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Two distinct sources of magnetospheric heating in the atmosphere: the aurora and the ring current

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Abstract

In this paper, we demonstrate that, besides the well-known corpuscular heating of auroral origin, there is another heat source in the equatorial region of the neutral upper atmosphere acting during and after geomagnetic storms as a consequence of the precipitation of ring current ions. The effect of the two sources has been separated on the basis of their induced diurnal variations using measurements from the CACTUS micro-accelerometer. In Almár and Illés-Almár [Adv. Space Res., this issue, 2004, doi:10.1016/j.asr.2003.04.060], the observational facts and our suggestion for the improvement of the CIRA'86 model are summarized to draw the attention of the constructors of the new CIRA model on two effects that are not yet built into the earlier CIRA models. In the present paper, we try to outline the possible physics behind the observational facts necessitating the improvement of the model.

Keywords: Upper atmospheric model; Total atmospheric density; Ring current; Geomagnetic effect; Corpuscular heating

1. Introduction

The literature considers the geomagnetic effect of the equatorial neutral atmosphere as a consequence of the auroral heating only, in spite of the fact that some results indicate a stronger response than is expected. The auroral heating reaches the equatorial zone through the action of meridional winds, with a 4–6 h time delay, and preferably in the morning hours (Prölss et al., 1988). Its decay rate corresponds approximately to that of *Kp*. According to our investigations (Illés, 1979; Illés-Almár et al., 1985, 1987, 1989, 1990a,b, 1992; Almár et al., 1992, 1996) the ring current – although not included into CIRA'86 model – is, however, playing an important role in the heating of the atmosphere at low latitudes. Its decay rate is roughly equal to that of the recovery rate of Dst, that is slower than that of the auroral heating.

2. Measurements and method

Three sets of observational material have made it possible to obtain these results. In the 1970s, some 30,000 drag measurements from 59 artificial satellites over a 7 year period were available. From the second half of the 1970s over 1,000,000 in situ measurements were made by the CACTUS micro-accelerometer on the French CASTOR satellite (Barlier et al., 1975). In the 1980s, the DBI micro-accelerometer on the Italian San Marco V satellite made about 500,000 in situ measurements (Arduini et al., 1993). The time interval of the drag material was 1965–1972, that of the CACTUS material from 1975 to 1979, while that of the San Marco V was from May to December 1988. The time resolution of the drag data was about 1–2 days, only very rarely – at best – about 2 h; that of CACTUS was about 10 min, while that of San Marco V was about 1 min. The advantage of the drag data was that density values were simultaneously available at several heights and practically at every latitude in a time span that contained numerous large geomagnetic storms. The advantage of the micro-accelerometer

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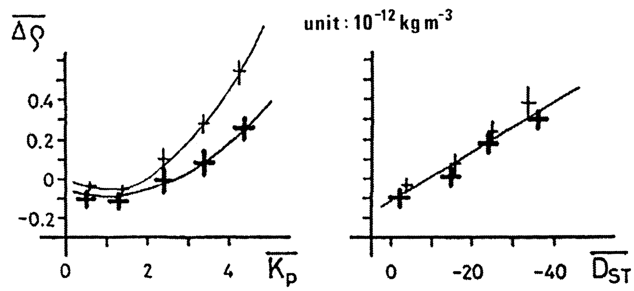

Fig. 1. Deviation of measured density (averaged for *Kp* and Dst intervals) from the corresponding model values with $Kp = 0$ as a function of geomagnetic indices. Measurements apart from storm-time refer either within (thin crosses) or outside (heavy crosses) the recovery phases. $\Delta\rho$ is double valued function of *Kp* (Illés-Almár et al., 1989).

measurements was their very good time resolution, but with the disadvantage that temporal and spatial variation could not be separated. Both accelerometer measurement sets occurred during solar activity minima, so the number of large magnetospheric storms was limited.

The basis of our investigation was a comparison between the density measurements and actual CIRA'86 model values. The residuals $f = \rho^{\text{observed}}/\rho^{\text{model}}$ have been examined as a function of several parameters. The scatter around 1 would mean a perfect model. In the case of the drag data the Jacchia-71 = CIRA'72 (CIRA'72, 1972) model was used, while in the case of the micro-accelerometer measurements, the MSIS'86 (= CIRA 1986) upper atmospheric models were used.

3. Results

3.1. Kp alone is not sufficient to characterize the geomagnetic response of the upper atmosphere

Until now, *Kp* (or *Ap*) geomagnetic index was used in the international models to describe the density changes in connection with geomagnetic storms. The density, however, does not return to the quiet level as quickly as the *Ap* index does, but for several days it remains higher (Illés-Almár et al., 1985; see Fig. 3 in Almár and Illés-Almár, 2004). Separating the quiet time residuals into two groups – according to their position being outside or inside the recovery phase of a storm – prolonged recovery of the density showing itself up as a double valued function of *Kp* (left side of Fig. 1). That is, *Kp* alone is not satisfactory for the description of the geomagnetic effect. In the MSIS'86 model, the problem is handled by a complicated weighted mean value of *Kp*, the consequence of which is a broad but decreased amplitude of the geomagnetic effect in the model density compared to measurements (dotted line in Fig. 2). This averaging procedure somehow solves the problem of the slow recurrence of the density to quiet level in the post-storm period, but does not reproduce the amplitude and, at the same time, it produces another inadequacy before the storm.

On the contrary the residuals for the two periods (inside or outside the recovery phase) are a single valued function of Dst (right side of Fig. 1), and really a dependence on Dst of the MSIS residuals remained (Fig. 4 in Almár and Illés-Almár, 2004). Accordingly, an improvement of the MSIS'86 model could be carried out introducing a Dst dependent multiplicative factor with a 2 h time delay with respect to Dst (our dMSIS model, Almár et al., 1992; Illés-Almár et al., 1997; Almár and Illés-Almár, 2004). This improved model follows the data much better (see solid line in Fig. 2). The time delay of only 2 h points to the fact that this heating could not come from the distant auroral oval (a 6 h time delay is incorporated into the CIRA model with respect to *Kp*).

3.2. The description of the diurnal variation in the MSIS'86 model is not satisfactory either

In *quiet periods* the inadequacy of the model is substantial only after midnight in the form of a nighttime maximum (Fig. 3 and the upper curve on Fig. 5(a)). The existence of this secondary maximum was often mentioned in the literature by other authors also. Probably it is in connection with compressional heating of the zonal winds originating from the subsolar point. In Fig. 3 the

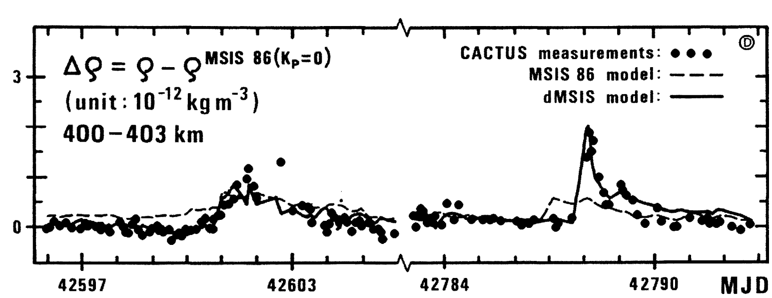

Fig. 2. Case study demonstrating that the averaging procedure for *Kp* geomagnetic index in the MSIS'86 model is not satisfactory, because it cannot describe the sharp density increases in connection with geomagnetic storms. Our dMSIS model, containing the Dst geomagnetic index as well, follows the data much better (Almár et al., 1996).

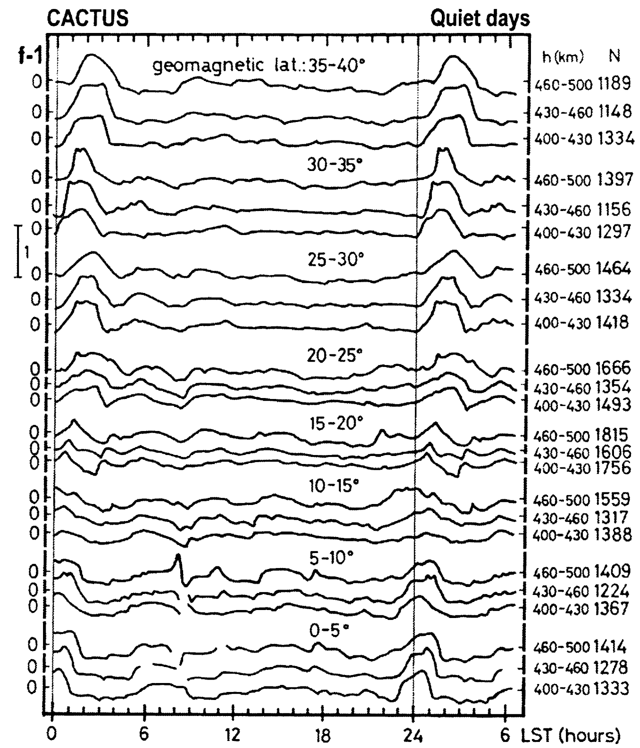

Fig. 3. Running mean curves of CACTUS density residuals according to MSIS'86 model during quiet days separated according to geomagnetic latitudes and heights. The nighttime maximum and its shifting in phase with latitude are conspicuous. N is the number of points. The curves are plotted in identical scales and shifted vertically to one another, together with their zero-points. The unit of the vertical scale is also indicated separately as a bar of length 1 parallel to the vertical axis.

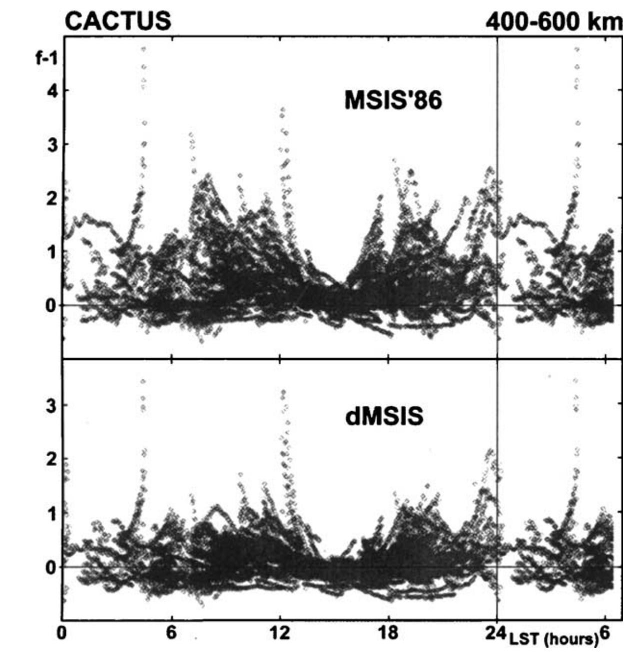

Fig. 4. The diurnal course of the density residuals of CACTUS measurements with respect to the MSIS'86 model (upper part) and to the dMSIS model (lower part) for the first day of 21 geomagnetic storms.

diurnal courses of the residuals are plotted for three height intervals and separated according to geomagnetic latitude. The wider and compressed humps in the 15–25° latitude intervals – unlike those at lower and at higher latitudes – can be the consequence of the ion drag braking the winds in the latitude range of the increased electron density at the equatorial ionospheric anomaly (Raghavarao, 1994). The separation of the residuals according to the geomagnetic latitude also demonstrates that this hump shifts toward the morning hours with increasing geomagnetic latitude.

The diurnal variation of the residuals on *disturbed days* has an interesting character. On the upper part in Fig. 4 the instantaneous residuals with respect to MSIS'86 are plotted, while on the lower part with respect to our dMSIS model for each of the first days of 21 geomagnetic storms. On the one hand, the significant decrease of the scatter in the dMSIS residuals, as compared to MSIS'86, demonstrates that *adding Dst to the parameters was an important step in the improvement of the model*. On the other hand, the variance is significantly larger at 7–13, at 17–21 and at 23–24 h than around 15 h or 22 h. This is not a consequence of a selective LST distribution of the f-values, belonging to small or large Dst values.

To investigate the density variations around geomagnetic storms by the superposed epoch method, running mean diurnal curves have been constructed on *consecutive days* on the one hand (Fig. 5(a)), and consecutive 3 h for the 21 h elapsed after the Dst minimum on the other (Fig. 5(b)). Fig. 6 shows the LST dependence of the residuals as well, but separated according to geomagnetic latitude for three days: before the storm, for the storm-day, and for the first post-storm day. The curve-series on both figures show the diurnal variation of the excess density with time. The density excess is not a uniform function of LST, but five real, more or less separate humps are distinguishable based on the diagram of the 3 h time resolution (see arrows in Fig. 5(b)):

Arrow No. 1. The midnight hump (LST 22–1 h) appears in the 3–6 h elapsed after the Dst minimum (Fig. 5(b)) and disappears after 3 days (Fig. 5(a)). If separated according to geomagnetic latitudes (Fig. 6), the amplitude of the hump increases towards the equator.

Arrow Nos. 2 and 3. The double morning hump (LST 3–8 h) appears in 3–6 h elapsed after the Dst minimum (Fig. 5(b)) and is visible until the third day (Fig. 5(a)).

Arrow No. 4. The midday hump (LST 10–14 h) lives at least 6 days (Fig. 5(a)). If separated according to geomagnetic latitudes (Fig. 6), its amplitude increases at higher latitudes up to 40°.

Arrow No. 5. The evening hump (LST 17–21 h) disappears after 3 days (Fig. 5(a)). Its amplitude increases at higher latitudes at least up to 40° (Fig. 6).

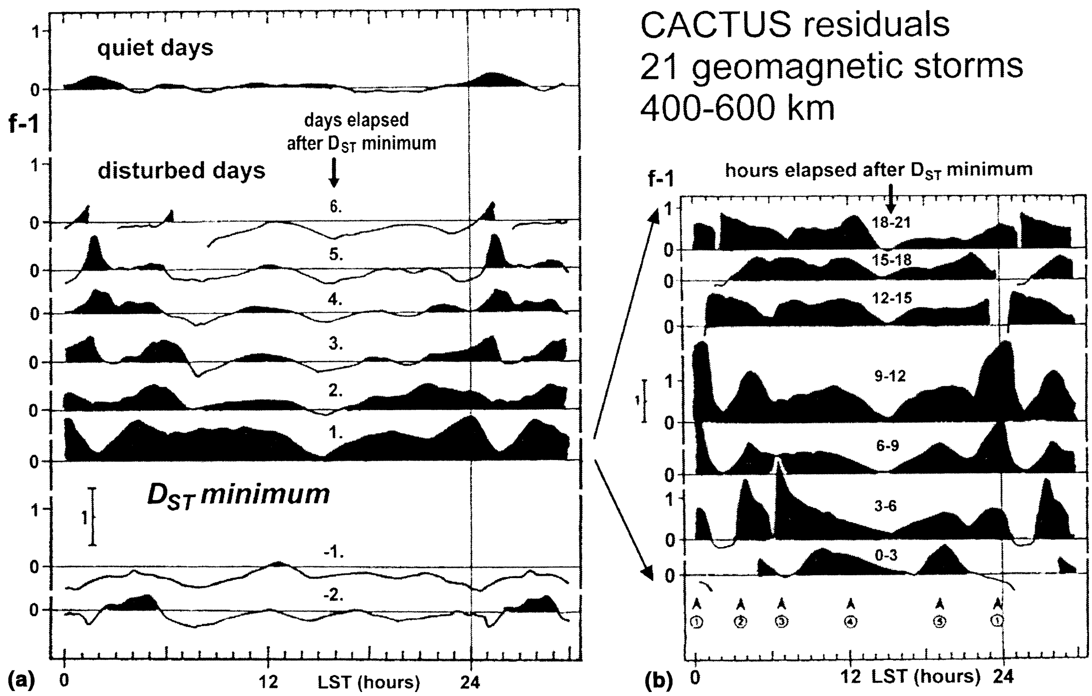

Fig. 5. Series of running mean curves constructed for the residuals of CACTUS measurements with respect to the MSIS'86 model by superposed epoch method for quiet days (the top and bottom curves on (a)) and in the vicinity of 21 geomagnetic storms in the middle. (a) Shows the diurnal variation of the density residuals each day. (b) Each 3 h of the first day after Dst minimum. Arrows indicate secondary maxima (or "humps") in the residuals on the basis of the (b) diagram. The curves are plotted in identical scales and shifted vertically to one another, together with their zero-points. The unit of the vertical scale is indicated on both parts (a) and (b) also separately as bars of length 1 parallel to the vertical axis.

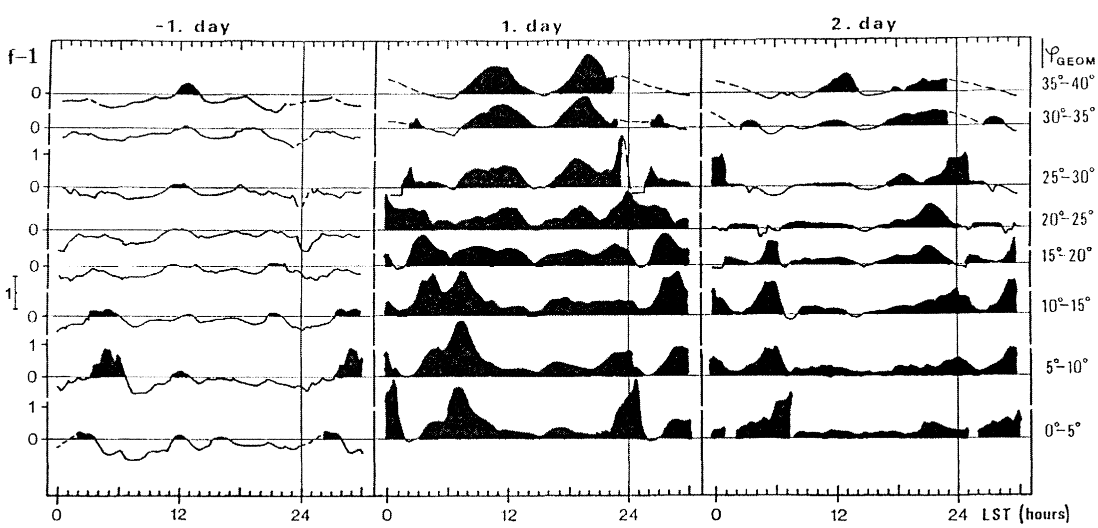

Fig. 6. The same as in Fig. 5 but only for the day preceding the storm (−1. day), for the storm-day (1. day) and the following day (2. day) – separated according to geomagnetic latitude. The curves are plotted in identical scales and shifted vertically to one another, together with their zero-points. The unit of the vertical scale is indicated also separately as bar of length 1 parallel to the vertical axis.

It is to be noted, however, that large residuals can be seen at several LSTs appearing especially on the first day of the storms (Fig. 4), and developing later in a complicated manner – sometimes shifting to other LSTs with passing time (Fig. 2 in Almár and Illés-Almár, 2004.). These humps in the LST function of the residuals may represent the different places of the enhanced energy input. The sharp density increases in LST cannot be explained by winds launched by the auroral heating. The winds would rather smooth the LST variation during that time, as they reach the equator. These sharp density variations in LST are more likely in connection with the rough distribution of the precipitating particles originating from the ring current and causing a heating of beam-like character in situ at the equatorial latitudes. This is demonstrated especially by the sharp rising of the residuals on Fig. 4 at 13 h that occurred at the same LSTs on two consecutive days (observed on six transits). The hump around midnight (on the very first day) according to P. Bencze can be in connection with the injection of the ring current particles from the plasma sheet, while the hump around 18 h LST with the bulge of the plasmasphere.

On Fig. 6 one can see that the hump at 24 h is sharp in both LST and in geomagnetic latitude. It appears only below 10°, indicating again a heating mechanism other than that due to auroral processes. The hump at 7 h ceases at 20° geomagnetic latitude, while other humps are even increasing with geomagnetic latitude. Unfortunately, we cannot follow them at geomagnetic latitudes above 40°, because of the 30° inclination of the CASTOR satellite's orbit. However, we cannot exclude the possibility that they rise again at the latitudes typical of SAR arcs.

4. Conclusion

The residuals of the CIRA models have been analyzed using independent observational data. The behavior of the excess density humps in the diurnal course seems to be inconsistent with the character of residuals due to a probable insufficiency of the model in the description of the auroral heating effect, but the residuals may originate rather from the ring current heating, as was mentioned also by Tinsley (1979, 1981), Tinsley and Burnside (1981), Hernandez et al. (1982) and Biondi and Meriwether (1985). This ring current heating is of maximal strength near the magnetic equator and corresponds to different thermospheric density enhancements in different LST sectors or even in narrower LST intervals. The "beam like" character of the ring current heating may be the physical process causing the larger density increases in certain LST sectors. This may be due to irregularities in the distribution of O^+ ions in the ring current at mid-latitudes, or possibly results from localized interactions between the plasmasphere and the ring-belt current. Localized interactions can occur if the mutual positions of the plasmasphere and the ring current belt change within a short time, or plasma waves – producing wave particle interaction – appear preferably at certain local times. All these considerations support that the disturbance daily variation of the geomagnetic effect with its humps is a real phenomenon and not only due to the scatter of the data (Bencze et al., 1993; Bencze and Illés-Almár, 1986).

The complexities of the observational facts mentioned above force the complicated form of the diurnal term required in our ddMSIS model (Almár and Illés-Almár, 2004). This also explains why we still do not consider our model to be final.

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