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Improved dynamic geomagnetic rigidity cutoff modeling: testing predictive accuracy

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Abstract. In the polar atmosphere, significant chemical and ionization changes occur during solar proton events (SPE). The access of solar protons to this region is limited by the dynamically changing geomagnetic field. In this study we have used riometer absorption observations to investigate the accuracy of a model to predict K_p-dependent geomagnetic rigidity cutoffs, and hence the changing proton fluxes. The imaging riometer at Halley, Antarctica is ideally situated for such a study, as the rigidity cutoff sweeps back and forth across the instrument's field of view, providing a severe test of the rigidity cutoff model. Using observations from this riometer during five solar proton events, we have confirmed the basic accuracy of this rigidity model. However, we find that the model can be improved by setting a lower K_p limit (i.e., K_p=5 instead of 6) at which the rigidity modeling saturates. We also find that for L>4.5 the apparent L-shell of the beam moves equatorwards. In addition, the Sodankyla Ion and Neutral Chemistry model is used to determine an empirical relationship between integral proton precipitation fluxes and nighttime ionosphere riometer absorption, in order to allow consideration of winter time SPEs. We find that during the nighttime the proton flux energy threshold is lowered to include protons with energies of >5 MeV in comparison with >10 MeV for the daytime empirical relationships. In addition, we provide an indication of the southern and northern geographic regions inside which SPEs play a role in modifying the neutral chemistry of the stratosphere and mesosphere.

1. Introduction

Solar proton events (SPEs) are a major space weather phenomena that can produce hazardous effects in the near-Earth space environment. The occurrence of SPEs varies during the 11-year solar activity cycle. In active years, especially during the falling and rising phases of the solar cycle, SPEs may average one per month, but during solar minimum years the occurrence is very low, e.g., ~1 per year. SPEs cause 'upsets' to Earth-orbiting satellites, increased radiation exposure levels for humans onboard spacecraft and high-altitude aircraft, ozone depletions and disruption to HF/VHF communications in mid- and high-latitude regions. A detailed understanding of all these impacts depends upon knowledge of the dynamic rigidity cutoffs as SPE particles are partially guided by the geomagnetic field. Higher rigidities are required for a particle to reach lower geomagnetic latitudes, and thus all particles with rigidities larger than the minimum can penetrate to that latitude (and all higher latitudes). The geomagnetic cutoff rigidity is a dynamic quantity depending on the Earth's internal and external magnetic fields [*Smart and Shea*, 2003; *Kress et al.*, 2004].

Experimental measurements of geomagnetic cutoff rigidities have generally been based on satellite observations. Few experimental studies have derived cutoffs during the most disturbed conditions during geomagnetic storms. Theoretical calculations have primarily focused on tracing particles through models of the Earth's field producing grids of estimated cutoff rigidities distributed over the Earth at a given altitude [e.g., *Smart and Shea*, 2001]. *Birch et al.* [2005] used satellite measurements of the edge of the polar cap sampled four times each day, and found that cutoff latitudes reduce by 5-8º during storms. They compared the results with particle-tracing models, which underestimated the effects of a severe storm. *Rodger et al.* [2006] used the model of K_p-dependent geomagnetic rigidity cutoff energies based on the Tysganenko-89 magnetic field model [*Smart and Shea*, 2001], to investigate for the first time, detailed comparisons of theoretical cutoff rigidities and ground-based measurements during a large geomagnetic disturbance. Energy cutoffs on satellite derived proton fluxes were used to calculate the predicted cosmic noise absorption levels for the Halley imaging riometer (IRIS) during a single SPE event in November 2001. The predicted absorption levels showed good agreement with those experimentally observed for low and mid levels of geomagnetic disturbance levels (K_p<5). However, in very disturbed conditions (K_p≈7-9) the rigidity energy cutoffs indicated by the IRIS observations appeared to saturate around those predicted for K_p≈6 by the particle-tracing approach. This suggested that the geomagnetic latitude limit for the penetration of SPE protons during large geomagnetic storms is rather more poleward than had been indicated previously.

Imaging riometer systems (IRIS) like the one at Halley, Antarctica, are well suited for examining geomagnetic cutoffs, because the receiver arrays provide an image of the ionospheric absorption levels in a 200 km × 200 km horizontal region above the instrument by measuring the absorption of cosmic radio noise at a given frequency (usually 20-40 MHz). Using riometers it has previously been shown that there is an empirical relationship between the square root of the integral proton flux (>10 MeV) and cosmic noise absorption (CNA) in daytime, at least when geomagnetic cutoff effects do not limit the fluxes [*Kavanagh et al.*, 2004]. The same study concluded that variations in the spectral hardness of the SPE proton flux and atmospheric collision frequencies do not cause significant departures from the linear relationship observed.

In this paper we examine ground-based measurements during five SPEs, based on the observations from the imaging riometer at Halley, Antarctica, which is situated such that the rigidity cutoff sweeps back and forth across the instrument's field of view during each SPE. We calculate riometer absorption, using input proton fluxes modified by rigidity cutoff calculations, and contrast the varying, predicted and observed, rigidity cutoffs during each geomagnetic disturbance. We also use the Sodankyla Ion and Neutral Chemistry (SIC) model to determine an empirical relationship between integral proton precipitation fluxes and nighttime ionosphere riometer absorption to complement the daytime relationship already published, and to study rigidity effects during winter time SPEs.

2. Experimental Setup

The riometer utilizes the absorption of cosmic radio noise by the ionosphere [*Little and Leinbach*, 1959] to measure the enhancement of D-region electron concentration by energetic charged particle precipitation [*Stauning*, 1996]. The riometer technique compares the strength of the cosmic radio noise signal received on the ground to the normal sidereal variation referred to as the quiet-day curve to produce the cosmic noise absorption. The instantaneous ionospheric absorption in decibels is derived from the ratio of the prevailing signal level to this curve [*Krishnaswamy et al.*, 1985]. In typical operations the absorption peaks near 90 km altitude, where the product of electron density and neutral collision frequency maximizes. In this paper we consider experimental observations from selected beams of an imaging riometer located at Halley (75.6ºS, 26.32°W, *L*=4.6), as shown in Figure 1.

At Halley the system is a snow-buried 49-beam imaging riometer, operating at 38.2 MHz and sampled every 1 sec [*Rose et al.*, 2000]. Several receivers are multiplexed through a phased array of 64 crossed-dipole antennas to achieve narrow beam scanning of the D region. The beam width is 13º. In the meridian plane the most equatorward and poleward beams intersect the D region ionosphere about 1º north (equatorward) and south (poleward) from the vertical central beam, respectively. Absorption values for obliquely orientated (non-vertical) beams are automatically corrected to vertical following the technique described by *Hargreaves and Jarvis* [1986].

In this study we analyze data collected at Halley during five SPEs. The SPE periods are July 2000, November 2000, two periods in November 2001, and October 2003. Prior to, and after these events the Halley imaging riometer performance was severely limited by snow buildup as the IRIS was buried [*Rose et al.*, 2000] as a result of ever-increasing snow accumulation on the antenna array.

3. Estimates of Rigidity Cutoffs

It has been recognized for some time that geomagnetic rigidity cutoffs are well-ordered in terms of the McIlwain *L*-parameter [*Smart and Shea*, 1994; *Selesnick et al.*, 1995]. The *L*-variation of the geomagnetic rigidity cutoff has been determined for quiet times from ≈10,000 nuclei observations made by the MAST instrument on the SAMPEX satellite [*Ogliore et al.*, 2001]. These authors report that the geomagnetic rigidity cutoffs, R_c, for quiet times are given by

$$R_c = 15.062\ L^{-2} - 0.363 \qquad \text{(in GV)} \qquad (1)$$

representing average conditions for K_p=2.3. As noted above, dynamic vertical cutoff rigidities dependent upon magnetic activity levels have been determined by particle-tracing [*Smart and Shea*, 2003] using the K_p-dependent Tsyganenko magnetospheric field model. These authors have reported that the change of proton cutoff energy with K_p is relatively uniform over the range of the original *Tsyganenko* (1989) model (K_p<5), but the cutoff changes introduced by the *Boberg et al.* [1995] extension to higher K_p is non-linear such that there are large changes in proton cutoff energy for a given *L*-value at large K_p values. *Rodger et al.* [2006] made use of the K_p-dependent variations in the effective vertical cutoff energies at a given IGRF *L*-value at 450 km altitude determined from this modeling [*Smart et al.*, Fig. 5, 2003], but with a slight modification to ensure that the geomagnetic rigidity cutoff varies as 15.062 L^{-2}, as observed in the SAMPEX experimental data. Note that the change in cutoff energy with geomagnetic activity is strongly non-linear at the highest disturbance levels. In order to interpolate down to lower altitudes (e.g., 100 km), *Rodger et al.* [2006] followed the approach outlined by *Smart and Shea* [2003] again using the IGRF determined *L*-value. This exploits the basic relationship between R_c and *L*, i.e.,

$$R_c = V_k L^{-2} \qquad (2)$$

where V_k is an altitude independent constant. Thus by knowing the value of V_k for the IGRF L-value at 450 km altitude above a given location, one can determine R_c at 100 km once one knows the L-value for that location at 100 km altitude. In the Rodger-approach the upper limit for K_p in the rigidity model is K_p=6. When K_p exceeds this level then it is forced to K_p=6 in the rigidity calculations, a limit selected through contrast with the November 2001 experimental observations.

The rigidity cutoff relationship developed by *Smart and Shea* [2003], and tested and improved by *Rodger et al.* [2006] is further investigated here using a series of SPEs observed by the imaging riometer at Halley.

4. Daytime riometer data and calculated absorption

Figure 2 shows three days of experimentally-observed cosmic noise absorptions recorded by two of the meridional beams of the Halley IRIS instrument (i.e., pointing N-S) during the 8-11 November 2000 SPE with 15 min averaging. In the upper panel CNA are shown for the IRIS southernmost beam 1 (L=4.80, solid line, which we term the "poleward beam"), and in the middle panel the northernmost beam 7, (L=4.32, long dashed line, which we term the "equatorward beam"). The beams map to the ionosphere so as to be viewing ~1° north and south in latitude (i.e. 75.6°S ±1°). These two beams represent the two most extreme locations for rigidity cutoff effects that the instrument can observe. The bottom panel shows the variation of K_p during the SPE. In addition, both the upper and middle panels show the variation of the non-cutoff absorption that would be expected if there were no influence of rigidity on the proton fluxes into the atmosphere (short dashed line) based on the relationship between daytime absorption and proton fluxes developed by *Kavanagh et al.* [2004], i.e., using Absorption=0.09 × (>10 MeV proton flux)$^{0.5}$. This line therefore represents the variation of the proton fluxes throughout the event. The equivalent absorption levels using rigidity affected proton fluxes determined through the approach outlined in section 3 for each beam location are also shown (asterisk in the south, diamond in the north), again calculated using the *Kavanagh et al.* [2004] relationship. The time resolution of these calculations is limited to 3-hours because of the K_p dependence of the rigidity cutoff model.

The SPE of 8-11 November 2000 generated peak GOES proton fluxes of 14,800 >10 MeV protons cm^{-2} str^{-1} s^{-1} at 16 UT on 9 Nov, and a peak K_p of 6^+ at 9-12 UT on 10 Nov. As such, this event occurred during a moderate geomagnetic storm. During November the atmosphere above Halley, Antarctica, is fully sunlit and thus the use of the *Kavanagh et al.* [2004] daytime absorption relationship is appropriate. In the southern (poleward) beam absorption levels of ~4 dB are observed during the period of highest proton fluxes, while in the northern (equatorward) beam absorption levels of ~2 dB are observed. These values are generally in good agreement with the estimated absorption levels when the effects of varying rigidity cutoffs are included, and significantly below the non-cutoff levels of ~8 dB absorption. When the proton fluxes are very low the predicted absorption remains close to zero whatever the K_p level, thus it is only possible to compare the predicted absorption with the observed absorption when the proton fluxes are elevated. For the SPE of 8-11 November 2000 this is after 00 UT on 9 Nov, lasting until the end of 10 Nov. Of the fifteen 3-hourly bins, 5 show significant over estimates (~2 dB) in the predicted absorption in the southern (poleward) beam, while only 2 over estimates occur in the northern (equatorward) beam. The remaining periods show reasonable agreement between the predicted and observed absorption levels typically to within ±0.5 dB. Periods where the absorption is higher than the predicted absorption level are likely to be influenced by additional factors such as electron precipitation [*Shirochkov et al.*, 2004], which leads to additional absorption on top of the proton-induced absorption, and are therefore not well described by the proton-only *Kavanagh et al.* [2004] relationship. One example of this occurrence is 00-06 UT on 9 November 2000, where higher than predicted absorption is seen on both beams.

There are two periods where the data and theory disagree during the 8-11 November 2000 event. At 6-12 UT on 10 Nov K_p reaches 6, and the theoretical absorption levels are the same as the non-cutoff case, i.e., a very high proportion of the proton fluxes should be impacting the atmosphere above the riometer. But, both the northern and southern beam absorption levels indicate that there is still significant rigidity cutoff influence at this time. The second anomalous period occurs at 14 UT on 9 Nov in the southern (poleward) beam. The theoretical absorption levels increase from ~2 dB to ~4 dB in response to a small increase in K_p from <2 to 3^+. This is not seen in the observed absorption.

Figures 3, 4, and 5 show plots in the same format as Figure 2, and represent SPEs occurring during 26-29 November 2000, 5-8 November 2001, and 28-31 October 2003 respectively. The peak proton >10 MeV fluxes were 942, 31700, and 29500 protons $cm^{-2}\, str^{-1}\, s^{-1}$ while the maximum K_p values were 6^+, 9^-, and 9 respectively. Thus Figure 3 represents a small SPE, and Figures 4 and 5 represent two very large SPEs, with the latter cases associated with very large geomagnetic disturbances.

Although the proton fluxes are significantly lower during the 26-29 November 2000 SPE when compared with the 8-11 November 2000 event, the maximum K_p values are the same (6^+). Thus these two events are comparable in many ways. Figure 3 shows that the theoretical absorption levels in the southern (poleward) and northern (equatorward) beams are over estimated in comparison with the absorption data, particularly when K_p=~6 in the northern (equatorward) beam, and K_p=4-6 in the southern (poleward) beam. This is particularly apparent when the proton fluxes are high, and the absorption levels significantly elevated. Of the twenty three 3-hourly bins where proton fluxes are high, 9 show significant over estimates (~0.5-1 dB) in the predicted absorption in the southern (poleward) beam, while only 5 over estimates occur in the northern (equatorward) beam.

The two large storms shown in Figure 4 and 5 have a wider range of K_p values, but follow similar patterns of behavior as Figure 3. The northern (equatorial) beam shows good agreement between the theoretical absorption and the observed data until K_p>~6. Under these conditions the theoretically determined rigidity cutoffs predict very little influence of cutoff rigidity (i.e., low cutoff energies) on the proton fluxes and thus high absorption levels, but the observed absorption levels are more consistent with K_p=~5 and thus a significant influence due to rigidity cutoffs limiting the proton fluxes. The southern (poleward) beam shows good agreement between theoretical absorption levels and observed absorption for very high K_p (K_p>6), but over estimated absorptions when K_p=4-6. During high K_p (K_p>6) the theory predicts, and the observations show, that there is little or no cutoff rigidity affect on the absorption levels for this beam location. Of the twenty three 3-hourly bins where proton fluxes are high in Figure 4, six show significant over estimates (~2 dB) in the predicted absorption in the southern (poleward) beam, while only 3 over estimates occur in the northern (equatorward) beam. Of the nineteen 3-hourly bins where proton fluxes are high in Figure 5, five show significant over estimates (~2 dB) in the predicted absorption in the southern (poleward) beam, while 8 over estimates occur in the northern (equatorward) beam. This represents an unusual event because the northern beam is less well modeled than the southern beam. The primary reason is because of the unusually long-lasting very high K_p levels leading to less errors in the southern beam in comparison with the northern beam.

The Halley riometer data during the SPE of 5-8 November 2001 was previously used to test the improved rigidity cutoff calculations developed by *Rodger et al.* [2006]. The cutoff rigidities were applied to the proton fluxes in the same way as this study, but the SIC model was used to calculate the riometer absorption instead of using the empirical relationship as we do here.

Comparing Figure 4 in this study with Figure 7 of *Rodger et al.* [2006] shows that combining the empirical relationship with rigidity modified proton fluxes agrees closely with the SIC model results. In addition, the right panel of Figure 3 of *Rodger et al.* [2006] showed that the absorptions calculated by the SIC model in the absence of rigidity cutoff effects reproduces the empirical relationship reported by *Kavanagh et al.* [2004].

So far we have described riometer absorption observed during four SPEs that occurred during the southern hemisphere summer, and thus under daytime conditions. In the next section we determine a nighttime relationship between proton fluxes and riometer absorption in order to investigate rigidity cutoff effects during polar winter nighttime conditions.

5. Nighttime riometer absorption using the Sodankylä Ion and Neutral Chemistry Model

As in *Rodger et al.* [2006] we use the SIC model to produce lower ionospheric electron density profiles during SPEs, but this time in the winter-time (i.e. nighttime) *D*-region above the Halley Bay IRIS instrument. During the daytime it is possible to calculate the non-cutoff riometer absorption using >10 MeV proton fluxes through the empirical relationship of *Kavanagh et al.* [2004], confirmed using the SIC model by *Rodger et al.* [2006]. Here we want to investigate the relationship between proton fluxes and riometer absorption during nighttime conditions in order to investigate rigidity cutoff effects during polar winter conditions.

We assume that the proton spectra at the top of the atmosphere will be determined only by the fluxes of experimentally observed proton flux spectra reported by GOES-borne instruments at geosynchronous altitude. The angular distribution of the protons is assumed to be isotropic over the upper atmosphere, which is valid close to the Earth [*Hargreaves*, 1992]. A SIC modeling run has also been undertaken without any proton forcing (i.e., zero proton fluxes), reasonable at Halley for low K_p conditions. The results of the no-forcing "control" SIC-run allow the calculation of "quiet-time" conditions.

Each run of the SIC model is based on a neutral background atmosphere given by MSISE-90 and provides concentration profiles of neutral and ionic species. Following *Banks and Kockarts* [1973; Part A, p. 194], we calculate the electron collision frequencies of N_2, O_2, and He from MSIS and of O and H from SIC using the neutral temperature profile of MSIS, which we can assume to be equal to electron temperature below 100 km. Electron density is obtained from SIC by subtracting the sum of negative ion concentrations from the sum of positive ion concentrations. Finally, we use the method of *Sen and Wyller* [1960] to compute differential absorption dL/dh and integrate with respect to height. This method takes the operational frequency of the riometer into account and assumes a dipole approximation for the geomagnetic field to obtain the electron gyrofrequency at the respective altitude and latitude.

The Sodankylä Ion and Neutral Chemistry (SIC) model is a 1-D chemical model designed for ionospheric D-region studies, solving the concentrations of 65 ions, including 29 negative ions, and 15 neutral species at altitudes across 20–150 km. This study makes use of SIC version 6.9.0. The model has recently been discussed by *Verronen et al.* [2005], building on original work by *Turunen et al.* [1996] and *Verronen et al.* [2002]. A detailed overview of the model was given in *Verronen et al.* [2005]. We summarize here to provide background for this study.

In the SIC model several hundred reactions are implemented, plus additional external forcing due to solar radiation (1–422.5 nm), electron and proton precipitation, and galactic cosmic radiation. Initial descriptions of the model are provided by *Turunen et al.* [1996], with neutral species modifications described by *Verronen et al.* [2002]. Solar flux is calculated with the SOLAR2000 model (version 2.27) [*Tobiska et al.*, 2000]. The scattered component of solar Lyman-α flux is included using the empirical approximation given by *Thomas and Bowman* [1986]. The SIC code includes vertical transport [*Chabrillat et al.*, 2002] which takes into account molecular [*Banks and Kockarts*, 1973] and eddy diffusion with a fixed eddy diffusion coefficient profile. The background neutral atmosphere is calculated using the MSISE-90 model

[*Hedin*, 1991] and tables given by *Shimazaki* [1984]. Transport and chemistry are advanced in intervals of 5 or 15 minutes. While within each interval exponentially increasing time steps are used because of the wide range of chemical time constants of the modeled species.

Daytime absorption has been shown to be described by proton fluxes with energies >10 MeV. However, during nighttime conditions the undisturbed D-region has lower electron number densities, such that lower energy protons are expected to play a significant role. Nighttime ionization conditions are more complicated than during the day, with a negative charge transition from electrons to negative ions occurring at sunset [*Verronen et al.*, *2006*] as a result of changes in atomic oxygen. Thus we would expect different relationships between absorption and solar proton fluxes at night than during the day. Figure 6 shows the relationship found between SIC calculated polar nighttime riometer absorption and proton fluxes with energies >5 MeV, taken from the proton fluxes which occurred during the January 2005 SPE. These calculations indicate that nighttime absorption is proportional to (>5 MeV proton flux)$^{0.75}$. This finding differs from the daytime relationship, not only in the power, but also the proton flux threshold. This agrees with previous work on nighttime absorption calculations, which suggested a threshold of 1-5 MeV [*Sellers et al., 1977*], although both day and night calculations in that study used a square root power relationship. A lower threshold of >5 MeV during nighttime means that K_p would have to be lower in order to cutoff the same fraction of the proton fluxes as during the day. The lower energy threshold is also consistent with the riometer absorption coming from higher altitudes during the night than the day.

During the period when IRIS data from Halley is available there was one significant SPE in nighttime conditions. In Figure 7 we show the observed and calculated absorption during the large SPE of 13-16 July 2000. The format of the plot is the same as Figures 2-5. To calculate the theoretical absorption values we have used the relation Absorption = 0.001×(>5 MeV proton flux)$^{0.75}$. The plot shows that the theoretical and observed absorption values agree well, with overestimates in the theoretically predicted absorptions occurring only on the southern (poleward) beam when K_p>7. No significant periods of over estimation occur on the northern (equatorward) beam. Of the eleven 3-hourly bins where proton fluxes are high in Figure 7, five show significant over estimates (~0.5 dB) in the predicted absorption in the southern (poleward) beam, while four over estimates occur in the northern (equatorward) beam.

Notably there are almost no data points in Figure 7 where either the predicted absorption or the observed absorption reach the same levels as the non-cutoff values during high proton fluxes (mainly 15 July). This is despite very high K_p values, and is partly as a result of the rigidity model limiting K_p to a maximum of 6, and also a result of the >5 MeV energy threshold used during the night. At the latitude of Halley IRIS northern (equatorward) beam the proton cutoff energy limit for K_p=6 is ~9 MeV [*Rodger et al.*, 2006]. This means that protons with energies >9 MeV will reach to the latitude of this beam, but energies less than that will not be able to make it so far equatorward. During the day, when a >10 MeV proton flux energy threshold for the absorption calculation applies, and the K_p-dependent rigidity cutoff is ~9 MeV, 100% of the >10 MeV GOES proton fluxes will penetrate to that location, and thus contribute to the riometer absorption. However, during the night when a >5 MeV proton flux energy threshold applies, and the K_p-dependent rigidity cutoff is ~9 MeV, the calculations predict that only ~30-90% of the >5 MeV GOES proton fluxes penetrate to that location and contribute to the riometer absorption. Note that the 30-90% range is determined by the proton spectra, i.e., what percentage of the total proton number flux is greater than the rigidity cutoff energy. Thus at nighttime the only time that the predicted absorption gets close to the non-rigidity cutoff levels is on those occasions when the proton spectrum is very hard, i.e., there are high fluxes of protons with high energy (>10 MeV) in comparison with the lower energy protons (5-10 MeV).

7. Discussion

We have investigated the rigidity cutoff model developed by *Rodger et al.* [2006] based on previous work by *Smart and Shea* [2003]. Using a study of riometer absorption data during four daytime SPEs, i.e., high latitude summer measurements where the Sun is above the horizon all the time, we have shown that it is possible to reproduce the riometer data using a simple empirical relationship based on the incident proton fluxes, and a K_p-limited rigidity calculation.

For the southern (poleward) beam of the Halley IRIS K_p=6 represents a rigidity cutoff energy of 0.0 MeV, and once K_p=6 is reached the predicted absorption is the same as the non-rigidity absorption levels. This can be seen in Figure 3 at the beginning of 27 Nov 2000, where the asterisks (rigidity calculation) overlap the short dashed line values (non-rigidity calculation). However, the observed absorption is not consistent with this picture, and when K_p>4 the predicted absorption is also over estimated. This suggests that the rigidity cutoff limit (K_p=6, 0.0 MeV for the southern beam) needs to be higher than the proton flux energy threshold (10 MeV in daytime). Either decreasing the K_p "saturation" limit, or lowering the proton flux energy threshold can achieve this.

During the two large SPEs, when K_p approached 9, the southern (poleward) beam absorption was close to that of the calculated rigidity and non-rigidity cutoff absorption levels (Figures 4 and 5), whereas this was not true when K_p=4-6 in the previous analysis. This clearly indicates that the K_p=6 saturation limit to the rigidity cutoff model is too low and needs to be higher.

For the northern (equatorward) beam of the Halley IRIS K_p=6 represents a rigidity cutoff energy of 9 MeV, thus the rigidity cutoff energy and the proton flux energy threshold (10 MeV) are similar, and when K_p=6 is reached the predicted absorption values are the same as the non-rigidity levels. However, the observed absorption does not reach the non-rigidity level during high proton fluxes, and as a result this suggests that the K_p=6 saturation limit is too high or the absorption threshold is too high.

Absorption data from the single nighttime SPE (July 2000) is reasonably modeled using a >5 MeV proton flux energy threshold. The behavior of the observed absorption on the southern (poleward) beam is very similar to the daytime examples in that the predicted absorption is over estimated when $K_p \geq 6$. This is because at $K_p=6$ the rigidity cutoff energy is 0.0 MeV which is lower than the proton flux energy threshold of >5 MeV. The northern (equatorward) beam behavior is slightly different from the daytime case because for $K_p=6$ the rigidity cutoff energy (9 MeV) is more than the proton flux energy threshold (>5 MeV), and thus although the predicted absorption is still an overestimate at high K_p, it is not as large as the maximum non-cutoff case.

Using the rigidity cutoff model of *Rodger et al.* [2006] and empirical estimates of riometer absorption from proton fluxes we have been able to reproduce the absorption seen by the Halley riometer at two *L*-shells ($L=4.32$ and 4.80). Typically reasonable estimates of absorption were made 58-74 % of the time for the southern (poleward) beam, and 65-87 % of the time for the northern (equatorward) beam. The success of the *Rodger et al.* [2006] rigidity cutoff model is dependent on a balance between the rigidity cutoff energy for the protons at any given *L*-shell, and the proton flux energy threshold for the protons. At the times when the empirical estimates are in error there is usually an over estimate in the predicted absorption levels, caused by the $K_p=6$ saturation limit used in the rigidity cutoff calculation. In order to improve the success rate for the northern (equatorward) beam the K_p saturation limit in the rigidity model would have to be decreased to $K_p=5.5$ or the daytime proton flux energy threshold decreased to >5 MeV. For the southern beam changing the K_p saturation limit to 5 would be more appropriate, but no changes of the daytime proton flux energy threshold would make any significant effect.

Changing the proton flux energy threshold introduces significant difficulties in modeling the riometer absorption because of hysteresis in the relationship between the proton fluxes and absorption for any proton flux energy threshold values other than 10 MeV during the day and

5 MeV during the night. Thus we restrict ourselves here to investigate the effects of the K_p saturation limit used in the rigidity cutoff calculation. Figure 8 shows the northern and southern beam absorption during the solar proton event of 05-08 November 2001. The figure is the same format as Figure 4, except that the saturation limit has been changed to K_p=5, and the location of the southern (poleward) beam moved by 0.6° equatorwards. These changes have the effect of increasing the rigidity cutoff energy for the northern beam from 9 MeV to 28 MeV, and increasing the rigidity cutoff energy for the southern beam from 0.0 MeV to 8 MeV. In practice this means that the northern beam does not achieve the non-rigidity cutoff absorption maximum during this storm, in agreement with the observations. Generally the Halley northern (equatorward) beam will not achieve the non-rigidity cutoff absorption maximum unless the proton spectrum is very hard and has little flux between 10-28 MeV. The southern beam will still experience absorption at the non-cutoff maximum, but the more equatorward location of the beam results in lower levels of absorption when K_p is just below the saturation limit. Both of these effects result in much better agreement between the calculated absorption and the observed absorption for this large geomagnetic storm in comparison with the results shown in Figure 4.

However, for moderately disturbed solar proton events, where K_p remains close to the saturation limit the calculated absorption is not in such good agreement with the observations. Figure 9 shows the adjusted absorption for the 26-29 November 2000 period to be contracted with Figure 3. The K_p=5 saturation limit has reduced the northern beam absorption, and reduced the southern beam absorption when K_p is close to the K_p=5 saturation limit. However, during higher K_p the southern beam does not experience the maximum non-rigidity cutoff absorption levels that the relocated beam calculations predict. Overall there is a 50% decrease in the number of 3-hour data bins that previously showed poor agreement between the calculated and observed absorption.

The adjustments to the rigidity cutoff calculations made here are relatively subtle. By changing the location of the southern (poleward) beam better agreement between theory and observations is obtained at times, and this indicates that initially the two beam locations were too far apart (i.e., smaller than the 2° of latitude assumed initially). The adjusted location for the southern (poleward) beam represents a separation from the northern beam of 1.4° of latitude, which can be interpreted as indicating that the dominant altitude that the absorption is occurring at lower altitude i.e., 60 km instead of the 90 km initially assumed. The lower K_p saturation limit improves the agreement between theory and observations, particularly on the northern (equatorward) beam during most geomagnetic conditions. The K_p change has little effect on the southern (equatorward) beam, which appears more sensitive to changes in beam location. This suggests that at L>4.5, and for high K_p, significant changes in L-shell location have occurred for the beam, in particular that the geographic location of the beam has moved to a lower L-shell. Some of this change can be accommodated by the lowering of the peak absorption altitude of the southern beam, which equates to a shift equatorwards for this riometer beam as K_p increases and greater latitudinal penetration of proton fluxes occur.

For large geomagnetic storms, such as that of 05-08 November 2001, the adjustments made here to the *Rodger et al.* [2006] rigidity cutoff model allow us to improve the absorption estimates. In Figure 10 we plot the predicted southern hemisphere absorption levels during the high proton flux period that occurred at 00 UT on 06 Nov 2001, when K_p reached 8^+. This calculation was undertaken using the improved rigidity cutoff model. The plot shows the region of high absorption with levels of 14 dB, where all protons with energies greater than 10 MeV can access the polar atmosphere (i.e., rigidity cutoff effects are unimportant to the riometer absorptions). Surrounding this contour is an outer region where the absorption levels gradually reduce to the limits of detectability for most riometers (roughly 0.1 dB). This can be thought of as an extreme example of SPE-produced riometer absorptions, occurring when both K_p and proton fluxes are very high. The outer zone of rigidity influenced absorption lies mostly at 50°S, except in the region of the Antarctic Peninsula where it is located at ~70°S. From the riometer absorption calculations we can see that the transition in access levels for energetic protons to the stratosphere and mesosphere is controlled by geomagnetic rigidity, with the shift from no-access to total access occurs over the range L=3-4.5, or across ~10° of latitude. For locations which are equatorward of the limits of the outer zone shown in Figure 10, SPEs should never lead to significant changes in riometer data. This provides an indication as to the limits inside which SPEs can play a role in modifying the neutral chemistry of the stratosphere and mesosphere [Verronen, 2005].

8. Summary

In the polar atmosphere, significant chemical and ionization changes occur during solar proton events. The access of solar protons to this region is limited by the dynamically changing geomagnetic field. In this study we have used riometer absorption observations to investigate the accuracy of a model to predict K_p-dependent geomagnetic rigidity cutoffs, and hence the changing proton fluxes. The imaging riometer at Halley, Antarctica is ideally situated for such a study, as the rigidity cutoff sweeps back and forth across the instrument's field of view, providing a severe test of the rigidity cutoff model. Specifically we investigate the accuracy of the rigidity cutoff model developed by Smart and Shea [2003], and improved by Rodger et al. [2006]. Using observations from the Halley riometer during five solar proton events, we have confirmed the basic accuracy of this rigidity model. However, we have shown that although the rigidity cutoff model can be used to reasonably estimate the absorption due to precipitating proton fluxes, it can be further improved by setting a lower K_p limit (i.e. K_p=5 instead of 6) at which the rigidity process saturates. We also find that for *L*>4.5 there is significant change in the geomagnetic location of a riometer beam during a large geomagnetic storm, such that the apparent *L*-shell of the beam moves equatorward. This is in part explained by the decreasing altitude of peak riometer absorption as protons penetrate more readily at higher K_p into the rigidity dominated zone.

We have also used the Sodankyla Ion and Neutral Chemistry model to determine an empirical relationship between integral proton precipitation fluxes and nighttime ionosphere riometer absorption, in order to allow consideration of winter time SPEs. We find that during the nighttime the proton flux energy threshold is lowered to protons with energies of >5 MeV in comparison with >10 MeV during the daytime.

Where both K_p and proton fluxes are very high the transition in access levels for energetic protons to the stratosphere and mesosphere is controlled by geomagnetic rigidity, with the shift from no-access to total access occurs over the range *L*=3-4.5, or across ~10° of latitude. The outer zone of rigidity influenced absorption lies mostly at 50°S, except in the region of the Antarctic Peninsula where it is located at ~70°S. In the northern hemisphere this will equate to ~45°N. These latitude bounds provide an indication as to the limits inside which SPEs can play a role in modifying the neutral chemistry of the stratosphere and mesosphere.

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Figure 1. Map showing the region in Antarctica in which our study is undertaken. The square marks the location of Halley (75.6ºS, 26.32°W, L=4.6), while the open circles show the northern (equatorward) and southern (poleward) IRIS riometer beams used in our study.

Figure 2. [Upper panel] The variation of the non-cutoff absorption that would be expected if there were no influence of rigidity on the proton fluxes into the atmosphere (short dashed line) during 08-11 November 2000, compared with the observed absorption on the Halley IRIS southernmost beam 1 (L=4.80, solid line). [middle panel] The variation of the non-cutoff absorption as in the upper panel (short dashed line), compared with the observed absorption on the northernmost beam 7, (L=4.32, long dashed line). The equivalent absorption levels using rigidity affected proton fluxes for each beam location are also shown (asterisk in the south, diamond in the north). [bottom panel] The variation of K_p during the SPE period. The horizontal dotted line represents the K_p saturation limit used in the rigidity model calculations.

Figure 3. As Figure 2 but for 26-29 November 2000

Figure 4. As Figure 2 but for 05-08 November 2001

Figure 5. As Figure 2 but for 28-31 October 2000

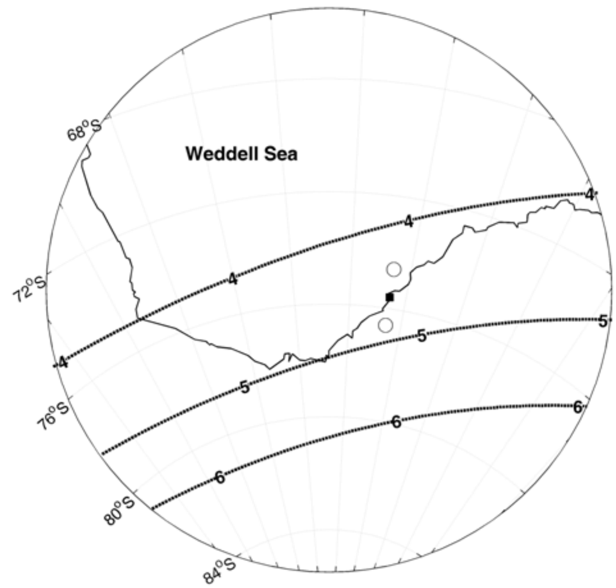
Figure 6. Comparison between the SIC calculated nighttime cosmic noise absorption for the Halley IRIS parameters and >5 MeV proton fluxes (crosses). The grey columns indicate the number of samples in each energy range (as labeled). A linear fit indicates a clear relationship between the riometer absorption and the proton fluxes.

Figure 7. As Figure 2, but using the nighttime empirical absorption/proton flux relationship for the wintertime SPE, 13-16 July 2000.

Figure 8. As Figure 2, but using K_p=5 instead of K_p=6 as the cutoff limit for 05-08 November 2001, and with the southern (equatorward) beam moved to a lower L-shell.

Figure 9. As Figure 2, but using K_p=5 instead of K_p=6 as the cutoff limit for 26-29 November 2000, and with the southern (equatorward) beam moved to a lower L-shell.

Figure 10. Map of the predicted levels of absorption globally for the peak fluxes during 06 Nov 2001 based on the improved K_p-dependent geomagnetic rigidity cutoff model.



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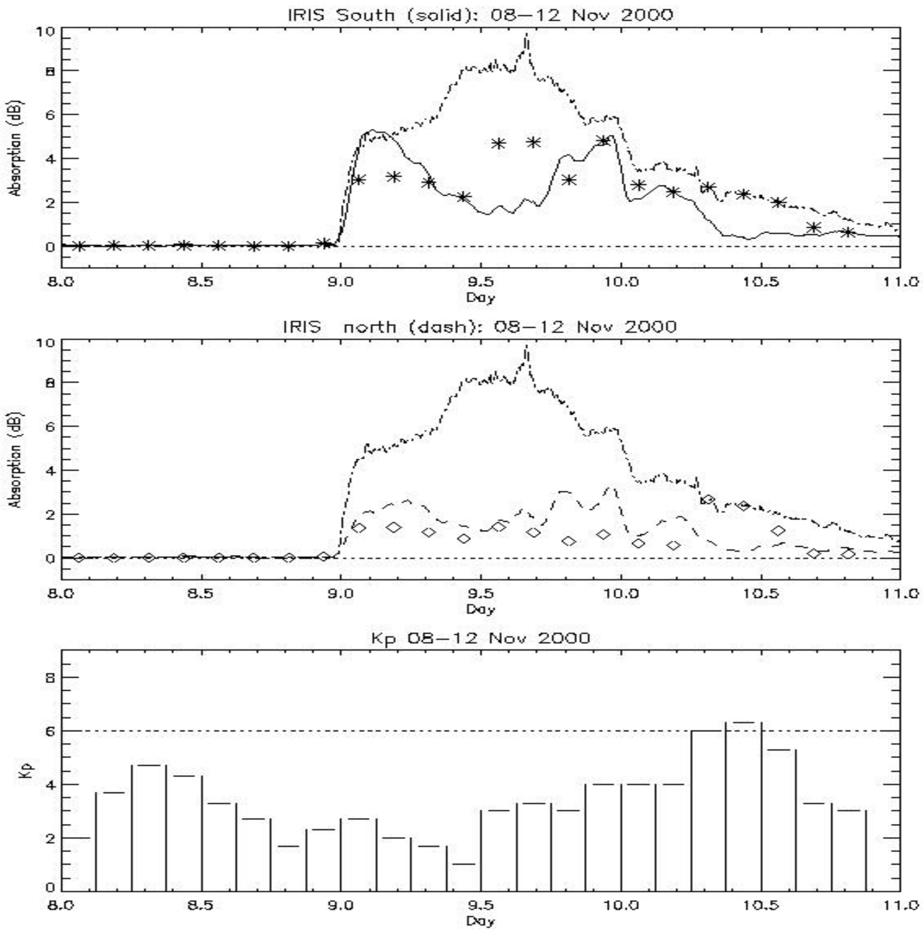

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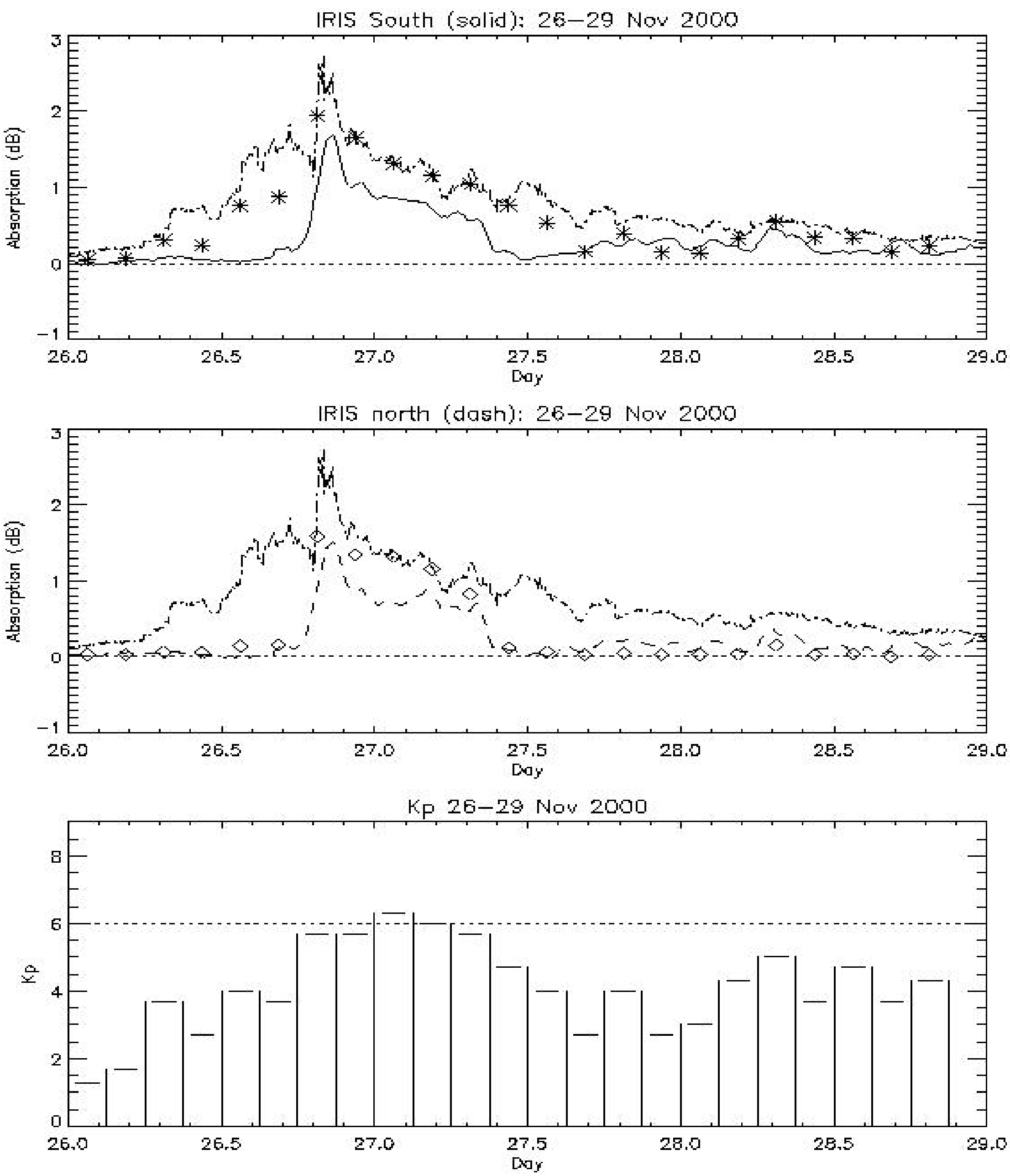


Figure 3. As Figure 2 but for 26-29 November 2000.

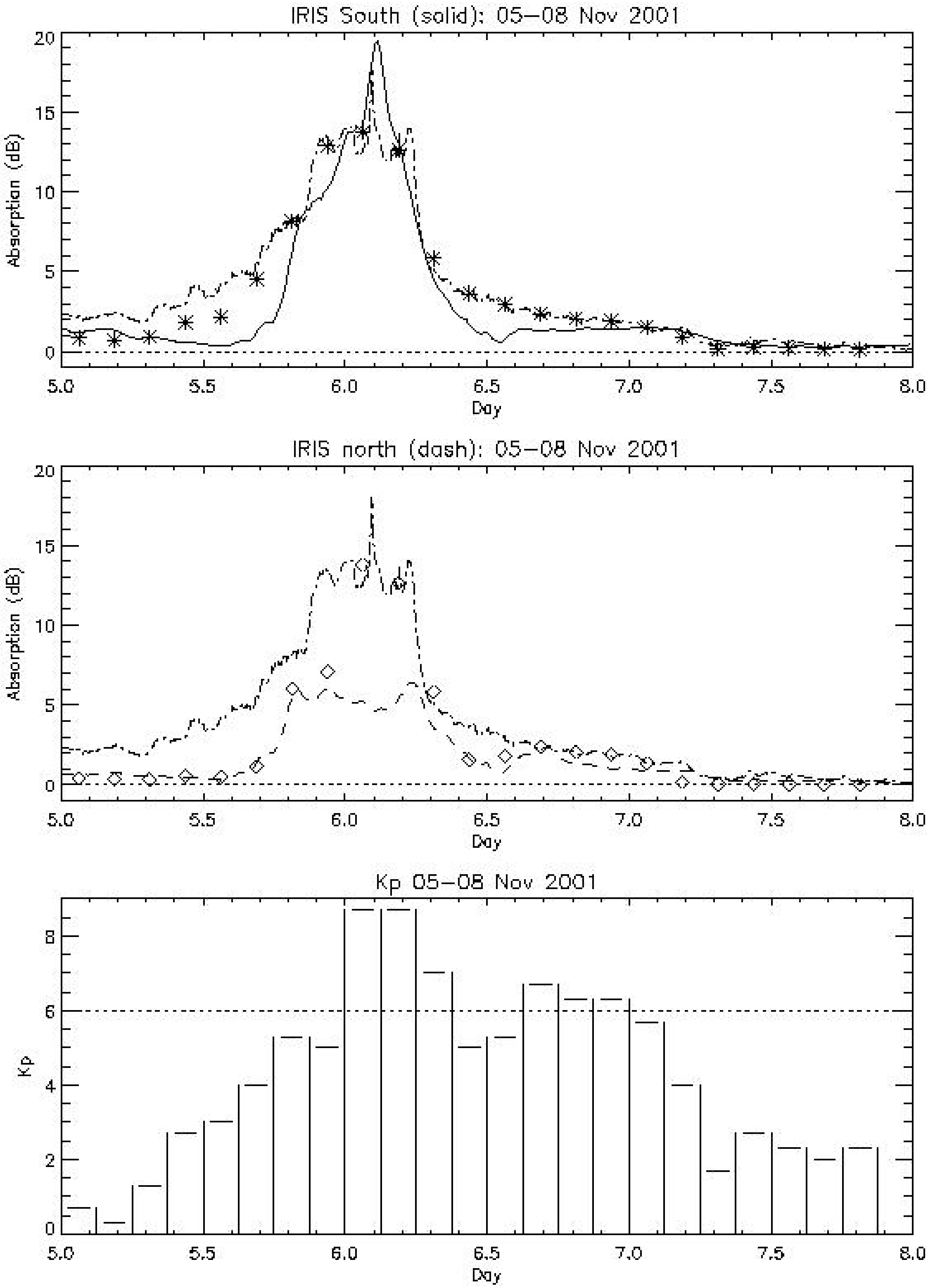


Figure 4. As Figure 2 but for 05-08 November 2001

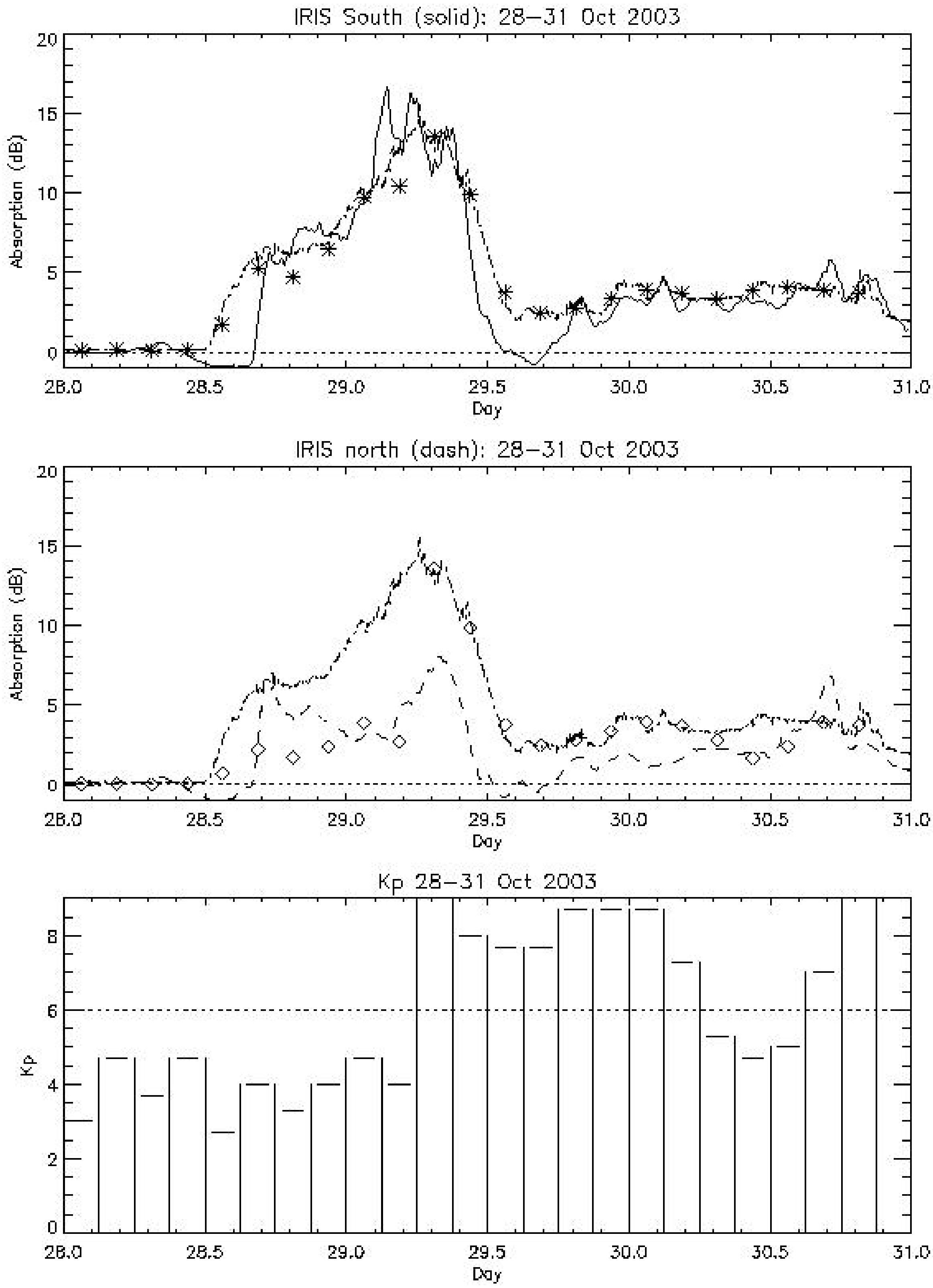
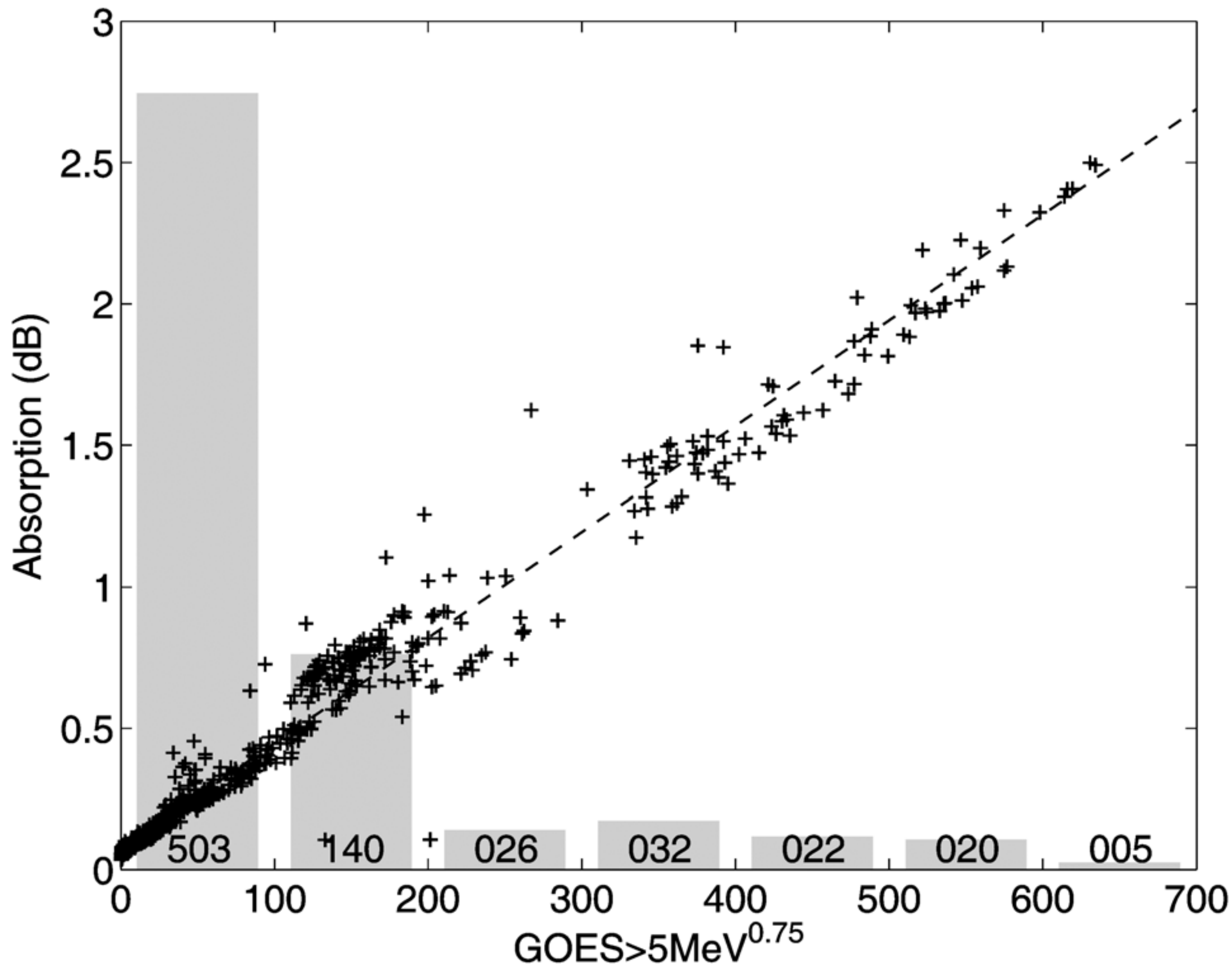


Figure 5. As Figure 2 but for 28-31 October 2003.



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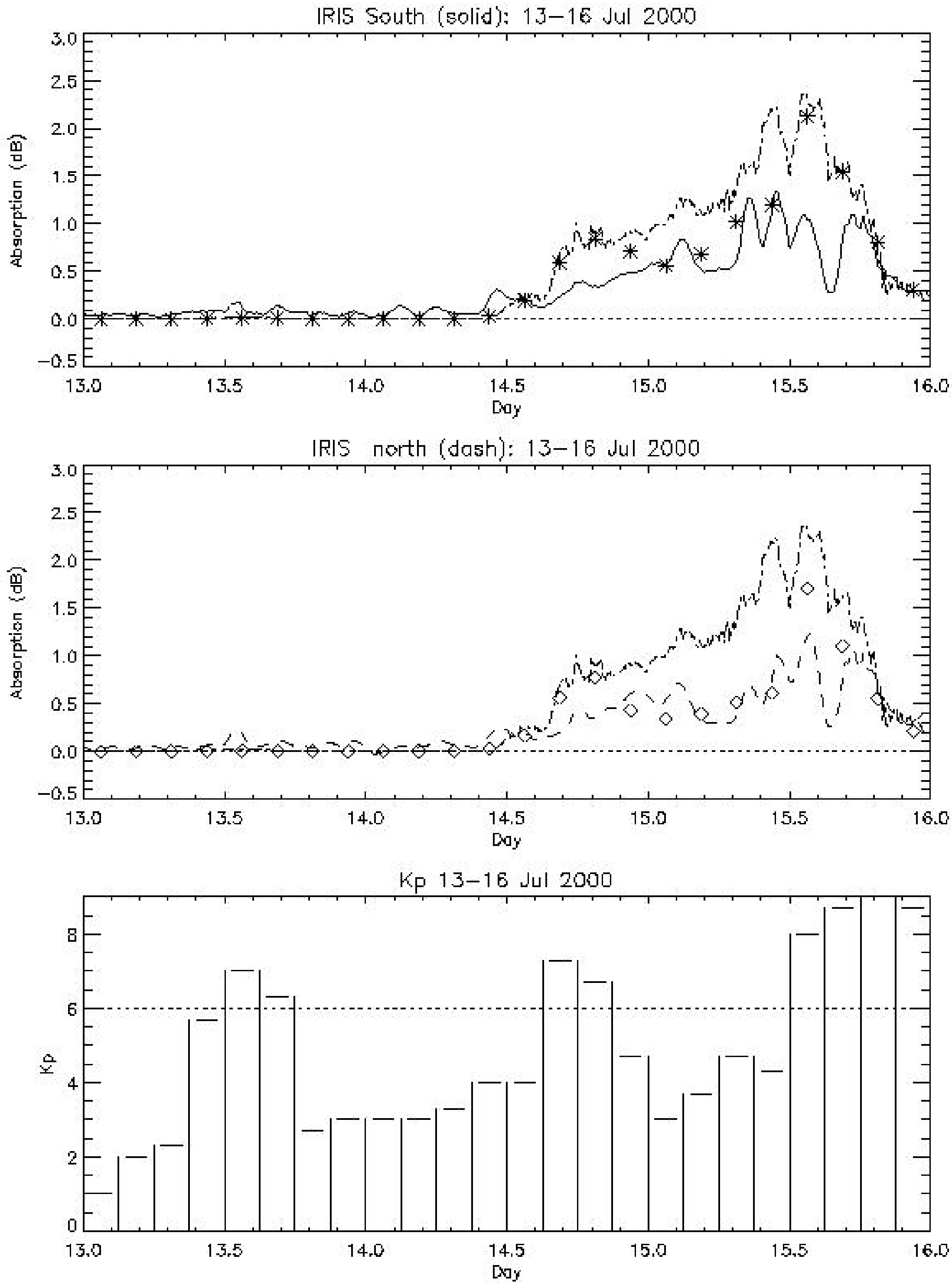

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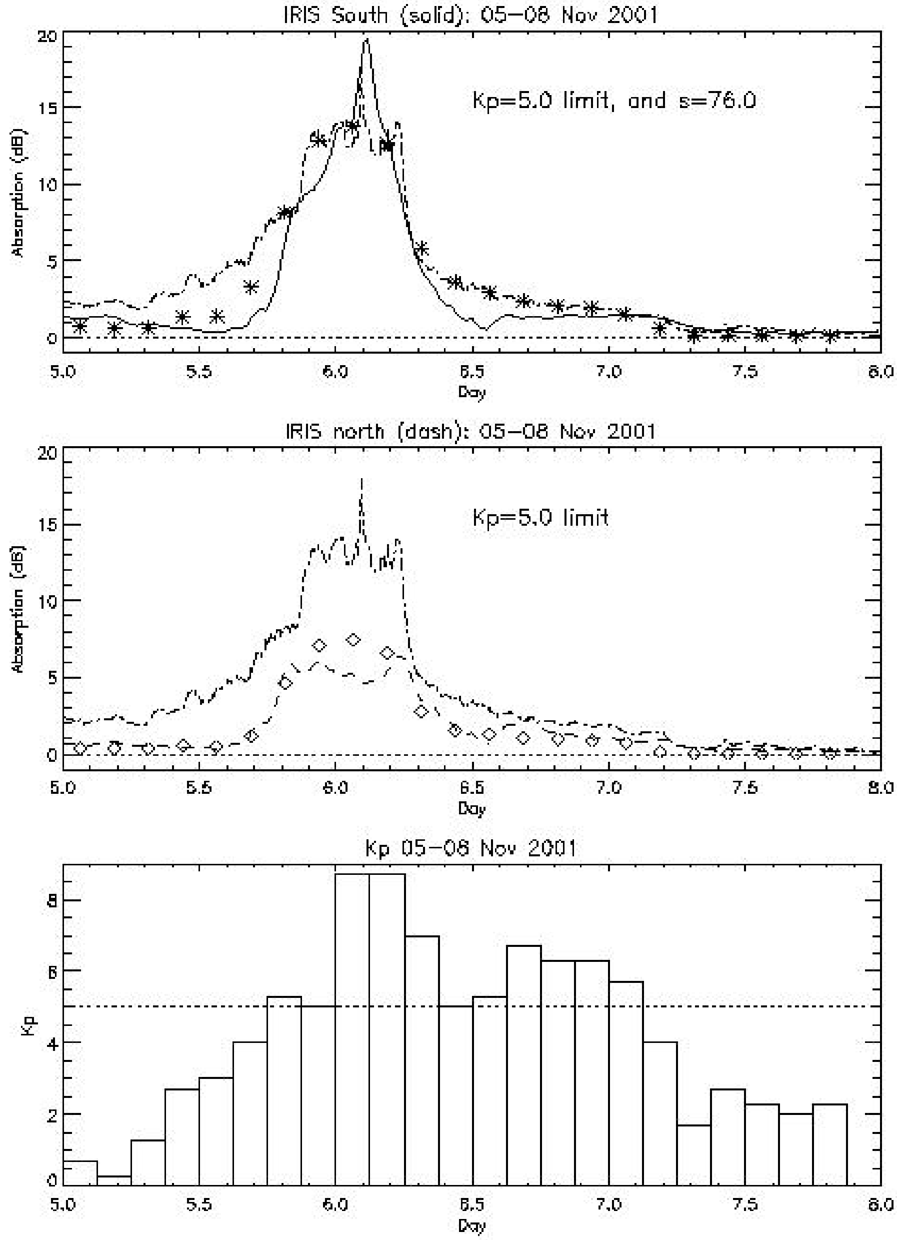

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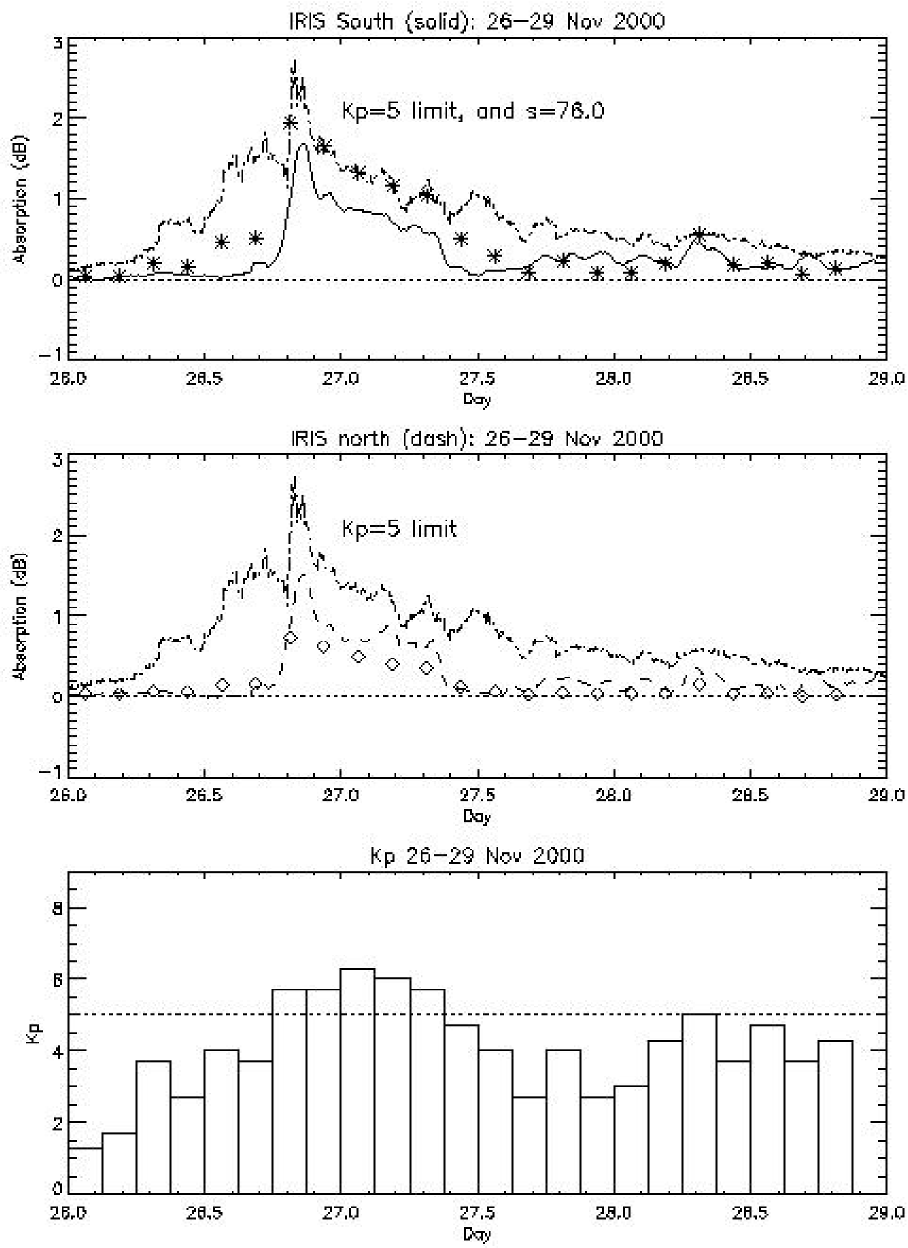
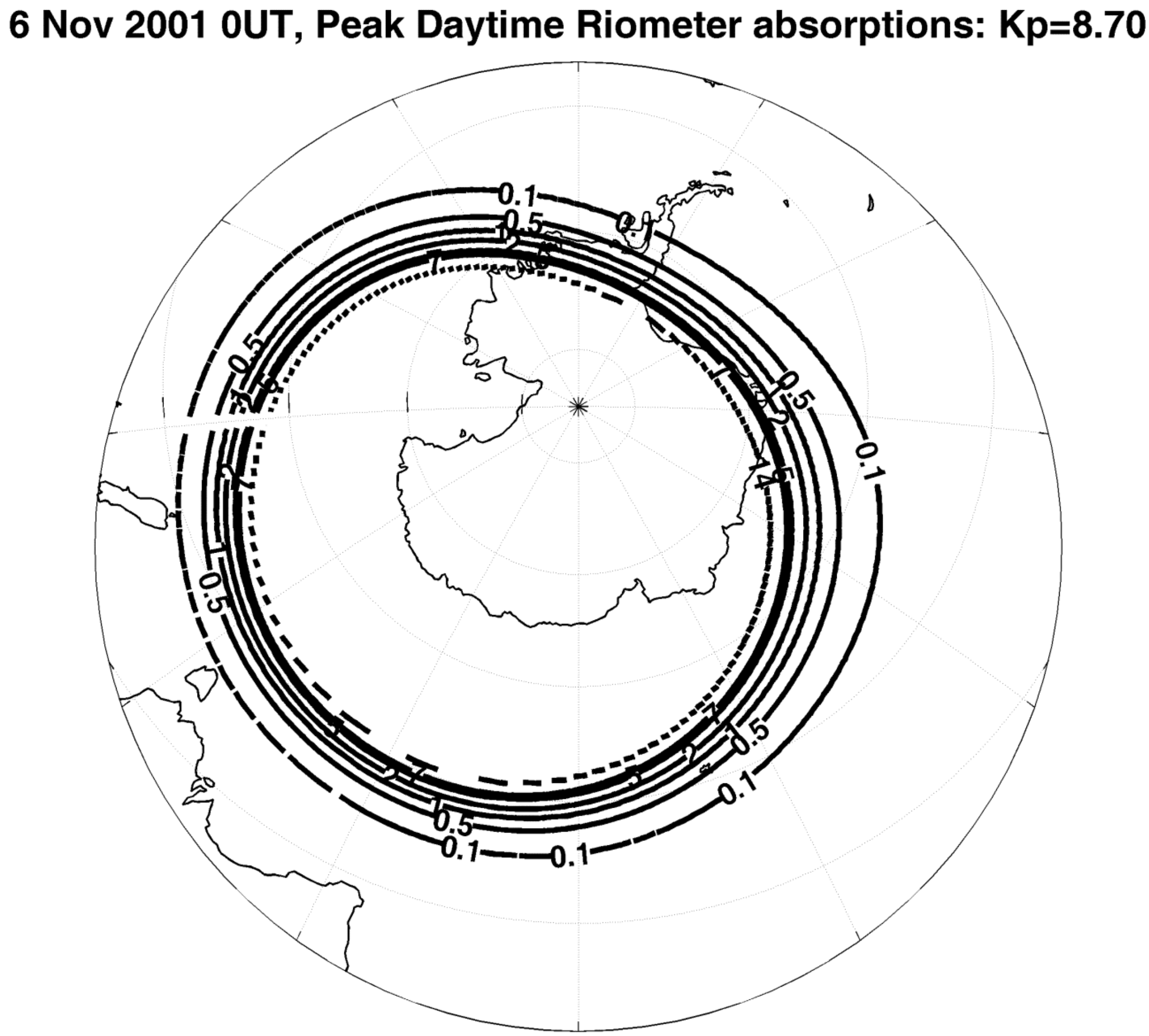


Figure 9. As Figure 2, but using K_p=5 instead of K_p=6 as the cutoff limit for 26-29 November 2000, and with the southern (equatorward) beam moved to a lower *L*-shell.



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