Acceleration Mechanisms for Auroral Electrons

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Anomalous resistivity and laminar shock mechanisms for the acceleration of electrons responsible for the discrete auroral arcs are reviewed. Ion acoustic or Buneman mode instabilities are shown unlikely to play any significant role in magnetospheric field line resistivity or electron acceleration. Although ion cyclotron turbulence is commonly observed, it is concluded that it is also unlikely to contribute to auroral acceleration. The double layer, oblique and V laminar shock models are reviewed. The relationship among these shock models and the relationship of the shock to the anomalous resistivity models is described. It is pointed out that the double layer model is inconsistent with the highly structured auroral forms. The V-shock model fits the observations so well that it appears that a fundamental understanding of the acceleration process for the discrete aurora has been achieved.

1. Introduction

Ever since the first rockets were fired into the aurora over two decades ago, it has been known that auroral emissions have been caused by energetic electrons (1 to 10 keV) impacting on the upper atmosphere. What has for so long remained a mystery is how these electrons are accelerated—in particular, how these electrons are accelerated in the intricate patterns necessary to produce the highly structured auroral forms like those shown in Fig. 1.

The purpose of this review is to present some of the theoretical predictions and pertinent observational evidence of the more promising electron acceleration mechanisms. Also a theoretical review of anomalous resistivity and laminar shock models is given and followed by a selective review of satellite and ground-based observations with the purpose of identifying the most promising acceleration mechanism. Attention is confined to the mechanisms responsible for the discrete auroral arcs.

2. Theoretical Review of Auroral Acceleration Mechanisms

2.1 *Turbulent resistivity*

An important class of acceleration mechanisms is generally referred to as turbulent resistivity. For a complete review see PAPADOPOULOS (1977). The essential idea behind the turbulent resistivity models is that a current-carrying plasma consisting of counterstreaming ions and electrons becomes unstable by any one of a variety of

Fig. 1. A high-speed all-sky camera photograph of an active aurora illustrating the detailed structure of the discrete aurora.

instabilities. The resulting wave fields scatter the particles, inhibiting their flow thereby giving the plasma a finite resistance to the free flow of electric current parallel to the magnetic field and making it possible to maintain an electric field parallel to the magnetic field. Since $\mathbf{J} \cdot \mathbf{E}$ is positive in a resistive plasma, electrical energy is going into the energizing of plasma particles.

PAPADOPOULOS (1977) has identified three basic resistivity mechanisms resulting from instabilities excited by the electric currents carried by the plasma, namely the Buneman, ion acoustic and ion cyclotron instabilities. The Buneman instability occurs when the relative drift velocity between ions and electrons exceeds the electron thermal speed, while the ion acoustic instability occurs when the electron temperature greatly exceeds the ion temperature and when the relative drift between ions and electrons exceeds the thermal velocity of the ions at the electron temperature, $V_D > (T_e/M_i)^{1/2}$. When the ion temperature is equal to the electron temperature the two instabilities become indistinguishable. Both instabilities operate in the absence of a magnetic field, or in the presence of a magnetic field the instabilities are essentially one-dimensional with the electric field vector of the wave parallel to the magnetic field.

The ion cyclotron instability, first proposed by KINDEL and KENNEL (1971) has the lowest threshold for excitation when the ion and electron temperatures are comparable. This instability occurs only in a magnetized plasma, and modes can be

excited corresponding to each harmonic of the ion gyrofrequency, the $n=1$ mode having the lowest threshold of excitation. The conditions for excitation of the $n=0$ mode are approximately the same as the ion acoustic instability, and the $n=0$ mode reduces to the ion acoustic mode when the direction of propagation becomes parallel to the magnetic field.

The conditions for excitation and the linear growth rates for the current-driven instabilities in a homogeneous plasma are well known, but the effect of these instabilities upon particle populations can only be determined by nonlinear calculations or by numerical simulations. Because of limitations on these methods, there is some uncertainty about the effects, but the general picture that seems to emerge is described below.

If an electric field is applied parallel to the magnetic field in a cold plasma, the electrons and ions will be accelerated in opposite directions until the relative streaming speed exceeds the electron thermal speed. At this point the Buneman instability sets in and results in the heating of the electrons, raising the threshold for instability and quenching the instability. This allows the electric field to further accelerate the electrons until instability sets in again and the cycle is repeated. The result is a streaming population of electrons in which the thermal and streaming speeds are equal and increasing linearly with time, no stable state being achieved in a homogeneous plasma.

The ion acoustic instability on the other hand preferentially heats the ions. If the ion temperature is much less than the electron temperature, a stable resistance can be maintained up to the point where the ion temperature reaches the electron temperature. At this point the instability would take on some of the characteristics of the Buneman instability, and likely both ion and electron temperature would rise together. The result would then likely be ion and electron temperatures and streaming speeds rising linearly with time with the streaming speed comparable to the electron thermal speed. The electron and ion temperature would be nearly equal with no steady state resistance.

However, in a magnetized plasma, the ion cyclotron instability would be excited first. Nonlinear calculations indicate that the instability goes into heating the ions, which raises the threshold drift velocity, bringing the system toward stability and reducing the plasma resistance. The ion cyclotron mechanism also does not seem to lead to a stable plasma resistivity. (The reader interested in further details is referred to PAPADOPOULOS (1977) and references therein.)

The models described above all assume a homogeneous plasma of infinite extent. When the finite size of a system is considered, the effect of the current-driven turbulence could be quite different. If cold populations of electrons and ions were to enter a region of turbulence of finite extent, it might be possible to maintain a steady resistivity because new particles would be continuously entering the system. But the magnitude of the potential that could be maintained across a turbulent region would be comparable to the temperature gain of the particles. Hence it does not appear that significant acceleration potentials could be maintained by anomalous resistivity.

The calculations of anomalous current-driven instabilities have largely neglected effects of variation of the plasma parameters in directions perpendicular to the magnetic field lines. The Buneman and ion acoustic instability models alone are incompatible with such variation. Variations perpendicular to the magnetic field lines must involve coupling to ion or electron cyclotron waves.

There may also be drift wave instabilities, basically utilizing plasma inhomogeneities as their source of free energy, which have enhanced growth rates due to the presence of field-aligned currents. Since these instabilities involve only a few resonant electrons, it is likely that they may be stabilized by the formation of small plateau in the electron distribution function (PAPADOPOULOS, 1977).

Anomalous resistivity models do not seem to lead to electron acceleration or preferential electron heating in a homogeneous magnetized plasma. But, in a finite region of anomalous resistivity maintained by ion cyclotron turbulence, a small fraction of incident electrons might have sufficient energy to escape trapping. These electrons would be freely accelerated by the small parallel component of the electric field. Hence anomalous resistivity models can possibly accelerate electrons with beam characteristics, but the accelerated electrons would contain only a fraction of the $\mathbf{J} \cdot \mathbf{E}$ energy dissipated.

2.2 *Current-driven laminar shock models*

The laminar shock models are related to the instabilities described in the previous subsections, except that in the nonlinear state the waves evolve into a solitary wave, Doppler shifted to zero frequency. The potential jump associated with the wave can accelerate electrons in one direction and ions in the other. In a laminar shock, there is no heating of the particles, so the accelerated beam has essentially the same temperature it had before it was accelerated. Thus if the magnitude of the potential jump is large in comparison to the thermal energies of the entering particles, the emerging beams would essentially be monoenergetic. In the laminar models most of the $\mathbf{J} \cdot \mathbf{E}$ energy would go into the electron beam with a lesser amount in an ion beam accelerated in the opposite direction, so the laminar shocks are far more energy efficient than the turbulent resistivity models.

The best known of the laminar shock models is the double layer described by BLOCK (1972) and CARLQVIST (1972). The double layer is a time-independent nonlinear state of the ion acoustic or Buneman mode current-driven instabilities, depending on the streaming speeds and temperature of the particles entering the shock. The potential jump can have almost any magnitude, so that the plasma resistivity, defined as the ratio of the potential jump to current density, can be arbitrarily large. The thickness of the double layer when the potential jump, $\Delta\phi$, is large in comparison to the thermal energies is the order $(e\Delta\phi/m\omega_p^2)^{1/2}$, where ω_p is the plasma frequency. Double layer solutions corresponding to a wide variety of plasma models can be constructed with relative ease (MONTGOMERY and JOYCE, 1969; DAVIDSON, 1972; KAN, 1975), making the double layer theory much more tractable than the turbulent resistivity theories.

One-dimensional numerical simulations of the double layer have been carried out by GOERTZ and JOYCE (1975) in which they traced the motion of a large number of charge sheets moving in a self-consistent electric field. In this simulation, charge sheets with a Maxwellian distribution of velocities of one sign were introduced from one side of the domain, and charge sheets of the opposite sign were introduced from the other side. The simulation was initiated with a small perturbation in the flow. A solitary potential wave developed and evolved into a quasi-stable potential profile resembling a hyperbolic tangent function; and resulting in a significant potential difference between the two ends of the simulation domain. The most noteworthy feature of the simulation is that the system evolved into a laminar rather than a turbulent state. This simulation suggests that instabilities in a current carrying plasma will evolve into a laminar rather than a turbulent state, provided zero-frequency modes can be excited.

In a magnetized plasma, the double layer theory is only compatible with electric fields parallel to the magnetic field, or equipotential surfaces normal to the magnetic field. Since at high latitudes the magnetic field is nearly vertical, the precipitation caused by double layers would be uniform and of great horizontal extent, which is inconsistent with the highly structured auroral forms.

The oblique shock model represents a generalization of the double layer model to shock normal directions oblique to the magnetic field. SWIFT (1975) showed that as long as the magnetic moment of the incident ions was preserved, the electric potential, ϕ , of the oblique shock satisfied the modified Poisson equation

$$\kappa \frac{d^2}{d\eta^2} \phi + \frac{1}{2} \frac{d}{d\eta} \kappa \frac{d}{d\eta} \phi = -4\pi e(n_i^* - n_e) \quad (1)$$

where $\eta = z - \alpha x$ is a coordinate normal to the shock plane and α is the tangent of the angle between the shock normal direction and the magnetic field. κ is given by

$$\kappa = 1 + \alpha^2(1 + c^2/V_a^2) \quad (2)$$

where V_a is the local Alfvén velocity. n_e is the electron density, and n_i^* is the ion density computed as if the ions were completely magnetized. The z -coordinate is parallel while x is perpendicular to the magnetic field. The effect of the polarization drift of the ions is included the plasma dielectric c^2/V_a^2 .

Because of the large effective dielectric, the thickness of the shock is the order of an ion gyroradius, namely $(e\Delta\phi/m_i\Omega_i^2)^{1/2}$, where Ω_i is the ion gyrofrequency. Because $c^2/V_a^2 \gg 1$, it can be seen that the shock structure is insensitive to the magnetic field direction. When the shock normal becomes parallel to the magnetic field the double layer solutions are recovered. As in the double layer theory, SWIFT (1975) showed that it is possible to construct a wide variety of oblique shock models and that it is possible to support an arbitrarily large potential jump.

This result did not completely solve the problem of accounting for electron precipitation in a spatially confined region because the SWIFT (1975) theory referred to plane shocks of infinite extent. However, SWIFT (1976) was able to take advantage

Fig. 2. Equipotentials of the V-shock model. Solid lines represent equipotential surfaces, and the electric field is toward the center axis of the figure. Above the level z_0 and below the level z_1 are the asymptotic regions where equipotentials are parallel to the magnetic field. At $|x| > a$ the electric field perpendicular to the magnetic field is arbitrary, and the field lines are everywhere equipotentials.

of the freedom in shock normal direction and construct a two-dimensional shock model in which the equipotentials are curved surfaces. Thus it was shown possible to construct a shock model which satisfied the nonlinearly coupled Poisson-Vlasov system of equations of the type proposed by SWIFT *et al.* (1976) in which the equipotential contours assume the form of a V as shown in Fig. 2.

As noted previously, the laminar shock models should lead to essentially monoenergetic ion and electron beams on either side of the shock. The electron beam, especially when it encounters the cold ionospheric plasma is known to be unstable to a variety of instabilities. SWIFT and KAN (1975) and MAGGS (1976) have proposed that the electron beam generate waves on the resonance cone which is responsible for auroral hiss. PERKINS (1968) suggested a beam-plasma instability at the upper hybrid resonance frequency, while BOSWELL (1976) has detected the emission of Bernstein waves by the interaction of an electron beam and plasma in a laboratory device. Hence, instabilities are likely to have a significant effect in broadening the energy spectrum of the beam, so it is unlikely that a simple monoenergetic beam would actually be observed in the ionosphere as a result of acceleration by a laminar shock.

3. Observations

In this section a selected set of observations is reviewed to decide among the mechanisms reviewed in the previous section which best account for the acceleration of electrons responsible for the discrete auroral arcs like these shown in Fig. 1.

Fig. 3. A model for auroral precipitation which includes a double layer pieced together with oblique shocks.

First, as mentioned previously, the discreteness of the arcs rules out the double layer, or the Buneman mode and ion acoustic turbulent resistivity models as stand-alone mechanisms. But do these mechanisms play a role in auroral acceleration when pieced together with the oblique shock model in the case of the double layer, or with ion cyclotron waves in the case of the turbulent resistivity model?

Figure 3 shows such an example of a laminar shock model. It can be seen from the figure that a satellite passing under the shock structure would observe an increase in the energies of the precipitated particles, a region of constant energy followed by a region of decreasing energy. The energy profile would be characterized by a flat plateau in the energy versus time plot.

Of the energy versus time profiles published by FRANK and ACKERSON (1971) none seem to show the predicted plateau. In fact, the name 'inverted V' given to the precipitation events associated with the discrete aurora suggests the lack of a plateau. Careful triangulated observations (ROMICK and BELON, 1967) of auroral luminosity with a pair of meridian scanning photometers indicates that the depth of penetration into the atmosphere across an auroral arc increases rapidly and then decreases sharply; no evidence of a plateau in auroral luminosity is seen. Hence, there seems to be no evidence supporting any role of the double layer model in discrete auroral precipitation. The same arguments suggest the lack of any role of the ion acoustic or Buneman instabilities in turbulent resistivity models for discrete auroral arcs.

On the other hand, the inverted V-structure of auroral precipitation (FRANK and ACKERSON, 1971) is an explicit feature of the V-shock model of SWIFT *et al.* (1976) shown in Fig. 2. In fact, the inverted V-events prompted GURNETT (1972) to propose an equipotential model for auroral electric fields which had many similarities to the V-shock model. The energy gain is proportional to the number equipotentials an electron crosses in moving downward along the magnetic field lines. An electron near the center axis of Fig. 2 crosses more equipotentials than an electron to either side of the central axis.

Perhaps the most definitive evidence on the nature of the auroral acceleration mechanism has been provided by S3-3 satellite in a polar orbit with an apogee of about 8,000 km altitude over the north pole. MOZER *et al.* (1977) report direct observations of dc electric fields with peak magnitudes of 500 mV/m, far stronger than has ever been observed in the ionosphere. The large electric fields are often observed as double structures of opposing perpendicular electric fields accompanied by a component parallel to the magnetic field pointing away from the earth. The high-magnitude electric fields appear to be embedded in a larger region of ion cyclotron turbulence. Within the region of high-magnitude electric field beams of O^+ and H^+ ions of ionospheric origin of a few keV energy have been observed moving up the magnetic field lines (SHELLEY *et al.*, 1976). The high-magnitude electric field structures also occur where the onboard magnetometer indicates field-aligned currents greater than 10^{-6} A/m².

Unfortunately the S3-3 observations were not accompanied by simultaneous ground based auroral observations. However, there exist other observations which provide direct links between strong perpendicular electric fields and the visual aurora. HALLINAN and DAVIS (1970) using television imagery of auroral arcs observed rapid auroral ray motions. They interpreted these motions as $E \times B$ drift and deduced perpendicular electric fields a higher than had ever been observed within the ionosphere. Anomalously large electric fields at high altitudes have also been observed with the barium-shaped charge experiments. By tracking the $E \times B$ motion of a field-aligned streak of barium plasma, the electric field along the streak can be determined. WESCOTT *et al.* (1975, 1976) and JEFFRIES *et al.* (1975) have observed separate instances of sudden rapid motion of flux tubes containing the barium. In each case the rapid movement coincided with the appearance of aurora on the field lines. In one experiment (WESCOTT *et al.*, 1976) the barium streak above 4,000 km altitude was observed to brighten suddenly accompanied by rapid drifts corresponding to electric fields, referenced to the 100 km level, in excess of 250 mV/m. The barium plasma below 4,000 km did not experience the same large electric fields.

The appearance of aurora has also been associated systematically with upward field-aligned currents. KAMIDE *et al.* (1976) and KAMIDE and ROSTOKER (1977) have shown that upward field-aligned currents are observed where there are auroral arcs. SESIANO and CLOUTIER (1976), using a rocket-borne magnetometer and ground-based observations, have also shown that regions of visual aurora and upward field-aligned currents coincide.

Returning to the V-shock model of Fig. 2, it can be seen that it is consistent with the presence of strong electric fields on auroral field lines. A field-aligned current is also a necessary condition for the formation of the shock (SWIFT, 1976). The V-shock model also requires the upward acceleration of ions originating from below the shock, which are also observed. Thus the observations seem to provide strong support for the V-shock mechanism.

The observations of MOZER *et al.* (1977) also show the existence of ion cyclotron turbulence, and HUDSON *et al.* (1977) have shown that observed levels of ion cyclotron turbulence are sufficient to support a 1 mV/m parallel dc electric field, which over 1,000 km of field-aligned path would be sufficient to accelerate electrons to auroral energies. Field-aligned electric currents are also observed in connection with the ion cyclotron turbulence. The question is whether ion cyclotron turbulence play any significant role in the acceleration of auroral electrons.

All of the observations of high-altitude electric fields and acceleration of ions and electrons, including evidence presented by TEMERIN *et al.* (1977) and TORBERT and MOZER (1977), associates the acceleration processes with the shock type structures depicted in Fig. 2 rather than with the larger region of ion cyclotron turbulence in which the shocks are imbedded. Further, TORBERT and MOZER (1977) report that electrostatic shocks and auroral arcs have similar occurrence frequencies, similar geographical distribution mapped along the magnetic field lines, similar dependence on magnetic activity and similar thicknesses. On the other hand, ion cyclotron turbulence is observed to occur on field lines occupied by V-shocks as well as in regions between V-shocks. Hence the statistics of ion cyclotron occurrence and particle acceleration appear to be different. Moreover, the effect of ion cyclotron turbulence seems to be that of heating the ions (KELLEY *et al.*, 1975), which would make the ion cyclotron mechanism an inefficient source of electron or ion beam energy. Although not conclusive, the weight of evidence indicates that the V-shock is the only mechanism responsible for accelerating electrons that produce the discrete auroral arcs.

Ion cyclotron turbulence and V-shocks are found in the same regions, so they are likely related. It has previously been mentioned that the V-shocks represent the $n=0$ ion cyclotron mode whereas the $n \geq 1$ modes are associated with the ion cyclotron turbulence. The V-shocks and cyclotron waves also occur on field lines which GURNETT and FRANK (1977) have observed intense plasma wave turbulence extending out to at least $40 R_E$ in the magnetospheric tail. From the S3-3 satellite data TEMERIN (1977) has identified some of this turbulence as zero-frequency turbulence. Potential differences across the magnetic field lines will be associated with the turbulence.

The picture that seems to emerge is that the potential differences will result in electric currents between the ionosphere, which may be regarded as an approximate equipotential surface, and the turbulent eddies generated in the magnetosphere. The currents will first give rise to $n \geq 1$ ion cyclotron turbulence because that is the most easily excited (KINDEL and KENNEL, 1971). The ion cyclotron turbulence does not

significantly inhibit the field-aligned currents so current densities can rise considerably above the $n=1$ instability threshold. In some turbulent eddies, the field-aligned current increases to where the $n=0$ ion cyclotron mode becomes unstable. At this point the V-shocks develop, resulting in the acceleration of electrons and formation of auroral arcs. Hence the auroral arcs arise out of a much broader background of turbulent eddies, field-aligned currents and ion cyclotron turbulence.

In conclusion, among the acceleration mechanisms reviewed, the V-shock model appears to be unique in its fit of the observational evidence. The fact that explicit solutions to the Poisson-Vlasov system of equations for the V-shock model have also been exhibited demonstrates that the V-shock model is consistent with well-known physical laws. It appears that a fundamental understanding of the acceleration mechanism for the discrete aurora has been achieved.

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