Fine Structure in the Energy Spectrum of Low Energy Auroral Electrons

By

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Introduction

The study of low energy auroral particles has been pursued because of a desire for greater understanding of a number of high latitude geophysical phenomena. Measurements of total particle energy down flux have been made together with measurements of auroral luminosity at selected wavelengths in order to derive energy input to light output ratios.

Knowledge of the total energy flux incident upon the atmosphere together with the particle energy spectrum are essential in understanding the behavior of the auroral zone ionosphere. This knowledge can in turn be used in calculations concerning the ionospheric absorption of cosmic radio noise, details of ionospheric chemical processes (the importance of negative ions, for example), or ionospheric conductivities and their influence upon the auroral electrojet.

Observations of the dynamic behavior of auroral particles, changes in their energy spectrum, intensity fluctuations, motions on the part of the region of precipitation are all of interest insofar as this behavior reflects dynamic interactions of these particles with the magnetospheric environment. Such studies can further contribute to the understanding of the often very dynamic appearance of the visual aurora.

The detailed observations of auroral particles have also been undertaken in efforts to deduce the nature of the processes which are responsible for the energization and precipitation of these particles. Of particular interest in this respect is the study of the energy spectrum of primary auroral particles in the hope that some unique spectral characteristic or behavior (e.g., diurnal variation or latitude variation) would emerge that could be linked to specific acceleration or precipitation mechanisms.

Observations

Historically just such a unique spectral characteristic was observed by one of the very first direct measurements of auroral electrons (McIlwain, 1960). These observations were made onboard a rocket fired into a bright (probably breakup) auroral display. The detector was CsI-phototube mounted behind an electromagnet. The magnet current was varied to obtain the energy spectra of the primary electrons. Although this detector was not sensitive to electrons of less than 3 keV McIlwain concluded from the altitude profile of the auroral luminosity that less than 25% of the light in this display was produced by electrons of less than 3 keV energy. Further it was found that no more than 10% of the incident energy was in the form of electrons of more than 10 keV energy. Finally range-energy observations made as the rocket re-entered the atmosphere indicated that the energy spectrum of these electrons had a very strong peak (or monoenergetic component) at 6 keV. McIlwain concluded that these electrons could not have been accelerated by any statistical process and suggested that electric fields played a role in the electron energization.

Both McIlwain and the NRL group (Davis, et al, 1960) also observed spectrums that did not have this sort of structure but were smooth and could be reasonably well represented by an exponential. McIlwain suggested that these smooth spectrums may have resulted from instabilities generated by the monoenergetic particle population and associated with the breakup of quiet auroras. This view anticipated by some time suggestions made by Evans (1967[a]).

Although for several years after McIlwain's rocket flight (1958) there were no additional observations of structure in the energy spectrum of low energy auroral particles. Recently, with the growing use of open windowed electron multipliers as particle detectors, numerous instances of such spectrums have been reported.

Evans (1967b) presented spectrums taken on two rockets flights through breakup aurora. Figure 1 shows the first such spectra where rather than a peak it is seen that the differential spectrum is nearly flat up to about 10-12 keV then drops very abruptly above this "cutoff" energy. The second spectrum (Figure 2) displays a pronounced peak at an energy near 5.5 keV. Both of these spectrums were obtained using a six detector array, each detector sensitive to different and rather broad energy bands. The fact that in both cases the structure in the spectrum is essentially contained entirely within a single analysis band illustrates the possible danger in attempting to obtain an energy spectrum by measurements taken at so few energies. Indeed, Matthews and Clark (1968) suggested this as a possible source of a disagreement between observed particle influxes and measured electron density above an aurora.

Albert (1967a,b) flew a relatively highly resolving detector system through a breakup phase aurora and obtained the electron spectrums shown in Figure 3. A rather broad but very prominent peak in the differential intensity is seen near 10 keV. Although these spectrums are not strictly monoenergetic the peak is so unique that nearly the same significance should be attached to it; i.e., that 10 keV represented a characteristic energy or potential in some sense.

Evans (1968), using an electrostatic energy analyzer and taking many data points as the analyzer voltage was swept slowly, obtained the auroral electron spectrum shown in Figure 4. The peak is at about 3.7 keV but as important is the very rapid decrease in intensity above this energy. The electron intensity falls by about an order of magnitude between 3.7 keV and 4.7 keV, an e-folding energy of less than 0.5 keV which is about the resolving power of the detector system. This characteristic energy remained very constant ($\pm$ 1 keV) over a period of about 200 sec in contrast to the great variability normally observed in auroral particle spectra. This data was also noteworthy in that it was obtained above a quiet pre-breakup aurora with any geomagnetic disturbance at the time being less than 20γ.

A more recent but very similar spectrum is shown in Figure 5. Here the characteristic peak is at 2.7 keV while the electron intensity fall-off at higher energies is as rapid as the example shown in Figure 4. The geophysical situation differed between these two cases in that the latter example was obtained during a breakup phase aurora which was accompanied by a negative magnetic bay. As perhaps befits this aurora, the characteristic energy was not nearly as stable as in the prior case but instead varied from about 2 keV to over 5 keV over a period of $\approx$ 100 sec.

A final example of structure in auroral electron spectrum is provided by Westerlund (1968) (Figure 6). Here the measurements extend to much lower energies than in the prior examples. It is seen that the peak at near 10 keV is superimposed upon a smooth energy spectrum which continued to rise down to the threshold energy of less than 100 eV. It is also of significance that this smooth background was observed at all times while the 10 keV electron beam appeared only when the rocket passed over discrete auroral forms. A suggestion that a similar low energy electron component accompanied the near monoenergetic electron component can be observed in the spectrum displayed in Figure 4.

Also similar to the first observation of Evans was the great stability of the characteristic energy of the auroral electron beam observed by Westerlund over a period of more than 200 seconds.

It should be noted that in the examples given here no spectrum could be called truly monoenergetic in the sense that all incident electrons were of the same energy. Usually the peak width (width at half maximum intensity) is on the order of 25% - 50% of the peak energy. It seems to be characteristic that the spectrum falls very rapidly at energies higher than the peak energy while at lower energies smaller, but significant, fluxes are present. The overall impression is that of an originally nearly monoenergetic beam of electrons that have passed through a small amount of material which degraded some of them in energy.

Discussion

The major question surrounding these spectrums is, of course, the origin or physical significance of the characteristic energies. Explanations may be put into two general classes. First, that the appearance of electrons of such a marked energy spectrum is due to some energy selection process, and, secondly, that the energy spectrum is a direct consequence of the process that energized the electrons.

An example of the first class could be a process which selected electrons in only a narrow energy range and precipitated them. For instance such a model might envision a population of electrons trapped on an auroral zone line of force and possessing a smooth energy spectrum. A very energy selective dumping process could then be invoked to precipitate only the observed electrons into the atmosphere.

Such selective dumping mechanisms are difficult to envision. A process which depended upon a wave resonating with an electron's gyrofrequency would require that the wave sense the .2% difference in gyrofrequencies of a 3.7 keV and 4.7 keV electron - a very pure wave indeed. Other dumping mechanisms encounter similar problems.

Alternatively one might invoke a model in which there existed a reservoir of already energized auroral electrons and some means by which these electrons were energy analyzed so that the energy spectrum of electrons on field lines outside this reservoir would be peaked. An energy independent dumping mechanism could then precipitate these pre-selected electrons into the atmosphere. That the geomagnetic field itself provides such energy analysis is a possibility. However, judging from the characteristics of laboratory magnetic electron spectrometers, one would expect that such analysis, being dependent upon the electron velocity, would result in a selected spectrum having a high energy tail and sharp low energy cut-off rather than what was observed.

The addition of an electric field transverse to the geomagnetic field would produce a model analogous to the laboratory crossed field analyzer and thus considerably improve the energy resolution of this giant analyzer. It is of interest to point out that in such an analyzer the charged particles undergo changes in kinetic energy as they cross electrical equipotentials. In the case of the magnetosphere the available transverse potential differences are of the same order and greater than the characteristic energies observed in the auroral particles. Thus, as is discussed below in greater detail, this crossed field model could as well be responsible for the energization of these charged particles as the energy analysis of pre-accelerated particles.

Alternatively to models which would utilize energy selection processes to produce, at a point just above the atmosphere, a flux of electrons having such unique spectrums are models which produce such spectrums as a direct result of the process that energized the electrons. One example of this class could be the acceleration of plasma by electric fields parallel to magnetic field lines. Plasma introduced at the low potential end of such a region would result in a highly collimated and monoenergetic beam of electrons at the exit end of the accelerating region. That electrons of lower energy than the maximum are observed may be taken to indicate that either the plasma is introduced into the "accelerator" over a fairly wide range of potentials or that there is an energy degradation process (ionization or the generation of waves) that affects a portion of the energized electron beam.

Westerlund, in fact, has exposed in his study of the smooth, low energy, background electron flux, a suggestion that these may have been produced by such a parallel electric field. A strong anisotropy directed down along the field line was observed in the pitch angle distribution of these low energy electrons as was a gradual and very small shift in the spectrum upward in energy as the rocket instrument moved to higher L shells. Both these observations, particularly the former, could be naturally explained by invoking weak parallel electric fields (total potential drop $\approx$ 100 volts).

On the other hand the more energetic electron fluxes observed by both Evans and Westerlund did not display this anisotropy along the magnetic field line as expected had these electrons been produced by such an acceleration. An explanation could be that the longitudinal electric field lay very far from the point of observation so that mirroring of the particles as they penetrated into stronger geomagnetic fields destroyed the original high degree of anisotropy.

Hence it appears that these rocket experiments cannot be regarded as being inconsistent with the production of keV energy electrons by the acceleration of plasma by parallel electric fields at large geocentric distances. As it is a very controversial question theoretically whether such fields can be established and sustained over long periods of time (> 200 sec) if required to produce some 10^{-5} to 10^{-6} watts/sec/cm^2/flux tube power dissipation in the form of primary auroral particles, it is wise to consider still more alternatives to explain these observations.

In particular the role of transverse electric fields should be examined. Such fields have long been supposed to account for the auroral electrojet and recently direct observations of them have been made by Föppl, et al. (1968) and Wescott, et al. (1968) using ionized cloud techniques and also by Mozer and Bruston (1967) and Aggson (1967) using a probe approach. The maximum potential differences in the magnetosphere are thought to be some 30 kV to 60 kV, far in excess of the 3 to 15 keV characteristic electron energies that have been observed.

At least two models have been set forth which utilize the $\vec{E}_\perp$ in charged particle acceleration. That of Speiser (1965, 1967) and Taylor and Hones (1965) basically differ only in that Taylor and Hones require that auroral zone geomagnetic lines of force be closed in the sense that the auroral particle can be guided the entire length from one hemisphere to the other while Speiser's model takes these same field lines to be open. Speiser considers the geomagnetic tail with a neutral plasma sheet having a very low (1 to .01γ) magnetic field strength. This picture is supported in a gross fashion by satellite field and plasma observations. An $\vec{E}$ is imposed across the neutral sheet from dawn to dusk (the same magnetospheric $\vec{E}$ which is presummed to drive the auroral electrojet). Speiser shows that plasma injected into the neutral sheet at large geocentric distances will be accelerated by the electric field while being turned toward the earth by the magnetic field. Exit of these particles from the neutral sheet is possible only when a particle drifts into the stronger tail field (15 to 30γ) at a very low pitch angle (otherwise the tail field turns the particle back into the neutral sheet). Upon exit the particle is guided down this field line presumably to the auroral zone atmosphere. By suitable choices of $\vec{E}$ and $\vec{B}$ in the tail Speiser is able to produce near monoenergetic and isotropic electron fluxes at the top of the atmosphere.

Taylor-Hones assume that the auroral zone line of force can support trapping of particles of auroral energies. They take advantage of the fact that the azimuthal drift of these trapped particles due to gradients and line curvature in the geomagnetic field need not be parallel to the $\vec{E} \times \vec{B}$ drift induced by the transverse electric field. Thus the magnetically controlled drift can drive these trapped particles across equipotentials and energize (or de-energize) them. The characteristic energy of charged particles observed on a given line of force is to be associated with the potential of that line as referenced to the point where the original low energy plasma was introduced into this electric-magnetic field geometry.

One serious problem seems to exist with the Taylor-Hones type of acceleration. This is the necessity that the particles involved be quasi-trapped (i.e., the particles can complete a bounce between hemispheres but not necessarily an azimuthal drift) before significant energization can occur. This appears to be inconsistent with the observations of isotropy in the electron influx just above the aurora where a particle loss cone of nearly 90° is expected. This could be accounted for by supposing an extremely strong de-trapping or isotropizing mechanism; so strong that isotropy could be maintained at low altitude above the visual auroral form on a time scale of seconds (the bounce period of an auroral electron).

Albert noticed in his data that the characteristic energy of his electron beam systematically increased as the rocket moved equatorward. He attributed this to the effect of poleward directed, transverse electric field, the electron energy being identified with the potential of the associated magnetic field line. Thus concluding that the electrons that he observed were energized by being driven through these potential differences, Albert felt that the requirement for particle isotropizing mechanisms implicit in the Taylor-Hones gradient drift acceleration was far too strong and that the electrons were energized by the Speiser model and deposited on open field lines. It is of interest to point out that there seems to be a contradiction in Albert's data. That is that while the increase in electron energy as the rocket-borne instrument moved southward implied a northward directed electric field, the negative magnetic bay (westward flowing electrojet) that was in progress during his flight implied (if, as usually is assumed the current is primarily Hall current) a southward directed electric field. This may be explained away if the auroral electrons involved are energized (or de-energized) slowly. This feature is consistent with a gradient drift mode of energization where many bounce periods are required for significant energy change but not with the Speiser accelerations which energizes the particle within seconds. And so the conclusions of Albert regarding the possible geometry of the auroral zone magnetic line of force should perhaps not be regarded as definitive.

Westerlund also concluded that the auroral zone lines of force were open on the basis of his data. First because the near monoenergetic component of the electron flux he observed was near isotropic and closed field lines would then imply particle dumping mechanisms and secondly he observed virtually no shift in the characteristic energy of these electrons (although the rocket instrument sampled "L" shells from L = 9 to 12) which would imply transverse electric fields. Westerlund suggested that perhaps some wave-particle acceleration akin to a traveling wave accelerator, could produce a peaked electron energy spectrum by fortuitous choices in values and gradients of electron densities, magnetic fields, and the like. The author feels that in the case of a phenomenon that has been rather often observed and observed to be rather stable that explanations appealing purely to circumstances should be rejected.

Quite apart from this there is some independent evidence that the auroral zone line of force is closed. First is the observation of detailed conjugacy in visual auroral forms made by Belon and Mather (1967) and secondly the close correlation between ATS (6.6 R_e) observations and those made at the foot of the auroral zone field line (Lenzniak, et al. 1967). In view of these data processes which can efficiently detrap energized electrons to produce the visual aurora and so make the Taylor-Hones $\vec{E} \times \vec{B}$ plus magnetic drift energization process feasible should be investigated.

Summary

Auroral electron energy spectrums having structure, especially peaks, must now be viewed as a common occurrence, if not the typical. This strongly indicates electrostatic fields have played a role in the acceleration process although alternatives cannot be eliminated as yet except upon the grounds of plausibility.

In resolving the problems outlined in this paper answers to the following subsidiary problems should first be obtained.

1) Is the auroral zone line of force open or closed in the sense that a 10 keV electron could be trapped upon it?

2) Are there realistic processes which could produce and sustain nearly constant potential drops of 10 kV along magnetic lines of force?

3) Are there realistic and efficient processes for dumping pre-energized and trapped particles off lines of force, preferably in longitudinally extended sheets, to produce the visual aurora?

It is felt that the answers to these questions, most important the first, must be obtained before the full significance of the particle spectral observations can be ascertained.

Captions

Figure 1. An example of an electron energy spectrum above an active aurora (Evans, 1967). Note the abrupt cutoff in the spectra above 12 kev.

Figure 2. Another example of an electron energy spectrum above an active aurora (Evans, 1967). Here the feature is a peak near 6 kev.

Figure 3. A series of peaked energy spectrums obtained by Albert (1967b). He interprets the increase in the characteristic energy with time as evidence for a transverse, northward directed electric field.

Figure 4. An electron energy spectrum obtained above a quiet phase aurora, (Evans, 1968). The slope of the spectrum above 3.7 kev indicates an e-folding energy of about 400 eV.

Figure 5. An energy spectrum similar to that in Fig. 4 except obtained above an active, breakup aurora. The characteristic energy is ~ 2.7 kev.

Figure 6. A series of spectrums obtained by Westerlund (1968). The peak at 10 kev was present only when the rocket was above an auroral form while the smooth background was always observed.

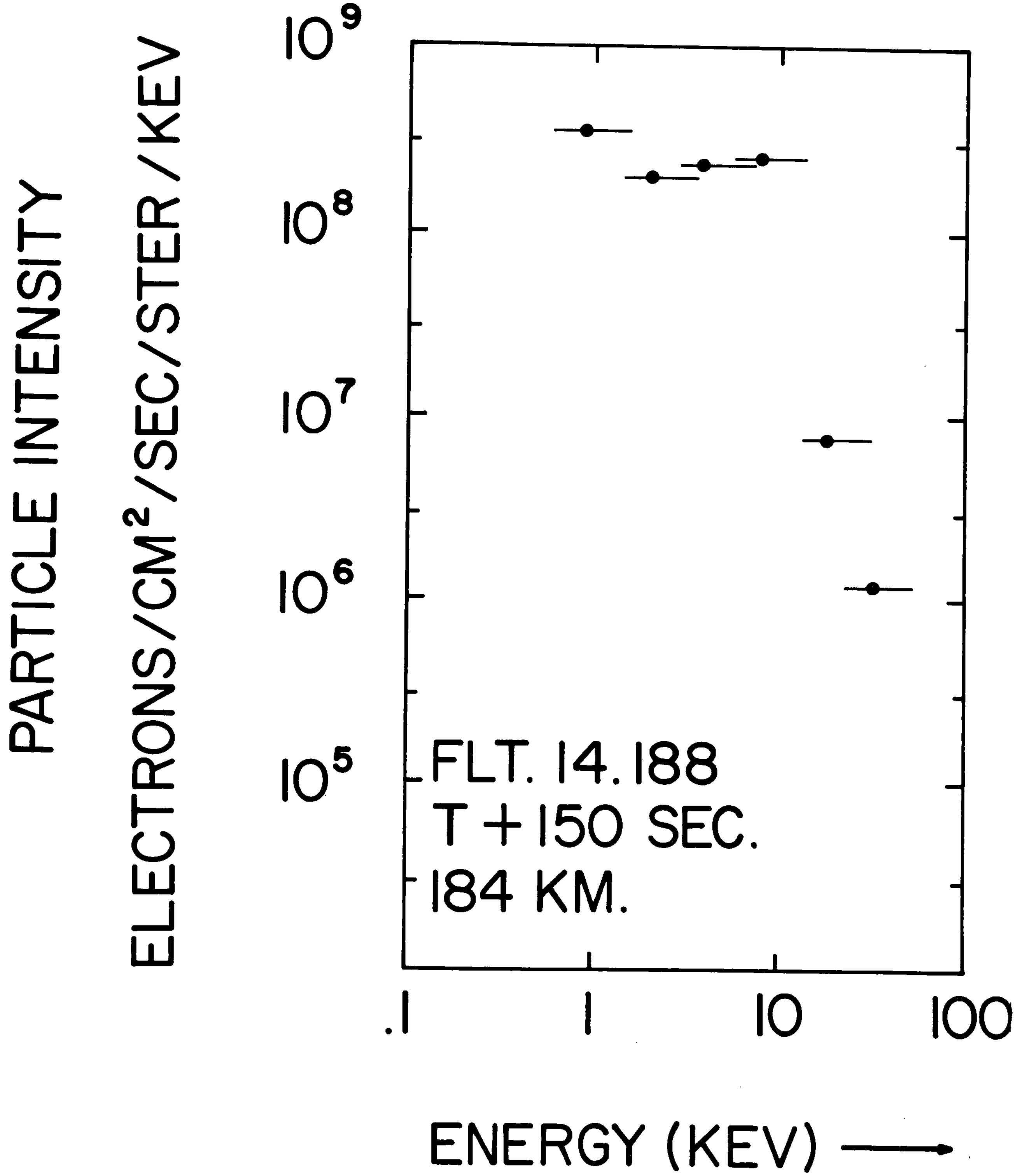

PARTICLE INTENSITY
ELECTRONS/CM²/SEC/STER/KEV
10⁹
10⁸
10⁷
10⁶
10⁵
FLT. 14.188
T + 150 SEC.
184 KM.
.1
1
10
100
ENERGY (KEV)

FIGURE 1

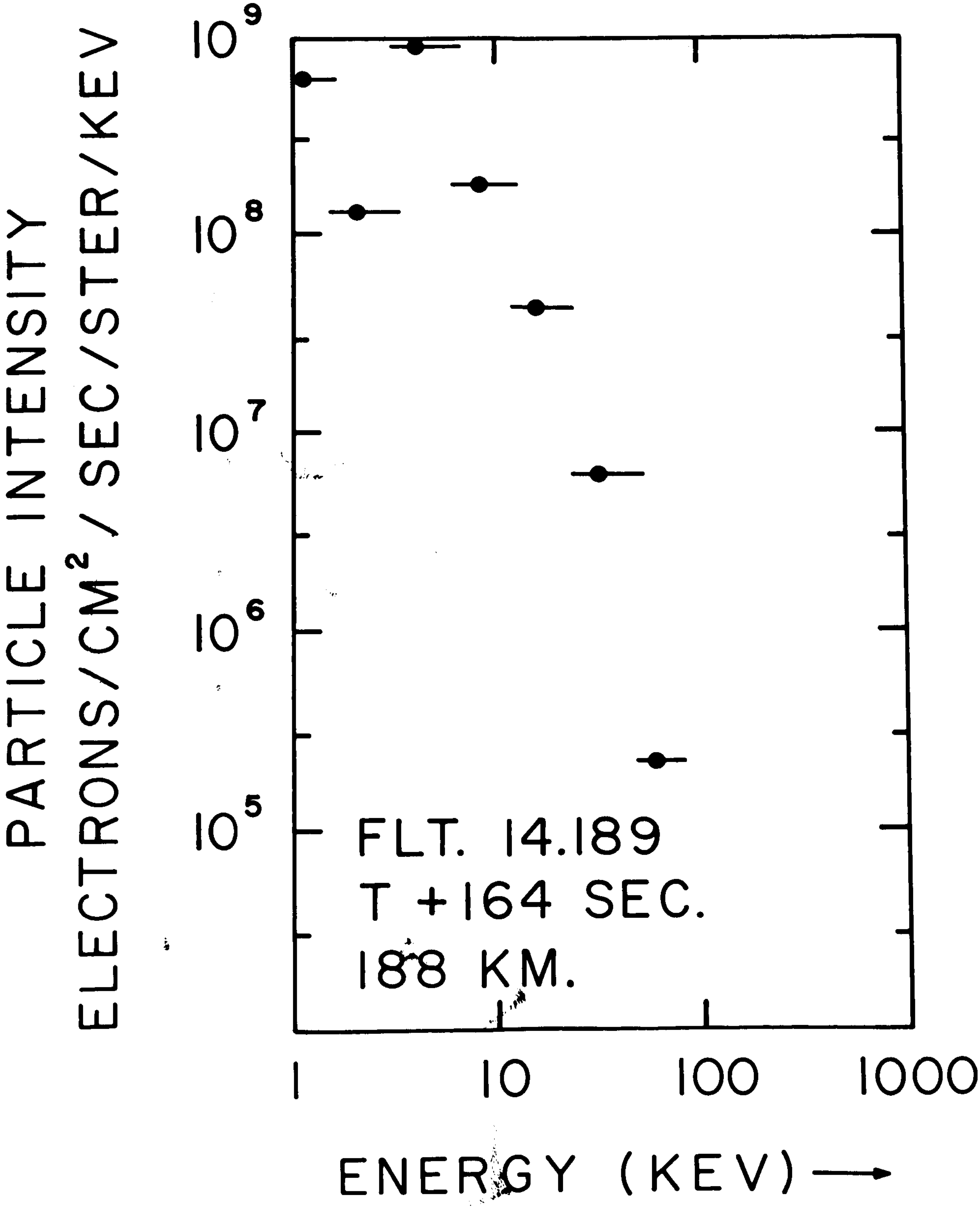
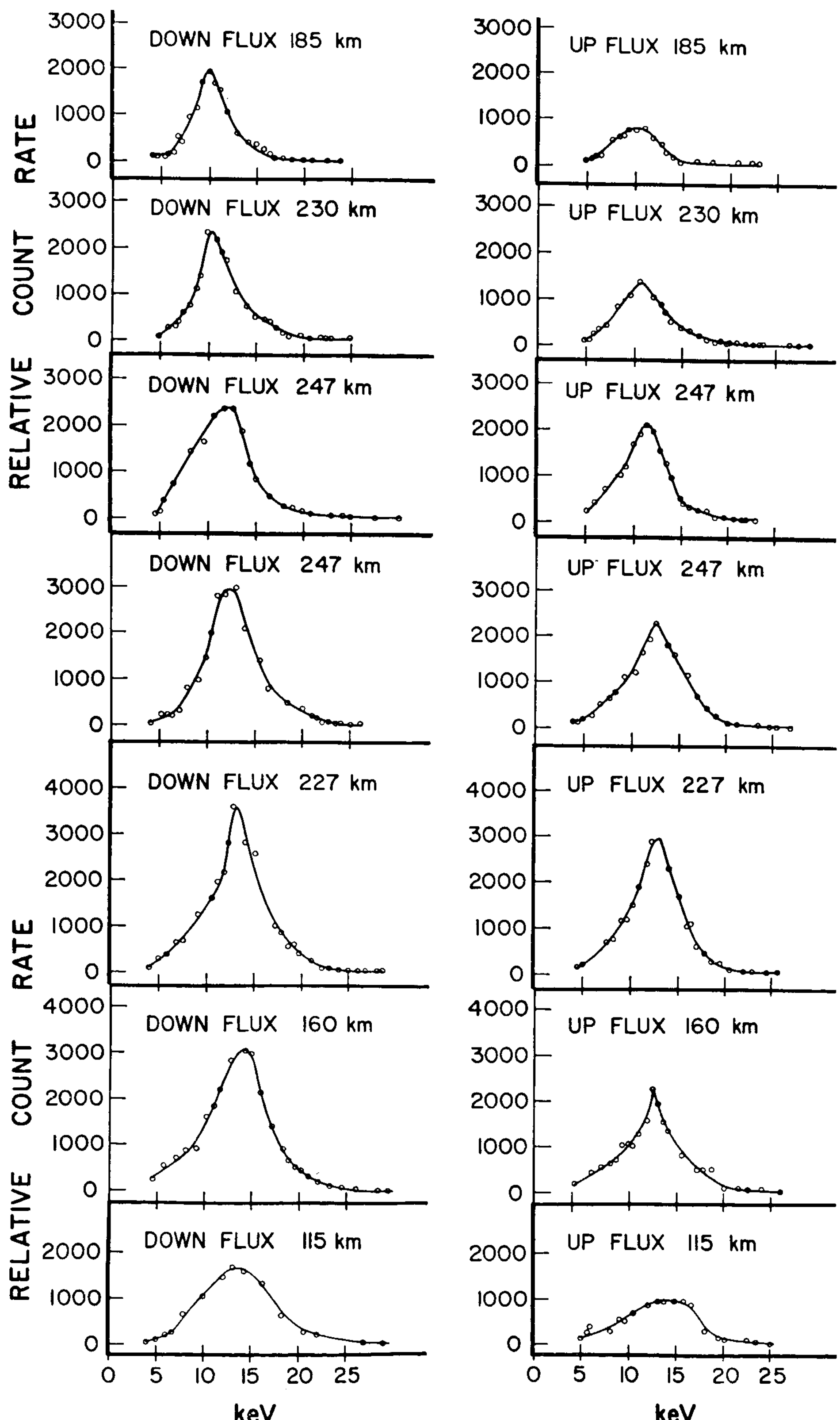
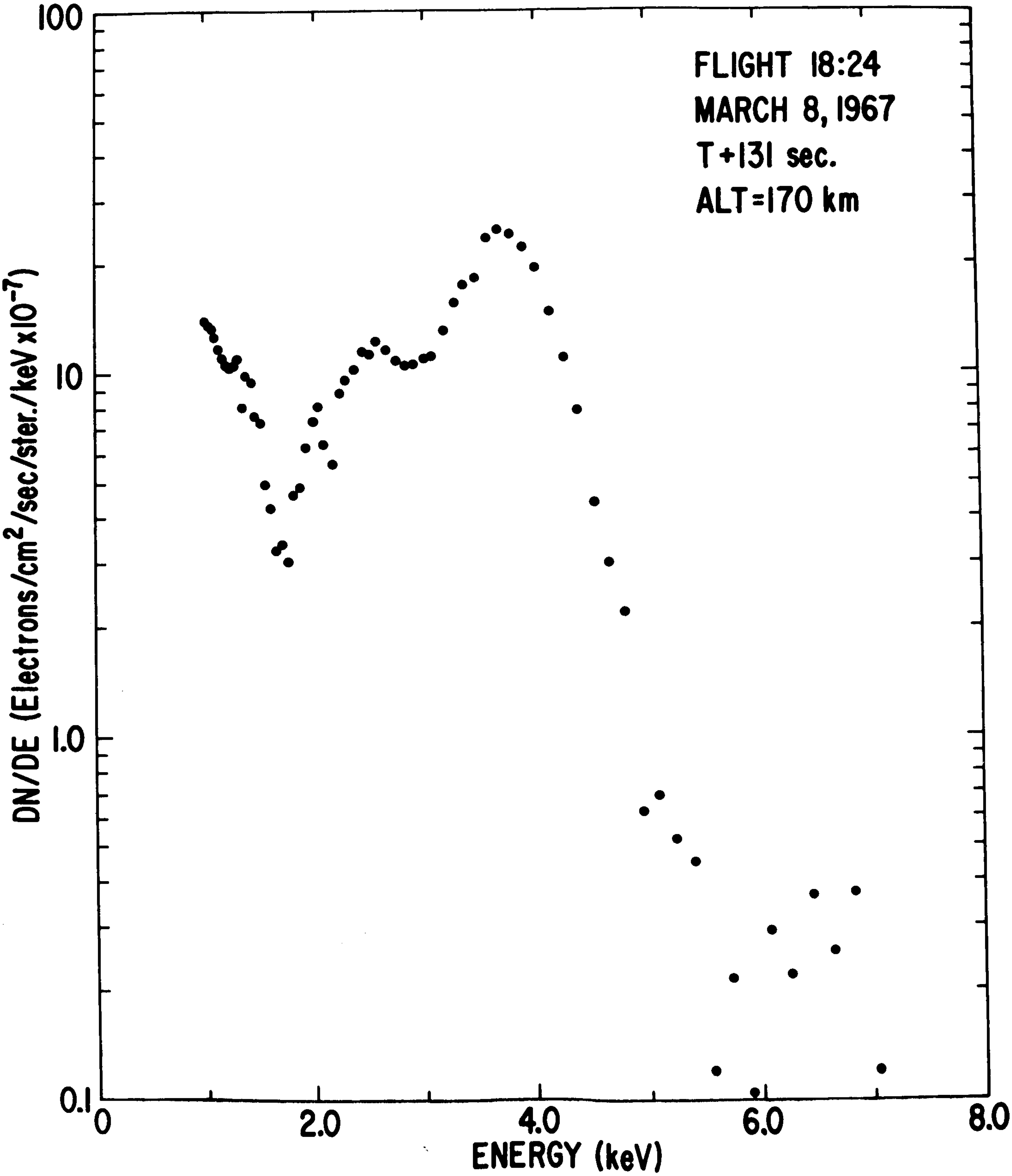

PARTICLE INTENSITY
ELECTRONS/CM^2 / SEC/STER/KEV
10^9
10^8
10^7
10^6
10^5
FLT. 14.189
T +164 SEC.
188 KM.
1
10
100
1000
ENERGY (KEV)

FIGURE 2



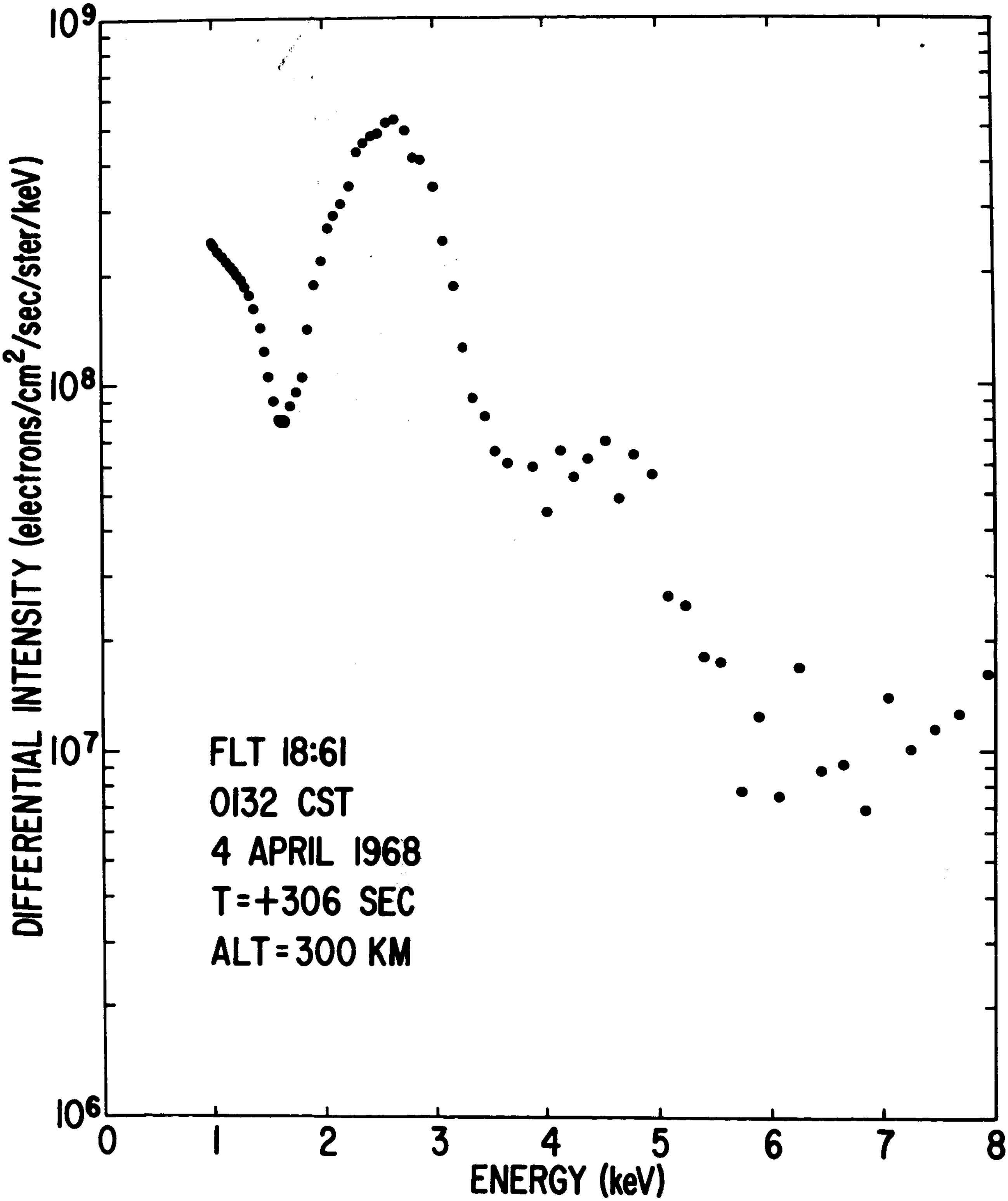
RELATIVE COUNT RATE
RELATIVE COUNT RATE
DOWN FLUX 185 km
UP FLUX 185 km
DOWN FLUX 230 km
UP FLUX 230 km
DOWN FLUX 247 km
UP FLUX 247 km
DOWN FLUX 247 km
UP FLUX 247 km
DOWN FLUX 227 km
UP FLUX 227 km
DOWN FLUX 160 km
UP FLUX 160 km
DOWN FLUX 115 km
UP FLUX 115 km
0 1000 2000 3000 4000
0 5 10 15 20 25
keV
keV

FIGURE 3



FLIGHT 18:24
MARCH 8, 1967
T+131 sec.
ALT=170 km
DN/DE (Electrons/cm^2/sec/ster./keV x 10^{-7})
100
10
1.0
0.1
0
2.0
4.0
6.0
8.0
ENERGY (keV)

FIGURE 4



DIFFERENTIAL INTENSITY (electrons/cm²/sec/ster/keV)
10⁹
10⁸
10⁷
10⁶
0
1
2
3
4
5
6
7
8
ENERGY (keV)
FLT 18:61
0132 CST
4 APRIL 1968
T=+306 SEC
ALT=300 KM

FIGURE 5

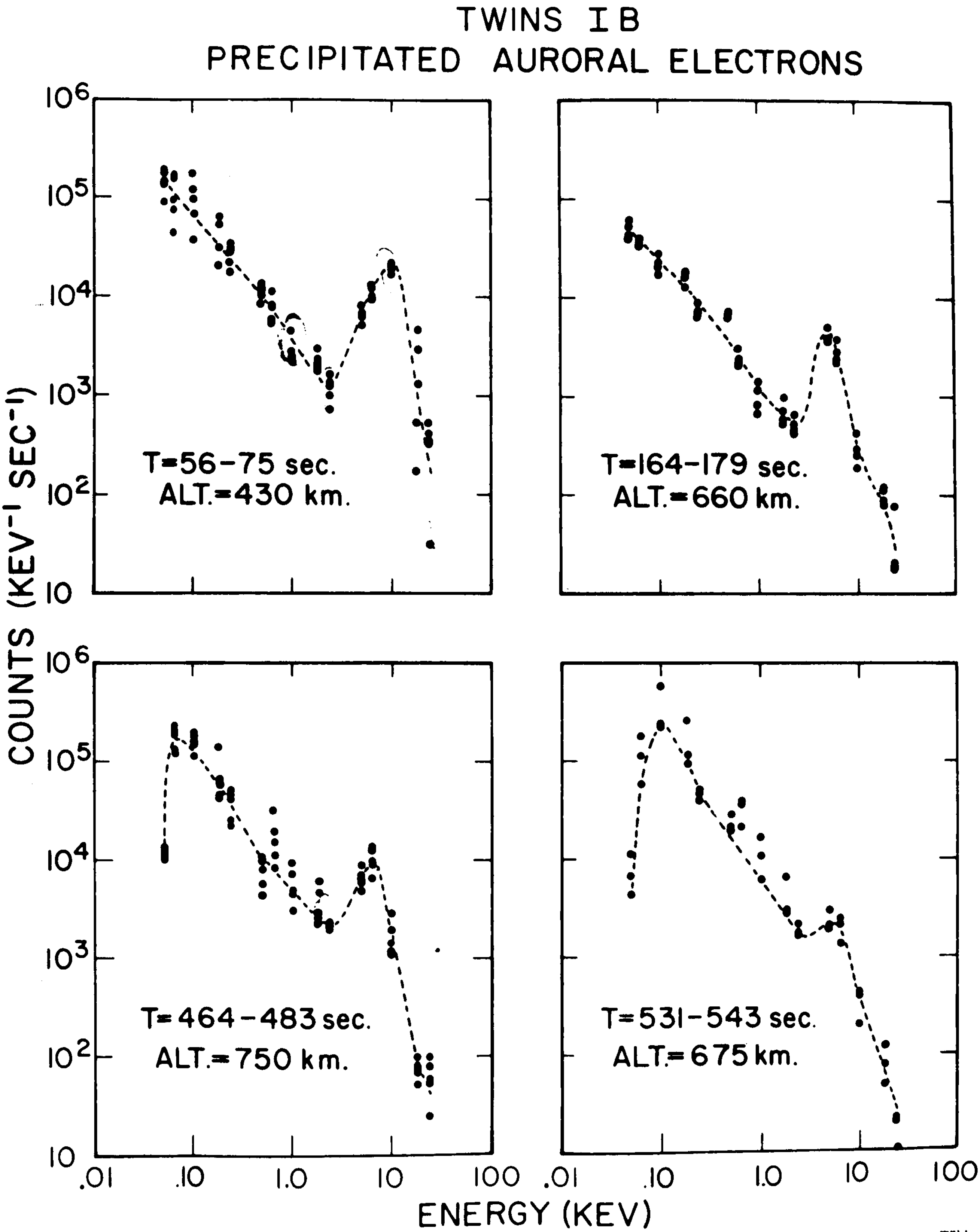

TWINS IB
PRECIPITATED AURORAL ELECTRONS
COUNTS (KEV^{-1} SEC^{-1})
ENERGY (KEV)
T=56-75 sec.
ALT.=430 km.
T=164-179 sec.
ALT.=660 km.
T=464-483 sec.
ALT.=750 km.
T=531-543 sec.
ALT.=675 km.
10^6
10^5
10^4
10^3
10^2
10
.01
.10
1.0
10
100

FIGURE 6

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