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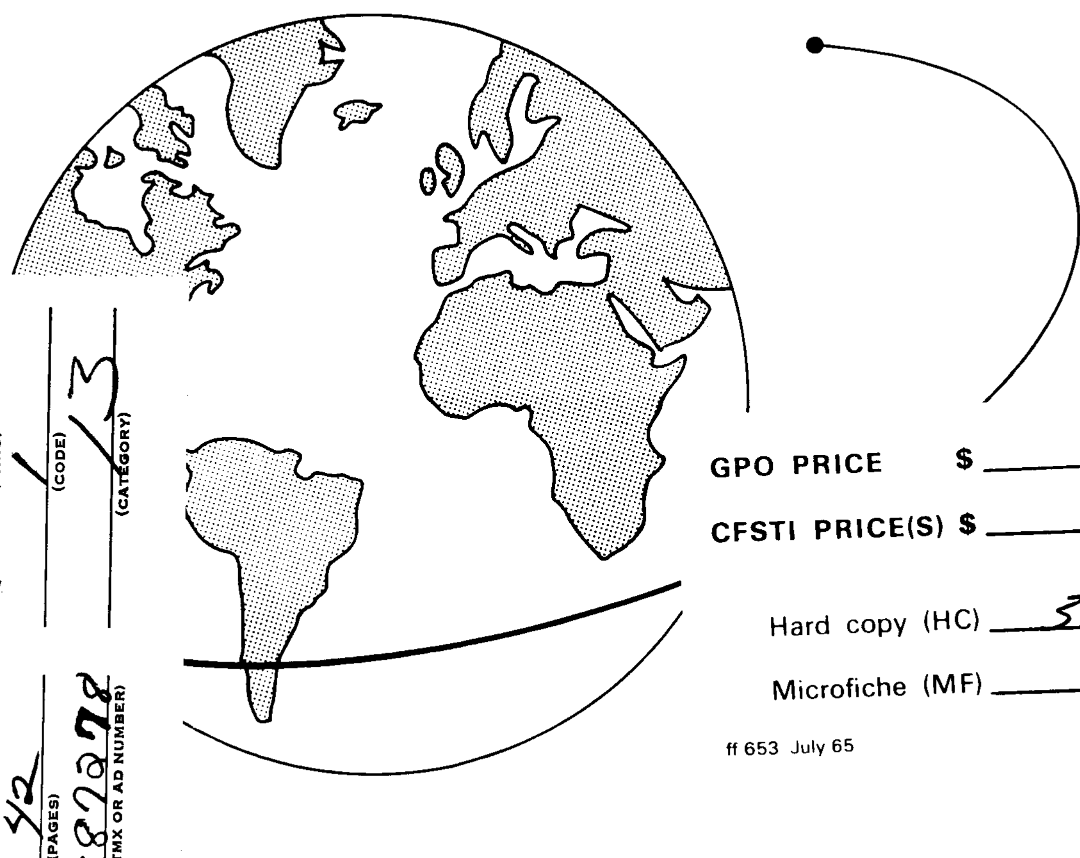
LUIGI G. JACCHIA and JACK W. SLOWEY



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ABSTRACT

The variations with solar and geomagnetic activity have been eliminated by the use of appropriate models, and the diurnal variation has been isolated in the densities derived from the drag of seven artificial satellites with perigees between 250 and 650 km. An analysis of the diurnal variations leads to the following conclusions:

A. Contrary to previous suggestions, the diurnal bulge does migrate in latitude in phase with the subsolar point at all heights.

B. The diurnal bulge peaks at 2 p.m. local solar time (LST) irrespective of solar activity; the minimum density occurs between 3 and 4 a.m.

C. The amplitude of the diurnal variation seems to fluctuate in a manner that cannot be entirely accounted for by variations in solar activity.

D. The significant high-latitude residuals from the diurnal-variation model observed on the drag of Explorer 19 and Explorer 24 may be explained by the formation at exospheric heights of a region of greater helium density above the poles during the winter months, caused by a seasonal variation in the height of the turbopause.

RÉSUMÉ

Les variations liées à l'activité solaire et géomagnétique ont été éliminées par l'emploi de modèles appropriés et la variation diurne a été mise en évidence dans les densités déduites du calcul de la traînée de sept satellites artificiels aux périgées compris entre 250 et 650 kilomètres. Une analyse des variations diurnes mène aux conclusions suivantes:

A. Contrairement aux suggestions antérieures, le maximum diurne varie effectivement en latitude et en phase avec le point subsolaire à toutes les altitudes.

B. Le maximum diurne a lieu à 14 heures (heure sidérale locale), indépendamment de l'activité solaire; la densité minimale a lieu entre 3 et 4 heures.

C. L'amplitude de la variation diurne semble fluctuer d'une façon qui ne peut être entièrement dûe aux variations de l'activité solaire.

D. Les résidus significatifs à haute altitude provenant du modèle à variation diurne qui ont été observés sur la traînée d'Explorer 19 et d'Explorer 24 peuvent être expliqués par la formation - à des altitudes exosphériques - d'une région à plus grande densité d'hélium au-dessus des pôles pendant les mois d'hiver dûe à une variation saisonnière de l'altitude de la tropopause.

КОНСПЕКТ

Изменения вследствие солнечной и геомагнитной деятельности были устранены путем применения подходящих моделей, и суточное изменение было изолировано в плотностях, выведенных из драга семи искуственных спутников с перигеями между 250 и 650 километрами. Анализ суточных изменений приводит к следующим заключениям:

А. Вопреки предыдущим предположениям суточный горб перемещается по широте в фазе с подсолнечной точкой на всех высотах.

Б. Суточный горб достигает максимума в 2 часа после полудня, м.з.в. независимо от солнечной деятельности; минимальная плотность происходит между 3-мя и 4-мя часами утра.

В. Амплитуда суточного изменения кажется колеблющейся таким образом, который не может быть полностью объяснен изменениями солнечной деятельности.

Г. Значительные высоко-широтные разности суточного изменения, наблюдаемые при драге Эксплорера-19 и Эксплорера-24, могут быть объяснены образованием на экзосферических высотах области высшей плотности гелия над полюсами втечение зимних месяцев, вызываемым сезонным изменением в высоте турбопаузы.

DIURNAL AND SEASONAL-LATITUDINAL VARIATIONS IN THE UPPER ATMOSPHERE

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1. THE EFFECT OF THE DIURNAL VARIATION ON SATELLITE DRAG

In view of recent results from the drag analysis of high-inclination Explorer balloon satellites (Jacchia and Slowey, 1966; Keating and Prior, 1967), which seemed to cast some doubt on the global model of the diurnal variation previously derived from lower inclination satellites (Jacchia, 1965a, b), it seemed desirable to reanalyze all the suitable observational material in order to obtain a clearer picture of the density distribution in and above the thermosphere. The time for such an analysis appeared particularly favorable, since a considerable amount of new satellite-drag data had been accumulated during the quiet-sun years, when erratic density variations connected with solar activity were less likely to interfere with the diurnal variation. The drag of a satellite yields densities at or around perigee, and since it generally takes the perigee a few hundred days to move from daylight into night and back to daylight, a plot of the perigee densities shows the diurnal variation in slow motion, so to speak. Variations connected with solar and geomagnetic activity, and the semiannual variation, will thus appear superimposed on the diurnal variation and must be eliminated if we want to have a clearer picture of the latter. Empirical formulas have been established to take into account these parasitic variations (Jacchia, 1965b), and we have used them in this paper to isolate the diurnal oscillation; these formulas, however, cannot be perfect, so it helps if the parasitic variations are smaller, as they were during the quiet-sun period.

During the hundreds of days into which the diurnal cycle is stretched by the drag plot, the perigee of the satellite moves back and forth in latitude, with a different period, and so does the subsolar point on the earth's surface.

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If the center of the diurnal bulge follows the migrations in latitude of the subsolar point, the combination of this motion with that of the perigee will cause a complicated pattern of waves in the drag plot. If the center of the diurnal bulge does not follow the migrations of the subsolar point, there will still be waves, caused only by the latitude variations of the perigee, but their pattern will be quite different. If we take the atmospheric densities derived from the drag of a single satellite, suppress all the known atmospheric variations except the diurnal variation, and compare the plot of these corrected densities with the theoretical variation obtained using first a migrating and then a stationary bulge, it should be possible to decide in favor of one or the other by inspecting the pattern of the secondary waves in the diurnal-cycle oscillation. The decision should be clear-cut in the case of satellites with moderate orbital inclinations; for those with higher inclinations we can expect trouble if there is a seasonal-latitudinal variation in the atmosphere.

The satellites used in the present analysis are listed, with some of their pertinent characteristics, in Table 1. The latest satellite in the table (San Marco 1) was added only because it is the lowest satellite for which we have density data, although no significant results could be expected from it in view of the short interval covered by the observations; we thought it would be useful, however, to see how the data would fit in the diurnal-variation model.

We have made our analysis on temperatures rather than on the original densities. All temperatures were derived from the observed densities with the use of Jacchia's (1965b) models, henceforth referred to as J65. The reason for using temperatures is obvious: Since the temperature is assumed to be independent of height above the thermopause, the relations between the temperature and the various parameters that govern atmospheric variations are much simpler than the relations between these parameters and the density. All formulas for the different types of atmospheric variations in J65 are based on temperatures. These temperatures may be affected by large systematic errors because of the oversimplifications introduced in the models; they do, however, reproduce the observed densities, and that is all that counts for an analysis such as this.

Table 1. Characteristics of satellites

Satellite	A/m (cm^2/g)	t	$\bar{z}_p$ (km)	$\bar{z}_A$ (km)	i	$T_{\odot}$ (days)
Explorer 1 (1958 Alpha)	0.17	Feb. 1958 July 1966	360 345	2550 1500	33°.2 33.2	332 225
Vanguard 2 (1959 α1)	0.24	Feb. 1959 Oct. 1966	560 560	3320 3280	32.9 32.9	459 457
Explorer 8 (1960 ξ1)	0.11	Nov. 1960 Oct. 1966	420 420	2290 2130	49.9 49.9	231 230
Injun 3 (1962 βτ2)	0.070	Dec. 1962 May 1966	250 240	2780 2100	70.4 70.3	96 87
Explorer 17 (1963 ι1)	0.036	Apr. 1963 Oct. 1963	270 270	900 900	57.6 57.6	106 110
Explorer 19 (1963-53A)	13.0	Dec. 1963 Oct. 1966	610 670	2400 2200	78.7 78.7	92 91
Explorer 24 (1964-76A)	12.2	Nov. 1964 Oct. 1966	540* 550*	2500 2400	81.4 81.4	93 91
San Marco 1 (1964-84A)	0.032	Dec. 1964 Feb. 1965	205 205	800 800	37.8 37.8	338 338

*The average perigee height rose to 600 km in February 1966 and then decreased.

A/m = area-to-mass ratio; t = beginning and end of period covered by analysis; $\bar{z}_p$ = average perigee height; $\bar{z}_A$ = average apogee height; i = orbital inclination; $T_{\odot}$ = synodic period of perigee (length of diurnal cycle).

All the densities were derived from orbital analyses based on satellite positions obtained from field-reduced photographs with Baker-Nunn cameras. In the analysis of the diurnal variation, we used 10-day means of the temperature residuals, in which we gave each individual observation a weight proportional to the interval of differentiation of the positional data from which the acceleration (and thus the temperatures) was derived. This procedure, as previously explained (Jacchia and Slowey, 1966), minimizes possible errors introduced by inadequate correction for magnetic-storm activity.

2. RESULTS FROM LOW-INCLINATION SATELLITES

Results obtained from three satellites with low to moderate orbital inclinations (from 33° to 50°) are shown graphically in Figures 1, 2, and 3. The top of the diagram is a plot of the quantity $\Delta T = T - T_0$, where T is the "exospheric" temperature obtained from the observed perigee density, and T_0 the minimum nighttime temperature on the globe, computed taking into account solar and geomagnetic activity, and the semiannual effect according to formulas (6), (8), (9), and (14) in J65. The two curves below the ΔT plot show the theoretical diurnal variation D, with a maximum amplitude normalized to 1.0, according to two different models. The upper curve is computed using the model of J65, in which the bulge migrates in latitude with the subsolar point; the lower curve is computed using the model of Jacchia and Slowey (1966), in which the bulge is stationary on the equator and elongated in the north-south direction, with the parameters m = 1.5, n = 2.5; D is defined as

$$D = \frac{T_c - T_0}{RT_0} \quad , \tag{1}$$

where T_c is the exospheric temperature for the geographic location of the satellite perigee, computed from the bulge model, starting from an arbitrary value of T_0; and (1 + R) is the ratio of the maximum temperature at the center of the bulge to the minimum temperature in the opposite hemisphere. The variations in latitude of the satellite perigee, the declination of the sun, and the 10.7-cm solar flux are shown for reference in the lower half of the figures.

The theoretical curve computed using the migrating bulge of J65 shows lively secondary waves in the vicinity of the maxima, caused by the interplay of the variations in latitude of the perigee and of the bulge. The second theoretical curve is much smoother around maxima, since the variations in

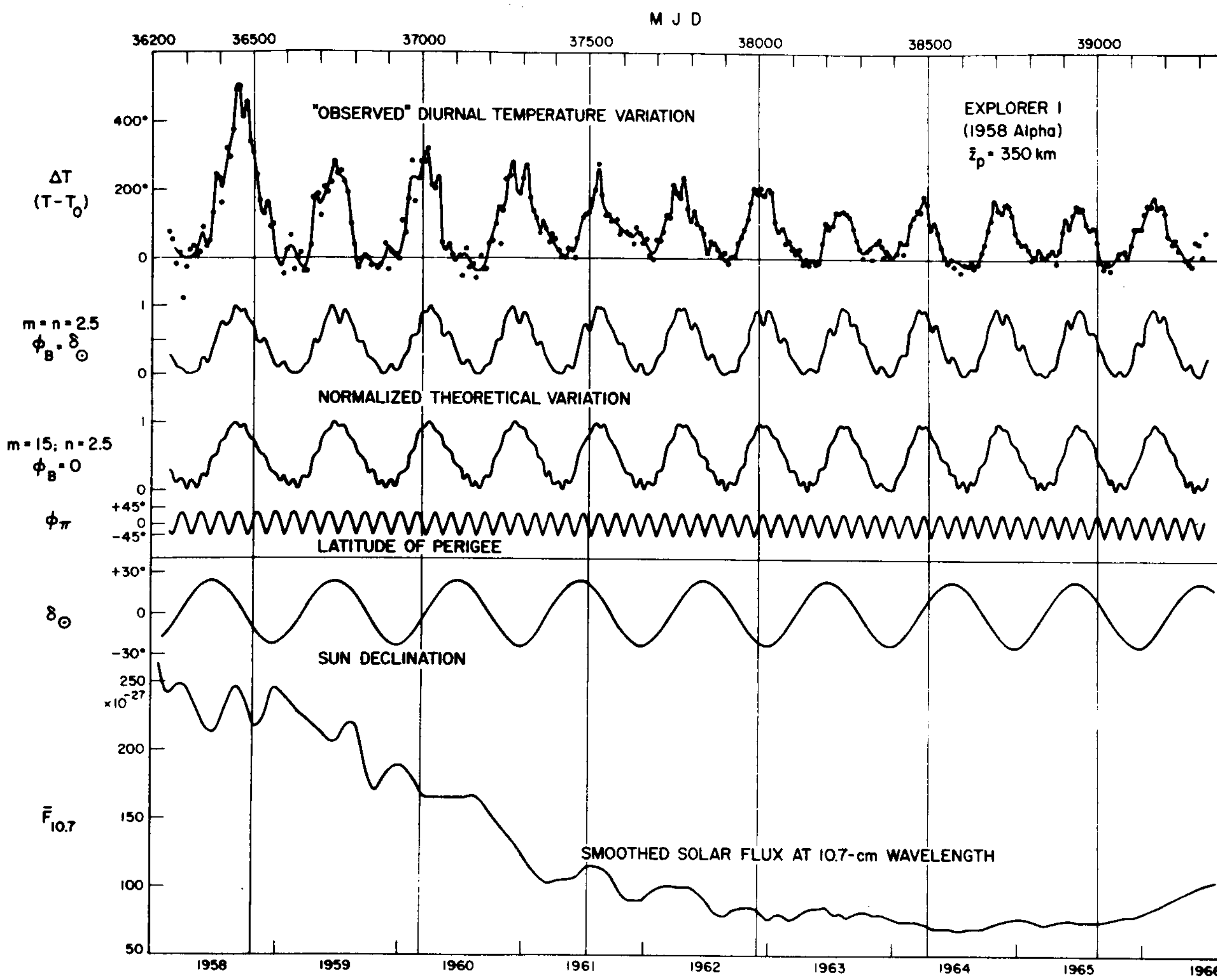

Figure 1. The diurnal temperature variation as derived from the drag of Explorer 1. The observed variations (top) are compared with the normalized theoretical variations according to the models of J65 and Jacchia and Slowey (1966). Curves of the latitude of perigee, the declination of the sun, and the smoothed 10.7-cm solar flux are added for reference. MJD in the abscissa is the Modified Julian Day (Julian Day minus 2 400 000.5).

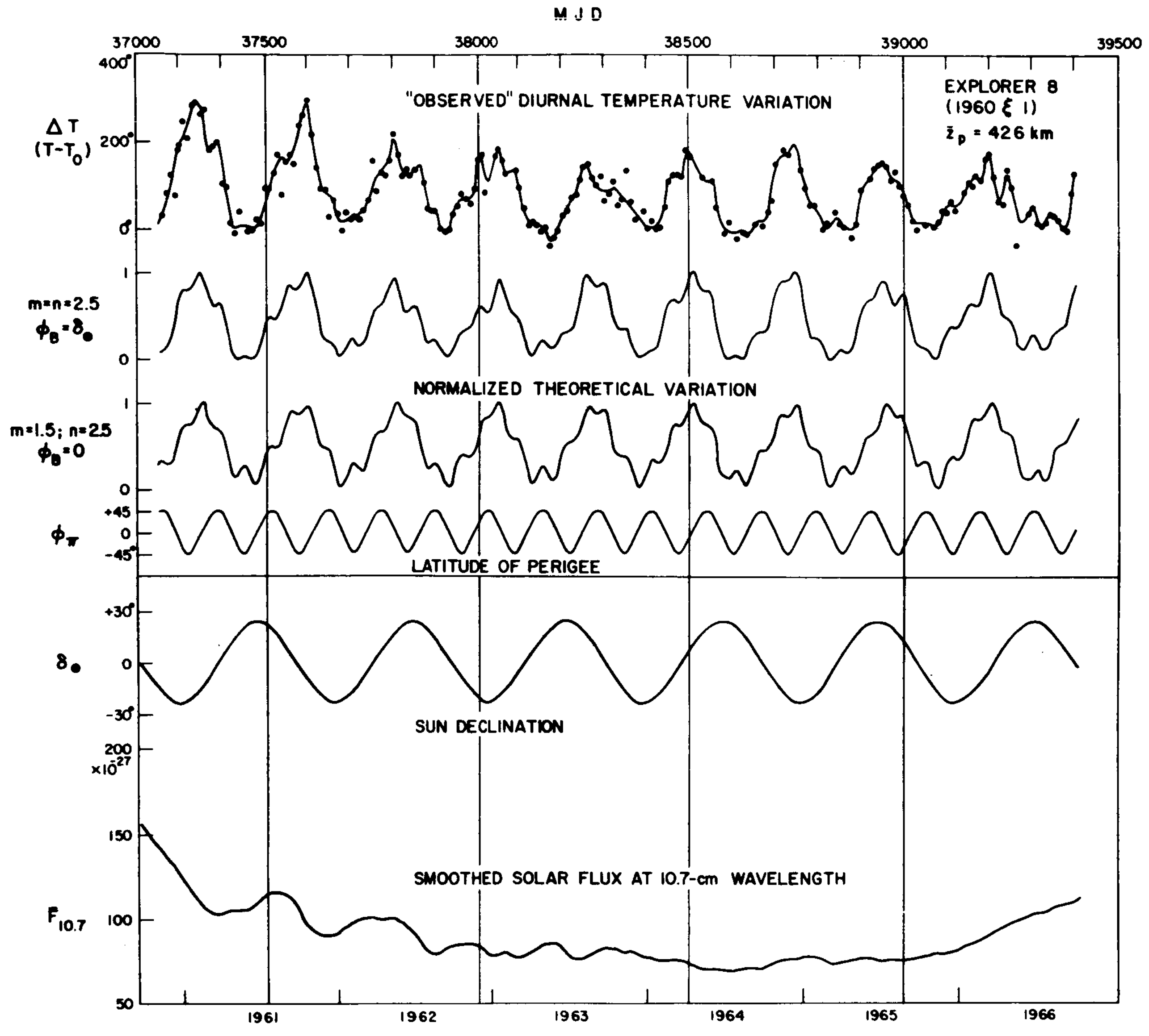

Figure 2. The diurnal temperature variation as derived from the drag of Explorer 8. The observed variations (top) are compared with the normalized theoretical variations according to the models of J65 and Jacchia and Slowey (1966). Curves of the latitude of perigee, the declination of the sun, and the smoothed 10.7-cm solar flux are added for reference. MJD in the abscissa is the Modified Julian Day (Julian Day minus 2 400 000.5).

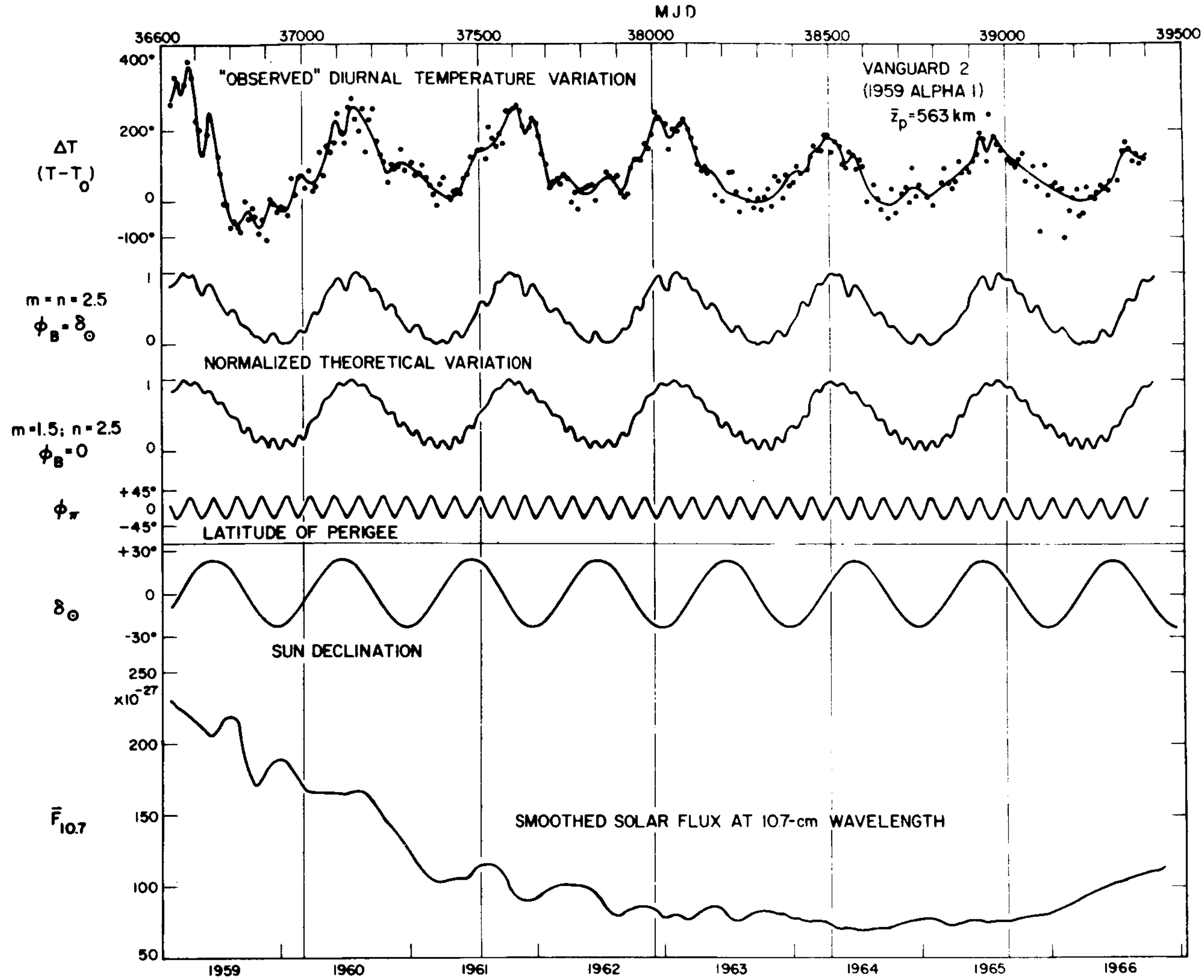

Figure 3. The diurnal temperature variation as derived from the drag of Vanguard 2. The observed variations (top) are compared with the normalized theoretical variations according to the models of J65 and Jacchia and Slowey (1966). Curves of the latitude of perigee, the declination of the sun, and the smoothed 10.7-cm solar flux are added for reference. MJD in the abscissa is the Modified Julian Day (Julian Day minus 2 400 000.5).

latitude of the bulge are missing; around minima, however, there are lively secondary waves. These are produced as the perigee of the satellite crosses the equator in the vicinity of the antibulge point, where, owing to the elongation of the bulge, the isotherms now crowd together. A simple glance at Figures 1 to 3 will show that it is the first model, that of the migrating bulge of J65, that is much closer to reality; as is to be expected, this fact emerges with greater clarity during the period of the quiet sun, and can be seen in all three figures. The approximate perigee heights of the three satellites are: Explorer 1, 350 km; Explorer 8, 420 km; Vanguard 2, 560 km. The perigee height of Vanguard 2 is intermediate between those of Explorer 19 and Explorer 24, whose data gave rise to the hypothesis of the stationary, elongated bulge, so we must conclude that this hypothesis is not correct and that the cause of the large residuals at high latitudes for these two satellites must be sought elsewhere. Before we turn our attention to this problem, however, let us examine further aspects of the diurnal variation.

3. AMPLITUDE AND PHASE OF THE DIURNAL VARIATION

Table 2 gives a summary of the observed data on amplitude and phase of the diurnal variation for the three low-inclination satellites dealt with in the previous section, and for three additional satellites: Injun 3, Explorer 17, and San Marco 1. The last was included only because of its low perigee height, in the hope of extracting some information from the 200-km region, where observations are scarce. The table gives the date corresponding to the observed maximum or minimum, and the theoretical value of D, as defined by equation (1), corresponding to it; the 10.7-cm solar flux $\overline{F}_{10.7}$, smoothed in such a way as to eliminate the effect of solar rotation; the maximum and mininum temperatures, T_M and T_m, derived from the observed densities; and the local solar time (LST) of the maximum or minimum. The last three columns refer to the computation of the relative amplitude (1 + R) and give, in addition to this quantity, the temperature $\overline{T}_0$ computed from $\overline{F}_{10.7}$ for a point intermediate between the maximum and the minimum from which the amplitude was computed, and the observed temperature difference δT between these extremes.

Equation (6) in J65 was used to compute $\overline{T}_0$. Since the perigee of a satellite does not necessarily cross the center of the bulge or of the antibulge at every cycle, the observed temperature range δT may be somewhat smaller than the temperature difference between these two points; this can be seen by inspecting the D column in Table 2. When the length of the diurnal cycle is much greater than the cycle of latitude variation for the satellite perigee, the chance of a central crossing of the bulge and of the antibulge is increased; this is the case of Vanguard 2, for which D always varies by its full range from 0.00 to 1.00. To take this effect into account, we computed R from

$$R = \frac{\delta T + (1 + D_m - D_M)\overline{R}\,\overline{T}_0}{\overline{T}_0} \quad , \tag{2}$$

Table 2. Data on amplitude and phase of the diurnal variation for six satellites

Year	D	$\bar{F}_{10.7}$	T_M	T_m	LST	$\bar{T}_0$	δT	1 + R
Explorer 1 (1958 Alpha)								
1958.3	0.00	245		1300°	$3^h.7$	(1250°)	(510°)	(1.41)
1958.7	0.99	245	(1805°)		14.8			
1959.1	0.00	225		1200	4.6	1200	305	1.26
1959.5	0.99	206	1435		14.2			
1959.8	0.00	180		1040	2.0	1075	335	1.31
1960.2	1.00	166	1325		13.2			
1960.6	0.00	165		970	2.4	960	320	1.34
1960.9	1.00	130	1160		14.5			
1961.3	0.01	105		800	5.3	815	255	1.32
1961.6	0.99	114	1095		13.8			
1962.0	0.00	96		780	5.0	775	220	1.30
1962.3	0.97	100	1015		13.8			
1962.7	0.00	80		700	4.0	725	218	1.32
1963.0	0.95	80	925		13.9			
1963.3	0.02	85		710	4.7	710	160	1.23
1963.6	0.99	80	850		14.0			
1964.0	0.00	77		700	(3:)	690	170	1.25
1964.3	0.97	73	860		14.9			
1964.6	0.00	69		650	(4:)	675	195	1.29
1964.9	1.00	74	870		15.6			
1965.2	0.00	73		685	4.9	690	155	1.23
1965.5	0.97	75	850		14.7			
1965.8	0.01	77		680	1.0:	710	200	1.29
1966.1	0.98	85	905		14.4			
				Mean	m $3^h.7$ M 14.3			

Table 2 (Cont.)

Year	D	$\overline{F}_{10.7}$	T_M	T_m	LST	$\overline{T}_0$	δT	1 + R
Vanguard 2 (1959 α1)								
1959.3	1.00	217	1585°		14^h:	1270°	400°	1.31
1959.9	0.00	180		995°	0.5			
1960.6	1.00	165	1280		13.1	1040	340	1.33
1961.3	0.00	105		805	4.6			
1961.8	0.99	95	1025		14.1	800	253	1.32
1962.4	0.00	90		760	3.5			
1963.0	1.00	79	940		14.4	720	220	1.30
1963.7	0.00	81		710	3.1			
1964.3	1.00	72	855		13.7	700	178	1.25
1965.0	0.00	75		680	2.5			
1965.6	1.00	75	870		13.8	690	188	1.27
1966.3	0.00	93		755	2.8			
				Mean	m $2^h.8$ M 13.9			
Explorer 8 (1960 ξ1)								
1961.1	1.00	110	1100		14.9	835	285	1.34
1961.4	0.00	107		805	4.3			
1961.8	1.00	93	1040		13.5	750	270	1.37
1962.0	0.03	95		775	3.2			
1962.4	0.92	99	995		16.3	720	212	1.32
1962.8	0.01	84		710	3.5			

Table 2 (Cont.)

Year	D	$\overline{F}_{10.7}$	T_M	T_m	LST	$\overline{T}_0$	δT	1 + R
Explorer 8 (1960 ξ 1) (Cont.)								
1963.1	0.92	80	905°		$14^h.7$	700°	210°	1.34
1963.4	0.03	85		690°	2.0			
1963.6	0.97	78	860		15.8	710	150	1.22
1964.0	0.01	76		695	2.0			
1964.3	1.00	73	860		15.0	670	185	1.28
1964.6	0.00	69		655	3.1			
1965.0	1.00	76	885		14.0	690	195	1.28
1965.2	0.01	74		680	3.5			
1965.5	0.90	75	860		16.2	690	148	1.24
1965.9	0.00	78		705	5.3			
1966.2	0.99	90	915		14.2	710	170	1.26
1966.6	0.10	103		770	3:			
				Mean	m $3^h.3$ M 15.0			
Injun 3 (1962 βτ2)								
1963.25	0.96	80	855		—	720	184	1.27
1963.40	0.00	81		670	—			
1963.79	0.98	82	865		—	705	170	1.25
1964.12	0.00	75		668	—			
1964.29	0.78	72	835		—	670	170	1.29
1964.66	0.00	70		635	—			
1965.04	0.93	77	830		—	690	190	1.29

Table 2 (Cont.)

Year	D	$\overline{F}_{10.7}$	T_M	T_m	LST	$\overline{T}_0$	δT	1 + R
Injun 3 (1962 βτ2) (Cont.)								
1965.37	0.01	76		620°	–			
1965.54	0.98	75	805°		–	690°	192°	1.29
1966.03	0.97	83	920		–			
Explorer 17 (1963 ι1)								
1963.38	0.92	85	865		$13^h.9$	710	140	1.20
1963.50	0.01	79		680	3.2			
1963.66	0.73	80	825		14.5	700	104	1.19
San Marco 1 (1964-84 A)								
1963.99	0.83	76	(815)		–	690	84	(1.19)
1964.08	0.38	76		(660)	–			

where D_m and D_M are the values of D corresponding to the minimum and the maximum, respectively, and $\overline{R}$ is the mean value of R, taken as 0.28 according to J65. The relative amplitude (1 + R) could be computed from both the ascending and the descending branches of the ΔT curve, but then successive values of R would not be independent of each other; therefore, we always limited ourselves to one branch of the curve.

Figure 4 shows a plot of R, as obtained from the three low-inclination satellites of the preceding sections, i.e., Explorer 1, Vanguard 2, and Explorer 8, compared with a graph of $\overline{F}_{10.7}$. As can be seen, all three satellites give comparable values of R, in spite of their great range in perigee heights, but there seems to have been some variation of R in the course of the 8 years covered by the observations. The fact that we obtain similar values of R for different heights would indicate that the temperature scale of the models is essentially correct. We must not forget, however, that the J65 models are static models; they may well give a correct relation between $\overline{F}_{10.7}$ and $\overline{T}_0$ in the solar-cycle variation and still be systematically in error when we compute the temperature range in the diurnal variations from the observed density ranges. Even if this is the case, the fact that satellites at different heights give essentially the same values of R means that diurnal density variations can be satisfactorily predicted with static models; we must, however, not attach more than a relative value to the diurnal temperature variations.

Figure 4 shows that R was close to 1.32 from 1959 to early 1963; but from mid-1963 on, it was decidedly lower, around 1.26. The graph shows a sudden drop around 1963.4, at a time when solar activity had almost reached its minimum and there was no solar phenomenon that could be obviously blamed for such an occurrence. Because of some scatter in the data, the suddenness of the drop might at first be doubted were it not for the fact that it appears in the data of two satellites, Explorer 1 and Explorer 8. The third satellite, Vanguard 2, also shows the drop, but the long duration of its diurnal cycle makes it impossible to tell how sudden it was. The drop in amplitude is visible at first glance in the ΔT curves in Figures 1 and 2. Although R was

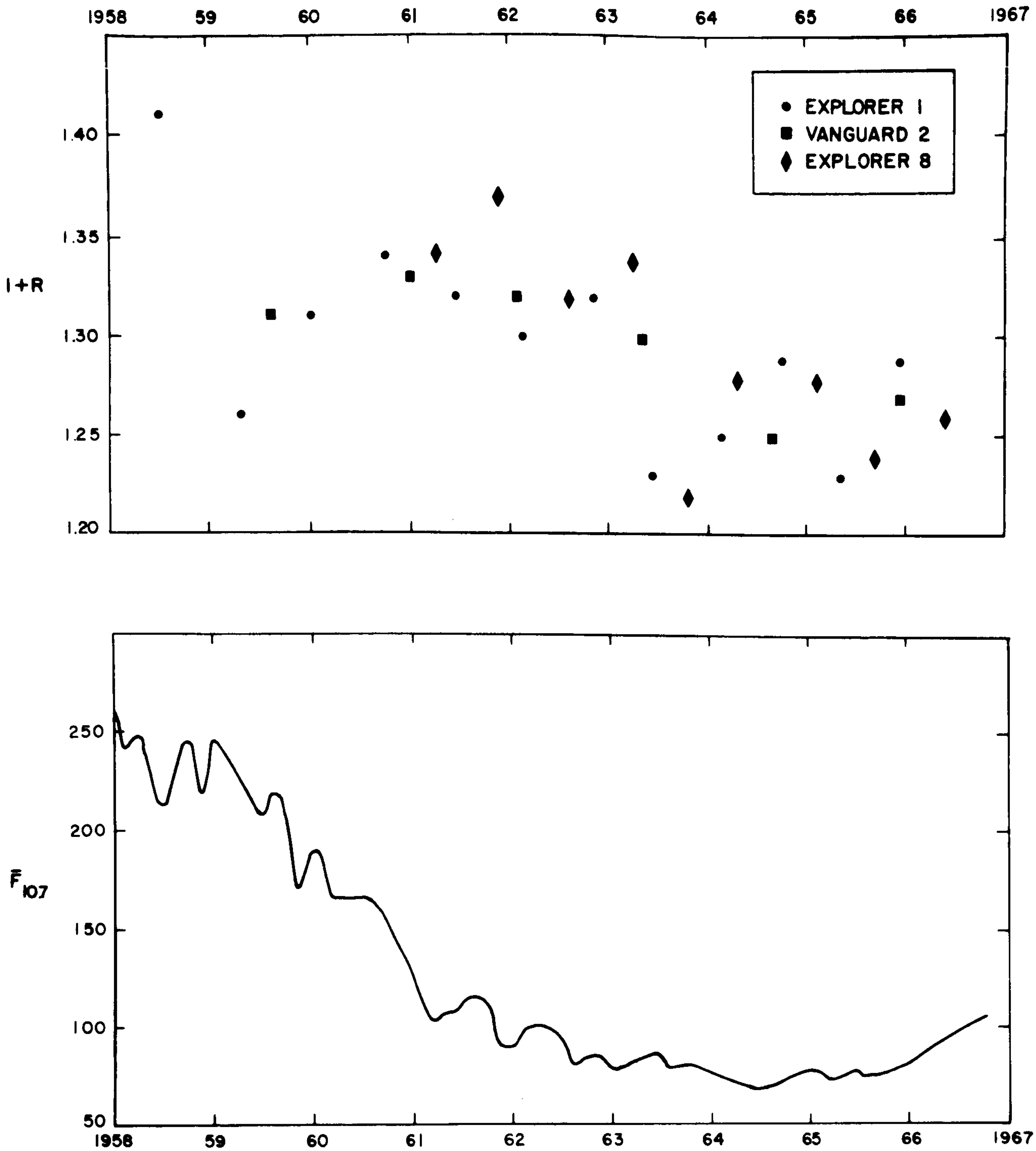

Figure 4. Relative amplitude of the diurnal temperature variation as derived from the drag of three satellites with moderate orbital inclinations, plotted as a function of time and compared with the smoothed 10.7-cm solar flux.

smaller at sunspot minimum than at sunspot maximum, it would appear that there is no simple relation between its magnitude and solar activity, as can be seen in Figure 5, where R is plotted against $\overline{F}_{10.7}$. The large scatter in R for $\overline{F}_{10.7} < 85$ is a consequence of the drop in R when $\overline{F}_{10.7}$ was nearly constant at minimum.

In conclusion, it appears that: (1) the relative amplitude (1 + R) of the diurnal variation is not constant; (2) although loosely connected with solar activity, its variations cannot be directly related to the 10.7-cm solar flux; (3) R appears to be subject to erratic fluctuations; (4) a good average value for R is 0.30.

For lack of information concerning variations in temperature and composition at that height, both the J65 and the CIRA 1965 models assume constant boundary conditions at 120 km. The existence of minor variations in the boundary conditions would not cause serious discrepancies in the models of atmospheric variation above 300 km; at lower heights, however, we must expect to observe variations that are larger than those predicted by the models. This has been found to be true for the variations with solar and geomagnetic activity at 200 km (Jacchia, 1965c) and for the diurnal variation in the same height region (King-Hele and Quinn, 1966). We must expect, therefore, to find somewhat greater values of R when we analyze satellites with low perigee heights. As we can see from Table 2, however, no substantial difference in R is found from the data of Injun 3 ($\overline{z}_p$ = 250 km) and Explorer 17 ($\overline{z}_p$ = 270 km). Apparently the observed discrepancy starts only at somewhat lower heights. No reliance should be placed on the single value of R computed from the San Marco satellite ($\overline{z}_p$ = 200 km), observations of which cover only a secondary wave of the diurnal cycle.

The ΔT curve that represents the observed diurnal variations in the top diagram of Figures 1 to 3 and Figure 6 should reach zero at minimum when D = 0, if $T_m = T_0$, i.e., if the observed and the computed global minimum temperatures coincide. Thus an inspection of Figures 1 to 3 and Figure 6 should immediately reveal how good the assumed relation between $\overline{F}_{10.7}$ and T_0 is.

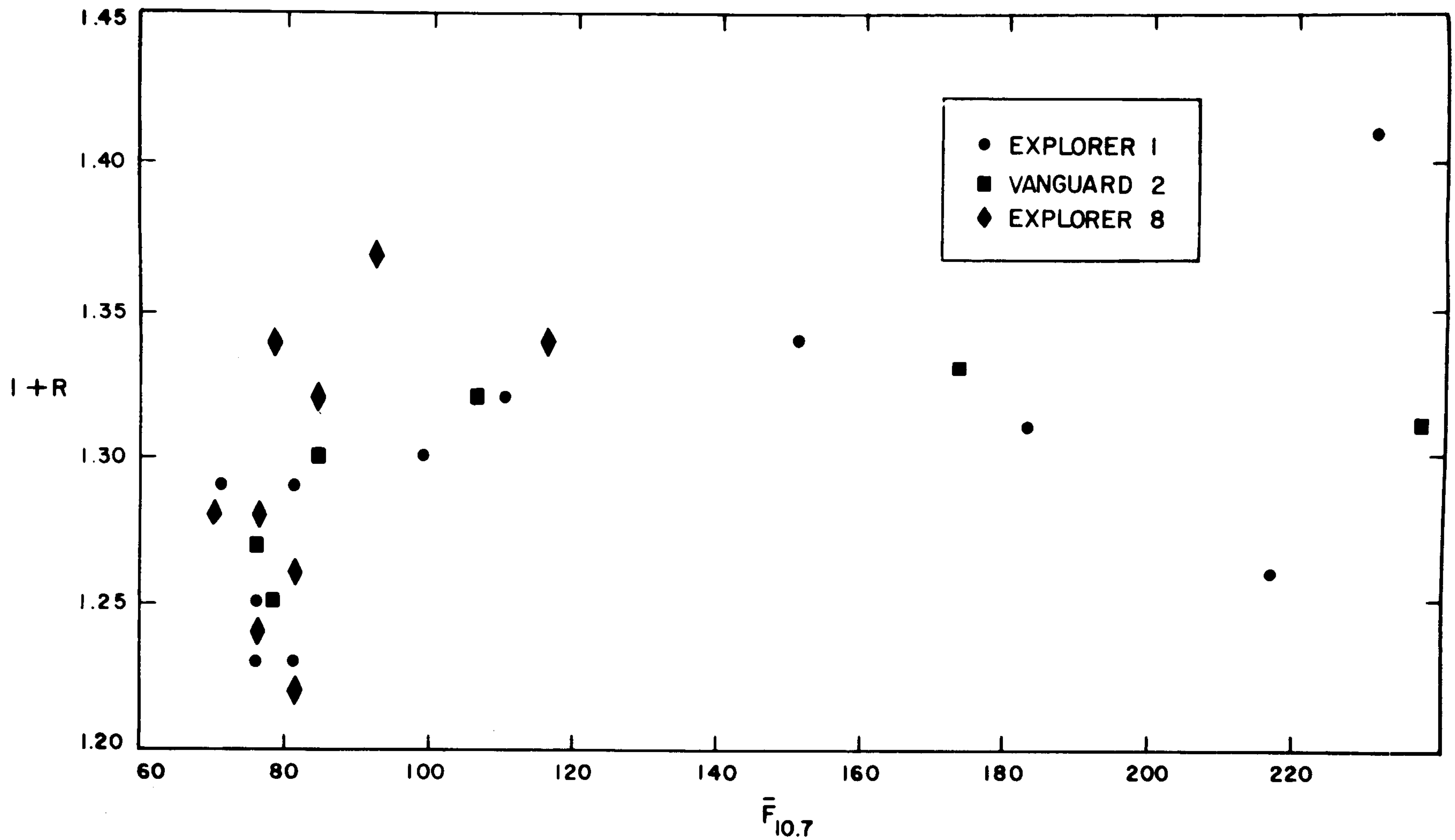

Figure 5. Relative amplitude of the diurnal temperature variation as derived from the drag of three satellites with moderate orbital inclinations, plotted as a function of the smoothed 10.7-cm solar flux.

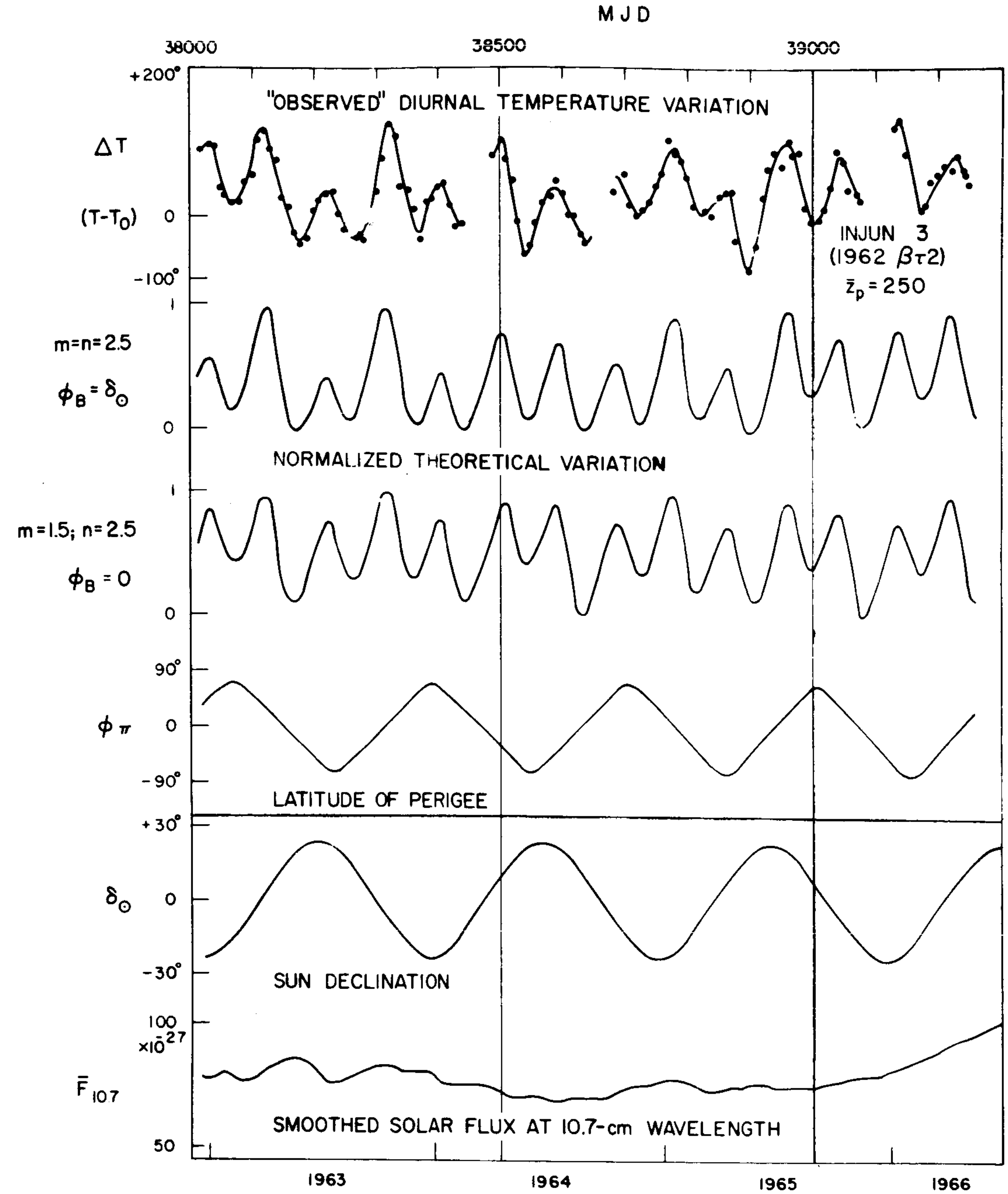

Figure 6. The diurnal temperature variation as derived from the drag of Injun 3. The observed variations (top) are compared with the normalized theoretical variations according to the models of J65 and Jacchia and Slowey (1966). Curves of the latitude of perigee, the declination of the sun, and the smoothed 10.7-cm solar flux are added for reference. MJD in the abscissa is the Modified Julian Day (Julian Day minus 2 400 000.5).

If we consider that during the interval covered by the diagram of Explorer 1 (Figure 1) T_0 had a range of 650°, we must conclude that the observed residuals are really quite small, and the near absence in them of a systematic trend is amazing. Actually, a small systematic trend is noticeable if we plot the values of T_m and T_M obtained from Explorers 1 and 8 and Vanguard 2 against $\overline{F}_{10.7}$. In this plot, which is shown in Figure 7, we have also drawn the straight lines corresponding to the minimum and maximum temperatures according to J65, i. e., $\overline{T}_0 = 418° + 3.°6\ \overline{F}_{10.7}$, and $\overline{T}_{max} = 1.28\ \overline{T}_0$. Although there is no reason why the relation between $\overline{T}_0$ and $\overline{F}_{10.7}$ should be linear, we would not attribute any physical reality to the curvature shown in Figure 5, inasmuch as the curvature is dependent on the relation between s and T_∞ in equation (5) of J65, and the present observational material allows considerable leeway in the form of that relation.

The amplitude of the diurnal variation is easier to determine than its phase. A plot of the observed temperature against LST could give the correct picture of the diurnal variation only if the satellite were in an equatorial orbit, and if the diurnal bulge were perpetually centered on the equator. In the general case, however, the satellite perigee will not cross the center of the bulge, so the maximum temperature will be recorded at a point either east or west of it, where the LST will differ from that of the bulge. The difference, of course, can be very large for high-inclination satellites; for satellites of low inclination, however, it will result in a scatter that may be considered tolerable. In addition to scatter we must, of course, expect systematic differences from this effect whenever there is commensurability between the cycle of the diurnal and of the latitude variation of the satellite. In spite of this drawback, we have determined the LST of the maximum and the minimum in the plot of temperature against LST for the three satellites that were used in the analysis of amplitudes. The averages for each satellite are:

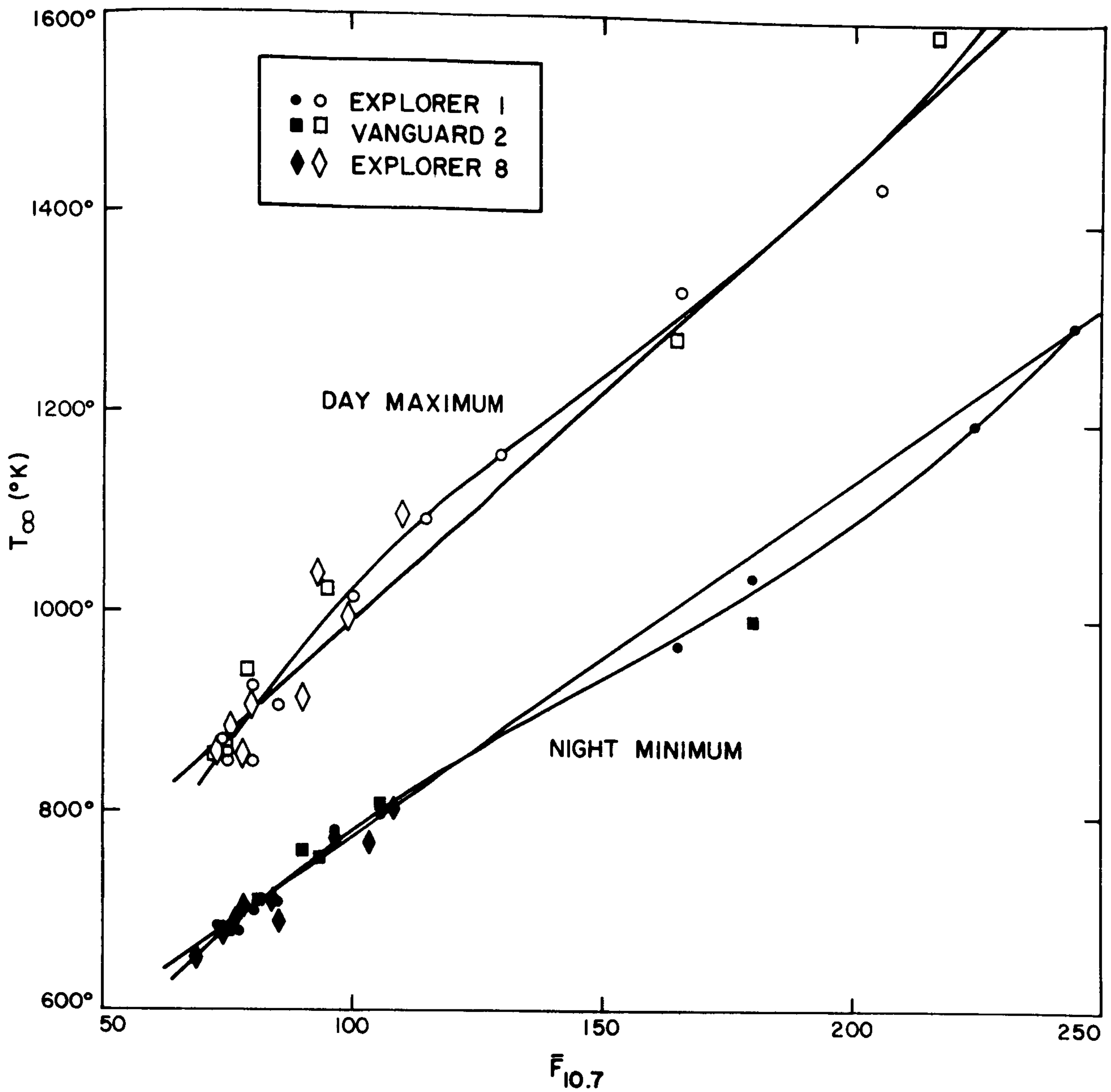

Figure 7. The extremes of the diurnal temperature variation as derived from the drag of three satellites with moderate orbital inclinations, plotted as a function of the smoothed 10.7-cm solar flux. The curves are an attempt to fit the observed data; the straight lines represent the relations of J65, i.e., $\overline{T}_0 = 418° + 3.°60\ F_{10.7}$, and $T_M = 1.28\ T_0$.

	Minimum	Maximum
Explorer 1	$3^{h}.7$	$14^{h}.3$
Vanguard 2	2.8	13.9
Explorer 8	3.3	15.0

The J65 model gives $3^{h}.8$ for the LST of the minimum and $14^{h}.2$ for the time of the maximum. These times are very close to those obtained from Explorer 1, the data on which should be considered more reliable in view of the low inclination of its orbit, the shortness of its diurnal cycle, and the large number of cycles that were observed.

4. RESULTS FROM HIGH-INCLINATION SATELLITES, SEASONAL VARIATIONS

Results from the two atmospheric-density satellites in near polar orbit (Explorers 19 and 24) have shown that the models of atmospheric variations obtained from low-inclination satellites do not represent adequately the variations at high latitudes. The discrepancy was first attributed to seasonal variations (Jacchia, 1966), but later it was suggested (Jacchia and Slowey, 1966) that the residuals could be explained assuming that the diurnal bulge is elongated in the directions of the poles and does not migrate in latitude with the seasons. Keating and Prior (1967) actually found that the best results could be obtained with a bulge that, around the solstices, peaked even farther from the sun, in the winter hemisphere! As explained in the paper by Jacchia and Slowey, the fact that the cycle of the latitude variation for these two satellites is very close to 6 months made it very difficult to decide whether the observed discrepancies were caused by a seasonal variation or by an imperfection in the global model of the diurnal variation.

The announcement by Jacobs (1967) that low satellites in polar orbit exhibit a 24-hour oscillation, which he interpreted as caused by a heat bulge centered around the magnetic pole, led us to investigate whether additional heating in high geomagnetic latitudes could explain the discrepancies shown by Explorers 19 and 24. We experimented with various models in which the heat bulge was made successively sharp and diffuse, single-peaked and ring-shaped; in the last case, we even changed the diameters of the ring and the latitude of its center. None of these experiments led to satisfactory results, and we convinced ourselves that, if the discrepancies were caused by a heat bulge in high latitudes, this bulge had to be there only during the winter months and must disappear in summer. Experiments with such a seasonal bulge gave good results and have led us to conclude that the bulge is unconnected with geomagnetic activity. We cannot confirm the results obtained by Jacobs; if the large 24-hour oscillation he observes in the motion of satellites were caused by drag, it would imply the existence above the magnetic pole of a phenomenal atmospheric bulge that, apart from being unreasonably pronounced, could not fail to appear in the drag of Explorers 19 and 24. We feel that the origin of the 24-hour oscillation must be sought in an effect other than atmospheric drag.

Explorer 19 and Explorer 24 are balloons 12 feet in diameter, and the effect of radiation pressure on them is very great. As a consequence, their orbital eccentricity undergoes large oscillations, which are reflected in a variable perigee height. The perigee height of Explorer 19 has fluctuated between 595 and 695 km during the 3 years covered by the observations, and that of Explorer 24 between 526 and 612 km in a 2-year interval. As was previously mentioned (Jacchia and Slowey, 1966), hydrogen becomes important above 650 km when the temperature drops below 700°; thus, any uncertainty in its concentration would affect the temperatures derived from densities in the case of Explorer 19 when its perigee is high and temperatures are low. Since the density of hydrogen, contrary to that of helium and atomic oxygen, increases with decreasing temperature, we find that, according to the J65 model, the total density at 700 km reaches a minimum around 600°. This means that at low exospheric temperatures the density becomes insensitive to temperature, and therefore, the determination of temperatures from densities becomes less accurate; actually, a density lower than the minimum would give an imaginary temperature. Over most of the interval covered by the observations, the perigee of Explorer 17 was below 700 km, and the exospheric temperature was above 700°, so there was little danger involved in deriving temperatures from the model, except for a period of 2 or 3 weeks in July 1965 and July 1966. In any case, to avoid trouble, we computed density rather than temperature residuals for both Explorer 19 and Explorer 24.

In Section 2, we found that at low and moderate latitudes the J65 model of a nonelongated diurnal bulge migrating with the subsolar point is in agreement with observations. A look at Figure 6, in which the diurnal variation has been isolated in the data from the high-inclination (70°), low-perigee

(250 km) satellite Injun 3, shows that this model of the bulge is valid also at high latitudes. We have, therefore, computed density residuals for Explorer 19 and Explorer 24 using the J65 model of the diurnal variation. Inspecting the plots of these residuals, we find that they are largest, and positive, when the satellite perigee passes near a pole around the winter equinox; no comparable negative residuals occur when it approaches the poles in summer. We have tried to represent the residuals by adding to the computed temperatures the term

$$\Delta_s T = A\left[\left(\frac{\epsilon - \delta_\odot}{2\epsilon}\right)^B \sin^C\left(\frac{\pi}{4} + \frac{\phi}{2}\right) + \left(\frac{\epsilon + \delta_\odot}{2\epsilon}\right)^B \sin^C\left(\frac{\pi}{4} - \frac{\phi}{2}\right)\right] \quad , \qquad (3)$$

where A, B, and C are arbitrary constants, ϵ is the obliquity of the ecliptic, $\delta_\odot$ the declination of the sun, and ϕ the latitude. In this model a residual $\Delta_s T$ has two components: one, corresponding to the first term in the bracket, comes from the heating of the north polar region, and the other from the south polar region. The first term reaches a maximum in December, and the second in July. In this manner, we create a density bulge in the winter hemisphere; A determines its magnitude, B its duration, and C its extent in latitude.

For the higher of the two satellites, Explorer 19, we found by trial and error that the residuals can be fitted remarkably well by equation (3), using the following values of the constants:

$$A = 180°, \; B = 2.5, \; C = 6 \quad .$$

The result of this fitting is shown in Figure 8. For Explorer 24 we find that, while we can still use the same values of B and C, we have to reduce A to about one-half, to 90° ; but, in spite of the fact that the residuals for this satellite are a little smaller than those of Explorer 19, the fit is less satisfactory (see Figure 9). And finally, for the low-orbiting Injun 3, we find no trace of any winter bulge. Thus the amplitude A of the winter bulge appears to be a function of height:

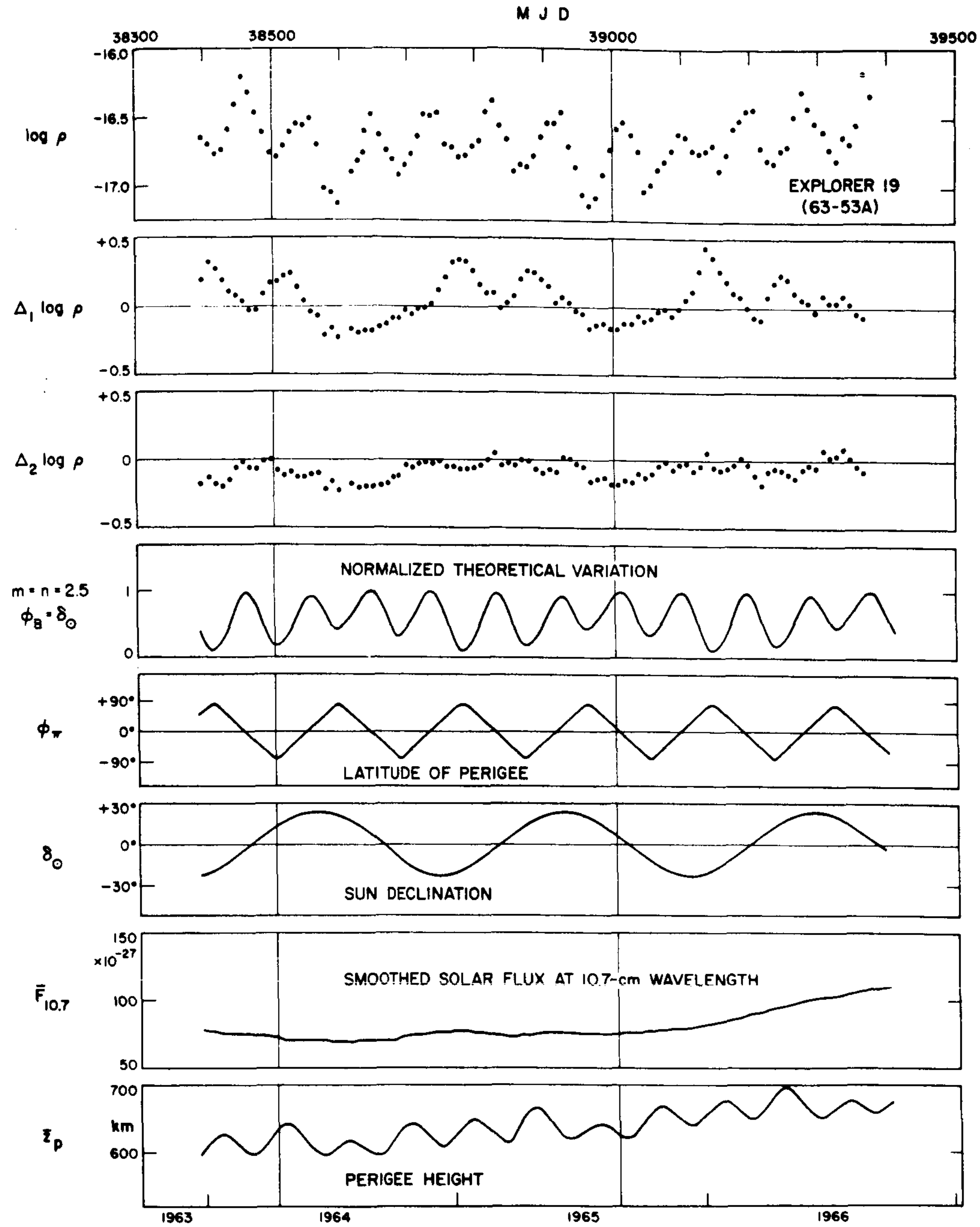

Figure 8. Data from Explorer 19: observed densities (top strip) and residuals $\Delta_1 \log \rho$ from the J65 atmospheric model (second strip). The third strip shows final residuals $\Delta_2 \log \rho$ after applying corrections for seasonal-latitudinal variation according to equation (3), with A = 180°. Auxiliary data are shown in following strips. MJD in the abscissa is the Modified Julian Day (Julian Day minus 2 400 000.5).

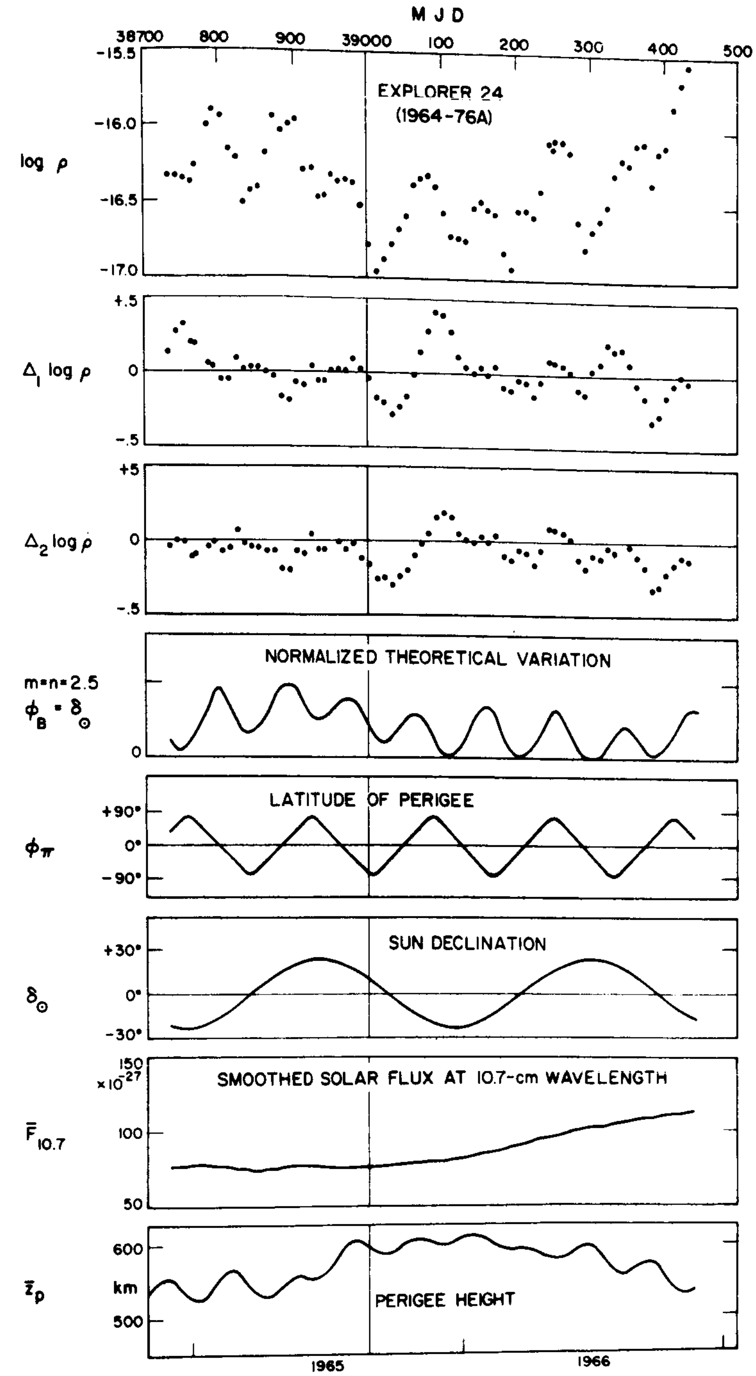

Figure 9. Data from Explorer 24: observed densities (top strip) and residuals from the J65 atmospheric model (second strip). The third strip shows final residuals Δ_2 log ρ after applying corrections for seasonal-latitudinal variation according to equation (3), with A = 90°. Auxiliary data are shown in following strips. MJD in the abscissa is the Modified Julian Day (Julian Day minus 2 400 000.5).

at $z \approx 650$ km $A = 180°$

at $z \approx 550$ km $A = 90°$

at $z = 250$ km $A = 0°$.

If the winter bulge were of thermal origin, A should be independent of height. We must, therefore, conclude that the bulge has a different origin.

An inspection of Table 3 will show that the value of A seems to be roughly proportional to the relative helium content of the atmosphere. For temperatures of 700° to 800°, such as were prevalent during the years from 1963 to 1966, helium accounted for approximately 40 to 70% of the atmosphere at the height of Explorer 19, for 10 to 50% at the height of Explorer 24, and for a negligible fraction at the height of Injun 3. The concentration of helium in the upper atmosphere is very sensitive to a change in the height of the turbopause; according to Kockarts and Nicolet (1962), a decrease of only 5 km is sufficient to increase helium concentrations by a factor of 2. Recently, Cook (1966) has invoked such a mechanism to explain the abnormally large semiannual density variation at the height of 1100 km derived from the drag of Echo 2.

Table 3. Helium content of the atmosphere (percentage of mass)

z (km) \ T(°K)	600°	700°	800°	900°
400	0.08	0.04	0.02	0.01
500	0.38	0.20	0.10	0.06
600	0.63	0.56	0.33	0.18
700	0.60	0.80	0.67	0.45
800	0.50	0.84	0.86	0.74

It would appear that a seasonal variation in the height of the turbopause could explain the formation of a winter helium bulge that would account for all the features observed in the data of Explorer 19 and Explorer 24, including the less satisfactory fit of equation (3) to the latter satellite. The perigee heights of both satellites underwent large fluctuations, exploring regions of different helium concentrations, but the variation of helium content was much greater for Explorer 24. It should be clear that, if we have to deal with a density bulge caused by an excess of helium, the thermal bulge of equation (3) will fit the observations relatively well only if there is no change of relative helium content with height. If our explanation is correct, a better approximation should be obtained by introducing a variation in the partial density of helium alone as a function of latitude and season. While this procedure is simple in principle, it requires a considerable alteration in the program we are using now to analyze atmospheric densities; in the meantime, we feel justified in offering our results in the present form.

5. ACKNOWLEDGMENTS

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BIOGRAPHICAL NOTES

LUIGI G. JACCHIA received his doctorate from the University of Bologna in 1932. He continued working with the university as an astronomer at its observatory.

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Mr. Slowey came to SAO as a physicist in 1956 and was concurrently a lecturer in General Education at Harvard College until 1960. Since 1959 he has been an astronomer for SAO and, since 1961, a scientific consultant for IBM Corporation. His fields of concentration include orbits of artificial satellites and the earth's upper atmosphere.