At the Edge of the Earth's Magnetosphere: A Survey by AMPTE-UKS [and Discussion]

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At the edge of the Earth's magnetosphere: a survey by *AMPTE-UKS*

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[Plates 1–3]

A survey is made, by using measurements from the *Active Magnetospheric Particle Tracer Explorers – United Kingdom Satellite*, of the interaction between plasmas of solar and terrestrial origin at the outer edge of the Earth's magnetosphere. The position of the boundary and its rate of movement are related statistically to solar-wind dynamic pressure and its variations. The first results are presented of a new type of analysis which aims to clarify the nature of the boundary layer that develops between the two plasmas by reordering, on the basis of a consistent relation between electron density and temperature, the normally erratic progress made by a spacecraft across the constantly moving region. Distinctive patterns found consistently for the electron and ion transitions suggest that diffusion, viscosity and loss to the atmosphere govern the boundary layer. Various possibilities are discussed for the topology of the region. Electron acceleration within the boundary layer is identified; its cause and relevance to dayside auroral precipitation are discussed. There is an indication that the transition in the magnetic field, across the magnetopause current layer, lies within, rather than immediately outside, the boundary layer.

1. INTRODUCTION

The wide range of events taking place within the enclave in the solar wind formed by the Earth's magnetosphere, such as plasma convection, charged-particle acceleration, the aurora and various forms of enhanced coupling between the magnetosphere and ionosphere during substorms, are all powered by energy drawn from the solar wind into the magnetosphere at the boundary between these two plasma régimes. In broad terms, the dividing surface becomes established where the dynamical pressure of solar-wind protons and other ions in this particle-dominated plasma is balanced by the magnetic pressure of the magnetosphere's magnetically dominated plasma. Balance is reached typically some 10 R_E† upstream from the Earth's centre and 14 R_E along the dawn and dusk flanks. The *United Kingdom Satellite* (*UKS*) (Ward *et al.* 1985), of the *Active Magnetospheric Particle Tracer Explorers* (*AMPTE*) mission (Bryant *et al.* 1985), with its apogee of 18.5 R_E was well equipped to explore the form and manner of the confrontation between solar-wind and magnetospheric plasmas. We shall examine some of the more general properties of the boundary region as revealed by the particular blend of high-resolution particle and field measurements made by the *UKS*. The first results of a new type of analysis, aimed at clarifying the nature of the transition between the solar wind and magnetosphere, are also presented for discussion.

This brief survey is centred on, and ordered by, the properties of the plasma particles instead

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† $R_E = 6.371 \times 10^6$ m.

of the magnetic field which is usually taken as reference; the data on which it is based were obtained in the main from the *AMPTE* database (Hapgood & Doidge 1986), available from the Rutherford Appleton Laboratory (RAL) through the computer network.

2. LOCATION OF THE BOUNDARY

During its five-month lifetime, between 15 August 1984 and 15 January 1985, when a sudden catastrophic failure brought its excellent performance to an end, the *UKS* made 49 recorded crossings of the region. Because of the nature of the orbit, the crossings were made at low magnetic latitude (less than 25°) and at magnetic local times (MLTS) which ranged from 15h30 MLT, through 12h00 MLT, directly upstream, to 05h00 MLT on the dawn flank; as shown in figure 1.

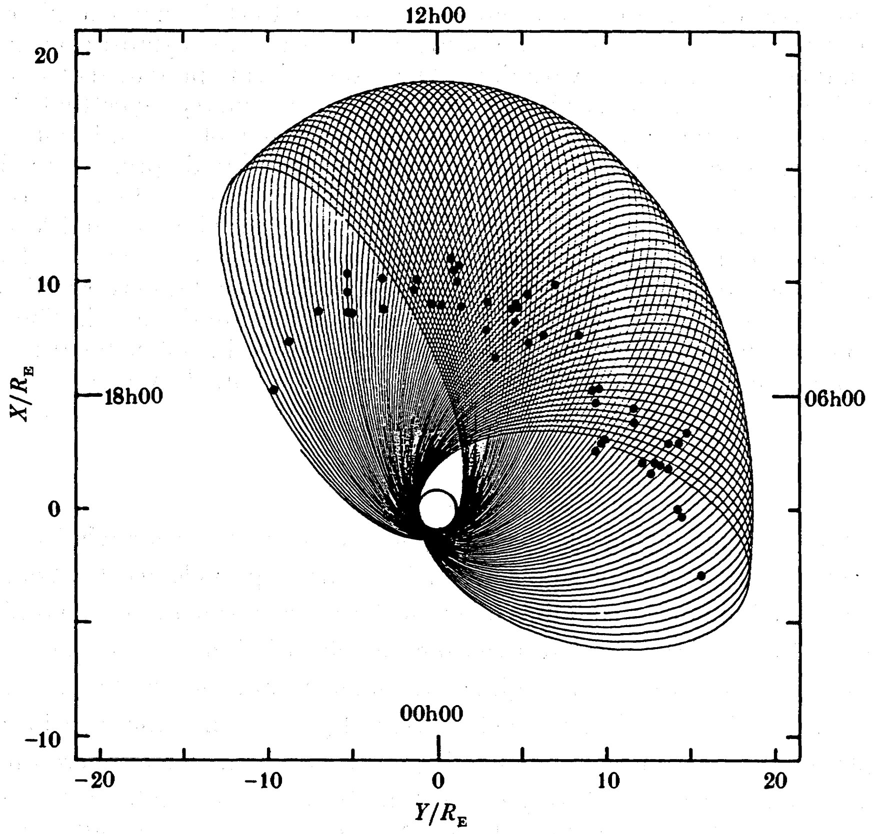

FIGURE 1. The 82 orbits completed by *AMPTE-UKS* projected onto the geocentric solar ecliptic (GSE) *XY*-plane. Recorded crossings of the boundary between solar and terrestrial plasmas are indicated. Times are magnetic local times.

A number of the five-hour stretches of data-taking, to which the *UKS* was constrained for reasons of battery capacity, included not only the solar-wind/magnetosphere boundary, but also the transition further upstream at the bow shock, where some of the directional energy of the solar-wind ions, predominantly protons, is converted into heating of the ions and electrons to form a magnetosheath of modified solar wind, in which form it confronts, one minute or so later, the terrestrial magnetic field and plasma at the boundary we are discussing. One such stretch of data, taken on 4 November 1984 on the inward leg of orbit 43, is shown in figure 2, plate 1. The transition from the denser and cooler magnetosheath to the more diffuse and hotter magnetosphere is clearly evident. On this occasion it took place at a geocentric distance of 8.9 R_E and at a magnetic local time close to noon. This location is plotted along with the other 48 shown in figure 1. The general locus of these points agrees well with the comprehensive survey made by Holzer & Slavin (1978). If we adopt the empirical elliptical shape found by Holzer & Slavin to represent these points, we may reduce the array to a frequency histogram of geocentric 'stand-off' distances at 12h00 MLT. This is shown in figure 3. The mean stand-off distance is 9.8 R_E and the 2-sigma limits are 7.5 and 12 R_E, defining a dynamic range of 1.6.

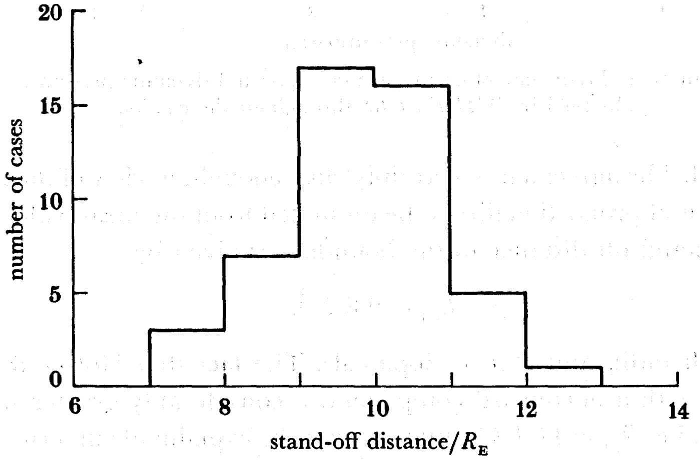

FIGURE 3. Frequency of occurrence of stand-off distances of the boundary between solar and terrestrial plasmas, as derived from figure 1 by using an empirically derived ellipse (Holzer & Slavin 1978) to represent the boundary.

How does the stand-off position and its range compare with what is expected?

If we forget for the moment the complexities introduced by the bow shock, and just consider the pressure balance between, on the one hand, the solar wind as a streaming, highly conducting, weakly magnetized plasma, and on the other, an originally dipolar magnetic field, it can readily be shown that the stand-off distance will vary as (dynamic pressure)$^{-\frac{1}{6}}$. This follows, as was pointed out by Ferraro (1952), from the fact that the dipole field, B, (proportional to (radial distance)$^{-\frac{1}{3}}$), immediately outside the contact surface is reduced to zero, and the field immediately inside is consequently doubled in strength to exert a pressure $2B^2/\mu_0$, proportional to (radial distance)$^{-\frac{1}{6}}$. It is impossible, of course, from a single spacecraft to observe the boundary and to monitor the solar wind at the same time. Neither could this be performed using the combination of the *UKS* and its orbital companion the *AMPTE Ion Release Module*, because throughout the operational life of the *UKS* the separation between the spacecraft in the outer portion of the orbit was maintained at only *ca.* 100 km to perform active ion-release experiments. However, we can test the relation by using a statistical approach based on the range of dynamic pressure recorded by the *UKS* ion spectrometer (Coates *et al.* 1985) during the many excursions made into the solar wind. A frequency histogram of these pressures is shown in figure 4. The mean pressure is 1.1 nPa and the 2-sigma limits are 0.15 and 3.60 nPa. The dynamic range defined by the latter quantities leads to an expectation of $24^{-\frac{1}{6}} = 1.7$ for the dynamic range of the stand-off distance, which compares well

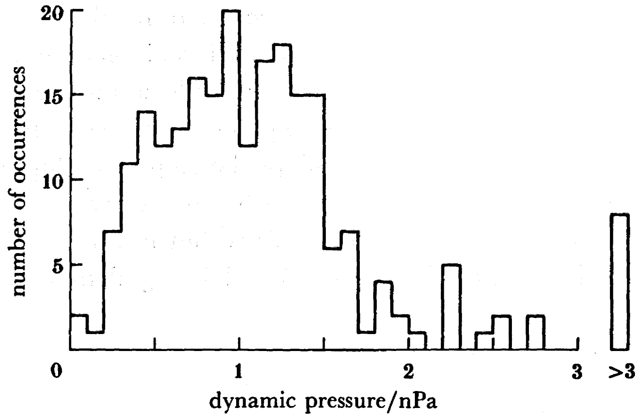

FIGURE 4. Frequency of occurrence of solar-wind dynamic pressures observed by *AMPTE-UKS* throughout the mission.

with the observed 1.6. The agreement is certainly close enough, in view of the nature of the test, to permit the constant of proportionality to be estimated from the mean values. We find, then, that the geocentric stand-off distance of the boundary is given by

$$R_{so} = 9.3\,P^{-\frac{1}{6}}, \tag{1}$$

where R_{so} is in Earth radii, and P in nanopascals. The fact that Holzer & Slavin find, for interplanetary fields with a northward component, a considerably greater stand-off distance for the same pressure, i.e. $R_{so} = 11.4\,P^{-\frac{1}{6}}$, may perhaps be explainable in terms of the unusually high preponderance (2:1) of southward to northward-component interplanetary magnetic fields, encountered near the boundary during the *AMPTE-UKS* mission (Southwood *et al.* 1986), with a consequently higher than usual capacity for erosion of the magnetosphere.

3. THE BOUNDARY LAYER

Let us now focus on what is observed during crossings of the boundary between solar and terrestrial plasmas. On some occasions the transition is fast, smooth and monotonic, as on 4 November 1984 in orbit 43 (figure 2). More generally though, it is erratic and prolonged, indicating the presence of a substantial boundary layer, as on 19 December 1984 in orbit 68, shown in figure 5, plate 1. A boundary layer of some form is really to be expected in order to form a bridge between the highly disparate solar and terrestrial plasmas. Boundary layers in solid, liquid and gaseous forms are very common in nature; and plasmas readily exhibit the properties shown by other states of matter, together invariably, with a number of complex variations of their own.

How thick is the boundary layer, and how stable is it?

If we knew the solar-wind pressure and its rate of change during each of the crossings we could estimate, by using equation (1), both the position and rate of change of position of the boundary. The latter could be combined with the spacecraft's velocity and the time taken to make the crossing to yield the width of the boundary layer. Although it cannot be done this way, as we do not have simultaneous solar-wind measurements, we can obtain an estimate from the following statistical analysis.

We find that the time taken by the spacecraft to cross 'permanently' from the magnetosphere

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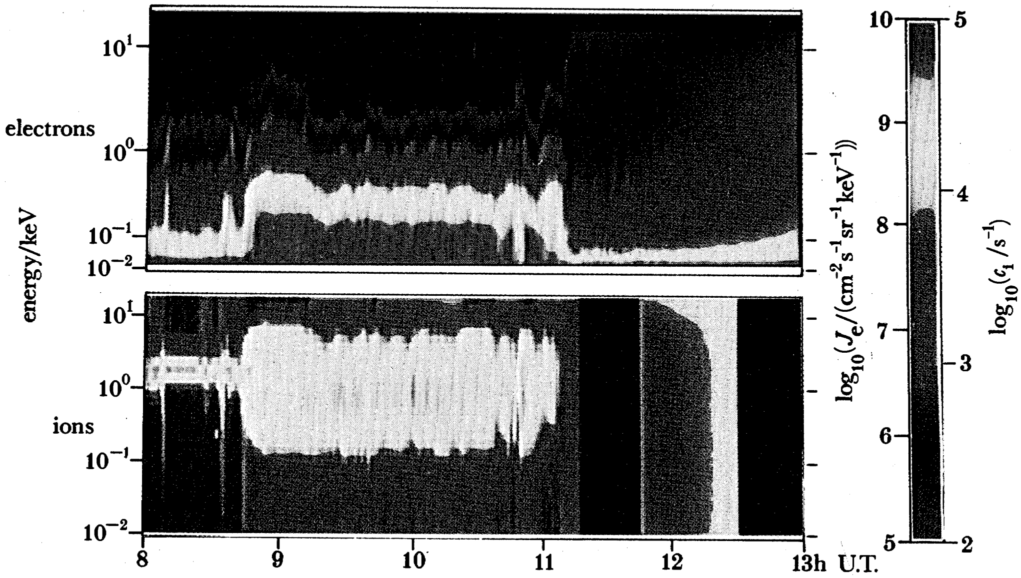

FIGURE 2. Electron intensities, J_e, and ion count rates, c_i, (the latter proportional to intensity times energy) on 4 November 1984 on the inward leg of orbit 43. Intensities and count rates are colour coded and are shown as functions of energy. The adjoining scale gives the logarithms of the electron intensity and the ion count rate. The spacecraft was in the solar wind until 08h40 U.T., when it crossed the bow shock into the magnetosheath. The crossing of the boundary between solar and terrestrial plasmas was made at around 11h05 U.T.

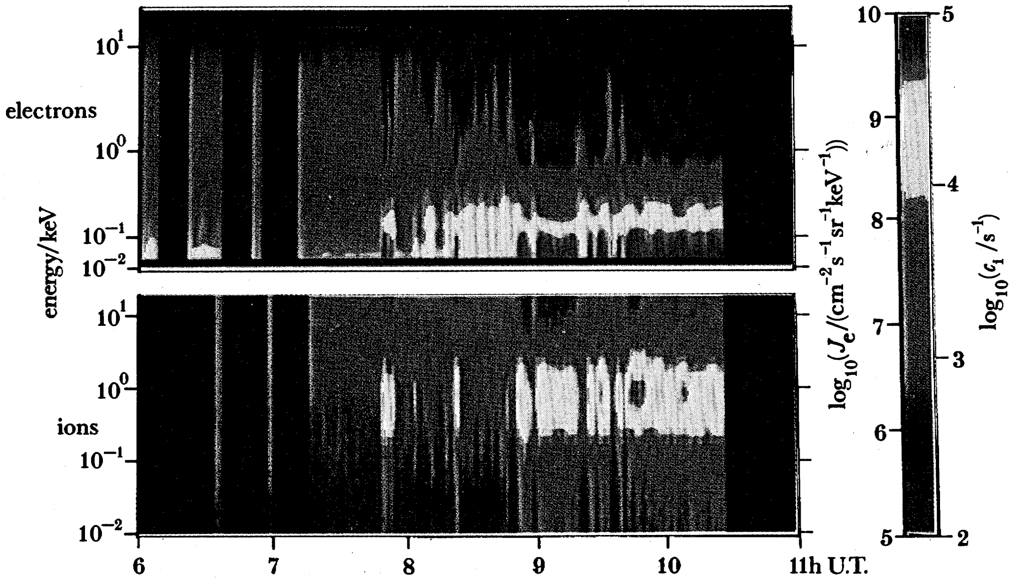

FIGURE 5. Electron intensities, J_e, and ion count rates, c_i, on 23 November 1984 outward leg or orbit 54. Intensities and count rates are colour coded and are shown as functions of energy. The crossing from magnetosphere to the magnetosheath (between 07h55 and 09h45 U.T.) was both prolonged and erratic, demonstrating the existence of a substantial and moving boundary layer. The three stretches of data beginning at 06h00 U.T. represent a 'real time' search for the boundary layer while conserving power to explore the layer as fully as possible when it was reached.

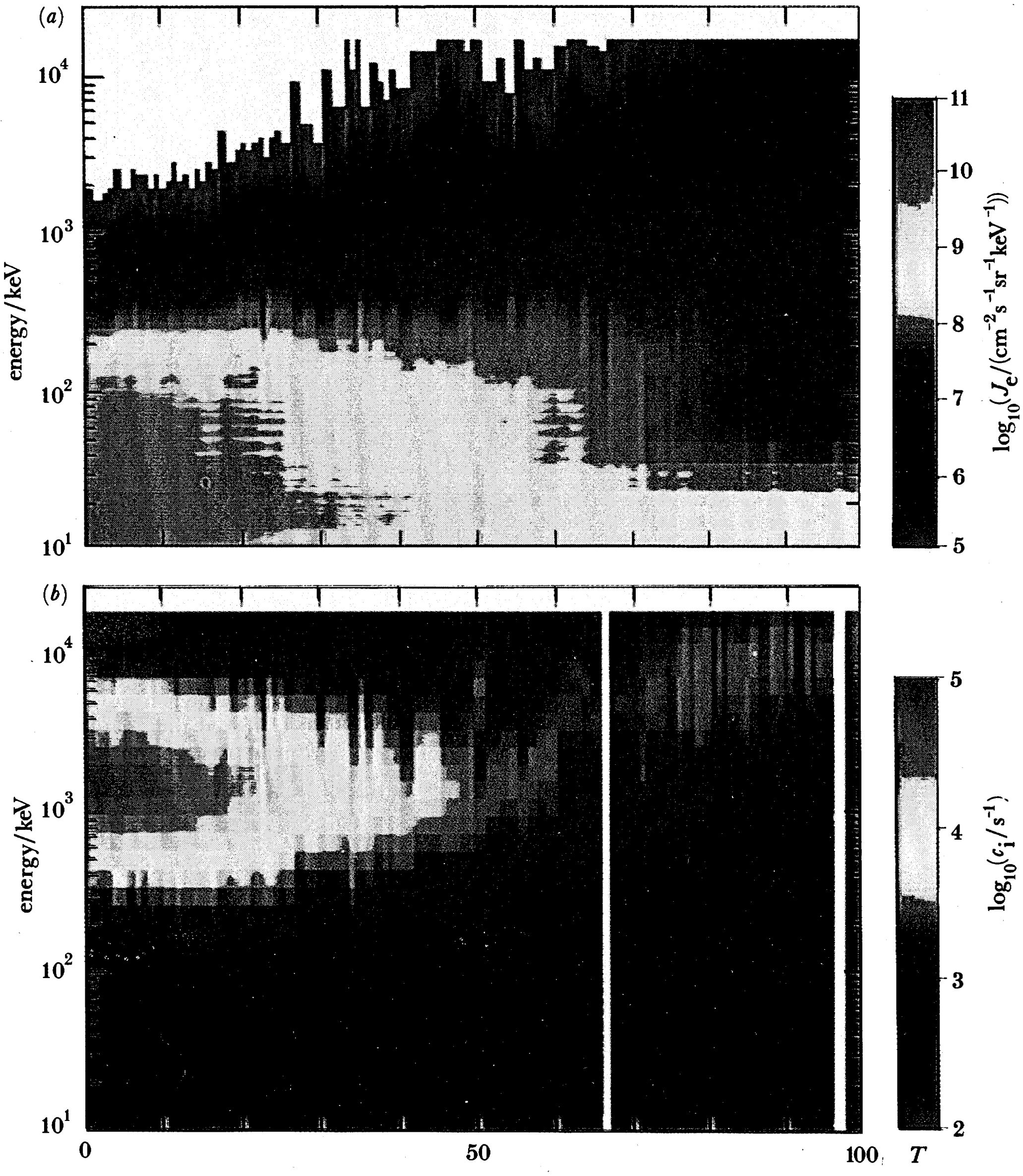

FIGURE 9. Transitions through the boundary layer between 06h40 and 11h30 U.T. on 6 December 1984 on orbit 61 for (*a*) electrons and (*b*) ions, reconstructed in terms of the derived transition parameter, *T*. Electron intensities and ion count rates are colour coded and shown as functions of energy in kiloelectronvolts. Other units are as in figure 2. In both cases the measurements represent one-minute averages including all directions of incidence.

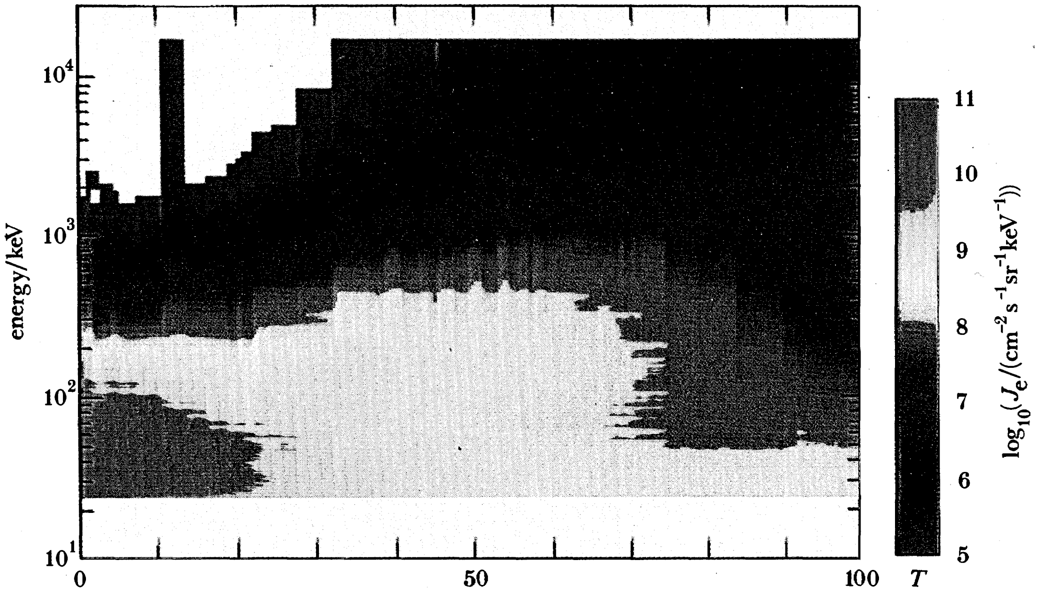

FIGURE 10. Transition of electron intensities through the boundary layer between 08h00 and 10h00 U.T. on 10 November 1984 on orbit 47, showing a particularly strong enhancement of intensity at energies 100–300 eV midway through the transition.

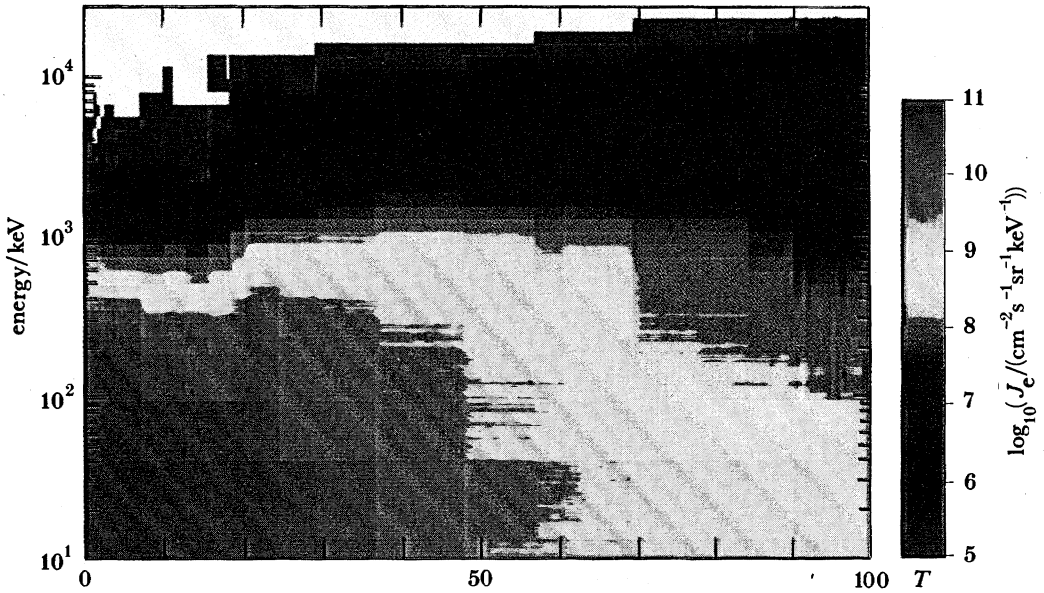

FIGURE 14. Transition of electron intensities as a function of energy in kiloelectronvolts during the excursion into FTE plasma between 10h43:00 and 10h47:20 U.T. on 28 October 1984. Other units are as in figure 2. There is a marked similarity to the much slower transitions across the boundary layer depicted in figures 9*a* and 10.

to the magnetosheath, or vice versa, varied from a few minutes to more than 4 h, the mean being 56 min (see figure 6). By comparing consecutive hourly means of the dynamic pressures encountered during the periods in the solar wind, and converting, by means of equation (1), pressure variations to variations in stand-off distance, for which the frequency distribution is shown in figure 7, we find that the expected rate of movement of the boundary had a root mean square (r.m.s.) value of 0.48 R_E h^{-1} (0.84 km s^{-1}). Now, the mean radial velocity of the spacecraft at boundary distances is known from the orbital dynamics to be typically 1.1 R_E h^{-1} (2 km s^{-1}). We can therefore obtain upper and lower estimates for the radial thickness of the boundary layer by assuming, on the one hand, that the spacecraft and boundary were always moving in the opposite direction (i.e. at a relative velocity of 1.58 R_E h^{-1}), and on the other, in the same direction (i.e. at 0.62 R_E h^{-1}). Taking the products of these relative velocities with the mean crossing time of 56 min, we find upper and lower limits of thickness of 1.5 and 0.6 R_E, and hence a best overall estimate of 1 R_E, in good accord with earlier estimates (see, for example, Hones *et al.* 1972; Eastman *et al.* 1976; Paschmann *et al.* 1976).

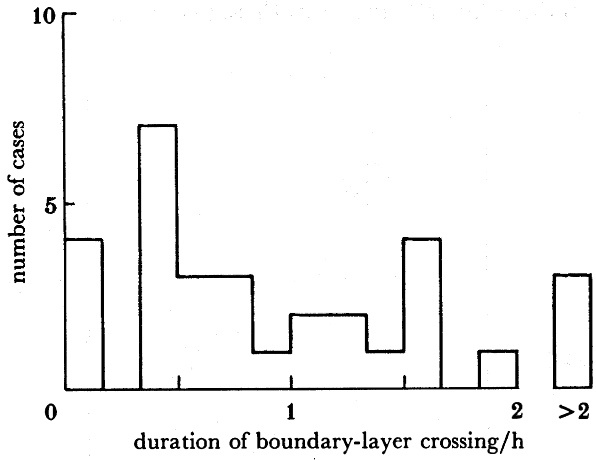

FIGURE 6. Frequency of occurrence of durations of boundary-layer crossings.

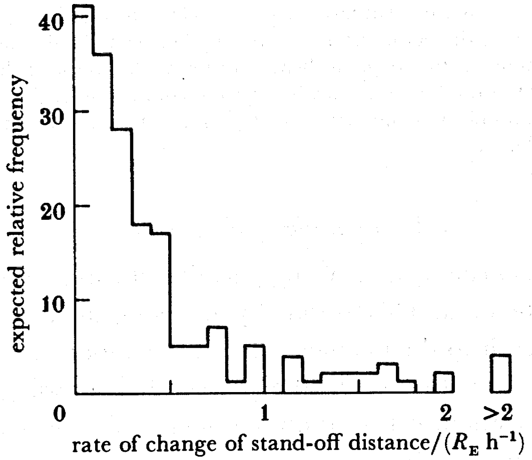

FIGURE 7. Frequency of occurrence of rates of change of boundary stand-off distance expected from observed hourly rates of change of solar-wind dynamic pressure.

We see from the above that the movement of the boundary is not negligible with respect to the spacecraft's velocity, even when hourly averages are used to estimate it. Shorter-term variations will be even faster, making a typical traverse through the boundary layer decidedly erratic, as indeed is found in practice, as we saw for example in figure 5.

How can we examine the transition across the moving boundary layer?

To reveal the transitions undergone by the electrons, ions and magnetic field across the layer, we attempt below to reconstruct an assumed orderly transition by using a very consistent and distinctive relation that we have noted between the mean electron energy over the observed range of 12 eV–25 keV (see Shah *et al.* 1985), deemed the 'temperature' T_e, and the (partial) electron number density, N_e, measured over the same range. We show in figure 8*a*, for the boundary crossing of 6 December 1984 in orbit 61, a scatter plot of one-minute evaluations of these quantities joined chronologically. There is clearly a great deal of oscillation backwards and forwards along a fairly well-defined track. If we remove the joining lines, we are left with a scatter plot (figure 8*b*) in which the low-temperature, high-density magnetosheath produces a cluster at the top left and the high-temperature, low-density magnetosphere congregates at the bottom right. The boundary layer traces a path between the two.

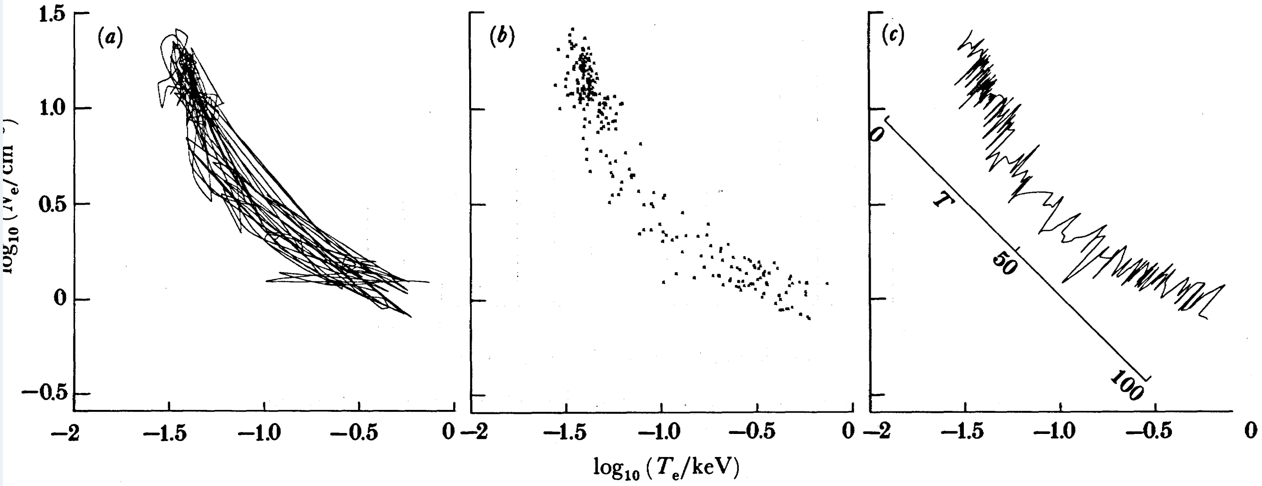

FIGURE 8. Relationship between one-minute values of (partial) electron density N_e and electron 'temperature' T_e (actually mean energy) during the boundary layer crossing between 06h40 and 11h30 U.T. on 6 December 1984 on orbit 61. Measurements in the magnetosheath cluster at the top left; those in the magnetosphere at the bottom right; while those in the boundary layer form the connecting region. (*a*) Successive values joined by straight lines. (*b*) Scatter plot of the same readings. (*c*) Joining of values reordered in terms of the transition parameter T, described in the text.

3.1. *Transition parameter T*

The strong correlation between T_e and N_e suggests that it can be used as the basis of a non-chronological ordering of the data. This is done by following the transition along the locus of points from the magnetosheath to the magnetosphere. We adopt as a working assumption, to be discussed further below, that the region the spacecraft is crossing remains monotonic in structure while varying in position. A transition parameter, T, was defined along a linear axis approximating the transition track by

$$T = 100(r_{\max} - r)/(r_{\max} - r_{\min}), \tag{2}$$

where $r = \log(N_e) - k \log(T_e)$. The axis of reordering was chosen as the straight line most closely representing the observed locus; the constant k being the gradient of this line. For this study we used $k = 1.0$.

The reordering using this scheme is shown by figure 8*c* to be very effective in providing a smooth, continuous transition. It should be said that the parameter chosen here to achieve the reordering is not the only possible one, nor is it necessarily the most effective; it is just one of a number of possible expedients the details of which have little effect on the final result. Bearing in mind our working assumption that the region the spacecraft is crossing remains monotonic in structure, we may use the transition parameter to reorder, not only the electron densities and temperatures, but also the full electron energy–time spectrograms, and indeed the ion spectrograms, magnetic measurements and wave measurements. We examine the results of this process and interpret them, initially, in terms of the simplest possible geometry. Other possibilities are discussed later.

3.2. *The electron transition*

The transition spectrogram of electron intensities shown in figure 9*a*, plate 2, is typical of the full set of crossings. The magnetosheath is to the left ($T = 0$), and the magnetosphere to the right ($T = 100$). The fact that the transition is smooth comes as no surprise of course, as this has been engineered. However, this does not detract from the possible validity of this most straightforward interpretation. It would seem that Nature has solved the problem of matching the extreme distributions in the most direct and elegant way. A net diffusion of lower-energy electrons to the right (inwards), and higher-energy electrons to the left (outwards) with the medium energies remaining balanced, would explain the overall appearance. The fact that density gradients prevail implies that there are also losses of electrons from the boundary region. The losses on these tubes of force, which connect to the ionosphere and atmosphere at auroral latitudes, represent one form of the solar-wind–atmosphere interaction.

A feature often present in most of the transition spectrograms – and almost invariably seen on inspection of electron measurements in the boundary layer using the full five-second resolution (D. S. Hall, personal communication, 1988) – is an increase of intensity at energies between 100 eV and 1 keV midway through the transition. A marked example, occurring on 10 November 1984 in orbit 47, is shown in figure 10, plate 3. Because diffusion is unable to create an enhancement, we must deduce that these electrons have been accelerated, and that the acceleration mechanism is energy, or velocity, dependent, i.e. that it is a resonant process. Furthermore, as we know that these accelerated electrons have their highest intensities along, and counter to, the magnetic vector (Chaloner *et al.* 1987), we can see that this resonant acceleration occurs preferentially parallel (and possibly antiparallel also) to the magnetic vector. If the electrons at the smallest pitch angles were to precipitate into the atmosphere without further change of energy the input power density would amount to a few milliwatts per square metre, i.e. enough to produce a visible aurora, though not a strong one which would demand more than ten times this power density. As pointed out by Chaloner *et al.* the details of the energy spectrum are indeed very similar to those observed precipitating into the atmosphere above the dayside aurora (McEwen 1977). One process which might, in principle, provide the acceleration is electrostatic wave turbulence in the lower-hybrid mode, a process suggested for resonant electron acceleration at the bow shock (Bryant *et al.* 1986; Bryant 1987), on auroral field lines (Bingham *et al.* 1984, 1988) and for the *AMPTE* ion-release experiments

(Hall *et al.* 1986; Rodgers *et al.* 1986). For the source of energy we turn to the ion distribution.

3.3. *The ion transition*

We may use the reordering of times deduced from the electrons to reorder the ions, and so construct the counterpart transition spectrogram for this species. The smooth transition which we find in the ions in figure 9*b*, plate 2, is not this time a necessary consequence of the analysis. Again, we can only admire the elegant way that the transition is effected; the main difference between these positive ions (protons) and electrons being due to the lower ratio of thermal- to drift-velocity for the ions. All crossings show a very similar pattern. Although the transition is not, in general, being traced along flow lines, there are strong indications of diffusion from both sides, driven by the intensity and density gradients at the different energies.

The ion drift velocity for 6 December is plotted against transition parameter T in figure 11*a*. The number-density transition is shown in (*b*). We see that the deeper the ions penetrate (from the left) the lower is their drift speed, reducing here from *ca.* 400 km s^{-1} to *ca.* 200 km s^{-1}. There is a suggestion that the speed increases again, to *ca.* 300 km s^{-1} in the innermost region, implying possibly a viscous-like interaction between the magnetosheath and magnetospheric plasmas. One of the many questions remaining to be answered is whether the reduction in ion

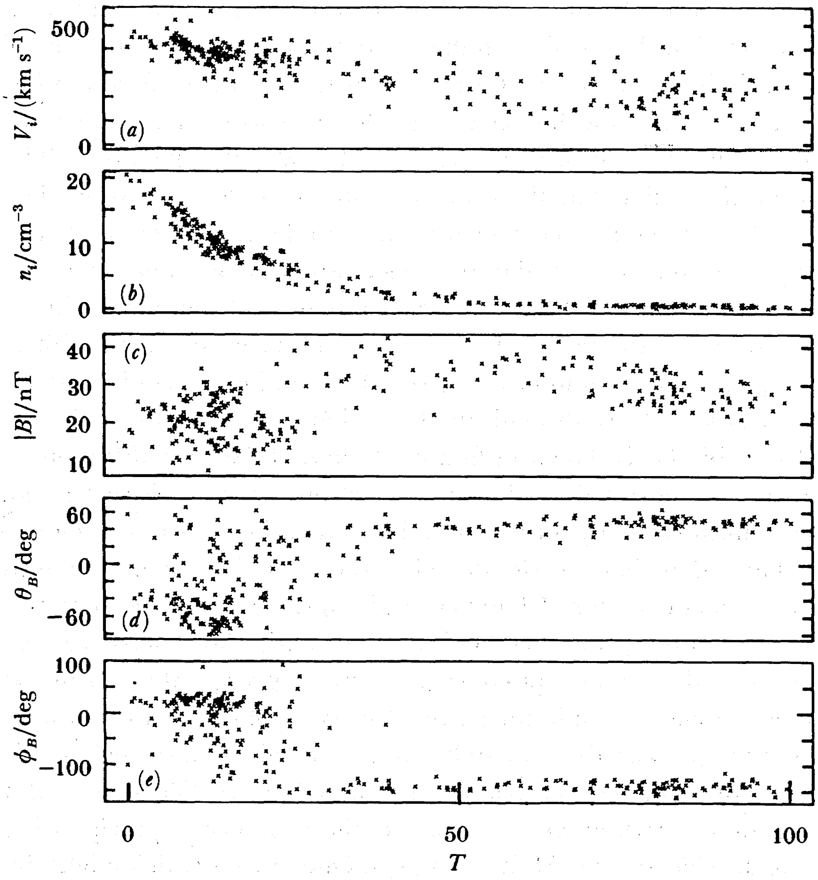

FIGURE 11. (*a*) Ion velocity and (*b*) number density; (*c*) magnetic field strength, (*d*) latitude and (*e*) longitude for the boundary crossing of 6 December 1984 on orbit 61, reordered in terms of the transition parameter, T. Note that the ion velocity and density have undergone a significant change before the main transition in the magnetic field, i.e. the magnetopause, is reached near $T = 25$.

speed may ultimately be the source of energy for the electron acceleration. The braking of an ion beam will certainly give rise to lower-hybrid waves which could be the agents for energy transfer to electrons (McBride *et al.* 1972). An estimate of the power density delivered to the boundary layer by the ions is 1 mW m^{-2}. Noting, however, that this may occur over the whole of the area subtended by the magnetosphere (of radius 14 R_E on this occasion) and that the electron power is delivered over only 1% of the Earth's surface, we find that the efficiency required for the mechanism of power transfer is only 1 in 10^4. A two-stage process is therefore not an unreasonable possibility.

If this resonant wave acceleration, which acts most strongly at energies in the region of the mean or thermal energy of a plasma, is found to operate here it will, at *ca.* 100 eV, provide a compelling 'missing link' between the other proposed sites of the bow shock, at *ca.* 10 eV, and the nightside aurora at 1–10 keV.

3.4. *Magnetic field transition*

The magnetic field transition for 6 December is shown in the lower three panels of figure 11. Moving from the left, we see that the magnitude and direction are at first highly variable, the latitude being primarily negative, i.e. opposed to the geomagnetic field. The magnitude increases sharply and the direction rapidly becomes less variable at $T = 25$. The magnitude reaches a maximum of 40 nT in the centre of the boundary layer defined by this analysis, which compares with an undisturbed, uncompressed dipole field at 14 R_E of 11 nT. (The factor-of-two enhancement mentioned earlier would not be a good approximation here, where neither the field outside, nor the plasma pressure inside, are negligible.)

We note that in this analysis the magnetic transition occurs earthward of the region where the electron and ion number densities, the ion velocity and other parameters have undergone significant change.

3.5. *Terminology*

The various regions discussed here in terms of their plasma characteristics and possible formative processes are well known, though, to our knowledge, have not been demonstrated before to be quite so consistent in structure. The layer over which the switch of the magnetic vector from negative to positive latitude and from low to high magnitude takes place is the magnetopause, or magnetopause current layer. The outermost part of the boundary layer, in which we see a diffusion of low-energy electrons inwards, has been termed, at these near-equatorial latitudes, the low-latitude boundary layer (LLBL) (Eastman *et al.* 1976). The innermost region, where we see a diffusion of higher-energy particles outwards, has been termed the halo (Sckopke *et al.* 1981). It seems, therefore, from the foregoing that the magnetopause is located within the boundary layer, roughly midway through the LLBL. This latter observation, which appears to cause some conflict among the definitions, will be further discussed below.

3.6. *Boundary deformation and penetration*

Until this point we have interpreted our findings in terms of the simplest possible configuration of the boundary layer, as illustrated schematically in figure 12*a*. There are, of course, other possibilities. A simple deformation of the boundary (figure 12*b*) is entirely possible, and might indeed be expected as the result of a Kelvin–Helmholtz instability for which the free energy is the velocity shear between the magnetosheath and magnetosphere (Dungey 1955). Our analysis would suggest, in agreement with the finding by Hall *et al.* (1985)

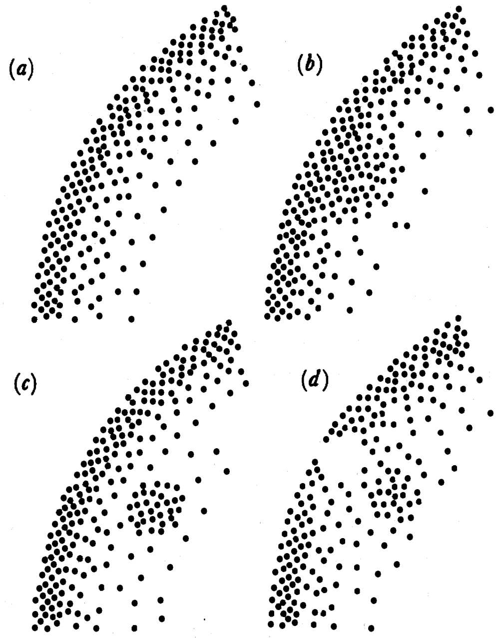

FIGURE 12. Schematic representation of possible topologies of the boundary layer. (*a*) Simplest geometry. (*b*) Undulating surface. (*c*) Penetration by a cloud of the outer (magnetosheath) plasma. (*d*) Interpenetration in an FTE.

that, if this occurs, the corrugated or undulating boundary layer thus formed is qualitatively similar, following the same sequence of densities and temperatures, wherever the transition is observed.

Another possibility (figure 12*c*) is that a cloud of magnetosheath plasma penetrates into the boundary layer, or magnetosphere, as an isolated region. Such has indeed been proposed by Lemaire & Roth (1978) as the essence of a dynamo for an auroral-particle acceleration model. The idea has been further developed by Lundin & Dubinin (1985) as the basis of a dynamo for auroral-zone field-aligned currents. Again, our results would not deny such a possibility; they would only suggest that, if it does occur, the transition sequence between the cloud and its surroundings is similar to that across other sections of the boundary layer.

Another process that has been invoked, and which might, when observed, appear to be very similar to a penetrating cloud, is the flux transfer event (FTE) (Russell & Elphic 1978). Such events are, however, manifestations of something very different, as depicted in figure 12*d*, in which a magnetic connection is formed between solar-wind and terrestrial magnetic-flux tubes, at the site of which magnetosheath plasma is accelerated by magnetic tension and is allowed to flow, rather than diffuse, into the magnetosphere. By the same token magnetospheric plasma flows outward into the magnetosheath. One such event showing many of the expected symptoms occurred at the *UKS* spacecraft on 28 October 1984 on the outward leg of orbit 40 (Farrugia *et al.* 1989). It took place within just over 4 min, so it would be unlikely to have been revealed, however different it might have been from the usual slower transition, by our analysis of this orbit by using one-minute values. We have, though, performed the analysis described in §3 for the electrons using the full five-second resolution that is available. In figure 13 the background of points gives, as before, the locus traced by repeated transitions and partial transitions from the magnetosheath and magnetosphere made between 09h15 and 14h00 U.T.

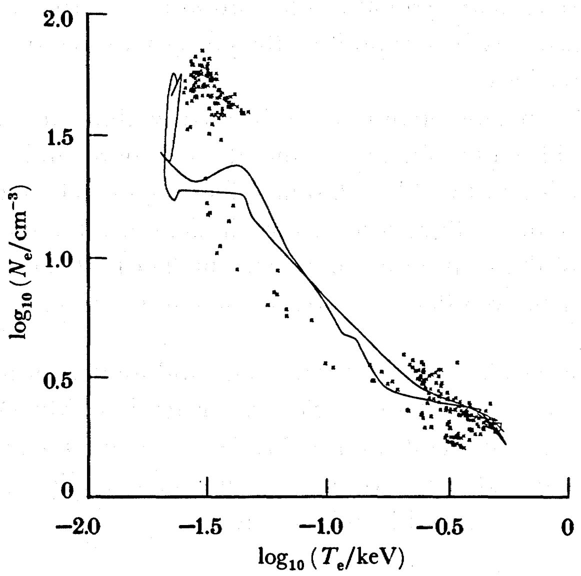

FIGURE 13. Relation between electron density and electron temperature, during the excursion from the magnetosphere into the candidate FTE of 10h43:00 to 10h47:20 U.T. on 28 October 1984 on the outward leg of orbit 40 (continuous lines), with the boundary layer crossing between 09h15 and 14h00 U.T. as a background (crosses) for comparison. The similarity of the end points of the two loci suggests that the excursion could be understood as being the result of a brief change of position of a simple boundary such as that depicted in figure 12*a*, *b*, rather than necessarily indicating an encounter with a more complex topology such as those of figure 12*c*, *d*.

The excursion from the magnetosphere into the FTE plasma and back again, made between 10h43:00 and 10h47:20 U.T., is traced by the continuous lines. It is clear that, although the routes taken in crossing the boundary layer and in making the excursion into the FTE are different, the end points are very closely the same. The electron transition spectrogram for the excursion, shown in figure 14, plate 3, has the same general characteristics as those of figure 9*a* and figure 10. It appears, therefore, on this evidence, that the excursion could be understood as the result of a rapid oscillation of the stand-off distance of the boundary layer. The speed of movement required, say, 1 R_E in 2 min (i.e. 50 km s^{-1}) is well below the Alfvén speed which would be the most immediate limitation.

A full and unambiguous resolution of such questions of underlying geometry must await the four-point measurements to be performed in the mid-1990s by the four spacecraft of the Cluster mission within the European Space Agency's Horizon 2000 programme (Longdon 1984).

4. CONCLUSIONS

The main conclusion from this brief survey and preliminary study is that the interaction between solar and terrestrial plasmas takes place generally through a diffuse boundary layer across which the properties of the two plasmas gradually merge. This is as the interaction was first interpreted by Hones *et al.* (1972) and Eastman *et al.* (1976). We find that the boundary layer encompasses and contains the regions known as the low-latitude boundary layer and the Halo. Diffusion, viscosity and loss into the atmosphere at auroral latitudes appear to be the governing processes. However, this is clearly not the whole story; the region is well understood to be a highly complex one, as demonstrated in the recent review by Lundin (1987).

A magnetic-field-aligned velocity-resonant acceleration of electrons also occurs, for which electrostatic wave turbulence may be responsible, the power required deriving one step earlier in the braking of solar-wind ions.

The indication that the magnetopause is embedded within the boundary layer is a preliminary result which will require further examination. It needs to be shown, for example, whether the changes occurring in the solar plasma before the magnetopause is reached might be explained as a false ordering of fluctuations. First indications, though, from the clustering of points, the smoothness of the transitions, and from the fact that there is also a gradient in ion-flow direction, are that the reordering represents a genuine transition.

We are much indebted to Dr B. R. Read, for devising and implementing the *AMPTE-UKS* database on which this survey was based. We are grateful to Mr D. S. Hall for helpful discussions of the electron measurements and to Mr D. R. Lepine for his contribution to the analysis. Dr A. D. Johnstone and Professor D. J. Southwood kindly agreed to the ion and magnetic measurements being included in this survey.

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Discussion

M. Saunders (*Imperial College, London, U.K.*). Previous studies of the magnetopause boundary layer have shown that its structure depends on the direction of the magnetosheath magnetic field. Has Dr Bryant examined the effect of this parameter on the electron observations he reported?

D. A. Bryant. We have not yet done this. However, we have established that the transition sequence was the same on all crossings, in which there was a 2:1 mixture of southward- and northward-directed magnetosheath fields, as Dr Saunders and his co-authors have shown. It appears, therefore, that the type of structure does not depend significantly on field direction.

B. Hultqvist (*Swedish Institute of Space Physics, Kiruna, Sweden*). By organizing the data according to the transition parameter you may organize 'away' the irregularities in the boundary layer. We have clear indications from the *Prognoz* 7 spacecraft that the irregularities seen in the boundary layer are real irregularities and not caused by the spacecraft returning into the magnetosheath by the motion of the magnetopause. We could therefore conclude that the irregularities in the boundary layer contain ionospheric ions which are not seen in the magnetosheath.

D. A. Bryant. We believe that we can deduce from the systematic relation between the electron density and temperature, and other bulk parameters, and from the consistent appearance of the electron and ion transition spectrograms that, whatever the topology of the boundary, the transition sequence is the same. This result is perfectly consistent with a complex geometry such as the one Professor Hultqvist describes, and which is depicted in figure 12*c*. We cannot, however, avoid being drawn towards the most straightforward picture, i.e. figure 12*a* or perhaps figure 12*b*, that is consistent with all known facts. We would certainly expect ionospheric ions that have become magnetospheric ones to diffuse throughout the whole boundary layer which we see as a diffuse region of merging between magnetosheath and magnetospheric plasmas.

S. Schwartz (*Queen Mary College, London, U.K.*). The thickness found for the boundary layer, particularly that part of it where the density changes the most, is *ca.* 500 km and comparable with the local gyroscales. It is not obvious, therefore, that it needs a 'diffusive' process to account for variations on these kinetic scales.

D. A. Bryant. I believe that the gyroradius is considerably less than 500 km, even for the protons, in which case some form of diffusion will indeed be required. I agree, though, that it is a point that needs to be considered. (A subsequent check confirmed that the gyroradius of a 1 keV proton in a 40 nT field, is 115 km, i.e. only 2 % of the estimated width of the boundary layer.)

S. W. H. Cowley (*Imperial College, London, U.K.*). If the plasma density depletion occurs mainly outside the magnetopause, as Dr Bryant's observations appear to show, could a 'depletion effect' of the type originally described by Zwan & Wolf (1976) be contributing? If so, the depletion would be caused by compression of the magnetosheath plasma against the magnetopause and subsequent flow along the field lines away from this region, rather than by spatial diffusion.

D. A. Bryant. That is certainly a possibility. If we are able to confirm, after further analysis, that the depletion outside the magnetopause is real, and not an artefact of an ordering of fluctuations in the magnetosheath, the results would represent clear experimental evidence of just such an effect.

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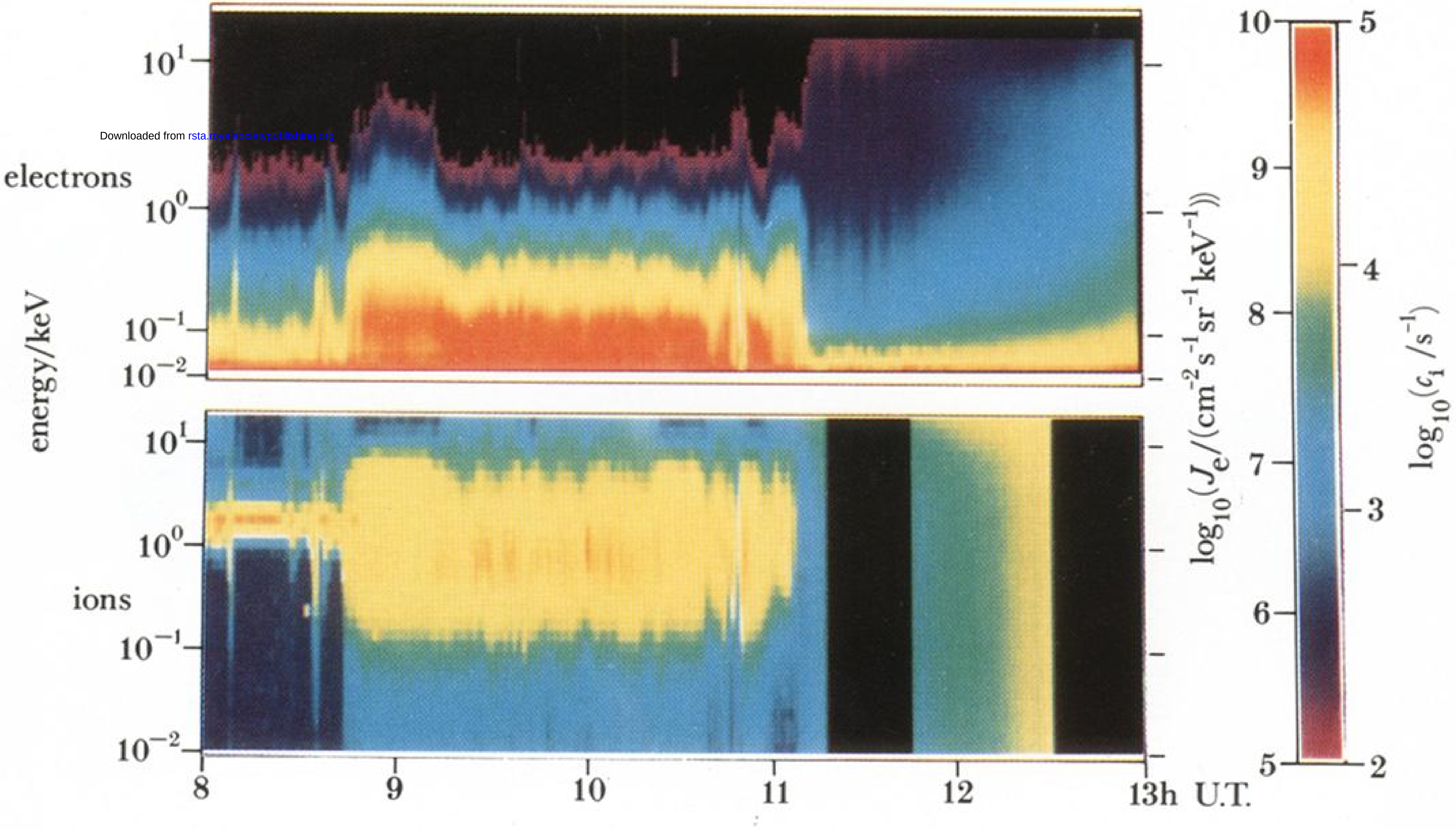
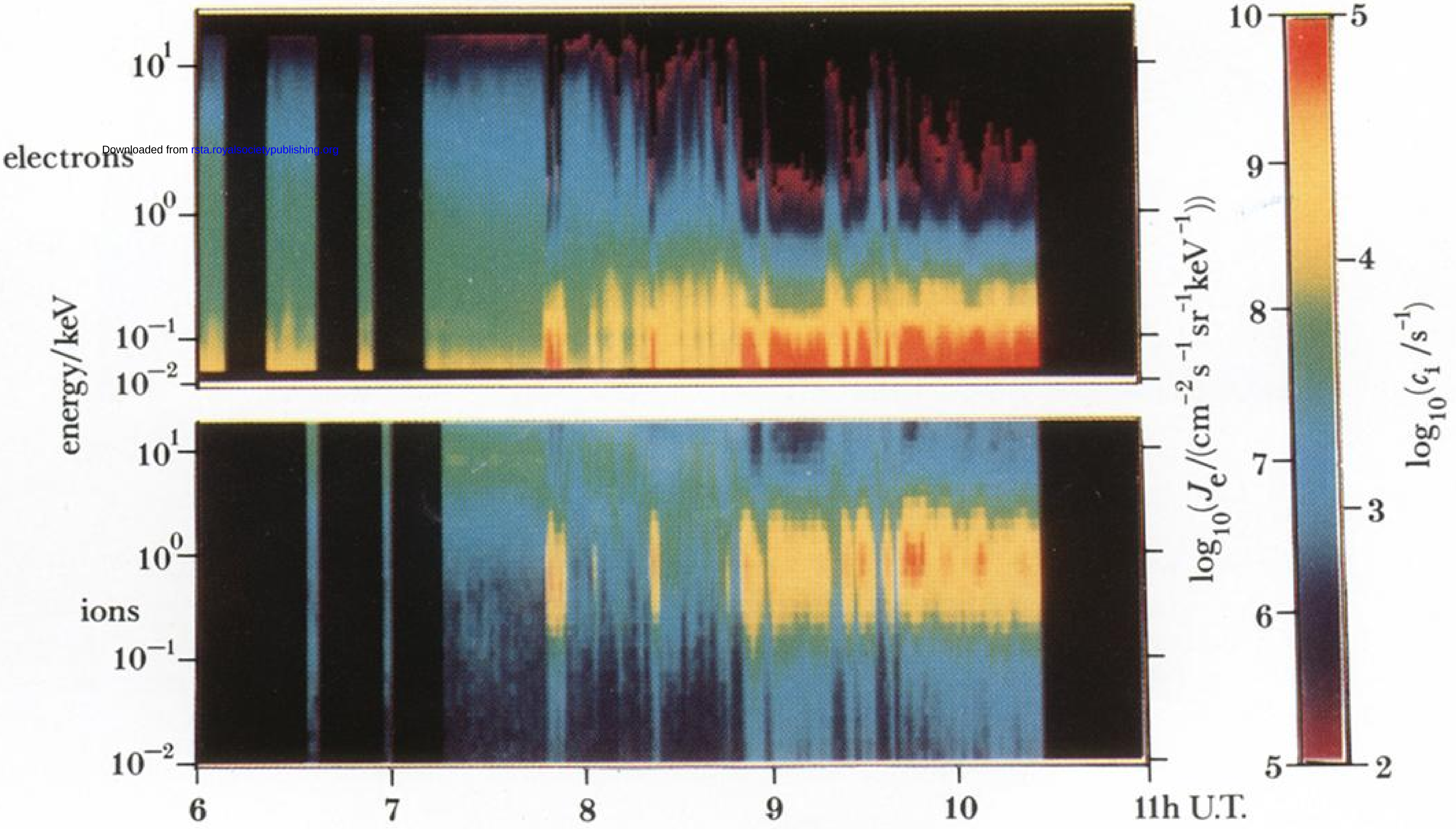
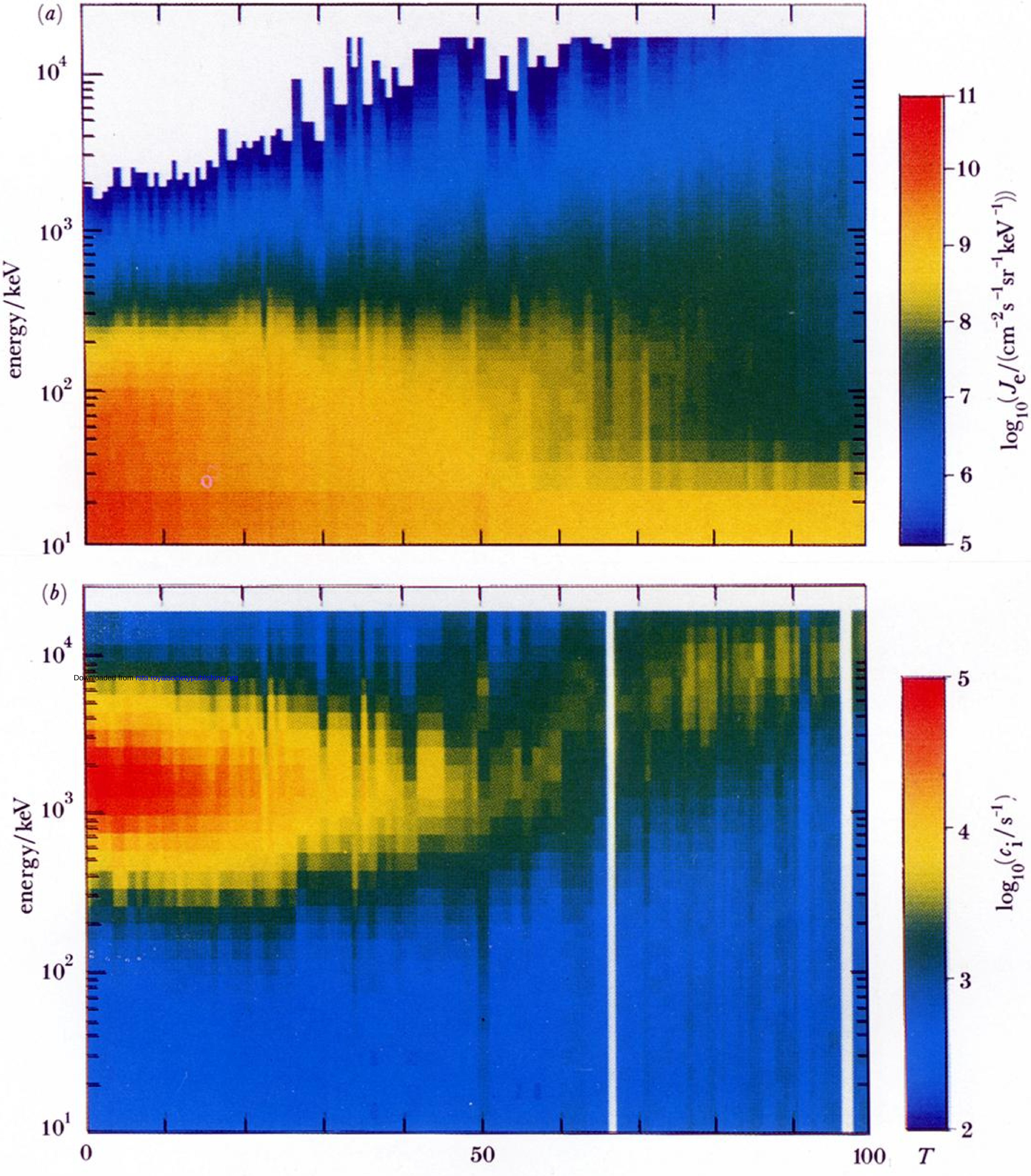


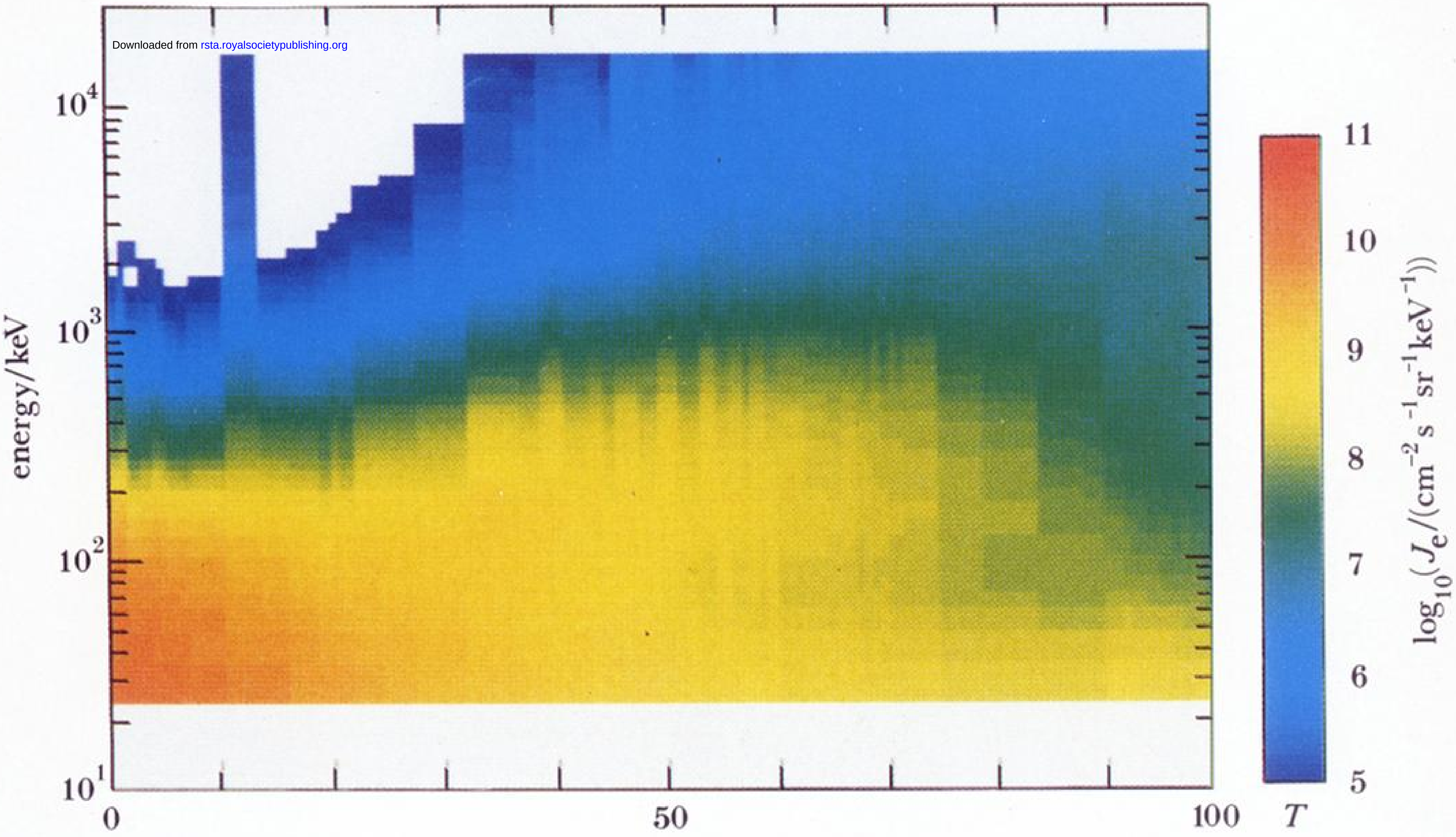
IGURE 2. Electron intensities, J_e, and ion count rates, c_i, (the latter proportional to intensity times energy) on 4 November 1984 on the inward leg of orbit 43. Intensities and count rates are colour coded and are shown as functions of energy. The adjoining scale gives the logarithms of the electron intensity and the ion count rate. The spacecraft was in the solar wind until 08h40 U.T., when it crossed the bow shock into the magnetosheath. The crossing of the boundary between solar and terrestrial plasmas was made at around 11h05 U.T.



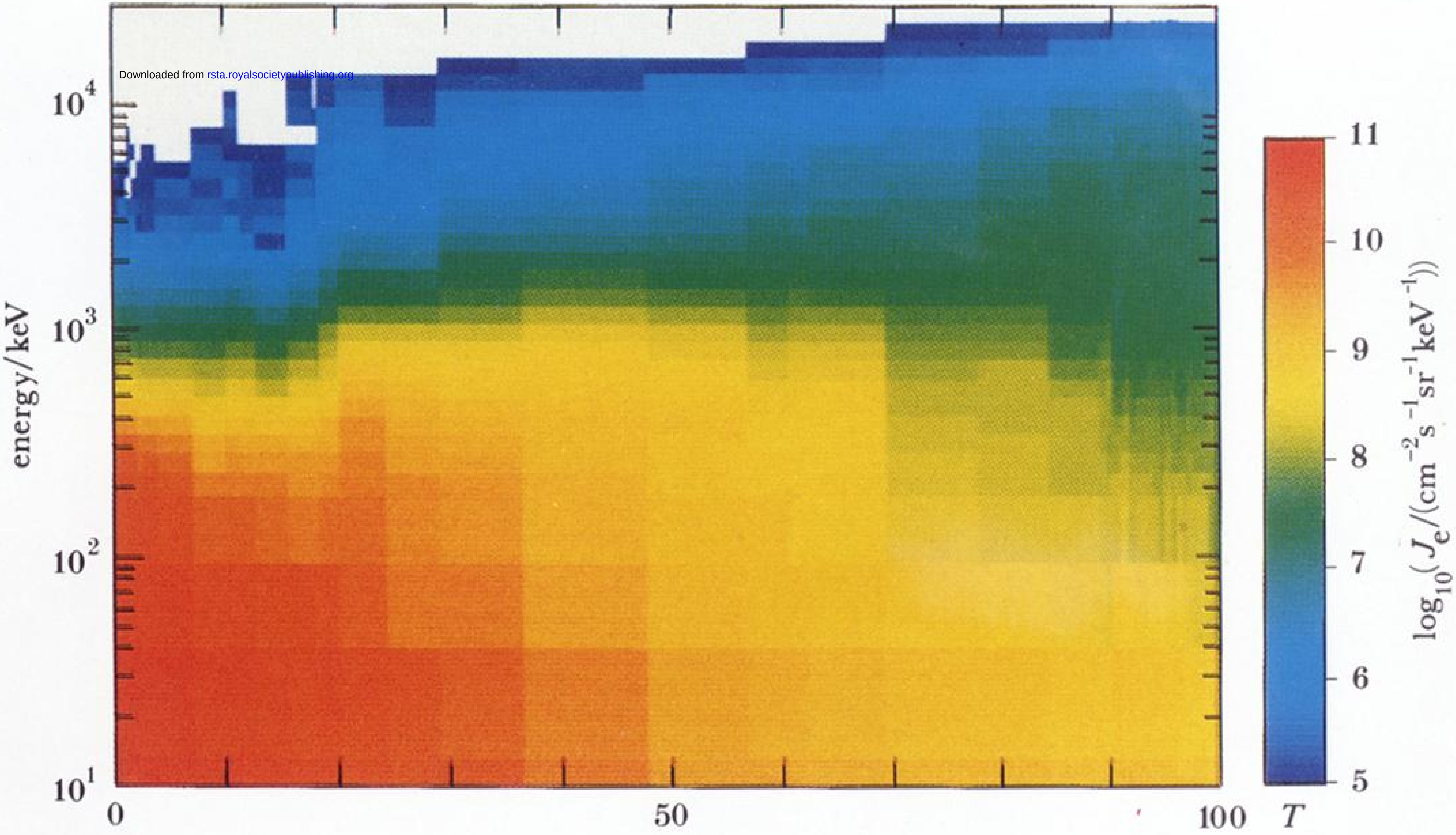
GURE 5. Electron intensities, J_e, and ion count rates, c_i, on 23 November 1984 outward leg or orbit 54. Intensities and count rates are colour coded and are shown as functions of energy. The crossing from magnetosphere to the magnetosheath (between 07h55 and 09h45 U.T.) was both prolonged and erratic, demonstrating the existence of a substantial and moving boundary layer. The three stretches of data beginning at 06h00 U.T. represent a 'real time' search for the boundary layer while conserving power to explore the layer as fully as possible when it was reached.



IGURE 9. Transitions through the boundary layer between 06h40 and 11h30 U.T. on 6 December 1984 on orbit 61 for (*a*) electrons and (*b*) ions, reconstructed in terms of the derived transition parameter, *T*. Electron intensities and ion count rates are colour coded and shown as functions of energy in kiloelectronvolts. Other units are as in figure 2. In both cases the measurements represent one-minute averages including all directions of incidence.



GURE 10. Transition of electron intensities through the boundary layer between 08h00 and 10h00 U.T. on 10 November 1984 on orbit 47, showing a particularly strong enhancement of intensity at energies 100–300 eV midway through the transition.



IGURE 14. Transition of electron intensities as a function of energy in kiloelectronvolts during the excursion into FTE plasma between 10h43:00 and 10h47:20 U.T. on 28 October 1984. Other units are as in figure 2. There is a marked similarity to the much slower transitions across the boundary layer depicted in figures 9*a* and 10.