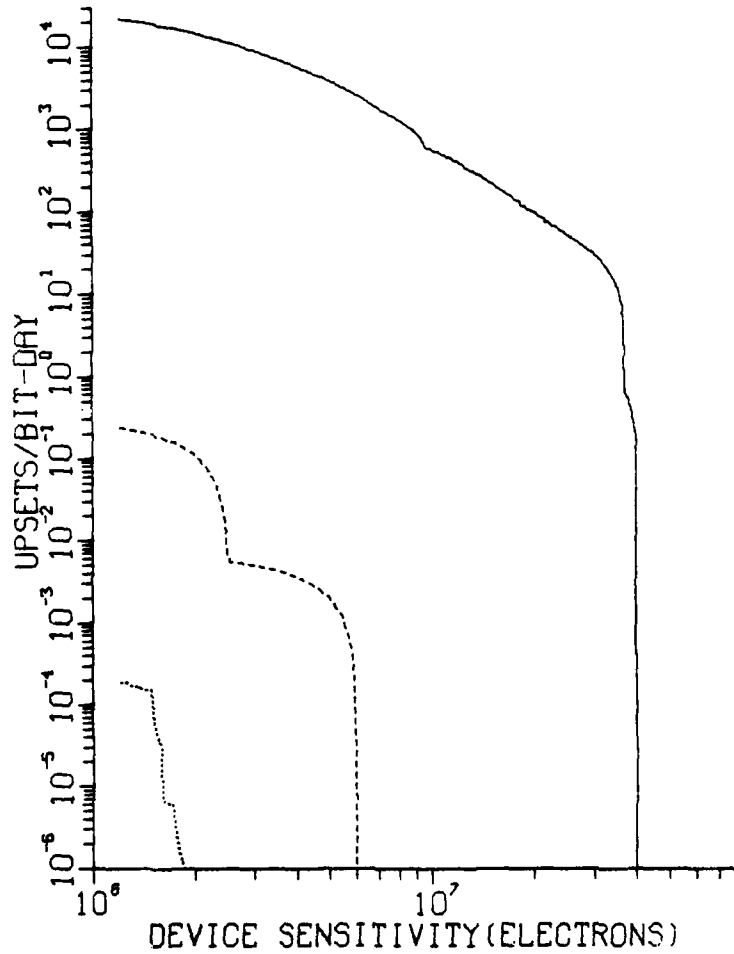


Figure 8.3

A comparison of predicted upset rates that would be observed at  $L = 1.7$  and at the geomagnetic equator. The curves have the same definitions as given in Fig. 8.1 except that the solid curve shows the upsets resulting from trapped heavy ions. The results are behind 25 mils of aluminum.

GEOMAGNETIC EQUATOR

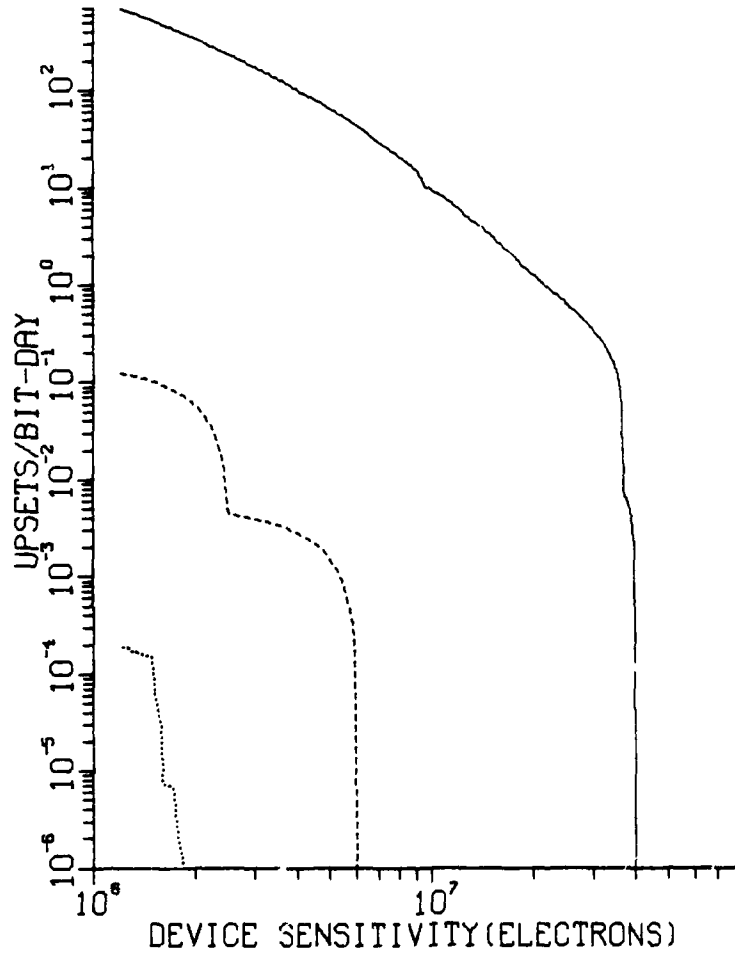


Figure 8.4

The same as Fig. 8.3, but behind 100 mils of aluminum.

energetic heavy ions are actually present in sufficient numbers to be an important cause of soft upsets.

There is very little data on the actual flux of trapped helium and heavy ions above 10 MeV/u. Thus, we used the available data and theoretical estimates to determine the heavy ion flux above 10 MeV/u. We found that there is apparently a small flux of helium nuclei and a smaller flux of heavier nuclei in the magnetosphere at all times. We also found reports of long-lasting enhancements of the low energy heavy ion flux after large solar flares.

We used the measured heavy ion flux outside Skylab to estimate the resulting upset rates as a function of device sensitivity. The data from Skylab were also used to estimate the equatorial trapped heavy ion flux and this estimate was in turn used to estimate the instantaneous upset rate at the geomagnetic equator.

We have shown that heavy ions would be the dominant cause of soft upsets for lightly shielded spacecraft on the Skylab orbit and probably at higher altitudes as well. The upset rates we estimate at the geomagnetic equator are very high and are dominated by trapped heavy ions for any reasonable amount of shielding. These results are dependant on the correctness of the assumed pitch angle distribution and the assumption that the Skylab oxygen nuclei were actually trapped.

While no  $\alpha$  particles above 10 MeV/u have been unambiguously detected, theoretical estimates of their flux make it seem likely that they will also be an important cause of upsets for sensitive components in much of the magnetosphere. All these results are for what we believe to be quiet-time conditions. Alpha particles and heavy ions are more likely to dominate upset rates during the period following a large solar flare. Large enhancements in alpha and heavy ion fluxes have been measured following several flares.

The state of the meager data base and theory on energetic trapped heavy ions is such that estimates of the kind presented here depend on interpretations of experimental results and extrapolations using the available theory. It is surely possible to construct trapped helium and heavy ion flux estimates that are much lower or higher than those given here without contradicting any of the existing theoretical or experimental work. In some of the cases considered here, it is possible to reduce the estimated heavy ion to proton and helium to proton ratios below that which would make these heavier ions dominate the upset rates. It is also possible to make estimates that would lead to predicted upset rates from helium and heavy ions that are higher than those made here. The point is that trapped helium and heavy ions cannot be ruled out as important causes of soft upsets on satellites operating on orbits below 14,000 nautical miles. In fact, it is likely that these heavier trapped ions will be the dominant cause of soft upsets at some times and in some parts of the magnetosphere even for well-shielded spacecraft.

Based on the data and theoretical work now available, it is not possible to model the heavy ion spectra above 10 MeV/u, or to predict the heavy ion distribution around the magnetosphere. Additional experimental work is needed to measure heavy ion fluxes if reliable estimates of the effect of trapped heavy ions on micro-electronics are to be made.

## 10.0 Acknowledgements

The authors would like to thank Drs. J. B. Blake and S. M. Krimigis for their extensive discussions on trapped heavy ions. Many of their suggestions on the importance of radial diffusion and the origin of the flare associated flux enhancements have been incorporated in the report without specific attribution. The authors would also like to thank Dr. James I. Vette, Prof. R. Stephen White, Dr. H. H. Heckman and Dr. Walther N. Spjeldvik for their comments on the report.

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