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Introduction and Review of Rocket Observations of Primary Auroral Particles

A close connection has long been observed between the occurrence of solar activity and a subsequent auroral display. This has led to the suggestion that the sun is the basic source of energy for the generation of the aurora. Recent measurements of the flow of solar plasma outward from the sun, when integrated over the frontal area of the earth's magnetosphere, have shown directly that the solar wind does indeed carry an energy flux sufficient to drive the aurora ($\sim 10^{20}$ ergs/sec against an estimated 10^{17} – 10^{18} ergs/sec dissipated in the aurora). (O'Brien, 1964)

Assuming that the solar wind does provide the energy necessary to drive the aurora one encounters the problem that the energies of the particles comprising this flow are far below those energies required to excite the auroral glow. Further if a closed field model of the magnetosphere is assumed, these particles are excluded from auroral lines of force. Thus mechanisms for the transfer of energy – if not the solar particles themselves – across the magnetospheric boundary must be invoked.

On the other hand in an open model of the magnetosphere, those magnetic lines of force which extend backward in the tail and terminate in the interplanetary field may allow direct access of the low energy solar wind particles (and the energy they possess) onto the auroral lines of force. It only would remain to accelerate these particles to the energies needed to drive the aurora and precipitate them into the auroral zone atmosphere.

In either case it is the entire process by which the auroral particles are energized and precipitated which has become the central problem in the field.

Quite apart from the questions of particle energization and energy balance are the constraints placed upon auroral theories by the behavior of the visual aurora itself. The appearance of thin stable forms, the development of a display during a night, the abrupt change in the character of the aurora at the time of auroral break-up, and the very rapid but often systematic motions and luminosity fluctuations seen in active aurora are a few of the many diverse properties that a comprehensive auroral theory should account for (if a single mechanism is in fact at work).

Many of these observations have themselves suggested theoretical models. For example, the occurrence of very thin arcs may be taken to indicate a mechanism involving acceleration or particle loss along neutral lines, while the observation of rapid motions in auroral forms and variations in brightness could point toward instabilities in the outer magnetosphere as responsible for the particle influx (Chamberlain, 1966).

Similarly, knowledge about the properties of the auroral particles being precipitated will aid the development of auroral theory both by providing quantitative observations with which theoretical predictions may be compared and by exposing possible characteristics in the particle influx which could immediately be linked to specific acceleration mechanisms. Among the parameters to be studied in an effort to better describe the properties of this unknown acceleration process are the energy spectrum and particle intensities over the entire range of interest (less than 1 keV to more than 100 keV), any periodic or random time variations in these quantities, and spatial properties – location and extent – of the precipitation.

Three methods, each with its own advantages have been used to investigate the primary auroral particle flux – satellite, sounding rocket, and balloon. The long life of a satellite makes it an ideal tool for determining such averaged properties of the auroral particle bombardment as its latitude limits, any diurnal variation in the position or intensity of the influx, average flux values, and the like (O'Brien, 1964; Fritz and Gurnett, 1965). However, the high velocity of a satellite makes it less useful for the study of rapid time variations or any fine spatial structure in these particle fluxes. Also, coordinated satellite-ground observations to describe in great detail a single auroral event have proven difficult to make, but are of extreme importance (J. E. Evans, 1965).

Balloon-borne scintillation counters are used to investigate the precipitation of electrons of energies greater then $\sim$30 keV by detecting the bremsstrahlung x-rays generated in the atmosphere by these particles. Although the very important lower energy electrons remain inaccessible to these detectors, the stationary nature of a balloon platform allows spatial-temporal effects in the precipitation to be separated and the rapid time variations in the energetic electron influx to be investigated very effectively (Anderson, 1964).

Sounding rockets provide an opportunity to study directly the entire energy spectrum of both auroral electrons and protons. In addition the use of extensive ground observations to supplement and aid in the interpretation of the data obtained by the rocket instrumentation is facilitated by the fact that exact time and conditions at the time of firing are chosen by the scientist. Although spatial-temporal ambiguities enter into the interpretation of time fluctuations measured by the rocket instruments, the rocket's slower velocity compared to a satellite's allows solution of this problem in special cases.

The initial use of the rocket in auroral zone studies was by Van Allen (1957), who found an influx of electrons of energies greater than 50 keV into the atmosphere to be associated with auroral zone latitudes. No correlation could be made, however, between these particle measurements and visual aurora because of the summer season.

The first such measurements of the primary particle spectrum associated with the visual aurora were made during IGY by Davis et. al. (1960), then with the Naval Research Laboratory, and McIlwain of Iowa

(1960). The prime detectors used by both groups were similar, being scintillation detectors where the total energy deposited in the scintillator by the incident particles was measured. Particle energy discrimination by means of a swept magnetic spectrometer was used by McIlwain. The results of both series of flights generally confirmed what had been inferred previously from ground observations:

1. That by far the major portion of the energy influx associated with the visual auroral form was carried by electrons rather than protons – the modest proton fluxes that were detected were found to be uniform over large areas and not dependent upon being near an aurora.

2. Most of the electron influx was made up of particles having energies less than 10 keV.

Specifically, Davis' group observed a net energy influx of ~2 ergs/ cm^2/sec/ster associated with a faint auroral form. The differential energy spectrum of these electrons was determined through atmospheric absorption observations to be roughly of the form E^{-2} over the energy range 8 keV to 30 keV.

McIlwain observed on one flight a very steep electron energy spectra of the form $e^{-E/5\,keV}$ for energies greater than 3 keV.

The second of McIlwain's flights, which penetrated a bright arc, encountered energy influxes as large as 2000 ergs/cm^2/sec. Analysis of the energy spectra data produced the striking result that this precipitation was composed in the main, of electrons of energy ~6 keV. This observation strongly suggests that an electrostatic mechanism was responsible for the particle energization and has often been cited in support of auroral theories invoking such an acceleration.

McDiarmid et al (1961) have launched a series of rockets during times of auroral absorption (as opposed to visual aurora) to study the primary electron influx under these conditions. In one instance, electron fluxes of $10^5/cm^2/sec/ster$ (energy greater than 30 keV) were encountered having an energy spectra deduced from atmospheric absorption of the form $e^{-E/22\ keV}$. It is seen that this precipitation is much richer in the higher energy particles. Balloon data has shown that auroral zone x-rays (hence energetic electron bombardment) are often associated with auroral absorption and hence the requirement for absorption at launch clearly biases McDiarmid's flights toward hard electron fluxes (Brown, 1966; Barcus, 1965).

Investigations of the particle influx associated with visual aurora have been continued by Cummings et al (1966) and Evans (1965). Rocket flights to investigate particles linked with other auroral zone effects such as the disturbed ionospheric or x-ray production have been continued by McDiarmid and Budzinski (1964) and Lampton and Anderson (1966). In general the results from rockets passing through aurora have substantiated earlier ones in that electrons of lower energies (i.e., $\sim$10 keV) are the primary energy source for the auroral glow but often admixtures of more energetic electrons are encountered which may indicate that two particle sources – each with a characteristic energy – should be considered.

The particle intensities measured during these flights have proven to be highly variable in space and time (as well might have been expected from visual observations of auroral forms), changes of decades in flux over a fraction of a second or a few 10's of meters distance being often seen. The energy spectra observed during these flights have likewise been variable with no characteristic shape apparent as yet. The range in electron energy and fluxes involved may be gauged by setting McIlwain's observation of intense fluxes of electrons near 6 keV energy with very few above 10 keV at one extreme and the satellite observation of fluxes of auroral electrons of energy greater than 40 keV which approached $10^9/cm^2/sec/ster$ (60 $ergs/cm^2/sec/ster$) at the other (McDiarmid and Burrows, 1965).

McDiarmid et al reported in 1961 a case of a flux of 40 keV electrons directed upward from the atmosphere which was much too large to be accounted for by the backscattering of the observed downward flux. The existence of a vertical electric field between the rocket and the top of the atmosphere was suggested as accounting for this.

Mozer and Bruston (1966) made a similar observation of the anomalous reflection near the top of the atmosphere of auroral protons in the energy range above 140 keV. This also was explained by postulating a low altitude acceleration of the proton influx which prevented them from reaching the atmosphere and being lost.

Recently Cumming et al (1966) have detailed an instance of the ratio of the downward to upward fluxes of 40 keV electrons (as measured at supplementary pitch angles) approaching 1 as compared to the 0.1 – 0.2 predicted by atmospheric scattering. A number of explanations for this were examined, among them:

1. A pitch angle distribution in the downward flux which peaked strongly at a value not viewed by the detectors thus leading to a gross underestimate of the downward flux.

2. A strong spatial distribution in the precipitation which would result in detecting large fluxes of backscattered electrons from a nearby, intense downflux not sampled by the detectors.

3. A modification of the normal B mirror condition imposed upon the incident electrons by strong, local ionospheric current systems.

Although this observation could not be accounted for in its entirety, it is clear that these anomalous reflections of auroral particles just above the atmosphere are due to processes occurring close to the atmosphere and thus presumably unconnected with the fundamental energization of these particles.

Investigations concerning time variations in the incident auroral particles have been conducted primarily with balloon instrumentation and the results are appropriate to the more energetic electrons. Examples of periodicities in the particle precipitation have been observed over the period range from ≈ 1000 sec to ≈ 1 sec (Anderson, 1964). Photometric observations of the aurora indicate that the short period limit may be extended to 0.1 sec at least (Johansen and Omholt, 1966).

Explanations for the appearance of periodicities in the particle precipitation seem to fall into two categories. The first would be to ascribe the fluctuations to a mechanism which modulates the precipitation of previously or independently energized auroral particles. Barcus and Christensen (1965) propose a model to account for a very pure 75 second periodicity in bremsstrahlung x-rays detected at balloon altitude which makes use of hydromagnetic wave in the outer magnetosphere to modulate the ambient field and thus the size of the loss cone for particles accelerated in that region.

Very short period fluctuations in the particle precipitation on the other hand, may be a reflection of fundamental frequencies or rise time in a dynamic particle acceleration mechanism – for example a plasma instability.

The high time resolution study of sudden changes in auroral particle fluxes detected at the atmosphere can, in principle, provide information about the distance between the point of observation and the point of particle release or energization through measurement of the velocity dispersion of the particles. One such observation of possible velocity dispersion leading to a source distance of several earth radii has been reported by Anderson and Milton (1964).

Only the most rapid of these time variations lend themselves to study by rocket instrumentation because of the difficulty in separating spatial motion from pure temporal effects. In spite of this, the ability of the rocket-borne detector to study the full range of particle energies with a greater sensitivity than possible with balloon instrumentation together with the possible use of ground based, high speed observations of the aurora to aid in separating time and motion has led a number of groups (Lampton and Anderson, 1966; LeQuey et al, 1965; Evans, 1965) to specific rocket-borne studies of transients in the auroral particle influx.

Rocket measurements of the primary auroral particles are continuing with increasing emphasis upon the study of the lower energies with the greatest possible time resolution. Much greater effort is also being put into providing extensive ground-based observations (TV camera photography especially), during these flights so as to better interpret the often very ambiguous rocket data (Westerlund et al, 1965).

The following details some recent results of two rocket flights launched into aurora upon which observations were made of electron energy spectra which suggest electrostatic acceleration of particles, and still another observation of the anomalous reflection of particles from a point above the atmosphere.

Instrumentation Details

The instrumentation in these rocket payloads was directed almost exclusively toward the detection of primary auroral electrons over the energy band extending from 1 keV to more than 300 keV. Special emphasis was put on achieving rapid time response on the part of the detector and counting systems so as to better study rapid variations in the energy spectrum or flux of the incident electrons.

Electrons having energies in the range below 30 keV were examined using channel electron multipliers in a magnetic spectrometer configuration. The detectors are identical to those previously used for auroral studies (Evans, 1965) except that the energy resolution was sharpened to about 70% of the analyzer center energy E_o and improved shielding and baffling was introduced to better suppress the contribution of multiply scattered electrons to the detector count rate.

Six such detectors were included in the payload with center energies E_0 nominally at 1 keV, 2 keV, 4 keV, 8 keV, 16 keV, and 32 keV. A seventh background detector was used to demonstrate that no significant portion of the count rates of the six exposed detectors was due to penetrating radiation.

Electrons having energies greater than 50 keV were detected using a plastic scintillator-phototube detector. An electron integral energy spectrum was obtained by feeding the phototube pulses to a three channel threshold discriminator. The thresholds were nominally set to pulses corresponding to energy losses in the scintillator of 60 keV, 120 keV, and 250 keV. An aluminum layer over the plastic scintillator suppressed the effect of auroral light on the detector response. The possibility that a large number of low energy electrons incident onto the scintillator could result through pulse pile-up in a spurious 50 keV count rate was reduced by using very fast pulse circuitry. No instance was encountered of a low energy particle flux sufficiently large to cause such a pile-up effect.

The count rates from each of these individual electron detectors were fed through logarithmic count rate circuits the outputs of which were telemetered continuously to the ground. In this manner more than three decades of dynamic range in count rate could be handled while preserving better than 30 ms response time to variations in flux. The count rates as decoded on the ground are accurate to about 10%.

A Zn S powder scintillator detector identical to that described by Davis et al (1960) was included in the payload to provide a measure of the integrated energy influx (above a 4 keV threshold set by an aluminum layer over the scintillator used to suppress light). This instrument was primarily intended to act as an independent check on the performance of the particle counters.

A photomultiplier tube coupled to an optical interference filter having a broad transmission band centered about 3914 Å was flown to provide a rough measure of the auroral brightness and to indicate whether the responses of any of the particle detectors was due in part to auroral light emissions.

All these detectors were mounted such that their fields of view were co-aligned at an angle of 45° to the rocket spin axis. This permitted intercomparisons between detectors without confusing phase lags because of the rolling motion of the rocket.

The rocket spin rate and aspect were provided by a flux gate magnetometer.

Table 1 summarizes these detectors and their characteristics.

Results of Measurements of the Primary Electron Influx Associated with the Aurora

The first of the two flights discussed here – identified as 14.188 – was launched from Fort Churchill, Manitoba, at 2351 local time on 9 February 1966 into a rather structured and active auroral form covering an extensive portion of the sky. By 127 seconds after launch the brightness of the display had decreased somewhat, and all sky photographs show that the form had become considerably more homogeneous. The rocket was above this broad homogeneous form during the entire flight.

DETECTOR	ENERGY BAND	FLUX DYNAMIC RANGE
CHANNEL MULTIPLIER	1 KEV	$5 \times 10^6 - 5 \times 10^9$ ELECTRONS/CM^2/SEC/STER/KEV
	2 KEV	$2.5 \times 10^6 - 7.5 \times 10^9$ "
	4 KEV	$10^6 - 10^9$ "
	8 KEV	$5 \times 10^5 - 5 \times 10^8$ "
	16 KEV	$2.5 \times 10^5 - 2.5 \times 10^8$ "
	32 KEV	$10^5 - 10^8$ "
PLASTIC SCINTILLATOR	> 60 KEV	$10^4 - 10^7$ ELECTRONS/CM^2/SEC/STER (E>60 KEV)
	> 120 KEV	$10^4 - 10^6$ "
	> 250 KEV	$10^4 - 10^6$ "
ZnS TOTAL ENERGY DET.	E > 4 KEV	0.1–300 ERGS/CM^2/SEC/STER
3914 Å PHOTOMETER		THRESHOLD ~ 500 RAYLEIGH

The magnetic activity during the display was modest. The maximum excursion in the X component being 240 γ observed at the time of launching. This field component recovered toward its quiet value at the rate of 15γ/min throughout the flight.

Both the rocket performance and the operation of the various particle detectors were normal except for the total energy scintillator. Detector operation was checked by noting that all particle detectors displayed both a roll modulation equal to the 2.4 rps rocket spin rate and in phase with the output of the aspect magnetometer (indicating that the response was due to a stimulus which was controlled by the geomagnetic field) and through the decrease in count rates as the rocket re-entered the atmosphere due to the absorption of the incident particles. The total energy scintillator appeared to respond properly early in the flight as regards to both the typical roll modulation and an observed increase in energy flux as the rocket exited from the atmosphere. After approximately +200 sec of flight, however, the output of this detector decayed toward the phototube dark current and during re-entry no evidence of a decrease in energy influx due to atmospheric absorption was observed. This is in spite of the channel multiplier detectors showing such an absorption curve (figure 3) and the all sky photograph clearly displaying a homogeneous glow at the point of re-entry. No firm explanation has been found for this apparent loss of sensitivity, but the thermal shock caused by heat conducted from the payload outer skin may have played a role.

The motion of the rocket was such that during a full precession period the detectors scanned pitch angles ranging from $\sim 0°$ to $\sim 100°$.

A possible problem with respect to the channel multiplier low energy electron detectors – especially pertinent to the first flight – is the chance that electrons could gain access to the detector by scattering through an air vent intended to hasten the evacuation of air from the detector housing during ascent. If such were the case, these electrons would give rise to a spurious background rate and thus questionable data.

The access to this port lies along a line $\sim 130°$ from the normal electron entrance and is largely obscured by portions of the rocket payload. This fact – that electrons entering this port must be incident along an axis so different from the intended look angle of the collimator – allows an estimate to be made of the magnitude of this effect by examining the spin modulation shown by all detectors. It was determined that up to +200 sec, the behavior of the magnetic electron spectrometers during a roll closely duplicated the roll modulation of the total energy detector, in particular that portion of the roll which viewed the particle loss cone was virtually identical on both types of detectors.

Such a result indicates that the channel multiplier response is due primarily to electrons incident along the same axis as those particles causing the response in the total energy detector. Further consideration along these lines would place the upper limit on the contribution to the net electron multiplier count rates by such unwanted electrons at about 30%. This has no significant effect upon the important details of the electron spectrum results presented below.

The area of this vent was reduced by over an order of magnitude for those detectors flown on the second and third flights in this series (14.189 and 14.190) which presumably would reduce the effect of electrons entering this vent still further.

It is unfortunate that the apparent loss of sensitivity of the total energy detector on 14.188 (and the clear failure of this detector on the second flight, 14.189) prevents a detailed intercomparison to be made of the absolute responses of the array of detectors so as to further examine the exact effect, if any, of the electron scattering in this air vent. It is relevant to add, however, that preliminary results from the third flight in this series (14.190, not reported upon here), when all detectors operated satisfactorily, show excellent agreement between the observed response of the total energy detector and that response predicted by integration of the responses of the individual channel multiplier detectors.

Figure 1 shows the one second average count rate of the 4 keV electron detector during the flight. (This average suppresses the roll modulation exhibited by the detector and, thus, the details of the pitch angle distribution.) The lack of significant time structure in the count rate history of this detector was typical of the behavior of all detectors during the flight and bears out the homogeneous nature of the auroral form.

The rocket, during the portion of the flight above the atmosphere, moved about 50 km horizontally approximately along the magnetic meridian – a distance which would map along the field lines into many hundred km in the equatorial plane. The lack of any spatial structure in the electron bombardment over this distance would seem to speak against the view that the precipitation should take place along neutral lines or sheets where much structure is expected - particularly in the north-south plane.

Although valuable information on the energy spectrum of the primary auroral electrons encountered on this flight is obtained by means of the array of detectors aboard the rocket, ambiguities in the generation of such a spectrum are present and a discussion of the problem is felt worthwhile.

Because the detectors used are not of infinitely high energy resolution - indeed the width of the energy window accepted by the magnetic spectrometers is quite broad - it is, in principle, impossible to recover the exact details of the energy spectrum of incident electrons. This arises from the fact that the net count rate of an individual detector is dependent not only upon the particle intensities but also upon the shape of the energy spectrum being measured. It is this need for assuming a spectral shape prior to generating the energy spectrum from the data which results in a lack of uniqueness on the part of the results. However, if the spectrum to be measured is well behaved in the sense of being smooth over the width of the detector energy window, the assumption of nearly any shape (for example - exponential) in the analysis will yield an energy spectrum which would both reproduce the responses observed on the detectors, and be expected to be a reasonable reproduction of the energy distribution of the particles being measured.

On the other hand, if the actual energy spectrum is discontinuous – for example; monoenergetic or exhibiting abrupt changes of intensity over an energy increment small compared to the resolution of the detectors – an analysis assuming smoothness, in spite of yielding a spectrum accounting for the observed count rates, will lead to a very distorted view of the actual spectrum. This distortion often takes the form of an unreasonable amplification of the magnitude of the discontinuity present in the actual spectrum. In such cases as this it seems best to take an empirical approach rather than an analytical one in dealing with the electron energy spectrum.

The spectrums inferred from the data obtained on 14.188 appear to be of this discontinuous nature and thus the emphasis is placed upon describing the salient features of the spectrum rather than attempting an accurate reproduction. The differential particle intensities were generated from the observed count rates taking into account the detector efficiencies, the shape of the analyzer energy window, and using a weighting factor found to be applicable over a fairly wide range of spectral slopes. The resultant intensities ordinarily would be regarded as zeroth order approximations but, as pointed out above, further refinement is not felt to be appropriate.

Figure 2 displays three such electron differential energy spectrums obtained at times when the rocket spin axis was aligned roughly with the magnetic field thus eliminating distortion due to any peculiarities in the pitch angle distribution. The flux of electrons of energy greater than 60 keV remained less than $10^4/cm^2/sec/ster$ throughout the flight and this data has not been incorporated in figure 2.

The most notable features of the spectrums are the relatively flat character below 10 keV and the very rapid fall off in intensity above 10 keV. Comparison between the count rates of the 18 keV and 8 keV detectors suggest that the energy at which the intensity decline begins cannot be much higher than 12-13 keV. While the point of initial decline can be lower than 12 keV, if it were significantly lower in energy, the intensity at 8 keV would need be increased in order to achieve the observed count rate. A peaking in the differential particle flux would then result in the energy range near 8 keV. The data cannot preclude such an intensity peak but the constant intensity observed from 1 keV to 8 keV might suggest such a peak is not present.

Data obtained during the reentry of the rocket into the atmosphere (figure 3) show that these electron fluxes are reduced by more than a factor of 20 at an atmospheric depth of 1.5×10^{-4} gms/cm^2 confirming that few electrons of energy greater than 10 keV could have been present in the primary beam.

Existence of a well defined maximum energy in the electron influx would be consistent with an electrostatic accleration having energized the electrons in the case where a maximum potential difference was available for the acceleration. Models based upon statistical processes such as instabilities or Fermi accelerations would generate electron energy spectra having a high energy tail which is definitely not observed on this flight.

The second of the two flights discussed here (14.189) was launched into a moderately active breakup phase aurora at 2356 local time on

18 February 1966. The rocket performance was normal and all detectors operated properly except the total energy detector which failed during first stage burning.

The auroral display at the time of launch was composed of a folded band in the zenith – into which the rocket penetrated – together with a widespread diffuse aurora background of modest intensity. The brightness of the zenith form reached a maximum of more than 15 kR at 135 seconds after launch and promptly faded to a nominal 2 - 5 kR level as measured by a ground-based photometer.

The magnetometer at Churchill displayed a 200γ negative bay in the X component of the field at the beginning of the display and remained remarkably close to this depressed level throughout the flight.

Corresponding in time to the peak auroral luminosity was a 1.2 db peak in the absorption of 30 mc/sec radio noise by the ionosphere as observed with the launch site riometer. This absorption decayed roughly as the zenith form faded.

The attitude of the rocket during the flight was such that the spin axis was aligned roughly perpendicular to the geomagnetic field. Thus the array of detectors scanned electron pitch angles ranging from 45° to 135° as the rocket spun with a 22 second period.

Figure 4 displays the count rate responses of the 4 keV and 60 keV electron detectors during the flight. It is seen that the low and high energy electrons behave in a strikingly different fashion. The 4 keV electron influx maintains a rather constant level throughout the flight and only a modest variation in count rate as the detector viewed pitch angles from 45° to 135°. This history was typical of both the 1 keV and 2 keV detectors also.

In contrast to this the higher energy electrons exhibit both a decreasing electron influx as the flight progresses and a much larger ratio of electrons detected at a ptich angle of 45° to those aetected at 135° than the case at lower energies. Moreover, rapid time variations (a factor 10 within a few seconds at T + 145 sec) in the electron flux above 60 keV are evident although superimposed upon the 22 second period roll modulation.

It is the decrease in the influx of the more energetic electrons which best follows the observed decrease in the intensity of the zenith auroral form. This suggests that while the diffuse background aurora was caused by a low energy influx, the structure was generated by a spatially restricted beam of electrons much richer in particles of energy greater than 10 keV.

The energy spectrum inferred from the available detector count rates on 14.189 is discontinuous in much the same fashion as was observed on 14.188. Consequently only the best approximations to the electron differential intensities are used to obtain the spectral details and no further refinement is attempted.

Figure 5 displays two such spectrums, one obtained early in the flight when the intense influx of higher energy electrons was observed, the second later in the flight when the flux of 60 keV electrons had become negligible. These spectrums represent one second averages taken when the detector array was viewing particle pitch angles of near 45°.

The most striking aspect of these spectrums is the apparent peak in the electron intensity in the energy range 4 - 8 keV. Indeed one possible spectrum which would be consistent with the observed count rates is composed of the superposition of a spectrum which is smooth between the 2 keV and 15 keV points in figure 4 and a near monoenergetic flux of electrons of some energy between 4 keV and 8 keV. A comparison of the relative responses of the 4 keV and 8 keV detectors together with a knowledge of the analyzer energy pass band would suggest the energy of such a beam would be ≈ 5.5 keV and a total flux of $\approx 3 \times 10^9$ electrons/ cm^2/sec/ster involved. Such a beam alone would account for one-half of the estimated total energy influx into the atmosphere.

The significance of observing a near monoenergetic beam of auroral electrons cannot be underestimated as it would point very explicitly toward an electrostatic acceleration mechanism. For this reason the data from the three detectors (2 keV, 4 keV and 8 keV) which together set off the peak in the energy distribution were examined for an indication of malfunction in flight, while calibration and assembly records were consulted for any prior history of abnormality.

The presence of roll modulation in the count rate to prove that the response is dependent upon magnetic aspect, and the characteristic decrease in count rates during re-entry because of atmospheric absorption are two reliable qualitative checks upon the operation of these low energy particle detectors. All three detectors in question exhibit the proper behavior in these respects. In addition the following specific causes of abnormal operation were eliminated on the basis of flight data or discounted on the basis of pre-flight calibration and check-out data.

a. The miscalibration or shift in the calibration of a logarithmic count rate circuit.

b. The interference from either power supply ripple or from the telemetry transmitter.

c. Corona pulsing from exposed high voltage.

d. An abnormally low gain channel multiplier used in the 2 keV detector which would not produce pulses of sufficient amplitude to trigger the threshold discriminator.

e. The misalignment of the particle detector with respect to the collimators and magnet.

f. Significant contribution to the count rates by auroral ultraviolet light.

g. The contribution to the count rates by electrons scattering through the air vent as described earlier.

Although the failure of the total energy detector prevents the magnitude of this process from being estimated directly, the experience on flight 14.188 using a completely open vent together with the excellent agreement observed between measurements made by these detectors and a total energy detector on a subsequent flight (14.190) suggest that these spurious counts cannot contribute more than about 10% to the total count rate.

The possibility remains that a partial obstruction in the collimator could result in an abnormally low count in the 2 keV detector relative to the incident flux (as inspection of figure 5 shows, a factor of four increase in the 2 keV count rate would largely remove the peaking of the differential energy spectrum). X-ray photographs of this detector assembly taken after calibration do not show an obstruction or other abnormality and it is believed highly unlikely that any foreign matter could have been introduced during final checkout. It may be of interest to note that if the 2 keV detector were arbitrarily ignored, the spectrum would appear much as that encountered on 14.188 except that the energy at which the decline in the electron intensity sets in is somewhat lower than that seen on 14.188.

It was concluded on the basis of the above considerations that there is no reason for discarding any detector as producing invalid data and that the differential energy spectrum of these low energy electrons did in fact possess a peak near 6 keV.

As was pointed out above this sort of energy spectrum was inferred by McIlwain from data obtained on one of his rocket firings during I.G.Y.

It is significant that this peak in the spectrum was a persistent feature during this flight – the position of the peak shifting perhaps a few hundred volts lower in energy late in the flight. This stability is achieved even though the more energetic electrons observed by the plastic scintillator undergo a large variation. This may be indicative that the generation of these 60 keV electrons proceeds more or less independently of the production of the lower energy particles.

It was mentioned above that the lower energy electrons viewed by the 1 keV, 2 keV, and 4 keV detectors were further distinguished by the large ratio of electron flux detected at 135° pitch angles to that detected at 45°. Figure 5 displays the energy spectrum observed when the detector array was viewing particles having 135° pitch angle at a time one-half of a roll after the first of the two spectrums in figure 4 was observed. It is seen that the 1 keV, 2 keV, and 4 keV fluxes have decreased by less than a factor of two while the high energy fluxes display more nearly a factor of 10 reduction.

The origin of an anomalously high count rate in these detectors when viewing downwards cannot be due to electrical interference of any sort causing spurious counts. The possibility that auroral ultraviolet light exciting the channel multipliers was examined. The detectors do not view auroral light directly at the 45° pitch angle orientation but comparison between the photometer and the particle detector data when the array is oriented downwards reveal some degree of response of the channel multipliers to the ultraviolet was present. This amounted to about 200 counts per second and represented a significant contribution to the responses of the 15 keV and 30 keV detectors. It has been corrected for in the spectrum obtained when viewing downwards. However this introduces only an approximate 10-15% correction to the 2 keV count rate and considerably less to the 4 keV or 1 keV responses and thus cannot account entirely for the detection of the large upflux.

The uniformly low count rate of the background channel multiplier detector in the payload eliminates response to x-rays or energetic particles as an explanation for this observation.

The possibility that scattering electrons could produce the 30% spurious contribution to the count rate necessary to attain the nominal 10:1 ratio between downward directed and upward directed electron fluxes at 1, 2 and 4 keV is remote.

Thus it is concluded that this observation of an abnormally large outflux is valid. It may be noted that this conclusion is not affected by the factors such as collimator obstructions which entered into the discussion of the validity of the spectrum.

Inspection of the spectrum observed when the detectors view the outflux at a pitch angle of 135° reveals the same peaking of the particle intensity near 6 keV energy indicating that the reflection of these electrons from some point above the atmosphere was nearly elastic. However, the fact that the flux of electrons detected by the 8 keV detector displayed a 10:1 ratio between influx and outflux (compare figures 4 and 5) shows that some energy loss on the part of the electrons was present. The very sharp low energy cutoff of the magnetic spectrometers would require only a 500 keV to 1 keV energy loss on the part of the incident electrons to completely remove the monoenergetic portion of the beam from the response band of the 8 keV detector.

Data obtained during the re-entry of the rocket into the atmosphere (Figure 7) reveal that the response of the lower energy detectors begins to decline at an atmospheric depth of about 10 μgm/cm^2 (130 km altitude) and that the reflection (or absorption) is essentially complete by 30 μgms/cm^2 ($\approx$117 km altitude). Comparison of Figure 6 with the corresponding absorption curve obtained on 14.188 (Figure 3) points up the rapidity with which the electrons are removed from the beam during the re-entry of 14.189.

No model has been formulated to explain this observation but if a field aligned electric field were invoked to account for the reflection, a field strength on the order of 10^{-3} V/cm would be required roughly over the altitude interval 120-130 km. This field is very nearly that proposed by McDiarmid et al (1961) to account for a similar observation of electrons reflected from above the atmosphere.

To move somewhat further into the realm of speculation the question of how the position of the peak in the spectrum maintains its stability arises. If the electrons being measured are trapped on closed field lines, those electrons reflected from below the rocket will presumably spiral back on the field line to the southern hemisphere where they will either be 1) lost into the atmosphere, 2) be reflected subject to the normal B_{mirror} condition or 3) be reflected by some even more efficient mechanism similar to that apparently operative in the northern hemisphere. Vestine (1960) shows that for a magnetic line of force passing near Churchill, the B_{mirror} condition will be met at a higher altitude in the southern than the northern hemisphere. This may suggest that reflection of electrons should be at least as efficient in the south as it is observed to be in the north. Thus in order to maintain the spectral shape electrons must receive at some point in their trajectory between the two hemispheres, an additional amount of energy roughly equal to that loss observed in the atmosphere. This balance appeared too fortuitous to be in fact true.

An alternative explanation would be that the line of force down which the electron influx was directed was open, not closed. The particle influx was then entirely composed of freshly precipitated electrons, while those electrons reflected from the atmosphere were lost entirely from the beam.

Summary and Conclusions

The most significant result of the auroral electron measurements performed on the two flights described above is felt to be the observation on two separate occasions of differential energy spectrums which are suggestive of electrostatic acceleration mechanisms having been responsible for the energization of the auroral electrons. While the prominent peak at ≈ 5.5 keV in the energy spectrum encountered on 14.189 is the most dramatic indication of this, the sharp high energy cutoffs evident in the spectrum observed during 14.188 are no less associated with electrostatic processes, the absence of a tail of high energy electrons being the distinguishing feature.

It is further seen that the process responsible for the electron influx exhibited great stability in time – as witness the constancy of the energy spectrum during the flights, particularly the position of the spectral peak observed on 14.189 – and the homogeneous nature of the influx over 50 km distance. These points additionally serve to eliminate the more dynamic mechanisms, for example, plasma instabilities, as being the source of the electron energization and precipitation.

As a general rule the flight data indicated that while the influx of electrons < 10 keV remained quiescent the flux of electrons > 40 keV underwent large variations, believed to be time variations rather than spatial. A similar conclusion about the relative behavior of low and high energy auroral electrons was reached by Sharp et al (1965) on the basis of satellite observations. It is very tempting to describe this as being due to a static precipitation of low energy electrons together with a differing, more dynamic process which generates the energetic electrons. The energy and particle reservoir needed for the generation of the higher energy electrons may be in fact the low energy (<10 keV) electron population.

Certainly the theoretical explanations for the full range of auroral behavior would become simpler if two basic acceleration and precipitation mechanisms rather than a single could be operating semi-independently of one another.

The observation of an apparent reflection of the incident electrons from above the atmosphere represents still another instance of such an effect to add to that data of Mozer and Bruston, McDiarmid et al, and Cummings et al. While the full explanation of these reflections is yet to be proposed it is likely that acceptable models will involve details of the electric and magnetic field structure in the lower ionosphere.

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FIGURE CAPTIONS

Figure 1: One second averaged response of the 4 keV electron detector during the flight of 14.188.

Figure 2: Sample electron differential energy spectrums observed on Flight 14.188.

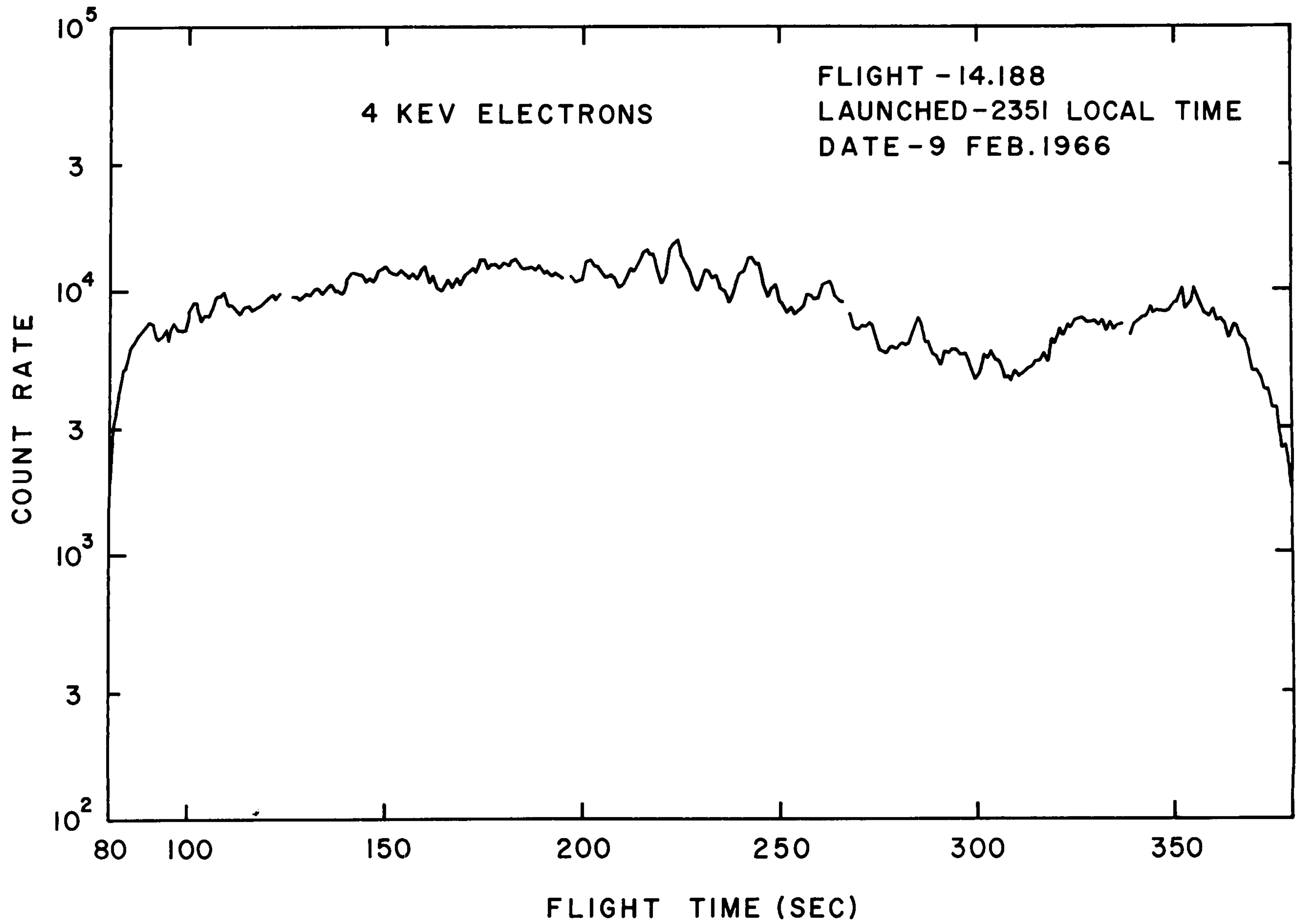
Figure 3: The relative responses of the low energy electron detectors during re-entry of 14.188 as plotted against atmospheric depth.

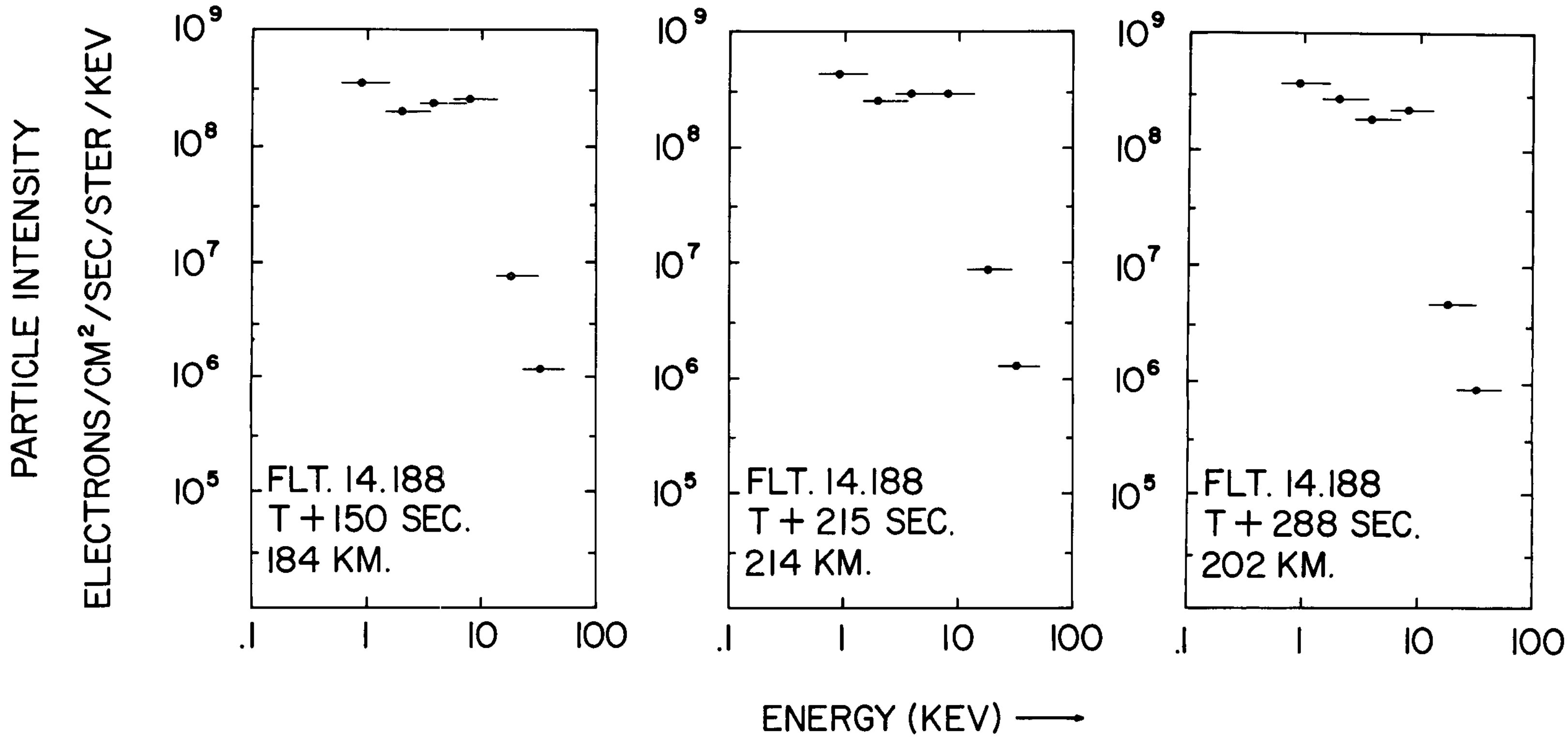
Figure 4: One second averaged responses of the 4 keV and 60 keV electron detecotrs during the flight of 14.189.

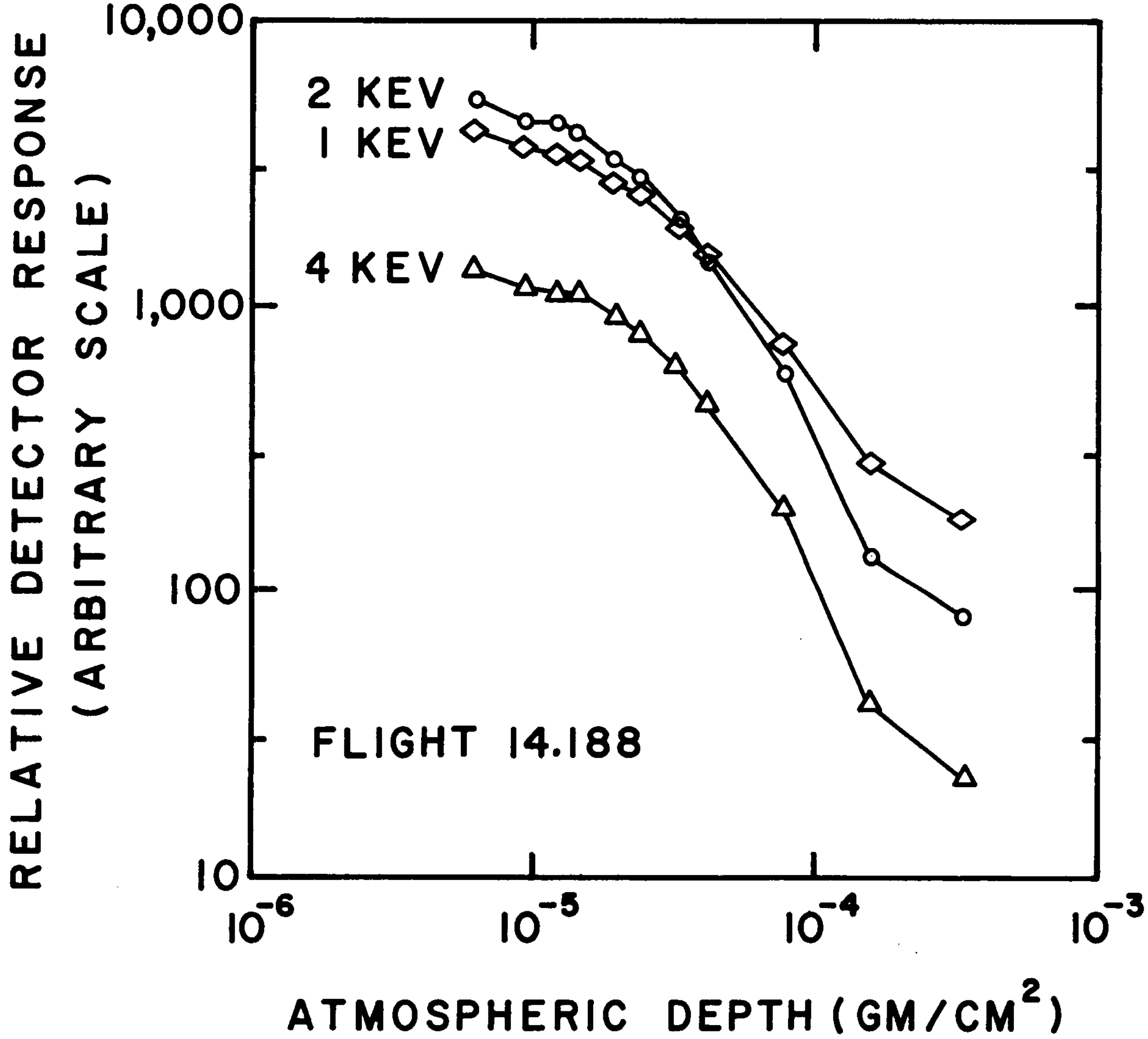
Figure 5: Sample electron differential energy spectrums observed on flight 14.189 at a pitch angle of 45°.

Figure 6: An electron differential energy spectrum observed on flight 14.189 when the detector viewed a pitch angle of 135°.

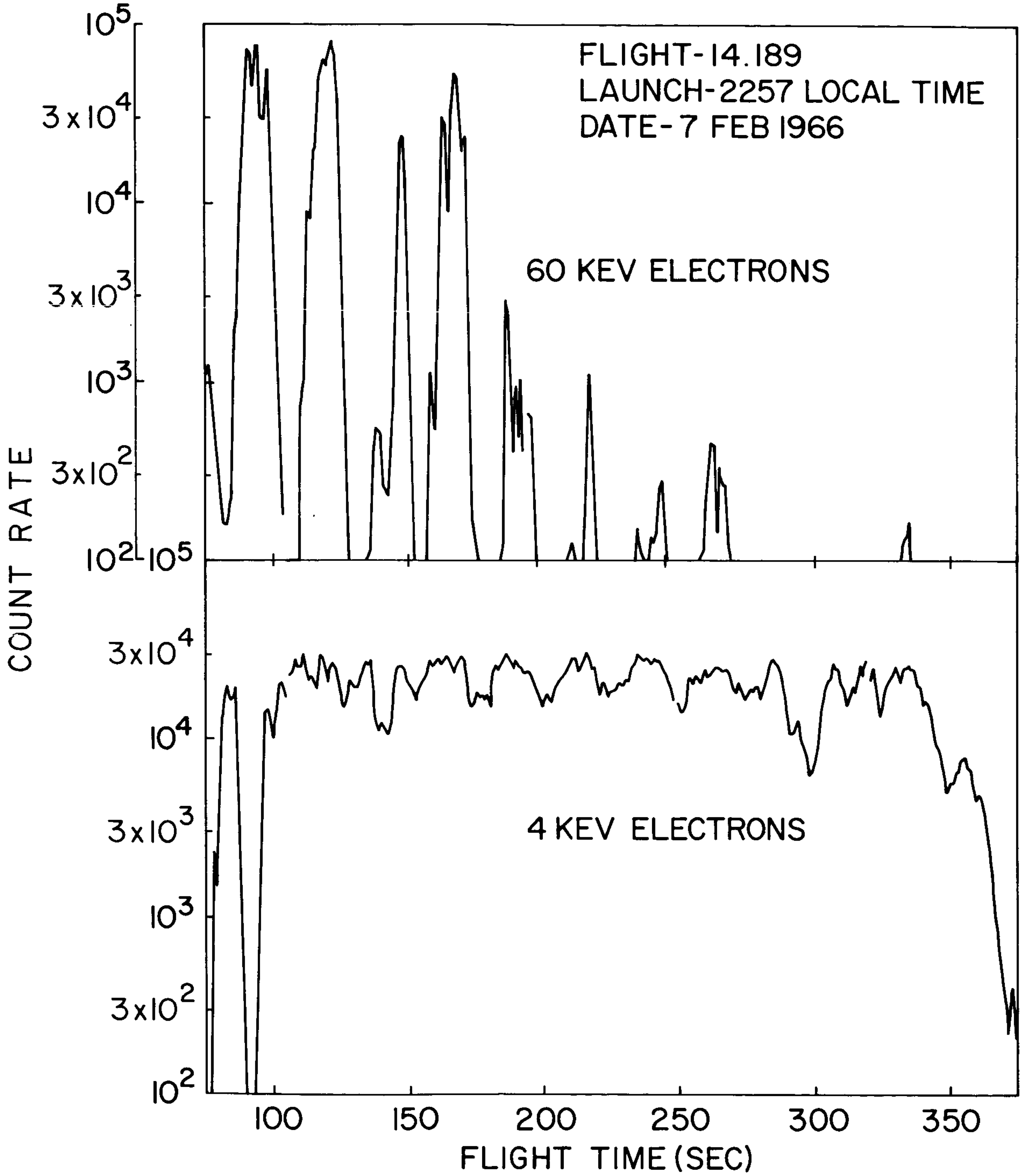
Figure 7: The relative responses of the low energy electron detectors during re-entry of 14.189 plotted against atmospheric depth (compare with figure 3).


4 KEV ELECTRONS
FLIGHT - 14.188
LAUNCHED - 2351 LOCAL TIME
DATE - 9 FEB. 1966
COUNT RATE
FLIGHT TIME (SEC)
10^5
3
10^4
3
10^3
3
10^2
80
100
150
200
250
300
350

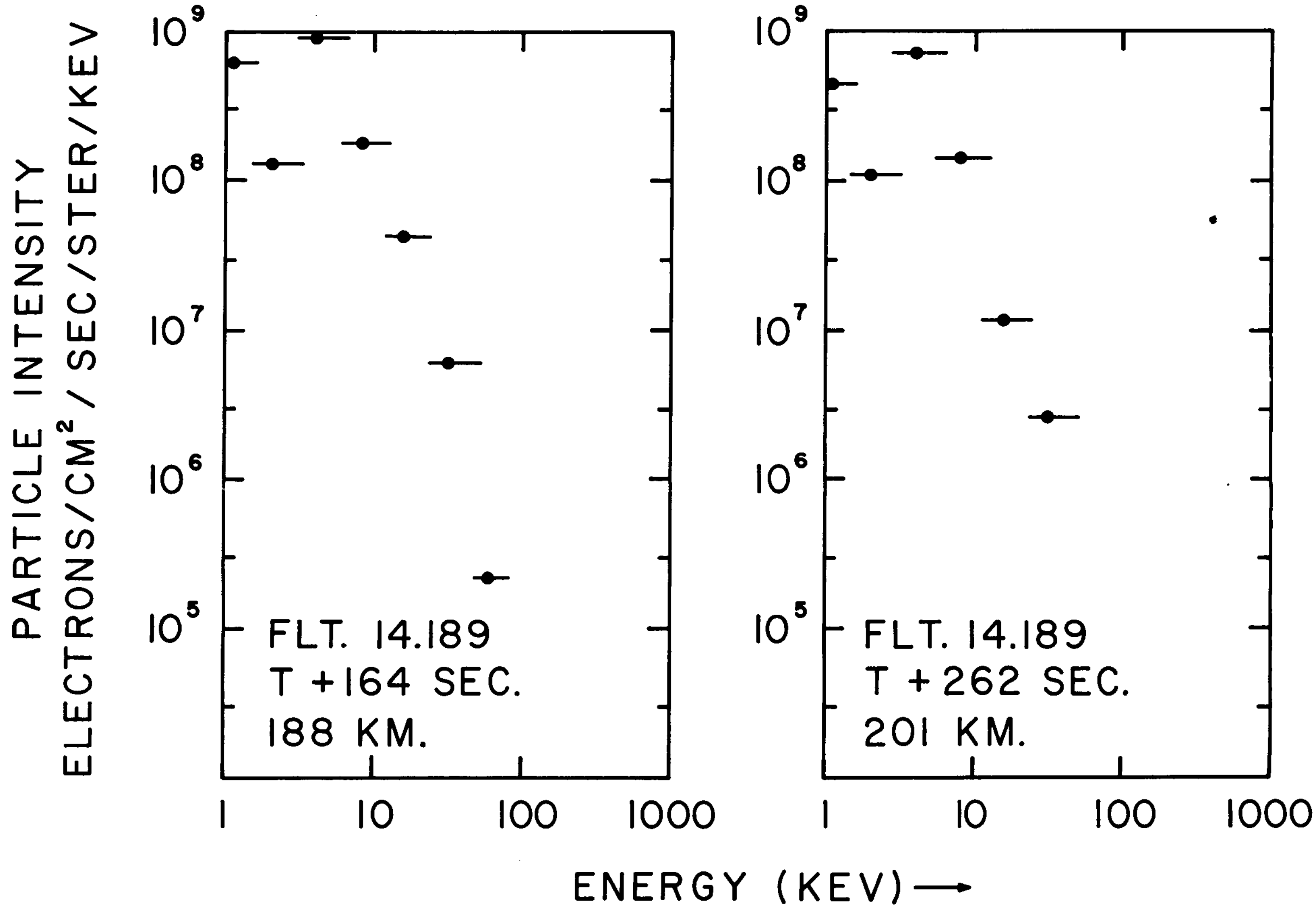

PARTICLE INTENSITY
ELECTRONS/CM²/SEC/STER/KEV
10⁹
10⁸
10⁷
10⁶
10⁵
FLT. 14.188
T + 150 SEC.
184 KM.
FLT. 14.188
T + 215 SEC.
214 KM.
FLT. 14.188
T + 288 SEC.
202 KM.
.1
1
10
100
ENERGY (KEV)



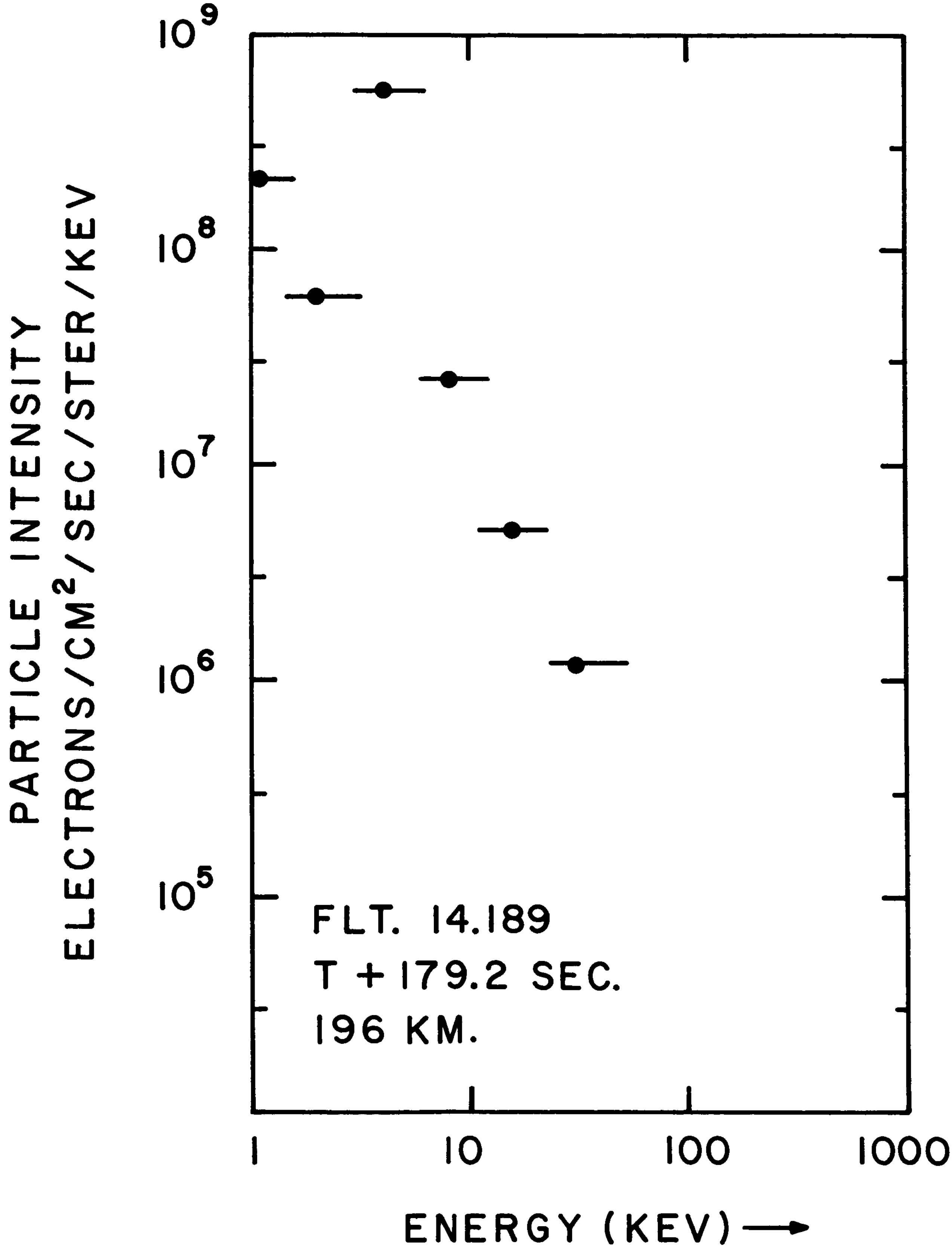
RELATIVE DETECTOR RESPONSE (ARBITRARY SCALE)
10,000
1,000
100
10
2 KEV
1 KEV
4 KEV
FLIGHT 14.188
10^{-6}
10^{-5}
10^{-4}
10^{-3}
ATMOSPHERIC DEPTH (GM/CM^2)

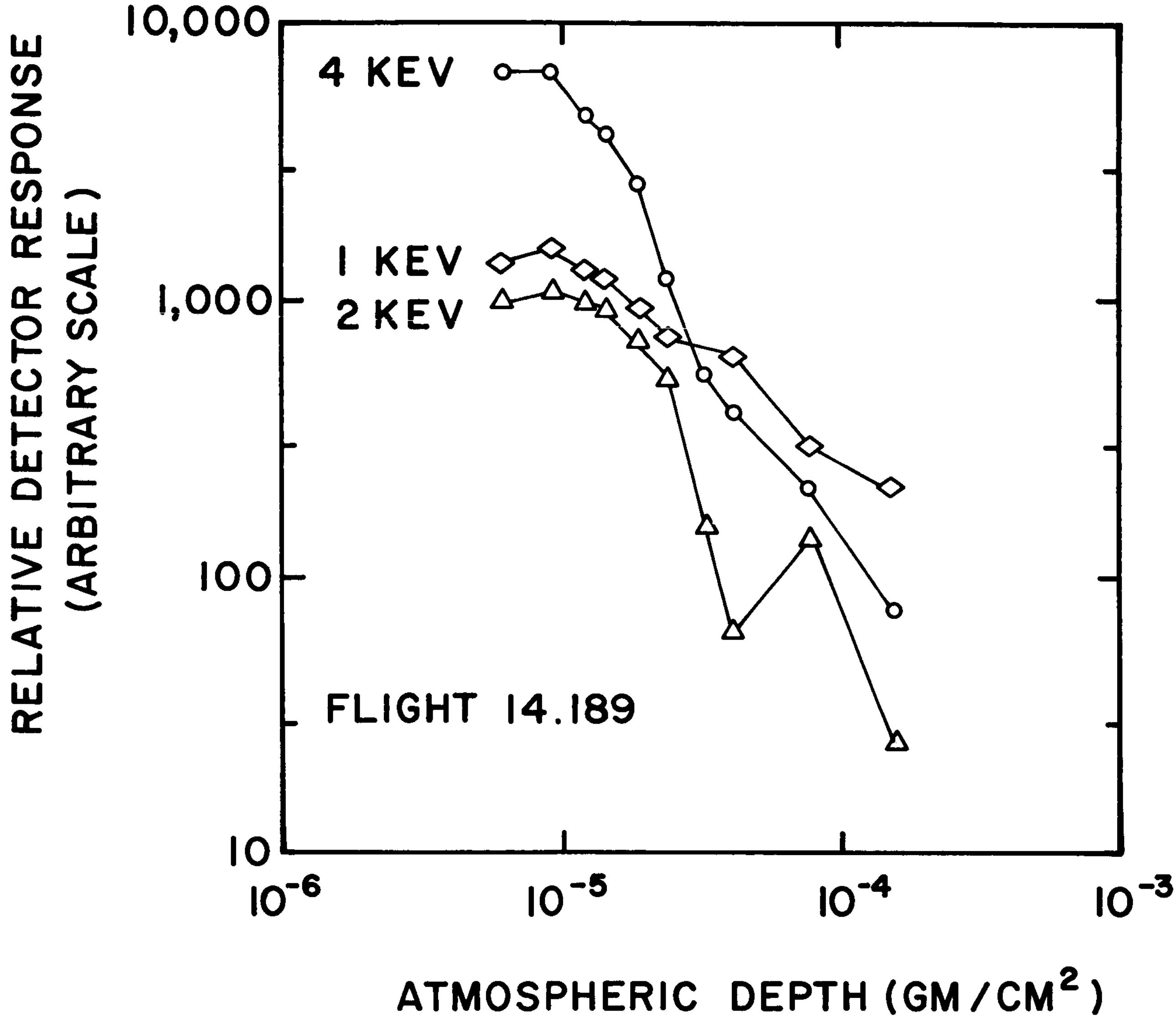


FLIGHT-14.189
LAUNCH-2257 LOCAL TIME
DATE-7 FEB 1966
60 KEV ELECTRONS
4 KEV ELECTRONS
COUNT RATE
10^5
3x10^4
10^4
3x10^3
10^3
3x10^2
10^2
100
150
200
250
300
350
FLIGHT TIME (SEC)



PARTICLE INTENSITY
ELECTRONS/CM²/SEC/STER/KEV
FLT. 14.189
T +164 SEC.
188 KM.
FLT. 14.189
T + 262 SEC.
201 KM.
ENERGY (KEV)


PARTICLE INTENSITY
ELECTRONS/CM²/SEC/STER/KEV
10^9
10^8
10^7
10^6
10^5
FLT. 14.189
T + 179.2 SEC.
196 KM.
1
10
100
1000
ENERGY (KEV) →



RELATIVE DETECTOR RESPONSE (ARBITRARY SCALE)
10,000
1,000
100
10
4 KEV
1 KEV
2 KEV
FLIGHT 14.189
10^{-6}
10^{-5}
10^{-4}
10^{-3}
ATMOSPHERIC DEPTH (GM / CM^2)