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Formation of the Stable Auroral Arc That Intensifies at Substorm Onset

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Engineering and Technology Group

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FORMATION OF THE STABLE AURORAL ARC THAT INTENSIFIES AT SUBSTORM ONSET

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Abstract. In a companion paper, we present observational evidence that the stable, growth-phase auroral arc that intensifies at substorm expansion phase onset often forms on magnetic field lines that map to within ~1 to 2 R_e of synchronous. The equatorial plasma pressure is 1 to 10 nPa in this region, which can give a cross-tail current > 0.1 A/m. In this paper, we propose that the arc is formed by a perpendicular magnetospheric-current divergence that results from a strong dawn-to-dusk directed pressure gradient in the vicinity of magnetic midnight. We estimate that the current divergence is sufficiently strong that a > 1 kV field-aligned potential drop is required to maintain ionospheric-current continuity. We suggest that the azimuthal pressure gradient results from proton drifts in the vicinity of synchronous orbit that are directed nearly parallel to the cross-tail electric field

Introduction

A fundamental feature of an auroral substorm is the intensification and break-up of a pre-existing, stable auroral arc at the onset of the expansion phase [e.g., Akasofu, 1964; Fukunishi, 1975]. The intensification is accompanied by the abrupt decrease in the magnitude of the horizontal magnetic field measured on the ground that is traditionally used to identify the onset of the substorm expansion phase. Understanding the auroral intensification is critical to understanding the physics of magnetospheric substorms. A prerequisite for this is a determination of the processes that lead to the formation of the arc that intensifies. However, there has been remarkably little attention given to this topic. Here we use observed features of the pre-intensification arc and of the magnetosphere prior to substorm onset (during the period referred to as the "substorm growth phase") to construct a theory for the formation of the arc.

The visible arc is extended in longitude and narrow in latitude (~1 to 10 km). Such narrow arcs typically result from precipitating electrons having distributions of the form associated with significant (more than a few hundred eV) acceleration by magnetic field-aligned potential drops, $\phi_{\parallel}$ [Lyons, 1992, and references therein]. We presume that the pre-intensification arc results from such accelerated electrons, so that understanding the arc's formation requires understanding the formation of a significant $\phi_{\parallel}$. Here we put forward a proposal for how this $\phi_{\parallel}$ is formed over a longitudinally extended region. We do not, however, consider how the visible arc becomes very narrow.

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Observational Basis

In the companion paper [Samson et al., 1992b], we show that the arc forms within a 1° to 2° wide latitude region of intense atmospheric emissions from proton precipitation. We present evidence that the precipitation occurs along magnetic field lines that are ~5° equatorward of the open-closed field-line boundary and cross the equator at radial distances of ~5 to 10 R_e on the night side. The 1° to 2° latitudinal width for the emissions is an upper limit to that of the actual proton precipitation from the magnetosphere since charge exchange spreads emissions from a very narrow beam over nearly 2° in latitude [Davidson, 1965]. Mapping this width to the equator implies that the equatorial source region for the intense atmospheric emissions is $\lesssim$ 1 to 2 R_e in radial extent. It has also been found [Baumjohann et al., 1981; Robinson and Vondrak, 1990; Samson et al., 1992a] that the pre-intensification arc lies equatorward of the ionospheric reversal in the north-south electric field known as the Harang discontinuity.

Auroral arcs nearly always occur in regions of isotropic (in pitch angle) proton precipitation [Lyons et al., 1988], and such precipitation is expected to result from violation of the guiding-center approximation within the dawn-to-dusk, cross-tail current sheet [Sergeev et al., 1983; Lyons and Speiser, 1982]. Sergeev et al.'s calculations show that only modest equatorial magnetic-field distortions within the current sheet are necessary for the precipitation to be isotropic, and that isotropic precipitation should occur from the entire radial extent of the cross-tail current. Samson et al.'s [1992b] observations show that the pre-intensification arc forms in the region of strongest precipitating proton energy fluxes. Thus, its equatorial source region must be the portion of the cross-tail current sheet that has the highest particle pressures during the growth phase.

The nightside distribution of plasma sheet pressure versus radial distance for periods shortly preceding substorm expansion phase onsets has recently been analyzed by Kistler et al. [1992]. Their observations were somewhat off the equator, so they presented the total pressure (plasma plus magnetic). They argued that the particle pressure should dominate the magnetic pressure at the equator, so that the total pressure should be a good indicator of the plasma pressure at the equatorial crossing of a field line. We adopt this assumption to estimate equatorial pressures in the present analysis, though it may lead to some errors at the lower radial distances (~5 to 7 R_e) considered here due to finite equatorial magnetic pressure.

Kistler et al [1992] found that the pre-onset pressure increases monotonically with decreasing radial distance, reaching 1.5 nPa at 10 R_e and 4 nPa at 7 R_e. They had no observations further earthward. Spence et al. [1989] compiled observations that show the plasma pressure increasing to ~10 nPa near 5 R_e, though these observations were not sorted by substorm phase. Based on these studies, we conclude that the highest plasma sheet pressures during a substorm growth phase are at equatorial radial distances of ~5 to 10 R_e. This agrees with the location of the source region for the intense proton precipitation inferred by Samson et al. [1992b]. The ~1 to 10 nPa pressures within this region and their monotonic increase with decreasing radial distance presumably result from the earthward convection of ions into regions of increasing magnetic field strength, B. The observation of magnetic field distortions near synchronous orbit during the growth phase of substorms [McPherron et al., 1973; Thomas and Hedgecock, 1975] is consistent with having high plasma pressures and with the isotropic precipitation of protons from this region via violation of the guiding center approximation.

To estimate the growth-phase, cross-tail current near synchronous orbit, we assume pressure balance and a total pressure of 5 nPa. This gives a magnitude for the x-component of the lobe magnetic field of 112 nT. (Here x is normal to the cross-tail current and parallel to the plane of the tail current sheet, and z is normal to the plane of the current sheet). In agreement with this, increases in the x-component of B to ~110 nT have been seen during the growth phase of substorms at synchronous orbit [McPherron and Manka, 1985, and two examples in Figure 7 of Nagai, 1987]. Neglecting the variation of B_z with x, a lobe field strength of 110 nT implies a cross-tail current (integrated over z) of magnitude 0.175 A/m. This is consistent with the magnitudes of 0.3 A/m and > 0.1 A/m inferred from magnetic field observations near synchronous orbit during the substorm growth phase by Pulkkinen et al. [1991] and Kaufmann [1987], respectively.

Theory

Here we show that a growth-phase plasma pressure of ~5 nPa near synchronous orbit can lead to the formation of the pre-intensification arc provided the pressure has a sufficiently large azimuthal gradient in the dawn-to-dusk direction. We also propose that the required azimuthal gradient exists near synchronous orbit and that it results from the predominant particle drift in the direction of the cross-tail electric field. Here we use "near synchronous orbit" to mean a region within about 1 to 2 R_e of synchronous orbit.

The precipitating electrons that form auroras carry an upward field-aligned current. However, the maximum current density $j_{||}$ that can be carried by these electrons is given by $j_{||,max} = en(K_{th}/2\pi m_e)^{1/2}$ for $\phi_{||} = 0$. Here n and K_{th} are, respectively, the density and thermal energy of the magnetospheric electron distribution. For $n = 1\ cm^{-3}$ and $K_{th} = 300$ eV, $j_{||,max} = 5 \times 10^{-7}\ A/m^2$. It is necessary that $e\phi_{||} > K_{th}$ for electrons to carry a larger $j_{||}$. Such a $\phi_{||}$ increases the electron flux within the loss cone for a given magnetospheric value of n and K_{th}. Auroral arc field lines have $j_{||} > 5 \times 10^{-7}\ A/m^2$, which requires that the electrons are accelerated by a $\phi_{||} > 300$ V [see Lyons, 1992, and references therein]. Thus, understanding the formation of the pre-intensification arc amounts to understanding what drives an upward $j_{||} > 5 \times 10^{-7} a/m^2$.

To evaluate $j_{||}$, we make use of the relation [Vasyliunas, 1970; Birmingham, 1992] between $j_{||}$, the plasma pressure P, and the flux tube volume V.

$$j_{||} = (B_i/B_E)\,\hat{\mathbf{B}} \cdot \nabla P \times \nabla V \tag{1}$$

for isotropic pressure. This relation is obtained from the balance between $j_{||}$ and the divergence of the magnetospheric current perpendicular to **B**. Here $j_{||}$ is the upward current density at the ionosphere and B_E and B_i are the magnetic field intensities at the equator and in the ionosphere; the gradient operator is evaluated at the equator, and $V = \int ds/B$ is evaluated from the equator to the ionosphere.

Near synchronous orbit, ∇V is directed nearly radially outward, and we expect the radial component of ∇P to be directed inward. Thus, it is necessary that ∇P and/or ∇V have an azimuthal component directed from dawn to dusk in order to drive an upward field-aligned current. Such an azimuthal gradient should also modify magnetospheric electric fields and thus particle drifts. This is because $j_{||}$ must be consistent with current continuity in the ionosphere as well as the magnetosphere, and it is necessary to have $\nabla \cdot \mathbf{E} < 0$ in the magnetosphere to have an upward directed $j_{||}$ from the ionosphere (Lyons [1992], and references therein). As a result, a divergence of the perpendicular magnetospheric current must modify the magnetospheric electric field (via small accumulation of negative charge density) sufficiently to give $\nabla \cdot \mathbf{E} < 0$ and current continuity in both regions. Iijima et al. [1992] suggested that growth-phase, field-aligned currents could result from an inward radial component to ∇V. We do not consider this possibility here since the increase in plasma pressure with decreasing radial distance is consistent with the usual increase in equatorial B and thus an outwardly directed ∇V.

To illustrate our proposal for forming the azimuthal pressure gradient, we show sketches of equatorial proton trajectories and equipotentials in Figure 1. The trajectories are based on calculations by Chen et al. [1992] for equatorially mirroring 20 MeV/Gauss protons (which corresponds approximately to the precipitating ion energies in Samson et al. [1992b]), and the equipotentials are based on those for a uniform convection electric field added to corotation. Both the trajectories and the equipotentials have been qualitatively adjusted for expected effects of azimuthal pressure gradients.

Two related features of the ion motion on the night side that can give rise to a dawn-to-dusk directed pressure gradient

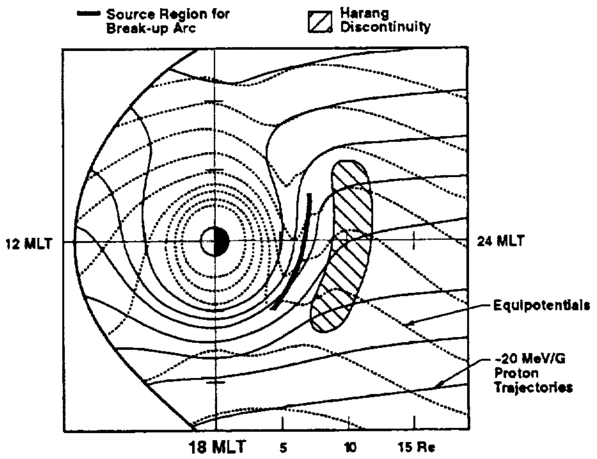

Fig. 1. Sketch of proton trajectories and equipotentials in equatorial plane during a substorm growth phase. Trajectories are based on those for 20 MeV/Gauss protons; equipotentials are based on those for a uniform cross-tail electric field plus corotation. Both have been qualitatively adjusted for the expected effects of azimuthal pressure gradients near the Harang discontinuity and the source region for the pre-break-up arc.

are included in Figure 1. First, as ions convect earthward from the tail, magnetic drift and a reduced particle source from the tail flanks (relative to that from the far tail) causes a depletion of ions on the dawn side relative to the dusk side and a dawn-to-dusk gradient in particle pressure [Erickson et al., 1991; Spence and Kivelson, 1992]. This causes a divergence of current across the tail that must be balanced by upward field-aligned currents. This requires $\nabla \cdot \mathbf{E} < 0$ in the tail, which results in an x-component of electric field that reverses in direction. Erickson et al. [1991] and Liu and Rostoker [1991] proposed that this feature of the ion motion is responsible for the Harang discontinuity. The model of Erickson et al. shows the electric field reversal to occur at a radial distance of $\sim 10\ R_e$.

The negatively charged region associated with the Harang discontinuity is identified by the shading and associated distortion of equipotentials in Figure 1. The x-component of electric field in the tail in this region maps to the ionosphere as the north-south electric field that reverses direction at the Harang discontinuity. The x-component of electric field also modifies magnetospheric particle drifts. The earthward-directed electric field beyond $\sim 10\ R_e$ causes a drift towards dawn that partially cancels the magnetic drift towards dusk. This may allow protons to drift closer to the Earth than they would otherwise, which could increase the plasma pressure and the cross-tail current near and within $10\ R_e$.

The second feature of the ion motion that can cause a dawn-to-dusk pressure gradient occurs as ions drift earthward of $10\ R_e$. Here the magnetic drift speed increases significantly relative to the electric drift speed, and ion drifts become predominantly azimuthal. The tailward-directed electric field component earthward of $10\ R_e$ adds to this azimuthal drift. Near midnight, the azimuthal drift causes proton trajectories to become approximately parallel to the cross-tail electric field. This is illustrated in Figure 1 as occurring between about 5 and $8\ R_e$. As a result, protons should gain considerable energy as they drift towards dusk, which may lead to a significant azimuthal pressure gradient earthward of that considered by Erickson et al. [1991] and Liu and Rostoker [1991].

We propose that this azimuthal pressure gradient develops in the region of large plasma sheet pressure and cross-tail current near synchronous orbit and causes the formation of the pre-intensification arc. This proposal is supported by the observation [Baumjohann et al., 1981; Robinson and Vondrak, 1990; Samson et al., 1992a] that the arc lies equatorward of the ionospheric mapping of the Harang discontinuity in a region of northwest-directed electric fields. The northward component is expected from the ionospheric mapping of the tailward-directed component within $\sim 10\ R_e$, and the westward component is expected from the mapping of the cross-tail electric field. Robinson and Vondrak found the westward electric field to be 10 to 20 mV/m within the arc. This gives a 7 to 14 keV energy gain for each hour of local time that a proton drifts along the arc's direction. Kistler et al.'s [1992] observations show thermal energies of ~20 keV near synchronous orbit, so that an azimuthal drift of 1 to 3 hr in local time should roughly double the energy of a typical proton.

To evaluate our proposal's feasibility, we use Eq. (1) to estimate the intensity of $j_{||}$ and to thus determine whether a significant $\phi_{||}$ is required. Kistler et al.'s [1992] observations show the equatorial pressure gradient near $7\ R_e$ to be $\partial P/\partial r \approx -2\ \mathrm{nPa}/R_e$. It would be desirable to evaluate ∇V in a magnetic field model self-consistent with an assumed pressure distribution. However, here we obtain an estimate for $\partial V/\partial r$ by simply taking its dipole value $1.83 L^3/B_0\ \mathrm{m}^3/R_e$, where B_0 is the equatorial surface-field strength. To estimate the azimuthal gradient of P, we assume that the pressure increases by 2nPa over 2 hr in local time. We also assume that the magnetic field stretches as P increases so that the equatorial magnetic field strength decreases as P increases. This gives an azimuthal gradient in V, which we take to be a doubling of the dipole value over 2 hr in local time. (We cannot find much literature on nightside azimuthal pressure or magnetic field gradients, but Fairfield [1986] found equatorial magnetic field magnitudes on the dusk side of the tail to be about 1/3 of those near midnight at $-20 < x < -10\ R_e$.) For $L = 7$, these values give the estimate that $j_{||} = 3 \times 10^{-6}\ \mathrm{A/m^2}$, the contributions from the assumed azimuthal gradients of P and V being approximately equal. This is 6 times greater than the maximum current density estimated above for $\phi_{||} = 0$, and it thus requires a $\phi_{||}$ of a few kV. This is required to form the pre-intensification arc.

The distortion of equipotentials in the vicinity of the arc source region is schematically illustrated in Figure 1. In the figure, we show the source region for an actual arc to be narrower than the 1 to $2\ R_e$ region of distorted potentials associated with the upward field-aligned current; however, we offer no explanation at this time for this narrowness.

Conclusions

We have discussed observational evidence that the auroral arc that intensifies at substorm onset is formed on magnetic field lines that map to within ~1 to $2\ R_e$ of synchronous orbit, where plasma pressures are ~1 to 10 nPa during the substorm growth phase. These large pressures cause an enhanced cross-tail current, which may have a magnitude > 0.1 A/m. This current is associated with a distortion of the magnetic field that should be sufficient to isotropize proton pitch-angle distributions via violation of the guiding center motion. This will cause the proton precipitation observed in the vicinity of the pre-intensification arc.

We propose that the plasma pressure in this region has a strong dawn-to-dusk directed gradient, which drives a field-aligned current upward from the ionosphere. We estimate that the magnitude of $j_{||}$ is sufficiently large that a field-aligned potential drop $\phi_{||} \gtrsim 1$ kV is necessary for precipitating electrons to carry the current. This potential drop energizes the precipitating electrons that form the arc. As illustrated in Figure 1, we propose that the pressure gradient results from the azimuthal proton drift near synchronous orbit, which is in the direction of the cross-tail electric field.

We expect the pre-intensification arc to form in the region of northwest-directed (in the northern hemisphere) electric field equatorward of the Harang discontinuity, as has been observed. Also, to maintain current continuity in the ionosphere, we expect the northward component of the electric field to be reduced in the vicinity of the arc, as observed by Robinson and Vondrak [1990] and illustrated in their Figure 14a (also see Samson et al., [1992a]). The related electric potential distribution in the equatorial plane is illustrated in Figure 1. It is reasonable to expect that the substorm expansion phase is initiated on the magnetic field lines of the arc that intensifies. Under this assumption, our proposal is consistent with recent observational evidence [e.g., Lopez et al., 1990, Lui et al., 1992] that a substorm expansion phase is initiated near synchronous orbit via cross-tail current disruption.

Finally, since we expect the protons in the vicinity of synchronous orbit to be precipitated with approximately isotropic distributions, it may be possible to relate proton precipitation measurements to the equatorial plasma pressure during the growth phase. For an isotropic equatorial particle distribution, pressure $P = (4\pi/3)m\int fv^4 dv$, and energy flux per steradian $\varepsilon = (m/2)\int fv^5 dv$, where m is mass and f is the particle distribution function. For a Maxwellian distribution of thermal speed v_{th}, we obtain $\varepsilon = (v_{th}/\pi^{3/2})P$. The total precipitating energy flux, $\varepsilon_P = 2\pi\int \varepsilon \cos\alpha \sin\alpha d\alpha = \pi\varepsilon$, where α is pitch angle, so that for $P = 1$ to 10 nPa and a proton thermal energy of 20 keV, we obtain $\varepsilon_P = 10^{-3}$ to 10^{-2} joules/m^2-s. The optical observations of Fukunishi [1975] and Samson et al. [1992b] imply a proton energy deposition into the atmosphere of 10^{-3} joules/m^2-s (based on 70 R of Hβ emission per 10^{-3} joules/m^2-s [Strickland, private communication, 1992]). This represents a minimum estimate for ε_P because of the ~2° spread in the emissions that results from charge exchange. Proton measurements from polar-orbiting satellites could be used to search for the large values of ε_P we expect. However, such measurement would need to extend to significantly higher energies than are typical. For example, a 20 keV Maxwellian would have 70% of ε_P at energies above the 30 keV upper limit on DMSP satellites, and the fraction would be even higher if a high-energy tail to the distribution were included.

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