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THE SHAPE AND LOCATION OF THE DIURNAL BULGE IN THE UPPER ATMOSPHERE

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THE SHAPE AND LOCATION OF THE DIURNAL BULGE IN THE UPPER ATMOSPHERE[1]

L. G. Jacchia[2] and J. Slowey[3]

ABSTRACT

An analysis of the drag of the two balloon satellites in near-polar orbits launched in the course of the last 2 years (Explorers 19 and 24) has afforded the opportunity of our studying the distribution of density and temperature at high latitudes, and has led to strange results concerning the shape and behavior of the diurnal atmospheric bulge. The picture of a bulge in which temperature and density decrease nearly symmetrically in all directions from a location that follows the latitude migrations of the subsolar point would seem to need considerable revision, at least for heights above 500 km. It appears that the bulge is noticeably elongated in the north-south direction and that its center does not move much from the equator — a picture that is reminiscent of that of the ion density distributions in the F_2 layer. Some possible implications are discussed, as well as sources of error that may have affected these results.

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1 This work was supported in part by Grant No. NsG 87-60 from the National Aeronautics and Space Administration.

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1. THE DIURNAL BULGE

A day-to-night variation in the density of the upper atmosphere was recognized in early investigations of satellite drag (Jacchia, 1959; Priester and Martin, 1960; Wyatt, 1960). In the sunlit hemisphere the density is greater than it is in the dark hemisphere, so the effect of the diurnal variation is to produce an atmospheric bulge, which is often referred to as the "diurnal bulge." With the discovery of the phenomenon it was established that densities peak at 2 p.m. local solar time. Jacchia (1960) assumed at first that the density in the bulge decreased symmetrically in all directions from its center, and that this center migrated north and south of the equator following the migrations of the subsolar point.

As more satellite drag data became available, a moderate asymmetry in the bulge became evident. It was established that the morning minimum occurs around 4 a.m., so that the decay in density from the center of the bulge at 2 p.m. is somewhat steeper on the morning side than on the evening side. This east-west asymmetry was incorporated in a more sophisticated model of the bulge (Jacchia, 1964a), in which formulas are given for the diurnal variations of the exospheric temperature above any point on the globe; densities can then be derived from multitemperature atmospheric models (Jacchia, 1964b). In the absence of any evidence to the contrary, this new model retained the assumption that the center of the bulge migrates in latitude, being always located at the same latitude as the subsolar point. Although the new model made it possible to modify the shape of the bulge in the north-south as well as in the east-west direction, no use was made of this feature because the lack of drag information from high-inclination satellites had left the polar regions of the upper atmosphere largely unexplored.

Densities derived last year from the drag of the Explorer 19 and the Explorer 24 satellites (inclinations 79° and 81°, respectively) showed that in the polar regions the temperature of the upper atmosphere exhibits seasonal departures from those given by the new bulge model (Jacchia, 1964a, b). These departures were first interpreted as true seasonal variations; it now appears, however, as we shall see, that they can be explained by a north-south elongation of the bulge and by the assumption that the center of the bulge does not move much from the equator. Such changes in the shape and location of the bulge can be taken into account in Jacchia's (1964a) model of global temperature variations by simply modifying two parameters. In order to see how this is done, we have to reexamine the features of the model in some detail.

2. THE MODEL OF GLOBAL TEMPERATURE VARIATIONS

We assume that the lowest daily minimum temperature T_0 is reached at latitude $-\phi_B$, where ϕ_B is the latitude of the center of the bulge, i.e., the point where we have the highest daytime maximum temperature $(1 + R)T_0$. Let us further assume that for any other latitude ϕ the daytime maximum temperature T_D and the nighttime minimum temperature T_N can be represented by the expressions

$$T_D = T_0(1 + R \cos^m \eta) \quad ,$$

$$T_N = T_0(1 + R \sin^m \theta) \quad , \tag{1}$$

where

$$\eta = \frac{1}{2} |\phi - \phi_B| \quad ,$$

$$\theta = \frac{1}{2} |\phi + \phi_B| \quad .$$

As can be seen, the exponent m controls the temperature decay from the center of the bulge in the north-south direction.

We shall represent the diurnal variation at a given latitude ϕ by

$$T = T_N(1 + A \cos^n \tfrac{1}{2}\tau) \quad , \tag{2}$$

where

$$A = \frac{T_D - T_N}{T_N} = R\,\frac{\cos^m \eta - \sin^m \theta}{1 + R \sin^m \theta} \quad ,$$

and τ is a function of local solar time. If we make $n = m$ and $\tau = H + \beta$, where H is the hour angle of the sun and β a constant, we shall have a circular-symmetric bulge located on a meridian where the hour angle of the sun (counted from culmination) is $-\beta$. If we want to introduce an asymmetry between the morning and the evening sides, we must add a periodic term in the expression for τ; we can then write

$$\tau = H + \beta + p \sin (H + \gamma) \qquad (-\pi < \tau < \pi) \quad . \tag{3}$$

Here the parameter p controls the degree of asymmetry, while by a proper choice of γ we can make the temperature rise faster than the decline or vice versa, or even make the maxima and minima sharper or shallower. The sharpness of maxima and minima, however, is more effectively controlled by the exponent n, especially when γ is used to introduce an east-west asymmetry. It should be noted that, when $p \neq 0$, the introduction of a value of γ different from zero will shift the hour of the maximum and minimum temperatures, so that β and γ must be varied simultaneously in any curve fitting by equation (3).

3. NUMERICAL PARAMETERS FOR THE MODEL

In Jacchia's (1964a) paper the following numerical values had been adopted: $\beta = -45°$, $\gamma = +45°$, $p = 12°$, $m = n = 2.5$. The value of R had been taken as 0.30 to fit Nicolet's density profiles, but was later reduced to 0.28 for use with Jacchia's (1964b) density models. The choice of $m = n$ made the bulge nearly circular-symmetrical in the vicinity of the center, in spite of a moderate east-west asymmetry coming from a morning temperature rise faster than the evening decline. The local solar times of the temperature minimum and maximum resulting from the above parameters are 3^h47^m a.m. and 2^h13^m p.m., respectively. It had also been assumed that $\phi_B = \delta_\odot$, where $\delta_\odot$ is the declination of the sun.

The values of p and γ are fairly well established on the basis of numerous density and temperature profiles determined from low-inclination satellites as their perigees crossed the diurnal bulge; the different steepness of the ascending and the descending branches of the curve can be clearly seen in the plots against time of temperature derived from satellite drag (Jacchia and Slowey, 1965). Another feature that emerges from these plots is the slightly greater sharpness of the maxima compared to the minima, which indicates a value of n somewhat greater than 2 (for which value maxima and minima would be equally sharp), but definitely much smaller than 3. The uncertainty in the adopted value $n = 2.5$ should not exceed 0.2.

While n appears to be a well-determined parameter in the 1964 model, the same cannot be said of m, for whose evaluation high-inclination satellites are necessary, but were not available at the time.

In the absence of better information it was assumed that $m = n$. This did not seem to be too bad a hypothesis under the assumption of direct solar heating, because, roughly speaking, it made the temperature a function of the zenith angle of the sun (with a 2-hour lag). It was expected, however, that departures from such a model would be found at high latitudes, especially around the solstices, owing to the excess heating during the long polar days and the excess cooling during the polar nights.

In retrospect we can say that a first intimation that m might be smaller than n came from a paper by Bourdeau, Chandra, and Neupert (1964), in which a comparison was made between extreme-ultraviolet measurements by the OSO-1 satellite and exospheric temperatures deduced by Jacchia and Slowey (1963) from the drag of the Explorer 9 satellite. To eliminate the effect of the diurnal variation, Bourdeau and collaborators used a formula given by Jacchia (1964c) for a circular-symmetrical bulge:

$$T = T_0 (1 + 0.33 \cos^r \frac{\psi'}{2}) \quad , \tag{4}$$

where T_0 has the same meaning as in equation (1), and ψ' is the angular distance from the center of the bulge, which was supposed to be located at a point 30° east in longitude from the subsolar point. It was found that the best results were obtained using for r a value between 1 and 2. The OSO-1 measurements covered a little over 2 months, from March to May 1962. During that time, owing to its very small motion in right ascension relative to the sun (0.°15 a day), the perigee of Explorer 9 was moving essentially in a north-south direction with respect to the bulge, with a total range of 68° in latitude. Thus, the value of r found by Bourdeau et al. should very nearly correspond to m in equation (1).

The effect of changing m in the model of the bulge is depicted in Figure 1, where isotherms are shown for the case of $T_0 = 1000°$, $\phi_B = 0°$, $R = 0.28$, and $n = 2.5$. The three maps are for $m = 2.5$, $m = 1.5$, and $m = 1.0$, respectively.

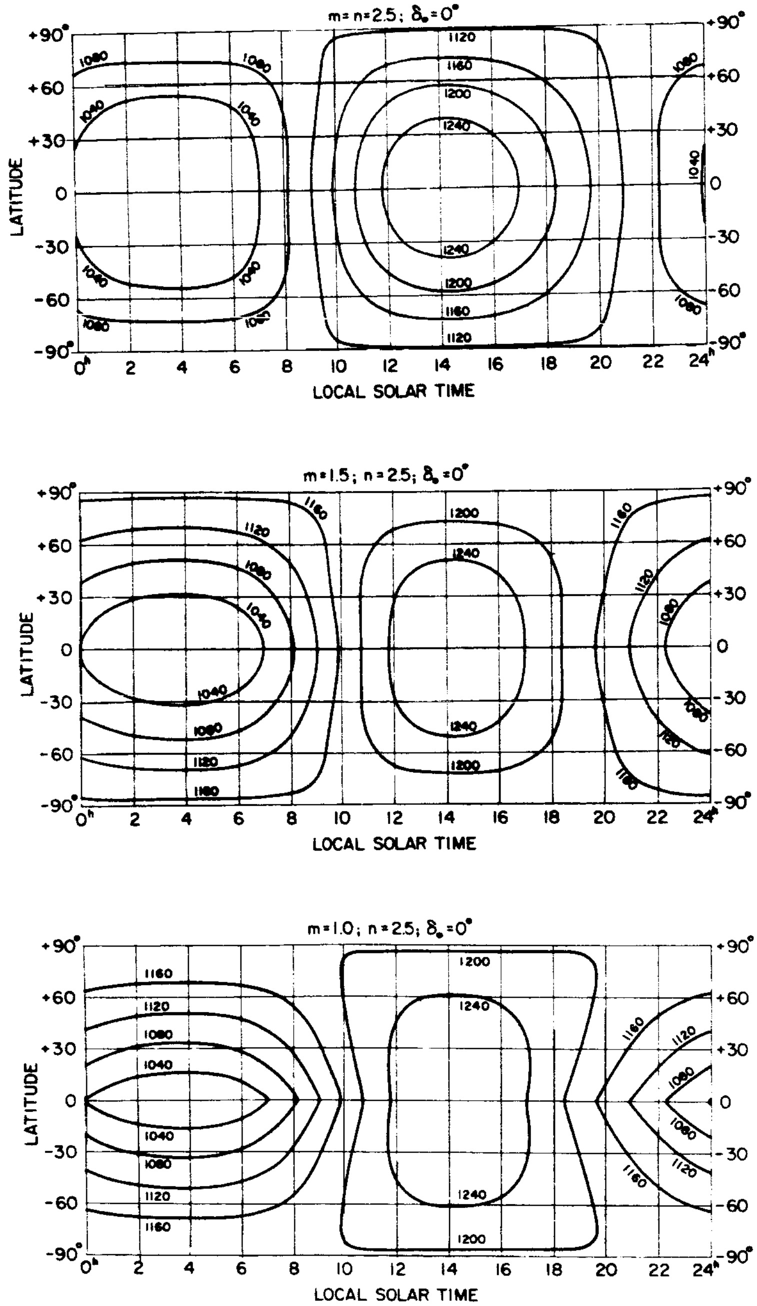

Figure 1. Upper-air temperature distribution according to equation (2), using three different values of m.

4. RESULTS FROM HIGH-INCLINATION SATELLITES

Explorer 19, a 12-foot balloon satellite launched on 19 December 1963 for the exploration of the polar atmosphere, has an orbit with an inclination of 78°.6 and a perigee height of 600 km. It showed soon through its drag analysis that the densities derived for high latitudes departed considerably from our model (Jacchia, 1964a, b) of atmospheric variations. The perigee of the satellite moves in latitude with a period of 183.7 days, which differs by only 1 day from a half year. In such conditions the interpretation of the residuals becomes hazardous, since it is difficult to separate a true seasonal effect from residuals left by an inadequate model of the diurnal variation. The only other high-inclination satellite on our observing list at that time, Injun 3 (1962 $\beta\tau 2$), did not help much to improve the situation, because its perigee moves in latitude with a period of 325 days, or nearly a year—with the result that for 2 years it reached it maximum latitude (70°), whether north or south, always in the vicinity of the winter solstice of the respective hemisphere.

Explorer 24, another 12-foot balloon satellite, was launched as a sequel to Explorer 19 on 21 November 1964 in an orbit with an inclination of 81°.4 and a perigee height of about 550 km. Its perigee moves in latitude with a period of 166.4 days, which differs a little more from a half year than that of Explorer 19, but its launching was timed for the perigee to arrive in the north polar regions near the winter solstice, just as was the case of Explorer 19. Consequently during its first year of performance Explorer 24 has closely duplicated the results of Explorer 19. All this explains why we had to allow considerable time to elapse before interpreting the data from the two high-inclination Explorers, in spite of the inevitable pressure to make results from research satellites available to the scientific community. Actually, we did not wait long enough, as evidenced by the premature announcement of a latitude-dependent seasonal effect (Jacchia, 1965).

Results obtained from the drag analysis of the Explorer 19 and Explorer 24 satellites are presented in Figures 2 and 3. The top strip of each figure shows 10-day means of the exospheric temperatures derived from the atmospheric densities[2] using Jacchia's (1964b) model. To minimize the effect of magnetic storms, which tend to confuse the picture, in taking the means we gave each individual observation a weight proportional to the interval of differentiation of the positional data from which the accelerations (and thus the temperatures) were derived. The temperature diagrams for both satellites clearly show semiregular oscillations with a period of a little over 90 days, where maxima correspond to close approaches of the perigee to the center of the diurnal bulge (compare with the curve of ψ_0' given in the fifth strip, which represents the distance of the perigee from the point on the equator where the local solar time is 2 p.m.). The depth of the temperature minima around MJD 38600 and 38965 in the diagram of Explorer 19 may be a little exaggerated, owing to an excess of hydrogen in the atmospheric models. While for heights lower than 600 km and temperatures higher than 800° the uncertainty in the relative hydrogen content of the atmosphere does not affect the total density, it does so at the perigee height of this satellite when the temperature is low. In the models the variation of hydrogen with temperature is the one that would be expected in the course of the 11-year solar cycle; we cannot expect it to hold also for the diurnal variation. If we assume that there is little variation in the hydrogen density from day to night, the temperatures derived from the model will be too low when they dip below 750°. This is probably the explanation of the large negative residuals in Figure 3 around MJD 38600 and 38965.

[2]For a description of the method used in deriving air densities, see Jacchia and Slowey (1965). The effect of radiation pressure was taken into account.

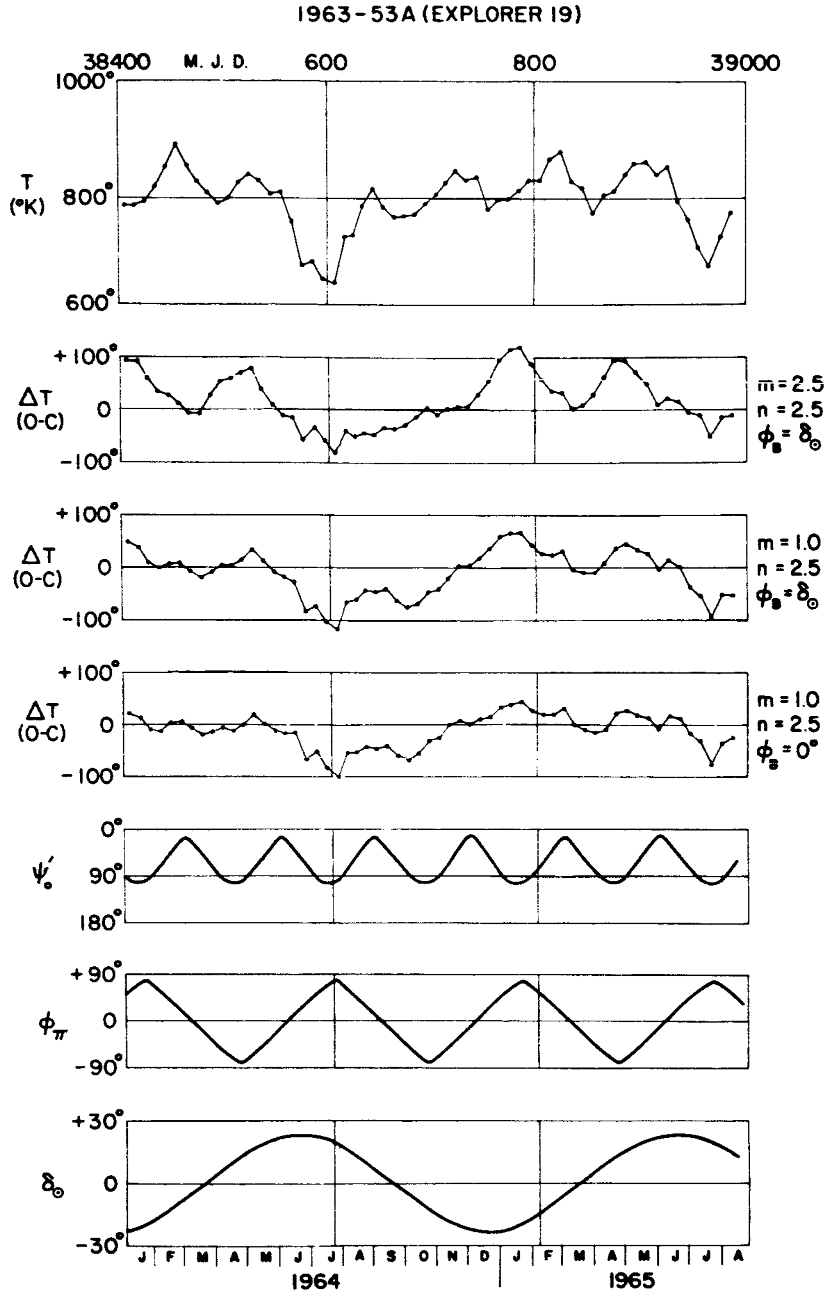

Figure 2. Exospheric temperatures from the drag of the Explorer 19 satellite (1963-53A) and residuals from the atmospheric model using different assumptions regarding m and ϕ_B. MJD in the abscissa is the Modified Julian Day (JD minus 2 400 000.5). The angle ψ_0' (see text), the latitude of perigee ϕ_π, and the declination of the sun ($\delta_\odot$) are plotted at the bottom of the diagram.

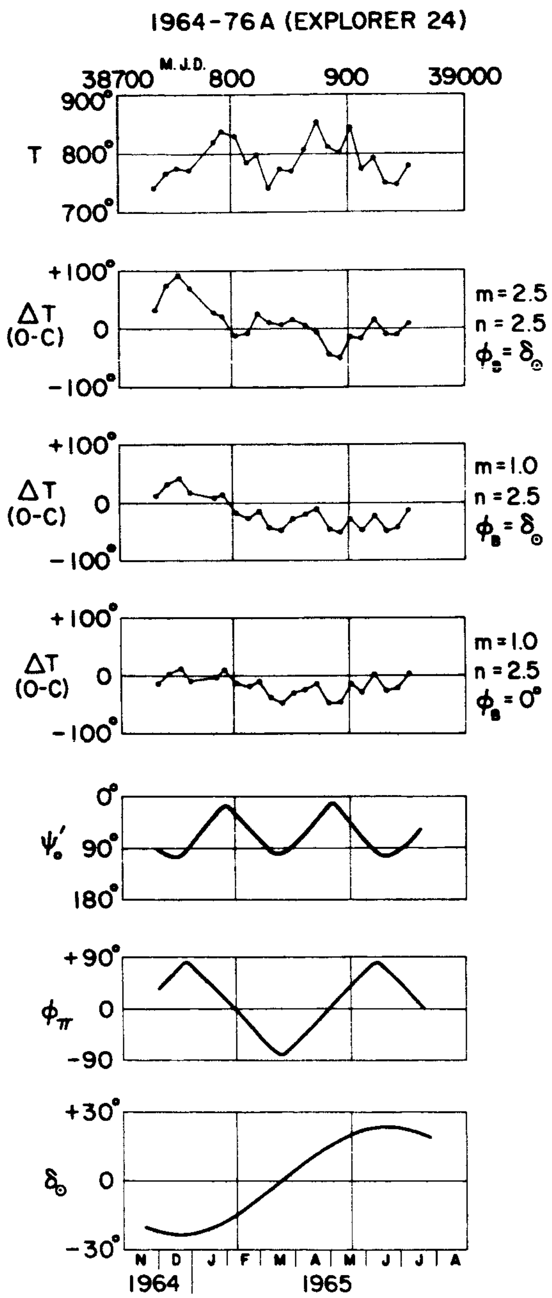

Figure 3. Exospheric temperatures from the drag of the Explorer 24 satellite (1964-76A) and residuals from the atmospheric model using different assumptions regarding m and ϕ_B. For further explanations see the legend to Figure 2.

The second strip shows the difference between the observed temperatures and those computed with the formulas given by Jacchia (1964b), using the observed data of the 10.7-cm solar flux and the geomagnetic index a_p, and taking into account the diurnal and the semiannual variations; the plot again shows 10-day weighted means of the temperature residuals. All the parameters of the diurnal-variation model were left unchanged, so we used $m = n = 2.5$ and $\phi_B = \delta_\odot$. In the curves of residuals we can again spot, although intermittently, oscillations with the same period of a little over 90 days, but their maxima and minima are strongly out of phase with respect to those of the temperature curves. The curve for Explorer 19 practically repeats itself after 365 days, reflecting the fact that after 1 year the perigee of this satellite comes back to almost the identical position with respect to the sun. The fact that the period discernible in the residuals is that of the motion of the perigee with respect to the bulge indicates that the model of the bulge used as a basis for the computed temperatures is in need of improvement. And, since systematic residuals of this size are not observed among low-inclination satellites (see Figure 4, which shows the same data for Explorer 1, inclination 33°), we must conclude that the picture of the bulge is rather satisfactory at low, but not at high latitudes. In other words, in equations (1) and (2) the exponent n should be acceptable, but not the exponent m.

Experiments with m have shown that the oscillations in the curve of residuals substantially decrease when m is made smaller in the case of high-inclination satellites; for low-inclination satellites no appreciable change in the residuals is observed when m is varied.

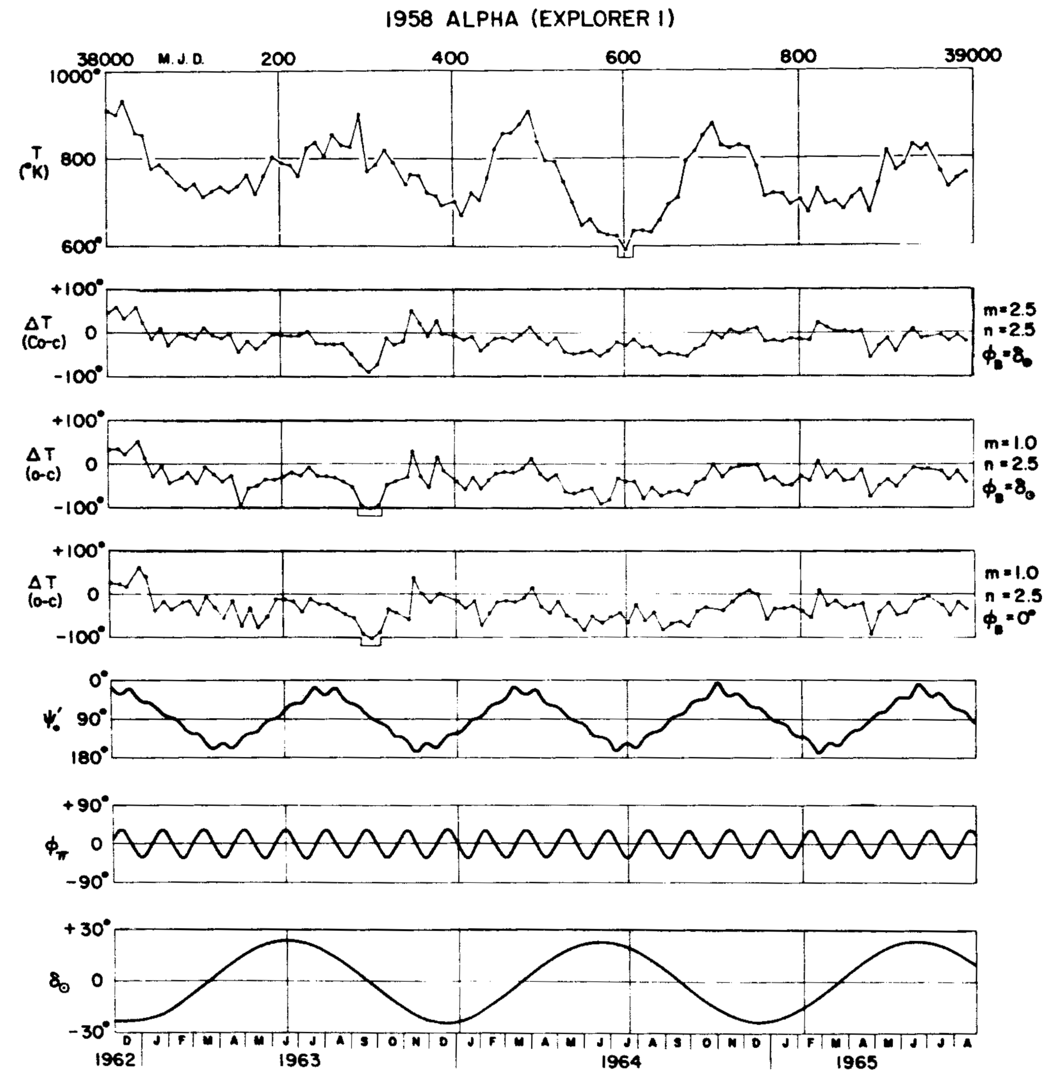

Figure 4. Exospheric temperatures from the drag of the Explorer 1 satellite (1958 Alpha) and residuals from the atmospheric model using different assumptions regarding m and ϕ_B. For further explanations see the legend to Figure 2.

This can be seen by one's comparing the second strip ($m = n = 2.5$) of Figures 2, 3, and 4, with the third strip in the same figures, which shows residuals for the case of $m = 1.0$, $n = 2.5$. It thus appears that the diurnal bulge is strongly elongated in the north-south direction.

Although greatly diminished in amplitude, the oscillations in the curves of residuals for Explorer 19 and Explorer 24 can still be discerned even when we make $m = 1.0$. A further decrease of m does improve the residuals for these two satellites a little, but only at the price of increasing the residuals for low-inclination satellites. This situation presumably arises from the fact that the bulge model, although remarkably flexible considering the small number of numerical parameters it uses, is not capable of absolute perfection in representing all the details of the diurnal variation. In particular, an elongation of the bulge in the north-south direction cannot be accomplished in the model without squeezing together, in the same direction, the isotherms around the nighttime minimum (see Figure 1), in a manner which becomes highly improbable if we make $m < 1$. A look at Table 1, which gives the average departure of the temperature residuals, irrespective of size, from their means, shows the worsening of the situation for Explorer 1 when m is decreased too much.

The great improvement that is obvious in the plot of residuals for Explorer 19 and Explorer 24 when m is changed from 2.5 to 1.0 is not apparent from Table 1, because the change in m, while decreasing the amplitude of the 90-day oscillations, does not do much to decrease the slower systematic variation, which gives the greatest contribution to the tabulated values. The amplitude of this slower oscillation can be decreased, however, by decreasing the range of ϕ_B, and Table 1 clearly shows a large drop in the tabulated mean residuals for the two high-inclination satellites when we make $\phi_B = 0°$; those of the low-inclination Explorer 1, on the contrary, are hardly affected by the change. From the last line of Table 1 we see that $\phi_B = 0°$ gives smaller residuals than $\phi_B = (1/2)\delta_\odot$. For $\phi_B = (1/2)\delta_\odot$ we computed only the case of m = 1.5, n = 2.5 for Explorers 19 and 24; a complete set of mean residuals for all cases was deemed to be an unneccessary luxury for the time being.

Table 1. Average departure of temperature residuals from their mean*

	m	n	1963-53A (Explorer 19) $i = 78\overset{\circ}{.}6$	1964-76A (Explorer 24) $i = 81\overset{\circ}{.}4$	1958 Alpha (Explorer 1) $i = 33\overset{\circ}{.}2$
$\phi_B = \delta_\odot$	2.5	2.5	45.8	28.5	42.8
	1.5	2.5	43.2	26.5	44.3
	1.0	2.5	41.8	25.3	47.7
$\phi_B = 0°$	2.5	2.5	35.5	23.4	43.2
	1.5	2.5	33.2	19.7	44.3
	1.0	2.5	33.2	18.9	46.9
$\phi_B = \frac{1}{2}\delta_\odot$	1.5	2.5	37.8	22.1	--

* The great improvement which is obtained by decreasing m, as evidenced by Figures 2 and 3, is not apparent from this table, for reasons explained in Section 4.

The conclusion is that the best results are obtained assuming that the diurnal bulge is elongated in the north-south direction ($1.0 < m < 1.5$, $n = 2.5$) and is permanently centered on the equator. We cannot exclude, of course, that the center of the bulge may move somewhat with the seasons, but the evidence is that this motion, if present at all, is much smaller than the full range of 47° of the subsolar point.

5. POSSIBLE IMPLICATIONS

If we assume that the diurnal bulge is the effect of heating in the region of EUV absorption (100-200 km), and that above that region very little additional heating occurs and the temperature is kept constant by heat conduction, we would expect the maximum daytime temperatures to occur near the latitude of the subsolar point; actually, at the solstices we could fairly expect the bulge to shift or protrude even further in the direction of the summer pole on account of the long polar days. It is difficult to reconcile an elongated bulge, stationary on the equator, with such a theory. It is true that the theory is quite unrealistic because it ignores the dynamic aspect of atmospheric heating, and a dynamic model for the upper atmosphere of a spherical, rotating earth presents such formidable difficulties that no attempt at constructing one has had any success so far.

A resemblance between the distribution of exospheric temperatures according to Jacchia's (1964a) model and the ion densities in the F_2 layer was pointed out by King et al. (1964), who invoked a mutual interaction between ions and neutral particles, involving mass motion, to explain the anomalous behavior of the F region. In a paper on the same subject King and Kohl (1965), after computing the magnitude of the drag exerted by F-region ions on neutral atmospheric particles, concluded:

> ... It appears from the foregoing discussion that the force which controls the movement of the atmosphere is the ion drag. The movement of charged particles is determined by the Earth's magnetic field, of course, and it has been shown here that, although the number of ions is much smaller than the number of neutral air atoms

> in the F-region, the movement of air is also controlled by the Earth's magnetic field as a consequence of the drag exerted by the ions on the moving atmosphere....

Whether such atmospheric motions, if they prove to be real, can radically alter the temperature distribution in the upper atmosphere remains to be seen. It is interesting, however, to note that the contour maps of critical frequencies in the F_2 layer show a double maximum in midafternoon, centered on the magnetic equator; more correctly, a trough along the magnetic equator separates two distinct maxima located at roughly the same longitude. If the resemblance between the ion-density and the temperature distributions is to be considered more than just coincidental, and if we assume that the isotherms deduced from satellite drag are a smoothed version of the ion-density contours, we do obtain a diurnal bulge centered on the geographic equator and elongated in the north-south direction. The elongation comes from a blurring of the double maximum and from the swinging back and forth of the bulge in the north-south direction with a 24-hour period and a range of 22°, as it follows the magnetic equator.

Since there is no evidence other than a mere resemblance between the ion and temperature distributions to justify such a picture, we do not wish to do more than just offer it as a possibility to be explored. We do feel, however, that if the bulge has to be anchored to the equator, it must prove necessary for us to look for ions guided by the magnetic field of the earth, to do the work. It is true that most of the heating occurs well below the F_2 layer; there remains, however, the possibility that in the F_2 layer the heat may be redistributed through mass motion controlled by ion drag. If this hypothesis is correct, we might expect that the shape and location of the bulge undergo a change with height as we proceed from the thermosphere to the F_2 layer; in other words, ϕ_B and m would be functions of height — or better, of the density. Satellites with low perigee, high inclination, high eccentricity, and low area-to-mass ratio (to ensure long lifetimes) are needed to prove or disprove this point. A reexamination of the Injun 3 data, now under way, seems to indicate that the hypothesis might be correct, but data from more satellites are necessary.

Although the mechanism through which the atmosphere is heated during geomagnetic disturbances is not known, the existence of such heating and the large day-to-day temperature variations that accompany the most minute changes of the geomagnetic field show that the presence of ions in the earth's magnetic field is an important controlling factor of the upper-air temperature. The semiannual temperature variation also lacks a good explanation; meanwhile the equally mysterious semiannual variation in height of the F_2 layer, exactly in phase with the temperature variations as pointed out by W. Becker (see Jacchia, 1965), again points in the same direction. It looks as though the role of the magnetic field of the earth in controlling the temperature of the upper atmosphere might be considerably more important than was supposed heretofore.

We want to end with a word of caution. The present results have been obtained from two balloon satellites in similar orbits. The effect of solar radiation pressure on the drag of these satellites competes with that of the atmosphere and, although we have taken this effect into account in deriving atmospheric drag, we must be aware of the uncertainties that can derive from it. In addition, we must remember that at the perigee heights of these satellites there occurs, in the observed temperature range, a rapid transition from atomic oxygen to helium; even hydrogen becomes nonnegligible for Explorer 19 at the lowest temperatures. Since the concentration of helium and hydrogen cannot be considered to be well established, we must expect some uncertainty from this source in the computed temperatures. On the other hand, Satellite 1959 Alpha 1 (Vanguard 2), with a perigee height of 565 km, intermediate between those of Explorer 19 and Explorer 24, gives no anomalous results concerning the diurnal variation. Since the orbital inclination of this satellite is only 33°, we feel we are justified in believing that the anomalies of the two Explorers at high latitudes are real. In any case, a long-lived, high-inclination satellite with a lower perigee height (300 to 400 km) would be desirable to confirm the present results.

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