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The importance of solar illumination for discrete and diffuse aurora

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Abstract. We present a comprehensive overview of the occurrence of discrete and diffuse aurora in the night-side Northern Hemisphere at invariant latitudes 55° – 75° . Twenty-one months of Freja observations (1 January 1993 to 30 September 1994) from the Northern Hemisphere, obtained at ~ 1700 km altitude, are included in this investigation. We investigate the importance of seasonal effects, solar illumination and geomagnetic activity for the auroral precipitation. The seasonal variations in the occurrence of discrete aurora are separated from the dependence on solar illumination of the ionosphere. When the effects of sunlight are eliminated, aurora is found to be more common during the summer. The occurrence of diffuse, as well as discrete aurora, is suppressed by solar illumination of the ionosphere. This dependence of diffuse auroral precipitation on ionospheric conditions is not predicted by theories that attribute diffuse aurora to equatorial pitch-angle diffusion of hot magnetospheric electrons.

Keywords. Ionosphere (Particle acceleration) – Magnetospheric physics (Auroral phenomena; Magnetosphere-ionosphere interactions)

1 Introduction

The aurora can only be seen against a dark sky, and the chances of observing an aurora are obviously much better in winter when nights are also dark at auroral latitudes. This variation in the visibility of the aurora has inspired people to ask whether the precipitation of the energetic electrons that cause the aurora also varies with the seasons. Since the first observations of a seasonal dependence of auroral electron precipitation by Berko and Hoffman (1974), using the satellite Ogo 4, more observational investigations of the seasonal dependency have been conducted. For example, Liou et al. (1997) used the ultraviolet imager on board the Polar satellite to investigate the Lyman-Birge-Hopfield auroral emission at 1700 Ångström. They found that the nightside discrete auroras are more common during the winter than during the summer. Barth et al. (2004) used data from the

Student Nitric Oxide Explorer, together with a model of thermospheric photochemical processes influencing the observed density of nitric oxide, to deduce the flux of precipitating auroral electrons. A clear minimum in the electron flux was found around midsummer. Newell et al. (1998) used data of precipitating auroral electrons from the DMSP satellites to investigate correlations with the solar flux at 10.7 cm (the F10.7 number). They found that the number of intense auroras is uncorrelated with the solar activity in the absence of solar illumination, but negatively correlated with solar activity in the presence of solar illumination. Hence, there is observational evidence for the seasonal dependence and the importance of solar illumination for discrete aurora. These dependences are usually attributed to the effects of sunlight. Hamrin et al. (2000) pointed out that this anticorrelation of auroral activity with solar illumination of the ionosphere can be explained if the electron acceleration process is sensitive to the density in the auroral region. Newell et al. (1998), on the other hand, endorsed the ionospheric feedback mechanism (Atkinson, 1970; Sato, 1978; Lysak, 1991) as a cause for the variation in auroral activity with solar illumination.

Commenting on the observation by Newell et al. (1998), that intense auroras occur mainly when the ionosphere is in darkness, Borovsky (1998) pointed out the paradox that if the auroral generator in the equatorial plane is connected to a sunlit ionosphere in one hemisphere and a dark ionosphere in the other, most of the current should follow the high conductivity path through the sunlit ionosphere. This paradox can be resolved by noticing that the current is restricted by Ampère's law, $\mathbf{J}=\nabla\times\mathbf{B}/\mu_0$. As long as the magnetic disturbances are symmetric, then the currents must also be symmetric.

In this article we use 21 months (1 January 1993 to 30 September 1994) of electron precipitation data from the satellite Freja to investigate separately the importance of solar illumination and seasonal effects on the occurrence of diffuse aurora.

2 Data processing

The joint Swedish and German satellite Freja (Lundin et al., 1994a,b) has a set of high resolution field and particle instruments, and an auroral imager, for studies of space plasma

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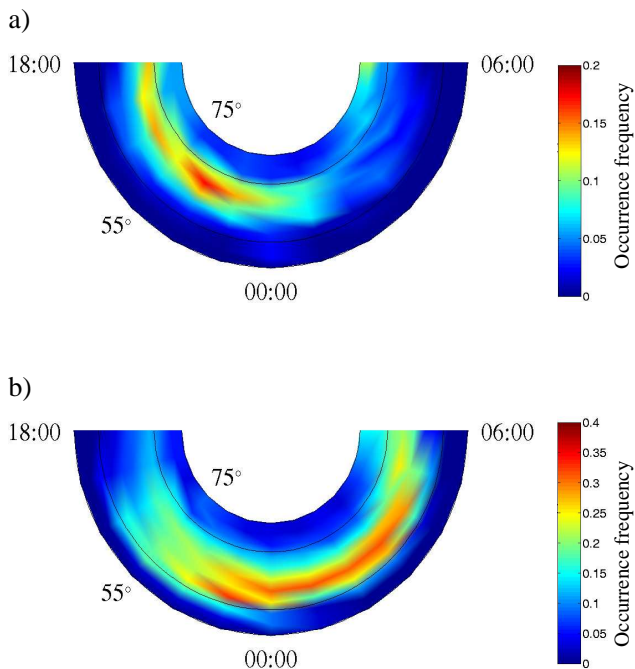


Fig. 1. The occurrence of (a) discrete aurora and (b) diffuse aurora versus MLT and ILAT. The location of 60° and 70° ILAT are indicated by solid lines. Note the different colour scales.

wave-particle interaction processes. Freja passes the auroral region in the Northern Hemisphere at an altitude of approximately 1700 km and the orbit has an inclination of about 63°. This low-inclination orbit makes data from the Freja satellite suitable for investigations of auroral phenomena, since the spacecraft, at times, moves along the auroral oval instead of across it. The satellite is Sun-pointing and spin-stabilized, with a spin period of 6 s.

Using the original data from the Freja electron spectrometer, TESP, (Boehm et al., 1994) a reduced set of overview data with a time resolution of a few seconds was constructed. In this article we use 21 months of such overview data for a statistical investigation of the occurrence of discrete and diffuse aurora. We included data from the Northern Hemisphere from 1 January 1993 to 30 September 1994. This period of time is within the declining phase of the solar cycle. To focus on the properties of the nightside auroral magnetosphere, we use data from 18:00 to 06:00 MLT and we only include data from 55° to 75° invariant latitude (ILAT).

In our study we only include electron energy fluxes of $\sim 0.5 \text{ mW/m}^2$ or more. This correspond to fluxes above $\sim 1 \text{ mW/m}^2$ at the ionosphere. It should be noted that since we normally only measure field-aligned electrons, the minimum fluxes mentioned above are quite uncertain and might vary depending on the full electron distribution. To estimate the total electron flux corresponding to the observed field-aligned electrons, we have used samples of detailed data including several TESP sectors.

The discrete aurora is caused by precipitating electrons that have been accelerated by a strong magnetic field-aligned

potential drop, which generates the well-known inverted-V signature in electron energy spectrograms. Hence, the discrete aurora is characterized by a narrow peak in the electron energy flux spectra obtained by Freja. The diffuse aurora on the other hand, is believed to be caused by plasma sheet electrons which undergo pitch-angle diffusion and precipitate down into the ionosphere and upper atmosphere without further acceleration. Hence, no well-defined peaks in the energy flux spectrum are expected during periods of diffuse aurora.

We have developed a computer algorithm to sort the measured electron precipitation into the categories 1) discrete aurora and 2) diffuse aurora by investigating the electron energy flux spectra (Fellgård, D.: Classification and analysis of Freja electron data in the auroral region, Master Thesis in Physics, Umeå University, Sweden, unpublished manuscript, 2004). Visual inspection of a sample of spins with auroral electrons indicated that about 95% of them could be unambiguously classified as discrete or diffuse, and essentially all unambiguous spins were correctly classified by our algorithm.

Our database includes electron measurements from about 119 500 spins in the MLT-ILAT range, 18:00–06:00 MLT and 55°–75° ILAT. Out of this set of data we have identified $\sim 7\,200$ spins of discrete aurora and $\sim 17\,300$ spins of diffuse aurora. To reduce statistical fluctuations we have excluded few very active days with $K_p \geq 6-$ from our database. Further comments on the K_p variations are given in the discussion. In Fig. 1 the occurrence of discrete and diffuse aurora versus MLT and ILAT is shown. We clearly see the different distributions in local time for discrete and diffuse aurora. The discrete aurora is most common in the evening sector and the diffuse aurora in the morning sector. This is consistent with Liou et al. (1997), who observed that the maximum of nightside discrete aurora is centered around 22:30 MLT and 68° ILAT, and also Hardy et al. (1985) and Chen and Schulz (2001), who showed that diffuse aurora is more common in the morning sector. This clearly shows the reliability of the database used in this study.

3 Discrete aurora

It is widely accepted that the occurrence of discrete aurora is suppressed by sunlight. This effect is usually explained theoretically by the influence of sunlight on the electron density. The electron acceleration process is believed to be sensitive to the electron density in the auroral acceleration region. In the absence of solar illumination the density is low, and as suggested by Rönmark (1999), a low electron density in the acceleration region forces the electrons to be accelerated to energies of several keV, to be able to carry an imposed field-aligned current between the ionosphere and the magnetosphere. Furthermore, as shown by André et al. (1998), broadband ELF waves, as well as EMIC waves and lower hybrid waves, can heat ions to such high energies that they can escape the gravitational field of the Earth. This ion outflow naturally reduces the electron density further. Hence, in the

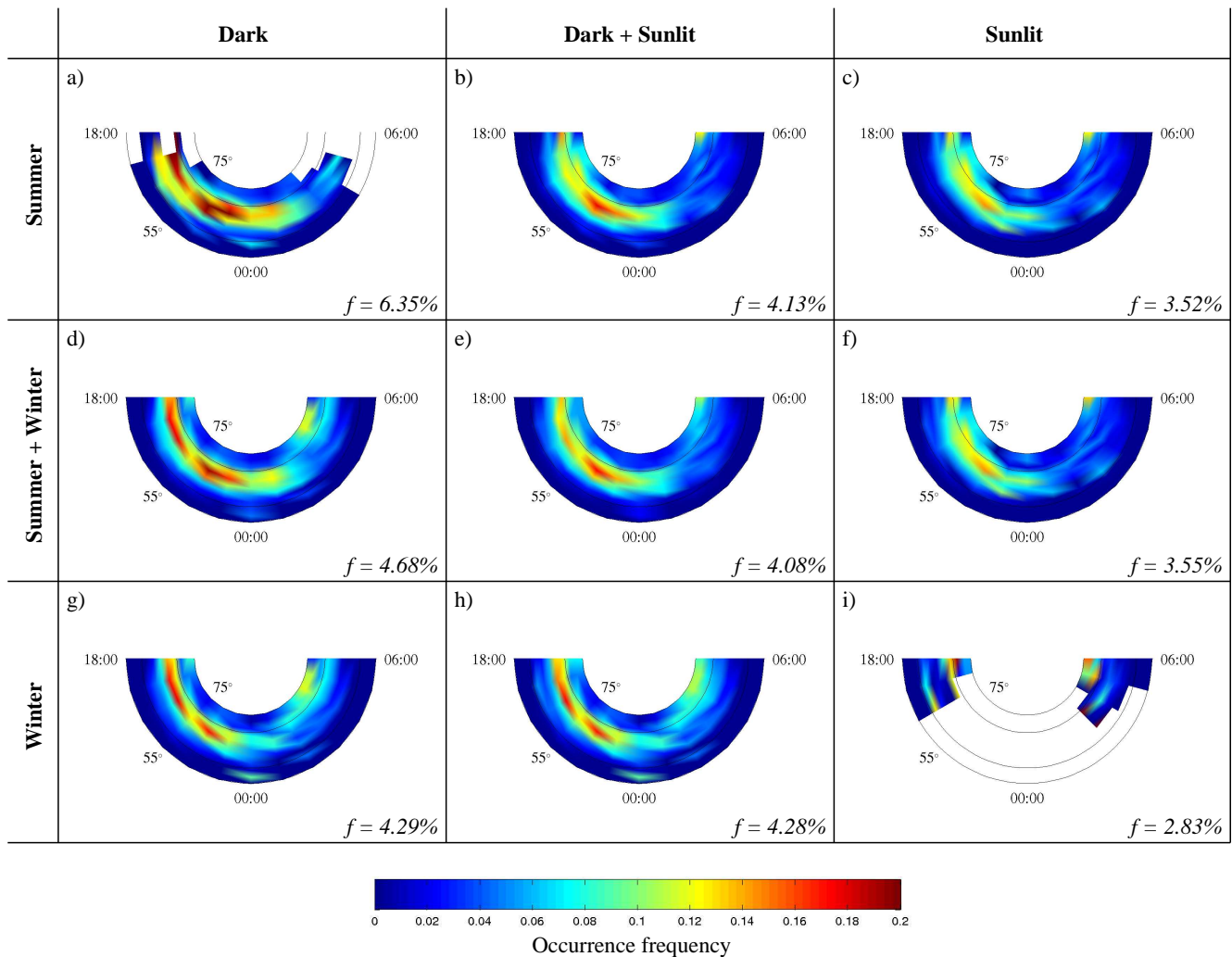


Fig. 2. The occurrence of discrete aurora in the Northern Hemisphere during various conditions. See the text for more details.

absence of solar illumination the average electron density is in general lower, ion heating is stronger, and the average density depletions are deeper, and this affects the occurrence of aurora (Newell et al., 1996, 1998; Hamrin et al., 2000).

In the literature the importance of solar illumination for the occurrence of discrete aurora is often illustrated by showing observations of a seasonal dependence (Berko and Hoffman, 1974; Barth et al., 2004). Since a dark nightside ionosphere at auroral latitudes is strongly correlated with winter, a higher probability of discrete aurora in darkness has been seen as synonymous to a higher probability during winter (Newell et al., 1998). However, there is a lack of direct observational evidence separating the effects of solar illumination from seasonal effects. Can the variations in the auroral occurrence frequency be fully explained by the effects of solar illumination or are there independent seasonal effects, such as the tilt of the Earth’s axis, which can also be of importance?

To answer this question we use our database of electron measurements to conduct a detailed investigation, which allows us to separate the effects of solar illumination from the seasonal dependence of discrete aurora. We sort our data into a winter and a summer subset, and we also check whether or not the ionospheric footpoint (at 100 km altitude in the Northern Hemisphere) of the flux-tube passed by Freja is sunlit. Moreover, we divide our data set into MLT–ILAT bins of size 1 h MLT × 2° ILAT, and each satellite spin of 6 s is assigned to an MLT–ILAT bin. For each bin containing observations from more than 10 spins, the local occurrence frequency is calculated by dividing the number of spins classified as discrete aurora with the total number of spins in the bin. In addition, an average occurrence frequency f is calculated as the average of the local occurrence frequency over local time and invariant latitude.

The result can be found in Fig. 2. In the first and third columns we plot the occurrence of discrete aurora in the absence and presence of solar illumination, respectively. The

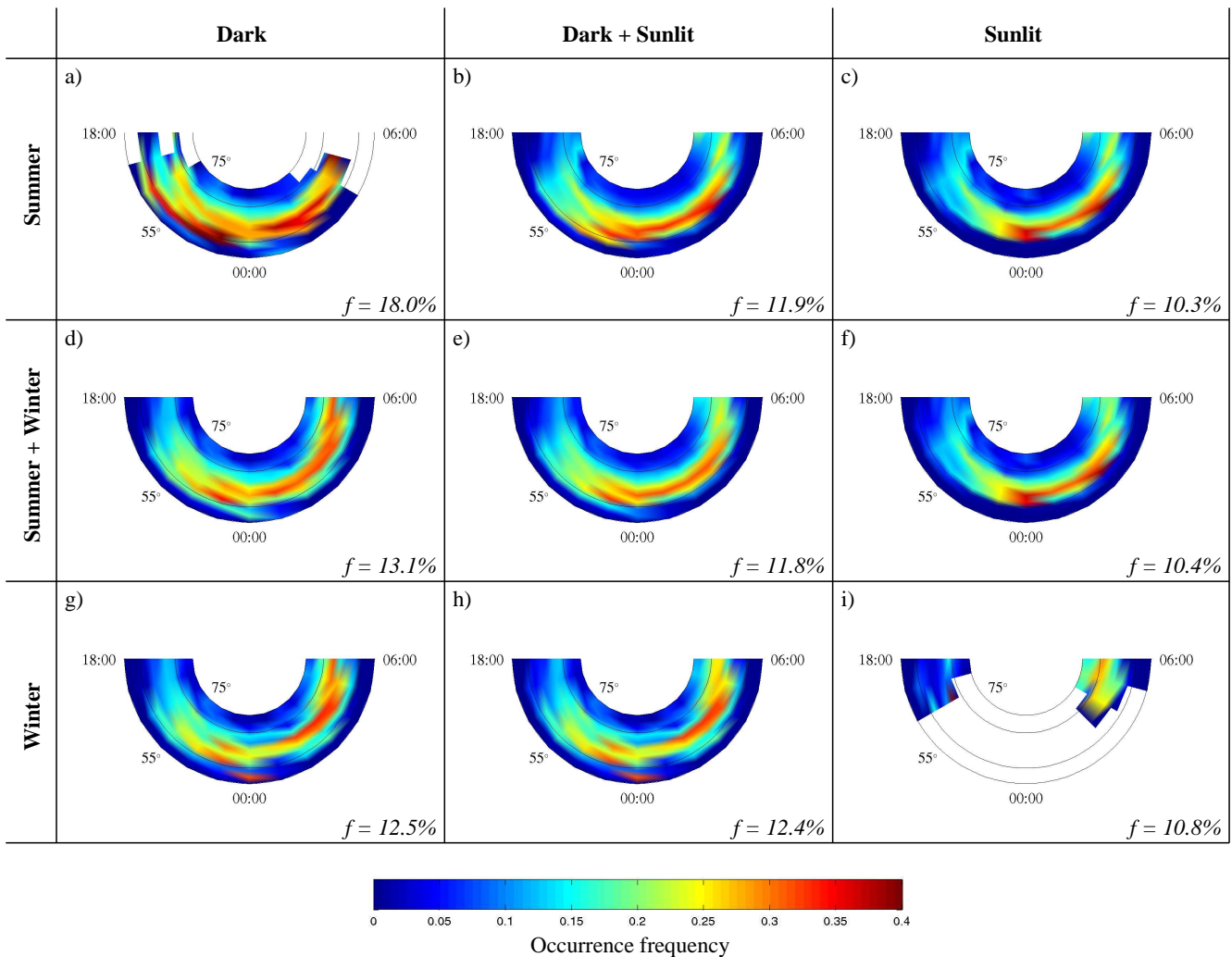


Fig. 3. The occurrence of diffuse aurora in the Northern Hemisphere during various conditions. See the text for more details.

middle column shows all data irrespective of the solar illumination. Moreover, the top row shows data measured during the summer (21 March to 20 September) and the the bottom row during winter (21 September to 20 March). Data collected from both seasons are shown in the middle row. The average occurrence frequency is given in the lower right corner of each figure.

Comparing only Figs. 2d and f we see that aurora is more common in darkness than in sunlight, but we cannot unambiguously estimate the quantitative effect of solar illumination on the occurrence rate. As discussed above, the ambiguity is caused by the large overlap between data obtained in darkness (Fig. 2d) and in winter (2h), and similarly between data obtained during sunlit (Fig. 2f) and summer (2b) conditions. However, focusing on data from only one season, local summer in the top row of Fig. 2, and comparing the plots in Figs. 2a and c, we see that discrete aurora is much more common in the absence of sunlight. Unfortunately, it is impossible to attempt the same type of analysis for the winter

subset of the data. A glance at Fig. 2i only confirms that sunlight is scarce during winter nights. Looking at data obtained in darkness, it is clear that the occurrence frequency is higher in summer (Fig. 2a) than in winter (2g). Notice that this is opposite to the expected result that discrete aurora in general should be more common in winter (Liou et al., 1997; Barth et al., 2004). Disregarding light conditions when comparing summer (Fig. 2b) and winter (2h) we also find that in our data the occurrence rate is slightly higher during winter due to the strong correlation between winter and darkness.

Our observations confirm that the probability of discrete aurora is strongly enhanced when the ionosphere is in darkness. We also find that under dark conditions there is an hitherto unobserved, slightly weaker, tendency for discrete aurora to be more common during summer. The strong anticorrelation between summer and darkness implies, that in particular the seasonal dependence is difficult to observe when overlapping data sets are used.

4 Diffuse aurora

Using our data base we can also investigate seasonal effects and the importance of solar illumination for the occurrence of diffuse aurora. In Fig. 3 we present the occurrence frequency sorted by solar illumination (first to third column) and season (first to third row), as in Fig. 2. The occurrence frequency is computed and normalized in the same way as for the discrete aurora, but note that since diffuse aurora is more common, the colour scale is different.

To investigate the importance of solar illumination we focus on the data measured during the summer. Inspecting Figs. 3a and c we see a clear tendency of the diffuse aurora to be more common when the ionosphere is in darkness. A similar but significantly weaker dependence of diffuse aurora on solar illumination is seen in data from both seasons, as illustrated by Figs. 3d and f. Comparing Figs. 3b and h we notice that when the dark and sunlit data are combined, we see a slight tendency of diffuse aurora to be more common in the winter than in the summer, but this is mainly due to the correlation between winter and darkness. From the observations made in darkness (compare Figs. 3a and g) we see that the probability of diffuse aurora is significantly enhanced during summer. However, since there are few dark summer nights at auroral latitudes in June and July, our results do not necessarily imply that the auroral occurrence frequency is highest around midsummer.

To our knowledge, this is the first report of a clear correlation between diffuse auroral electron precipitation and a dark ionosphere, as well as the summer season. The diffuse aurora is expected to be caused by hot plasma sheet electrons that are pitch-angle scattered into the loss cone by whistler mode waves near the equatorial plane (e.g. Kennel and Petschek, 1966; Johnstone et al., 1993). These electrons are then assumed to precipitate into the atmosphere without further acceleration at high latitudes. Although existing theories do not predict this, it is conceivable that the north-south asymmetry of the nightside geomagnetic field may lead to a seasonal asymmetry in the electron precipitation rates. However, we have not found anything in existing theories for diffuse aurora that suggests an asymmetry between the sunlit and dark ionosphere, and in this perspective the correlation indicated by Figs. 3a and c is completely unexpected.

5 Discussion

The influence of sunlight on the occurrence of discrete aurora is discussed extensively in the literature (Newell et al., 1996, 1998; Barth et al., 2004). The underlying mechanism is probably related to the reduced ionization rate in darkness, which leads to lower electron densities, as discussed by Hamrin et al. (2000). This study confirms the importance of solar illumination, and shows that its effects can be partly masked by the tendency of aurora to be more common during summer. Since the probability of observing aurora is strongly suppressed by sunlight, it is not surprising that the higher

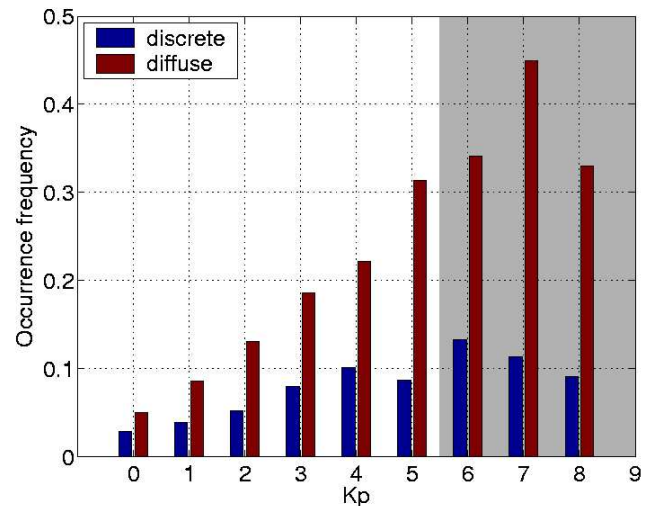


Fig. 4. The occurrence of discrete and diffuse aurora as a function of K_p index. $K_p > 6$ (shaded) are not used in this study.

occurrence frequency of aurora during (dark) summer nights has remained undetected.

Using a database from a single satellite, it is difficult to rule out that the unexpected higher probability of diffuse aurora in darkness, shown in Fig. 3, is an artefact, caused by some unknown sampling bias. It seems highly unlikely that contributions from discrete auroral precipitation that erroneously has been classified as diffuse aurora have a significant effect. Much of the enhanced probability of diffuse aurora in darkness is seen well after midnight or at latitudes $< 65^\circ$ ILAT, where discrete aurora is comparatively rare. Aurora is more common during periods of high magnetic activity, as expressed by the planetary K_p index. This is illustrated in Fig. 4, where we present the dependence on K_p of the occurrence frequency of discrete and diffuse aurora within the entire region, 18:00–06:00 MLT and 55° – 75° ILAT. The blue and red bars correspond to discrete and diffuse aurora, respectively. We clearly see the expected dependence of auroral occurrence on the K_p index. Note that the statistics for high K_p values correspond to fewer measurements and are therefore less accurate. To rule out that the difference between Figs. 3a and c is caused by different levels of geomagnetic activity, we have compared average K_p values. During the $\sim 53\,000$ spins in sunlight that is the basis for Fig. 3c (and 2c), the average K_p was 2.21. Figure 3a (and 2a) is based on $\sim 18\,300$ satellite spins when Freja was measuring during dark summer nights, and the K_p averaged over these times was 2.66. From Fig. 4 we see that when K_p increases by one unit, the occurrence frequency increases by about 0.06. Hence, the increase of K_p by 0.45 between Fig. 3c and Fig. 3a corresponds to an increase in the occurrence frequency of 0.027, and we conclude that the observed increase in the occurrence frequency by 0.077 (from 10.3% to 18%) cannot be explained by a difference in average geomagnetic activity. During dark winter (Figs. 2g and 3g), the average K_p was as high as 2.75, but the occurrence frequency was

still lower than during dark summer. Still, there may be other sources of bias in our data, and an analysis of independent data from another satellite may be required to confirm that diffuse auroral precipitation is affected by sunlight.

6 Summary and conclusions

In this study we use 21 months (1 January 1993 to 30 September 1994) of electron precipitation data from the Freja satellite to investigate variations in the probability of aurora due to seasonal effects and solar illumination. We confirm that the probability of discrete aurora is significantly enhanced when the ionosphere is in darkness. The observations made above a dark ionosphere show that when the influence of sunlight is eliminated, aurora is more common during the summer than during the winter.

We also find a completely unexpected anticorrelation between the occurrence probability of diffuse aurora and solar illumination. It can be expected that the variation of the angle between the Earth's axis and the magnetotail may influence the conditions for electron precipitation and create a seasonal variation in the auroral occurrence rate, but there is no obvious asymmetry that can explain why diffuse aurora should be more common on the dark hemisphere. Pitch-angle diffusion is most efficient near the geomagnetic equator, where only a small deflection is required to scatter the electrons into the loss-cone. Since pitch-angle diffusion mainly is an equatorial phenomenon, it is difficult to understand how the resulting precipitation can be asymmetric in the way implied by our data. If the effects of a sunlit ionosphere on diffuse aurora suggested by our observations can be confirmed by future studies, a revision of existing models for diffuse auroral electron precipitation will clearly be required.

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