Simultaneous ground and satellite observations of an isolated proton arc at subauroral latitudes

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[1] We observed an isolated proton arc at the Athabasca station (MLAT: 62.3°N) in Canada on 5 September 2005, using a ground-based all-sky imager at wavelengths of 557.7 nm, 630.0 nm, and 486.1 nm (H/β). This arc is similar to the detached proton arc recently observed by the IMAGE satellite [Immel et al., 2002]. The arc appeared at 0500–0640 UT (2100–2240 MLT), coincident with strong Pc 1 geomagnetic pulsations in the frequency range of the electromagnetic ion cyclotron (EMIC) wave. The isolated arc did not change its structure and intensity during the late growth and expansive phases of a small substorm that occurred at 0550 UT. From particle data obtained by the NOAA 17 satellite, we found that the isolated arc was associated with the localized enhancement of ion precipitation fluxes at an energy range of 30–80 keV at L ~ 4. Trapped ion flux enhancements (ring current ions) were also observed at two latitudinally separated regions. The localized ion precipitation was located at the outer boundary of the inner ring current. The DMSP F13 satellite observed signatures of an ionospheric plasma trough near the conjugate point of the arc in the Southern Hemisphere. The trough is considered to be connected to the plasmapause. These results indicate that the source region of the isolated arc was located near the plasmapause and in the ring current. We conclude that the observed isolated proton arc at subauroral latitudes was caused by the EMIC waves, which were generated near the plasmapause and resonantly scattered the ring current protons into the loss cone.


1. Introduction

[2] The hydrogen Balmer series emissions (Hα and H/β) were first observed in the aurora via ground-based instruments made at Oslo more than a half century ago [Vegard, 1939]. The Hα and H/β emissions are produced by neutral hydrogen that in turn is created when incident auroral protons pick up electrons in charge exchange collisions. The proton auroral lines observed from ground are Doppler shifted to shorter wavelengths as a consequence of the motion of the hydrogen atoms toward the ground, which in turn is a consequence of the motion of the precipitating protons [Vegard, 1948; Meinel, 1951]. This is very different from the situation with the electron aurora and was in fact the first experimental evidence that aurora of any type is a result of the precipitation into the atmosphere of particles from outer space. The precipitating protons pick up electrons and subsequently loose them in successive collisions as they are decelerated. The electrons that are lost from the hydrogen atoms in these collisions then cause what is referred to as “secondary electron aurora,” so that typical electron auroral emissions are present in all regions of proton precipitation, regardless of whether or not there are precipitating (i.e., primary) electrons [Eather, 1968]. The early study of the proton aurora since its discovery to the late 1960s was reviewed by Eather [1967].

[3] Recently, global images of the proton aurora have been provided by the Far Ultraviolet (FUV) Spectrographic Imager (SI) on board the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite [Burch, 2000; Mende et al., 2000]. The IMAGE SI-12 data show multiple examples of proton arcs spanning several hours of local time that are detached and equatorward from the main proton oval in the afternoon sector [Immel et al., 2002]. This phenomena is referred to as the “detached proton arc.” Using low-altitude satellites, mean energies of the precipitating protons that cause these arcs were found to be 20–30 keV [Immel et al., 2002]. The arcs appear in the afternoon sector during geomagnetically active times when...
the magnetosphere is compressed and the interplanetary magnetic field has rotated from either south to north or from west to east [Burch et al., 2002]. Spasojevic et al. [2004] reported a direct link between a detached proton arc seen in SI-12 images and a plasmaspheric plume that was simultaneously observed in the IMAGE Extreme Ultraviolet (EUV) images and geosynchronous low-energy plasma observations. The mechanism and condition responsible for the proton precipitation are usually ascribed to ion-cyclotron waves that scatter protons into the loss cone in a region populated by both cold plasmaspheric and energetic ring current particles [Jordanova et al., 2001].

[4] In the past, events referred to simply as “detached arcs” were reported in ISIS 2 optical observations [Anger et al., 1978; Moshupi et al., 1979]. The ISIS-2 detached arcs occurred in the dusk-evening sector. Simultaneous ISIS-2 particle data show precipitation of primary electrons [Wallis et al., 1979]. The phenomenology of those detached arcs were similar to those of the more recently observed proton detached arcs. Further, the precipitating protons do create secondary electron aurora and so it is not impossible that the earlier reported detached arcs were indeed proton detached arcs.

[5] Magnetic pulsations in the Pc 1 and Pc 5 frequency range were observed in the vicinity of a detached proton arc [Immel et al., 2005]. The Pc 1 magnetic pulsations have a similar frequency to that of the ion cyclotron waves in the equatorial plane.

[6] Fraser et al. [2005] reported two case studies using fluxgate magnetometer data from the GOES-8 and GOES-10 geosynchronous satellites that EMIC waves are observed within plasma plumes extending to geosynchronous orbits.

[7] A close relationship between the localized (within ~1° in latitude) enhancement of proton (>30 keV) precipitation observed by low-altitude satellites and the Pc 1 pulsation recorded on the ground was reported by Yahnina et al. [2000, 2002] in the subauroral region. Their findings support the ion cyclotron mechanism of the Pc 1 generation according to which both wave generation and particle scattering occur in the source region. However, there have been no simultaneous observations of proton precipitation, proton arc, and Pc 1 geomagnetic pulsation at subauroral latitudes yet.

[8] In this paper we report the ground-based observation of an isolated proton arc, which appeared when intense geomagnetic Pc 1 pulsations were observed in the premidnight sector at 1830–2300 MLT. The arc corresponds to a localized enhancement of the precipitating ions which was isolated equatorward from the main ion oval. This isolated proton arc is very similar to the detached proton arc observed by the IMAGE satellite.

2. Observation

[9] We have been conducting an auroral observation using a high sensitive all-sky imager, an induction magnetometer, and a meridian-scanning filter-tilting photometer at Athabasca, Canada, since September 2005. Athabasca (54.7°N, 246.7°E, magnetic latitude (MLAT): 62.0°N) is located in the subauroral region at L ~ 4. The imager and the photometer are part of the Optical Mesosphere Thermosphere Imagers (OMTIs) [Shiokawa et al., 1999, 2000]. The all-sky imager uses a thinned and back-illuminated cooled charge coupled device (CCD) with 512 × 512 pixels and has seven interference filters that transmit wavelengths of 557.7-nm (O, filter bandwidth: 1.76 nm), 630.0-nm (O, 1.64 nm), 720–910 nm (infrared OH-band), 486.1-nm (H/Ι, 1.32 nm), 572.5-nm (background), 844.6-nm (O, 1.30 nm), and 589.3-nm (Na, 1.56 nm). In this study we use auroral images with a time resolution of 2 min for 557.7-nm, 630.0-nm, and H/Ι, which have exposure times of 5 s, 15 s, and 25 s, respectively. We take 2 × 2 binning of the CCD pixels (256 × 256 in total). The induction magnetometer measures variations of a three-component geomagnetic field with a sensitivity of 0.45 (V/nT) at 6 Hz with a turnover frequency of ~6 Hz.

[10] Figure 1 shows interplanetary and ground auroral/field variations during the isolated proton arc event of 5 September 2005. Figures 1a–1d show proton density (cm⁻³), GSM-X component of solar wind velocity (km/s), and GSM-Z and GSM-Y components of interplanetary magnetic field (IMF) variations, respectively, obtained by the ACE spacecraft at X = 219 Re. These data are shifted 43 min by taking a travel time from the ACE spacecraft to the Earth into account. Figures 1e–1g show north–south cross sections (keograms) of auroral structure for 557.7 nm, 630.0 nm, and H/Ι observed by the all-sky imager at Athabasca. The vertical axis of the keogram is converted from azimuth-elevation coordinates to geographical coordinates, assuming auroral altitudes of 120 km for 557.7 nm and H/Ι and 200 km for 630.0 nm. The keogram shows variations of auroral intensity in the meridian at the geographical longitude of Athabasca (246.7°E). Figure 1h shows X, Y, and Z components of magnetic field variations at Meanook, which is 17 km southwest of Athabasca. Figure 1i shows the dynamic spectrum of H component geomagnetic field variations observed by the induction magnetometer at Athabasca in the frequency range of 0.10–32 Hz.

[11] An isolated arc was visible at 0500–0640 UT in all three emissions, as seen in Figures 1e–1g. The arc moved equatorward gradually from 53.5°N to 51°N (MLAT = 61.2°–58.8°). The arc remained in 630.0-nm emission lasted until 0740 UT at reduced intensity. Since the sky was cloudy prior to 0500 UT, the appearance time of the arc was not unclear. A small auroral substorm took place at 0550–0700 UT, as characterized by the intense auroral emissions in the northern sky of the keograms in Figures 1e–1g and by magnetic field variations in Figure 1h. The growth phase of the substorm seemed to start from 0400 UT, when the IMF-Bz turned to negative. The isolated arc did not change its structure and intensity before or after the substorm onset.

[12] A strong Pc 1 geomagnetic pulsation was observed by the induction magnetometer at Athabasca at 0230–0730 UT, as shown in Figure 1i. The peak frequency of Pc 1 increased from 0.3 Hz to 1.0 Hz from 0230 UT to 0730 UT. At the starting time of the Pc 1 pulsations IMF Bz suddenly increased from zero to ~4 nT and remained positive (eastward) until 1100 UT, as shown in Figure 1d. The Pc 1 pulsation that was observed during this arc event was the most intense of all the Pc 1 pulsations observed with this instrument during September and October 2005.

[13] During the isolated arc event in Figure 1, the NOAA 17 satellite crossed near the arc from low to high latitudes.
Figure 1. From top to bottom are shown proton density (cm\(^{-3}\)), GSM-X component of solar wind velocity (km/s), and GSM-Z and GSM-Y components of IMF variations obtained by the ACE spacecraft, variations of auroral intensity at 557.7 nm, 630.0 nm, and H\(\beta\) in a north–south meridian (keograms) obtained at Athabasca, magnetic field variations (X, Y, and Z components) obtained at Meanook near Athabasca, and dynamic spectrum of H component geomagnetic field variations, obtained at Athabasca on 5 September 2005.
Figure 2 shows ground-based auroral images (10° x 10° in latitude and longitude, 1135 km x 656 km in horizontal distances) obtained at Athabasca from 0456:02 to 0502:36 UT on 5 September 2005. The images have been converted from the original all-sky coordinates to geographical coordinates by assuming auroral altitudes of 120 km for 557.7 nm and Hβ and 200 km for 630.0 nm. Geomagnetic north is 17° eastward from geographic north. The image center is the zenith of Athabasca. The red lines and squares indicate the track and footprints of the NOAA 17 satellite, respectively.

In Figure 2, an auroral arc extends from east to west at a latitude of 53°N (62.6° MLAT). The arc width is about 1° in latitude. The arc seen in the 630.0-nm images is located east of that in the 557.7-nm and Hβ images. From auroral images with a longer time sequence (not shown), we recognized that the arc at 630.0 nm moved to the location of arcs at other wavelengths with a delay of ~8 min. The NOAA satellite footprint crossed the arc from low to high latitudes at 0458:36 UT.

The NOAA 17 satellite is in a circular polar orbit at an altitude of about 800 km. The satellite measures precipitating and trapped electrons and ions with energies less than 20 keV using the Total Energy Detector (TED) and those larger than 30 keV using the Medium Energy Proton and Electron Detector (MEPED) [Evans and Greer, 2000]. At high latitudes (L > 3) the orientation of the MEPED allows observation of the particles both within the loss cone (precipitating particles) and outside the loss cone (locally trapped particles).

Figure 3 shows electron and ion energy spectra during the arc crossing shown in Figure 2. Figures 3a–3d...
September 5, 2005

NOAA 17

![Image of electron and ion spectra](image)

**Figure 3.** From top to bottom are shown precipitating (~70° to the horizontal plane) and trapped (~10° to the horizontal plane) electron and ion spectra at energies of 30–2500 keV (electrons) and 30–6900 keV (ions) and precipitating electron and ion spectra at energies less than 20 keV at angles of ~75° and ~50° to the horizontal plane, observed by the NOAA 17 satellite on 5 September 2005. The white dashed line indicates the time when the NOAA 17 satellite crossed the arc.

are the precipitating (~70° to the horizontal plane) and trapped (~10° to the horizontal plane) electron and ion spectra at 30–2500 keV (electrons) and 30–6900 keV (ions) observed by the MEPED instruments. Figures 3e–3h are the precipitating electron and ion spectra at energies less than 20 keV observed by the TED instruments at angles of ~75° and ~50° to the horizontal plane. The vertical dashed line indicates the time (0458:36 UT) when the NOAA 17 footprint crossed the isolated arc, as shown in Figure 2. The dashed line lies on a localized enhancement of energetic ion precipitation mainly at energies of 30–80 keV, as shown in Figure 3b. This localized ion precipitation is separated from the main ion precipitating region at latitudes higher than 64° MLAT and most likely associated with the isolated arc. Figure 3d shows that the region of trapped ions (30–250 keV), which correspond to the ring current, is separated into two regions, at ~59°–62° MLAT and ~64°–69° MLAT. These two belts may be a consequence of two previous injections. Actually, there was substorm-like magnetic activity at 0050–0230 UT on 5 September in high-latitude magnetic field data with corresponding small variations visible in Figure 1b. The dashed line and the localized ion precipitation in Figure 3b are located at the poleward boundary of the lower-latitude ring current ion belt in Figure 3d. Figure 3f shows that ions at energies below 20 keV also precipitate in the isolated arc region with a wider latitudinal range of ~59°–63°MLAT. Weak electron precipitation at energies below 20 keV is also seen in Figure 3e at isolated arc latitudes. Electrons precipitate significantly at higher latitudes above 65° MLAT, which
may be associated with the auroral emission seen in the higher-latitude portion of auroral images at 557.7 nm and 630.0 nm.

During the present arc event, the DMSP F13 satellite also crossed near the conjugate point of the arc in the Southern Hemisphere from high to low latitudes at 0627–0628 UT. Figure 4 shows the H\(_\beta\) arc image at 0628 UT with the DMSP satellite footprints. The IGRF-2005 model [Macmillan and Maus, 2005] was used to map the satellite location to the conjugate hemisphere. The line and squares indicate the track and footprints of the DMSP satellite, respectively, every 20 s at an altitude of 120 km. The satellite probably crossed the arc at 0627:20–0628:00 UT out of the field of view of the image.

Figure 5 shows electron and ion temperatures, ion drift velocity perpendicular to the satellite track, ion density, and precipitating electron and ion energy spectra obtained by the DMSP F13 satellite at an altitude of 840 km in the Southern Hemisphere at 0626:03–0629:03 UT on 5 September 2005. The time interval of possible arc crossing in Figure 4 is shown by the two dashed lines. The arc occurred at the region of increasing electron temperature and decreasing ion density. The horizontal plasma velocity turns from east to west in this region, and a strong westward drift with a maximum speed of \(\sim 1000\) m/s was observed. This region corresponds to the equatorward boundary of precipitating electrons and ions. Flux enhancements corresponding to the isolated arc are not seen in these electron and ion energy spectra.

3. Discussion

We have investigated relations among an isolated proton arc, precipitating particles, and Pc 1 geomagnetic pulsations, observed at subauroral latitudes of \(\sim 60^\circ\) MLAT. The isolated proton arc appeared in the premidnight sector at 2100–2300 MLT for about 2 hours. The latitudinal width of the isolated arc was about 1\(^\circ\). The arc moved equatorward gradually from 61.2\(^\circ\) MLAT to 58.8\(^\circ\) MLAT. The intense Pc 1 pulsation started from 1830 MLT (before the start of auroral observation) at Athabasca and lasted until after the arc moved equatorward of the field of view of the Athabasca imager. The frequency of Pc 1 geomagnetic pulsations gradually increased from 0.3 Hz to 1.0 Hz. Data from the NOAA 17 satellite show that particles precipitating in the isolated arc were energetic ions at energies of 30–80 keV. This enhancement of precipitating ion flux was separated equatorward from the main ion oval. Data from the DMSP F13 satellite at the geomagnetic conjugate point of the arc show ion density reduction and electron temperature enhancement, which are the signatures of the ionospheric plasma trough. This result suggests that the magnetospheric source of the isolated arc was located near the plasmapause. The DMSP F13 satellite also observed intense westward ion drift, similar to the subauroral ion drift (SAID) [e.g., Spiro et al., 1979].

The proton aurora tends to be spread out due to charge exchange. Therefore the thickness of the isolated arc is expected to be broader than that of the ion precipitation. For the present event, the latitudinal width of the proton arc was a little wider than 1 degree and that of the proton precipitation was narrower than 1 degree. Davidson [1965] calculated the auroral intensity distribution of Balmer \(\alpha\) emissions excited by proton beams. Figure 8 in their paper shows that the auroral intensity becomes 1/10 at a latitude 0.8 degree away from 10 keV protons injection, which is comparable to the present event.

The precipitating particles and the latitude of the isolated proton arc observed from our ground-based imager are similar to the detached proton arc observed by the IMAGE satellite at latitudes equatorward of the main proton oval. The presence of precipitating protons and absence of precipitating electrons are associated with the detached proton arc [Immel et al., 2002; Burch et al., 2002].

Immel et al. [2005] considered that the driving mechanism of the energetic proton precipitation to the...
detached arc is electromagnetic ion-cyclotron (EMIC) waves, which are generated through the temperature anisotropy of energetic ring current ions, and scatter protons into the loss cone. Immel et al. [2005] observed enhancements of wave activity at ion-cyclotron frequencies using a ground-based magnetometer near the conjugate point of detached arcs. In this paper we observed intense Pc 1 geomagnetic pulsation in the frequency range of the EMIC waves and energetic ion precipitation coincident with the isolated ion arc.

For the present isolated arc event, data from the DMSP satellite show signatures of the ionospheric plasma trough in the vicinity of the isolated proton arc. The trough corresponds to the plasmapause in the magnetosphere [e.g., Yizengaw et al., 2005]. Two separate regions of trapped ion flux enhancements were observed by the NOAA 17 satellite, and ion precipitation was observed at the outward boundary of the inner ring current.

Ion-cyclotron resonant interactions, which generate the EMIC wave, often occur in the ring current region because of anisotropic pitch-angle distribution of charged ring current particles due to the temperature anisotropy. Model calculations by Kozyra et al. [1984] and Jordanova et al. [2001] show that growth rate of the EMIC wave reaches maximum inside the plasmapause.

The EMIC wave efficiently scatters energetic ring current ions resonantly into the loss cone and thus represents an important ring current loss mechanism [Kennel and Petscheck, 1966; Cornwall et al., 1970]. Energy and momentum exchange can occur when the Doppler-shifted wave frequency matches the cyclotron frequency of the individual resonant particles. Recently, Erlandson and Ukhorskiy [2001] found, using data from the Dynamic Explorer 1 satellite, that the proton flux in the loss cone which precipitate into the atmosphere was correlated with the He EMIC wave spectral density. Yahnina et al. [2000, 2002] found a close relation between ground-based observations of Pe 1 geomagnetic pulsations and satellite in situ observations of localized enhancement of precipitating energetic protons.

Figure 5. From top to bottom are shown electron and ion temperatures, ion drift velocity perpendicular to the satellite track, ion density, and precipitating electron and ion energy spectra obtained by the DMSP F13 satellite at an altitude of 840 km in the Southern Hemisphere. The time interval of possible arc crossing in Figure 4 is shown by the two vertical dashed lines.
In this paper we also report a localized enhancement of energetic ion precipitation that caused the isolated arc together with the Pc 1 geomagnetic pulsation. The isolated arc initially appeared at 61.2° MLAT and moved to lower latitudes to 58.8° MLAT. Using the Tsyganenko 96 model, magnetic field strengths at the equatorial plane are estimated to be 175.89 nT and 362.71 nT for 61.2° MLAT and 58.8 MLAT, respectively. The ion cyclotron frequencies at 175.89 nT and 362.71 nT are 2.68 Hz and 5.51 Hz for H+, 0.64 Hz and 1.34 Hz for He+, and 0.17 Hz and 0.35 Hz for O+. The observed frequency of the Pc 1 geomagnetic pulsation at the time of the isolated arc appearance was 0.6 Hz. The frequency went up gradually to 1.0 Hz when the arc disappeared at 0640 UT. These EMIC waves are in the frequency range close to the He+ gyrofrequencies at the equatorial plane. According to the arc motion, the frequencies estimated from the model calculation become 2.0 times larger from 61.2° MLAT to 58.8° MLAT. The change of the observed frequency of Pc 1 geomagnetic pulsations is \( \sim 1.7 \) (= 1.0 Hz/0.6 Hz), which is comparable to the model calculation. Therefore the equatorward movement of the isolated arc seems to be consistent with the increase of the Pc 1 frequency. This result supports that the observed Pc 1 pulsations came from the equatorial plane which connects to the isolated arc.

4. Conclusion

Using a simultaneous data set obtained by a multi-channel all-sky imager, an induction magnetometer, the NOAA 17 satellite, and the DMSP F13 satellite, we have investigated the generation mechanism of an isolated proton arc observed on 5 September 2005, at Athabasca, Canada (MLAT \( \sim 62^\circ N \), L \( \sim 4 \)). The observed characteristics can be summarized as follows:

1. An isolated proton arc (wavelengths of 557.7 nm, 630.0 nm, and Hα) was observed in the premidnight sector at 0500–0640 UT (2100–2240 MLT) at \( \sim 59°–61° \) MLAT.
2. The arc was not affected by a small substorm that took place at 0550 UT.
3. Strong Pc 1 geomagnetic pulsations were simultaneously observed at frequencies of 0.30–1.0 Hz at 1830–2300 MLT.
4. The NOAA 17 satellite observed a localized enhancement of precipitating ions at energies of 30–80 keV with a narrow latitudinal width at the latitude of the arc. The satellite also observed trapped ring current ions separated into two latitudinal belts. The ion precipitation associated with the isolated arc was located near the outer boundary of the inner ring current.
5. The DMSP F13 satellite observed signatures of the isospheric plasma trough (decrease in ion density and increase in electron temperature) and intense westward plasma drift near the conjugate point of the isolated arc in the Southern Hemisphere.

These observations support the following scenario of the generation of the isolated arc: Ring current particles, which were isolated from the main ring current, trigger ion cyclotron instability in the vicinity of the plasmapause. This instability generates EMIC waves, which scatter the energetic protons resonantly into the loss cone to cause the observed isolated proton arc. The EMIC waves were observed as strong Pc 1 geomagnetic pulsations by the ground-based induction magnetometer. From model calculations, we found that the equatorward movement of the arc was consistent with the increase of the observed Pc 1 frequencies.

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