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THE OBSERVATION OF A NEAR MONOENERGETIC FLUX OF AURORAL ELECTRONS

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ABSTRACT

Rocket borne observations were made of a nearly monoenergetic beam of electrons in association with a pre-breakup auroral display. The characteristic energy of this beam was about 4 KeV and was very stable over a 150 second period of time. The nature of this energy spectra strongly suggests that the electron energization was by the electric fields associated with some static 4 KeV potential difference in the magnetosphere.

A model in which this potential was established directly along a magnetic field line cannot be uniquely excluded by these observations but is discounted on other grounds. The alternative is a model in which the required electric field is transverse to the magnetic field lines. Such electric fields are known to exist and have been measured directly. Energization of low energy electrons by an electric field of this geometry would appear to require that these electrons be stably trapped on closed lines of magnetic force, the energization occurring by virtue of gradient and line curvature drift across equi-potential lines. It is this process, which is similar to that proposed by Taylor and Hones (1965), that is believed to have produced the auroral particles observed in this aurora.

The electrical potential differences known to be available in the magnetosphere although sufficient to produce these 4 KeV electrons

are inadequate to produce the 100KeV electrons seen in association with the aurora. Thus the existence of at least two acceleration mechanisms is firmly established.

THE OBSERVATION OF A NEAR MONOENERGETIC FLUX OF AURORAL ELECTRONS

Introduction

The observation of structure or of monoenergetic components in the energy spectrum of precipitating auroral particles would have great significance insofar as pointing toward electrostatic fields as being the agent responsible for energizing these charged particles.

Several such observations have been presented in the literature. The earliest was that of McIlwain (1960) where the particle influx associated with a very bright aurora appeared to be composed primarily of 6 KeV electrons. Evans (1966) reported two instances of structure in the spectrum of low energy auroral electrons, The first was of a monoenergetic component in the electron flux at an energy near 6 KeV. The second observation was of a very sharp knee in the electron spectra in the region of 12 KeV. Both these observations were hampered by the fact that only a limited number of detectors, each having a rather poor.energy resolution, were used to perform the intensity and spectral measurements. Thus any structure in the spectrum that had a scale finer than the spacing between the energy bands being sampled by the detectors, could not be described in as great a detail as desired.

Albert (1967 a, b) using an electrostatic energy analyzer coupled with a scintillation detector – an instrument having much greater energy resolution than those used previously – observed a near monoenergetic beam of auroral electrons. The center of the intensity peak in this spectrum was at about 10 KeV and the width of the peak was on the order of 4 KeV.

This paper discusses still another instance of monoenergetic auroral electrons where the spectral measurements were made with enough detail to permit some conclusions to be made about the origin of the particles,

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The instrument used to perform these measurements was a cylindrical curved plate electrostatic analyzer employed to discriminate the charge and energy of the incident charged particles and a channel multiplier used to detect those electrons which passed the analyzer. Figure 1 displays the response of the detector system to an isotropic flux of electrons as a function of electron energy (E_o, the center energy being set by the voltage on the analyzer plates). It is seen that the detector is not highly resolving. However, detailed spectral measurements of a particle beam are possible by sweeping the plate voltage slowly so that successive intensity observations are made at center energies that differ by only a small amount from one another. The voltage sweep on the plates was generated by changing a capacitor slowly, then discharging it quickly by using a relay to switch a low resistance across the capacitor, On this flight the charging portion of the sweep took ~ 1.55 seconds and in that period covered the energy range between 1.5 KeV and 15 Kev. The discharge cycle took .050 seconds. During the sweep the detector response was sampled and transmitted by a PCM telemetry system at the rate of 224 times per second. The change in center energy, E_O, between successive samples was less than 100 electron volts. Two identical detectors operated in this fashion were flown in the rocket to provide redundancy.

Three additional detectors, identical in every respect to the swept detectors except that the plate voltages were fixed, were included to provide intensity measurements in three bands about 2 KeV, 6 KeV, and 10 KeV. This was done not only to provide checks on the operation of the swept analyzers, but also to remove any ambiguity introduced into the spectral measurements by time or spacial variations in the electron flux.

A photometer sensitive to 3914 Å auroral light, a total energy scintillator and a solid state detector, with its lowest channel set to detect 40 KeV electrons, completed that portion of the payload of interest here.

Flight Description

This instrument package was launched from Fort Churchill on a Nike Tomahawk (18:24) on 8 March 1967 at 2307 local time. The rocket penetrated through a very widespread, reasonably bright auroral display. Figure 2 is a 4 sec all sky camera exposure of the display taken 60 seconds after the launch with the position of the rocket marked by the circle. Ground based photometers operated by the National Research Council registered on intensity of 6 kR in 5577 Å at + 60 seconds. This display remained bright until about 285 seconds after launch when much of the form began to fade.

Although the display appeared visually to be active at the time of launch, post flight data indicated that it was in fact a pre-breakup display. The magnetometer at Churchill revealed insignificant (10 - 20γ) magnetic fluxuation during the flight. Some 30 minutes after the rocket flight a magnetic bay (amplitude $\approx$ 100γ) occurred in association with the break up phase of the visual aurora.

The launch site riometer registered no significant absorption during the rocket flight although a small event occurred during the subsequent break up.

Both the rocket and the instrumentation performed satisfactorily throughout the flight although a malfunction of a despin mechanism resulted in a final spin rate of 0.5 rps rather than the expected 0.1 rps.

Observations

Figure 3 displays the electron intensity detected by the fixed band 2 KeV detector during the flight. The drop in intensity toward the later part of the flight is in qualitative agreement with the decrease in auroral luminosity during the same period.

Figure 4 displays three fairly typical energy spectrums obtained by the swept energy detectors during this flight. The presence of the prominent peak in these spectrums (indicative of a strong monoenergetic component in the beam in the region of 3.7 - 4 KeV) was a most striking and characteristic feature of the spectrums observed over most of the period that auroral particle fluxes were detected. The details of the analyzer response function have not been incorporated into the spectrums presented in Figure 4. The peak is in reality much sharper than it appears. Figure 5 super-imposes upon an observed spectrum the curve that would have been expected had the **beam** been composed purely of 3.8 KeV electrons (the data here has been smoothed by an 11 point running average method). Although there is poor agreement at low energies, pointing up that a portion of the influx are electrons of less than 3.8 KeV, the fit above 3.8 KeV is very good indeed. The conclusion is that the slope of the spectrum above the peak is very steep, the e - folding energy being less than 100 eV.

The relative absence of energetic electrons is the beam during this period is confirmed by the response of the solid state detector (D. Williams, private communication) showing no more than 10^4 electrons/cm^2/sec/ster of energies greater than 40 KeV in the beam. The low energy character of the beam is further shown by the relative absence, compared with other flights, of ionization below an altitude of 115 km as measured by a Langmuir probe onboard the rocket (T. Aggson, private communication). The responses of the three fixed band detectors agree closely with the responses of the two swept energy units whenever identical energy bands were examined. These various qualitative agreements can leave no doubt that the important spectral features of the primary electron influx associated with this auroral display have been accurately determined by the detector complement.

As significant as the monoenergetic aspect of the spectrums is the stability in the position of the intensity maximum during a lengthy period of the flight. Figure 6 exhibits this feature as a plot of the energy of the peak electron intensity against time. During this same time it is estimated that the rocket moved only 25 km (or 1/4 degrees in magnetic latitude) across magnetic field lines. This stability, as observed on what is nearly the same line of force must be a reflection of the stability of the electron acceleration mechanism and is a strong constraint on such a mechanism.

The slow roll of the rocket coupled with the sweeping nature of the detector (which took about the same time as a roll) resulted in pitch angle data on the particle influx being a composite of sweeps over many seconds of flight. The stable nature of the influx suggests that distributions obtained over a period of seconds would not be grossly incorrect. During the extended period over which the nearly monoenergetic beam was observed there was no indication that these electrons were anything but isotopic (to within a factor of 2) over the upper hemisphere, from pitch angles of 0" to 80". The total energy detector response was in agreement with this observation. Quantitatively, the electron influx, typified by the spectrums in Figure 4, involved a total of about 4 x 10^8, 4 KeV electrons/' cm^2/sec/ster – an energy flux of 2.5 ergs/cm^2/sec/ster. This flux is in reasonable agreement with what would have been expected from the ground based estimate of 6 kR for the intensity of 5577 Å emission.

Discussion

There can be little doubt that the electrons observed during most of this flight into this prebreakup aurora are the result of a simple electric field interaction. The characteristic energy of about 4 KeV is to be interpreted as the potential difference between the point of injection of, presumably, low energy charged particles into the field and the point of observation. The additional fact that the bulk of the primary electrons had nearly the same final energy indicates that the points or region of initial plasma injection had a common potential (if indeed there was more than a single point). However the presence of electrons in the beam of energies lower than the peak energy speak for these electrons being introduced into the electric potential distribution at some intermediate point, perhaps as a result of some atmospheric interaction. Similar low energy "straggling" may be observed in laboratory electrostatic accelerators if operated in a poor vacuum.

The very sharp cut off in particle intensity above 4 KeV is equivalent to an e-folding energy of less than 100 eV and may very well be related to the energy spectrum or temperature of the original injected plasma electrons – the thermal spread in energy having been simply displaced upward by 4 KeV. If so, then an energization ratio of not less than 40:1 has occurred.

While there is little question that static electric fields were responsible for generating the primary auroral electrons observed on this rocket flight, it is not so clear exactly what the geometry of this electric field is.

One possibility is that the electric field was imposed along the magnetic line of force. If a total of 4,000 volts potential drop were available, plasma introduced at one end of this line of force would produce precipitating 4 KeV charged particles at the other.

The existance of such electric fields along a line of force has been a point of controversy (see, for example, the review by Böstrom 1967). The usual argument against a longitudinal static field is that the large electrical conductivity along a plasma laden line of force would result in these charged particles moving very rapidly to short the electric field out. Mende (1967) for example contends that a longitudinal electric field would essentially drive the ionosphere outward into the magnetosphere – i.e. the existence of the ionosphere is sufficient to preclude such an electric field.

On the other hand Alfvén and Fälthammer (1963) have constructed a model whereby trapped ions and electrons which have differing pitch angle distributions and covering a region of low plasma density, can produce a static electric field along B. No estimate is made, however, on the lifetime of this field if it were to be used to accelerate and precipitate electrons on the scale observed on 18:24. Block (1966) has considered the problem of ionosphere moving quickly to cancel any longitudinal field (as Mende would contend) and argues that current limiting due to space charge effects, analogous to that observed in thermionic diodes, may inhibit such motion to a large extent.

Swift (1965) has proposed a model for energizing electrons that involves a longitudinal electric field. The rapid flow of plasma down the field line – which would short out the field – is prevented by wave particle interactions which effectively lower the conductivity by many orders of magnitude. However, the auroral particles that are produced are not predicted to be monoenergetic but rather the broad energy spectrum that results from these wave particle damping mechanisms. It is on this ground that the Swift model must be excluded as producing those electrons seen on 18:24.

Experimental observations are in a state similar to that of theory. Mende (1967) is able to put an upper limit of some 10^{-5} v/m for the longitudinal electric field strength at an altitude of 200 km over the auroral zone based upon the observation of ion clouds. This observation was obtained in the absence of aurora. Mozer and Bruston (1967) using a rocket borne electric field probes observed what appeared to be a longitudinal electric field of 20 mv/m directed along the magnetic field. This measurement was made at an altitude of some 300 km during an auroral display.

With the possible exception of the observations of stability over a period of 150 sec, there appears to be nothing in the particle observation to unambiguously prove or disprove a process involving a longitudinal, static electric field. The observation of stability, however, does put some constraints on the problem. If there were sufficient plasma available to short this longitudinal potential drop, it is generally conceded that the potential will not be sustained for much longer than the time taken by the plasma to move down the field line. In this case assuming the potential gradient to be constant down a field line of length D, the 4 KeV potential difference together with the 150 sec period of stability, would require that D be on the order of 500 Re. If on the other hand, the current flow represented by the energetic particles ($\sim 4 \times 10^{-10}$ amp/cm^2) were <u>not</u> sufficient to short the field (i.e. the plasma density was low), there would seem to be some sort of current limiting mechanism operating in feeding plasma onto the grounded end of the field line to be accelerated.

While the author does not feel it likely that these electrons were accelerated by a potential drop along a field line, the data should not be interpreted as precluding it.

The alternative is, of course, transverse electric fields such as are known to exist in the auroral zone. In this case it is not the electric force which produces energization (because the drift introduced by the electric field is in the direction of $\vec{E} \times \vec{B}$) but the magnetic drifts, caused by magnetic field gradients and line curvature, which may be in the direction of $\vec{E}$. If the auroral zone line of force were open, the distance through which the electron drifted in <u>one</u> traversal of the line of force must have been sufficient to have driven the electron through 4,000 volts potential. It is difficult to estimate the distance the electron would drift because of field gradients and line curvature on such an open field line, but some reasonable estimate may be provided by the drift rate in a closed field, dipole geometry. Akasofu and Chapman (1961) calculate that a 7 KeV electron on a L = 6 line of force drifts .015° of longitude per bounce. This is equivalent to about 1 km at the top of the atmosphere at a latitude of 60°. It is essentially this distance over which the particle must experience a 4,000 volts potential drop in order to be energized within one bounce period. The equivalent electric field must be much greater than 4 volts/meter (referenced to the top of the atmosphere) which is orders of magnitude greater than observed transverse fields (Böstrom 1964, Föppl, et al., 1967). It is doubtful whether the geometry of the open line is such that a drift rate of more than two orders of magnitude faster than this estimate would occur.

Thus if it is a traverse electric field involved in the energizations one is forced to conclude that these electrons where trapped on closed field lines and underwent energization by virtue of a magnetic drift through a transverse electric field. Only a modest electric field strength would be required because the total distance through which the particle drifts is much greater than possible with an open magnetic field geometry. Albert (1967 b) has reached just the opposite conclusion (i.e. the field lines were open) on the basis of pitch angle considerations. However, the resulting requirement that the electric field be of large magnitude (as discussed above) seems a much more compelling argument against the field line being open.

It should be noted that this general conclusion is consistent with at least two of the major features of the picture put forth by Taylor and Hones (1965) of the energization of plasma introduced into model geoelectric and geomagnetic fields. Specifically

1) Monoenergetic auroral particles are predicted and observed
2) Auroral particles being trapped on field lines before significant energization occurs is both predicted and inferred from these observations.

If this general picture is valid, then the interpretation that the slope of the spectral fall off above 4 KeV is related to the temperature of the injection plasma leads to some further conclusion. In the Taylor–Hones analysis use is made of the strict conservation of the first adiabatic invarient i. e.

$$E_e' = \frac{B'_m}{B_m} E$$

where E and B_m are the energy and mirror field of the original injected low energy electrons and E' and B'_m are the corresponding values after acceleration. The observation of 4 KeV electrons at a magnetic field strength of some 50,000γ together with the inference that these electrons originated from a plasma of temperature less than 100 eV leads to the estimate of not more than 1,200γ for the magnetic field strength at the injection point. This requirement is important as it serves to exclude ionospheric electrons as being the particle source for this acceleration.

In fairness, however, it must be pointed out that if there were strict conservation of the adiabatic moment as these electrons moved through the electric and magnetic fields one would expect a pitch angle distribution at the top of the atmosphere that was peaked near 90° to the field line – i. e. the existence of loss cone. However, the observed pitch angle distribution gave every appearance of being more nearly isotropic over the range from 0' to approximately 80°. Thus a more or less continual pitch angle redistribution of these electrons appears necessary as they bounce between hemispheres. Other alternatives, such as requiring the magnetic field line to be open, seem to introduce even more untenable assumptions. No mechanism to produce such a pitch angle redistribution is put forth here although a model along the lines of the whister-particle interactions suggested by Kennel and Petschek (1966) seems attractive.

Another area of apparent disagreement between the Taylor-Hones model and these observations of near monoenergetic electron beams that have been made is the absence of any characteristic energies greater than 12-14 KeV while the Taylor-Hones potential distribution would predict that monoenergetic electrons can be produced up to some 30-40 KeV. This disagreement may not be due to any fundamental error in the Taylor-Hones computations but rather that the electric field distribution that they used overestimated the field intensities. Such errors in magnitude may easily arise in the process of generating first polar ionospheric current pattern from magnetometer data, then assuming ionospheric conductivities to deduce the electric field pattern as Taylor and Hones did.

While such disagreements in magnitude between theory and observations should not be regarded as detracting from the fundamental agreements discussed here, they do point up the fact that the potentials differences available in the magnetosphere appear to be insufficient to produce those electrons energies greater than 40 KeV that are often observed in the auroral influx (Brown, 1966, Anderson 1965). Thus there must exist a second entirely different acceleration mechanism operating in the auroral regions of the magnetosphere to account for these particles. It is most probably this aspect of the auroral particle accelera- tion problem that has been discussed by Mozer (1965), O'Brien (1964), and Evans (1967), in papers reporting upon the behavior of this energetic component of the auroral particle population.

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Figure Captions

Fig. 1. The response of the curved plate analyzer channel multiplier detector to an isotropic flux of electrons as a function of electron energy.

Fig. 2. The 4 second exposure all-sky camera photograph of the auroral display taken at +60 seconds. The black dot marks the position of the rocket at this time.

Fig. 3. The count rate response of the 2 KeV electron detector as a function of time during the flight of 18.24.

Fig. 4. Three representative examples of the swept energy detector response as a function of "analyzer center energy" obtained during the period that the rocket was above the auroral display in Figure 2.

Fig. 5. Another sample of the swept energy detector response where the data scatter has been reduced by a running average technique. The solid line is that response that would have been expected had the electron beam had been purely 3.8 KeV electrons. The close agreement between the observed and hypothetical curves leads to the conclusion that the slope of the true energy spectra above 3.8 KeV is less than 100 eV.

Fig. 6. The energy of the peak in the electron energy spectra as a function of time while the rocket was above the auroral display.

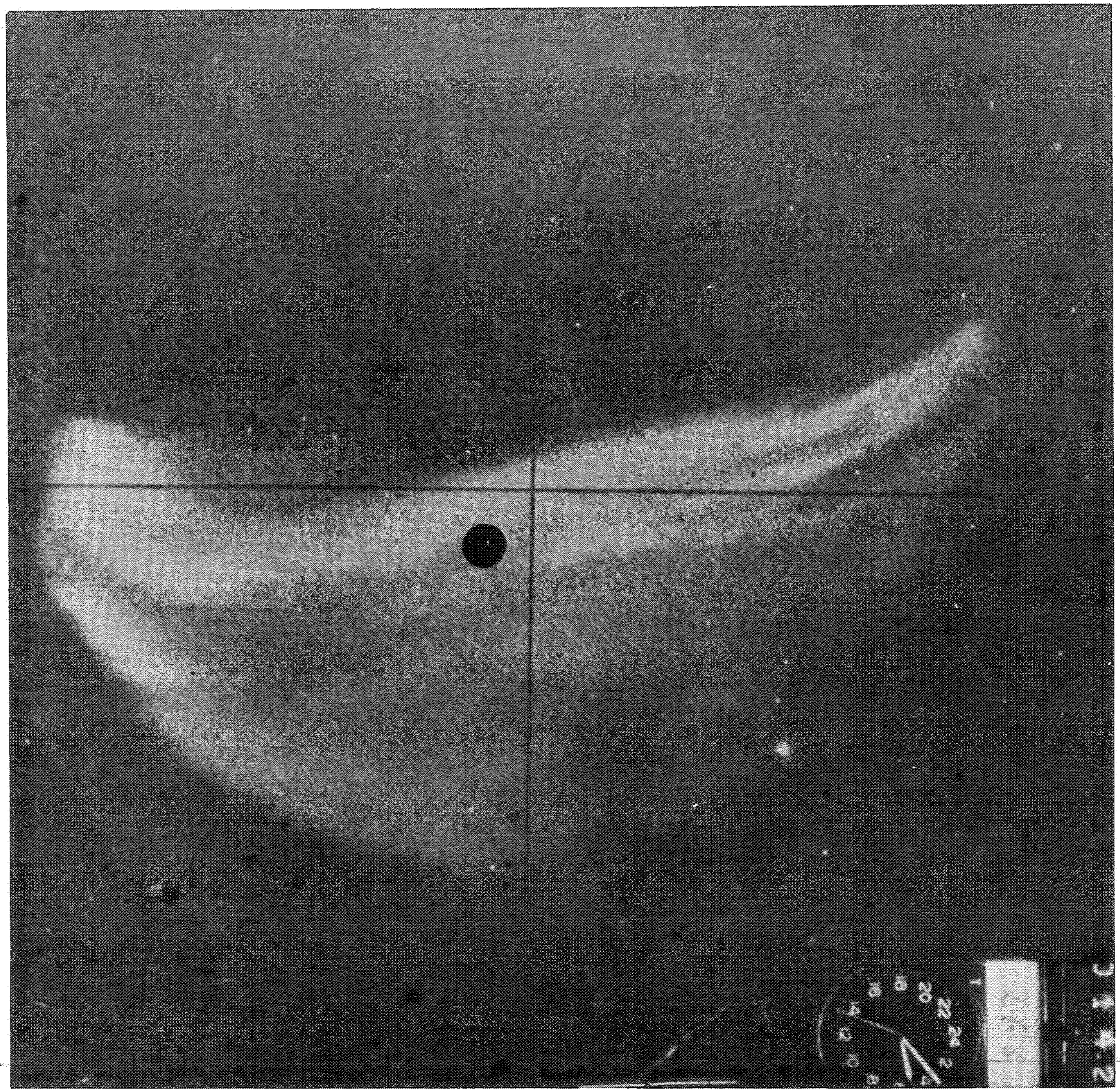


Figure 1

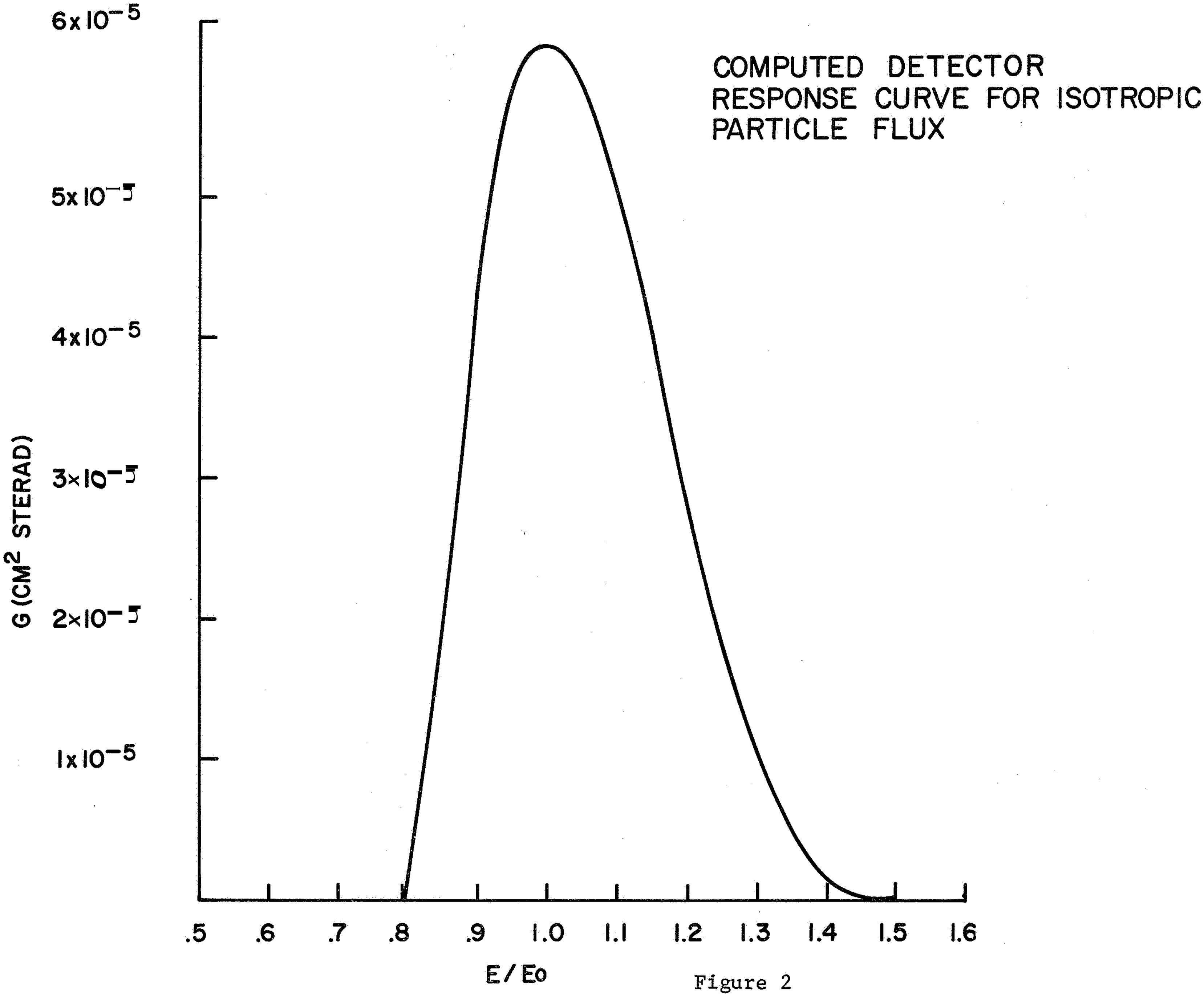

COMPUTED DETECTOR RESPONSE CURVE FOR ISOTROPIC PARTICLE FLUX
G (CM2 STERAD)
6x10-5
5x10-5
4x10-5
3x10-5
2x10-5
1x10-5
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
E/Eo

Figure 2

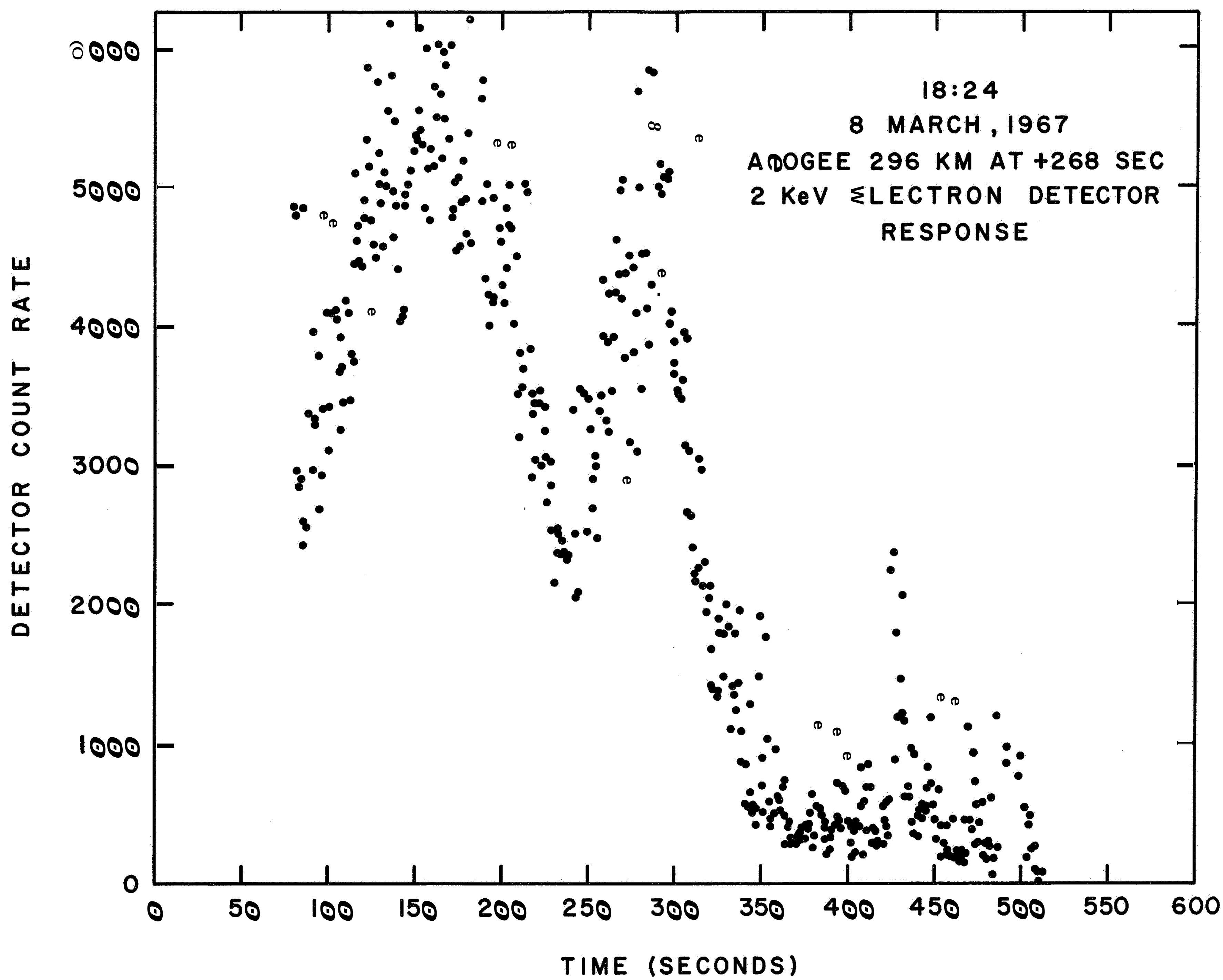

18:24
8 MARCH, 1967
APOGEE 296 KM AT +268 SEC
2 KeV ELECTRON DETECTOR
RESPONSE
DETECTOR COUNT RATE
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
250
300
350
400
450
500
550
600
TIME (SECONDS)

Figure 3

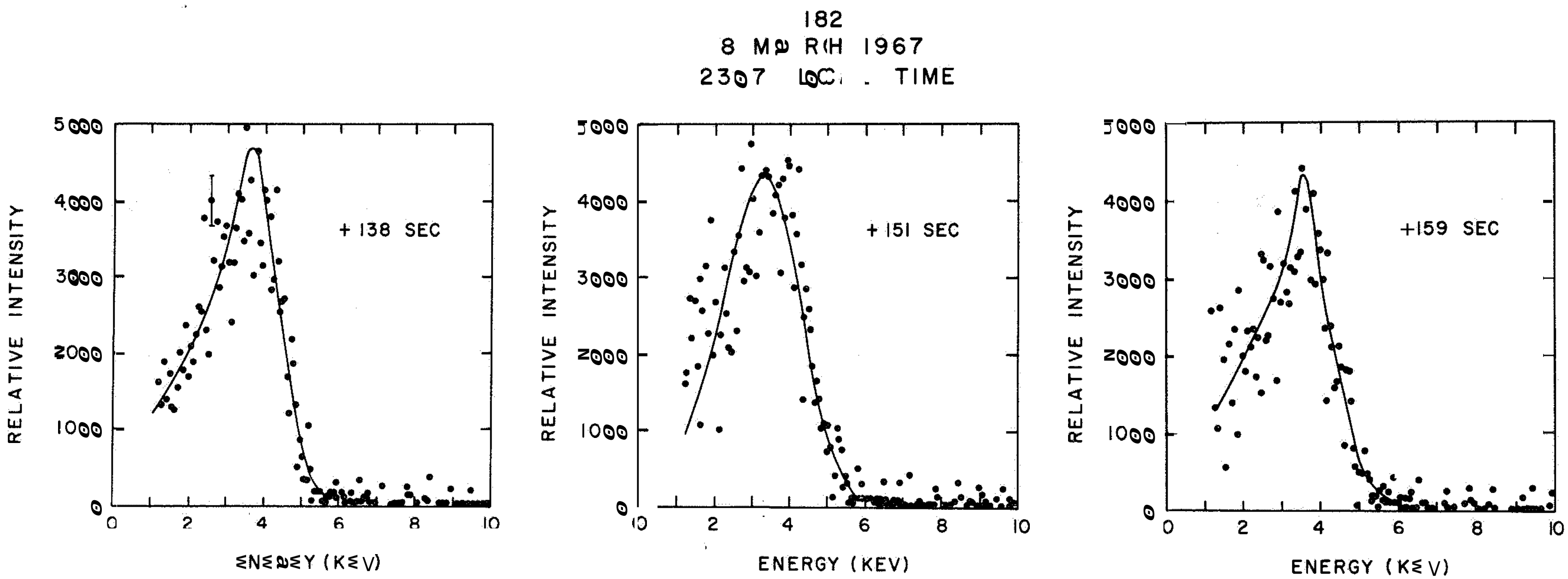

182
8 MARCH 1967
2307 LOC. TIME
RELATIVE INTENSITY
ENERGY (KEV)
+ 138 SEC
+ 151 SEC
+159 SEC
0
1000
2000
3000
4000
5000
0
2
4
6
8
10

Figure 4

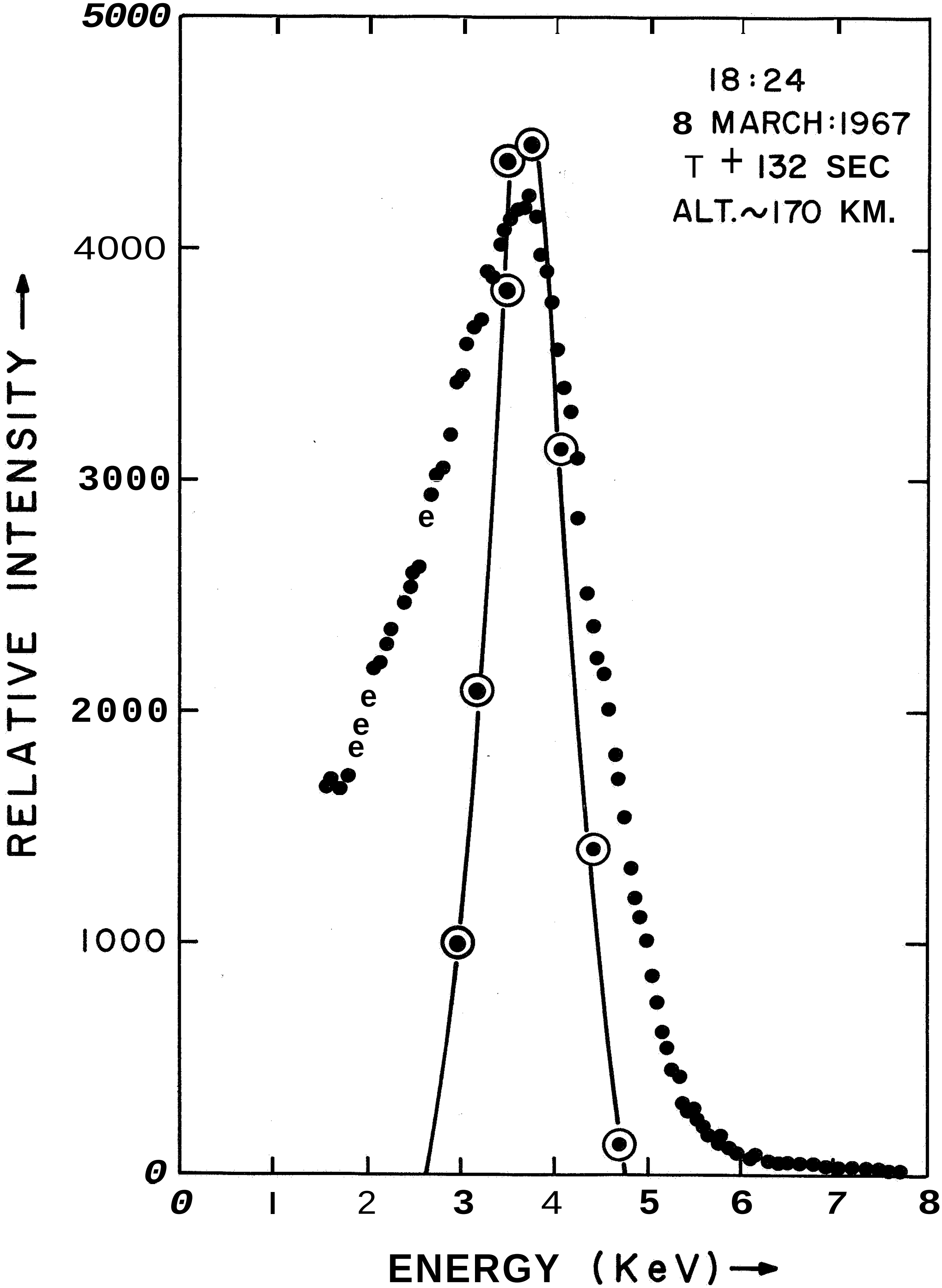
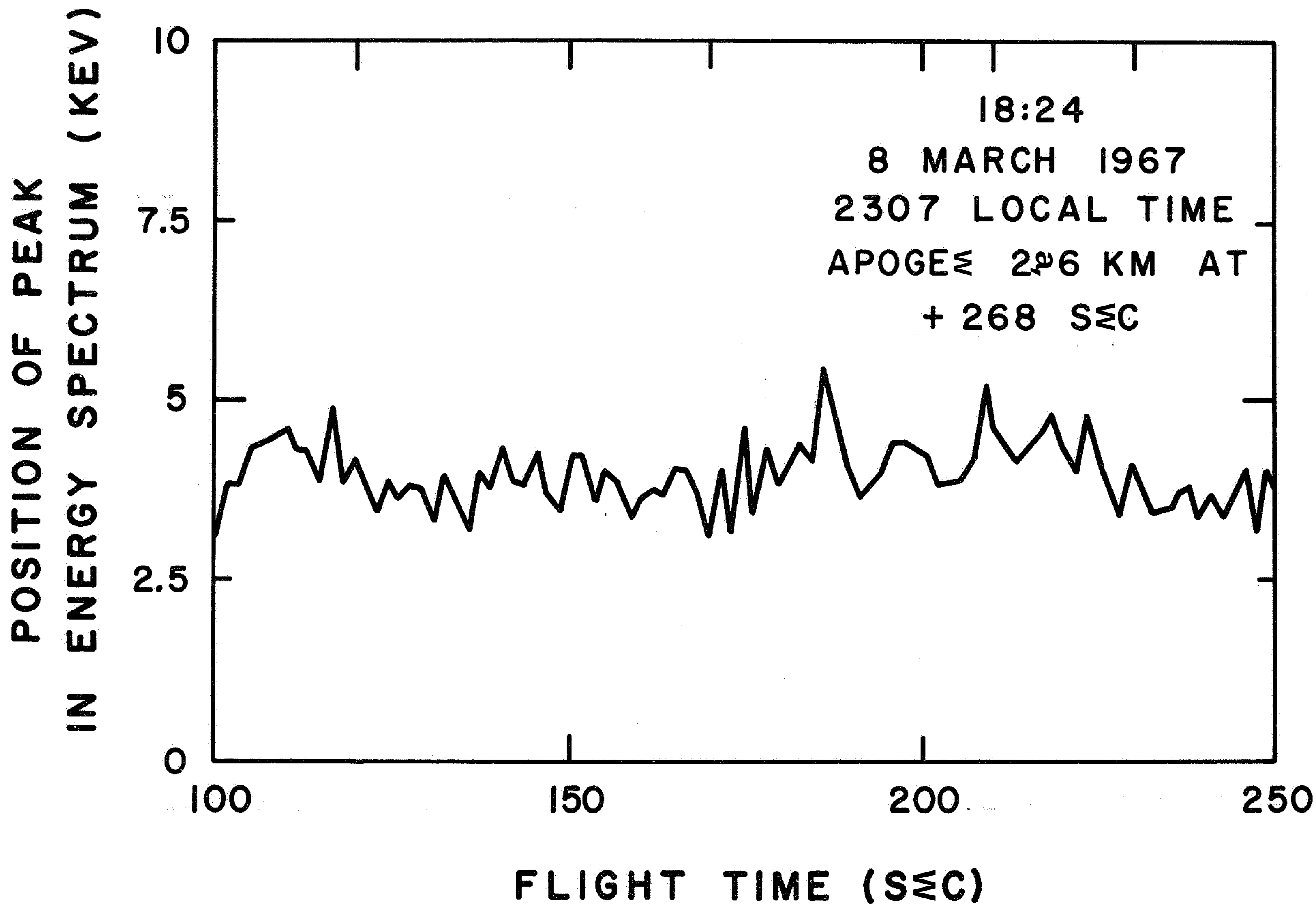

18:24
8 MARCH:1967
T + 132 SEC
ALT.~170 KM.
RELATIVE INTENSITY
ENERGY (KeV)
5000
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
8

Figure 5



18:24
8 MARCH 1967
2307 LOCAL TIME
APOGEE KM AT
+ 268 SEC
POSITION OF PEAK
IN ENERGY SPECTRUM (KEV)
10
7.5
5
2.5
0
100
150
200
250
FLIGHT TIME (SEC)

Figure 6