Large plasma velocities along the magnetic field line in the auroral zone

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In the auroral zone, ionospheric plasma often moves horizontally at more than 1 km s^{-1}, driven by magnetospheric electric fields, but it has usually been assumed that vertical velocities are much smaller. On occasions, however, plasma has been seen to move upwards along the magnetic field line at several hundred m s^{-1}. These upward velocities are associated with electric fields strong enough to heat the ion population and drive it into a non-thermal state[1,2]. Here we report observations of substantial upwards acceleration of plasma, to velocities as high as 500 m s^{-1}. An initial upthrust was provided by a combined upwelling of the neutral atmosphere and ionosphere but the continued acceleration at greater heights is explained by a combination of enhanced plasma pressure and the 'hydrodynamic mirror force'[3]. This acceleration marks an important stage in the transport of plasma from the ionosphere into the magnetosphere.

In the night sector of the auroral ionosphere large upward velocities along the magnetic field line have occasionally been recorded by EISCAT, the European incoherent scatter radar[4]. These events have usually occurred several degrees of latitude to the north of EISCAT, and are associated with electric fields of 40 mV m^{-1} or more[5,6]. The plasma velocity vector was determined by a matrix inversion of the three separate components of velocity as measured by the three EISCAT antennas. This gave an estimate of the field-aligned velocity at only a single height, which was subject to very large random errors from the unfavourable measuring geometry[7]. Large errors also affected the EISCAT measurement, even farther north, of downward velocities of 400 m s^{-1} (ref. 8).

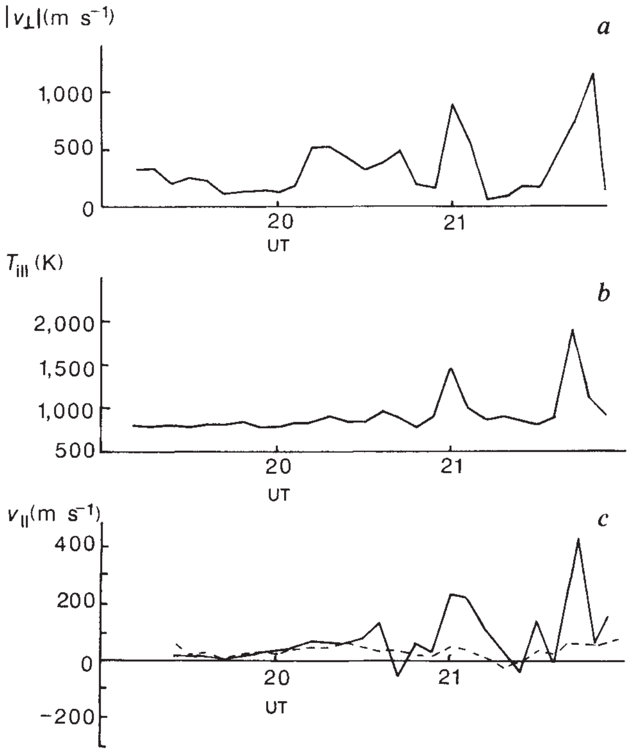

Fig. 1 Time variation of *a*, the magnitude of plasma velocity perpendicular to the magnetic field line; *b*, the ion temperature measured parallel to the field line at 300 km; and *c*, the plasma velocity parallel to the field line at 300 (dashed line) and 500 (solid line) km, as measured by EISCAT on 6 May 1987.

On 6 May 1987, two such events were observed at 21:06 and 21:42 UT, farther south than usual and lying on the magnetic field line that passes through the EISCAT transmitter. As a consequence, the field-aligned plasma velocity $v_{\parallel}$ was measured directly at all heights between 150 and 550 km with errors of $\leq$30 m s^{-1}. The EISCAT measurements are summarized in Figs 1 and 2, which show variations with time and height respectively.

During the two events, $v_{\parallel}$ at 300 km lay in the range 50–90 m s^{-1}, but it increased steadily with height until at 550 km values of 300–500 m s^{-1} were recorded. These upward velocities were equivalent to ion fluxes of 3–5$\times 10^{13}$ m^{-2} s^{-1}, an order of magnitude larger than the usual steady-state ionospheric outflow (the 'classical polar wind'[9]). In general, we expect four factors to determine $v_{\parallel}$: (1) the meridional component of the neutral wind; (2) vertical upwelling of the neutral atmosphere as a result of strong, localized Joule heating; (3) the gradient of plasma pressure in the topside ionosphere; and (4) gravity. Under quiet conditions, (1), (2) and (4) combine to drive a low flux ($\sim 10^{12}$ m^{-2} s^{-1}) of light ions from the top of the ionosphere. The application of a large electric field can, however, cause strong Joule heating of the neutral atmosphere in the upper E-region. It is estimated that under typical conditions the consequent upwelling of the atmosphere drives the plasma upwards with a velocity of 50–100 m s^{-1}, which is the upward velocity often seen in the midnight sector[10]. But these factors cannot explain velocities of 500 m s^{-1}, although such an initial upward velocity is essential in creating the opportunity for a much greater acceleration.

When the electric field is strong enough to drive the plasma perpendicular to the magnetic field line at a speed greater than the ion-acoustic speed, resonant charge exchange between the oxygen atoms and oxygen ions, and to a lesser extent other collisions, transfer energy to the ion population by frictional heating and change the ion velocity distribution from a Maxwellian towards a toroidal form[1,2]. Once the ion velocity distribution becomes anisotropic, the plasma becomes subject to a 'hydrodynamic mirror force' as a result of the divergence of the magnetic field lines with increasing height[3], and this acts in addition to the enhancement in upward pressure gradient from the increase in $T_{i\parallel}$, the ion temperature measured along the magnetic field line (see Fig. 2*a*).

Near the F-region peak, O–O$^+$ collisions cause a frictional drag. If we accept the commonly quoted value of the O–O$^+$ collision cross-section this would inhibit any large increase in upward velocity. Recent measurements have indicated, however, that the collision frequency may be smaller by a factor of two to three[11] (although other reports suggest an increase[12]). In either case the frictional drag decreases rapidly with increasing height in proportion to the drop in oxygen density, so that if the upwelling of the neutral atmosphere can carry the ions above 400 km, thereafter the combination of enhanced plasma pressure and the mirror force will accelerate the plasma with decreasing resistance.

Using the lower value of $\nu_{O\text{-}O^+}$ together with the MSIS86 model of the neutral atmosphere[13], we can estimate the frictional drag at each height. From the measured profiles of electron concentration, electron temperature and $T_{i\parallel}$ we can determine the gradient of plasma pressure. From the measured strength of the electric field we can determine the mirror force. If we take as the boundary condition the observed upward velocity at 300 km (50 and 90 m s^{-1} at 21:06 and 21:42 UT respectively) we predict a height profile of upward plasma velocity that is in good agreement with the observations (Fig. 2*b*).

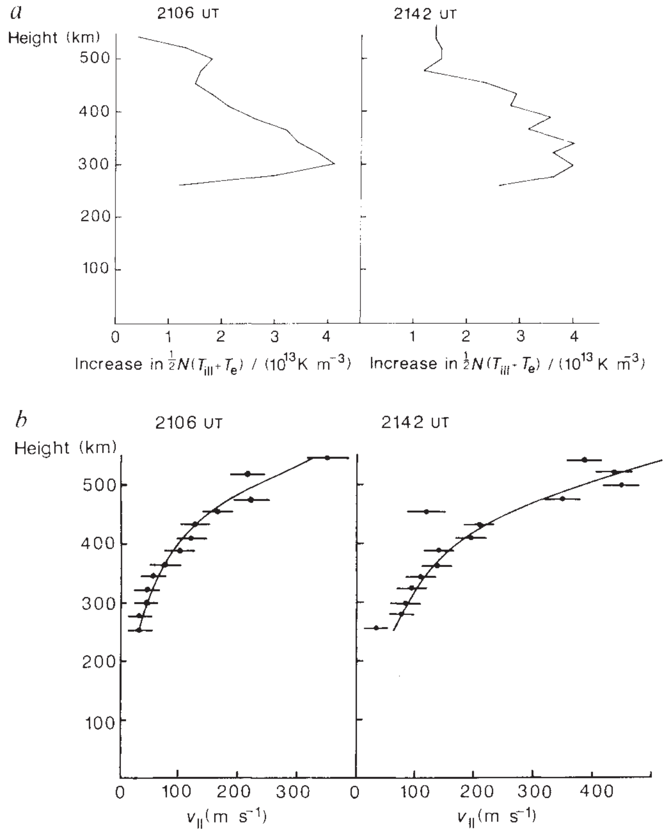

Fig. 2 Height profiles of *a*, the increase in plasma pressure at 21:06 and 21:42 UT on 6 May 1987 (N is the electron concentration and T_e is the electron temperature); *b*, the observed and model values of plasma velocity parallel to the magnetic field line during the two events. Observed values are dots with error bars, and predicted values are solid curves.

In determining the values of $T_{i\parallel}$ we have assumed that in the topside of the ionosphere the ion population is dominated by O^+. During upwelling it is possible that molecular ions might form a significant proportion of the ionospheric plasma at 300 km, in which case the true increase in $T_{i\parallel}$ at this height would be even more than our measurements suggest. At greater heights we can be certain that the proportion of molecular ions is negligible, so that if upwelling of molecular ions occurs the effect of plasma pressure will be even stronger than we have calculated.

This observed acceleration is transient, not steady-state. A strong electric field obviously plays a key role, by driving the Pedersen currents which cause Joule heating and an upwelling of the neutral atmosphere. It also drives the ion population at high speed through the neutral atmosphere, which leads to frictional heating and an enhanced gradient of plasma pressure, as well as the formation of an anisotropic ion-velocity distribution which brings the hydrodynamic mirror force into play.

But a strong electric field is not enough in itself; if it were, large upward velocities would be more common. It is also necessary that soft particle precipitation (<1 keV) create sufficient conductivity in the upper E-region for the Joule heating to be intense. On 6 May 1987 such precipitation was indicated by the increased ionization at ~150 km which was observed between a sharp onset at 21:00 and an equally sharp cutoff at 21:48 UT. The degree of frictional heating is also much greater if the neutral velocity is in the opposite direction to the plasma velocity: these conditions occur in the region of the Harang discontinuity, and it is precisely in this region that the large upward velocities reported here were observed.

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Where do channels begin?

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The closer channels begin to drainage divides, the greater will be the number of channels that occupy a unit area, and consequently the more finely dissected will be the landscape. Hence, a key component of channel network growth and landscape evolution theories[1-7], as well as models for topographically controlled catchment runoff[8], should be the prediction of where channels begin. Little field data exist, however, either on channel head locations[9-14] or on what processes act to initiate and maintain a channel[14-17]. Here we report observations from several soil-mantled regions of Oregon and California, which show that the source area above the channel head decreases with increasing local valley gradient for slopes ranging from 5 to 45 degrees. Our results support a predicted relationship between source area and slope for steep humid landscapes where channel initiation is by landsliding, but they contradict theoretical predictions for channel initiation by overland flow in gentle valleys. Our data also suggest that, for the same gradient, drier regions tend to have larger source areas.

We selected three areas in Oregon and California for a study of channel-head source areas on the grounds of accessibility, the range of slopes available, and their climatic and geological setting. The Coos Bay, Oregon, study area is located within an actively logged Douglas Fir (*Pseudotsuga mensiezii*) forest on private land in the Oregon Coast Range, is underlain by folded Palaeocene basalts and gently dipping Eocene sandstones[18], and receives a mean annual rainfall of ~1,500 mm (ref. 19). Of the 71 channel heads mapped in this area, 19 are associated with small-scale landslide scars, all of which predate recent logging activity. The plot of source area size against the local valley gradient at the channel head indicates a strong inverse correlation (Fig. 1*a*).

The southern Sierra Nevada study area is composed of two drainage basins on the Rankin Ranch, ~45 km east of Bakersfield, California. The region is covered by open oak woodland and grasslands, is underlain by Cretaceous granitic rocks[20] and receives an annual rainfall of ~260 mm (ref. 19). Evidence of previous landsliding and seepage erosion at abrupt channel heads was noted on steeper slopes; channels on gentle slopes, however, generally begin gradually and with evidence of overland flow. Most of the 33 channels mapped in this area begin as discontinuous channel segments. We defined a channel head as the farthest upslope location of a channel with well defined banks. The plot of source area against local hillslope gradient at the channel head for the southern Sierra data (Fig. 1*b*) also defines a clear inverse relationship. These data differ