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Magnetospheric plasmas

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The magnetosphere contains plasma with a proton temperature of tens of kiloelectronvolts (or hundreds of megakelvins). The protons are believed to drive two instabilities, one involving cyclotron resonance and the other the Alfvèn mode. Although population inversion has been observed, it is not theoretically necessary for either instability. The protons are heated in two stages, the second being compression. Three mechanisms contribute to the first stage, all of them associated with field-aligned currents, but their relative importance has not been established. Field-aligned proton beams are observed, some travelling upwards, some downwards. Electrostatic noise near the proton gyrofrequency is strong and observations of proton velocity distributions sometimes indicate cyclotron heating.

1. ORDERS OF MAGNITUDE

If the magnetosphere is compared with laboratory plasmas by scaling, the only major difference is that collisions are less important in the magnetosphere by a factor of millions. The plasma is not in thermal equilibrium, the concept of 'temperature' can be used only loosely and many of the particles are trapped by the mirror mechanism. In some regions it is useful to think in terms of superposition of two populations of either ions or electrons at very different temperatures. The spatial distribution is complicated and will not be described in detail. In general, the mass of the plasma is dominated by a population that is in rough equilibrium with the ionosphere; consequently it has a temperature of less than 1 eV. By contrast, the 'thermal' energy is dominated by protons of temperature greater than 10 KeV, which seems appropriate to this meeting. These protons are commonly called 'ring-current protons', a name which relates them to the early discoveries about magnetic storms, which can now be explained by elementary plasma theory. In the main phase of a storm, the disturbance can be described as a weakening of the field at all but very high latitudes, and could be due to a ring of westward current surrounding the Earth. The effect of a trapped plasma can be deduced either in terms of single-particle trajectories or from pressure balance. The latter approach immediately shows that the field is weakened in the region occupied by the plasma, but it is also easily seen that the field inside the ring in the equatorial plane is weakened. The contribution of any plasma population to this weakening turns out to be simply proportional to the energy of that population, and the contribution of the hot protons dominates. They are a permanent feature and magnetic storms are due to their enhancement. If it is accepted that the temperature in the magnetosphere is the same as that in laboratory plasmas, a simple account can be given of the scaling between them. While the magnetic field strength and the electron density both vary considerably, the Alfvèn speed varies less and at *ca.* 10^6 m/s is again the same as some laboratory values. The value of the ratio β of plasma to magnetic pressure is related to the Alfvèn speed and is of particular interest, but needs more accurate estimation. Here we are concerned with factors of millions: the scale of the magnetosphere is ten times that of the earth, giving 6×10^7 m, and suggesting a scaling factor of 10^7. Now since the characteristic speeds (thermal and Alfvèn) are

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the same, times should scale by 10^7 or frequencies by 10^{-7}. If gyrofrequencies scale this way, the field strength B should scale by 10^{-7} and indeed in the ring current region B is of the order of 10^{-7} T. Since n/B^2 is unchanged, n scales by 10^{-14} and the plasma frequency by 10^{-7} as desired. Scaling of collisions depends on the assumption that the cross section is unchanged, because it depends mainly on temperature, and then the collision frequency is proportional to n and scales by 10^{-14}. Thus the ratio of the collision frequency to any other frequency is reduced by a factor of ten million.

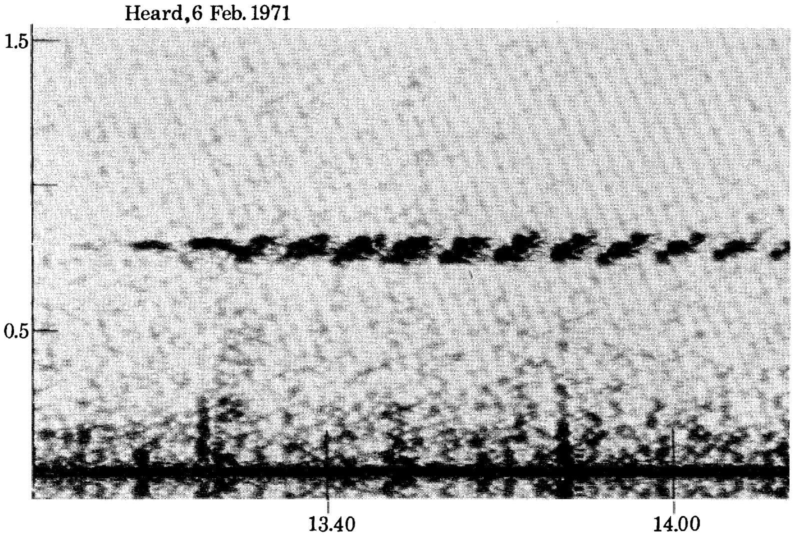

FIGURE 1. Dynamic spectrum observed on the ground. (From R. Gendrin 1973 *J. geophys. Res.* **78**, 763.)

2. INSTABILITY DRIVEN BY CYCLOTRON RESONANCE

Much of the interest in magnetospheric physics concerns wave particle interactions, whose importance is enhanced by the rarity of collisions. For instance, the lifetime for trapping is controlled by wave particle interactions. The well known quasilinear theory provides a good start towards theoretical understanding, and has many applications in the magnetosphere and can be tested therein. Particle distribution functions are measured as well as field perturbations and the theoretical problem can be divided into two questions: how is the noise produced and how does the noise affect the particle distribution? In quasilinear theory, both answers involve resonance between waves and particles. With regard to the amplification of waves in general it may be noted that population inversion is not necessary, though obviously it helps. Population inversion is sometimes observed and is not unexpected. Transient events may set up strong east–west gradients in the proton distribution, and subsequently the drift due to non-uniformity of the magnetic field changes the distribution, because the drift speed is proportional to energy. At some other longitude the higher energy particles arrive first and the drift tends to set up an inverted population. This process competes with wave particle interactions and sometimes wins.

The cyclotron resonant instability in mirror machines is well known. The waves are typically left-handed, circularly polarized at a frequency of a fraction of the cyclotron frequency, and such waves are a notable feature in the magnetosphere, if the cyclotron frequency is determined at the equatorial point on the field line through the point of observation. Resonance occurs for particles that see the frequency Doppler shifted up to the cyclotron frequency, so such particles

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must be moving in the opposite direction to the wave. It then follows that diffusion to smaller pitch angles implies diffusion to lower energy, so that a loss cone distribution of protons loses energy and amplifies the waves. The amplification is sensitive to the distribution, but another crucial factor must be mentioned. Kennel & Petschek (1966) pointed out that amplification has to compete with loss on reflexion at the ionosphere. The system should then adjust quite quickly to the situation where amplification balances reflexion loss and diffusion balances the combination of particle loss and the influx of particles due to drift motions. Pulsations corresponding to these waves have long been observed on the ground, and an example of a dynamic spectrum is shown in figure 1.

It was soon recognized that their propagation through the ionosphere was complicated, particularly due to the possibility of ducting by the ionosphere (Greifinger & Greifinger 1968). The dynamic spectra show a fine structure, as in figure 1, which can only be due to nonlinear effects. Observations on spacecraft have complicated the picture. They rarely show the same fine structure, though high coherence may be found over parts of the frequency band. It has been suggested that penetration of the ionosphere requires a duct consisting of a magnetic tube of excess plasma density. The waves from such a duct would be detected over a wide area of ground, but the ducts would occupy only a small fraction of the magnetosphere and a spacecraft would rarely pass through one (Gendrin *et al.* 1978).

The coefficient for pitch angle diffusion can be obtained from the magnetic spectral function simply by multiplying by the square of the charge : mass ratio. For protons, 10^{-18} T^2/Hz, which is observed in strong events, gives 5×10^{-3} rad/s. This demonstrates that the effect on the particle distribution is strong. Low altitude observations of protons generally show quite a high rate of precipitation, but this has yet to be related to pulsations.

3. The Alfvèn mode and its excitation by bounce resonance

It is necessary now to outline some further general features of the magnetosphere. Alfvèn waves can be guided along field lines, if their perpendicular wavelengths are short. These waves are reflected at the ionosphere and a field line can be viewed as a one-dimensional resonator. The reflexion involves some complications, but magnetic perturbations occur at ground level with comparable amplitude, if the perpendicular wavelength is not too short – less than 100 km – which leads to substantial attenuation (Hughes & Southwood 1976). The reflexion coefficient is higher on the day side than the night side and the nature of the pulsations observed depends on local time. It should be noted that local time is a more convenient coordinate than longitude. The 'ring current' is observed to be asymmetric and the hot protons have maximum temperature and density around dusk.

The interest here is in pulsations observed on geostationary space-craft with periods in the range 20–100 s. Hughes *et al.* (1978) used three spacecraft, so that east–west comparisons were possible. One of the spacecraft was moving slowly from one station to another and passed one of the other spacecraft, so that the east–west separation varied. Observations on the ground show that pulsations tend to be transient at night and narrow-band by day, but the inter-spacecraft comparisons revealed an additional difference between morning and afternoon. Morning pulsations show high coherence between spacecraft and small, but systematic, phase differences. These will not be pursued here, but they are useful in providing a standard of coherence, because the feature to be emphasized in the afternoon pulsations is their low coherence.

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The closest approach of two spacecraft occurred in local afternoon and high coherence was observed only while the separation in longitude was less than half a degree, so that the coherence length is less than one degree. One would not expect to observe this type of pulsation on the ground. The afternoon pulsations are also characterized by polarization with the magnetic disturbance mainly in the radial direction, and the amplitude ranges up to values corresponding to a tilt of the field line through several degrees. Their properties are appropriate for excitation by the hot protons via bounce resonance (Southwood *et al.* 1969). Analogously to gyroresonance, where the energy diffusion is dependent on pitch angle diffusion, for bounce resonance the energy diffusion is dependent on spatial diffusion across magnetic shells. Consequently the instability can in principle be driven by a spatial gradient without needing population inversion.

Both instabilities seem to be driven by the hot protons, which maximize around dusk, and both are affected by ionospheric reflexion, which deteriorates after dusk. Troitskaya *et al.* (1979) have begun to investigate correlations between them and established that they often occur together. It must now be noted that protons drift westwards owing to non-uniformity of the magnetic field, though for low energies, less than *ca.* 5 keV, the rotation of the earth overcomes this drift. The protons of higher energy drift from afternoon towards morning and it is plausible that the quasilinear effects of the two instabilities deplete the morning population as observed. The replenishment of the protons on the night side is discussed in the remaining sections.

4. ORIGIN OF THE HOT PROTONS

It is commonly believed that there is usually a dawn-to-dusk electric field in the equatorial magnetosphere with a total potential of tens of kilovolts, rising at disturbed times, known as 'substorms', to more than 100 kV. This was first deduced from magnetic measurements on the ground and confirmed by direct electric measurements on low altitude spacecraft, but only recently confirmed at great distances (Mozer *et al.* 1978). It is important here that the potential is comparable with the energy of a hot proton. Observations of both protons and electrons have been used to test simple models of the electric field (Kivelson & Southwood 1975) and the effect of sudden enhancements associated with substorms. Temporal variations and the associated diffusion will not be pursued here.

The drift due to a dawn-to-dusk electric field is towards the Sun. On the night side protons and electrons move in towards the Earth and gain energy. This can be seen to arise from their east–west drifts in a westward electric field or from conservation of the first two adiabatic invariants. Thus by tracing backwards, the hot protons come from a plasma with a temperature of a few kiloelectronvolts in a region called the 'plasma sheet' on the night side. In the plasma sheet, the field lines are stretched out by comparison to the dipole field and the field strength is a few tens of nanoteslas, so that the adiabatic invariants agree with the energy gain by an order of magnitude. Also $\beta \approx 1$. It should be noted that hot protons come out of the magnetosphere, and are noticeable quite far away (Williams 1979). While the plasma sheet is clearly a source of hot plasma, its own origin is much more complicated and is under intense investigation; it will now be discussed.

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5. The origin of the plasma sheet

The plasma sheet has a sharp outer boundary, which is approximately field aligned, on field lines connecting to the auroral zones. Outside there are the 'lobes' of the tail, of very low plasma density, which were the best vacuum known to man until Voyager entered the tail of Jupiter. A notable jump in β at the surface indicates the high β of the plasma sheet, but the density is still low and the jump is mainly in temperature. The dawn-to-dusk electric field is believed to extend throughout the plasma sheet and lobes, so that the plasma flows into the surface and is suddenly heated, but there are complications. Just inside the plasma sheet protons are observed flowing nearly parallel to the surface, showing the existence of another mechanism for increasing the temperature, which should also increase the density. If the flow were everywhere normal to B, the density should decrease like $|B|$. Average values suggest a moderate increase in density, but I am not aware of any measurements of the jump that would indicate the relative importance of the two kinds of heating mechanism. It should also be noted that observations of the boundary are usually obtained when the boundary is moving and its motion is often associated with substorms. It is convenient to discuss first protons flowing parallel to $\boldsymbol{B}$ and towards Earth.

The flow layer has been observed by several instruments, and De Coster & Frank (1979) obtained distribution functions showing the form of a 'mushroom cap', that is there was a bigger spread in $v_\perp$ than in $v_\parallel$. They suggested that the beams were accelerated by a parallel electric field, but they can alternatively be explained by the 'sling-shot' mechanism (Cowley 1980). The field lines of the plasma sheet are stretched out, sometimes beyond the moon, and magnetic observations show a sharp change of direction, showing that each field line is like the stretched elastic of a catapult. The field strength in the kink is weak, particularly for the outermost lines, which lie in the surface layer. The drift due to the dawn-to-dusk electric field is therefore large: Cowley estimates hundreds of kilometres per second compared to *ca.* 10 km/s in the lobes. For protons, the guiding-centre approximation breaks down at the magnetic kink, and a proton coming from the lobe at low speed leaves the kink with a speed of approximately twice the value of E/B in the kink, consistent with the observed flows. The values mentioned indicate that the flow layer should be inclined to the direction of $\boldsymbol{B}$ by a degree or so. Most of the protons will mirror near the Earth and the region of their return may show double streaming or simply high temperature. Cowley assumes the flow layer inner boundary to be defined by the return region. He obtains consistent estimates and also discusses the excess of parallel pressure in the plasma sheet. It seems that the kink instability might be stabilized by a kink, as explained by Cowley (1978).

Before discussing outward beams, we need another feature of the boundary layer. Thin layers of field-aligned current are very clearly demonstrated by east–west deviations of the direction of $\boldsymbol{B}$. The generator for these currents is presumed to be in the neutral sheet, but is outside the scope of this paper. Auroral arcs are associated with upward current, and velocity distributions for auroral electrons are shown in figure 2. Noise in the boundary layer, yet to be discussed, seems to cause significant anomalous resistivity and hence parallel electric fields. These can be deduced from measurements of $\boldsymbol{E}_\perp$, by assuming $\nabla \wedge \boldsymbol{E} = 0$ (Mozer *et al.* 1977). This is confirmed by the observation (Mizera & Fennell 1977), at altitudes of a few Earth radii, of upward flowing positive ions of a few kiloelectronvolts. There are too few to be the major source of the plasma sheet, but they might be the major source of the oxygen-ion component.

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Strong electrostatic noise is observed in a layer surrounding the field-aligned currents, and a spectrum is shown in figure 3. Caution is necessary because wavelengths may be short enough for Doppler shifting to be important, but the noise seems to be strong at and above the proton gyrofrequency. Independent observations (Lysak *et al.* 1980) of similar noise show narrow band features. On a crude basis 10^{-6} (V/m)^2/Hz gives a heating rate of 100 eV/s. If the layer is 1000 km thick, a proton drifting at 10 km/s takes 100 s to pass through and the temperature could rise to 10 keV. Thus the mechanism looks important and the power that would be extracted agrees in order of magnitude with a driving potential of a few kiloelectronvolts. Presumably the noise derives its energy directly from the electrons and contributes to the diffusion exhibited in figure 2. It must be noted that the noise is polarized mainly perpendicular to $\boldsymbol{B}$, so that the heating is mainly in $T_\perp$. Recently (Kintner *et al.* 1979) velocity distributions have been found which suggest that such a mechanism operates at low altitudes. Figure 4 shows a distribution peaking at a pitch angle of *ca.* 110° for several different velocities. This would result from perpendicular heating in a region where B was 11 % larger. In much weaker B the pitch angle would be small and this population would have $p_\parallel > p_\perp$, like that arising from beams.

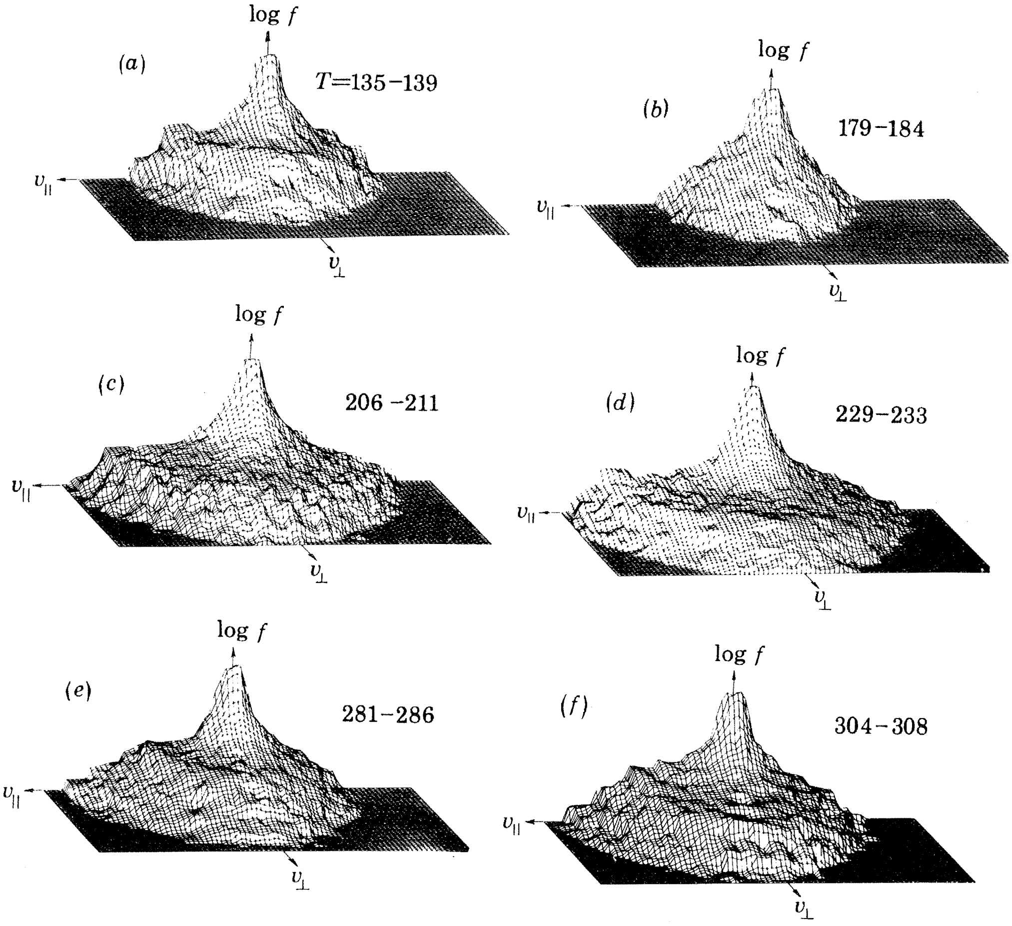

FIGURE 2. Velocity distributions for auroral electrons. (From R. L. Kaufmann 1978 *J. geophys. Res.* **83**, 586.)

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Prospects for better understanding of this boundary layer are good. The spacecraft pair I.S.E.E. 1 and 2 should provide reliable values of its thickness as well as improved instrumentation. Theory and numerical modelling can use the same approach as for shocks. The field-aligned currents can be described as an Alfvèn wave, but the beams are a complicating factor.

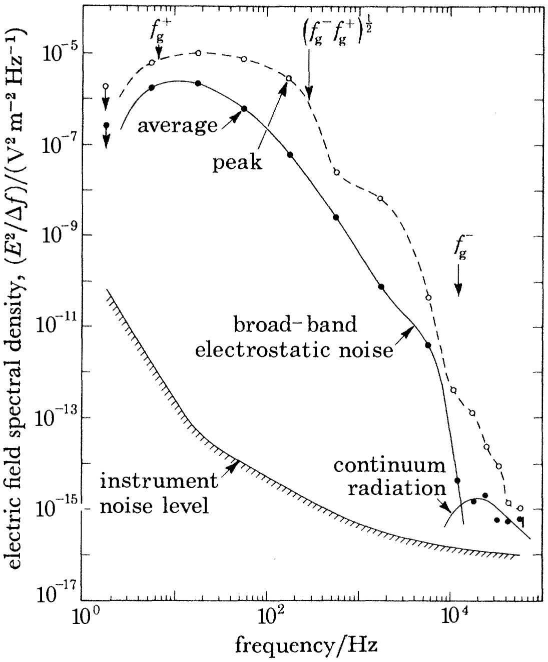

FIGURE 3. Spectrum of broad-band electrostatic noise. $E_{\text{peak}} = 35.6\ \text{mV m}^{-1}$, $E_{\text{r.m.s.}} = 10.8\ \text{mV m}^{-1}$. Data obtained from Hawkeye 1, orbit 63, day 289, 16 October 1974, 1240 to 1243 U.T. (From D. A. Gurnett 1977 *J. geophys. Res.* **82**, 1031.)

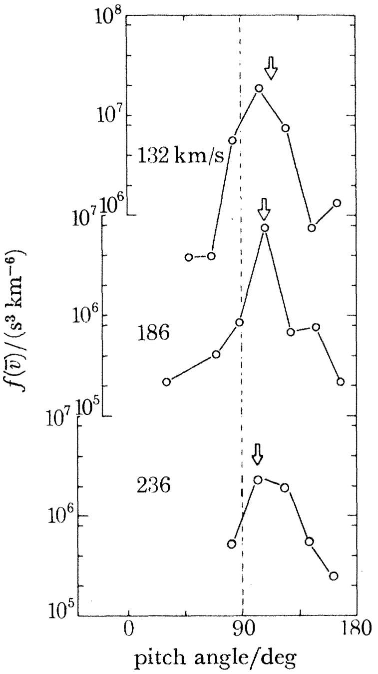

FIGURE 4. A proton velocity distribution suggesting perpendicular heating. (From P. M. Kintner 1979 *J. geophys. Res.* **84**, 7201.)

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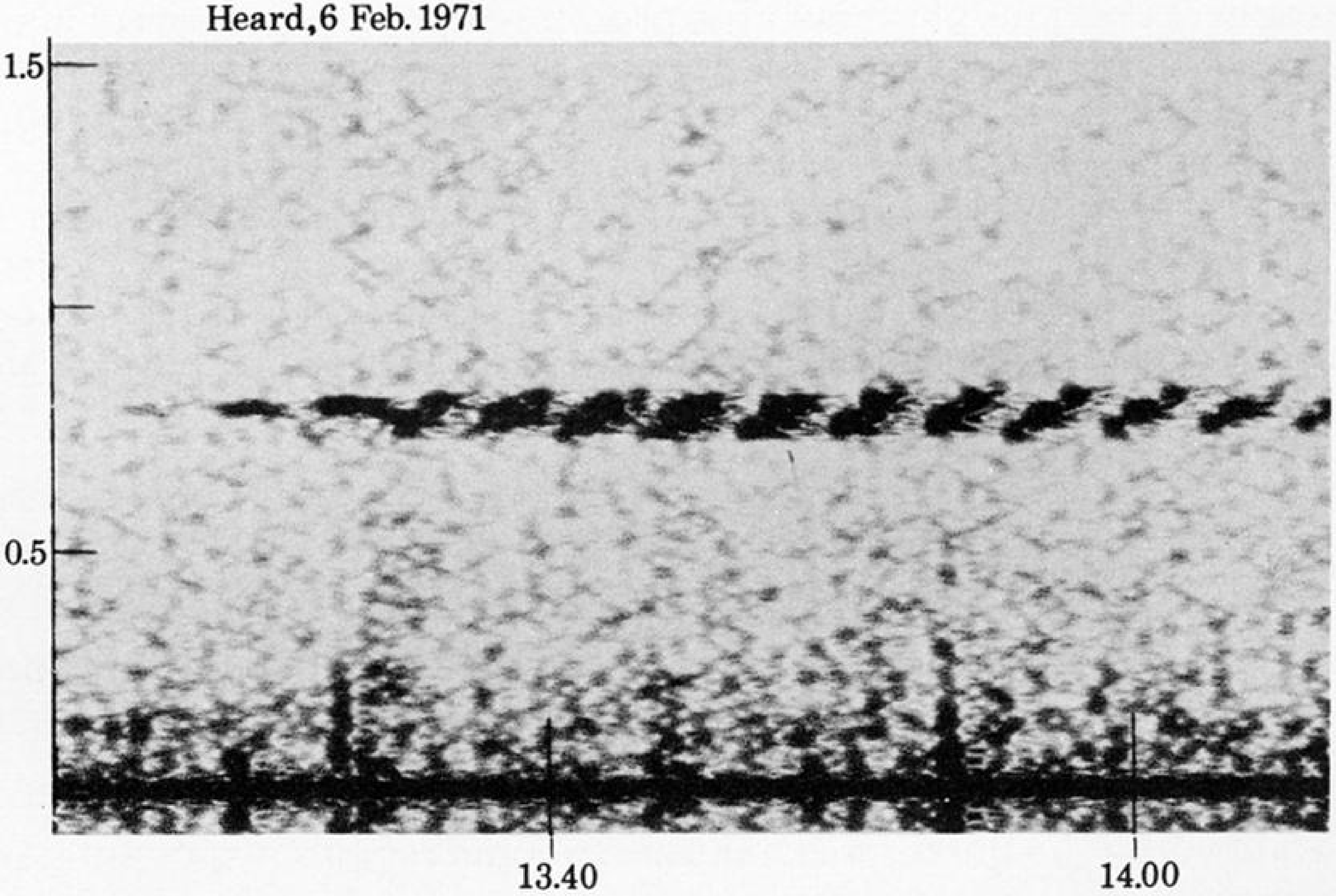

GURE 1. Dynamic spectrum observed on the ground. (From R. Gendrin 1973 *J. geophys. Res.* 78, 763.)

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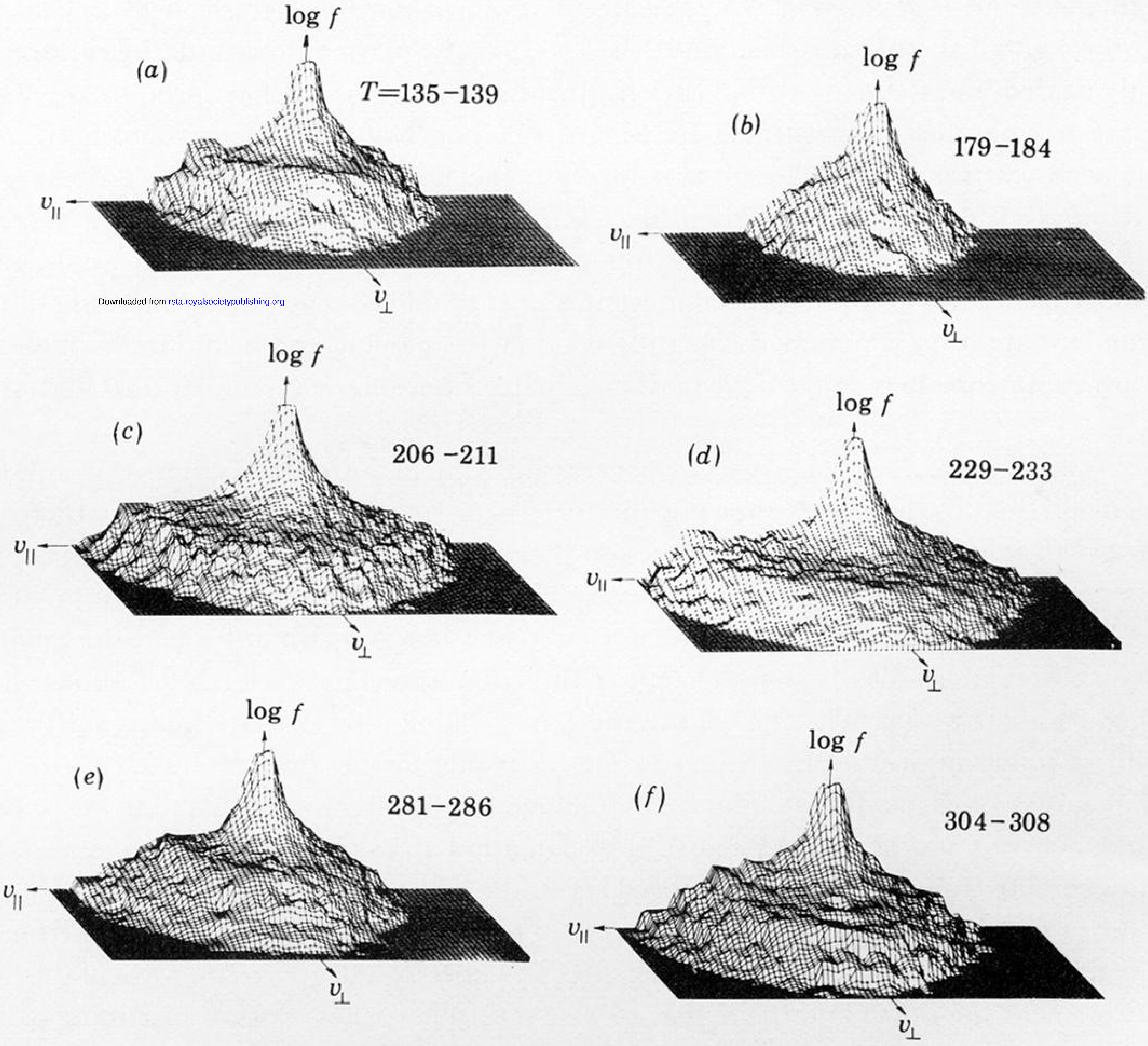

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