PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Geomagnetic Activity Effect Derived from Explorer 9 Drag Data

M. Roemer

*Phil. Trans. R. Soc. Lond. A* 1967 **262**, 185-194
doi: 10.1098/rsta.1967.0045

# Geomagnetic activity effect derived from Explorer 9 drag data

By M. Roemer

*Astronomische Institute der Universität Bonn, Germany*

The time delay between the peak of a geomagnetic storm and the corresponding maximum in atmospheric density was derived from precision drag data with a time resolution of 0·1 day. The mean delay time determined from about 100 events is $5{\cdot}2 \pm 0{\cdot}4$ h. This result is valid for the near-equatorial atmosphere in the height band from 300 to 770 km during the years 1961 to 1963. The amplitude of the variation in atmospheric temperature was studied as a function of the intensity of the geomagnetic storm. The temperature increase $\Delta T$ (degK) during a geomagnetic disturbance of intensity $k_p$ is given by

$$\Delta T = 20k_p + 0{\cdot}03 \exp (k_p).$$

This paper is being issued as Mitteilung der Astronomischen Institute Bonn nr. 82.

## 1. Introduction

In 1959 two transient increases in the drag of satellite 1958 $\delta 1$ were discovered which coincided in time of occurrence and in duration with two major geomagnetic storms (Jacchia 1959). Since this event rapid fluctuations of atmospheric density and temperature connected with both small and large geomagnetic disturbances have been derived from the drag of several satellites in the altitude region from some 160 to 1000 km and have become known as the geomagnetic activity effect. The amplitude of the density variation increases with altitude in a manner similar to that exhibited by the variations induced by variable solar activity, primarily by variable solar emission in the extreme ultraviolet (e.u.v.). For both effects the increase in amplitude with height reaches a maximum and then decreases when the helium belt is reached. This has led Jacchia (1965) to conclude that the energy dissipation which causes the two phenomena must occur at a comparable height level. Variations in solar e.u.v. flux certainly cannot cause the atmospheric variations connected with geomagnetic disturbances. Much more cannot be said with assurance concerning the heating mechanism during variations of the geomagnetic field.

The geomagnetic activity effect has been studied by the analysis of drag data from several satellites (Groves 1961; Jacchia 1961; Jacchia & Slowey 1963; Jacobs 1966; Jacchia Slowey & Verniani 1966; Moe 1966; Roemer 1966). In view of this fact the scope of this contribution, i.e. a detailed analysis of the geomagnetic activity effect from the data of only one satellite, seems to be severely restricted. But this limitation offers several advantages. The Explorer 9 satellite probed the atmosphere in the latitude region $|\phi| < 39°$. Therefore the statistics based on a finite number of events is not complicated by a possible latitude dependence. Further the perigee height varied from 770 to 300 km during the satellite's lifetime, providing information on an appreciable height band of the thermosphere and lower exosphere. In addition, this balloon satellite was the first satellite yielding precision drag data with a high time resolution. Thus Explorer 9 provides details about the geomagnetic activity effect since early 1961.

## 2. Time lag

A clue to the mechanism by which the atmosphere is heated during geomagnetic storms may be found by determining the time lag between geomagnetic variations and the response of the atmosphere. For this determination precision drag data with a high time resolution are necessary. The orbital elements used for the derivation of the drag of the Explorer 9 satellite were computed from precisely reduced Baker-Nunn camera photographs with the Differential Orbit Improvement Programme (Gaposchkin 1964). Values of the mean anomaly correction were read off at intervals of 0·2 day from a smooth curve drawn through the residuals representing the individual observations. The same set of values was used by Jacchia & Slowey (1963) and by Roemer (1966) in the analysis of the drag of the Explorer 9 satellite. As has been described in detail by Jacchia (1963) these data are used in the process of numerical differentiation in order to determine the acceleration or rate of change of period $\dot{P}$. In general the finite thickness of the pencil-drawn curve through the residuals causes an error in reading off the mean anomaly correction which is too large to allow a differentiation interval of 0·1 day. But as long as we are interested in the relative variation of $\dot{P}$ alone we can derive acceleration data with a resolution in time of 0·1 day by the use of the halfway Bessel formula in addition to the Stirling formula at tabular values. This procedure was adopted in this analysis in order to determine the time of occurrence of maximum drag during a geomagnetic disturbance.

Figure 1 represents one of the geomagnetic storms and the accompanying increase in atmospheric drag. The time when the peak acceleration occurred was compared with the time when the maximum of the 3 h planetary geomagnetic index $a_p$ was reached. This difference in time $\Delta t$ is the time delay by which the atmospheric response lags the maximum disturbance in the geomagnetic field. Maximum acceleration corresponds to maximum drag and thus to maximum density at perigee. The structure of the geomagnetic disturbance and of the accompanying variation in drag was used to attribute weights to the time delay data. A sharp single-peaked geomagnetic storm followed by a sharp atmospheric response was rated a weight 3 in a memory-based scale, e.g. weight 3 was given to the time lag derived from the event shown in figure 1. Weight 2 was attributed to a case when both the $a_p$ indices and the atmospheric drag exhibited a broad maximum. If the atmospheric response was not very similar in structure to the geomagnetic variation weight 1 was used for the resultant delay time. Not all of the geomagnetic disturbances during the lifetime of the Explorer 9 satellite could be used for the derivation of the time delay, even major storms sometimes had to be left out due to their irregular structure.

The resolution of the drag data is a nominal value given by the smallest meaningful differentiation interval. Since some smoothing occurs in the process of determining accelerations from a mean curve through individual observations (Jacchia 1963) we also compared the peak of the acceleration with the 0·2 day running mean of $a_p$ (solid arrow in figure 1) and with the 0·4 day running mean of $a_p$ (dashed arrow) in addition to the comparison with the original 3 h values of $a_p$. In general these three delay times differ from each other. The amount of the difference depends on the shape of the individual geomagnetic disturbance. The important result is that in the average the time delay does not depend on the smoothing of the $a_p$ indices, at least up to a smoothing interval of 0·4 day. The grand mean of the delay time derived from about 100 events is 0·220 ± 0·015 (s.d.) day, 0·210 ± 0·011 (s.d.) day and 0·217 ± 0·015 (s.d.) day for no smoothing, 0·2-day means and 0·4-day means of the $a_p$ indices, respectively.

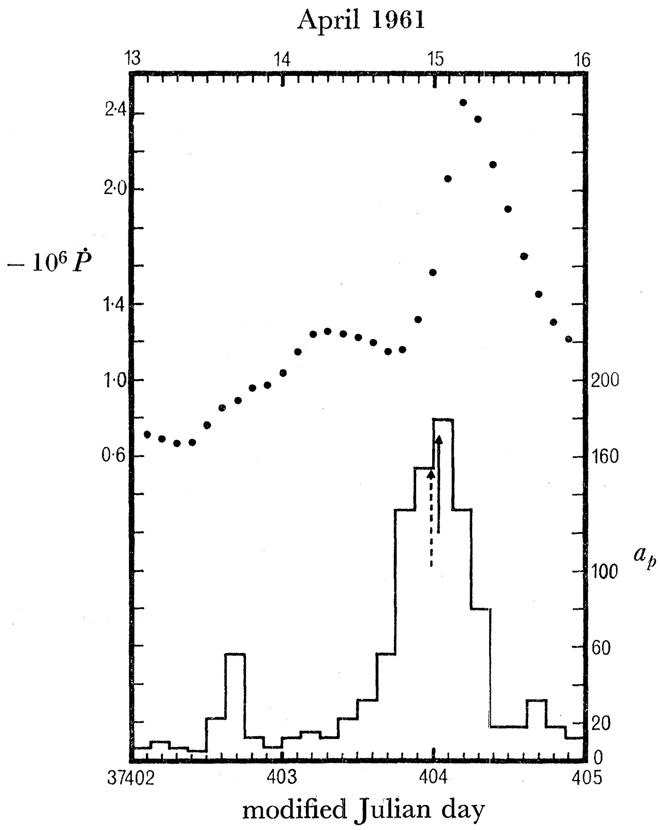


FIGURE 1. Transient increase in drag of the Explorer 9 satellite following the geomagnetic storm of 14/15 April 1961. In the lower half of the diagram the geomagnetic storm is represented by the 3 h planetary geomagnetic index $a_p$. In addition to the maximum of the original $a_p$ indices which occurs during the first 3 h of 15 April (modified Julian Day M.J.D. 37404) the location and the amount of the 0·2 day and 0·4 day running mean of $a_p$ is indicated by the solid and the dotted arrow, respectively. The upper part shows the rate of change of period $\dot{P}$ at 0·1-day intervals. From this diagram the lag of the sharp atmospheric response with respect to the peak of the geomagnetic storm is obvious.

These values confirm the earlier results from Explorer 9 (Jacchia & Slowey 1963; Roemer 1966). But Jacchia, Slowey & Verniani (1966) derived a mean delay of 0·29 day from four satellites in the low to medium geographic latitude region ($|\phi| < 55°$). Figure 2 illustrates this situation. The Explorer 9 data represent the situation in the years 1961 to 1963 while the events studied by Jacchia and collaborators begin in February 1963. The question remains open whether this difference in the mean time lag is due to a long-term effect in the solar cycle or whether it is caused by a systematic effect in the process of determining the individual time lag data. As long as this problem has not been solved it is impossible to combine all the individual data in order to improve the statistics.

During its lifetime the Explorer 9 satellite moved through the diurnal bulge relatively slowly from 8 to 23 h local time. The time lag data derived during this passage are quite evenly distributed. In figure 3 the individual data and the mean values for every hour local time are plotted. Obviously the time lag does not depend on local time of perigee indicating that the atmospheric response following a geomagnetic disturbance occurs at the same time for all longitudes in the equatorial region.

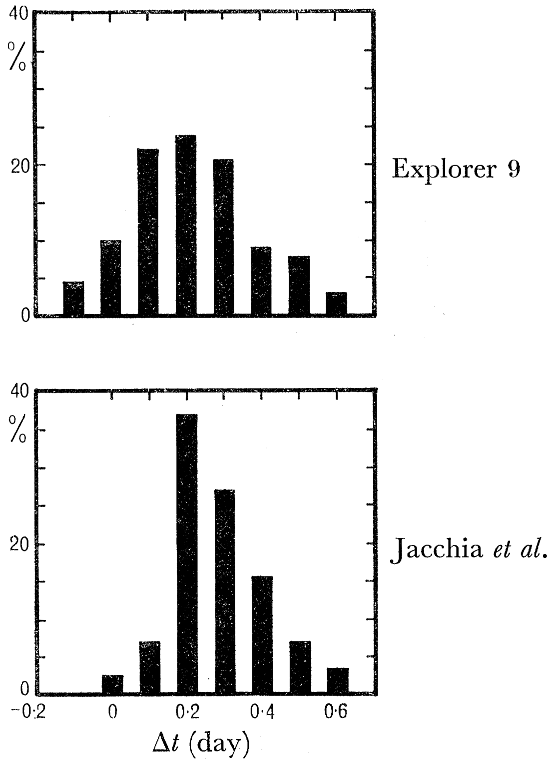


FIGURE 2. Histogram of the time lag data derived from (top) Explorer 9 and (bottom) of the results obtained by Jacchia *et al.* (1966). The mean time lag derived from the Explorer 9 satellite is 0·22 day, compared to 0·29 day determined from four satellites by Jacchia *et al.*

In figure 4 the individual time lag data are plotted versus perigee height. The data cover the altitude range from 770 to 300 km with a mean altitude of 620 km. Inspection of this diagram yields the result that the time lag is not different at different heights in the atmosphere. This result is substantiated by dividing the data in figure 4 in two groups. The mean delay time for perigee heights smaller than 600 km is $0{\cdot}20 \pm 0{\cdot}014$ (s.d.) day compared to a mean delay of $0{\cdot}22 \pm 0{\cdot}017$ (s.d.) day for altitudes above 600 km. Also Jacchia *et al.* (1966) do not find a dependence on altitude of the time delay. Results from low-perigee satellites presented by DeVries, Friday & Jones (1967) yielding a delay time between 0·5 and 0·8 day in the latitude region below 40 degrees have recently been revised by Jacobs (1966). From eleven satellites in the height band from 165 to 215 km Jacobs (1966) derived a least-squares time lag of 0·23 day without a significant dependence on geographic latitude. Summarizing these results from several satellites obtained by several investigators we might conclude that a dependence on altitude of the time lag is too small to be detected by the analysis of drag data so far. The revised results deduced from low-perigee satellites once again are in accordance with Jacchia's conclusion from the

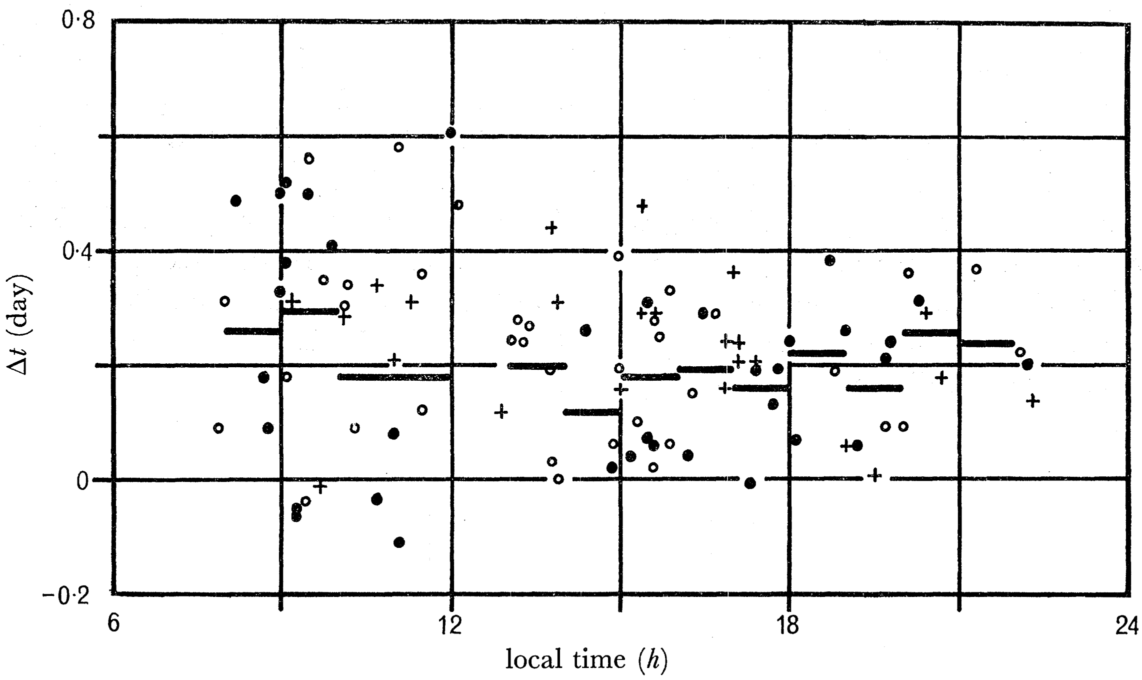


FIGURE 3. Time lag data from Explorer 9 plotted against local time of perigee. The individual time lag data Δt in days are plotted against the local time of perigee (+, weight 1; ○, weight 2; ●, weight 3). In addition, the average values for each hour local time are represented by horizontal bars. No dependence of the time lag on local time of perigee can be seen.

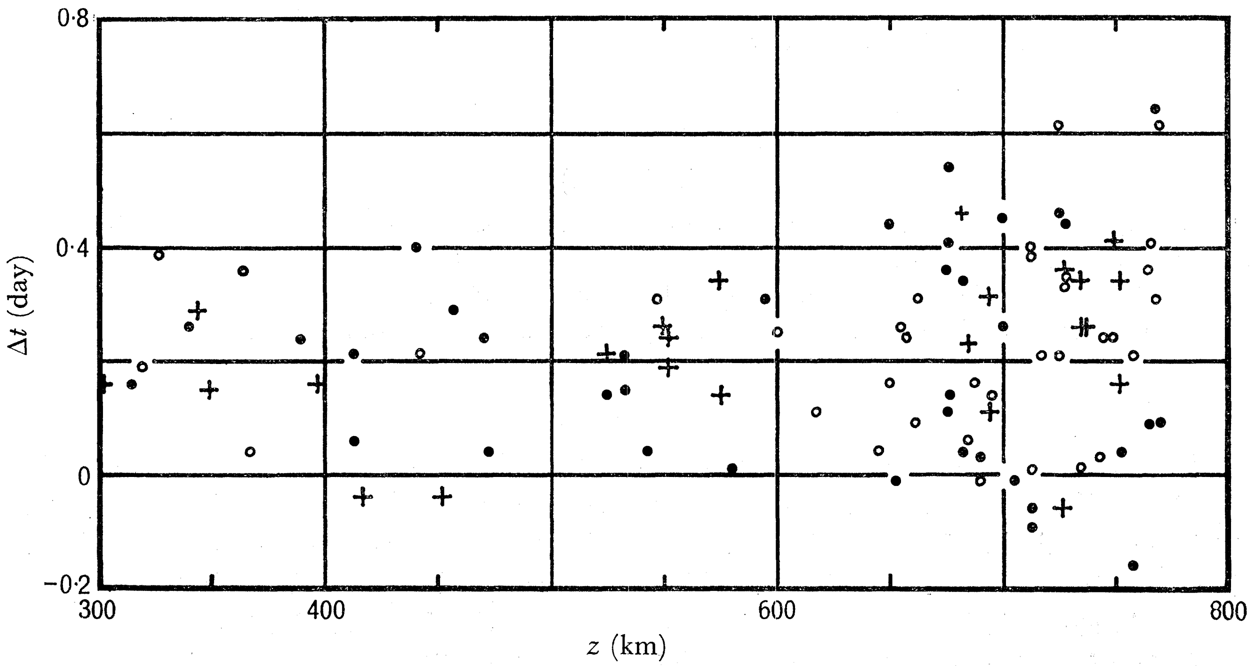


FIGURE 4. Time lag plotted against perigee height. Individual delay time data Δt (days) are plotted against perigee height z (km) (+, weight 1; ○, weight 2; ●, weight 3). Visual inspection of the data and also the division into two height bands does not show a dependence of the time lag on altitude.



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

amplitude dependence of the density increases on altitude, that the heating during geomagnetic disturbances occurs at a height considerably lower than 160 km (Jacchia 1965).

In addition, we tested whether the time lag depends on the amplitude of the atmospheric reaction following a geomagnetic storm. Figure 5 presents the time lag data plotted versus the increase in atmospheric temperature $\Delta T$. A division of the data into two groups yields the following results: the mean time lag is $0{\cdot}20 \pm 0{\cdot}024$ (s.d.) day for amplitudes in temperature $\Delta T < 80$ degK and $0{\cdot}24 \pm 0{\cdot}035$ (s.d.) day for stronger responses. This is in accordance with earlier results (Roemer 1966) that the delay time does not depend on the intensity of the geomagnetic disturbance. These facts lead to the conclusion that the response in the atmosphere follows the peak of the geomagnetic disturbance with the same lag, both for small disturbances and major storms.

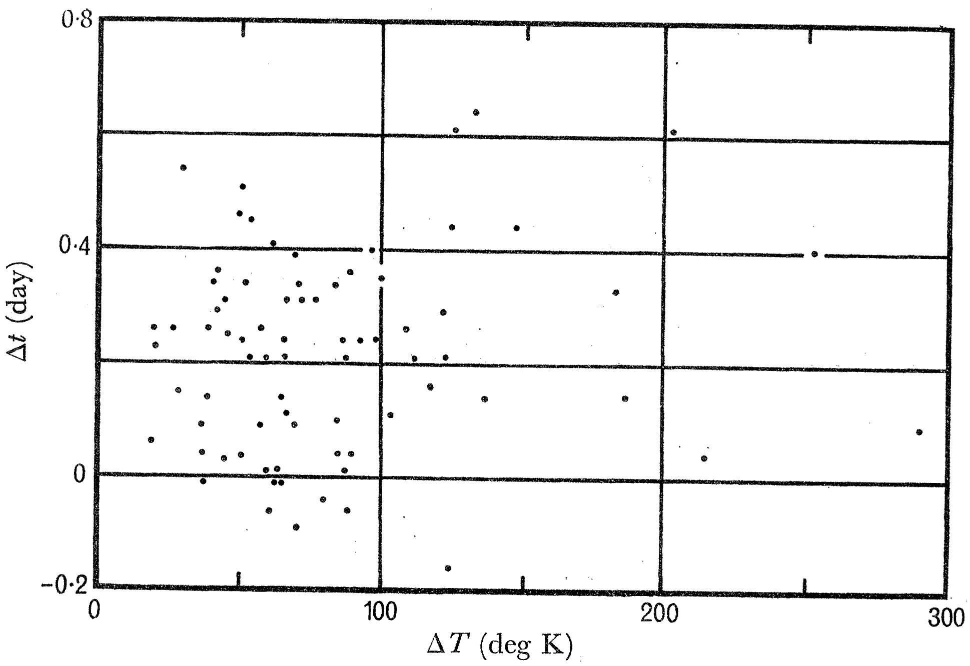


FIGURE 5. Time lag plotted against the intensity of the atmospheric response. No relation between the time lag $\Delta t$ in days and the amplitude of the temperature variation $\Delta T$ can be detected, indicating that the atmospheric response lags the peak of the geomagnetic disturbance by the same amount of time regardless of the intensity of the temperature increase.

## 3. HEATING

Early drag research beginning with Jacchia's findings on satellite 1958 $\delta$1 (Jacchia 1959) established the fact that the drag increases in the course of a geomagnetic disturbance. This drag variation is proportional to the variation in atmospheric density at perigee. Instead of analysing the density variation proper as function of the intensity of the geomagnetic storm it is often necessary to convert the density variations to temperature variations in order to relate different individual events at different perigee heights to each other. Especially in the case of the Explorer 9 satellite this procedure was necessary because the perigee altitude varied between 770 and 300 km during the satellite's lifetime. This conversion of density variations to temperature variations is done with the help of a suitable atmospheric model. This transformation cannot be expected to be perfect since the atmospheric models constructed so far assume equilibrium conditions, which are unlikely to be present in the short-lived atmospheric phenomena occurring during a geomagnetic storm.

The static diffusion model by Jacchia (1964) was used for the transformation. The density and temperature data analysed had been published by Jacchia & Slowey (1963) and by Roemer (1966). The nominal time resolution during periods of geomagnetic activity is 0·2 day. As has been mentioned earlier we expect the true time resolution to be smaller than the nominal value of 0·2 day. Therefore the temperature variation $\Delta T$ during a geomagnetic disturbance was not compared to the original 3 h planetary geomagnetic indices $a_p$ or $k_p$ but to the 0·2- and 0·4-day running mean of the magnetic indices.

Earlier studies had established the fact that the temperature variation $\Delta T$ is linearly related to $a_p$ for intense geomagnetic storms (Jacchia & Slowey 1963). For low-intensity geomagnetic variations $\Delta T$ is linearly related to the $k_p$ index (Jacchia & Slowey 1964; Newton, Horowitz & Priester 1964). In this study the planetary index $k_p$ was chosen as parameter for the intensity of geomagnetic activity since most of the disturbances during the lifetime of the Explorer 9 satellite are of the low to medium intensity category. The amplitude of the temperature variation $\Delta T$ was computed by comparing the peak temperature $T_{\text{max.}}$ to the mean of the two adjacent temperature minima, the one preceding the transient temperature increase $T_1$ and the one following the disturbance $T_2$:

$$\Delta T = T_{\text{max.}} - \tfrac{1}{2}(T_1 + T_2).$$

The same procedure was adopted to find the amplitude of the geomagnetic variation

$$\Delta \overline{k_p} = \overline{k_{p,\,\text{max.}}} - \tfrac{1}{2}(\overline{k_{p,\,1}} + \overline{k_{p,\,2}}),$$

where $\overline{k_{p,\,\text{max.}}}$ is the peak of the running mean of $k_p$ over 0·2 and 0·4 day.

The amplitudes of the temperature variation $\Delta T$ are plotted versus the amplitude of the geomagnetic disturbance $\Delta \overline{k_p}$ in figures 6 and 7 for running means of $k_p$ over 0·2 and 0·4 day, respectively. Two results can be obtained from the inspection of these diagrams. For low to medium geomagnetic disturbances $\Delta T$ is linearly related to $\Delta \overline{k_p}$ and this linearity breaks down for intense storms. The gradient $\Delta T/\Delta \overline{k_p}$ depends on the smoothing interval of the $k_p$ indices and is higher for the longer smoothing interval of 0·4 day. Contrary to the study of the time lag, the analysis of the heating is sensitive to the averaging process of the original 3 h $k_p$ indices. The division of the data into a group of geomagnetic variations with a maximum averaged index $\overline{k_{p,\,\text{max.}}} < 5$ and a group of intense storms yields the results of table 1.

Table 1

| | $\Delta T/\Delta \overline{k_p}$ (degK) (0·2-day average of $k_p$) | $\Delta T/\Delta \overline{k_p}$ (degK) (0·4-day average of $k_p$) |
|---|---|---|
| $\overline{k_{p,\,\text{max.}}} < 5$ | $15{\cdot}8 \pm 1{\cdot}2$ (s.d.) | $20{\cdot}6 \pm 1{\cdot}4$ (s.d.) |
| $\overline{k_{p,\,\text{max.}}} \geqslant 5$ | $20{\cdot}6 \pm 1{\cdot}2$ (s.d.) | $26{\cdot}6 \pm 1{\cdot}5$ (s.d.) |

Since the true time resolution of the observed temperature data is certainly smaller than the nominal value of 0·2 day we prefer the results for $\Delta T/\Delta \overline{k_p}$ derived from the 0·4 day

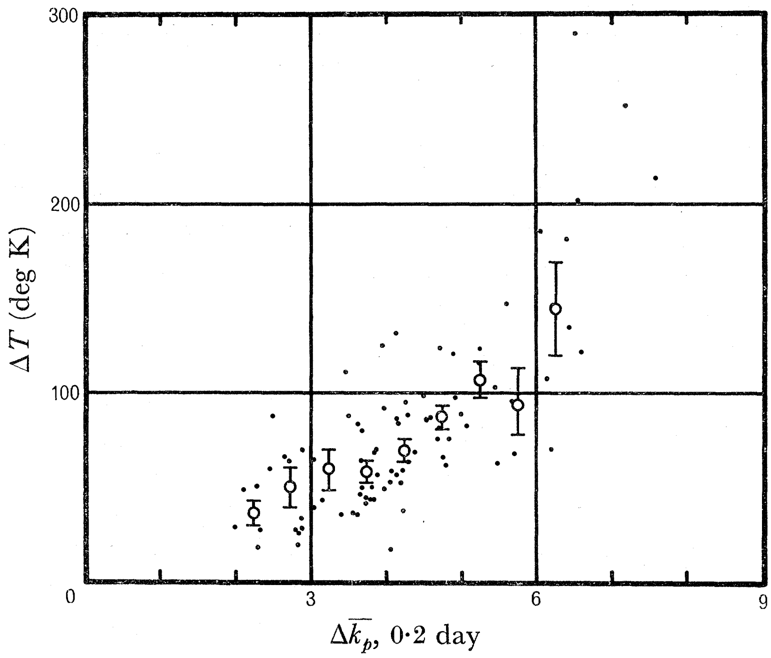


FIGURE 6. Temperature variation as function of the variation of the 0·2-day running means of the geomagnetic index $k_p$. The temperature difference between maximum and minimum $\Delta T$ is plotted versus the variation in the smoothed $k_p$ index $\Delta\overline{k_p}$, 0·2 day. In addition to the individual data average values are shown by circles with error flags. For $\Delta\overline{k_p}$ smaller than about 5 the gradient $\Delta T/\Delta k_p$ can be represented by a constant.

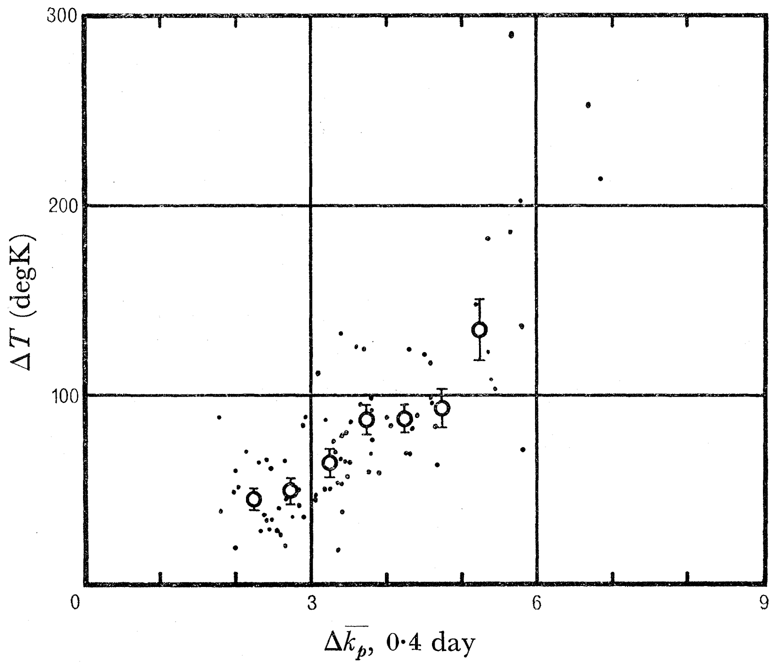


FIGURE 7. Temperature increase during a geomagnetic disturbance as function of the variation in the 0·4-day running means of $k_p$. The temperature increase $\Delta T$ is plotted versus the variation of the 0·4-day running mean of the $k_p$ indices $\Delta\overline{k_p}$, 0·4 day. A comparison with figure 6 shows that the slope of a curve which could be drawn through the mean values (circles with error flags) has a substantially higher gradient.

running means. The gradient $\Delta T/\Delta\overline{k_p} = 20{\cdot}6°$ derived from the low intensity variations was used to extrapolate the adjacent minima around the temperature maxima to the condition $\overline{k_p} = 0$ in every case. This transformation yields the total temperature variation during geomagnetic variations as a function of the 0·4 day running mean of $k_p$ (figure 8). In addition to the individual data a curve is drawn which represents the data fairly well and is given by

$$\Delta T = 20\overline{k_p} + 0{\cdot}03 \exp(\overline{k_p}),$$

where $\overline{k_p}$ is the average of the 3 h $k_p$ indices over 0·4 day.

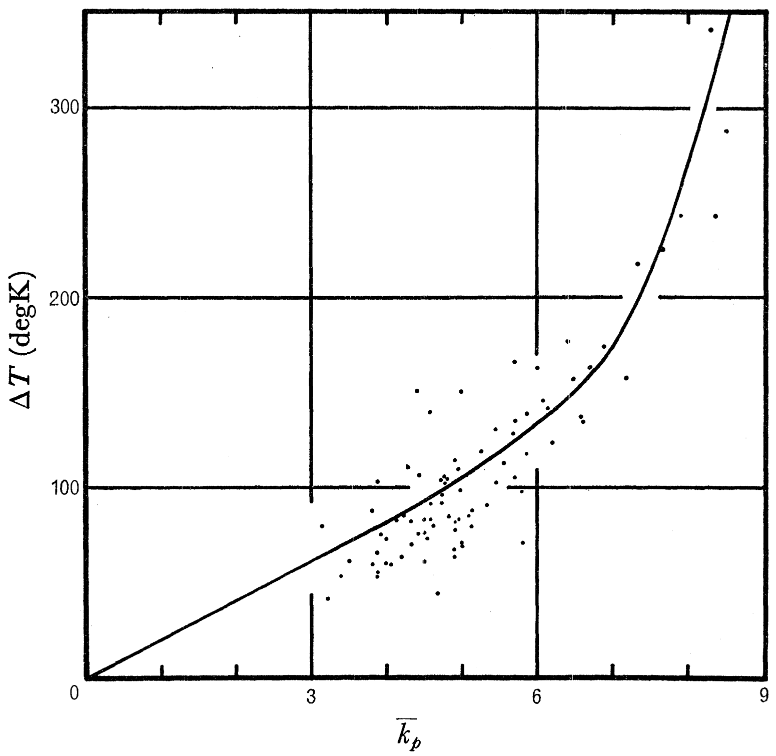


FIGURE 8. Atmospheric heating during a geomagnetic disturbance as function of the intensity of the geomagnetic activity. The increase in temperature $\Delta T$ from the condition $\overline{k_p} = 0$ to the maximum value of the 0·4-day running mean of the $k_p$ index $\overline{k_p}$ can be represented by the solid curve drawn through the individual data.

Owing to the influence of the smoothing interval on the gradient $\Delta T/\Delta\overline{k_p}$ we could not include an additional point with a high weight in figure 8. The analysis of the temperature variations during a geomagnetically quiet period of 45 days yields $\Delta T/\Delta\overline{k_p} = 21{\cdot}2°$ for a mean $\overline{k_p}$ of 1·2, where the temperature data have a nominal resolution in time of 0·5 day and 1 day means of $k_p$ were used (Roemer 1966). No dependence of $\Delta T/\Delta\overline{k_p}$ on either local time or altitude could be determined from the drag data of the Explorer 9 satellite.

Since the parameter $\Delta T/\Delta\overline{k_p}$ describing the heating of the atmosphere during geomagnetic activity is very sensitive to the smoothing interval of $k_p$ it is not easy to compare the results to those obtained from different satellites by different authors. But Jacchia *et al.* (1966) find a higher value, $\Delta T/\Delta\overline{k_p} = 28{\cdot}3°$ for $\overline{k_{p,\max.}} < 5$ and for medium latitudes

($|\phi| < 55°$), from their study of four satellites in the height band 250 to 615 km. As in the case of the time lag the results on the heating derived from the Explorer 9 satellite differ from results obtained in a similar altitude region later in the solar cycle. Although the significance of the comparison might be questionable owing to the influence of smoothing on the results, the possibility cannot be excluded that the differences in time lag and heating might be due to a long-term trend in the solar cycle.

I gladly acknowledge the hospitality of the Smithsonian Institution Astrophysical Observatory, Cambridge, Mass., where the major part of this analysis was initiated. I express my thanks to Dr Fred L. Whipple, director, and to Dr Luigi G. Jacchia for their stimulus and interest. Part of this work was supported by the Bundesministerium für wissenschaftliche Forschung under grant WRK 49.

## References (Roemer)

DeVries, L. L., Friday, E. W. & Jones, L. C. 1967 *Space Research VII* (edited by R. L. Smith-Rose), p. 1173. Amsterdam: North-Holland.
Gaposchkin, E. M. 1964 *Smithson. Astrophys. Obs. Spec. Rep.* no. 161.
Groves, G. V. 1961 *Space Research II* (edited by H. C. van de Hulst *et al.*), p. 751. Amsterdam: North-Holland.
Jacchia, L. G. 1959 *Nature, Lond.* **183**, 1662.
Jacchia, L. G. 1961 *Space Research II* (edited by H. C. van de Hulst *et al.*), p. 747. Amsterdam: North-Holland.
Jacchia, L. G. 1963 In *Dynamics of satellites* (edited by M. Roy), p. 136. Berlin: Springer.
Jacchia, L. G. 1964 *Smithson. Astrophys. Obs. Spec. Rep.* no. 170.
Jacchia, L. G. 1965 *Smithson. Astrophys. Obs. Spec. Rep.* no. 184.
Jacchia, L. G. & Slowey, J. W. 1963 *Smithson. Astrophys. Obs. Spec. Rep.* no. 125.
Jacchia, L. G. & Slowey, J. W. 1964 *J. Geophys. Res.* **69**, 4145.
Jacchia, L. G., Slowey, J. W. & Verniani, F. 1966 *Smithson. Astrophys. Obs. Spec. Rep.* no. 218.
Jacobs, R. L. 1966 *L.M.S.C. Tracking Note*, no. 80.
Moe, K. 1966 *Planet. Space Sci.* **14**, 1065.
Newton, G., Horowitz, R. & Priester, W. 1964 *J. Geophys. Res.* **69**, 4690.
Roemer, M. 1966 *Smithson. Astrophys. Obs. Spec. Rep.* no. 199.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF