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AND THEIR ASSOCIATION
WITH AIRGLOW AND AURORAE

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Abstract. Numerous measurements have now been made of the electrons and protons precipitated into the atmosphere to cause auroras. A review is given of the measurements from ground-based devices as well as those carried by balloons, rockets and satellites.

Studies have shown that, at least on some occasions, there are similar auroras at magnetically-conjugate locations. The implications as regards the unknown acceleration mechanism(s) are discussed. Balloon-and rocket-borne measurements have shown that the auroral precipitation phenomenon occasionally exhibits a periodicity that may be indicative of complex wave-particle interactions in the magnetosphere. A survey is given of direct measurements of particle precipitation, and definitive experiments to resolve many of the unknown particle-acceleration phenomena are discussed. It is shown that direct and indirect evidence is available to demonstrate that airglow is not excited by particle bombardment, but presumably by photochemical reactions.



INTRODUCTION

It had long been speculated (cf. Stormer, 1955, Vegard, 1921) that energetic charged particles bombarding the atmosphere are the direct cause of excitation of auroral light. It was shown by ground-based photometric measurements of Doppler-shifted Balmer emissions [Meinel, 1951] that there are indeed energetic protons spiralling down around geomagnetic field lines. Then several rocket probes launched during the IGY proved beyond doubt - by simultaneous measurements of both the bombarding particles and the emitted light - that most bright visible auroral displays result from intense fluxes of electrons with some 1 to 10 kev energy, accompanying which and sometimes separate from which are less intense fluxes of protons of somewhat higher energy [McIlwain, 1960, Davis, et al., 1960].

Then, at much the same time, it was discovered that the earth's magnetic field contained trapped within it intense fluxes of both energetic electrons and protons [Van Allen, 1961]. Subsequently, extensive rocket and satellite studies have probed the interrelation of the trapped radiation and of the auroral or precipitated radiation [O'Brien, 1967]. The resultant evolution of understanding of vast magnetospheric plasma processes has been extraordinary in its complexity, and in its expense, and in its scientific return. But it is difficult - due to the long-range planning and yet uncertain launch dates of many space projects - to isolate uniquely IQSY findings.

Therefore in this review I have taken the liberty of defining our present understanding of these phenomena, rather than merely discussing IQSY results per se, or in trying to present an historical review, for which the reader is referred to Chamberlain [1961], Walt [1965] and O'Brien [1967].

CHARACTERISTICS OF THE AURORAL PARTICLE FLUXES

Figures 1 and 2 from O'Brien [1967] illustrate the range of energy spectra of electrons and protons found in auroral particle fluxes. On the other hand, the occasional spectacular temporal variations have sometimes an appearance of erratic fluctuations (Figure 3) and sometimes a semblance of reasonably ordered periodicities (Figures 4 and 5). There is accordingly a mixture of ordered and disordered phenomena, and it must be admitted that as yet there is no theoretical explanation for either phenomenon, much less an explanation of both phenomena.

A particular characteristic of the auroral particle fluxes, as of the auroral luminosity itself, is their common concentration in two halo-like regions, one around each magnetic pole. Such a characteristic has been demonstrated in a very many ways, particularly from ground-based (e.g. Davis, 1962) and satellite-borne (cf. O'Brien, 1964 and Evans, et al., 1966) observations. Such a summary is, of course, a gross oversimplification since the latitude and the latitude range of auroral displays both vary from magnetic storm to magnetic storm (cf. Akasofu, 1964) and even during any particular storm. (Such morphological changes will be reviewed by Yu I. Feldstein at this meeting.) The relevant point in this review is that these changes must reflect morphological variations in the precipitated particles.

Now the first-order latitude variation in these fluxes can be understood as being a direct consequence of the local-time distortion of the magnetosphere, a distortion caused by the impinging solar wind (cf. Ness, et al., 1964; O'Brien, 1967). The most intense fluxes appear to be located just beyond (i.e. at higher latitudes than) the stably-trapped Van Allen radiation, whose longitudinal drift in such a distorted magnetosphere can

be shown qualitatively (cf. Mead, 1966 and Williams and Mead, 1965) to be in the same sense as the diurnal variation of the auroral zone location.

However, the auroral forms only crudely abide by such statistical patterns. Davis [1962] and Akasofu [1964] have used all-sky cameras to observe the detailed temporal variations. The auroral morphology will be dealt with elsewhere at this symposium. Here I wish to draw attention to the fact that the cause of most of the auroral luminosity is bombardment of the atmosphere by auroral particles, with the resultant implication that the morphology of the (unknown) acceleration processes is extremely complex indeed.

Akasofu, in a series of papers (cf. Akasofu, 1964) has carried through an excellent summary of the auroral morphology per se. However, to my knowledge, no-one has attempted to deduce from such studies the characteristics of the primeval particle sources themselves.

Actually, in order even to begin such studies, it is vital to remember that the system is a closed loop. That is to imply that changes in the atmosphere (or ionosphere) produced by charged-particle bombardment may have a "feedback" effect on the particle bombardment itself and thus on the morphology, et seq. We revert to this specific problem below.

Two of the most definitive satellite studies of auroral particle precipitation have been made by Johnson, et al. [1966] and by O'Brien [1964]. Yet, with due respect to these studies, wherever they have been definitive it has only been in the nature of refuting theoretical concepts rather than in confirming some others. The auroral physicist is akin to one wandering in the wilderness. Several experimental attempts have been made recently to resolve definitively a positive finding, e.g. the ratio of protons to alphas in auroras so as to use the p/α

ratio to determine whether the actual particles were once constituents of the solar wind, or - again - to determine time delays between the onset of increased fluxes of high- and low-energy auroral particles so as to deduce their transit times, and hence the (unknown) altitude of the auroral source and the transport mechanisms that effect the particle trajectories.

Several of these experiments have been successful - in the sense that the difficulties of rocketry were overcome - but no conclusive results have been published and confirmed as yet. But it is noteworthy that it is difficult to obtain from existing theories any precise prediction against which one can present any such experimental findings.

Without belaboring this point, one can state merely that there are two fundamental simple problems posed by the particles that cause auroras, viz.

(1) where did they originate (e.g. on the sun or in the outer magnetosphere) and,

(2) where did they acquire their ultimate (auroral) energy?

Formulation of definitive experiments to resolve these questions, and of definitive theories to suggest answers, remains a formidable and largely unsolved task.

Figure 6 from O'Brien [1964] illustrates some of the experimental problems posed by auroral particle fluxes. At a given magnetic latitude- or L-value (McIlwain, 1961) the particle flux can vary in time by a factor of about one million to one. Furthermore, in the auroral zone there is always some finite particle precipitation. So one must postulate an acceleration mechanism that, on the one hand, is always active, and on the other hand, varies in strength by a million to one. There are numerous other problems related to the broader question of the ultimate source of auroral particles, but here attention will be concentrated more on the effects of the particles themselves when they hit the atmosphere.

PARTICLE INTERACTIONS WITH THE ATMOSPHERE

The absorption in the atmosphere of energetic charged particles (such as cause auroras) may, at first approach, appear a simple problem, amenable to classical atomic physics treatments such as one might apply to absorption of such particles by metal foils of comparable effective thickness, e.g. 1 mg cm^{-2} . In fact, of course, an adequate treatment must be far more complex, and I consider that one of the major advances in auroral studies in recent years has been recognition of some of these problems and development of theoretical techniques to solve or at least to treat them (cf. Rees, 1963).

Consider, for example the problem of proton bombardment. In 1955, Bates [1955] pointed out that charge-exchange processes in the atmosphere would cause a precipitated proton to be neutralized repeatedly, whereupon it would, of course, not be restricted by the geomagnetic field to a spiralling path. Yet it was not until a decade later that a detailed theoretical treatment of this facet was published (Davidson, 1965). It was found that the resultant Balmer emission would be diffused over a zone several hundred kilometers wide about the initial region of precipitation. Clearly then, ground-based Balmer studies must be treated with great care if conclusions are to be derived about the morphology of the precipitating particle fluxes. Indeed, there remain still several problems in even equating Davidson's solution with the actual observations (Eather, private communication). It would appear that direct satellite and/or rocket measurements of protons at altitudes above some 400 km should be utilized for morphological studies.

Another significant study that has been begun - experimentally and theoretically - but is still quite incomplete, is the analysis of pitch-angle distributions of both down-going and upwards-moving particle fluxes. Mozer and Bruston [1966] have deduced

complex interactions between the particles and relatively strong electric fields in the ionosphere, with fields estimated to be some mv to some 100s of mv per meter, over altitude ranges sufficient to cause significant effects on protons and electrons with energies of 100s of kev. While there may be some question as to some of the conclusions derived from the rocket flights, there appears little doubt that the problems of angular distributions must be probed further.

One of the more significant problems that is also receiving theoretical and limited experimental attention is what I refer to as "atmospheric feedback" processes. By these I mean those atmospheric (and ionospheric) properties that may be modified by the precipitated particles but whose very modification may then affect detailed characteristics of the precipitation.

For example, Maehlum and O'Brien [1967] have treated the effects on the pitch-angle distribution and of the pitch-angle distribution as related to the magnetic field produced by auroral electrojets. Clearly, since the strength of the "anomalous" magnetic field is dependant on the ionization caused by the precipitated particles whose pitch-angle distribution may be perturbed by these fields, et seq, there is a feedback process and hence, of course, potential instabilities. In fact, Maehlum and O'Brien [1967] have established that under appropriate (and realistic) ionospheric conditions, wave-like or periodic processes may take place in the auroral formations. Thus studies are being directed for the first time quantitatively to an understanding of the extraordinary and bewildering variety of auroral morphological variations in space and time.

EXCITATION AND AIRGLOW

Due to some similarities between the phenomena of airglow and aurora, the postulate has sometimes been put forward that the normal world-wide airglow might be caused - like normal auroras - by bombardment of the upper atmosphere by energetic charged particles.

Various arguments against this hypothesis can be made, as follows:

- (a) the intensity of the N_2^+ emission at 3914\AA in airglow is only of the order of 1% of the atomic oxygen emission at 5577\AA , but it is about 50% in auroras. Since 3914\AA requires about 19 ev of excitation energy whereas 5577\AA requires only about 4 ev (cf. Chamberlain, 1961), the conclusion is often drawn that the excitation processes in airglow are "low-energy", e.g. photo-chemical, whereas in auroras they are "high-energy", i.e. due to particle bombardment.
- (b) airglow occurs even at the geomagnetic equator, and it is difficult to believe that energetic particles to provide the necessary excitation could persist on magnetic shells at such low latitudes.

Conclusive proof now exists that the normal night airglow is not excited by energetic particles precipitated from high altitudes. In a rocket flight at midnight over Wallops Island, simultaneous measurements were made of the nightglow 5577\AA and 3914\AA , and also of precipitated particles. It was shown directly that less than 3% (and possibly none) of the 5577\AA nightglow was caused by particle precipitation [O'Brien, et al., 1965].

There remain considerable mysteries in the excitation of mid-latitude "red" (i.e. OI 6300\AA) arcs. The spatial relationship of one such arc to an intense peak of Van Allen radiation

[O'Brien, et al., 1960] cannot be ignored, but neither can it be used at the present time to explain the phenomenon [Roach, 1961].

Another interesting effect that has been explained as due to particle bombardment is the pre-dawn atmospheric heating and associated excitation of 6300Å. Carlson [1966] has provided convincing evidence that both effects are due to photoelectrons produced when the conjugate point is sunlit but the observation point is not. Direct observations of the intensity and energy spectrum of these photoelectrons, and study of their variation with latitude, are clearly of considerable importance in the understanding of atmospheric (ionospheric), solar and magnetospheric phenomena.

CONCLUSION

If one looks at a fine auroral display, then the problems of auroral phenomena may well be viewed in the abstract as being essentially unreal or else as related to - shall we say - a "way out" happening. Yet it must be recognized that, in the complex particle-wave interactions that constitute auroral phenomena, there are plasma processes occurring that may have clues, albeit obscure, which can lead to understanding of controlled fusion processes wherein the energy of the hydrogen of sea-water is harnessed for electrical power production without the usual (i.e. fission-associated) disadvantages of contaminated radioactive debris. Auroral processes, in some manner as yet not comprehended by scientists, harness the power of the sun, and produce displays of Northern (and Southern) Lights that use up some one hundred thousand megawatts of power, or roughly the same amount of electrical energy that is dissipated by mankind in his largely meaningless struggle against the non-negligible positive entropy of the real world.

Particles hitting the atmosphere dissipate energy - that much is certain. As a consequence, visible photons are emitted - that too is certain. But the ultimate source of energy, that activates the particles that then hit the atmosphere is - like the House that Jack Built - involved in some curious and unsolved sequence of relations, that presumably link the solar-wind and solar-flare processes, with the "memory" of interplanetary space (i.e. with prior solar conditions), with the magnetosphere and its "memory", with the very rotation of the earth, and with the earth's atmosphere and ionosphere. Clues that will define a successful or accurate path through these complex phenomena are being acquired a piece at a time, and often in a tremendous flood of data that must be sorted and culled. For example, currently NASA satellites are sending back to earth some eighteen

million measurements (18 "megameasurements") each day [George Ludwig, private communication]. This is a reasonable indication of the complexities of the auroral and magnetospheric phenomena, and an indication of the need for extremely well-planned and definitive experiments.

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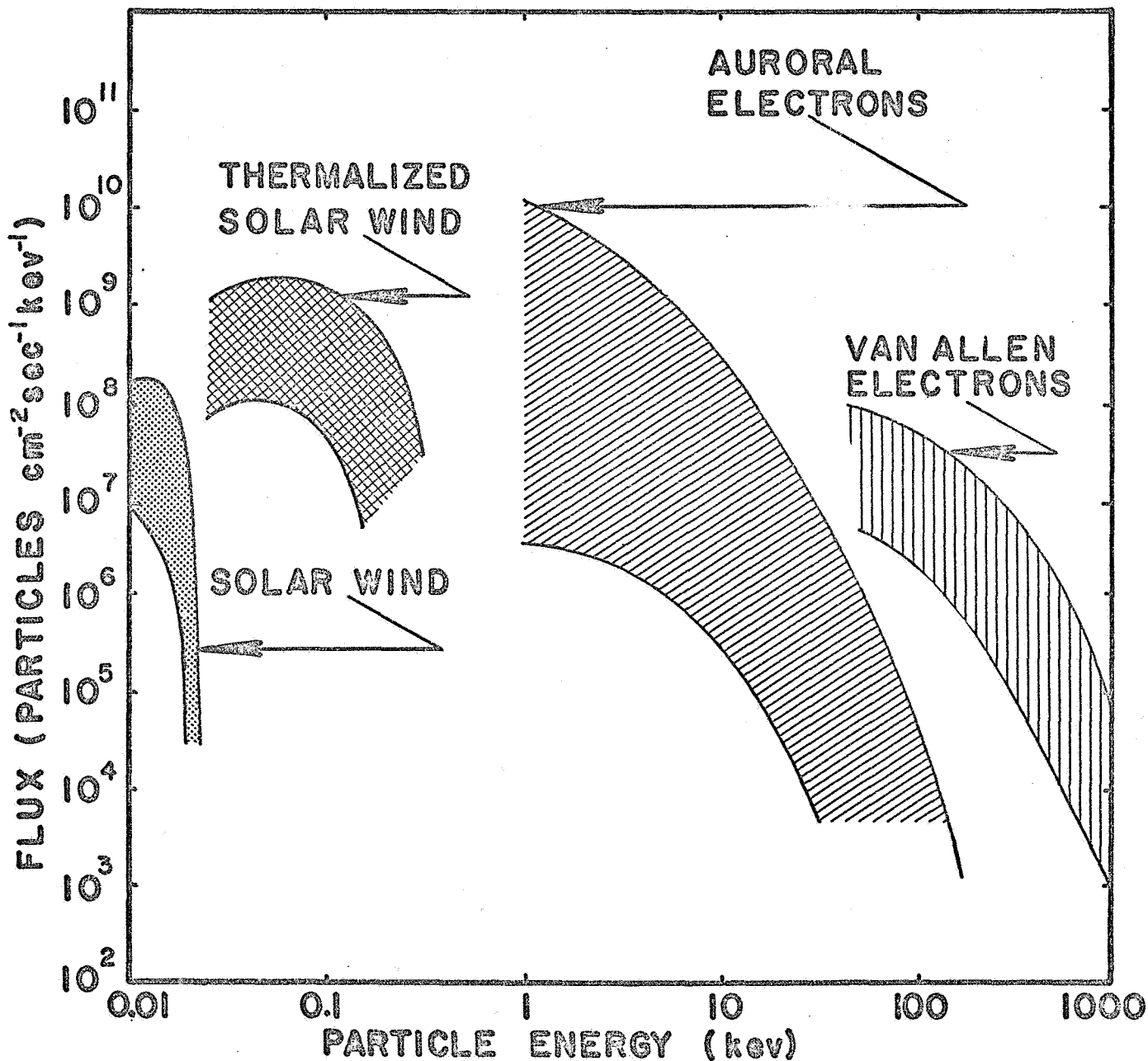
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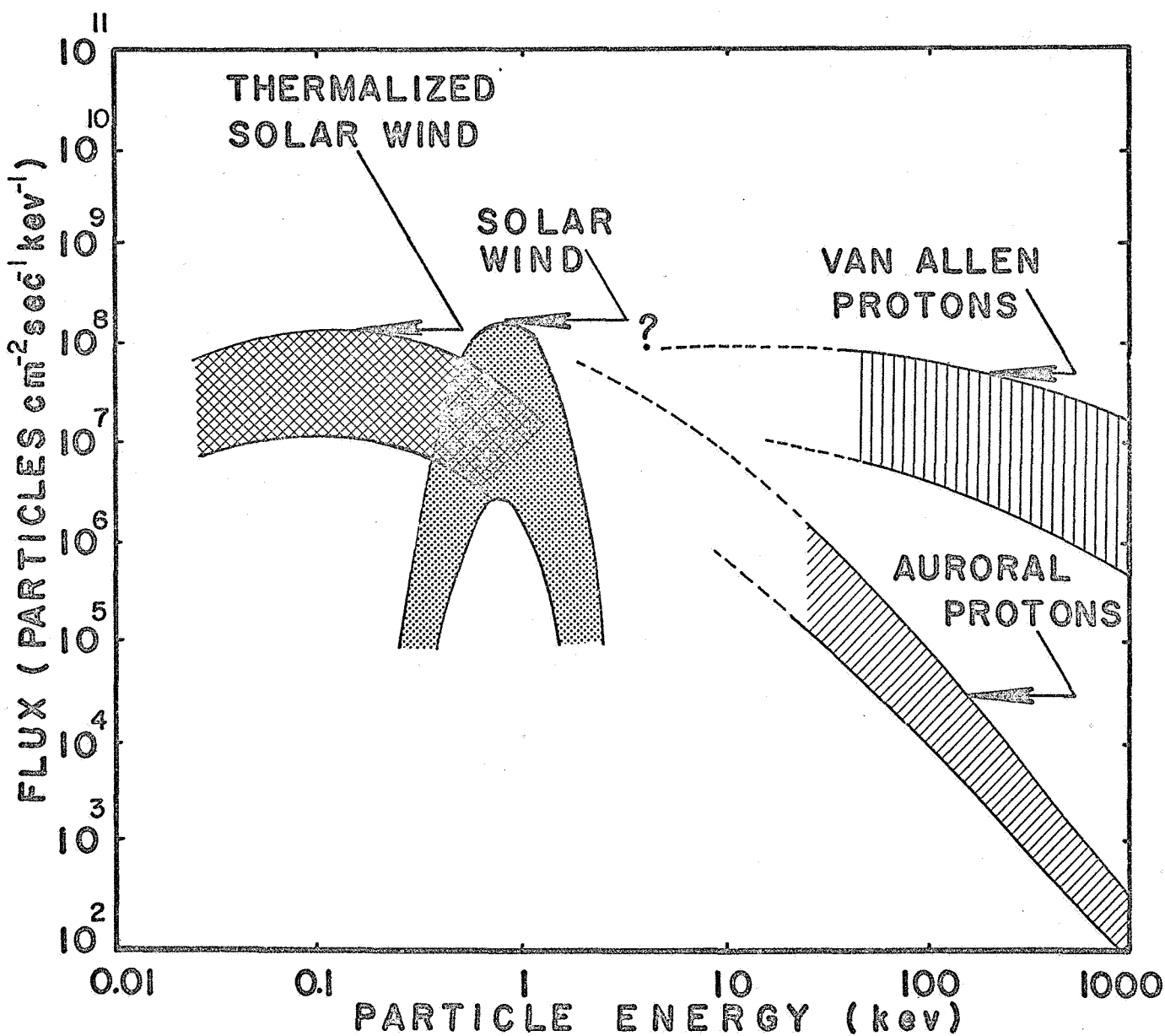
FIGURE CAPTIONS

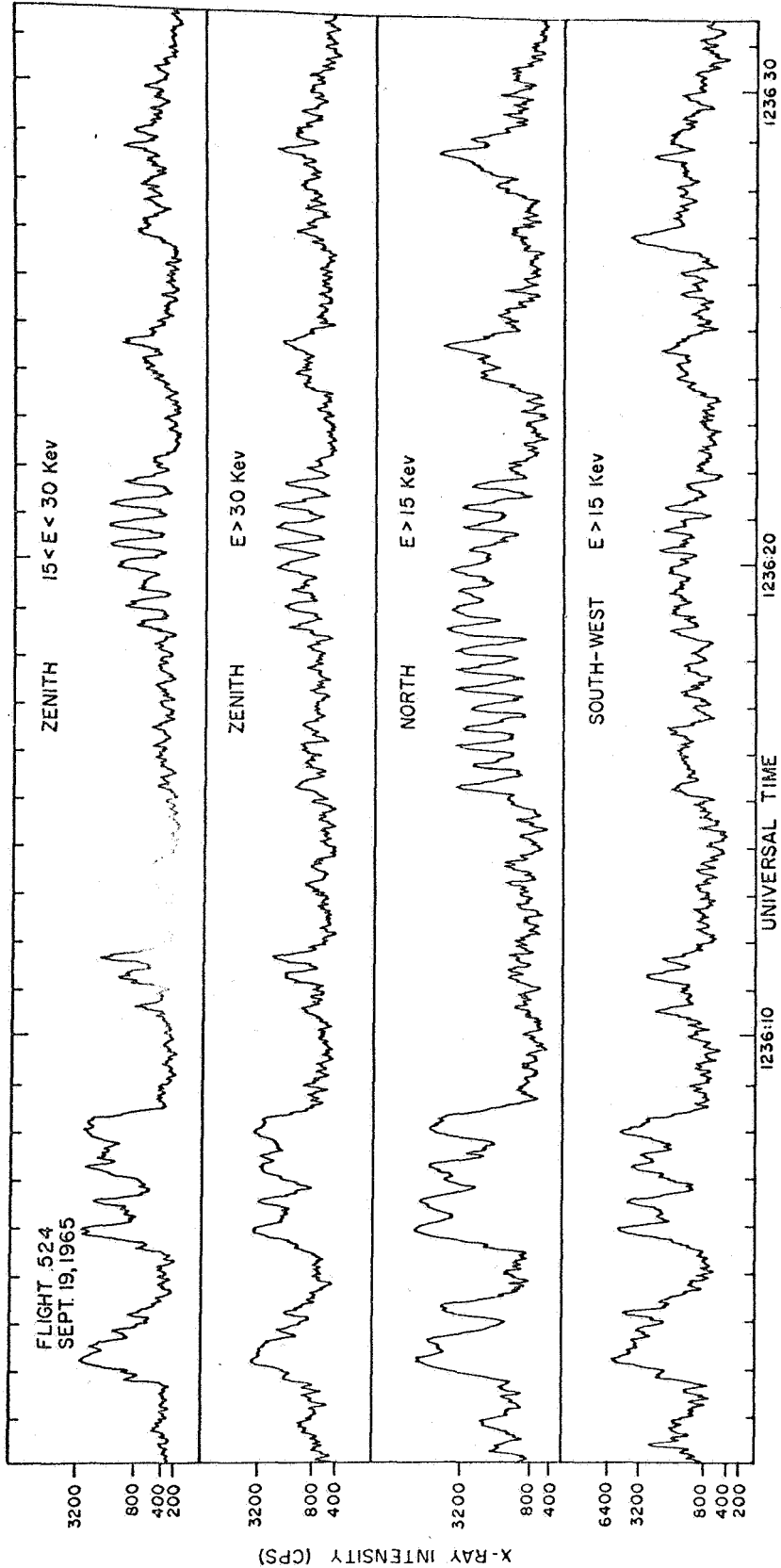
- Figure 1: Typical range of energy fluxes and spectra of electrons encountered at high altitudes in the environment of the earth (from O'Brien, 1967).
- Figure 2: Similar to Figure 1 but for proton fluxes.
- Figure 3: Examples of both "erratic" and "periodic" precipitation of electrons in auroral regions (from Parks, 1967).
- Figure 4: Example of periodic variations in the fluxes of essentially monoenergetic auroral electrons. Each point represents a summation of fourteen individual measurements made by rocket-borne detectors (from Winiecki, 1967).
- Figure 5: From data such as those of Figure 4, cross-correlation has been performed between the 800 μ secs measurements of the fluxes of 4.2 keV (LO) and of 9.7 keV (HI) energy electrons. The data indicate the important phase correlation of the periodicities of these particle fluxes. The slight phase difference of several milliseconds indicates either a modulation or acceleration at an altitude of less than 2000 km (from Winiecki, 1967).
- Figure 6: Examples of the very great temporal and spatial variations in intensity of particle precipitation in auroral regions, and also of the fact that there is always such precipitation (from O'Brien, 1964).

ENERGY SPECTRA of ELECTRON FLUXES



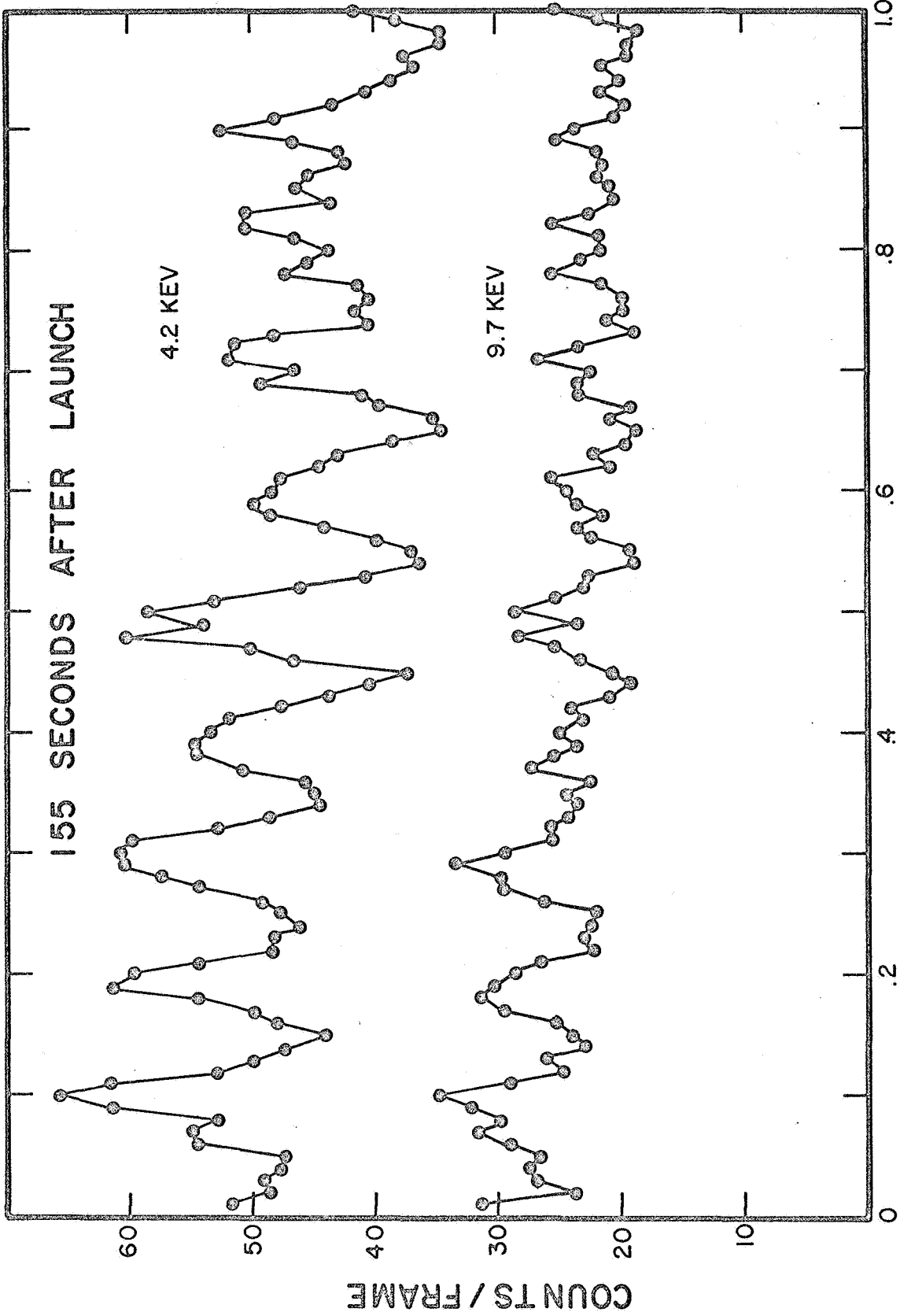
ENERGY SPECTRA of PROTON FLUXES





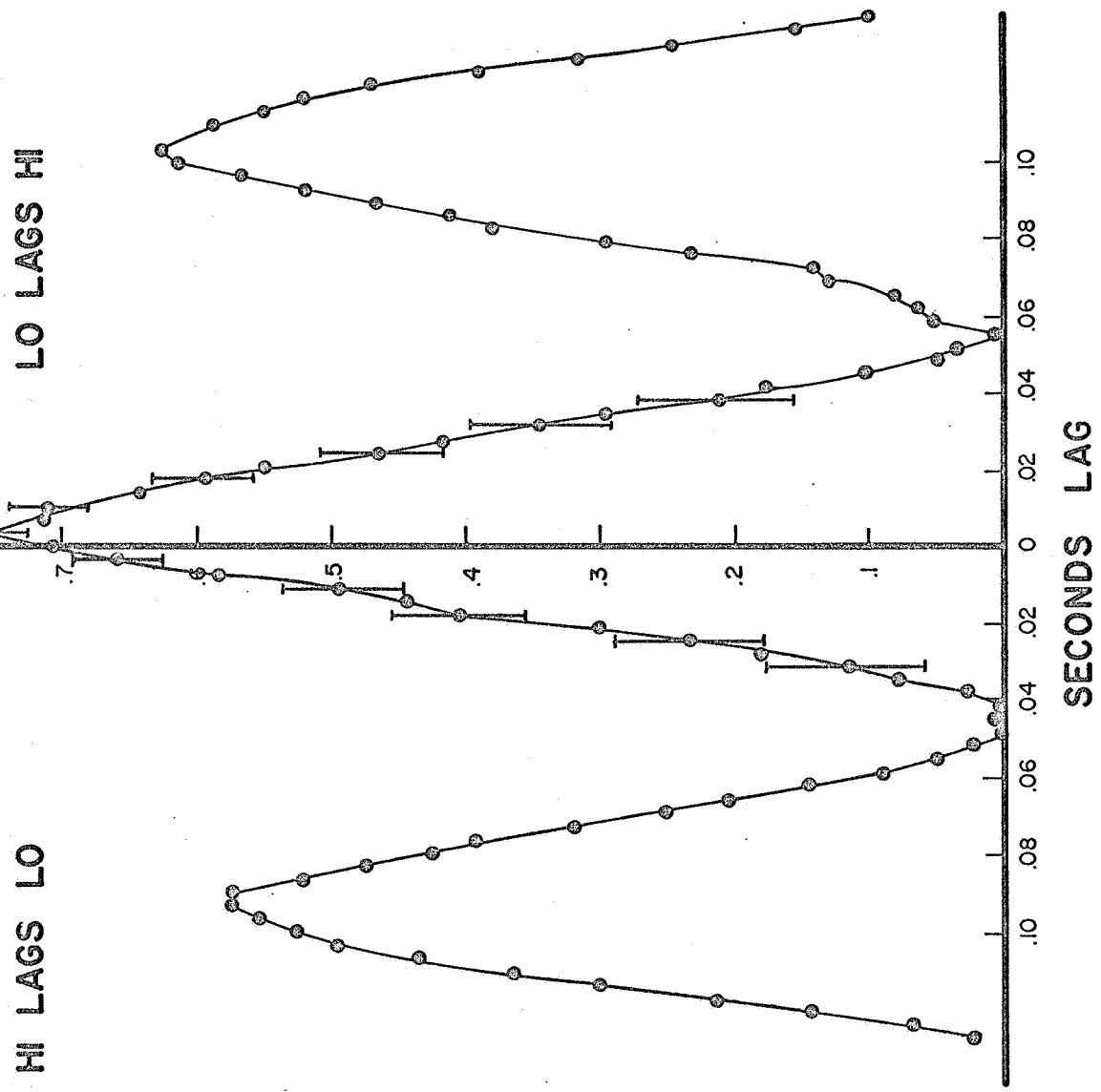
SAMMY 6 14 FRAME AVERAGES

155 SECONDS AFTER LAUNCH



SECONDS

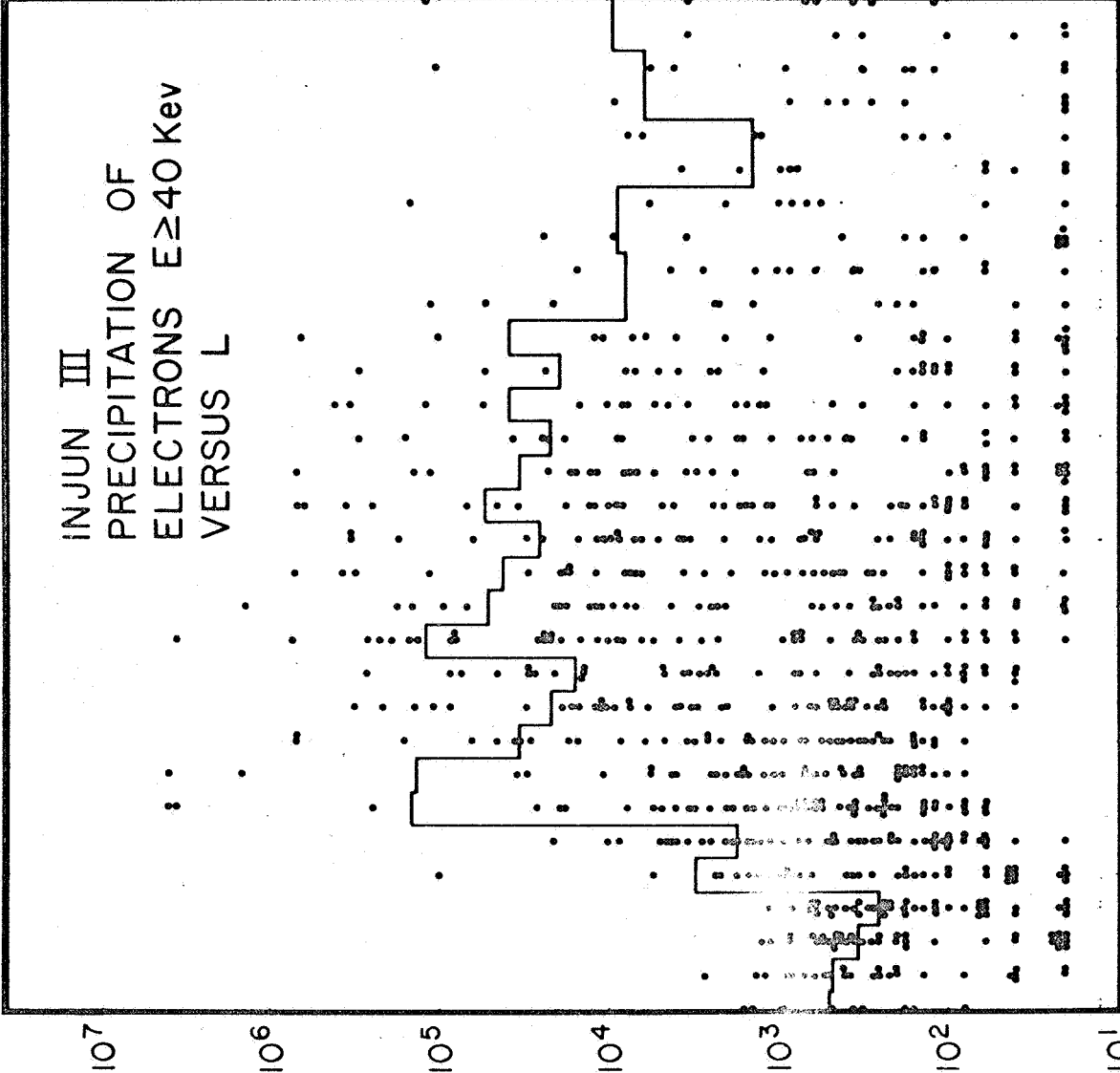
SARBY 6 HI & LO CROSS-CORRELATION COEFFICIENT
 155 TO 156 SECONDS AFTER LAUNCH



INVARIANT LATITUDE (Δ)

60° 65° 70° 75°

INJUN III
PRECIPITATION OF
ELECTRONS $E \geq 40$ KeV
VERSUS L



L (EARTH RADII)

FLUX
PARTICLES
 $\text{CM}^{-2} \text{ SEC}^{-1}$
 STERAD^{-1}