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Initial response and complex polar cap structures of the aurora in response to the January 10, 1997 magnetic cloud

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Abstract. On January 10th, 1997, a magnetic cloud originating at the Sun was incident on the Earth. The initial disturbance to the magnetosphere, as reflected in the activities of the aurora, was measured by the Ultraviolet Imager on the Polar Spacecraft. During this event we have observed the development of several unusual unique auroral forms that to our knowledge are unexplained in current models and theories. The observations were made on a global scale with unprecedented spatial and temporal resolution. The first activation of the aurora at local noon occurred within minutes of the arrival of the shock at 0107 UT. The substorm onset was observed at 0334 UT. During the intervening time significant polar cap precipitation occurred.

Introduction

The magnetic cloud on January 10th, 1997 induced large disturbances to the Earth's magnetosphere resulting in significant auroral activity throughout the 36 hours following the initial encounter. Several spacecraft and ground-based instruments detected what is likely the most complete coverage to date of an encounter of a magnetic cloud with the Earth. As such, it is the first study event of the ISTP era. The WIND spacecraft was located in the upstream interplanetary space, GEOTAIL was in the magnetopause region and POLAR was fortuitously located in a favorable position over the Northern Hemisphere (~7 – 8 Re) for its imaging instruments to record the initial auroral response to the arrival of the magnetic cloud.

We present, with unprecedented detail, the temporal and spatial evolution of the development of various global auroral structures as viewed by the Ultraviolet Imager (UVI) on POLAR. The UVI has an 8° circular FOV, and incorporates 4 narrow band filters (Torr et al., 1996). The global auroral images shown in this article come from the LBHL filter, covering the wavelength band ~160 – 180 nm. The UVI obtains an image every 36.7 seconds.

The period of interest extends from 01-04 UT. We show UVI images just prior to the initial encounter with the Earth's magnetosphere (~0107 UT) of the shock wave that preceded the leading edge of the magnetic cloud, of the interval when the transpolar arcs developed (~0220-0257 UT), and finally when a substorm onset occurred (~0334 UT). These detailed observations provide key insight to the ways that the magnetosphere interacts with the solar wind. These observations are, to our knowledge, not explained in current theories or models.

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Observations

Initial Encounter (0057 UT – 0217 UT): Plate 1a shows the UVI images just before the arrival of the shock as recorded by WIND (Figure 1) from a distance of (85 Re, -59 Re, -3 Re) in GSE coordinates. Assuming a planar structure to the IMF and solar wind velocity of 410 km/s, we estimate the delay time between WIND and the subsolar magnetopause to be 12-15 minutes. The UVI images, in units of photon flux, are constructed after subtracting the instrument background and correcting for flatfield distortions. The UVI images have been transformed to geomagnetic latitude/magnetic local time (MLT) plots to reveal latitudinal and local time features.

The onset of auroral precipitation observed by UVI at 0107 UT near local noon (Plate 1b), occurred 2-3 minutes after the shock wave compressed the magnetosphere. Note that precipitation occurred on the preexisting weak diffuse region. The shock induced precipitation proceeded along the dawn and dusk flanks toward the night side (Plate 1c). The precipitation was not uniform in MLT and the dawn fluxes were much stronger than the dusk side of the auroral oval. This dawn-dusk asymmetry was observed in every UVI image until the substorm onset ~2.5 hours later (see below). Note that initially the poleward boundary was contracted sunward of the 06-18 MLT meridian to nearly 80° latitude, while it was located at about 70° near midnight. Also, the sunward part of the dawn and dusk side oval was thick, almost 10° wide in latitude. These auroral features were observed when the interplanetary magnetic field (IMF) Bz component was pointing in the northward direction (Figure 1) (Makita et al., 1988).

At ~0125 UT, a bright but localized precipitation was observed near 0 MLT region (Plate 1d). This auroral bright spot may be associated with the arrival of the positive Bz pulse observed at ~0114 UT on WIND and/or with the arrival of the initial propagating disturbance in the distant tail region. The leading edge of the shock had by now propagated down to ~70 Re in the downstream direction. This bright spot was quite dynamic. It initially faded at ~0128 UT but reactivated at ~0134 UT (not shown) and remained relatively active with a constant brightness and size until ~0150 UT. At ~0150 UT (Plate 1e), this spot began moving toward the poleward edge and to the premidnight region of the oval. This bright spot remained active and during the time from to 0153 to ~0217, moved to 21 MLT and 85° latitude (Plate 1f).

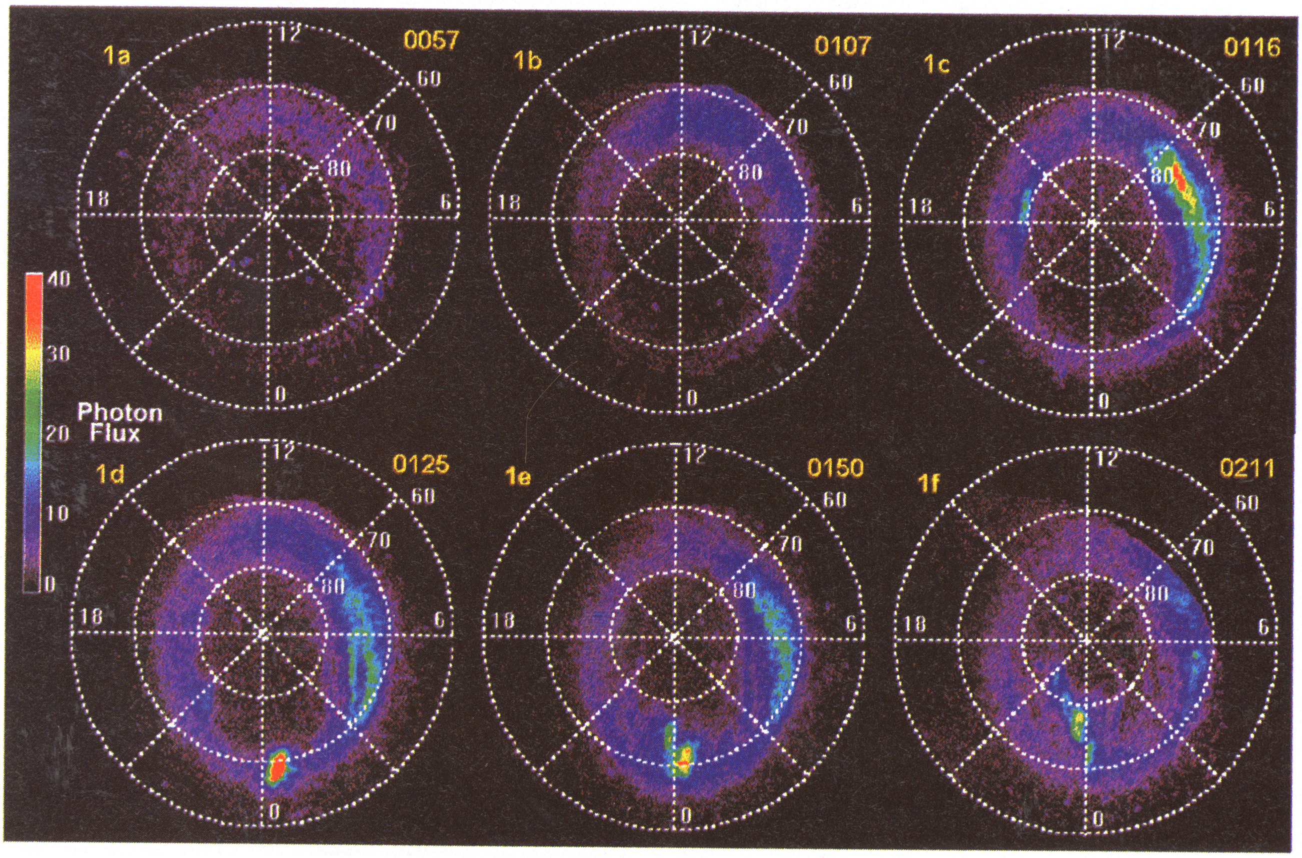

Plate 1. Global auroral MLT plots of the Ultraviolet Imager during the initial encounter of the January 10th magnetic storm from 0057 UT to 0211 UT in units of photon flux: (a) 0057 UT prior to the arrival of the shock, (b) 0107 UT first evidence of auroral activity around local noon, (c) 0116 UT propagation of the active region along the dusk and dawn flanks of the auroral oval, (d) 0125 UT first brightening at local midnight, (e) 0150 UT poleward movement of the bright spot, (f) 0211 UT further poleward and duskward movement of the bright spot.

The fading and reactivation of the bright auroral spot resembles features associated with a pseudo auroral break-up (Ohtani et al., 1993). But the poleward and duskward motions are well-known substorm features (Akasofu, 1968). These auroral dynamics occurred following very quiet IMF conditions observed during the one-hour interval (0000-0057 UT) prior to the arrival of the shock (Figure 1). The quiet IMF condition indicates that very little solar wind energy was coupled into the magnetosphere. Evidently, the magnetosphere could only support a pseudo break-up or a tiny substorm. Note that the ground-based Canopus magnetometers showed some activity ~0110 UT, ≤65 nT, but little activity at 0125 UT (not shown).

Sun-aligned Arcs (0220 UT – 0257 UT): The poleward and pre-midnight active region appears to tear away from the oval and move poleward. At 0220 UT, the poleward edge (78° Mlat) of the bright spot developed into a faint sun-aligned arc (Plate

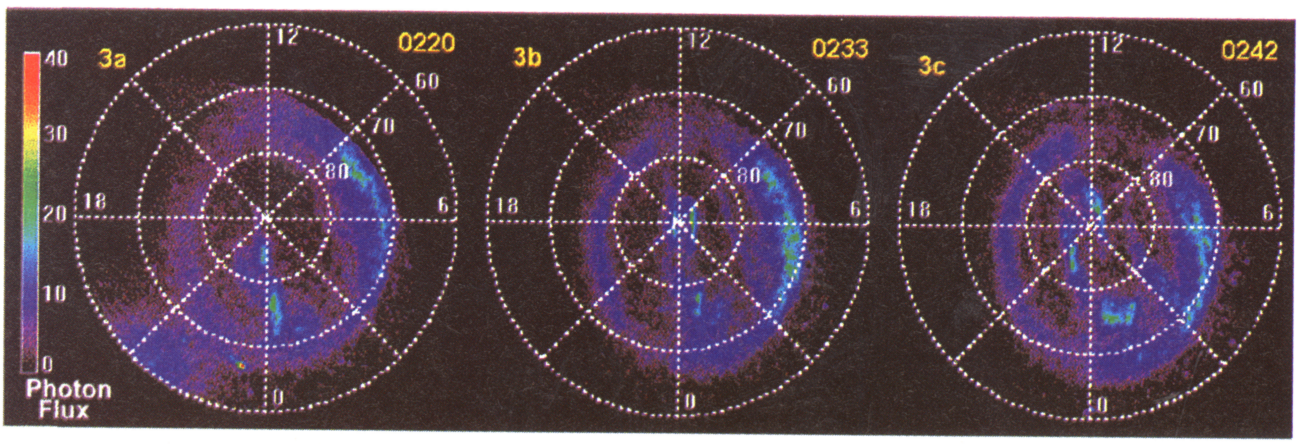

Plate 2. Global auroral MLT plots of the Ultraviolet Imager during the initial encounter of the January 10th magnetic storm from 0220 UT to 0242 UT in units of photon flux: (a) 0220 UT formation of sun-aligned arc, (b) 0233 UT separation of sun-aligned arc and initiation of second sun-aligned arc on the dawn side, (c) 0242 UT eastward motion of the bright spot near midnight.

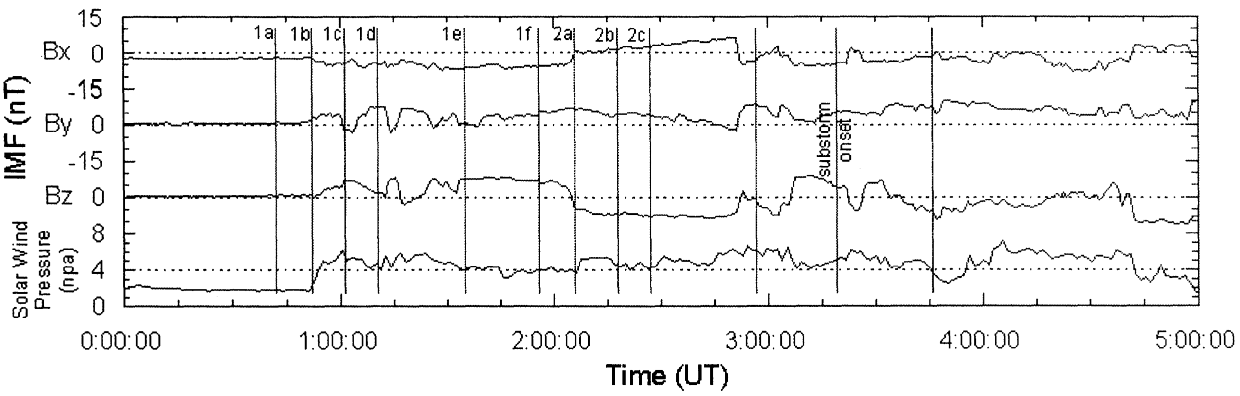

Figure 1. One minute averages of the interplanetary magnetic field and density measured by the WIND spacecraft located at 85 XGSE, -59 YGSE, -3 ZGSE for January 10th, 1997 from 0000 UT to 0500 UT. The vertical lines and labels correspond to the MLT plot Plate numbers assuming a 15-minute propagation time from the WIND spacecraft to the Earth.

2a). This sun-aligned arc reaches across the entire polar cap by 0223 UT, one end connected to the bright spot near midnight and the other near 13 MLT. Coincident with the completion of this arc, a bright region appears and moves sunward along the arc from 83° Mlat through the magnetic north pole (0220-0226 UT) (not shown) at a velocity of about 1°/minute, which is equivalent to 2 km/s in the ionosphere. At 0233 UT the sun-aligned arc split near the magnetic pole (Plate 2b). By this time, an additional arc started to emerge from the poleward edge of the dawnside flank and is distinct from the auroral oval. A slow shift of the bright spot near midnight is observed as it moved eastward to 01 MLT, 75° Mlat (Plate 2c) and subsided at 0242 UT. The split arc during this interval is connected on the dayside at 13.5 MLT, 77° Mlat and on the nightside over a broad region near 1.5 MLT, 68° Mlat. The dawn side arc drifts duskward to latitudes as high as 85° Mlat but always remains distinct from the split arc. The attachment point on the nightside at 3.5 MLT, 69° Mlat brightens from 0245 - 0248 UT then dims (not shown). The dawnside arc has completely faded away by 0257 UT, but portions of the split arc, while always faint, remain visible on the dusk side.

Note that we also observed that the equatorward boundary of the oval began to expand to lower latitudes for the 00 to 03 MLT region. The IMF Bz turned abruptly southward at ~0205 UT at WIND (Figure 1). Taking the ~15-minute time delay, this would correspond to approximately the same time when the sun-aligned arcs began to develop. The IMF Bz remained southward past 0300 UT throughout the transpolar arc activities. We note that a southward turning of Bz occurs at GEOTAIL between 0218 UT and 0220 UT (not shown).

Dynamics of the Auroral Oval (0259 UT – 0401 UT): Coincident with the weakening of the polar cap auroral activity at ~0259 UT, the activity of the auroral oval dramatically enhanced. We note, for instance, the oval thinned (recall the oval was thick for previous activities), the boundaries moved equatorward, the oval and polar cap regions expanded and a bright region occurred at 67° Mlat near 03-06 MLT. The rate of equatorward expansion is 0.1° Mlat/minute from 0130 to 0330 UT. We note that the equatorward expansion of the oval from 00-03 MLT began earlier around 0230 UT when the polar cap activity was present. The equatorward movement is consistent with the standard substorm growth phase (McPherron, 1979).

The time of the substorm onset is observed to be 0334 UT (denoted on Figure 1). The onset region near 00 MLT connects to the preexisting auroral activity on the dawn sector.

Intense activity persisted through 0547 UT when the UVI imaging ended as POLAR descended toward its perigee.

The IMF behavior during this interval, deduced from Figure 1, indicates that the substorm onset occurred more than one hour after the IMF Bz turned southward. Following this extended period of southward IMF, there were three northward turnings of Bz during the time interval from 0252 UT to 0325 UT (WIND time). The last northward turning at ~0325 UT (WIND time) comes closest to the substorm onset time observed by UVI, taking into account of ~9 minute delay, but whether or not it triggered the onset is not known.

To better view the dynamic nature of this event, including the onset of the substorm at 0334 UT, an animated movie of the MLT plots from 0000-0500 UT is available.[4]

Discussion

The complex auroral features presented in this paper are not well understood and to the best of our knowledge no models or theory can predict all of these features. The sequence of images we have shown should provide input to various models of solar wind and magnetospheric interactions. We have shown three types of auroral structures. The first occurred with the encounter of the magnetic cloud shock. Here precipitation occurred in wide latitudinal bands on preexisting diffuse regions on the dawn and dusk flanks and the IMF was always in the northward direction. This precipitation is interpreted to have been caused by the lowering of the trapped mirror points to altitudes below 100 km due to the compression of the magnetosphere. Preliminary analysis of the precipitation indicates that the characteristic energy during this time was ≥8 keV in the bright spot (Plate 1d), about 1.5 times higher than in the dawn and dusk flanks. This is the first quantitative measure of the average precipitating energy for a possible pseudo breakup or tiny substorm. The energy flux in the bright spot is calculated to be 1.4 Gwatts which accounts for 13% of the 10.8 Gwatts deposited in the auroral region at this time (0125 UT).

The second interval showed details of transpolar arc formation and evolutionary features. The dynamics of transpolar arcs are complex and the two examples we showed originated on the poleward edge of opposite sides of the oval: one on the dusk side

[4]Supporting GIF animated movie is available via Anonymous FTP from kosmos.agu.org, directory APEND (Username = anonymous, Password = guest).

and the other on the dawn side. These transpolar arcs developed from a localized auroral region following a pseudo-breakup or a small substorm while the IMF Bz was strongly negative and then dissipated prior to the substorm onset. The physics of what happened here is not understood. We calculate that the total power input to the auroral region remained constant at 10±1 Gwatts from 0130 to 0330 UT. This suggests that there were no additional sources of energy for the precipitation particles in the polar cap during this time. One possibility is that there was a rearrangement of the existing magnetic field line configuration that resulted in the redirection of the particles from the poleward edge of the oval to the polar cap and eventually back to the oval. Thus the source of particles for the polar cap precipitation is the same as for the poleward edge of the oval. The evolution of the transpolar structures from the poleward edges of the oval is consistent with this interpretation.

The dynamic features of the complex polar cap structures during this interval do not agree with any known models, however they do exhibit some previously reported properties. Both the split arc and dawn arc systems drifted in the duskward direction, in the direction expected in the Northern Hemisphere for continuously positive By (Frank et al., 1986). The southward turning while IMF By had a significant magnitude (Figure 1) suggests these arcs may be described by recent time-dependent models of theta bar formation [Newell and Meng, 1995; Cumnock et al., 1997; Chang et al., 1997], which are triggered by such IMF changes. Significant growth along the noon-midnight meridian for 30 minutes before the southward turning, however, suggests that the steady-state model of Kan and Burke (1985) for periods of continuously northward IMF may be more suitable to describe this arc. Furthermore, there may not be enough time between the turning at the magnetopause, observed by Geotail at 2:19 (not shown) and the beginning of theta bar completion within the polar cap at 2:20 for southward turning to be a trigger. Both of the foregoing reasons suggest the southward turning may have been merely coincidental to the formation of the theta along the noon-midnight meridian.

Finally we showed the sequence of events that eventually led to the onset of a 'traditional' substorm. The substorm occurred more than one hour after the IMF turned southward. The equatorward motion started around 0230 UT, an hour before the substorm onset at a rate of 0.1° Mlat/minute. There were three turnings of Bz in the northward direction and none of them appear to be clearly associated with the substorm onset.

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