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AN ANALYSIS OF THE ALTITUDE DEPENDENCE OF THE GEOMAGNETIC EFFECT BY MEANS OF "EQUIVALENT DURATIONS"

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Six geomagnetic storms were analysed by means of 35 equivalent duration (D) values determined from visual observations and orbital elements. Between 200 and 300 km the measured D values proved to be significantly larger than those calculated from the Jacchia 71 model, and an appropriate model correction is suggested. Above 300 km the coincidence with predictions of the model is satisfactory. In the case of two sudden atmospheric events, not correlated with strong geomagnetic activity, a single temperature increment can explain the observed density changes at all levels above 200 km.

1. Introduction

The equivalent duration D has been introduced [1] to characterize the total response of the atmosphere to corpuscular heating during geomagnetic storms. It is the integral of the relative density changes during a geomagnetic storm, i. e.

$$D = \int_{t_1}^{t_2} \frac{\varrho - \varrho_0}{\varrho_0} \, dt$$

a convenient measure of which is the length of time of a hypothetical disturbance having the same integral as the actual one, but giving rise to a constant 100% density increase for D days [1]. It can be determined either (i) by integrating directly the $\dot{P}$ or ϱ curves published in the literature (a very approximate method unless the time resolution of the data is extremely good), or (ii) by using the parallel displacement of a linear $P(t)$ curve or (iii) by the $O-C$ method described in detail in [1]. The second and third methods have been successfully applied to a whole series of orbital data derived from visually observed transits through the celestial equator by means of the PERLO programme [2], and complemented by published orbital elements (period, time of perigee passages) from the Current Gear Ratio Elements of NASA GSFC, as well as other sources [3—7]. The D values obtained by different methods are averaged; their estimated probable error is 40%.

Since D values obviously depend on the shape of the storm and on the altitude and position of the satellite's perigee, a model atmosphere must be used to provide D values for comparison. A computer programme based on the Jacchia 71 model [8] first calculates instantaneous density values ϱ every 3 hours, then selects an appropriate ϱ_0 corresponding to quiet atmospheric conditions and integrates the $(\varrho - \varrho_0)/\varrho_0$ curve in storm-time to obtain D_{J71}. The amplitude of the geomagnetic disturbance is defined as $A_{J71} = (\varrho_{\max} - \varrho_0)/\varrho_0$.

2. Results concerning Six Geomagnetic Events

Six large and isolated geomagnetic storms were selected between 1966 and 1970 and equivalent durations calculated in 35 cases. The results, together with model values, are given in Table 1. Within the limits of error, all D/D_{J71} values fit on one curve in the altitude diagram, where h is the height at λH^* above perigee (Fig. 1). H^* is the best estimate of H_p (scale height at perigee), $\lambda = z^* - {}^1/_2 z^{*2}$ for $0 \leqq z^* \leqq 1$; $\lambda = {}^1/_2$ for $z^* > 1$, where $z^* = ae/H^*$ [9]. The average value of D/D_{J71} between 200 and 300 km is 2.41, and its deviation from unity is clearly significant ($\sigma = 0.28$). In order to determine the density correction D_{J71} is plotted against A_{J71}, i.e. $(\varrho_{\max} - \varrho_0)/\varrho_0$ according to the J 71 model. The relation depends on the particular storm and is not linear (Fig. 2). A free-hand curve has been used to transform the measured D values into $A = (\varrho_{\max} - \varrho_0)/\varrho_0$, a quantity, though often published, in most cases distorted by the limited time resolution of the actual observations. The ratio A/A_{J71} has been plotted against height (Fig. 3,

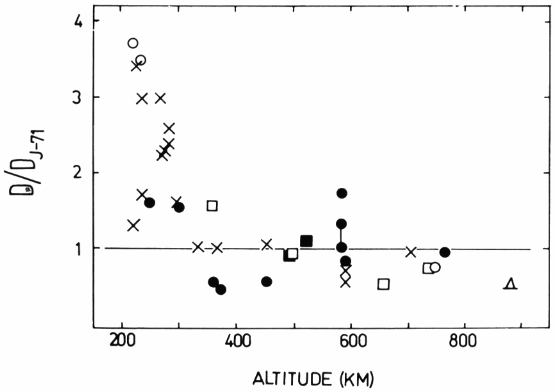

Fig. 1. Measured equivalent durations divided by the corresponding model values, as a function of altitude h. Different symbols represent different geomagnetic storms (see Table 1).

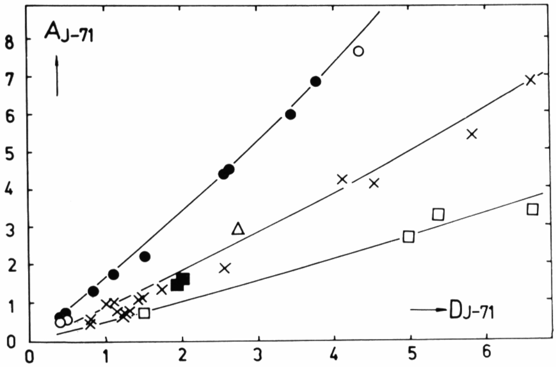

Fig. 2. Relation between amplitude and equivalent duration of different geomagnetic storms calculated by means of the Jacchia 71 model.

Table 1

Equivalent durations for 6 geomagnetic events

Storm MJD	*Ap* max	Ident.	*h* (km)	D_{obs}	Remarks	D_{J71}	A_{J71}
39369	112 ×	58001 A	368	1.72	e, [3]	1.72	1.36
		59001 A	591	2.20	e, [3]	4.10	4.23
		63053 A	703	5.50	a,d	5.82	5.40
		64076 A	590	4.29	a,d	6.60	6.83
		65011 A	282	3.10	c,d	1.30	0.78
		65011 B	284	2.97	c,d	1.15	0.75
		65011 D	298	1.60	a,d	1.00	0.97
		65052 A	235	2.05	c,d	1.20	0.61
		65095 A	226	2.65	c,d	0.78	0.45
		65095 B	236	2.38	c,d	0.80	0.53
		65112 P	267	3.29	c,d	1.10	1.03
		66009 B	453	4.77	c	4.53	4.12
		66036 A	274	3.30	c,d	1.45	1.15
		66043 A	220	1.61	c,d	1.25	0.69
		66061 A	270	3.12	c,d	1.40	1.13
		66065 A	333	2.60	c	2.56	1.92
39636	146 ●	58001 A	361	0.47	f, [4]	0.85	1.31
		59001 A	590	3.13	f, [4]	3.77	6.83
		60014 A	454	0.80	f, [4]	1.41	2.21
		62076 F	251	0.65	c, [5]	0.41	0.59
		63043 A	373	0.50	a	1.10	1.73
		63053 A	763	3.23	f, [4]	3.44	5.94
		64076 A	583	2.68	f, [4]	2.62	4.51
				3.41	a		
		65011 D	300	0.75	a	0.49	0.73
		65053 F	586	4.46	a, b	2.58	4.34
40018	103 ■	61001 A	490	1.80	b	1.94	1.50
		64076 A	524	2.19	b	2.00	1.59
40161	120 △	63053 A	881	1.85	a, b, c	2.75	2.90
40356	131 □	64004 A	655	2.76	e, [6]	5.36	3.28
		64035 A	357	2.33	c	1.50	0.70
		65082 LP	734	4.83	c	6.66	3.43
		67042 A	496	4.63	c, [7]	4.97	2.70
40654	150 ○	69082 DX	747	3.20	c	4.35	7.63
		69110 A	222	1.70	c	0.46	0.53
		70004 B	236	1.46	c	0.42	0.49

The remarks column is a one-letter code referring to the source and the method applied to determine D: a visual obs., $O-C$ method; b visual obs., P curve; c orbital elem., P curve; d orbital elem., $O-C$ method; e integral of P curve; f retransformation of ΔT into ρ and integral of ρ curve. Symbols refer to Fig. 1 and lower part of Fig. 3.

lower part), and a simple linear relation derived which might be used to correct model density values during strong magnetic storms up to 350 km. The factor, multiplying model $(\varrho - \varrho_0)/\varrho_0$ values between 200 and 350 km is $6.67 - 0.017$ h. The correction yields larger D_{J71} values. A similar correction is already included in the Jacchia 71 model for $h < 200$ km; our procedure is, however, more complicated, because it involves the determination of ϱ_0, corresponding to "background" geomagnetic activity.

In any case, an obvious implication of the equivalent duration curve is that during magnetic storms a considerable amount of energy is deposited below 350 km, causing a positive deviation from model density profiles.

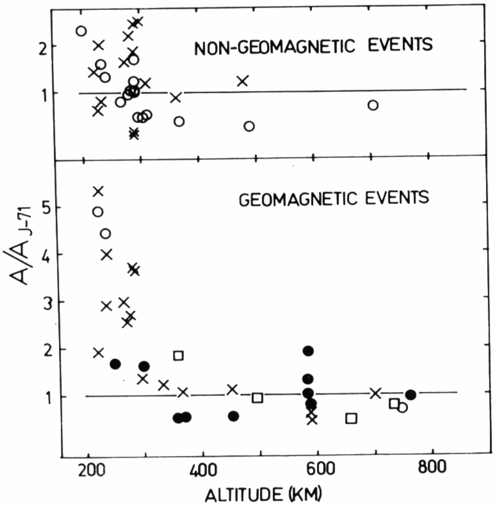

Fig. 3. Amplitude of the density changes, divided by the corresponding model values, during 6 geomagnetic storms (lower part) and during 2 non-geomagnetic events (upper part) as a function of altitude.

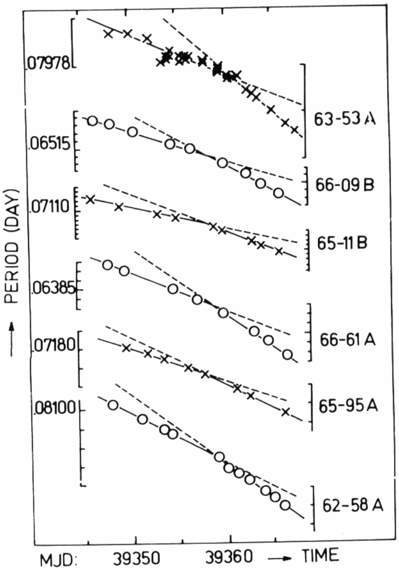

Fig. 4. A sample of period curves of different satellites around one of the "non-geomagnetic events".

3. Comparison: Analysis of two Non-geomagnetic Events

In order to investigate the possibility that this deviation is only a consequence of some systematic bias in our method, we carried out the analysis of two events of another type. Plotting P as a function of time, in August—October 1966 we observed quasi-simultaneous sudden changes in the slope of the $P(t)$ curve of many satellites (Fig. 4). In spite of the fact that these two events were not preceded by a geomagnetic storm or sudden increase in $F_{10.7}$, their reality seems to be unquestionable, since the effect can be traced on 33 diversely derived period curves of 19 satellites. These non-geomagnetic events and the usual geomagnetic storms are distinguished from each other by the fact that in the former case the atmosphere changes from one relatively stable situation to another.

Supposing that $\dot{P}_{\mathrm{b}}/\dot{P}_{\mathrm{a}} = \varrho_{\mathrm{b}}/\varrho_{\mathrm{a}}$ (where the indices b and a correspond to values before and after the event respectively) the amplitude of the density increase $A = (\varrho_{\mathrm{a}} - \varrho_{\mathrm{b}})/\varrho_{\mathrm{b}}$ can be calculated at different heights (Table 2). By means of these observed amplitudes adequate exospheric temperatures have been derived from model $d\varrho/dT$ curves. Accordingly the night-time minimum of the global exospheric temperature changed from 635 °K to 750 °K at MJD 39358 and from 750 °K to 815 °K at MJD 39387. Using these temperature values we calculated density amplitudes from the Jacchia 71 model and formed the A/A_{J71} ratios as previously. The result, as a function of height, is shown in the upper part of Fig. 3. The average amplitude ratio between 200 and 300 km is 1.30 ($\sigma = 0.40$), not differing significantly from unity.

Table 2

Acceleration changes for 2 non-geomagnetic events

Event		Ident.	h (km)	$\dot{P}_a/\dot{P}_b$	ϱ_a/ϱ_b J71
39358.7	○	62058 A	220	1.65	1.28
59.6		63053 A	706	2.12	2.67
60.0		64015 A	311	1.31:	1.58
57.8		65011 A	290	1.58	1.47
58.2		65011 B	291	1.79	1.47
59.5		65011 C	284	1.45	1.43
60 :		65020 A	289	1.80:	1.76
60.3 :		65020 B	290	1.72:	1.71
59.6		65020 C	286	1.67	1.65
59.6		65052 A	237	1.24	1.31
57.0		65095 A	238	1.41	1.32
55.6:		65095 B	234	1.47	1.30
57.8		65112 P	294	1.45	1.91
57.9		66009 B	491	1.64	3.34
58.3		66036 A	306	1.58	2.20
59.2		66061 A	278	1.73	1.77
58.9		66061 B	267	1.57	1.70
39360		66065 A	368	1.50	2.28
39385.6	×	62058 A	220	1.17	1.12
85.5		64015 A	308	1.35	1.29
90 :		65011 A	288	1.03:	1.23
87.0		65011 B	290	1.04	1.23
83.7		65020 A	288	1.47:	1.19
87.1		65020 C	282	1.40:	1.18
86.7		65052 A	233	1.10	1.12
87.3		65095 A	231	1.24	1.12
89.6		65095 B	234	1.16	1.12
85.9		65112 P	290	1.53	1.29
87.1		66009 B	479	1.84	1.70
87.8		66036 A	297	1.67:	1.27
89.3:		66043 A	225	1.12	1.19
87.6		66061 A	273	1.46	1.29
39385.5		66065 A	361	1.38	1.43

Symbols refer to upper part of Fig. 3.

4. Conclusions

Our results support Jacchia's conclusion that "since the characteristic time of geomagnetic disturbances is hours rather than days, static models cannot be expected to represent correctly both temperature and density variations" and a hybrid formula is needed to represent the geomagnetic variations in the thermosphere [8]. Recently Mayr and Volland also stated that "magnetic storm variations with a time scale about one day, comparable with the response time of the atmosphere, cannot be excited readily at all altitudes" [10]. On the other hand, we are unable to agree with Roemer's conclusion that "in the upper thermosphere the amplitude of the density variation during geomagnetic disturbances at various altitudes can be described by a single value of ΔT_∞ for a given storm" [11]. We are convinced that the distribution in height of the energy input (as characterized by the equivalent durations) during geomagnetic storms is different, at least below 300 km, from that of EUV absorption. Nevertheless more data and more careful correlation studies are needed before a final quantitative model correction can be made.

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