Seasonal effects on auroral particle acceleration and precipitation

K. Liou, P. T. Newell, and C.-I Meng
Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland

Abstract. Global auroral images acquired from the Polar ultraviolet imager in the Northern Hemisphere during the winter of 1996 and the summer of 1997 (4 weeks before and after solstice) are used to study seasonal effects on auroral acceleration and precipitation. The energy flux of precipitating electrons is inferred from auroral luminosity in the long-wavelength bands (1600-1800 Å) of N₂ Lyman-Birge-Hopfield (LBHI) auroral emissions, and the mean energy of precipitating electrons is inferred from the intensity ratio of LBHI to LBHs (1400-1600 Å, the shorter wavelength of LBH bands) auroral emissions. Results indicate that dayside and nightside regions of aurora reveal different seasonal effects: nightside (~1900-0300 MLT) auroral power is suppressed in summer, while dayside auroral power is enhanced in summer and forms the so-called postnoon auroral hot spots, all by a factor of ~2. The average energy of precipitating electrons is higher in the dark than in the sunlit hemisphere, while the number flux is lower in the dark than in the sunlit hemisphere for all regions. These changes, up to a factor of ~3, are local time and latitude dependent. The suppression of the nightside auroral power in summer is associated with a large decrease in the electron energy, whereas the enhancement of dayside aurora in summer is associated with a large increase in the electron number flux. The increase of dayside auroral power in summer may be associated with the large-scale upward field-aligned currents, which peak in summer. Results are also discussed in the context of a conductivity feedback instability and a cyclotron maser instability. The asymmetric seasonal effects on the dayside and nightside auroras suggest a voltage generator for the dayside magnetosphere and a current generator for the nightside magnetosphere.

1. Introduction

Synoptic auroral observations often reveal three preferred regions for the occurrence of optical intensification: the premidnight sector [Liou et al., 1997], the postnoon 1400-1600 magnetic local time (MLT) sector [Cogger et al., 1977; Liou et al., 1997], and the prenoon sector [Meng and Lundin, 1986; Liou et al., 1997]. Consistent results were also reported by Newell et al. [1996a] on the basis of millions of particle observations made in the auroral zones. The premidnight sector is the most probable region for observing discrete arcs, followed by the postnoon and prenoon regions, with the latter being the weakest one.

The auroral display appears to have seasonal effects. On the basis of millions of Defense Meteorological Satellite Program (DMSP) satellite crossings over the auroral zones over 9 years, Newell et al. [1996b] found that intense electron acceleration events (>5 ergs cm⁻² s⁻¹) that precipitate and produce discrete arcs in the premidnight sector are suppressed in sunlight; the winter-to-summer ratio is 1/3. Liou et al. [1997] analyzed auroral luminosity in the Lyman-Birge-Hopfield (LBH) bands (1600-1800 Å) acquired from the Polar ultraviolet imager (UVI) for a 4-month period from April to July in 1996 and found that the average auroral luminosity in the premidnight sector is systematically decreasing from April to July.

A dark hemisphere being a favorable condition for auroras is further supported by a growing body of indirect observations. Collin et al. [1998] studied the occurrence frequency of upward flowing ion beams, which are believed to be associated with field-aligned potential drops that accelerate electron downward, resulting in discrete arcs, in the auroral acceleration region with observations from the Toroidal Imaging Mass-Angle Spectrograph (TIMAS) instrument on board the Polar satellite from March 1996 to September 1997. They found that in winter, up-flowing ion beams were observed predominantly in the 1500-0100 MLT sector (as determined by the 30th percentile) with a peak over 50% in the premidnight sector 2-3 hours from midnight, while in summer

Copyright 2001 by the American Geophysical Union.

Paper number 1999JA000391.
0148-0227/01/1999JA000391$09.00
the oval occurrence frequencies were low (below 10%) and there were no clear occurrence maxima. Yamagishi et al. [1998] studied auroral conjugacy by using a pair of imaging riometers, which measure variations in the cosmic radio noise absorption caused by electron density enhancements in the D and E region ionosphere, and found that the winter hemisphere strongly favors auroral events. Satio et al. [1987] examined electric field measurements acquired between 500- and 4000-km altitude in the Southern Hemisphere from the ISIS 2 satellite and found that narrowbanded ELF emissions, which are highly correlated with inverted-V events, occurred primarily in the premidnight sector from 1700 to 2400 MLT and between 65° and 75° geomagnetic latitude and maximize in winter. Erlandson and Zanetti [1998] studied statistical properties of auroral electromagnetic ion cyclotron (EMIC) waves, which occur in regions of inverted-V electron precipitation [Gurnett and Frank, 1972], by using magnetic field observations acquired from the Freja satellite and concluded that the occurrence of these waves peaks at auroral latitudes in the premidnight sector (1800-0100 MLT) and in the winter hemisphere. The occurrence of auroral kilometric radiation (AKR), which is associated with auroral arcs [Gurnett, 1974; Kurth et al., 1975], was found to be seasonally dependent. Kasaba et al. [1997] investigated 3 years' worth of electric field observations from Geotail and Kumatomo and Oya [1998] examined 7 years' worth of plasma wave data from Akebono, and both concluded that AKR was more active in the winter than in the summer hemisphere, especially in the higher-frequency range.

These observational results suggest that the ionospheric “background conductivity” plays an important role in producing aurora (the term “background conductance” refers to a more-or-less steady ionospheric conductance with no contribution from auroral particle precipitation). Newell et al. [1996b] suggested that an ionospheric conductivity feedback mechanism [Atkinson, 1970; Holzer and Saito, 1973; Sato, 1978; Miura and Saito, 1980; Lysak, 1986] is responsible for the summer-winter asymmetry of auroral arc acceleration events in the premidnight sector. In this conductivity feedback model a large-scale electric field associated with convection is imposed. When an increase in the Pedersen conductivity occurs in the ionosphere, which can be produced by precipitating particles, the ionosphere may respond either by a current or by an electric field, depending on the background ionospheric conductivity. If the background ionospheric conductivity is too large, the ionosphere will respond to the conductivity enhancement with a polarization electric field which reduces the total convection electric field. On the other hand, if the background ionospheric conductivity is small, an increase in the Pedersen current prevails and a feedback mechanism may occur by coupling the enhanced current with the magnetosphere through field-aligned currents associated with Alfvén waves. As more currents are drawn out of and into the ionosphere and reach a certain value, a field-aligned voltage drop could result, producing electron acceleration in the form of field-aligned currents, which may result in an arc. Therefore the feedback mechanism works more effectively when the background ionospheric conductivity is lower.

Solar cycle effects on auroral field-aligned potential drops [Cattell et al., 1991] and intense electron acceleration events [Newell et al., 1998] serve as crucial evidence for the importance of ionospheric conductivity in auroral production. Cattell et al. [1991] studied the effects of the solar cycle, as indicated by the value of $F_{10.7}$, on the occurrence of electrostatic shocks using electric field and particle data acquired from the S3-3 spacecraft during the years from 1976 to 1979. They concluded that parallel potential drops are less common at solar maximum than at solar minimum at the satellite's altitude of ~8000 km. Newell et al. [1998] analyzed 12 years' worth (1984-1995) of DMSP particle data and concluded that under sunlit conditions the occurrence of intense aurora decreases linearly with increasing solar 10.7-cm radio flux, while under dark conditions no correlation was observed. Since ionospheric conductivity is higher at solar maximum than at solar minimum, these results are consistent with the seasonal effects on the occurrence of auroral acceleration and other related events.

None of the above investigations, however, address the question of whether the increase in overall aurora production in darkness is associated with an increase in the average energy or number flux of the precipitating electrons. Since energy and number flux contribute equally to the total energy deposition and hence aurora production, understanding seasonal effects on these two physical parameters is essential to resolving the auroral acceleration mechanism and is the subject that we investigate in this paper.

Unlike traditional in situ particle measurements, here we will take a slightly different approach by using remote-sensing techniques. The average energy and energy flux from precipitating electrons can be inferred from analyzing auroral luminosity at different emission bands [e.g., Strickland et al., 1989; Rees et al., 1988; Lammersheim et al., 1991; Germany et al., 1994]. Although remote-sensing diagnostics generally do not exhibit the same spatial or temporal resolution as in situ measurements, they offer an instantaneous global outlook not available from single satellite passes. In section 2 we describe the optical instrument and data preparation. The analysis results are given in section 3. The discussion and conclusions of the results are given in sections 4 and 5, respectively.

2. UVI Imager and Data Preparation

The ultraviolet imager (UVI) [Torr et al., 1995] is a snapshot type of camera aboard the Polar satellite.
The optical sensor operates from 1300 to 1900 Å, and it combines with specially designed narrowbandwidth (Δλ = 100 Å) interference filters to perform specific measurements. The major filter band passes on UVI are two atomic oxygen lines centered at 1304 and 1356 Å and two molecular nitrogen Lyman-Birge-Hopfield (LBH) bands centered at ~1500 Å (LBHs) and ~1700 Å (LBHI). With a circular field of view of 8°, typical spatial resolution provided by the Polar UVI is about 30-40 km at an assumed 120-km emission height for images taken near the apogee of ~9 Re. However, platform wobble degrades this resolution tenfold along the wobble direction.

Auroral emission in the N2 LBH bands is produced solely by impact excitation. This particular mechanism provides us with a diagnostic tool to measure precipitating electrons, with an assumption that proton contribution is insignificant. The O2 Schumann-Runge absorption continuum peaks within the shorter wavelength of LBH bands, decreasing with longer wavelength; thus the shorter-wavelength (LBHs) emission exhibits an energy-dependent loss mechanism, while the longer-wavelength (LBHI) emission does not. This particular feature in the LBHI emission provides a means for diagnosing the average energy and energy flux of precipitating electrons [e.g., Strickland et al., 1983; Lammersheim et al., 1991]. In general, the luminosity of the LBHI aurora is proportional to the total precipitating energy flux over the typical energy range of precipitating electrons, and the ratio of LBHI to LBHs luminosity is a function of the characteristic energy of precipitating electrons. Details for deriving these two parameters for UVI images were given by Germany et al. [1998].

Before converting precipitating electron energy flux and energy from auroral luminosity, a couple of steps of data preparation, which include line-of-sight correction and dayglow (contribution of UV luminosity from sunlight) removal, must be taken. The geographic latitude and longitude of each pixel of each frame, consisting of 200 × 228 pixels, are first calculated on the basis of an oblate spheroid model of the Earth [e.g., Liu, 1978]. Slant viewing pixels are normalized to local vertical by multiplication by the observation angle relative to local nadir. The slant correction assumes an emission height of 120 km. Note that the cosine function correction, which assumes a plane geometric for the atmosphere, is a good approximation for LBHI images but not for LBHs images because of the nonlinear competition between the slant path enhancement and absorption from O2, whose content reveals local time effects [Germany et al., 1998]. However, this deviation is significant only for high-energy electrons and large spacecraft look angles. To minimize this correction error, we sampled auroral images only when the altitude of the Polar satellite was more than 6 Re. This is approximately equivalent to limiting the look angles of the Polar UVI to within ~30°, or an uncertainty of 20% based on the model results of Germany et al. [1998].

The N2 LBH dayglow is produced by impact excitation from electrons resulting from solar EUV photolization in the upper atmosphere. Therefore the observed radiances changes with the variations of solar zenith angle and solar activity. Since the peak altitude of the LBH dayglow is about 175-200 km, where O2 density is low, the absorption is not significant. A cosine function should be well suited for the line-of-sight correction for the two filtered dayglows.

Dayglow can be removed from images by subtracting a modeled dayglow profile. To a reasonably good approximation, the dayglow profile is produced daily by averaging 1 day's worth of dayglow images to reveal the solar activity effect (all of the solar activity indices, such as the F10.7 index, are provided daily). A detailed procedure for the dayglow removal is as follows. After correcting for background, flat-field, and line-of-sight, the magnetic latitude (MLAT) and solar zenith angle (SZA) of each single pixel are calculated and pixels with magnetic latitudes above 55° MLAT are removed from the image in order to avoid contamination from auroras. The rest of the image pixel values are binned by SZA with 1° bins. Here we assume that pixels with similar values of SZA have similar dayglow emissions. This assumption is reasonable for small look-angle pixels, and our requirement of the minimum 6 Re for Polar altitude should satisfy this criterion. This photon fluxes-to-SZA profile is compiled on a daily basis to accommodate the daily F10.7 index, and a smoothed daily dayglow profile is obtained by calculating the nonlinear least squares fit to a Gaussian function. Finally, in the process of dayglow subtraction, negative pixels resulting from dayglow subtraction are set to zero values. The average difference between the observed dayglow and the model dayglow is calculated and found to be no more than 0.5 photon cm⁻² s⁻¹ for a wide range of SZA from 50° to 110°. This technique is robust and has been satisfactorily used in our previous study [Liou et al., 1997].

Since different UVI filters do not operate simultaneously, to ensure that both LBHI and LBHs images represent the same auroral phenomena, we select UVI imaging periods when only the two filters were in operation. Fortunately, this is the major operation mode after December 1996, when the second system replaced the primary system which failed in August 1996. Under this mode these two filtered images of the same integration periods are separated by ~2.5 min. In the present study the 36-s integration images are used because of a higher signal-to-noise ratio as compared to the 18-s images. To isolate the contribution of ionospheric conductivity from the solar EUV radiation, which started increasing after August 1997 (see Figure 1), we select UVI data from the summer of 1997 and the winter of the 1996, 4 weeks before and after each solstice.

The final step is to sort auroral images into a regular 1° magnetic latitude by 2° magnetic longitude bin in altitude-adjusted corrected geomagnetic (AACGM)
Plate 1. Winter maps of aurora intensities in the (left) LBHl and (right) LBHs bands in the altitude-adjusted corrected geomagnetic (AACGM) magnetic local time-latitude format derived from 8 weeks of Polar ultraviolet imager (UVI) data from December 9, 1996, to January 6, 1997. The middle and bottom rows show data coverage in terms of image numbers and standard deviations in the data, respectively.
Plate 2. Summer maps of auroral intensities in the (left) LBHI and (right) LBHs bands in the AACGM magnetic local time-latitude format derived from 8 weeks of Polar UVI data from June 9, 1997, to July 7, 1997. The middle and bottom rows show data coverage in terms of image numbers and standard deviations in the data, respectively.
Plate 3. Average number flux of precipitating electrons inferred from the two LBH bands of Polar UVI images for (top) winter and (middle) summer and (bottom) the winter-to-summer ratio.

Plate 4. Average energy of precipitating electrons inferred from the two LBH bands of Polar UVI images for (top) winter and (middle) summer and (bottom) the winter-to-summer ratio.

Plate 5. Average number flux of precipitating electrons inferred from the two LBH bands of Polar UVI images for (top) winter and (middle) summer and (bottom) the winter-to-summer ratio.
magnetic field coordinates [Baker and Wing, 1989]. Although the spatial resolution of UVI at apogee is much smaller (~40 km), the choice of the bin size must be compromised by the well-known wobble in the Polar despun platform, which smears the UVI images by 10 pixels in one direction. The whole data sets are then processed separately for summer (sulnit hemisphere) and winter (dark hemisphere) seasons, and auroral brightness is averaged to produce the final summer and winter auroral distribution in a typical MLAT-MLT format. The total number of images used is ~12,000 for winter and ~10,000 for summer.

3. Results

Plate 1 shows maps of LBHI and LBHs auroral emissions in the MLAT-MLT format for the winter of 1996. Data coverage for both filters is shown in the middle row of Plate 1. The data coverage varies with the daytime part of the Northern Hemisphere less imaged by UVI; there are less than ~7000 images covering the daytime oval below ~70° MLAT in some local times. This can affect the statistics for auroras occurring in the less covered regions. Fortunately, this may not be a problem because daytime auroras are rarely seen below 70° MLAT. The standard deviations in the data, shown in the bottom row of Plate 1, indicate that the magnitude of the data fluctuations is of the same order as the average luminosity, indicating large variations in the data. However, the LBHs emissions are less variable than the LBHI emissions.

A typical feature in the winter auroral distribution is that high LBH luminosities are clustered in the midnight sector, where substorms occur most frequently. The peak intensity is ~15 photons cm⁻² s⁻¹ and is located at ~2330 MLT and 68° MLAT. The intensity of the LBH aurora decreases away from this region and forms a so-called midday auroral gap [Dandekar and Pike, 1978]. The average auroral luminosity is higher in the LBHI than in the LBHs bands except for the dayside, where the two emissions are about the same.

In summer there are three intensity maxima along the oval (see Plate 2): the premidnight at ~2300 MLT; the postnoon centered at ~1430 MLT, and the early morning maximum at ~0500 MLT. The morning maximum seems to appear much earlier in local time than the usual prenoon “warm” spot. In general, the average premidnight emission levels for both LBH bands are comparable, resulting from a decrease in the LBHI emission and an increase in the LBHs emission from winter to summer. For the remaining oval the auroral luminosity is higher in the LBHs than in the LBHI bands. The midday auroral gap is less pronounced in summer than in winter; actually, it disappears in the LBHs bands, indicating a region of soft precipitation. Similar to the winter data, the summer data are characterized by large fluctuations except for the prenoon and postnoon regions, indicating that auroral precipitation is relatively stable in these two regions.

The incident energy flux from electron precipitation is inferred from the observed LBHI intensities. We first convert the LBHI emission values to the surface brightness by using the formula 1 photon cm⁻² s⁻¹ = 30.17 Rayleighs [e.g., Brittnacher et al., 1997]. Using the model results from Germany et al. [1998], we obtain a conversion factor of 0.274 erg cm⁻² s⁻¹/photons cm⁻² s⁻¹. Plate 3 shows the auroral power for the winter (top) and summer (middle) seasons as well as the winter-to-summer ratio (bottom). In order to highlight the statistical oval region, a threshold of 2 photons cm⁻² s⁻¹, equivalent to ~0.5 erg cm⁻² s⁻¹, is used. A common auroral region for summer and winter is obtained by applying the threshold to the summer and winter average. Although a larger area can be obtained by relaxing the threshold value, we feel it is not statistically meaningful to discuss regions of small auroral intensities and hence small signal-to-noise ratio. The typical auroral power in the premidnight sector is ~2 ergs cm⁻² s⁻¹ in winter and ~1.5 ergs cm⁻² s⁻¹ in summer. Two distinct and asymmetric regions are evident from the winter-to-summer ratio. An increase, though not uniform, of energy flux from summer to winter appeared in a large portion of the midnight oval from 1900 to 0300 MLT; away from this zone, energy flux shows a systematic decrease toward noon. The increase is largest (up to ~100% increase) at the equatorward edge of the midnight oval, and the decrease is highest (up to ~50% decrease) at the poleward edge of the noon oval. Characteristics of cusp particle precipitation for the summer/winter hemisphere have been previously investigated by Newell and Meng [1988]. They reported that electron-precipitating energy flux is lower in the winter cusp than in the summer cusp by a factor of
1.51 ± 0.05. Our result indicates a factor of 2 increase from winter to summer and is in good agreement with their particle results.

The average precipitating electron energy is inferred from the ratio of LBHI to LBHS intensity by using the numerical modeling results of Germany et al. [1998]. Plate 4 from top to bottom shows the average pattern of the precipitating electron energies for winter and summer and their ratio. The winter and summer energy maps are similar except for their magnitudes. Generally, the dayside portion of the oval is characterized by low-energy electron precipitation, and the nightside oval is characterized by high-energy electron precipitation, except for the dayside, low-latitude part of the oval, where electron energies seem to maximize at ~10 keV in winter and ~5 keV in summer. This region is likely to map to the ring current in which trapped and eastward drifting energetic electrons leak out of a loss cone. Poleward of this region, the area between 0300 and 1100 MLT corresponds to the least energetic electrons (~2 keV in winter and ~1 keV in summer). There is another energy maximum in the premidnight region centered at ~2230 MLT and 75° MLAT.

The average energy of precipitating electrons is higher in winter than in summer for the entire oval (see the bottom panel of Plate 4). The increase in the average electron energy from summer to winter varies depending on the latitude and local time. The largest increase (up to 3 times) in electron energies occurs at the equatorward edge of the prenoon oval, including the region of so-called “midday gap” that is often seen in UV auroral images. Interestingly, the precipitating electron energy in the cusp showed a large increase (by a factor of ~2-2.5) from summer to winter. This is qualitatively consistent with particle results reported by Newell and Meng [1988]. The energy increase from summer to winter in the premidnight sector varies from ~50 to 100%. Interestingly, there are two discernible regions of relatively high energy increases (~100%): one at the poleward edge and one at the equatorward edge of the premidnight oval. At ~1500 MLT, where auroras are the second most commonly found in the oval, the energy increase is also moderate, 100-150% from summer to winter. There are two regions with a least increase (<25%) in the energy of precipitating electrons: one in the dawn and one in the dusk sector. The dayside one is located at the high-latitude part of the oval and seems to be a low-latitude boundary layer (LLBL) that maps to the statistical locations of the region 1 downward field-aligned currents [Iijima and Potemra, 1976], while the duskside one is located at the equatorward part of the oval and likely maps to the statistical locations of the region 2 downward field-aligned currents [Iijima and Potemra, 1976].

So far we have shown that seasonal changes in the energy flux are different from seasonal changes in the energy of auroral precipitating electrons. This suggests that the auroral power is also controlled by changes in the number flux of precipitating electrons. The electron number flux can be derived from dividing energy flux by energy. Plate 5 shows from top to bottom the number flux patterns for winter, summer, and the summer-to-winter flux ratio. Surprisingly, electron fluxes drop substantially from summer to winter for the entire oval; the drop is not significant (between 0 and 25%) in the premidnight sector but systematically increases away from this region and reaches a maximum of ~20% near the local noon. This is generally in agreement with particle results reported by Newell and Meng [1988] that the cusp number flux is higher in summer than in winter. A dramatic increase in the number fluxes in the dayside regions, in particular the postnoon and prenoon sectors, from winter to summer is clearly present, causing the so-called auroral bright spots in these regions.

4. Discussion

It is well known that the shape and size of the auroral oval changes with geomagnetic activity [e.g., Feldstein and Starkov, 1967] and the occurrence and the intensity of discrete auroral arcs can be characterized by the planetary Kp index [e.g., Danielsen, 1980; Hardy et al., 1985]. In general, a larger value of Kp corresponds to a more intense auroral emission. In addition, the solar EUV radiation is another controlling factor (although lesser), at least for discrete arcs [Newell et al., 1998]. This is because photoelectrons that contribute to the ionospheric conductivity are controlled by the solar EUV radiation. However, the solar zenith angle is more important than the solar EUV radiation on photoionization in the ionosphere. The choice of the data periods for this study has taken these important factors into consideration. The average Ap index (a linear version of the Kp index) weighted by image numbers over the data sampling periods is 7.9 for winter and 8.7 for summer; therefore the geomagnetic effect should be roughly equally applied to both sunlit (summer) and dark (winter) conditions. The average F10.7 values for the two seasons are quite stable and similar, 73.3 for winter and 73.7 for summer. Actually, the solar EUV radiation will have less effect on auroras in darkness (winter) than in sunlight (summer). Although how it affects the dayside and nightside ionosphere/atmosphere and hence affects the formation of dayside and nightside auroras as a whole is not clear, the relatively stable and small solar EUV for the present study periods ensures that the solar EUV effects are minimal.

There are always sources of uncertainty associated with data processing and data analysis. The total uncertainty contributed by image processing, instrumental calibration, and conversion from a model that converts luminosity to energy is ~42% [Germany et al., 1998]. The average uncertainty associated with the dayglow subtraction is no more than 10%. Therefore the to-
tal uncertainty for the presented work is \( \sim 43\% \). These uncertainties are systematic and should not affect relative values significantly. For example, the line-of-sight effect was corrected with a cosine function and therefore may cause an underestimation of the LBHs band emissions [Germany et al., 1998]. This has no effect on the energy flux and the winter-to-summer energy flux ratio. However, the energy of precipitating electrons is overestimated. This may explain why energy values shown in Plate 4 are slightly higher than usual. The number flux of precipitating electrons is approximately proportional to the LBHs band emissions and therefore is underestimated. The winter-to-summer energy and number flux ratios should be much less influenced because this effect is seasonally independent. The wobble of the imaging platform can cause decreases in the peak intensity and increases in the minimum intensity of aurora and hence can smooth out the results. Assuming that this wobble-associated data smoothing is similar for both emission bands, the summer-to-winter ratio of auroral energy flux should remain unchanged. Likewise, a similar smearing effect should appear in the other two parameters but not in their ratios. The dayglow removal scheme used in our study should introduce an excess of emissions in the summer period. Therefore the summer emissions shown in Plate 2 should be lower (by no more than 10\%), and consequently, the winter-to-summer energy and number flux ratios should be larger. However, the average energy of precipitating electrons does not change because of the residual dayglow emissions in summer present in both long and short LBH emission bands.

On the basis of the above discussion, qualitative auroral features and quantitative ratio values derived from the present study still hold even if these systematic uncertainties are taken into account. This can also be justified by consistencies between the present results and previous study results. First, in addition to those previously described in section 3, the present results are also consistent with Hardy’s precipitation model [Hardy et al., 1985]. Although a direct comparison between the two results is not readily available because their data were sorted by \( Kp \) and the present data were sorted by season, the general characteristics of the energy flux, mean energy, and number flux distribution of precipitating electrons appear to resemble each other. For example, the most energetic electrons appear predominantly in the dawn sector; a second local maximum appears in the premidnight sector [see Hardy et al., 1985, Plate 1]; the number flux of precipitating electrons appears to be higher in the day sector and biased toward the prenoon sector [see Hardy et al., 1985, Plate 2]; and the energy flux of precipitating electrons has a minimum near the local noon. The magnitudes for all three physical quantities are also of the same orders. Actually, the energy flux is about the same, but the energy is \( \sim 50\% \) higher for Polar UVI than for DMSP, which consequently leads to a smaller number flux for UVI than for DMSP. The higher than usual electron energies inferred from UVI are most likely in part a result of the capability of the model of Germany et al. [1998] and in part a result of the uncertainty of data processing. Second, our results clearly indicate the suppression of the auroral power in the local sunlit nightside regions, which is consistent with our previous results from 4 months (April-July 1996) of Polar UVI data and with particle observations [Newell et al., 1996a]. It is important to note that Polar UVI cannot distinguish the fine-structured discrete aurora from the less structured diffuse aurora. We are not certain of the relative contributions from the two types of aurora to the average auroral pattern. The consistency between the optical results and the particle results strongly suggests that the main feature of the auroral emission observed by UVI represents discrete auroras.

In addition to confirming the strong winter bias of nightside auroral power, there are new significant findings from the present study. The most distinguishing one is that dayside auroral power is enhanced in sunlit conditions, in contrast to the nightside aurora. In a previous paper [Liou et al., 1997] we provided the first evidence of systematic dayside auroral enhancement from a less sunlit month (April) to a more sunlit month (July). The present results provide more convincing evidence about the asymmetry of seasonal effects on the dayside-nightside aurora. The average energy of precipitating electrons reveals seasonal effects too. Although there is a difference in how the season controls the dayside-nightside auroral emissions, the acceleration mechanism should be the same because the average energy of precipitating electrons that produce auroras decreases in the summer in all regions. The seasonal difference between the dayside and nightside auroral power is caused by an opposite seasonal change in electron number flux; that is, the electron number flux increases in summer in all regions. In the premidnight region, where discrete auroras are most common and optically intense, a weaker auroral power in summer is mainly caused by a weaker electron energy because the electron number flux does not change significantly there. Although electrons that produce dayside auroras are softer in summer, their energy flux actually increases in summer because of a much larger increase in the number flux, thus increasing the total dayside aurora power.

Clearly, the seasonal effects on auroral luminosities are a combination of the seasonal changes in the number flux and energy of precipitating electrons; thus any physical parameter that controls auroral acceleration mechanisms may contribute these changes in the auroral characteristics if it also presents seasonal changes. The most obvious one is the ionospheric conductivity, which is enhanced dramatically in sunlight as a result of photoionization of neutral particles in the thermosphere. After inspecting 22 auroral models [see, e.g.,
Borovsky, 1993], Neuw et al. [1996b] concluded that suppression of nightside auroral arcs in sunlight is a manifestation of a feedback instability [Atkinson, 1970; Sato, 1978] which works best in a low-background ionospheric conductivity region [Miura and Sato, 1980; Lysak, 1986]. This feedback instability can also explain the solar cycle effects on the electron acceleration events. Neuw et al. [1998] reported that intense aurora events under sunlit conditions decline linearly in frequency with increasing solar activity. Under dark conditions, there is no dependence of aurora on the $F_{10.7}$ number.

While the conductivity feedback model can successfully explain the summer-winter and solar cycle effects on the occurrence of auroral arcs, it cannot explain the asymmetric seasonal effects on the day-night aurora or the seasonal effects on precipitating electron energies found in the present study. Lysak [1991] generalized the conductivity feedback model by combining it with resonant cavity modes caused by the presence of a large contrast between the ionospheric and magnetospheric Alfvén speeds. In his ionospheric cavity feedback model, the feedback mode is modified by the presence of the cavity; thus the wave characteristic of the cavity modes is determined by the ionospheric conductivity. An important finding is that large electron-precipitating energy favors larger wavelength and larger phase velocity waves, which are preferentially excited at low conductivity. Although the detailed acceleration mechanism is not explained because of the restriction of the model, this ionospheric cavity feedback model suggests that the energy of precipitating electrons is higher in winter than in summer, in agreement with our findings.

It is important to note that the general feedback theory works only in the upward field-aligned current region and therefore cannot explain our results in which electron-precipitating energy is higher everywhere in winter relative to summer. One possible explanation is the wobble effect, which smooths out results. Another possibility is that there are always small-scale upward field-aligned currents embedded in the large-scale downward field-aligned currents. Indeed, inverted-V events are observed over all of the auroral regions, including the polar cap [Lin and Hoffman, 1979]. This may allow the feedback instability to work essentially everywhere. Interestingly, there are two auroral regions that show the least seasonal variations in the energy of precipitating electrons. These regions, one in the dusk sector but equatorward of the oval and one in the dawn sector but poleward of the oval, approximately map to the statistical large-scale downward field-aligned currents [Iijima and Potemra, 1978]. It is likely that auroras seen in these regions are associated with ion precipitation, which is less affected by field-aligned potential drops. Of course, ion precipitation takes place along the entire oval, and it contributes up to 17% of the hemispheric energy deposition [Hardy et al., 1989]. Since the LBH auroral emissions are solely produced by impact excitations with energetic particles and since the secondary electrons are responsible for most of the emission, ion precipitation can play an important role in producing the LBH auroras as well [Strickland et al., 1993].

The asymmetric response of the dayside-nightside aurora to season may simply reflect the asymmetric dayside-nightside seasonal variations of the large-scale field-aligned currents. It has been reported that the upward field-aligned currents on the dayside in summer are twice that in winter, while the nightside currents are about the same [Fujii et al., 1981]. However, later, with more data, Fujii and Iijima [1987] found a nightside effect during geomagnetic quiet conditions. It should be noted that Fujii and Iijima’s [1987] study does not include the midnight sector between 2000 and 0400 MLT, where intense discrete auroras occur most frequently [e.g., Neuw et al., 1996b]. Although their results indicate that large-scale region 1 currents between 0400 and 2000 MLT are primarily driven by voltage generators in the magnetosphere, the correlation between the region 1 currents and the ionospheric conductivity is generally poorer when closer to midnight. They concluded that the nightside portion of the magnetosphere is a combined voltage and current generator. This suggests that the magnetosphere may become a current generator in the midnight sector. As a consequence, an increase in the background ionospheric conductivity does not significantly increase the field-aligned currents in the midnight sector.

When the ionosphere is in darkness, the background conductivity is low. Only a small amount of current can be drawn out of the dayside ionosphere, and it produces weak auroras. Since the ionospheric conductivity on the nightside is much lower, it may not be able to support currents that the nightside magnetosphere wishes to drive. In order to preserve a divergence-free current, a large potential drop that can pull more electrons from the low-density magnetosphere is required and hence produces keV-energy electrons that consequently produce intense auroras. In summer the entire oval is in sunlight and the background ionospheric conductivity is high; hence the conductivity feedback mechanism may not be at work. However, the higher ionospheric conductivity background in summer, especially on the dayside, can draw more currents into the magnetosphere and hence can produce more auroras but at sub-keV energies.

As we mentioned earlier, the ionospheric feedback instability may not be the only mechanism that can account for the suppression of nightside auroral acceleration events in sunlight. In winter the ionospheric plasma density is low, and it is reasonable to assume that plasma density is lower in a magnetospheric region adjacent to the ionosphere. Since the production of auroral kilometric radiation (AKR) relies on a low-density plasma cavity in which resonant electromagnetic waves are trapped and then amplified, known as cyclotron
maser instability [Wu and Lee, 1979], the condition of \( \leq 1 \) cm\(^{-3} \) for the low-density plasma cavity should be met relatively more easily in winter, as the plasma density is already low compared to that in summer. This is consistent with the observations of Kasaba et al. [1997] and Kumamoto and Oya [1998], who independently reported that the winter hemisphere favors the production of AKR. It has been reported that substantial auroral precipitation can be attributed to a loss cone lasting on closed magnetic field lines by pitch angle scattering of energetic electrons in the loss cone [Calvert, 1987]. Since the AKR source region is associated with upflowing ions and inverted-V electrons [Ergun et al., 1998, and references therein], it is reasonable to conclude that the enhancement of AKR is closely related to the large increase in the acceleration events and auroral intensity in winter. Interestingly, it has been found that AKR intensity correlated well with the peak energy of inverted-V events [Green et al., 1979] although that study was subject to great uncertainties mainly because in situ particle measurements may not correspond to the intensity of AKR waves observed by the same satellite. Nonetheless, the result of Green et al. [1979] is consistent with the present result and suggests that a lower plasma density favors a higher energy of precipitating electrons produced in winter.

5. Conclusions

We have investigated the seasonal effects on auroral acceleration and precipitation by analyzing a large number of summer and winter auroral images acquired from the ultraviolet imager aboard the Polar spacecraft. On the basis of more than 20,000 auroral images in the LBH bands from Polar UVI observations and on the basis of the numerical modeling results of Germany et al. [1998], we have found the following main results: (1) In contrast to nightside auroras, which are suppressed in summer, dayside auroras are enhanced and reveal the so-called postnoon auroral bright spots in the sunlit hemisphere; (2) precipitating electron energy is higher in winter than in summer; and (3) electron number flux is smaller in winter than in summer. These results indicate that the suppression of nightside aurora in summer is mainly a result of a decrease in the average energies of precipitating electrons, while the enhancement of dayside aurora in summer is mainly a result of an increase in the number flux of precipitating electrons. It is strongly suggested that ionospheric conductance and plasma density in the acceleration regions play an important role in the auroral acceleration mechanism. The day-night asymmetric response of auroras to season suggests a voltage generator for the dayside magnetosphere and a current generator for the nightside magnetosphere.

Acknowledgments. We thank the two referees for their valuable comments. We acknowledge G. Parks as the principal investigator of Polar ultraviolet imager (UVI). This work was supported by NASA grant NAG 5-7724 to The Johns Hopkins University Applied Physics Laboratory. Janet G. Luhmann thanks the referees for their assistance in evaluating this paper.

References


K. Liou, C.-I Meng, and P. T. Newell, Applied Physics Laboratory, Johns Hopkins University, 11100 Johns Hopkins Road, Laurel, MD 20723-6099. (kan.liou@jhuapl.edu; ching.meng@jhuapl.edu; patrick.newell@jhuapl.edu)

(Received October 19, 1999; revised July 28, 2000; accepted September 8, 2000.)