Diffuse Auroral Precipitation

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In this review, we summarize one at least plausibly coherent view of the self-consistent coupling of convection in the plasma sheet to particle precipitation and the ionosphere. We focus upon our understanding of the plasma instabilities responsible for diffuse auroral precipitation. At present, the electrostatic ion and electron cyclotron harmonic loss-cone instabilities seem to be the best candidates. However, they depend sensitively upon the cold electron density and temperature deep in space on auroral field lines, parameters about which we have little or no experimental or theoretical information.

1. Introduction

Scientific interest in the \textit{aurora borealis} extends back to the ancient Greeks. Naturally, the first observations of aurora were made by the naked eye. The eye's spectral response, and particularly its sensitivity to contrast, thus shaped our conceptions of the aurora. Since its limitations are similar to those of the eye, the all-sky camera, which replaced visual observations for systematic auroral studies in the 1950's, served to systematize the morphology primarily of the discrete aurora so prominent to the naked eye. Only with the advent of satellite-borne energetic particle detectors and more recently scanning photometers did our awareness of a broad region of diffuse particle precipitation and light emission, corresponding roughly to the auroral oval, emerge. Because of its great extent, this diffuse auroral precipitation can be the dominant form of auroral energy dissipation (ANGER and LUI, 1973; LUI and ANGER, 1973; LUI et al., 1973; HULTQVIST, 1975).

The diffuse aurora seems to be caused primarily by the precipitation of 1–10 keV electrons. Moreover, recent studies have established that \(~1–100\) keV proton precipitation is an integral part of the diffuse aura (LUI and ANGER, 1973; LUI et al., 1973; EATHER et al., 1976). The zones of soft electron and proton precipitation generally coincide (HULTQVIST, 1975) and define an auroral oval similar to that deduced from discrete arc observations. While protons typically contribute no more
than 30% of the diffuse auroral light intensity (Mende and Eather, 1976; Hultqvist, 1975), the zone of diffuse proton precipitation can extend equatorward of the diffuse electron precipitation in the pre-midnight sector so that proton induced light emissions can predominate over a small range of invariant latitude in this sector (Fukunishi, 1975). Figure 1 shows a simultaneous ESRO 1A observation of precipitating soft electrons and protons which illustrates the above conclusions (Hultqvist, 1975).

We can ask two questions about the discrete aurora. First, where do the auroral particles come from and why do they precipitate where they do? Second, what causes the precipitation of electrons and protons? Because neutral and Coulomb collisions cannot be responsible for the observed precipitation, the second question can be refined to, what plasma instability and ensuing plasma wave turbulence causes the diffuse auroral precipitation? In this regard, it will be important to note that the auroral electron and protons generally have isotropic pitch angle distributions when they are observed in or near the auroral ionosphere (Hultqvist, 1975; Bernstein et al., 1974; Hultqvist et al., 1974).

In this paper, we selectively review the development of our still partial answers to these two questions. Since we will try to illuminate one at least plausible chain of arguments linking observation with theory, our review is by no means exhaustive. We apologize in advance for the sins of commission and especially omission inherent in our methodology.

Fig. 1. Proton and electron precipitation profiles. This figure illustrates the general similarity of the electron and proton diffuse auroral precipitation profiles (taken from Hultqvist, 1975).
2. Coupling of Convection and Precipitation

The general morphology and energy spectra of the diffuse auroral precipitation generally suggest a plasma sheet origin for the night side diffuse auroral particles (Eather and Mendes, 1972a, b; Eather et al., 1976). While there have been no simultaneous measurements of the energetic particle fluxes in the ionosphere and deep in space on identifiably the same auroral field line, the magnitudes of the precipitating particle fluxes are generally comparable to those found near the inner edge of the plasma sheet, a fact consistent with the measured pitch angle isotropy of the precipitating particle fluxes. Finally, the observed position of the sharp inner edge to the electron plasma sheet (Vasyliunas, 1968) is consistent with its mapping to the equatorward edge of the diffuse auroral electron precipitation.

The question of the origin and location of the diffuse auroral precipitation was first attacked by Petschek and Kennel (1966) and subsequently independently by Kennel (1969) and Vasyliunas (1969). The physical content of their essentially identical models involves two fundamental statements. First, earthward convection must replenish the supply of electrons and protons lost by precipitation to the auroral ionosphere. Second, because the particle pitch angle distributions are nearly isotropic, the precipitation lifetime approaches the strong diffusion limit (Kennel and Petschek, 1966; Kennel, 1969), independent of the mode of plasma turbulence responsible for the precipitation. Combining these two statements led to the physical consequences discussed below.

A flux tube in the plasma sheet would initially lose a small fraction of its particles as it convects towards the earth, even though isotropic particle fluxes are precipitating from it, because the strong diffusion minimum lifetime, which varies at \( L^{-4} \), is much longer than a characteristic flow time. Since at first the convection is virtually loss-free, the electrons and protons are heated by adiabatic compression. As the flow penetrates further into an increasing magnetic field, it reaches a point where the minimum lifetime becomes comparable to the flow time. Since the electron minimum lifetime is much smaller than the proton lifetime this happens first for the electrons. The prediction that protons would form a sharp inner edge equatorward of the electrons has proven false.

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**Fig. 2.** Coupling of strong diffusion particle losses with purely sunward convection near local midnight. Shown here is the qualitative precipitation profile expected in the least elaborate coupling model. The precipitation of energetic electrons has a sharp equatorward edge (corresponding to the inner edge of the electron plasma sheet) when the minimum lifetime becomes short enough to precipitate particles before they penetrate the earth's field further. The prediction that protons would form a sharp inner edge equatorward of the electrons has proven false.
electrons. At this point, electrons are rapidly removed from the convecting flux tube by precipitation. Since, for equal temperatures, the isotropic precipitation flux of electrons exceeds that of protons by a factor 43, the difference between electron and proton precipitation fluxes must be made up by a return flux of colder electrons streaming out of the ionosphere. Since a hot electron is exchanged for a colder one, the mean energy of the electrons in the convecting flux tubes decreases. Thus, this model predicts a sharp decrease of electron temperature at the 'inner edge of the electron plasma sheet' whose computed location generally agrees with observation (Vasyliunas, 1968) and with the general location of the equatorward edge of the diffuse auroral electron precipitation (Kennel, 1969). The precipitation profiles expected in this model are sketched in Fig. 2.

Since the proton minimum lifetime exceeds that of electrons, the protons should penetrate further than the electrons and form an inner edge deeper within the magnetosphere. A sketch of the latitude variation of electron and proton precipitation predicted by this simplest of all models of convection-precipitation coupling is sketched in Fig. 2; if the electron inner edge is at \( L \approx 6 \), the proton inner edge would be near \( L \approx 4 \). This last prediction of the theory has proven false: the electron and proton precipitation zones more or less coincide. However, refinements of the convection model may be able to ameliorate this discrepancy. By including the corotation electric field, coupling to the finite conducting ionospheric plasma and the effects of finite proton pressure, Jaggi and Wolf (1973) and subsequently others have shown that protons, originally convecting radially inwards can be deflected azimuthally around the earth as soon as they penetrate to \( L \)-shells where the high ionospheric conductivity created by electron precipitation has diminished. Thus, on the night side, one would not expect protons to penetrate significantly beyond the electron inner edge (D.J. Southwood, private communication, 1977). Since energetic protons can be precipitated only from flux tubes containing energetic protons, the zones of electron and proton precipitation should more or less coincide, with protons extending slightly equatorward of the electrons, particularly in the pre-midnight region towards which protons are carried by their magnetic field gradient drifts.

One further consequence of the above convection-precipitation coupling model was discussed by Coroniti and Kennel (1972). One would expect the night-side auroral ionosphere Pedersen and Hall conductivities to have strong north-south gradients with a peak just poleward of the projection of the inner edge of the electron plasma sheet, because the ionizing precipitating energetic electron fluxes such a peak. The idealized east-west electric field driving convection would drive strong north-south Hall currents in the auroral ionosphere. Because the ionospheric Hall conductivity is inhomogeneous, these Hall currents must close in the magnetosphere by field-aligned currents into the ionosphere at the equatorward edge and out of the poleward edge of the diffuse auroral precipitation region. The field-aligned current density maximizes on those field lines which connect to the maximum Hall conductivity gradients. They then speculated that strong convection could then increase the field-
aligned current density above its stability limits leading to regions of resistive dissipation and parallel electric field at high altitudes on the strong current field lines. This would then polarize the lower ionosphere in turn to produce a broad westward electrojet near the equatorward edge of the diffuse electron precipitation. Another physical consequence is implicit in this model: if ions are accelerated downwards by the parallel electric field, one would expect structured non-isotropic ion precipitation at the equatorward edge of the diffuse electron precipitation, whose intensity possibly correlates with the intensity of the diffuse electrojet.

Clearly the above model was oversimplified. It cannot describe the entire pattern of field-aligned currents threading the auroral oval, because it leaves out those currents that connect to the magnetopause and drive magnetospheric convection. Its geometrical assumptions are best suited to the local midnight sector. Even there, since the reaction of the induced ionospheric conductivity back onto the convective flow pattern was not taken into account—as well as finite proton pressure—its usefulness is primarily illustrative. It illustrates that field-aligned currents, parallel electric fields (and therefore particle acceleration) emerge naturally from a model of diffuse auroral precipitation. It also suggests a role for parallel electric fields in electrojet formation.

In summary, our first question—of the origin and location of the night-side diffuse aurora—seems now to have been answered in a general way. Soft auroral electrons and protons are precipitated from flux tubes which are convecting from the plasma sheet towards the earth's night side. Strong diffusion precipitation naturally forms a sharp inner edge to the electron plasma sheet. Because of their long minimum lifetimes, the protons do not form a sharp inner edge; their precipitation patterns should generally mirror proton convection patterns in deep space.

We also derive several hints from the model of diffuse auroral precipitation above which will guide our discussion of the plasma instabilities responsible for it. First, the general equality and isotropy of plasma sheet and diffuse auroral electron fluxes, the fact that the inner edge of the electron plasma sheet can be observed at a variety of magnetic latitudes (Vasyliunas, 1968), and the magnitude of the observed decrease in electron mean energy at the inner edge, all argue that nearly all electrons of plasma sheet origin which penetrate sufficiently closely to the earth are eventually precipitated. Furthermore, this strongly suggests that the instability responsible for diffuse auroral electron precipitation must occur near the geomagnetic equator (less than say 45° geomagnetic latitude). Waves near the equator can interact with all electrons on the flux tube; conversely, it is difficult to see how waves occurring only at high latitudes can reduce the 1–10 keV electron fluxes needed to account for the observations of the inner edge. The case is less clear for protons, but we will pursue the consequences of assuming an equatorial location for ion plasma turbulence shortly. Second, since the electron precipitation number flux must be neutralized by a return flux of colder electrons, plasma sheet convection and precipitation helps determine not only the hot plasma, but also the cold electron environment in which the instabilities responsible for the auroral precipitation operate. This environment
should permit two instabilities, one for electrons and one for protons, to grow. Finally, since the diffuse aurora is present at quiet as well as disturbed times, these instabilities must not require unusual circumstances for their growth. A source of free energy must nearly always be present to drive them.

3. Free Energy Sources

A self-consistent model of the coupling of convection to particle precipitation must demonstrate that convection naturally generates a source of free energy for the instabilities responsible for particle precipitation. In this section, we discuss these free energy sources, and in the next, some of the instabilities created by these sources.

One can divide up the free energy sources for plasma instabilities into a few general types. Among these are:

1) Electrical currents
2) Fast ion beams
3) Fast electron beams
4) Density and temperature gradients
5) Pitch angle anisotropy
6) Loss cone distribution

Given the great activity of the field lines connecting to the auroral oval, it is not surprising that all six are present there, at least at times. However, an extension of the chain of reasoning outlined in the preceding section indicates that all six are plausible theoretical consequences of the convection and precipitation model discussed in Section 2.

Even when no net electrical current need flow, a return current of cold electrons must stream out of the ionosphere to balance the difference between electron and ion precipitation fluxes. KINDEL and KENNEL (1971) suggested that this return current could be unstable to electrostatic ion cyclotron waves in the far topside ionosphere at altitudes above 1,000 km. When a net electrical current must also flow, the case for instability is even stronger. It is currently thought that ion cyclotron waves are involved in the formation of regions of strong parallel electric fields in the auroral topside ionosphere. Therefore sources 2) and 3)—fast ion and electron beams—may in practice be associated with regions of strong field-aligned current on auroral lines of force.

Several arguments suggest that field-aligned currents and fast electron or ion beams may not be the free energy source responsible for the diffuse aurora. Field-aligned currents tend to be spatially structured, and the precipitation we wish to understand is diffuse. Even if the field-aligned currents—or the precipitation return currents are diffuse, our present understanding suggests that they will create instabilities far from the geomagnetic equator that can interact with only a small fraction of the particles on a given flux tube. If fast electron and ion beams are created by parallel electric fields associated with strong field-aligned currents—they too would
be a highly structured free energy source which is probably strongest at disturbed times. Such beams have been observed primarily near the ionosphere and would probably produce turbulence at high latitudes. Finally, the first effect of beam-generated turbulence is to scatter particles out of the beam—from the loss cone onto trapped orbits. While such instabilities—which have not been discussed at all for ions in the auroral context—may be important for populating the auroral field lines with ions of ionospheric origin—it seems unlikely that we can ask them to drive the reverse process which precipitates ions back into the ionosphere.

The coupling of precipitation and convection naturally produces a sharp spatial gradient in electron temperature which is the inner edge of the electron plasma sheet. Coroniti and Kennel (1970b) and Chance et al. (1973) argued that this temperature gradient could be unstable to the growth of drift Alfvén waves, thereby producing micropulsations with 5–15 sec periods. However, unless the spatial gradient scale length is as small as an ion Larmor radius, drift waves must have frequencies well below the ion cyclotron frequency, so low that the particles first adiabatic invariant must be conserved. The isotropy of the observed precipitation fluxes suggest that the first adiabatic invariant is violated. The best such low frequency instabilities seem capable of is modulating the growth of the instability responsible for the particle precipitation. Coroniti and Kennel (1970a) suggested that drift and hydromagnetic wave modulation of whistler growth might account for the modulation of 40 keV electron and X-ray fluxes occasionally observed.

This leaves us with the last two, related, free energy sources—thermal anisotropy and a loss cone property. An initially thermally isotropic plasma will become anisotropic as it flows towards the earth on more or less dipolar field lines. Eventually, the perpendicular temperature $T_\perp$ will exceed the parallel temperature $T_\parallel$. Sufficiently large thermal anisotropies are known to be unstable to the growth of both electromagnetic and electrostatic waves.

The most familiar example of a loss cone distribution—whence it derives its name—occurs in laboratory mirror machines (Harris, 1959). There since the mirror ratio is small, of order two, the loss cone is large, and end losses ensure that the particle distribution contains virtually no particles with small perpendicular velocities $v_\perp$. In other words, $F(v_\perp=0)=0$. At the edge of the loss cone, $\partial F/\partial v_\perp>0$. This positive gradient in the perpendicular velocity distribution can destabilize waves with perpendicular phase velocities $\omega/k_\perp$ lying in the positive gradient region. In space, a strong loss cone property cannot be created by particle losses. The equatorial loss cone is small, and the precipitating particles are observed to be isotropic. However, Ashour-Abdalla and Cowley (1974) showed by including the effects of magnetic gradient drifts into a calculation of the distribution functions of a plasma convecting into an increasing magnetic field that a region of positive $\partial F/\partial v_\perp$ could be generated in the main part of the velocity distributions of ions or electrons. Thus, a loss cone property should be created in the convective flow of plasma towards the earth.

Our discussion of free energy sources is summarized pictorially in Fig. 3. A
series of heuristic arguments has led us to reject all but thermal anisotropy and a loss cone property as plausible free energy sources for the instabilities causing diffuse auroral precipitation. Both are consequences of flow into an increasing magnetic field, both can be present in the equatorial particle velocity distributions of electrons and ions.

We note that, despite many detailed observations of ion and electron distributions on auroral lines of force, we know of none that have specifically addressed the question of whether the loss cone property exists near the geomagnetic equator. By plotting the pitch angle distribution at constant energy, one can deduce something about thermal anisotropy. However, the quantity that enters instability calculations is the perpendicular velocity distribution at constant parallel velocity; to find the loss cone property, it is necessary that the data be plotted in this way.

4. Instabilities Responsible for the Diffuse Aurora

We have now refined our second question about the diffuse aurora to: “What instabilities capable of violating the particles' first adiabatic invariant use thermal anisotropy or a loss cone property as a free energy source?” To violate the first invariant, the waves should have frequencies near the particles’ gyrofrequencies. This leaves only four possible instabilities: those of the electromagnetic and electrostatic ion and electron cyclotron waves. Both electromagnetic and electrostatic cyclotron waves can be unstable to either free energy source.

Electromagnetic ion cyclotron waves (EMIC) and electromagnetic electron cyclotron waves (whistler mode waves) can be unstable when the pitch angle...
anisotropy of the ions and electrons, respectively, which resonate with them is sufficiently large (Kenel and Petschek, 1966; Cornwall, 1966). However, the work of Cornwall et al. (1970, 1971) made it clear by implication that these waves could not be responsible for the precipitation of 1–10 keV electrons and 1–100 keV protons on auroral lines of force. Beyond the plasmapause, the cold electron and ion density is so low that only higher energy electrons and protons can have cyclotron resonances with electromagnetic cyclotron waves. This is the first appearance of a theme underlying the rest of this paper: the determining influence of cold plasma, not only on which instability will occur, but also on the properties of the instabilities that do occur.

Now we turn to electrostatic cyclotron waves. The electrostatic wave experiment on OGO-5—the first to operate successfully beyond the plasmapause—detected a number of different plasma waves with frequencies exceeding the local electron cyclotron frequency. The dominant class had frequencies between multiples of the cyclotron and has come to be known as 'odd-half harmonic' or, more simply, '3/2' emissions. The facts that electrostatic waves interact with the main part of the particle distribution and not a high energy tail, and that the observed half-harmonic waves were, or nearly always, present near the equatorial plane on auroral lines of force led the TRW group to suggest that electrostatic electron cyclotron harmonic waves were responsible for the diffuse electron aurora (Kenel et al., 1970). Lyons (1974) showed by explicit calculation that the observed 1–10 mV/m amplitudes of electrostatic electron cyclotron waves were sufficient to put 1–10 keV electrons on strong diffusion, necessary to account for the observed isotropy of the precipitating electron fluxes.

Much theoretical effort has been devoted to explaining odd half-harmonic emissions. We can only briefly summarize it here. Fredricks (1971) first suggested the electron loss cone instability as a candidate explanation of odd half-harmonic emissions. To make his point, he chose a very strong loss cone distribution function with no spread in parallel velocity. Young et al. (1973) were the first to realize the extreme importance of cold electrons to the behavior of this instability. Addition of cold electrons—even with a density, a small fraction of the 1–10 keV hot electron density—enables much gentler loss cone distributions to destabilize the 3/2 emission predominantly observed. The work of Karpmann and his co-workers (Karpman et al., 1973, 1975) continued to emphasize the importance of cold electrons. They found that the cold electron density controls the frequency of the instability. The instability occurs only when the upper hybrid frequency based upon the cold electron density exceeds the electron cyclotron frequency, and then, the unstable frequencies never exceed the cold upper hybrid frequency. More recently Ashour-Abdalla and Kenel (1975, 1976a, b, 1978) showed that the cold electron temperature controls the spatial growth rate. When the cold electron temperature is sufficiently small, the spatial growth rates are very large, and very gentle loss cone distributions with almost filled loss cones can have appreciable growth rates. Thus, this instability seems capable of operating in strong diffusion conditions. Finally, Ashour-Abdalla
and Kennel (1977) argued that non-resonant quasilinear heating of the cold electrons plays a role equally as important as hot electron precipitation in reducing the spatial growth rates to the small values consistent with the maintenance of a steady state turbulence level.

Having given a general outline of our understanding of diffuse auroral electron precipitation, we now turn to the waves which are the best candidate at present for explaining diffuse auroral proton precipitation. In this case, theory preceded observation. Coroniti et al. (1972) suggested that a quasi-electrostatic mode could be excited at frequencies near but below the ion plasma frequency by an ion loss-cone distribution. In retrospect, this work suffered from the same defect as the equally pioneering work of Fredricks (1971) on the electron electrostatic cyclotron waves: it used too strong-loss cone distribution to be entirely realistic for the magnetosphere, especially during quiet times. Armed with previous experience on electron waves, Ashour-Abdalla and Thorne (1977) undertook a refined calculation of spatial and temporal growth rates, using a gentle ion loss cone distribution modeled upon observations and including cold electrons and ions. Just as their preliminary results appeared in print, so also did the Hawkeye observation of Gurnett and Frank (1977).

Fig. 4. Broadband electrostatic noise on auroral lines of force. Reproduced here from Gurnett and Frank (1977) is a spectrum of broadband electrostatic noise, which peaks at several times the proton cyclotron frequency. This noise was typically observed at intermediate latitudes on auroral lines of force.
In Fig. 4, we reproduce a spectrum of what Gurnett and Frank (1977) call broadband electrostatic noise. We note the following features:

1) The spectrum peaks at two to three times the ion cyclotron frequency.
2) The ion waves are observed on auroral field lines, consistent with the observed location of diffuse proton precipitation.
3) The observed amplitudes are sufficient to put protons on strong diffusion.

The fact that Hawkeye could only observe the broadband electrostatic noise at intermediate latitudes ($\lambda \sim 45^\circ$) makes theoretical arguments concerning their free energy source somewhat ambiguous. We could try to extend primarily ionospheric free energy sources (currents, beams) outwards, or we could extend equatorial sources (loss cone) to intermediate latitudes. Hopefully, this ambiguity will be cleared up by future observations, especially near the equatorial plane. We also note that electron cyclotron harmonic waves were not present at intermediate latitudes, which seems prima facie inconsistent with the observed simultaneous precipitation of electrons and protons. However, there is some indication that electrostatic electron cyclotron waves may be confined near the equatorial plane (Kennel et al., 1970) which needs to be clarified by further observation (Fredricks and Scarf, 1973).

![Fig. 5. Temporal and spatial growth rate of the ion loss-cone instability. Reproduced here from Ashour-Abdalla and Thorne (1977) is the temporal growth rate (top panels) and the spatial growth rate (bottom panels) plotted against frequency for the first few ion harmonics. The parameters chosen correspond to $L=10$ at the geomagnetic equator. $N_C$ and $N_H$ are the cold and hot ion and electron densities. $T_{\parallel H}$, $T_{\parallel E}$ are the hot ion and electron temperature. To have instability at all, it is necessary to choose $T_C \approx 100$ eV when $N_C/N_H \approx 0.1$. To have large spatial growth rates given instability, it is necessary that the cold ions remain cold (in this case 5 eV). For these conditions, the spatial growth rate favors the first few ion harmonics, consistent with observation (Gurnett and Frank, 1977).](image-url)
On the hypothesis that electrostatic ion cyclotron waves are responsible for diffuse auroral proton precipitation, we choose to consider them from the point of view of an equatorial free energy source. This requires that the broadband electrostatic noise extend from midlatitudes through the equatorial plane, so that it can interact with a large portion of the auroral proton population. With these preliminaries, we now return to the calculations of Ashour-Abdalla and Thorne (1977). They found that the cold ion temperature controls the spatial growth rate of the ion harmonic modes, in complete analogy with the electron modes. Moreover, as is shown in Fig. 5, the spatial growth rate peaks at low ion harmonics, in agreement with the above observations, whereas the temporal growth rate would peak at much higher frequencies, consistent with the original temporal growth rate calculation of Coroniti et al. (1972). Since in a spatially inhomogeneous system in steady state, one must use the spatial growth rate, we conclude that the electrostatic ion cyclotron harmonic loss cone instability can account for the observed spectrum, provided that

![Electrostatic Ion Cyclotron Waves: First Harmonic](image)

**Fig. 6.** Cold electron damping of electrostatic ion cyclotron waves. For the parameters shown in the figure, $T'_C = 5 \text{ eV and constant}$, and a gentle loss-cone distribution of hot ions (as defined in Ashour-Abdalla and Thorne (1977)), we have plotted the marginal stability boundary in $N_c/N_H$, $T_C/T_H$ space, where $T_C$ is the cold electron temperature. This plot illustrates the importance of cold electron Landau damping. The $T'_C^{-3/2}$ dependence may be understood as follows. A critical number of electrons with speeds near the ion wave phase speed, roughly the hot ion thermal speed, can damp the wave. For larger $T_C$, this critical number comprises a smaller fraction of the cold electron distribution, and so a larger total $N_C$ is required to damp the wave. Changing the strength of the hot ion loss-cone distribution can move this marginal stability boundary up and down, but will not change our general conclusion. Since we believe $N_C/N_H$ cannot be too small on auroral field lines ($N_C$ comes from precipitation neutralization) $T_C$ must be of the order of 100 eV to permit the ion loss-cone instability to grow.
nonlinear effects do not selectively suppress lower harmonic modes (which seems unlikely).

Whereas ions play no role in the electrostatic electron cyclotron instability, cold electrons determine whether or not the ion cyclotron harmonic waves can be unstable at all. Even a few electrons with speeds near the hot ion thermal speed can suppress the ion harmonic instability by their Landau damping. In Fig. 6 we plot the marginal stability boundary in a \((N_c/N_H, T_c/T_H)\) space where \(N_c\) and \(N_H\) are the cold electron and ion cold and hot densities, \(T_c\) is the cold electron temperature and \(T_H\) is the hot ion mean energy. The ions had a loss-cone distribution similar to those used in Ashour-Abdalla and Thorne (1977). For the parameters chosen, a fractional density \(N_c/N_H \sim 10^{-3}\) of \(T_c = 1\) eV electrons will suppress the instability. Since \(0.1 \leq N_c/N_H \leq 1\) on auroral field lines, ion loss-cone instability is possible only if the cold electron temperature is of the order of 100 eV. That is why we chose 100 eV in the preceding plot (Fig. 5).

Now let’s go through the logic. Broadband electrostatic ion harmonic waves exist. Our hypothesis of an equatorial loss-cone free energy source thus stands or falls on the question of the cold electron temperature deep in space on auroral field lines. We have no experimental information on this crucial parameter. We doubt that the electrons will be as cold as they are in the ionosphere (\(\approx 1\) eV), for several reasons:

1) Precipitation neutralization could actually be carried out by backscattered secondary electrons with a few hundred eV electrons.

2) Let us suppose that precipitation neutralization can actually be carried out by 1 eV particles initially. It is difficult to imagine that these electrons arrive at the equator with 1 eV after passing through the highly turbulent high latitude regions of the auroral lines of force.

3) Should the electrons manage to arrive at the equatorial plane with 1 eV energy, they would induce strong spatial growth rates for the electron cyclotron harmonic waves, which we can infer are present from the simultaneous observation of electron and proton diffuse aurora. A 1 eV electron can be heated to 100 eV in about 100 sec by 1 mV/m electron waves (Ashour-Abdalla and Kennel, 1978).

5. Discussion

We have highlighted attempts over the years to construct a self-consistent conceptual model of the interaction of the convecting plasma sheet and the night-side auroral ionosphere which includes the plasma turbulence responsible for particle precipitation. Up to now, this set of ideas has started with the density and temperature of the plasma sheet and a given driving convection electric field and then involves:

1) Particle precipitation fluxes and charge neutralization return fluxes

2) Inhomogeneous ionospheric conductivity profiles
3) Action of finite ionospheric conductivity and plasma pressure on the convective flow pattern

4) Locating field-aligned currents (exclusive of those in smaller scale structures such as arcs)

5) Implicitly, through field-aligned currents, current instabilities, parallel electric fields, and the generation and instability of fast ion and electron streams

6) Providing sources of free energy for the instabilities responsible for particle precipitation

7) Estimating self-consistently the plasma environment in which instabilities grow and saturate

A sketch of the elements of such a conceptual model is shown in Fig. 7. For every box in Fig. 7 there has been considerable theoretical and experimental effort over the past decade, but a complete linkage has to be made. In this paper, we have concentrated upon the right-hand side of this sketch, where the plasma turbulence fits in.

Clearly, more experimental and theoretical work on all elements of this conceptual model would be valuable. In the case of the electrostatic ion and electron cyclotron harmonic instabilities, which in our opinion are the best candidates for explaining diffuse auroral precipitation, we may list two important experimental objectives:

a) Determination of the cold electron temperature, and better yet, the distribution function on auroral field lines. We have concluded that further theoretical

Fig. 7. Elements of self-consistent models. Coupling convection, precipitation, and the ionosphere. Here is our version of the flow diagram relating the elements of these models. We believe important questions concerning electrons and ions of ionospheric origin flowing into the magnetosphere must be answered experimentally before theory can complete the linkages between elements sketched above.
progress on cyclotron harmonic instabilities will be limited until we know the electron temperature.

b) A complete phenomenological understanding of ion harmonic modes. Are they found near the equator, or on the dayside where the cold electron density should be higher? The situation with electron cyclotron harmonic instabilities is somewhat better, but still needs improvement.

We may also list two theoretical objectives:

a) Modelling the cold electron distribution on auroral field lines.

b) Improving our understanding of nonlinear saturation of the instabilities. In particular, since the wave energy density can exceed the cold plasma energy density, it is unlikely that an originally locally smooth cold plasma density profile can remain so.

One final comment for the future. Up to now, people have generally assumed that the ionospheric plasma source was a passive partner in the chain of interaction. We have already seen that this is not so. Cold electrons of ionospheric origin control the properties of electrostatic cyclotron instabilities. Clearly, we have underestimated the importance of the ionospheric source. We may not even know the ion composition on auroral field lines. Heavy ions have been observed streaming out of the auroral ionosphere and have also been observed in the geomagnetic tail and in the ring current at disturbed times. How are these ions accelerated? Do beam instabilities scatter them onto trapped orbits? How are these ions lost? Do they convect to the magnetopause, are they charge exchanged, do they have instabilities which can reprecipitate them to the ionosphere? These questions are sketched in Fig. 8. Questions such as these we believe are on the frontier of the problem of the coupling of the plasma sheet to the auroral ionosphere.
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