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Intermittency of riometer auroral absorption observed at South Pole

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Abstract

Auroral radio-wave absorption values measured at South Pole for 3 years using a riometer are analyzed in order to test whether they show evidence of intermittency. The properties of the parameters of the probability density functions determined for several magnetic local time sectors are found to be significantly different. The probability density functions for the pre-midnight sector show the typical shape associated to intermittency. No results are given for the afternoon sector because few auroral absorption events meet the selection criteria to give statistically significant results. It is suggested that if the precipitating particle population responsible for the riometer auroral absorption shared the intermittency features of the absorption then the present results would allow the study of the properties of the induction component of magnetospheric turbulence.

Keywords: Auroral absorption; Intermittency; Riometer; South Pole

1. Introduction

The study of intermittency of magnetospheric turbulence has been the subject of intensive discussions in the last few years. The very high values of the Reynolds number that characterize the solar wind and magnetospheric plasma, calculated for the case of Coulomb collisions ($\sim 10^{10}$–10^{12}), leads to the formation of the plasma sheet which can be considered as the turbulent wake downwind an obstacle (see reviews of Antonova, 2002; Borovsky and Funsten, 2003).

Evidence for turbulence comes from both satellite observations and ground based measurements. The former includes numerous results obtained from analyzes of the observations of strong fluctuations of the electric field at auroral altitudes using satellites such as Frejia, Fast and Polar (Mozer et al., 1980; Weimer et al., 1985), the results of electric field observations at high altitudes (Maynard et al., 1982), and the determination of bulk velocity fluctuation inside the plasma sheet (Angelopoulos et al., 1993, 1996, 1999; Ovchinnikov et al., 2000; Troshichev et al., 2002). It is clear now that the turbulent fluctuations lead to intense plasma sheet mixing (Antonova, 1985; Antonova et al., 1999) and to large values of the cross field quasi-diffusion coefficient (Borovsky et al., 1998) when the Antonova and

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Ovchinnikov (1999) model is used. Evidence for turbulence also comes from satellite observations of solar wind parameters as discussed by Burlaga (1991), Marsch and Tu (1997), Sorriso-Valvo et al. (1999) and Bruno et al. (1999), as already referred to by Stepanova et al. (2003).

As it is well known, ground-based observations have an advantage over satellite measurements since they could provide long time-series. Some of these can be considered as reflecting the basic characteristics of magnetospheric plasma, corresponding to a definite plasma flux tube, or to the global fluctuation of electric fields in the magnetosphere. This advantage has been taken into account in the analysis of the auroral electrojet (AE) index fluctuations (Consolini and De Michelis, 1998) and of the polar cap (PC) index fluctuations (Stepanova et al., 2003). The AE-index fluctuations represent both the large-scale electric field fluctuations and the fluctuations in the ionospheric conductivity, as signatures of both the electrostatic and the induction components of the magnetospheric electric field. The PC index fluctuations reflect the variations of the large-scale dawn–dusk electric field (Troshichev et al., 2000), as a signature of the electrostatic component. Thus, it seems particularly appropriate to seek the action of the induction component alone which could be done by analysing auroral absorption fluctuations.

Auroral absorption (Hargreaves, 1969, for a review) occurs primarily in the lower E and D regions of the Earth's ionosphere where electron-neutral particle collisions dissipate the energy of electromagnetic waves passing through these regions. The absorption depends on both the electron concentration and the collision frequency. The electron concentration is enhanced during auroral absorption events primarily by the ionisation of neutral constituents by energetic electrons precipitating along the geomagnetic field lines (Rees, 1992, for ionisation process). For many years it has been suggested (Hartz and Brice, 1967) that, in an over-simplified model, the energetic electrons responsible of auroral absorption are associated with both the substorm aurora (nighttime, so called 'splash' precipitation) and the diffuse aurora (morning, 'drizzle' precipitation). The locations and times of auroral occurrence do not necessarily coincide with absorption occurrence. Neither the acceleration mechanisms nor the sources of the energetic electrons need to be the same. In particular, for example, Stoker et al. (1996, 1997) have shown that in some cases the spatial structure of auroral absorption does not coincide with discrete optical structures but are adjacent to them. Furthermore, Wilson and Stoker (2002) found that the temporal and morphological differences between the optical and absorption structures can be consistent with two quite different magnetospheric processes. One is related to a softer electron precipitation (say <10 keV) resulting in auroral emissions in the E and F regions while the other produces precipitation of harder electrons (>10 keV) which ionize mostly the D region. It is this harder component that is associated with the morphology of auroral absorption occurrence. The morphology is fairly well known, the most significant dependencies of the absorption being with latitude (Gaussian variation) and time-of-day (double Gaussian variation) where both in turn have secondary dependencies on geomagnetic activity (e.g. Foppiano and Bradley, 1985, and references within).

In principle, since auroral absorption is strongly dependent on the energy flux spectra of precipitating electrons, some differences between auroral and sub-auroral absorption should be expected. Sub-auroral electron precipitation depends strongly on the pitch-angle distribution of the electrons at the equatorial plane where the effect is more noticeable in the morning/noon local-time sector (Kirkwood et al., 2001). The effect of anisotropic pitch-angle distribution is not important near midnight on the auroral latitudes where the isotropization of energetic particles takes place as the Larmor radii are comparable with the curvature radius of the geomagnetic field line (Sergeev et al., 1993). These features may be significant when tests for intermittency are applied to auroral absorption.

Now there are also differences in the time structure of auroral absorption events. Nighttime spike events have been associated with substorms in the magnetosphere (Hargreaves et al., 1997, 2001). The events are easily recognized for their sudden beginning, short duration (<2 min) and moderately maximum absorption (several dB at 38.2 MHz). It is natural to connect the acceleration mechanism of the particles producing the nighttime spike events to the substorm expansion-phase induction electric fields (e.g., Aggson et al., 1983) that arise during a reconfiguration of the magnetic field, a so-called dipolarization. This dipolarization is often interpreted as a cross-tail current disruption. The disrupted tail current is thought to be converted into field-aligned currents which are closed via a loop in the ionosphere (Lui, 1996). The induced electric field is predominantly in the dawn-to-dusk direction and is localized in space and time. Sudden increases in energetic electron fluxes at energies from tens to hundreds of keV have been observed by many satellites (see Birn et al., 1998 and references therein) and are ordinarily connected to the effect of the induction fields.

Another kind of spike event has also been reported (Stauning and Rosenberg, 1996). This type tends to occur in the daytime at high latitude. The daytime spikes have similar duration, however, in contrast to nighttime spikes exhibit smaller maximum absorption, somewhat smaller spatial coverage, and show little evidence of motion. The energetic particles responsible for this kind of events can be accelerated by the induction electric fields during magnetopause sporadic reconnection (Fedorov et al., 2001). Hargreaves et al. (2001) have studied the relationship between spike events and Pi-type micropulsations. They have shown that both the magnetic and the absorption pulsations are related to the acceleration processes at substorm onset and that these micropulsations cannot be a direct cause or consequence of electron precipitation. Kleimenova et al. (2002) showed cases when the brightenings of optical auroras were collocated with latitudinally localized bursts of pulsating riometer absorption and Pi3 geomagnetic pulsations.

In this paper we analyze a long series of auroral radio-wave absorption values determined from riometer observations at South Pole in order to investigate the properties of observed fluctuations and to confirm whether intermittency is present.

2. Data analysis

Radio-wave absorption values have been determined for South Pole (magnetic latitude of -74.2°) over many years from observations made by different types of riometers (relative ionospheric opacity meter, Little and Leinbach, 1959) using various techniques to derive the absorption values (see Hargreaves, 1969, for a review on early riometry). During the last decades, values for South Pole are routinely derived using the so-called ‘inflection point’ method to determine a reference ‘quiet curve’ (Krishnaswamy et al., 1985) from 38.2 MHz cosmic noise intensities received by a riometer using a broad-beam antenna (Rosenberg et al., 1991). The antenna is a circularly polarized cross-dipole antenna, which responds to the extraordinary mode of wave propagation in the southern hemisphere. It gives an approximately circular field of view, zenith oriented, of $\sim 60^\circ$ full angle measured at -3 dB level. The projection of the antenna pattern onto the ionosphere at 90 km height is a circle of approximately 100 km diameter. As it is usual practice with riometer observations, negative values of absorption are eliminated since they mostly relate to interference or to ‘quiet curve’ uncertainties.

The occurrence and statistical properties of auroral absorption at South Pole, which is located at the southern fringe of the southern auroral zone, have also been studied for many years (e.g. Hargreaves et al., 1964 and of Hargreaves and Cowley, 1967a, b). In particular, the day-to-day variability of auroral absorption values at South Pole has been found to be fairly well represented by cumulative amplitude-probability distributions of the log-normal type for a given time-of-day and level of geomagnetic activity (Krishnaswamy, 1987; Foppiano and Rosenberg, 1996). Fig. 1 shows distributions representative of 1997 corresponding to the morning hours (when the frequency of occurrence of auroral absorption is higher) and to the afternoon hours (when it is lower). These results are consistent with previous findings for many other locations within both the southern and northern auroral zones (Foppiano and Bradley, 1984, 1985).

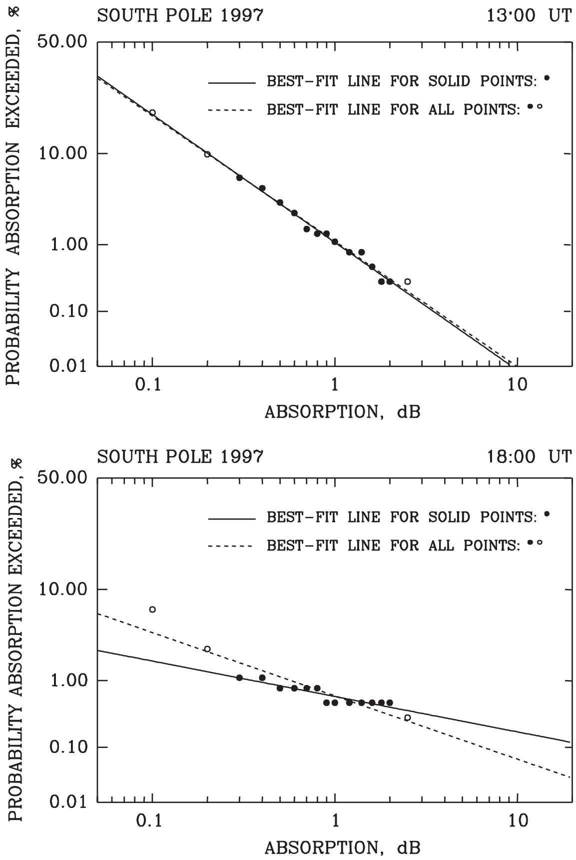

Fig. 1. Sample cumulative amplitude–probability distributions of equivalent 30 MHz riometer auroral absorption for South Pole (magnetic latitude of -74.2°) during 1997 (observed values at 38.2 MHz converted to equivalent 30 MHz using inverse squared frequency dependence). Lines are for best-fit log-normal distributions. Dashed line: best-fit for all data points. Solid line: best-fit to data points only within 0.3–2.0 dB range. Top: 13:00 UT ($\sim$10 MLT). Bottom: 18:00 UT ($\sim$15 MLT).

In the present paper, auroral absorption events at South Pole were first selected by visual inspection of one-day plots, giving 1 min absorption values, covering the 1995–1997 interval. This interval is considered to be representative of conditions of low solar activity level and fairly low geomagnetic activity level (Table 1). The selection criteria used were event time structure and maximum absorption value. Although this clearly precludes the inclusion of any PCA events in the database, it should be considered the possibility that some spiky events may get lost. Fig. 2 shows sample events from two different magnetic local time sectors. To

Table 1
Number of events selected and maximum event absorption

Year	Monthly mean sunspot number	Monthly mean Ap	Number	Maximum absorption (dB)
1995	9.0–31.1	8–19	217	4.6
1996	0.9–17.9	6–16	152	3.0
1997	5.7–51.3	4–14	110	3.6

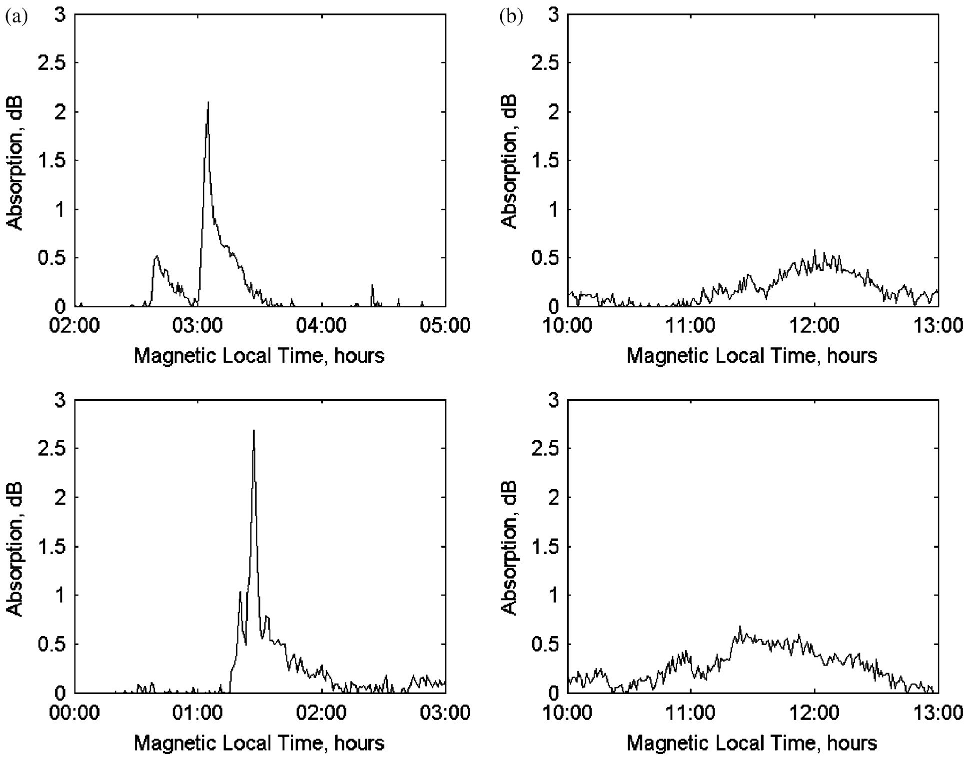

Fig. 2. Sample events of auroral radio wave absorption as determined by riometer at South Pole (magnetic latitude of −74.2°) for 1996 corresponding to two magnetic local time sectors. (a) Night: 27 March (top) and 22 September (bottom). (b) Morning: 18 April (top) and 17 November (bottom).

confirm that the selected events correspond to times for which South Pole lies within the auroral oval, Newell model images of the oval (Newell et al., 2002) corresponding to times nearest to each event were inspected whenever model images were available. Table 1 gives the number of events used and the maximum event absorption per year. Thus, the long series of auroral absorption values to be used here is simply the succession of all 1 min absorption values corresponding to all selected events.

To determine whether the properties of auroral absorption fluctuations depend on time-of-day, values were grouped according to magnetic local time (MLT). A 4 h overlapping grouping was used, e.g. the group labeled 00 MLT included values for 00:00 to 03:59, the next group, labeled 01 MLT included values for 01:00 to 04:59, and so on. Fig. 3 gives the number of absorption values used in each of the 24 sets. Obviously the number of absorption values is not the same for all hours, however this is not surprising since most riometer absorption statistics indicate that absorption is more frequent in the morning and around midnight with a pronounced minimum occurrence in the evening (Hargreaves, 1969).

The statistical study for each set follows closely to that used by Stepanova et al. (2003) for PC-index fluctuations or increments which in turn is an application of the method proposed by Castaing et al. (1990) to describe the distribution of velocity differences, observed at two points separated by a given distance x, in an intermittent

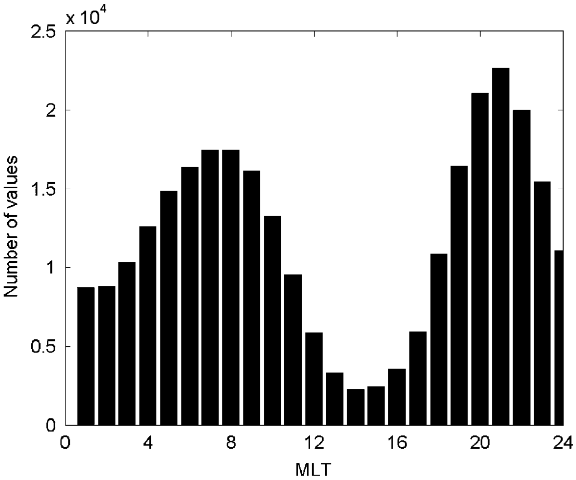

Fig. 3. Number of auroral absorption values used for probability density determination. Each histogram bar gives the number of values within a 4 h interval starting on the hour, e.g. the group labeled 00 MLT includes values for 00:00–03:59, the next group, labeled 01 MLT includes values for 01:00–04:59.

turbulent flow. In both, the present case of auroral absorption fluctuations $\delta L = L(t+\tau) - L(t)$, and the case of PC-index fluctuations, $\delta PC = PC(t+\tau) - PC(t)$, the fluctuations refer to a time scale parameter τ instead of the space parameter x of fluid velocity of Castaing et al. (1990). In this method each probability density function (PDF) of δL is expressed as a superposition of a Gaussian function and a log-normal distribution which describes the distributions of variances σ,

$$P(\tau) = \frac{A}{2\pi\lambda}\int_0^\infty \exp\left[-\frac{\tau^2}{2\sigma^2}\left(1 + a\frac{\tau/\sigma}{\sqrt{1+\tau^2/\sigma^2}}\right)\right] \exp\left[-\frac{\ln^2(\sigma/\sigma_0)}{2\lambda^2}\right]\frac{d\sigma}{\sigma^2}, \quad (1)$$

where A is a normalization factor, a is a skewness factor describing the asymmetry of the PDF tails, σ_0 is the most probable invariance and λ represents the log-norm variance of the Gaussian variances σ. Though it is not exactly the velocity difference in a turbulent flow, the auroral absorption fluctuations observed at a fixed location within the auroral oval could be considered as mirroring certain features of the turbulence in the magnetosphere associated to the substorm dynamics. An early association of this type was already suggested by Hargreaves and Cowley (1967a) for nighttime auroral absorption events.

For each of the 24 data sets PDFs of δL were determined corresponding to a range of values of τ from 8 to 256 min. δL calculations were done only within an auroral event, i.e. only for the longer events τ could reach 256. Then analytical PDFs were fitted to these observed PDFs using the Nelder–Mead algorithm, which is readily available in several statistical software packages. It should be noted that these normalized PDFs can be directly compared. Furthermore, i n order to study the dependence of the PDFs on time-scale τ, the dependence of λ^2 on τ is analyzed since λ^2 is a quantitative measure of intermittency. In particular, again following the analysis of Stepanova et al. (2003) , a power law has been fitted to the observed dependence of λ^2 on τ, as $\lambda^2(\tau) = \mu\tau^{-\alpha}$.

3. Results

Fig. 4 gives sample observed and fitted PDFs representative of pre-midnight and early morning MLT conditions for a range of values of τ. As it can be clearly seen auroral absorption fluctuations exhibit a strong non-Gaussian character only for pre-midnight hours for all values of τ. This may be related to the particular features of particle precipitation on that time sector indicating scale-dependence and absence of self-similarity of time fluctuations. Unfortunately, as already mentioned, no results can be derived for the evening time sector because few auroral absorption events meet the selection criteria to give statistically significant results.

Fig. 5 shows the observed and fitted power-law dependence of λ^2 on τ for 19–22 MLT as an example of the fitting afforded to the slowly decrease of λ^2 for increasing τ. In turn, Fig. 6 gives λ^2 as function of τ for all MLT hours and shows that indeed λ^2 tends to decrease slowly with τ for all MLT hours, however the absolute value of $\lambda^2(\tau)$ is higher for 18–24 MLT. This

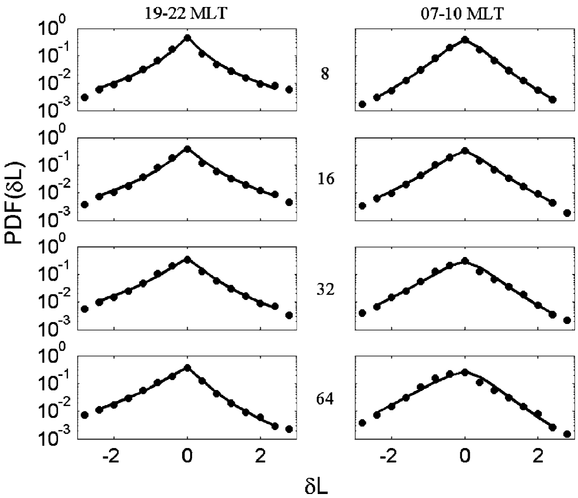

Fig. 4. Sample observed and probability density functions of auroral absorption fluctuations for a range of values of the time scale parameter τ (8, 16, 32 and 64 min). Left: 19–22 MLT. Right: 07–10 MLT.

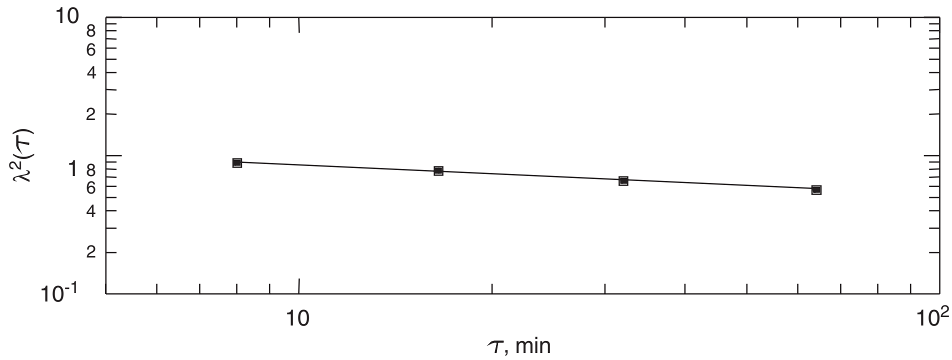

Fig. 5. Sample observed and power law fitted dependence of λ^2, a quantitative measure of intermittency of auroral absorption fluctuations, on τ, the time scale parameter (see text), for 19–22 MLT.

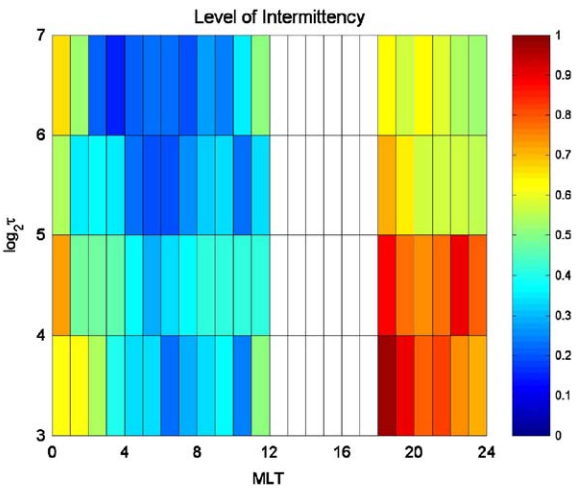

Fig. 6. Magnetic local time dependence of λ^2, a quantitative measure of intermittency of auroral absorption fluctuations, on τ, the time scale parameter (see text).

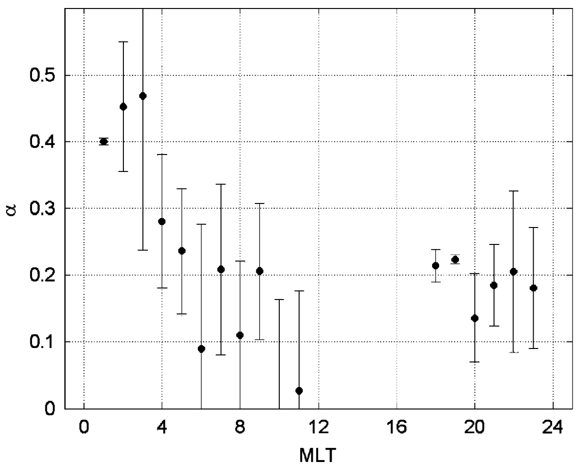

Fig. 7. Magnetic local time dependence of α, a parameter of a power law fitted to the observed dependence of λ^2 on τ (see text).

confirms the dependence of intermittency on MLT, the intermittency being significant only during nighttime. In particular, Figs. 7 and 8 show the MLT dependence of the power law α and μ parameters. As it can be seen, the values of α are smaller than 0.3 for all hours except between 01–03 MLT when they are slightly larger. Values of μ are clearly larger between 19 and 3 MLT than during the early morning, indicating that the source of intermittency is located in the night side.

4. Discussion and conclusions

Recently the study of the shape of the PDFs of observed fluctuations has become a powerful method to search for turbulent processes. This method has been used to study intermittency of series of values of solar wind parameters (Sorriso-Valvo et al., 1999), of AE-index (Consolini and De Michelis, 1998) and of PC index (Stepanova et al., 2003). In this paper the intermittency of auroral radio-wave absorption observed at South Pole has been studied. PDFs proposed by Castaing et al. (1990) have been fitted to observed auroral absorption fluctuations corresponding to different time scales for different MLT sectors. It was found that the log-norm variance of the Gaussian variances (λ), which characterizes the departure of a given PDF from the Gaussian one, varies with the time scale parameter (τ), indicating the presence of intermittency. Both the absolute value of λ and its dependence on τ are MLT dependent, and the maximum level of intermittency is observed in the nighttime sector. Table 2 compares the results of the power law fit to $\lambda^2(\tau)$ for PC-index, AE-index, and solar wind parameters already mentioned with those derived here for auroral absorption. As can be seen, the values of μ obtained for nighttime auroral absorption, which are consistent with intermittency, differ from those for PC fluctuations but are close to ones observed for turbulent AE-index. By contrast, values of μ for daytime auroral absorption indicate less intermittency and are closer to those for interplanetary magnetic field, solar wind bulk velocity and PC-index. (Kavanagh et al. (2004) demonstrated that cosmic noise absorption, specially on the day-side, shows a statistical response to increased level of solar wind speed and to southward IMF). We interpret these differences as resulting from different characteristics of the fluctuations of the electrostatic and the induction components of the magnetospheric electric field, being reflected on the fluctuations of the various indices. When fluctuations of the magnetospheric electrostatic field are the main influence on the characteristics of PC index fluctuations, electrons, accelerated by induction electric field, are the main source of the increase of auroral absorption during the night. Fluctuations of the induction field are one of the main characteristics of substorm process, which also affects partially the AE-index fluctuations. The results obtained show the difference between the characteristics of the electrostatic and the induction components of the field and the increase of the level of the intermittency during substorms.

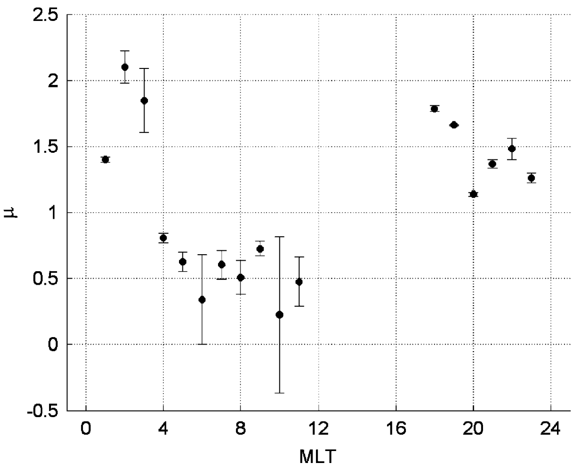

Fig. 8. Magnetic local time dependence of μ, a parameter of a power law fitted to the observed dependence of λ^2 on τ (see text).

Table 2
Parameters μ and α of power law fitted to λ^2, a measure of intermittency

	α	μ	
PC index, all seasons			
All	0.13±0.01	0.745±0.006	Stepanova et al. (2003)
PC<0	0.075±0.008	0.879±0.002	
PC>0	0.11±0.01	0.664±0.008	
PC index, winter			
All	0.06±0.01	0.688±0.008	Stepanova et al. (2003)
PC<0	0.00±0.01	1.226±0.004	
PC>0	0.08±0.01	0.718±0.006	
PC index, summer			
All	0.16±0.01	0.694±0.008	Stepanova et al. (2003)
PC<0	0.03±0.02	0.58±0.02	
PC>0	0.13±0.01	0.60±0.01	
AE-index			
AE, laminar	0.50±0.02	0.30±0.01	Consolini and De Michelis (1998)
AE, turbulent	0.50±0.02	1.33±0.10	
Interplanetary magnetic field			
Fast solar wind	0.19±0.02	0.90±0.03	Sorriso-Valvo et al. (1999)
Slow solar wind	0.18±0.03	0.75±0.03	
Bulk velocity			
Fast solar wind	0.20±0.04	0.38±0.02	Sorriso-Valvo et al. (1999)
Slow solar wind	0.44±0.05	0.54±0.03	
Auroral absorption			
Nighttime	0.14–0.43	1.2–2.2	Present results
Early morning	0.03–0.28	0.2–0.8	

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