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Observations of the Suprathermal Electron Flux and the Electron Temperature at High Latitudes

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Observations of suprathermal electrons in the energy range of 5–200 ev were obtained with retarding potential analyzers on Explorer 31 in the altitude range of 1700–3000 km over the northern high latitudes during the winter of 1965–1966. There are three distinct zones that mainly consist of a steady flux of photoelectrons in the midlatitudes, a high and variable flux containing precipitated particles in the auroral latitudes, and a low flux over the polar region. Evidence is presented to show that the magnetic field lines are closed at least up to $L = 7.7$ for these particles. The boundaries of precipitation vary with local time and are somewhat different from those of the auroral oval. The ambient electron temperature appears to be dependent on the level of flux in the auroral and polar region.

In recent years observations of energetic electrons precipitating over high latitudes have been extended to lower energies [*Evans et al.*, 1967; *Burch*, 1968; *Hoffman*, 1969]. These measurements in the topside ionosphere and magnetosphere were made with polar orbiting satellites and the energies were extended down to about 50 ev. They indicate the existence of a region of precipitation over the auroral zone that extends poleward of the auroral oval and is characterized by spectral softening and rapid temporal and/or spatial variation. This region has been described as a 'soft' zone [*Burch*, 1968] or 'burst' zone [*Hoffman*, 1969]. One of the important effects of the incidence of these low energy electrons on the earth's upper atmosphere is the production of ionization at *F*-region levels and above [*Maehlum*, 1968, 1969; *Burch*, 1969; *Rees*, 1969]. The high latitude termination of the flux near the magnetic pole appeared to be responsible for the low level of *F*-region ionization and also of 6300 A intensity [*Maehlum*, 1969; *Eather*, 1969]. In the present paper we report high latitude observations from Explorer 31 of still lower energy electrons in the range of 5 ev to 200 ev, which may be referred to as suprathermal electrons or ev range electrons. Extension of the spectrum to such low energies will help in understanding the temperature behavior of the ambient electrons, since the ev range electrons are more efficient in heating the ambient electrons. Our measurements refer to the total flux of the precipitating or escaping (primary and secondary) low energy electrons and to the ionospheric photoelectrons, which are also in the same energy range.

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MEASUREMENT TECHNIQUES

The present measurements are made with retarding potential analyzers aboard Explorer 31, whose perigee is 500 km and apogee 3000 km and which is spinning at a nominal period of 20 seconds. The spin axis is normally oriented perpendicular to the orbital plane and the sensors are mounted perpendicular to the spin axis. Therefore the sensor normals rotate in the orbital plane and cover a wide range of angles with respect to the geomagnetic field. There are three sensors which are referred to as (1) the electron sensor, (2) the ion sensor, and (3) the energetic electron sensor. They consist of multigrid traps with a collector and a ramp grid whose voltage is swept in the proper voltage range. The details of their operation are described by *Donley* [1969] and *Maier* [1969]. While sensor 1 and sensor 2 are designed mainly to measure temperatures and densities of thermal electrons and ions, sensor 3 is designed to measure the energetic electron fluxes at different threshold energies varying from about 2 volts to 200 volts. However, sensor 1 can also measure the integral flux of all electrons with energies greater than 5 ev and sensor 2 can measure the integral flux of all electrons with energies greater than 15 ev. In this paper we present the observations both in terms of integral fluxes as well as differential energy spectra. The data are presented from sensors 1 and 3. Sensor 3 worked satisfactorily for nearly 5 months after launch. This gives useful and comparative spectral data, covering the entire 24-hour period, for only the winter of 1965–1966 over the northern high latitudes. The altitude range is from 1700 to 3000 km. In the present study all the available passes have been analyzed and the representative passes are shown in the following figures.

Characteristic Features of High Latitude Fluxes

Figure 1 illustrates some typical observations made during a pass covering both auroral and polar latitudes. Under the X axis are shown the universal time, the (centered) dipole magnetic latitude, McIlwain parameter L, and the solar zenith angle χ_s at the location of the satellite. The solar zenith angles at both ends of the field lines at the 300 km level (χ_L in the local ionosphere and χ_C in the conjugate ionosphere) are also shown under the X axis. The parameter L is obtained from a spherical harmonic expansion of the main geomagnetic field. The Y axis shows the energetic electron flux per square centimeter per second. The integral fluxes of electrons above 5 ev are obtained from sensor 1 and those above 7 ev are obtained from sensor 3; both are plotted in the figure to demonstrate that they give essentially the same variation. In the following, fluxes from sensor 1 are used to describe various features of high latitude phenomena since more frequent observations are available from this sensor, and the fluxes from sensor 3 are used mainly for deriving differential energy spectra since it gives fluxes at different threshold energies. Referring to Figure 1 we find a fairly steady flux up to magnetic latitude of 68°, a large increase with irregular structure up to 76°, and a lower flux over the polar region above 80°. From this figure three zones may be defined: steady zone, high flux zone, and low flux zone. They correspond approximately to the midlatitude zone, the auroral

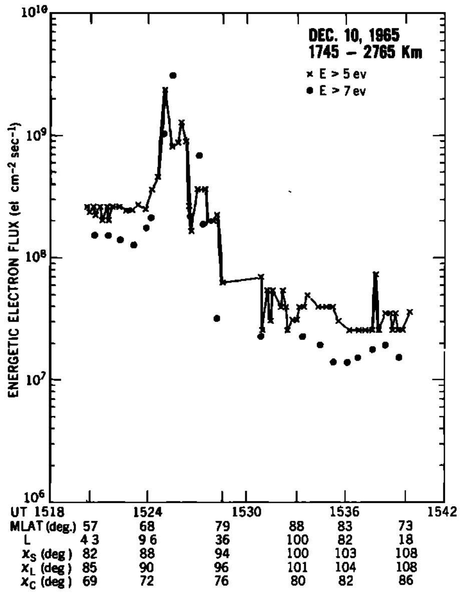

Fig. 1. High latitude variation of integral electron fluxes illustrating the presence of three flux zones.

zone, and the polar zone. As mentioned in the introduction the measured fluxes consist of ionospheric photoelectrons escaping upward from the F-region production levels, any possible precipitated electrons from the magnetosphere, and any resulting secondaries. At first, it may appear feasible to identify these two types by looking up or down the field line, but it should be realized that scattering effects and the production of secondaries will complicate the angular distribution. In fact, the observed pitch angle distribution, within the limits of the present technique, shows a more or less isotropic distribution. Therefore, we used the variation in the intensity levels as the criteria to distinguish the precipitated particles from the photoelectrons. The photoelectron flux is dependent on the solar zenith angle χ, the level being fairly constant for χ values ranging from 80° to 0°, while the precipitation flux (which includes primaries and secondaries) shows more variability with time and/or space. By using the above criteria, we find from Figure 1 that the steady flux in the midlatitude zone may be attributed to the ionospheric photoelectrons alone since this is the level normally observed both at low and midlatitudes when both ends of the field lines are sunlit. A steady

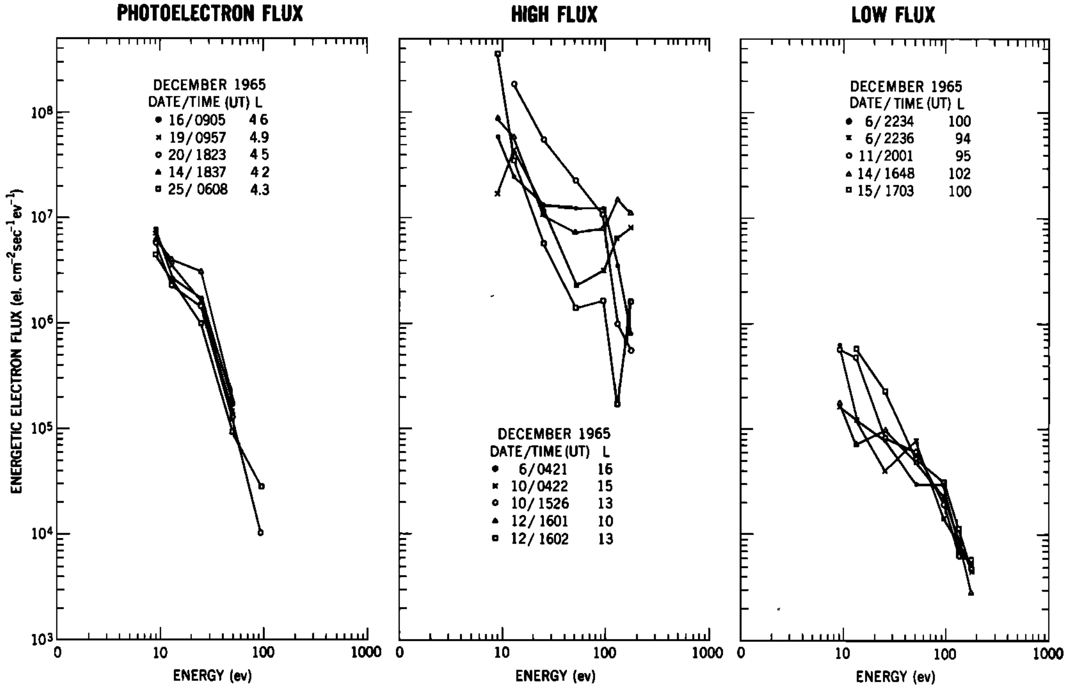

Fig. 2. Differential energy spectra of the suprathermal electrons in the three zones.

flux of low energy electron drizzle from the magnetosphere may be present but we believe that this is of lower magnitude, of the order of the nighttime background flux. At the time of conjugate sunrise the flux level increases gradually to reach a steady value later, indicating that this daytime value of steady flux is attributable to ionospheric photoelectrons. The higher level and greater variability in flux in the auroral zone indicate that there are appreciable numbers of precipitated particles in addition to photoelectrons.

In Figure 1 the zonal behavior of the integral flux is shown. However, it is necessary to know the differential energy distribution to establish that these levels really reflect flux levels of low energy electrons.

In Figure 2 the differential energy spectra are shown separately for each zone. On the left the spectra of the steady photoelectron flux are shown, the high flux spectra are shown in the middle, and the low flux spectra are shown on the right. It is immediately clear that the levels of the integral fluxes noted earlier in the three zones are reflected in the differential fluxes of low energy particles. For example, the flux of 10 ev particles is high in the high flux zone and low in the low flux zone. Therefore the integral flux levels for $E > 5$ ev can be taken as indicative of the fluxes of low energy electrons. It will be useful to compare our observed fluxes with similar measurements made by others for the available energy. For 100 ev energy electrons *Burch* [1968] observed a flux of about 10^6 cm^{-2} sec^{-1} ev^{-1} ster^{-1} in the 'soft zone' and *Westerlund* [1969] observed a flux of about 10^7 cm^{-2} sec^{-1} ster^{-1} in the 'auroral' region of L varying from 9 to 12. Figure 2 shows that in the high flux zone 100 ev electron flux lies in the comparable range of 10^6–10^7 cm^{-2} sec^{-1} ev^{-1}.

From Figure 2 it may be noted that the spectral shapes are also different in the three zones. In the midlatitude zone the shapes are very uniform and resemble the spectrum of photoelectrons observed at lower latitudes. In the auroral zone the spectral shape becomes highly variable. There is also a trend toward a second peak around 100 ev. In the polar zone the shapes are relatively less variable with a slow decrease of flux with increasing energy.

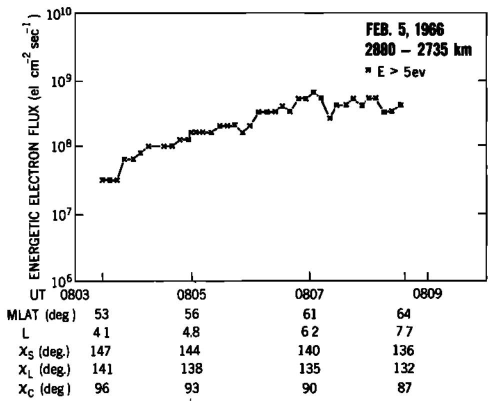

Fig. 3. Latitudinal variation of the electron flux during conjugate sunrise.

Closed Field Line Boundary for the Low Energy Electrons

It was mentioned earlier that in the mid-latitude zone the observed flux consists mainly of ionospheric photoelectrons. Since their production is controlled by the incidence of solar radiation, during the predawn period they will be observed at the time of conjugate point sunrise, if the geomagnetic field lines are closed as in the case of lower latitudes [*Rao and Maier*, 1970]. Thus, the incidence of conjugate photoelectrons can be used as a test for finding the closed field line boundary. Figure 3 shows high latitude observations in the northern hemisphere at the time of conjugate sunrise. This pass covers from 53° to 64° magnetic latitude and L values from 4 to 7.7. For this pass the local ionosphere is in darkness as can be seen from χ_L and sunrise is taking place in the conjugate ionosphere since χ_c is varying from 96° to 87°.

During this period the flux shows a gradual increase reaching almost a steady value. The smooth increase of flux during the conjugate sunrise indicates that these are the photoelectrons coming from the conjugate hemisphere. Since this behavior is observed up to $L = 7.7$ it is reasonable to conclude that the field lines are closed at least up to this L value during nighttime (MLT = 0130 hr). Beyond the closed field line boundary there will be a drop in the flux where the field lines become open. However, it is found that there is also precipitation from the magnetosphere superposed on the photoelectron flux, making it impossible to locate the drop in the photoelectron flux. Therefore, this technique has yielded only the lower limit on the boundary for the closure of field lines as tested by the south-to-north propagation of low energy electrons. This lower limit of $L = 7.7$ corresponds to an invariant magnetic latitude of 69°. It lies within the boundary (69° magnetic latitude) at local midnight determined by *Fairfield* [1968] from the magnetic field measurements. *McDiarmid and Burrows* [1968] have suggested that electrons with energy >35 kev are suitable tracers for identifying a closed field line configuration and that the latitude at which the 35 kev flux falls to cosmic ray background gives approximately the limit of closed field lines. By using this criterion they found that the boundary varies from 70° to 78° invariant magnetic latitude from 2100 to 0700 hr MLT. The present study yields a lower limit of the boundary at 69° invariant magnetic latitude at 0200 hr MLT which is within their boundary value. In this connection it may be pointed out that *Bennett* [1969] determined the limits over which the intervening magnetospheric domain permits the photoelectrons to propagate from one hemisphere to the other from a study of 6300 A airglow predawn enhancements at a few stations. He found a limit of $L = 3.2$ and inferred that this upper limit is imposed by magnetospheric electric fields of such magnitude and direction as to preclude propagation of the low energy conjugate photoelectrons. However, from the present direct observations, we find that the conjugate photoelectrons can reach the other hemisphere up to $L = 7.7$. This can be interpreted to mean that the electric fields are not of sufficient magnitude or direction to significantly perturb the electrons up to this L value.

Dependence of the Precipitation Zone Boundary on Magnetic Local Time

From a study of a large number of passes, it is found that the boundaries of the zones of precipitated particles depend on the magnetic local time. Before presenting the data for different times the main differences are first illustrated with a typical daytime pass and a typical nighttime pass which are shown in Figures 4*a* and 4*b* respectively. During daytime (Figure 4*a*) the steady photoelectron flux continues up

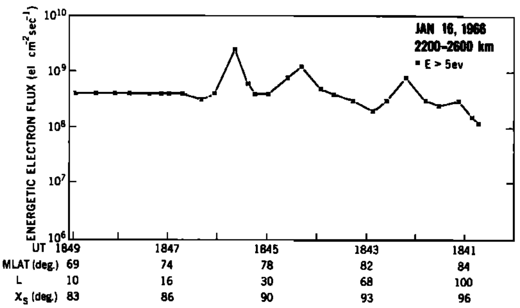

Fig. 4*a*. Daytime flux between 1240 and 1430 LT.

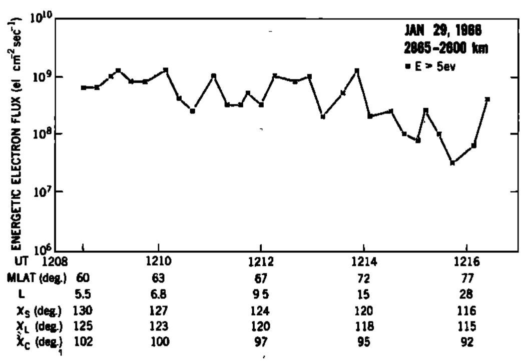

Fig. 4*b*. Nighttime flux between 0310 and 0415 LT.

Figure 4 shows latitudinal variations of the integral electron flux.

to magnetic latitude 75°, and precipitation occurs beyond that latitude. In contrast to this, at nighttime, precipitation starts at a much lower latitude. At night (Figure 4*b*), from 60° onwards, the flux is variable and larger than the steady photoelectron flux level, indicating that there is precipitation even at a latitude of 60°. In fact, at the beginning of the pass the flux is wholly due to precipitation since both χ_L and χ_c are greater than 96° (note from Figure 3 that the photoelectron flux from the conjugate hemisphere would be less than 10^8 el cm^{-2} sec^{-1} for $\chi_c > 95°$). After showing the major differences in the lower boundary of the

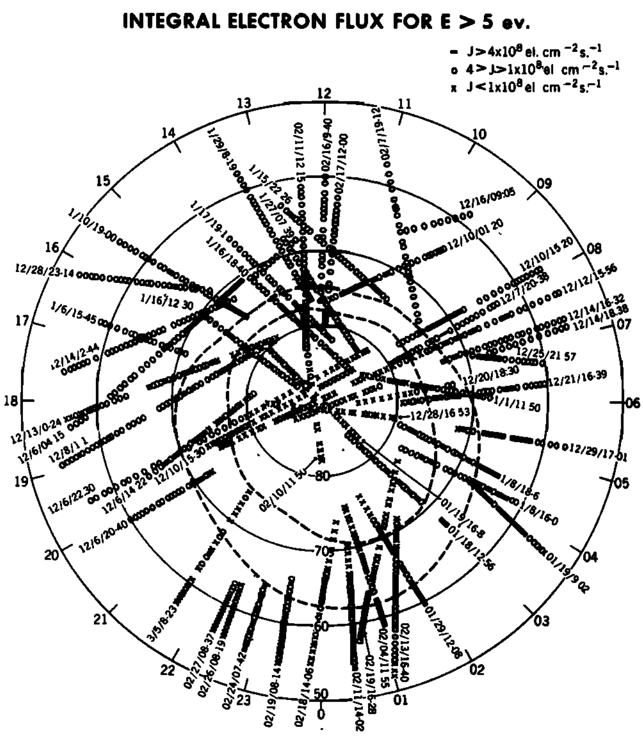

Fig. 5. Dependence of the precipitation zone boundaries on magnetic local time. The individual passes are labeled with the month, day, hour, and minute in UT of the start of the pass. The data presented were obtained from December 6, 1965, through March 5, 1966.

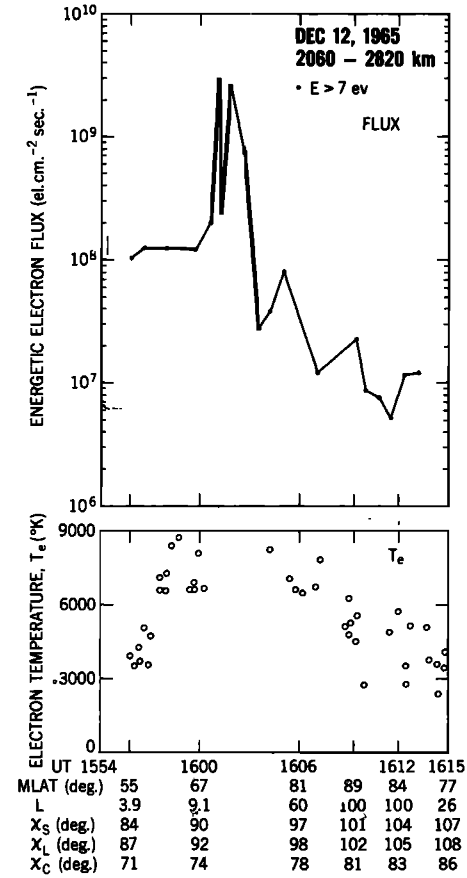

Fig. 6. Simultaneous observations of the suprathermal electron flux and the ambient electron temperature.

precipitation zone between day and night, the variation of the lower and upper boundaries of this zone with magnetic local time are shown in Figure 5. In this polar diagram the coordinates are geomagnetic latitude and magnetic local time (MLT). Observations from a number of passes during the period December 1965 to February 1966 are included to cover all the magnetic local times. All the available data are not plotted to avoid illegibility in the diagram, but those shown in the figure are representative. The observations are denoted by three symbols based on the magnitude of the photoelectron flux which is normally between 2–3 × 10^8 el cm^{-2} sec^{-1}. A slightly higher value than this, i.e., 4 × 10^8 el cm^{-2} sec^{-1} is chosen as upper boundary and a slightly lower value of 1 × 10^8 el cm^{-2} sec^{-1} is chosen as lower boundary. If the flux is higher than the upper boundary precipitation is considered to be present and if it is less than the lower boundary it is considered to be absent. The definition of the precipitation in this manner may not be accurate, but is considered reasonably indicative for the present purpose. Figure 5 shows that the high latitude boundary for precipitation of ev electrons lies at about 80° in the dayside and 70° in the nightside. The low latitude boundary lies at about 70°–74° in the dayside and 55°–60° in the nightside. So far we have been using the phrase 'auroral zone' in a flexible way to mark the region of auroral activity where the present 'high flux zone' also occurs. However, for comparison purposes, we must clearly define the auroral zone. In Figure 5 we have also shown the boundaries of the auroral zone (oval) as given by *Hartz and Brice* [1967], which are based on the frequency of incidence of various types of auroral phenomena, including short duration bursts of <20 kev electrons and discrete auroral forms [*Feldstein*, 1966]. It appears that, compared to the auroral oval, the boundaries extend toward the pole in the daytime and toward the midlatitudes in the nightside.

Effects of ev Electron Flux on the High Latitude Behavior of Ionospheric Electron Temperatures

The low energy electrons are very efficient in heating the ambient electrons through elastic collisions [*Dalgarno et al.*, 1963]. Therefore, it is natural to expect that the fluxes of these precipitating low energy electrons strongly influence the electron temperature in these high latitudes. Fortunately, we have simultaneous observations of the electron temperature, as determined by sensor 1, allowing us to study T_e in relation to the fluxes. Figure 6 illustrates the typical behavior of both the flux variation and the T_e variation. At midlatitude $T_e \approx 4000°$, which is the normal value observed under sunlit condition at these latitudes (i.e., the value of T_e under the incidence of the photoelectron flux). Figure 6 shows that northward T_e increases rapidly toward the region of high flux. Within the high flux region precise T_e measurements could not be made because of the interference of suprathermal particles in the electron current retardation curves of sensor 1. However, the nature of the retardation curves indicate a high temperature. North of the high flux zone, toward the magnetic pole, T_e decreases from a value of about 8000°K to about 4000°K in the polar region, corresponding to the decrease in flux. Thus, the decrease of T_e in the polar region appears to be caused by the decrease in the suprathermal flux. On the other hand, in the midlatitude region, T_e increases before the flux increases.

We have shown in a recent paper [*Rao and Maier*, 1970] that significant backscattering and/or mirroring of the suprathermal particles occur within the protonosphere. It is suggested that this coupling, plus possible wave interaction, can serve to inject electrons into orbits where they mirror above about 1500 km. It is possible that the proportion of thermal electrons scattering into such pseudo-trapped orbits may increase with L shell. Thus, the increase of temperature with latitude may result from an increased number of electrons in pseudo-trapped orbits storing heat energy in the magnetosphere.

In summary we may state that observations of suprathermal (ev energy) electron fluxes show three distinct zones consisting mainly of steady photoelectron fluxes in midlatitudes, high and variable fluxes of precipitating (including secondaries) particles in the auroral zone, and low fluxes in the polar zone. The boundaries of the precipitation zone are somewhat different from the auroral boundaries as determined by the precipitation of kev particles. Finally, the ambient electron temperatures in the auroral and polar regions appear to be controlled by the intensity of the flux of suprathermal electrons.

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