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Solar Protons in the Earth's Magnetosphere from Riometric and Satellite Data During Magnetic Storms in October 2003

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Abstract—The fluxes and penetration boundaries of solar energetic particles on the CORONAS-F satellite during October 2003 superstorms are compared with the riometric absorption measurements on a worldwide network of riometers. The dynamics of the polar cap boundaries is investigated at various phases of magnetic storms. The dependence of absorption on time of the day and on solar proton spectrum is calculated at various phases of a solar energetic particle event.

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INTRODUCTION

The solar energetic particles (SEPs) with energies from several to several hundred MeV generated during chromospheric solar flares penetrate relatively freely into the Earth's magnetospheric tail projected in the ionosphere onto the polar cap. In the ionosphere, the solar protons raise significantly the ionization level in the *D*-layer, causing the absorption of radio waves in the frequency range 10–50 MHz to increase. This type of absorption is called polar cap absorption (PCA), in contradistinction to similar effects produced by auroral electrons (Driatskii, 1974; Hargreaves et al., 1993; Ranta et al., 1995; Lazutin et al., 1969).

The most commonly used instrument for absorption measurements is the riometer that continuously monitors the absorption level of cosmic radio noise. Although the riometric absorption carries no information about the proton spectrum variations and, besides, is often "contaminated" by the absorption produced by auroral electron precipitations and radio bursts of both natural (the Sun) and anthropogenic origins, a large network of riometers allows their data to be used to monitor the temporal SEP variations both independently and in conjunction with low-altitude satellite measurements.

Previous comparisons of the total solar proton fluxes and PCA showed that the proton flux is proportional to the square of the absorption in decibels and that protons with energies above 10–15 MeV make a major contribution to the absorption (Patterson et al., 2001; Croom, 1973). Since the SEP spectra change both from event to event and during each SEP event and since the particle detectors on different satellites differ greatly in characteristics, the results of comparisons differ significantly. Therefore, individual comparisons for a specific satellite should be made for quantitative estimations.

In this paper, we discuss the results of our comparison of PCA with the CORONAS-F solar proton measurements during a series of SEP events and the accompanying extreme geomagnetic activity in October 2003. Our main objective is to determine the coupling coefficients for specific energy channels of the CORONAS-F particle detectors and to ascertain which proton energy ranges are most efficient in ionizing the ionospheric *D*-layer and how well the riometer data trace the dynamics of the proton flux and the motion of the proton penetration boundaries into the Earth's magnetosphere.

RESULTS OF MEASUREMENTS

The period of enhanced SEP intensity started on October 26 and ended on November 6, 2003. The series of October storms and the processes on the Sun and in interplanetary space that produced them were considered in detail in collective reviews of a collaboration of Russian scientists (Veselovskii et al., 2004; Panasyuk et al., 2004) and in separate papers published in two special issues of the Journal "Cosmic Research".

The CORONAS-F satellite has a nearly circular orbit with an inclination of 82.5° and an altitude of 415–445 km. The detectors whose data were used in

[†] Deceased.

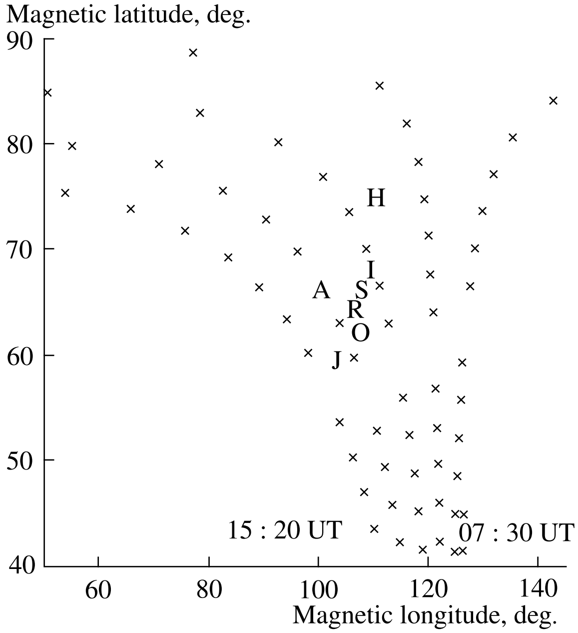

Fig. 1. Relative positions of the riometric stations from the Scandinavian chain (the uppercase letters of the station names are shown: Hornsund (H), Ivalo (I), Sodankyla (S), Rovaniemi (R), Oulu (O), and Juvaskyla (J)) and CORONAS-F trajectories (crosses) in magnetic coordinates on October 30, 2003.

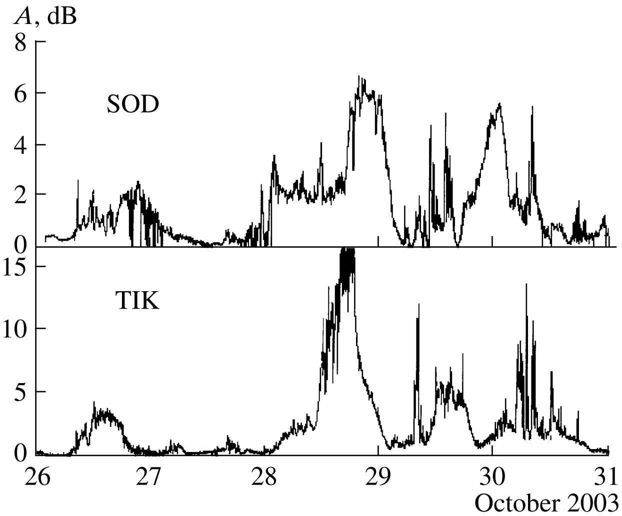

Fig. 2. Riometric absorption at Sodankyla (upper panel) and Tiksi (TIK) (lower panel).

this paper were described by Kuznetsov et al. (1995). Here, we used riometric data from the meridional chain in Scandinavia: Hornsund (the international code of the station is HOR, the corrected geomagnetic latitude is 73.8°), Ivalo (IVA, 65.0°), Sodankyla (SOD, 63.9°), Rovaniemi (ROV, 63.2°), Oulu (OUL, 61.5°), Juvaskyla (JYV, 58.8°), as well as the Tiksi station (TIK, 65.65°) of the Yakutsk meridian. Figure 1 shows the positions of the riometric stations from the Scandinavian chain and several CORONAS-F trajectories on October 30 in magnetic coordinates. Figure 2 shows a combined plot of riometric absorption at the Tiksi and Sodankyla stations. The absorption variations reflect both the actual temporal proton flux variation and the diurnal absorption wave with a maximum at daytime (noon in Sodankyla—at 10:30 UT and in Tiksi—at 03:40 UT).

Since the substorm activity was high in the period under consideration, to analyze the PCA variations, we must separate the contribution to the absorption made by auroral electron precipitations (auroral absorption—AA). There is no standard procedure for this separation. We used morphological differences between PCA and AA—the latter are short-lived and coincide with bay magnetic disturbances on the night side. On the morning and day sides, AA is more difficult to separate, since the absorption bays are smoother, last up to several hours, and are delayed in time relative to the substorm activations in the nighttime sector. Although an additional selection criterion, namely, the temporal solar proton variation measured on CORONAS-F, helps, there remains an uncertainty in identifying the source of the short-term variations at certain times, for example, during the main phase of the October 29 storm.

THE CORRELATION OF PCA WITH SOLAR PROTON FLUXES

Analysis of the physical processes that lead to the absorption of radio waves in the ionosphere (see, e.g., Driatskii (1974) predicts a linear relation between the square of the absorption and the proton flux J_p:

$$J_p = KA^2, \quad (1)$$

where A is the absorption in dB at a frequency of 30 MHz and K is a coefficient that depends on the operating riometer frequency, antenna parameters, proton spectrum, and ionospheric state.

Figure 3 compares the riometric absorption and the proton flux in the polar cap for the daytime and nighttime absorptions derived from our data. The accuracy of measuring PCA in a range up to 1 dB is determined by the accuracy of measuring the diurnal variation in undisturbed radio noise level and can be less than 0.1 dB. However, the noise level increased in the last decades and the difficulty of taking into account the contribution to the absorption from electron precipitations lead to a more significant scatter of points. Given the accuracy and possible errors in calculating the absorption, note a close agreement of the measurements of two chains between themselves and with the satellite proton flux measurements. The dotted lines in the plots are described by Eq. (1), where the coefficients K for the daytime and nighttime absorptions are, respectively, 400 and 2000 for proton energies 1–5 MeV and 10 and 100 for the energy range 14–26 MeV.

Since most of the authors assume that protons with energies above 10–15 MeV make a major contribution

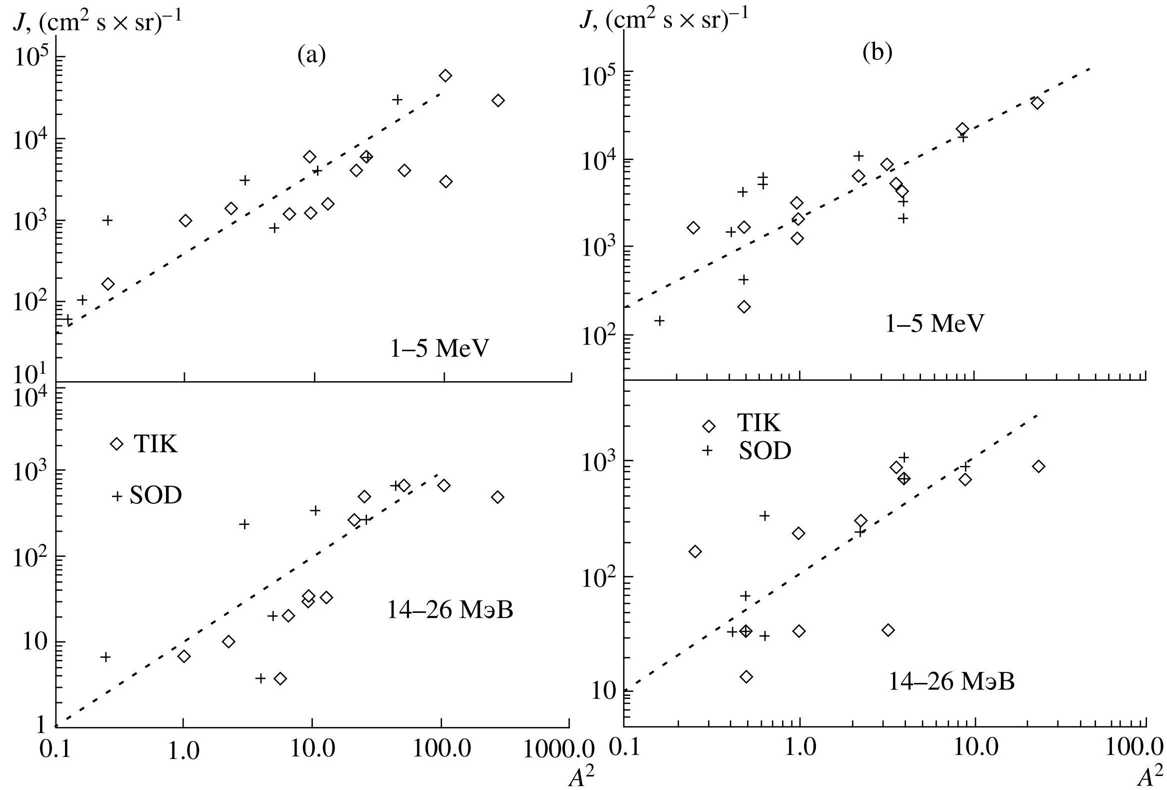

Fig. 3. Relationship between riometric polar cap absorption and proton flux measured in two CORONAS-F detector channels for the daytime sector. The crosses and diamonds pertain to the measurements in the Scandinavian and Yakutsk sectors, respectively. The data for the (a) daytime and (b) nighttime sectors.

to the absorption, a good correlation between PCA and 1–5-MeV proton fluxes is somewhat unexpected. This result is not a simple consequence of the synchronous proton flux variations as a whole. We have an opportunity to verify that protons with these energies actually contribute to the absorption. For example, Fig. 4 shows that the increase in absorption in the time interval 08–12 UT on October 30 is related to the rise in proton flux precisely in the energy range 1–5 MeV, since there is no flux rise in the remaining channels. A similar situation was observed at 02–07 UT on October 29. The pattern of proton flux variations again diverges: the flux of energetic protons decreases, while the flux of low-energy protons increases. According to the riometer data, the absorption in these time intervals also increases, which proves a significant contribution from protons with energies 1–5 MeV to the absorption.

Note that for the nighttime PCA, the numerical dependence on solar proton flux has been obtained for the first time owing to an extremely high intensity of the SEP event being analyzed. In previous papers, we find only a report on an approximately fivefold decrease in absorption in the nighttime sector compared to the daytime one (Driatskii, 1974). The above dependences show that this ratio is, on average, 3.7 at equal proton fluxes with energies 14–26 MeV and 2.3 at equal proton fluxes with energies 1–5 MeV. The difference in ratio is probably related to a change in the shape of the proton energy spectrum.

We can reconstruct the pattern of temporal proton flux variations from riometric data only in separate day-

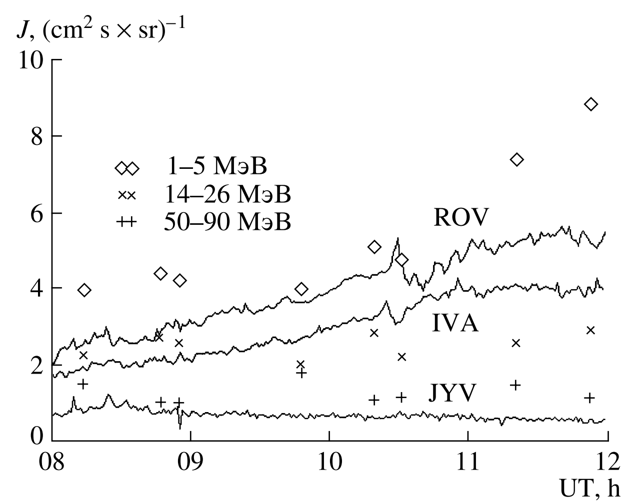

Fig. 4. Synchronous absorption and proton flux variations on October 30, 2003. The indices near the curves correspond to the international code of the stations.

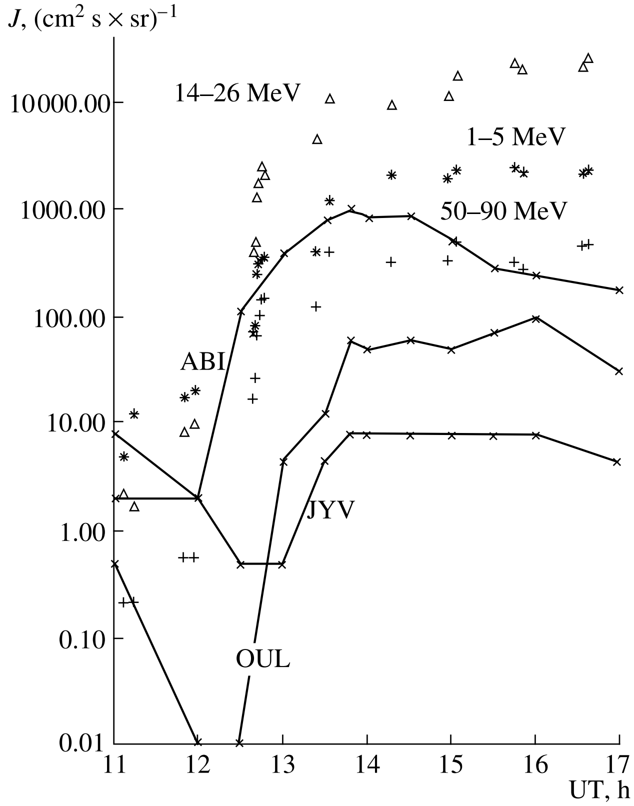

Fig. 5. Comparison of the 1–5-MeV proton flux (solid lines) measured from the riometric absorption at Abisko, Juvaskyla, and Oulu with the CORONAS-F proton flux measurements during the SEP flux increase on October 28, 2003.

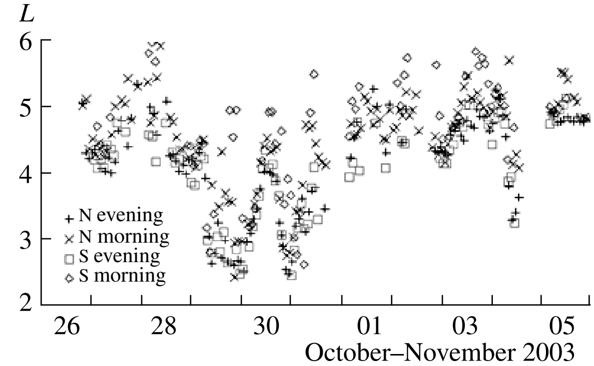

Fig. 6. Dynamics of the SEP penetration boundaries during 11 days of extreme magnetic storms in October–November 2003 from CORONAS-F measurements. Different symbols denote the boundaries determined from the evening and morning passages through the northern (N) and southern (S) polar caps.

time and nighttime intervals; the absorption in transitional intervals depends on the Sun's elevation and on other factors that are difficult to take into account. We also has to discard the intervals of strong auroral activity, which at this time were numerous and intense.

Figure 5 compares the measured and calculated (from the riometric absorption) temporal proton flux variations at the onset of a rise in SEP flux on October 28. For the high-latitude Abisko riometer (ABI, 65.3°), there is good agreement between the calculated proton flux and the in situ measurements. The reduced calculated flux for the other two riometers suggests that the latter are located at the proton penetration boundary, where the flux is attenuated significantly.

ABSORPTION AT THE POLAR CAP BOUNDARY

The penetration of solar protons into the Earth's magnetosphere and, accordingly, into the polar cap and the auroral zone is regulated by the level of magnetic activity. The penetration boundaries undergo significant displacements toward the equator at the main phase of a magnetic storm (there were 3 such intervals in the period under discussion) and away from the equator at the recovery phase synchronously with the *Dst* variation (Darchieva et al., 1990; Ivanova et al., 1985; Kuznetsov et al., 2007). Figure 6 shows the displacement of the 2–4-MeV proton penetration boundaries during October 2003 magnetic storms from CORONAS-F measurements.

Comparing the patterns of proton flux decrease at the SEP penetration boundary from in situ measurements and riometric data is of considerable interest. In Fig. 7, the proton flux with energies 14–26 MeV is plotted against the magnetic latitude for two CORONAS-F passages through the northern and southern caps in the intervals 13:20–13:40 and 14:06–14:30 UT on October 28, respectively. We see that the daytime boundary is displaced poleward compared to the nighttime one, which is similar to the displacement of the auroral oval. In addition, there is an asymmetry in the location of the southern and northern polar cap boundaries—the protons on the northern cap penetrate deeper than those on the southern one in the evening and vice versa in the morning.

The Scandinavian chain of riometers is located at this time on the sunlit side of the Earth where the absorption is strong, which allows comparison with in situ measurements to be made. In Fig. 7, the letters corresponding to the station name are arranged relative to the horizontal axis at the magnetic latitude of the station and along the vertical axis in accordance with the 14–26-MeV proton flux calculated from Eq. (1). We see good agreement of the latitudinal variation in SEP penetration boundary with the profile reconstructed from the data of the riometer chain in the daytime sector.

The Yakutsk chain was located at this time on the night side; as we see from the plot, the Tiksi station is clearly located in the zone of free proton penetration. However, the maximum absorption in Tiksi was no more than 0.5 dB, which gives an estimated flux that is almost an order of magnitude lower than the flux measured by the satellite in both the Southern and Northern

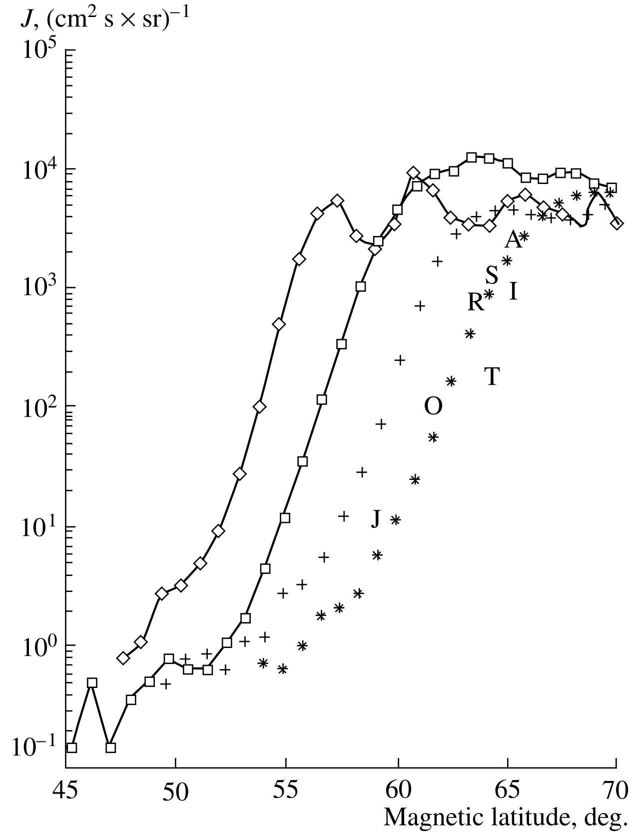

Fig. 7. Latitudinal variation of the solar proton penetration boundary and cosmic noise absorption at 14 UT on October 29, 2003. The solid lines denote the evening–night passages (diamonds—north, crosses—south); the individual symbols denote the morning–day passages (asterisks—north, crosses—south). The letters denote the proton flux calculated from the riometric absorption. T—Tiksi; the remaining symbols are the same as those in Fig. 1. The positions of the symbols along the horizontal axis correspond to the magnetic latitude of the station.

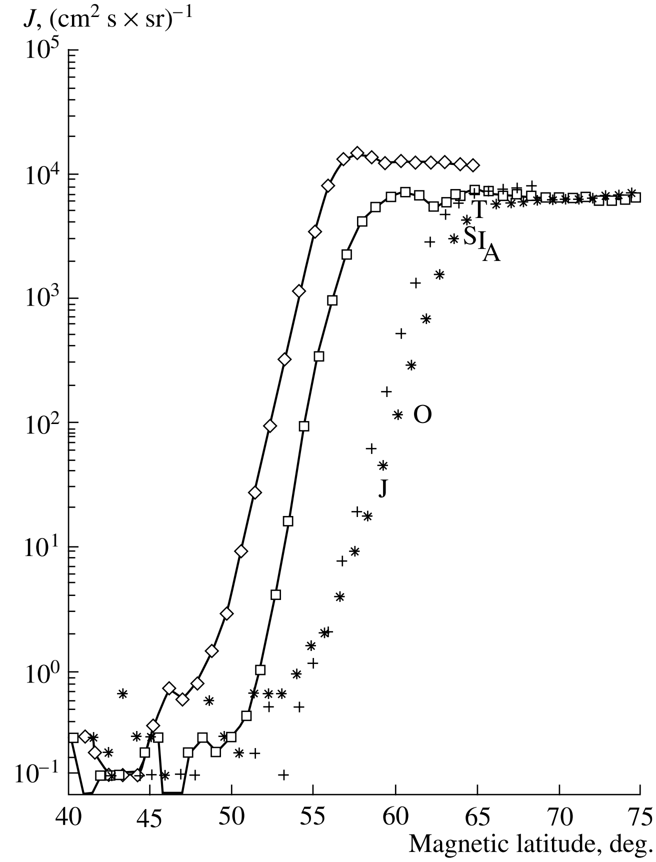

Fig. 8. Same as Fig. 7 for 12 UT on October 30, 2003.

Hemispheres (letter T). There was probably a polar cap asymmetry at this time, which is unseen during the passage of one satellite. The absorption in Tiksi increased to a normal value comparable to the particle flux measured in the cap 40 min later.

A similar plot for the passages on October 30 near 12 UT is shown in Fig. 8. Here, the magnetic activity was moderate; this was a break between two storms. There is no difference in the locations of the daytime boundaries of the Southern and Northern Hemispheres and, although the displacement of the nighttime boundaries decreased approximately to 2°, it was retained with the same sign. The riometric measurements are in good agreement with the in situ proton measurements. The relative positions of the Scandinavian chain of riometers and the satellite trajectory were favorable for comparison, as we see from Fig. 1.

It should be noted that here we do not set the objective of investigating the locations of the penetration boundaries in different longitude sectors. The *L-B* coordinates or the corresponding invariant latitude should be used for a proper comparison. Using the geomagnetic coordinates was dictated by the objective of comparing the in situ measurements with the riometric absorption.

CONCLUSIONS

The period of intense SEP events during strong magnetic storms in late October–early November 2003 provides a good opportunity for analyzing the relationship between riometric polar cap absorption and in situ solar proton measurements. Our analysis confirmed previously found trends and revealed new ones.

(1) PCA at daytime (the sunlit ionosphere) is related to the proton flux quadratically. We derived the coefficients of the relation between absorption and protons fluxes measured on CORONAS-F.

(2) We showed that not only protons with energies above 10–15 MeV, but also protons with energies 1–5 MeV make a significant contribution to the absorption. In two cases where the temporal variation in this channel diverged from that in higher-energy channels, the riometric absorption accompanied the change in the low-energy channel.

(3) A numerical relation between proton flux and PCA on the night (unlit) side of the Earth was obtained for the first time. We showed that the ratio of the absorption in the daytime and nighttime parts of the polar cap at equal solar proton fluxes varies within the range 2–4.

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