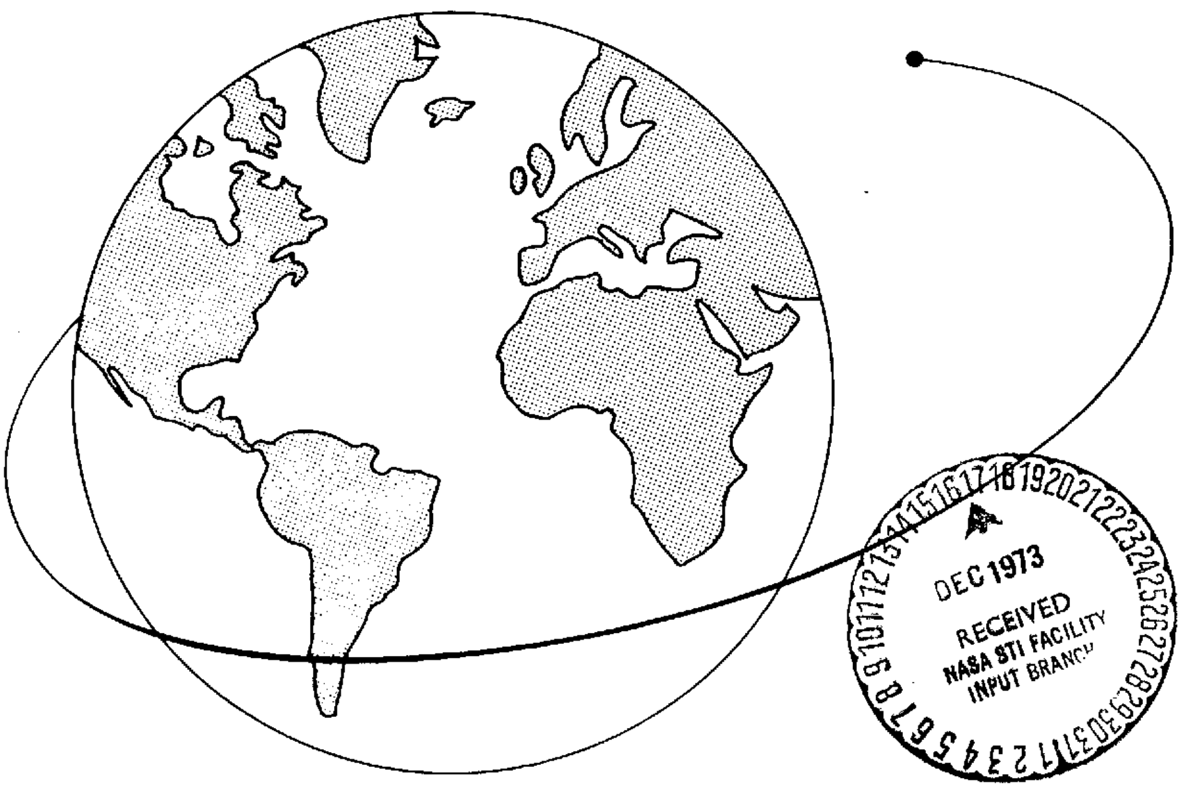
VARIATIONS IN THERMOSPHERIC COMPOSITION: A MODEL BASED ON MASS-SPECTROMETER AND SATELLITE-DRAG DATA

L. G. JACCHIA



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ABSTRACT

The seasonal-latitudinal and the diurnal variations of composition observed by mass spectrometers on the OGO 6 satellite are represented by two simple empirical formulae, each of which uses only one numerical parameter. The formulae are of a very general nature and predict the behavior of these variations at all heights and for all levels of solar activity; they yield a satisfactory representation of the corresponding variations in total density as derived from satellite drag. It is suggested that a seasonal variation of hydrogen might explain the abnormally low hydrogen densities at high northern latitudes in July 1964.

RESUME

Les variations saisonnières-latitudinales et diurnes de la composition observées par les spectromètres de masse du satellite OGO 6 sont représentées par deux formules empiriques simples, n'utilisant chacune qu'un seul paramètre. Ces formules sont de nature très générale et prédisent le mode de variation à toutes les hauteurs et à tous les niveaux d'activité solaire; elles fournissent une représentation satisfaisante des variations correspondantes de la densité totale dérivée du freinage du satellite. On suggère qu'une variation saisonnière de l'hydrogène pourrait expliquer les densités d'hydrogène anormalement faibles observées, en juillet 1964, aux hautes latitudes septententrionales.

КОНСПЕКТ

Сезонно-широтные и суточные изменения состава которые наблюдались масс-спектрометром на спутнике OGO 6 выражены двумя простыми эмпирическими формулами, каждая из которых употребляет только один цифровой параметр. Формулы являются очень общего типа и предсказывают ход этих изменений на всех высотах и на всех уровнях солнечной деятельности; они дают удовлетворительное представление о соответствующих изменениях общей плотности которая выводится из драга спутника. Предлагается что сезонное изменение водорода может объяснить анормально низкие уровни водорода на высоких северных широтах в июле 1964 г.

VARIATIONS IN THERMOSPHERIC COMPOSITION: A MODEL BASED ON MASS-SPECTROMETER AND SATELLITE-DRAG DATA

L. G. Jacchia

1. THE PROBLEM

One of the most remarkable discoveries in upper-atmosphere physics has been the finding, through the analysis of mass-spectrometer data on the OGO 6 satellite [Hedin et al., 1972, 1973], that all the known types of thermospheric variation are accompanied by large variations in composition that are not accounted for by static-diffusion models, clearly indicating the presence of large-scale convection phenomena. The importance of large-scale thermospheric circulation on atmospheric composition had been foreseen by Johnson [1964]: "Descending currents over the winter polar regions are to be expected, with a resulting enrichment of the oxygen content of the ionosphere there. There must be corresponding upward currents, either over the summer polar regions, low latitudes, or both; the nitrogen content of the atmosphere at ionospheric levels ought to be enriched where this occurs, due to a selective loss of oxygen by outflow at higher levels." Large seasonal-latitudinal variations of helium were discovered in 1967–1968 from mass-spectrometer, optical, and satellite-drag data; since it was difficult to think of the behavior of helium as being unique, similar variations should clearly have been expected for the other atmospheric constituents. The OGO 6 results have shown that changes in composition occur not only

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as a result of seasonal variations, but also wherever large-scale thermospheric motions are involved: in the diurnal and semiannual variation, as well as in the geomagnetic effect.

Hedin et al. [1972, 1973] constructed an *ad hoc* empirical model to represent the OGO 6 data on N_2, O, and He at 450 km; all the known and expected variations were expressed by means of spherical harmonics involving a set of more than 100 numerical coefficients. Although such a model adequately represents the observations within a narrow range of height and solar activity, safe extrapolation to other heights and levels of solar activity cannot be expected. A comprehensive, theoretical three-dimensional model of atmospheric variations formulated by Volland and Mayr [1972] is able, in principle, to account for some of the features revealed by the OGO 6 satellite [Mayr and Volland, 1972], but the complexity of the formulation and our present ignorance of many of the input quantities make its practical application very difficult. The various models produced by Jacchia [1965, 1970, 1971], which are widely used for comparison and prediction purposes, were mainly based on satellite-drag data and represent rather well the observed variations in total density; large discrepancies, however, show up in the comparison of the models with the OGO 6 composition data and with 6300 Å airglow temperature measurements [Blamont et al., 1973], also obtained from instruments aboard the OGO 6 satellite. In view of the demand for practical models that can adequately represent all atmospheric parameters, I feel justified in presenting a simple empirical solution that may help fill the void until something better is found.

2. CONDITIONS FOR A MODEL

I shall start by listing the observational conditions that our model must satisfy.

1. According to both the airglow temperature measurements and the composition data, the maximum diurnal temperature occurs at the equator at the time of equinoxes but drifts to very high latitudes near the summer pole (possibly to the pole itself) at the time of solstices.

2. N_2, O, and He show large annual variations, with maxima at the poles at the time of solstices. For these constituents, Table 1 lists values of $\Delta_1 \log_{10} n$, the logarithm of the ratio of the number density at the summer pole to the global mean, at a height of 450 km, as given by Hedin et al. Part of the seasonal variation in density is caused by the seasonal variation of temperature, which changes the scale height of the individual species. Subtracting the effect of temperature, we are left with $\Delta_2 \log_{10} n$; this represents the intrinsic seasonal variation, which is not accounted for by temperature changes. To compute the correction, we have used a global mean asymptotic ('exospheric') temperature of 1000 K and a corresponding temperature at the summer pole of 1140 K. We shall assume that at the winter pole, $\Delta_2 \log_{10} n$ has the same value with the opposite sign.

Table 1. Total and intrinsic density excesses at the summer pole (z = 450 km).

Constituent	$\Delta_1 \log_{10} n$	$\Delta_2 \log_{10} n$
N_2	+0.74	+0.24
O	+0.11	-0.15
He	-0.55	-0.60

3. According to rocket-borne mass-spectrometer data, the seasonal variation of He at 130 to 150 km is already large [Kasprzak et al., 1968; Krankowski et al., 1968], comparable to that at 450 km, while the variation of N_2 is quite small. Drag data from low satellites in polar orbit also exclude large seasonal variations of N_2.

4. Densities from satellite-drag data [Jacchia, 1971; Keating et al., 1973] show that at 600 to 800 km, the seasonal variation of helium is somewhat smaller than that shown in Table 1, with $\Delta_2 \log_{10} n$ of the order of -0.35 or -0.4 (accounting for some degree of smoothing inherent in the drag method).

5. The curves of the diurnal variation of N_2, O, and He are phase-shifted with respect to each other. According to Hedin et al., the maximum density at 450 km occurs at $14^h.9$ local solar time (LST) for N_2, at $14^h.4$ for O, and at $10^h.0$ for He. On the other hand, according to satellite-drag data [Jacchia et al., 1973], the maximum of the total density always occurs around $14^h.35$, irrespective of height, at least within the limits of 200 and 800 km. Around 600 to 800 km, the density peaks at $14^h.4$ even when the atmosphere is nearly pure helium.

3. SEASONAL-LATITUDINAL VARIATIONS; HYDROGEN

Concerning point 1, no particular difficulty arises in modifying the model of the diurnal temperature variation so as to have the maxima and minima shifted to higher latitudes around the solstices. In the Jacchia models, we have $\phi_B = \delta_\odot$, where ϕ_B is the latitude of the maximum-temperature point, and $\delta_\odot$ is the declination of the sun. All that is needed is to make $\phi_B = k\delta_\odot$, with $1 < k < \pi/2\epsilon$, where ϵ is the obliquity of the ecliptic; all the other equations remain the same. With the modification I recently suggested [Jacchia, 1973] for a latitude dependence for the parameter n (see equation (4) in the present paper), continuity across the poles is ensured for both temperatures and temperature gradients. Our recent finding [Jacchia et al., 1973] that $k = 1$ was predicated on the premise that there was no intrinsic seasonal variation of atomic oxygen. If we assume that such a variation does exist, we can adjust the total variation of O so that it adapts to any given temperature variation at the poles and still gives us the observed value of $\Delta_1 \log \rho$. In other words, since the total densities derived from satellite drag are mostly atomic oxygen densities, we can trade changes in oxygen densities for changes in temperature and still come out with essentially the same total densities. The OGO 6 mass-spectrometer data show that k must lie between 2.1 and 3.84 ($= \pi/2\epsilon$), so we shall assume $k = 3$.

Proceeding to point 2, if we plot $\Delta_2 \log_{10} n$ at a height of 450 km above the summer pole, as given in Table 1, against the mass M of the constituent (Figure 1), we see that the straight line $\Delta_2 \log_{10} n = 0.035\ (M - 20.8)$ represents the observational data within the limits of error. Since we have to deal with a phenomenon

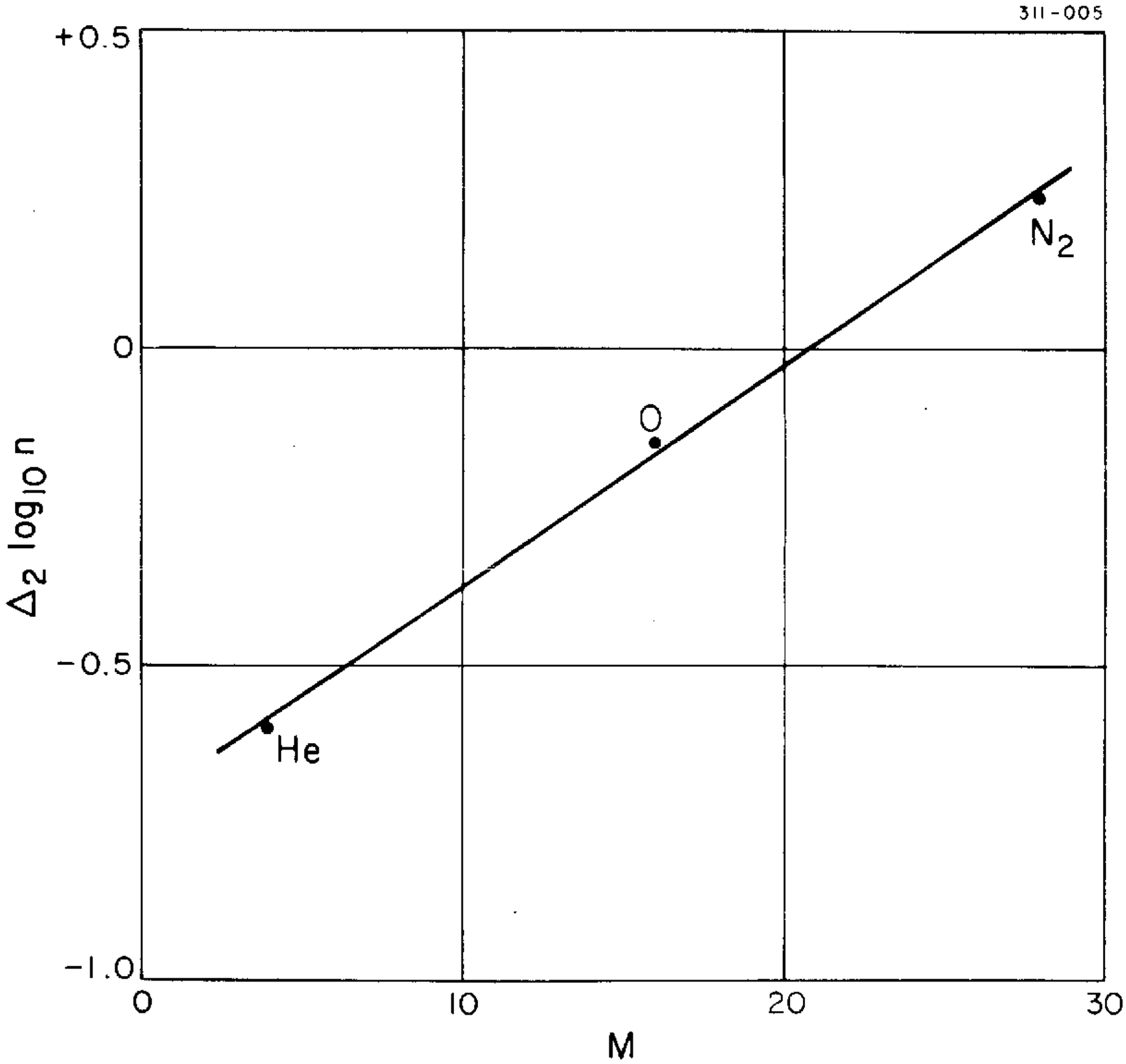

Figure 1. Intrinsic excess of three atmospheric constituents at 450 km above the summer pole, plotted against their masses.

originating with diffusion, we would expect that 20.8 is the effective mean molecular mass involved in the diffusion process. At 450 km, however, the mean molecular mass for a temperature of 1000 K is about 15.6 (I am using a modification of my 1971 model, based mainly on OGO 6 composition, which I call model 42E; at 450 km, however, where the atmosphere is nearly pure atomic oxygen, the choice of one model instead of another does not affect the mean molecular mass to any degree). To find a mean molecular mass $\overline{M} = 20.8$, we have to go down by almost 5 density-scale heights, to 214 km, where the total density is over 100 times greater than it is at 450 km. We shall now make the assumption that $\underline{\Delta_2 \log_{10} n}$ <u>is always proportional to $M - M^*$, where M^* is the mean molecular mass at the height at which the density is exactly 100 times greater than it is at the height under consideration.</u>

We now have to consider a factor that will give us the observed seasonal-latitudinal distribution. A logical choice is the difference, at a given height z, between the mean diurnal temperature at latitude ϕ, $T_m(z, \phi)$, and the mean equatorial temperature, $T_m(z, 0)$. We can thus write

$$\Delta_2 \log_{10} n = c(M - M^*) [T_m(z, \phi) - T_m(z, 0)] \quad . \tag{1}$$

The constant c has the approximate value c = 0.00024. For simplicity, let us identify T_m with $T_{1/2}$, the arithmetic mean between the daytime maximum and the nighttime minimum temperature. Following <u>Jacchia et al.</u> [1973], we can write $T_M/T_{1/2}(\infty, 0) = 1 + (r/2)$, where T_M is the global maximum of the asymptotic temperature; we then obtain

$$T_{1/2}(\infty, \phi) - T_{1/2}(\infty, 0) = \frac{r}{2} T_{1/2}(\infty, 0) (\cos^m \eta + \sin^m \theta - 1) \quad . \tag{2}$$

Here, $\eta = \frac{1}{2}|\phi - \phi_B|$ and $\theta = \frac{1}{2}|\phi + \phi_B|$. In the quoted paper, we had derived the value 2.2 for m, but m = 2.0 would seem more desirable, since it would make $T_{1/2}(\infty, 0)$ constant throughout the year and equal to the arithmetic mean of the mean asymptotic temperatures at the north pole, $T_{1/2}(\infty, +90°)$, and at the south pole, $T_{1/2}(\infty, -90°)$. Incidentally, with this model, the maximum and minimum values of $T_{1/2}(\infty, \phi)$ are always found at the poles, except at the equinoxes, where $T_{1/2}(\infty, \phi)$ is the same at all latitudes. To derive $T_{1/2}(z, \phi)$ from $T_{1/2}(\infty, \phi)$, use has to be made of model temperature profiles.

Figure 2 shows profiles of $\Delta_1 \log_{10} n$ and $\Delta_2 \log_{10} n$ computed from equation (1) for all major atmospheric constituents for an asymptotic temperature of 1000 K. As can be seen, the conditions posed in points 3 and 4 have been met: $\Delta_2 \log n$ is small at low heights (~150 km) for N_2, while for He, it is quite large; also, the latter reaches its maximum between 250 and 300 km and is considerably smaller at 700 km than at 450 km.

In Figure 2 we have also added dashed curves for the seasonal variations of hydrogen computed in the same manner, although we cannot expect hydrogen, whose concentration is mainly conditioned by thermal escape, to follow the same rules as the other constituents. Good reasons exist, however, for suspecting that hydrogen does, at least qualitatively, follow the general rule and show depletion at the summer pole. First, very low densities were derived from the drag of the Explorer 19 and Echo 2 satellites in July 1964, at the absolute minimum of solar activity. The effective heights at which the densities were derived were 750 and 1170 km, and, on the basis of the models, hydrogen should have been the major constituent at those heights (and practically the sole constituent at 1170 km). According to these data,

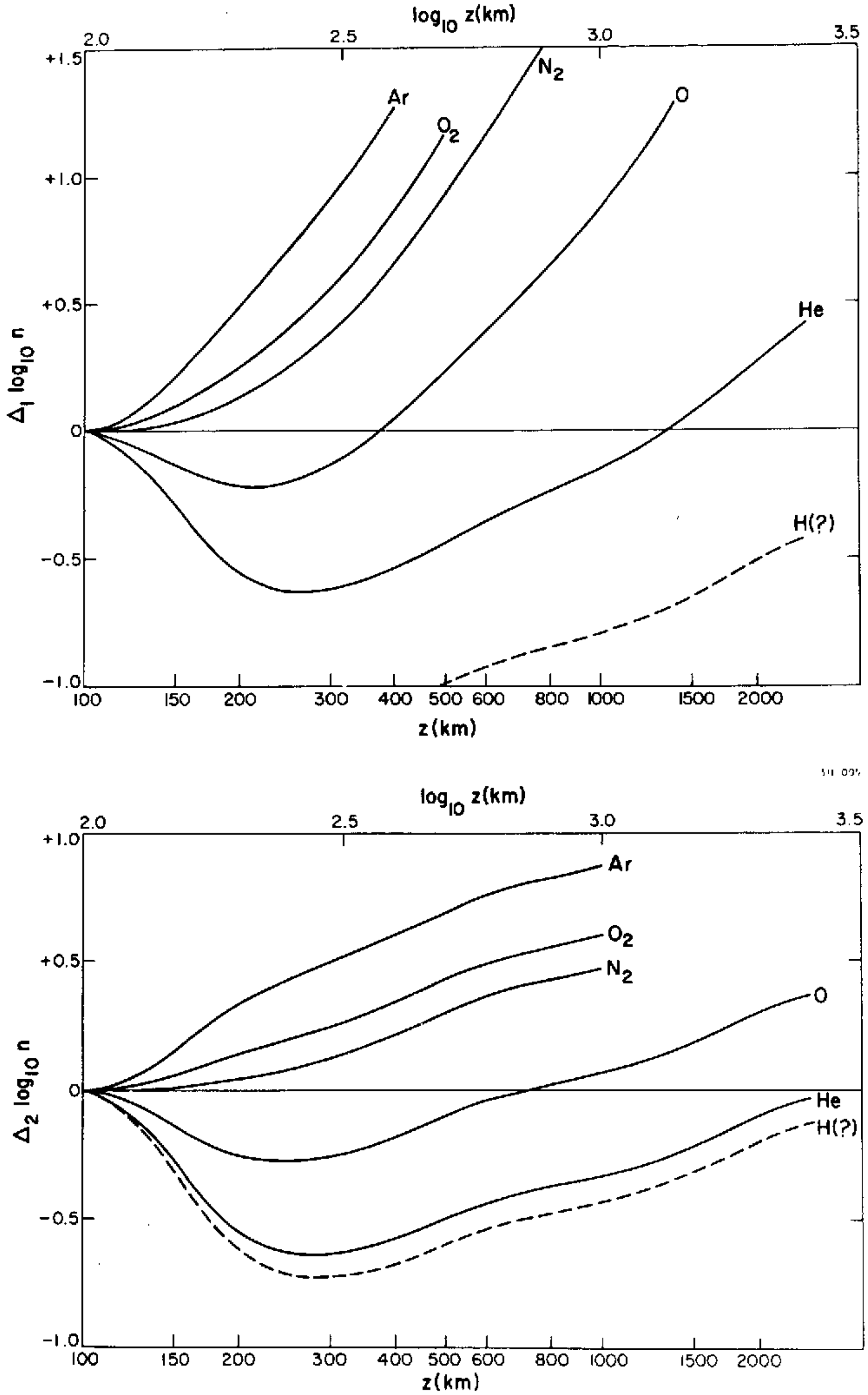

Figure 2. Excess of individual atmospheric constituents above the summer pole as predicted by equation (1). <u>Top</u>: excesses with respect to the global mean. <u>Bottom</u>: intrinsic excesses (i.e., corrected for pure temperature effects).

the hydrogen concentration was smaller than that given by the Kockarts-Nicolet [1962, 1963] model, although all recent measurements [Tinsley, 1970, 1973; Vidal-Madjar et al., 1973] would indicate an overall hydrogen density in excess of that of the Kockarts-Nicolet model by a factor of 2 or 3. The semiannual variation is insufficient to explain this large hydrogen depletion. It is significant that in July 1973, the perigee of both satellites was in the north polar regions; also, the eccentricity of the Echo 2 orbit was near maximum (0.02), allowing us to detect deviations from spherical symmetry in the atmosphere. A seasonal variation of hydrogen in the direction indicated by equation (1) would certainly help solve the problem. A further indication that such a variation might exist is offered by the hydrogen densities derived by Slowey [1973] at a height of 3600 km from the drag of satellite 1963 30D, which show lower values toward the summer pole.

4. DIURNAL VARIATION

Let us now consider point 5. It is clear that the differences in the hours of maximum density for N_2, O, and He at 450 km are not proportional to the differences in their masses. They are, however, linearly related to $\overline{M}/M$, as shown in Figure 3, where we have taken $\overline{M} = 15.6$. The straight line in the diagram corresponds to the equation

$$t_{max}(LST) = 15\overset{h}{.}8 - 1.5 \frac{\overline{M}}{M} \quad . \tag{3}$$

If we assume that this relation holds at all heights, we obtain the diagram of Figure 4, in which the hour of maximum density is plotted against height for the major atmospheric constituents, with the exception of hydrogen, for an asymptotic temperature of 1000 K. The heavier curve is the weighted mean of the hours of maxima for the individual constituents; for the weighting factor, we have used $W = nMa$, the mass density multiplied by the amplitude a of its diurnal variations. As can be seen, all conditions of point 5 are met. Although the hour of maximum varies greatly with height for the individual constituents, especially for helium, the weighted mean of the times of maximum – which should approximate that of the total density variation – remains almost constant around $14\overset{h}{.}4$ for heights below 600 km and rises only very slightly at greater heights. In pure helium (or pure atomic oxygen, for that matter), when $M = \overline{M}$, equation (3) gives $t = 14\overset{h}{.}3$, in agreement with observations. It is interesting that if we take $W = nM$ – i.e., if we drop the amplitude from the weighting factor – the weighted mean of the hours of maxima stays constant at $14\overset{h}{.}32$, within $\pm 0\overset{h}{.}03$, up to 800 km.

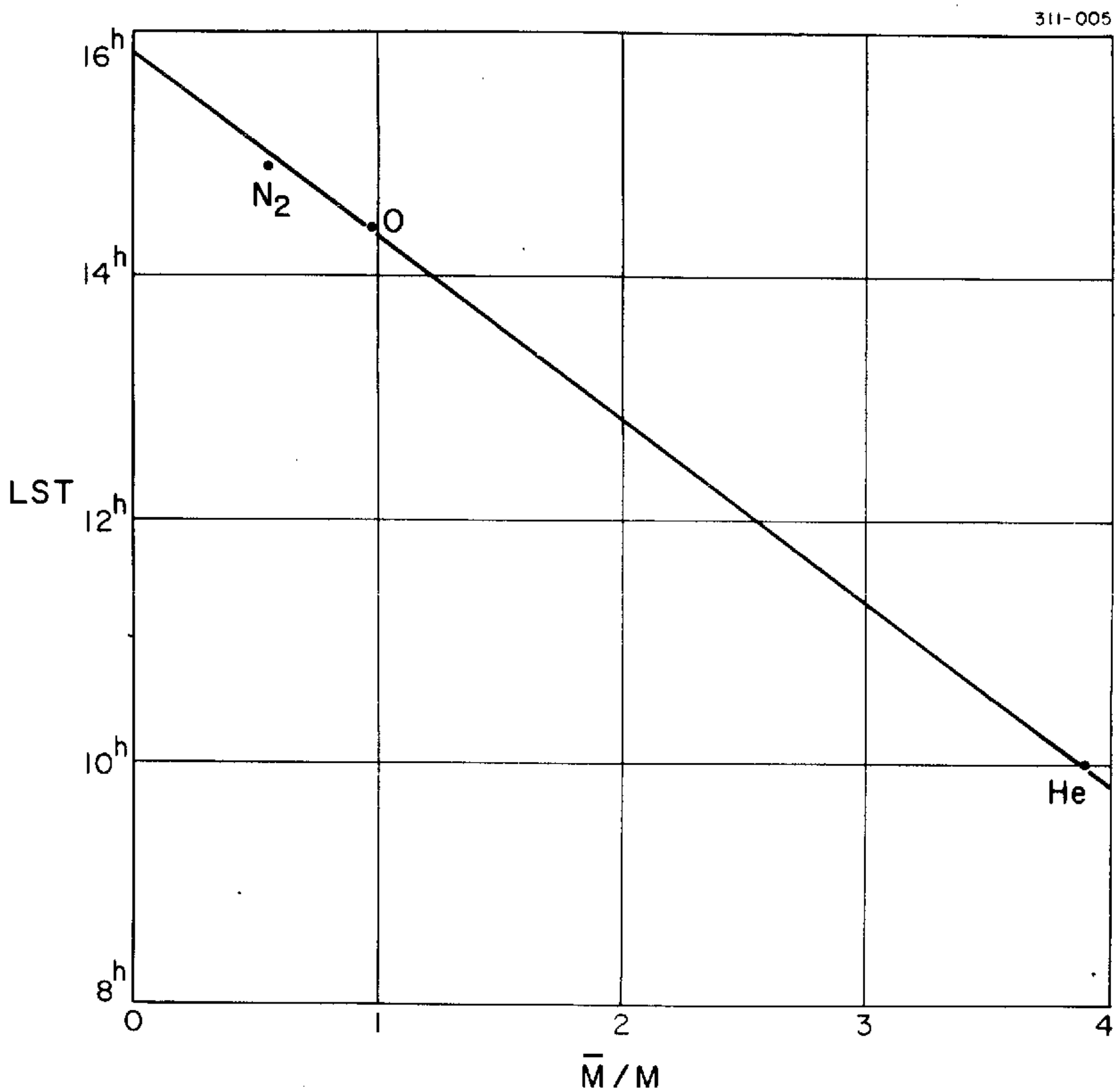

Figure 3. Hour of maximum in the diurnal density variation of three atmospheric constituents at 450 km plotted against $\overline{M}/M$.

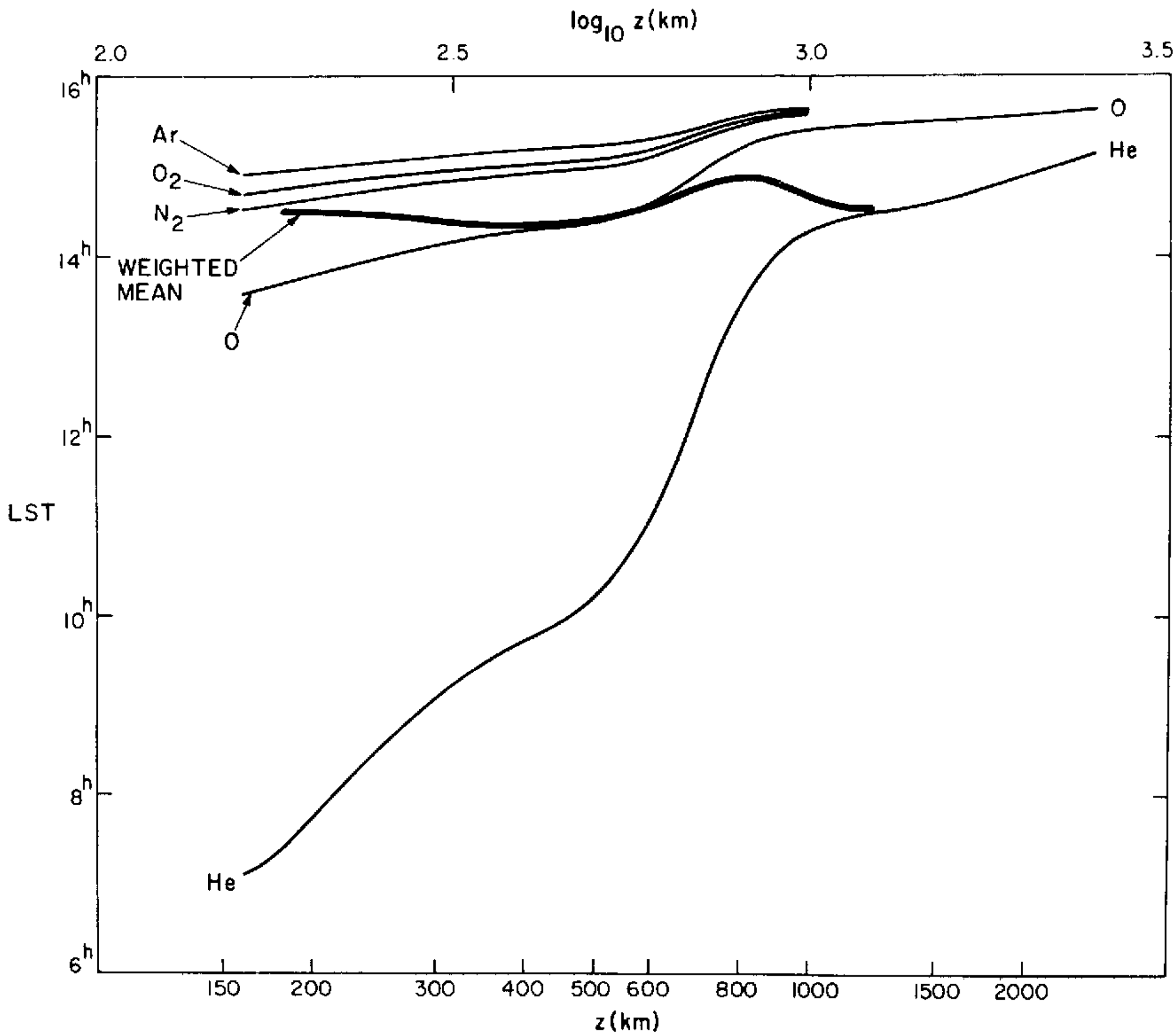

Figure 4. Hour of maximum in the diurnal variation for individual atmospheric constituents as computed from equation (3). The heavy curve is the weighted mean of the individual times of maximum and should approximate that of the total density variation.

If we want to use equation (3) in conjunction with Jacchia's model of the diurnal variation, we encounter some difficulties. The longitudinal temperature variation, with the modifications proposed by Jacchia et al. [1973], can be schematically represented by

$$T = A \cos^n \frac{1}{2} (H + \beta) \quad , \tag{4}$$

where A is a function of ϕ, ϕ_B, and solar activity; H is the hour angle of the sun; and n and β are constants whose most recently derived values are $n = 3.0$, $\beta = -35^\circ.0$. If we identify β with $t_{max} - 12^h$ and take t_{max} from equation (3), we are left with as many different temperatures as there are atmospheric constituents — which does not make any physical sense but will give essentially correct density variations for each species. If we make $\overline{M}/M = 1$, then equation (3), as we said, gives $t_{max} = 14^h.3$; this corresponds to $\beta = -34^\circ.5$, almost exactly the value given above, which was derived from satellite drag by means of static models. By employing this value of β for computing the actual temperature variation, we would be no worse off than we are at present when we use static models to compute it. The correct solution, of course, will have to wait for a workable three-dimensional dynamical model.

5. CONCLUSIONS

We have been able to represent the seasonal-latitudinal and the diurnal variations of composition in the thermosphere by using two empirical formulae, each of which uses only one numerical parameter. The general nature of the formulae makes them applicable to all heights and levels of solar activity. Although no obvious large discrepancies with observations can be detected at present, it will be interesting to watch how well the formulae hold when observations of composition are extended to a wider range of heights and solar activity. If further observations bear out the formulae, a consideration of their structure might provide better insight into the mechanism of the variations.

We would have liked to find similar formulae for the changes in composition observed in the semiannual variation and in the geomagnetic effect, and we hope that a further analysis of the original data may provide a lead in this direction. Considering the greater complexity (and our less complete understanding) of these types of variation, the material published so far does not seem to contain enough information to attempt such a task.

6. ADDENDUM

Observations by von Zahn et al. [1973], contained in a paper received after this manuscript had been prepared for publication, confirm the amplitude of the seasonal variation of argon and helium as predicted by equation (1). Argon is found to vary by at least a factor of 10, with a maximum at the summer pole; the helium variation, with a range from 1 to 20, is nearly twice as large as at 450 km. All this is in excellent agreement with the curves shown in Figure 2.

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BIOGRAPHICAL NOTE

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

Dr. Jacchia's affiliation with Harvard College Observatory began with his appointment as research associate in 1939. At that time he was studying variable stars. Since he joined SAO as a physicist in 1956, most of Dr. Jacchia's work has been on meteors and upper atmospheric research.