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ON THE SEMIANNUAL VARIATION
OF THE UPPER ATMOSPHERE

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ABSTRACT

Several possible mechanisms are investigated which could be invoked to explain the observed semiannual density variation in the thermosphere and exosphere. A variation of the height of the mixtopause leads to a large density variation for heights above 700 km. Below that height, however, the density is essentially invariant to this process. This invariance is to some degree caused by the neglect of downward heat transport by eddy diffusion at the bottom of the thermosphere. The limitations of using the simple mixtopause scheme in this context are discussed.

Another mechanism can be ruled out on the grounds that it fails to explain the observed amplitude at a height of 200 km. This mechanism is a small permanent heat flux conducted into the lower exosphere from above. A variation of this flux by 3×10^{-2} erg/cm^2 sec would yield a sufficiently large density variation only for heights above 300 km. The recent observations at heights below 200 km indicate that the temperature and density at the bottom of the thermosphere (90 to 120 km) vary with a semiannual period.

1) Introduction

During recent months more observational results on the semiannual variation in the atmospheric density have become available, which cover a large range of altitudes from 150 km up to 1130 km. (L. G. Jacchia, J. W. Slowey and I. G. Campbell (1968), G. E. Cook and D. W. Scott (1967, 1968), D. G. King-Hele (1968), King-Hele and J. Hingston (1967), King-Hele and D. M. C. Walker (1968)). These data provide the possibility for a comparison with theoretical calculations based on different hypotheses for a physical explanation of the effect.

The semiannual variation with its density maxima in March and October and minima in July and January is the least understood effect in the behavior of the upper atmosphere. While the 27-day variation can be traced to a variation in the solar XUV-radiation emitted from active areas above sunspots and while the increase of atmospheric densities during geomagnetic storms can be related to an increase of the solar wind speed, no clear evidence is so far available as to the cause of the semiannual variation. The effect was first noticed by H. K. Paetzold and H. Zschoerner in 1960 and thereafter often confirmed, most notably by Jacchia and his collaborators. These data together with the recent evaluations of the semiannual effect by King-Hele and his collaborators now cover the entire phase of decreasing solar activity and the beginning of the new solar cycle.

A very similar semiannual variation was known to exist in the geomagnetic activity. It was derived by A. L. Cortie in 1912 from his analysis of geomagnetic indices. Unlike the thermospheric density, which shows the effect every year in a clear fashion if the drag data are carefully analyzed, the effect in geomagnetic activity shows clearly only when averages of geomagnetic indices over at least a few years are used.

The close similarity between these two semiannual variations tempts one to assume that the necessary energy for the density variation is derived from a solar wind impinging on the magnetopause, but it is not all clear how the energy would be transported into the lower thermosphere. Moreover there are arguments that the effect is due to a semiannual change in the boundary conditions at the bottom of the thermosphere. This could be the result of a global wind pattern at the heights of the mesopause and of the turbopause. A meridional flow from the summer to the winter pole is actually observed in the drift of ionized trails of meteors at heights of about 90 km (A. Kochanski (1963)).

In general, the observed semiannual density variation can be represented by atmospheric models whose mean exospheric temperature changes systematically with a semiannual period where the amplitude of the temperature variation is directly proportional to the average level of solar activity as given by the 10.7 cm solar flux F (L. G. Jacchia 1965). This, however, does not imply that the effect is caused by an additional heat source which exhibits a half-year period and parallels the 11-year solar cycle. There is also no significant evidence at the present time that the XUV flux from the sun has a semiannual variation. Furthermore the validity of this empirical representation of the effect is essentially restricted to heights above 200 km. For all these reasons the empirical formula does not provide any insight into the physical process which causes the atmospheric density to vary with a semiannual period. This fact was clearly stated by Jacchia, but occasionally it has been overlooked by other authors. The rather large amplitudes of the semiannual effect found recently by King-Hele and collaborators for heights below 200 km and above 1000 km show the limitations of the empirical formula, since the amplitudes are too large to be represented by a simple ΔT-formula.

Occasionally, doubt has been cast on the existence of the effect, in particular by A. D. Anderson (1966) and by S. Chandra and B. V. Krishnamurthy (1967). Anderson suggested that the phenomenon had been misinterpreted and was actually a "latitudinal variation in disguise". This idea, however, was immediately disproved by D. G. King-Hele (1966) (see also King-Hele (1968)).

Chandra and Krishnamurthy tried to attribute the observed variation to variations in the solar XUV-heat flux as evidenced by the decimeter radiation. But only in 1958 and 1962 occurs a variation in solar activity which actually could support their idea. Thus it seems safe to state that the existence of a semiannual variation in the upper air density has been proved beyond doubt and that the density changes cannot be associated in a simple way with variations in the solar decimeter flux as it is possible for the 27-day variation and for the 11-year solar cycle effect. For recent reviews on the different effects in the thermosphere and lower exosphere see W. Priester, M. Roemer and H. Volland (1967) and M. N. Isakov (1967).

2) <u>The semiannual effect between 200 and 700 km</u>

The recent analysis by L. G. Jacchia, J. W. Slowey and I. G. Campbell (1968) covers a height range from 250 to 658 km for the time period from 1958 until 1966, that is, the entire decreasing phase of solar activity and the beginning of the new cycle. The results show all the familiar patterns of the semiannual effect with the minima between January 15 and 26 and between July 25 and 30 and the maxima between April 1 and 3 and between October 27 and November 1. It might be worthwhile to point out the strong asymmetry. The time between the April and October maxima is 210 days, while between the October and April maxima only 155 days pass. This extreme asymmetry is due to the fact that in these data the October maxima occur very late as compared with the long-time average date of the fall maximum (October 7) in the geomagnetic semi-annual effect (W. Priester and D. Cattani, 1962). There is no obvious explanation for the strong asymmetry in the atmospheric semiannual effect between 1958 and 1966. It remains to be seen whether a similarly strong asymmetry occurs in the geo-magnetic data for the same time period. The relatively small asymmetry generally found in the geomagnetic data was thought to be related to the fact that the northern winter season is shorter than the northern summer season because the earth passes through its perihelion early in January. It must, how-ever, be kept in mind that in many years large deviations from the average dates occur. On quite a few occasions there are dis-turbances in the semiannual effect which cannot be accounted for by other indices of solar activity as for instance the 10.7 cm flux or the geomagnetic indices. We shall discuss this point in the context of the observational data for heights above 1000 km.

3) <u>The semiannual effect above 1000 km</u>

The recent extended analysis of the semiannual effect at heights of about 1100 km by G. E. Cook and D. W. Scott (1967) revealed two remarkable features:

1) In 1964 and early 1965 the amplitude between maximum and minimum was found to be a factor of 2 to 2.5. This is clearly in excess of the value of 1.5 which one obtains from the CIRA 1965 model atmospheres by applying Jacchia's formula.

2) With the beginning of the new solar cycle in 1965 the amplitude of the effect sharply decreased as can be seen from Fig. 1 which presents the data obtained from the Echo 2 satellite for a height of 1130 km after adjustment to an average level of solar activity represented by an 10.7 cm flux $\overline{F}=100\cdot10^{-22}$ W m^{-2} Hz^{-1} (from G. E. Cook and D. W. Scott (1967)). When solar activity approached its next maximum the semiannual amplitude increased again (Cook and Scott (1968)).

Before embarking on possible explanations of the large amplitude observed in 1964 we want to discuss the sudden decrease of the amplitude in late 1965 and 1966 and its recovery thereafter. The amplitude at that time is represented by a factor of 1.4±0.1 which is in general agreement with the amplitude expected from the CIRA 1965 models in conjunction with Jacchia's ΔT-formula for the semiannual effect. Observe in Fig. 2 the difference between model 3 and 2 which have nightime minimum temperatures of 805 and 731 ^{o}K, respectively. The difference of 74 ^{o}K between these temperatures corresponds approximately to the value of $\Delta T=0.94\cdot\bar{F}$ from Jacchias formula for $\bar{F}=100$. After a closer inspection of the behavior of the semiannual effect in Fig. 1 after May 1965, which date can be taken as the onset of a new 11-year solar cycle, one is tempted to accept an interpretation as outlined by the two curves in Fig. 1. King-Hele (1968) has pointed out already that the minima show a double structure in his data derived from the Midas 2 satellite for a height of 480 km. A similar pattern seems to be apparent in the Echo 2 data beginning with the onset of the new solar cycle. The much better time-resolution of the Echo 2 data leads to an admittedly highly speculative interpretation. The observed data can be represented if the regular semiannual variation is superposed by another variation with about the same period but with a phase shift of 6 months and an amplitude of about 1/3 of the regular semiannual variation. Of course, the data are not conclusive enough to pursue this idea any further at the present time. The general decrease of the amplitude, after the onset of the new cycle seems to be rather well established. Also in the data by Jacchia, Slowey and Campbell (1968) the decrease of the amplitude in 1965/66 is indicated for heights between 250 and 600 km.

This behavior of the semiannual amplitude is not surprising, if there is a close relationship between this effect and the analog effect in geomagnetic activity. Priester and Cattani (1962) have shown that a remarkable decrease in the semiannual amplitude occurs at the time of the onset of a new cycle in the geomagnetic u_1 indices as defined by Bartels (1932). Thus it is very striking that a similar behavior seems to occur in the exospheric densities. Of course, more satellite data are needed to establish this result further. As far as the effect in geomagnetic activity is concerned the explanation given by Priester and Cattani was debated by J. Roosen (1966) on his statistics using Ap-data. As Bartels (1932, 1963) has shown, however, the usefulness of the Ap-data in this context is debatable since the major storms get a too large statistical weight. Since the semiannual effect in atmospheric densities is much more stable than in geomagnetic activity we have to wait for more data until at least one full solar cycle is observed.

G. E. Cook (1967) has argued that the excessive amplitude observed in 1964 and early 1965 is a result of a semiannual variation of the height of the mixtopause, that is, the level above which the atmosphere can be regarded as being in diffusive equilibrium. This level is expected to coincide closely with the turbopause, where the vertical turbulence vanishes. The effect of a variation of the height of the mixtopause is expected to yield significant density variations at the altitudes where the lighter elements - that is helium and hydrogen - are the dominant constituents. In order to evaluate this quantitatively we extended our computer program on the behavior of the thermospheric structure (I. Harris and W. Priester, 1962 a,b, 1965, 1968) in such a way that it reveals the effect of changes in the height of the mixtopause.

Before we discuss these calculations in detail we want to show what the resulting diurnal average density profile is if one applies Jacchia's formula for the semiannual variation to the CIRA 1965 model atmospheres (Fig. 2). As representative for the diurnal average values we used the CIRA model densities for 8 hours local time. This choice is somewhat arbitrary, but it should not have any significant effect on our conclusions. We also extrapolated the densities to 1200 km for the comparison with the results from Echo 2 and Calsphere 1 (G. E. Cook (1967). The extrapolation of the number densities of the different constituents from which the total density was calculated is based on the extension of the isothermal region. In Fig. 2 the density profiles for CIRA model 2 and 3 are given which correspond to a level of solar activity as represented by $\bar{F}=75$ and $\bar{F}=100$, respectively. Cook's data for the semiannual maximum and minimum densities for heights of 1130 km (Echo 2) and 1080 km (Calsphere 1) are also given. These densities are reduced to $\bar{F}=75$, the prevailing level of solar activity in 1964-1965. (It should be noted, that the data given in Fig. 1 are reduced to $\bar{F}=100$, the average activity level for the larger time period from 1964 through 1966).

For a level of solar activity of $\bar{F}=75$, the model 2 should represent the maximum of the semiannual variation. In order to obtain an appropriate density profile for the semiannual minimum we calculated a model (labeled 2* in Fig. 2), whose night time temperature T_{04} (at 4 hours local time) is lower by 75°K as compared to the profiles of model 2. This was accomplished by reducing the heat flux appropriately. The temperatures given on the three model curves are the "diurnal average temperatures" (temperatures at 8 hours local time) and the night time minimum temperatures. The latter values are set in parentheses.

It is apparent from figure 3 that the observed minimum data are well represented by model 2*, where the model 2 density at 1100 km is too low by approximately 30 percent. Due to the arbitrariness in the definition of the diurnal average, only the difference between the two models is a relevant quantity. The discrepancy between the observed and the calculated values is not as significant as stated by G. E. Cook (1967) with respect to Jacchia's static diffusion models.

However, the discrepancy between the observed amplitude of 2.1 at 1130 km and the CIRA amplitude of 1.5 still requires further explanation. Jacchia (1967) has argued that the discrepancy is only apparent, being caused by an error in the hydrogen content of the comparison models. This argument, however, does not apply to the CIRA 1965 models, because their hydrogen content is relatively low, even for a level of very low solar activity. This is born out by the fact that the contribution to the total density by hydrogen atoms at a height of 1100 km is negligible. In Fig. 2 the dotted lines give the density profile if hydrogen is omitted. The effect of a large amount of hydrogen would be to reduce the difference between the two profiles at greater altitudes effectively. Thus, Cook's observations of the large semiannual amplitude assure us that the hydrogen content of the exosphere, in particular for the years of low solar activity cannot have been grossly underestimated in the CIRA models.

For the altitudes from 250 to 600 km the amplitude between models 2 and 2* is in close agreement with the observed semiannual amplitudes (L. G. Jacchia, J. Slowey and I. G. Campbell (1968)). Model 2* provides the appropriate representation of the observations. But it should be pointed out again, that it does not provide insight into the cause of the semiannual effect since we have no physical justification for reducing the heat flux in such a way that it gives the required lower value of the exospheric temperature.

4) <u>Variation of the mixtopause height</u>

Since G. E. Cook (1967) invoked a semiannual variation of the height of the mixtopause as a possible explanation for the excessively large amplitude of the semiannual density variation, which he had observed at a height of 1100 km, we want to evaluate this idea more quantitatively and show how the thermospheric and exospheric density profiles are affected by such a variation. The motivation for this is the belief that the height of the mixtopause should be particularly sensitive to seasonal variations in a global wind pattern. A global circulation in the mesosphere and in the lower thermosphere has been suspected as a possible cause for the semiannual variation in the thermosphere and exosphere.

Introducing the term mixtopause, below which the atmosphere is fully mixed and above which diffusive equilibrium prevails, implies a simplification. In fact we have a layer with a gradual transition from mixing into diffusive equilibrium. This layer contains the turbopause which has been defined by F. D. Colegrove et al. (1965), (1966) as the altitude at which the eddy diffusion coefficient equals the molecular diffusion coefficient.

The processes occuring in the transition zone between 80 and 120 km are rather complicated due to the photodissociation of the oxygen molecules and the recombination. At heights above about 95 km the recombination of oxygen atoms cannot occur at the same rate as the dissociation of the molecules because of the rather low density at those heights. Therefore a downward transport of the oxygen atoms is required by an eddy mixing process. This would transport the O-atoms into heights with higher densities, where recombination is sufficiently rapid. It also removes a certain amount from the heat budget for heights above 100 km and releases it at heights around about 80 km in the process of recombination. Since in the transition zone the heat removed by infrared reradiation from oxygen atoms ($^3P_1$ - $^3P_2$ transition) is also quite important, a detailed account of the entire energy balance in this height range is not feasible as long as we do not have accurately measured density profiles of the major constituents. It is the purpose of our calculations to show whether the simple concept of a height variation of the mixtopause allows already to account for the semiannual variation. Of course, some caution is necessary regarding the neglected amount of heat transported downwards by eddy diffusion.

With these precautions we shall calculate the density and temperature profile for 4 different assumed heights of the mixtopause: 100, 105, 110 and 120 km. Our computer program (Harris and Priester (1965)) starts at a height of 100 km with boundary conditions as given in Table 1. They have been taken from CIRA 1965, part I. Since we know from the work of Colgrove et al. (1965), (1966) that an increase of the eddy diffusion coefficient from 4×10^6 to 8×10^6 $cm^2 \cdot sec^{-1}$ will lead to a decrease of the atomic oxygen density at 100 km by a factor of 2, it seems at the first sight that maintaining a constant oxygen number density at 100 km is not permitted within our calculation scheme. But it provides reasonable values for the number densities for heights of 120 km and above. They are in close agreement with the model calculations of Colgrove, Hanson and Johnson. The variation of the eddy diffusion coefficient given above corresponds to a change of the mixtopause height from 99 km to 106 km in our scheme. Since the mixtopause concept neglects the downward energy transport by eddy diffusion we shall have to consider its influence on the temperature and density structure in the entire height range above 120 km.

In Fig. 3 the results of the diurnal average density profile forthe height range from 500 to 1200 km are given. The values for 9 hours local time have been chosen as representative for the diurnal average. In the 4 models calculated the solar heat flux has been kept unchanged. The flux values were those from CIRA model 2 for $\bar{F}$=75. In Fig. 3 the values assumed for the mixtopause heights are given at the right-hand side. Furthermore the exospheric temperatures for 9^hlocal time are given as an additional parameter. In Table 2 the atmospheric data at a height of 120 km are given for the four chosen mixtopause levels.

TABLE 1

Table 1:	Boundary conditions at 100 km.
Temperature	208 ^{o}K
Density	5.00×10^{-10} g/cm^3
Pressure	3.07×10^{-1} dyn/cm^2
Scale height	6.5 km
mean molecular weight	28.2
Number densities:	
N_2	8.2×10^{12} cm^{-3}
O_2	2.0×10^{12}
O	5.0×10^{11}
He	5.5×10^{7}
H	1.7×10^{5}

TABLE 2

Atmospheric structure parameters at a height of 120 km for 4 models with mixtopause levels at 100, 105, 110 and 120 km, respectively. The data are the values at 9^hl.t., The diurnal variation at 120 km is very small in these models.

	Height of the mixtopause 100 km	105 km	110 km	120km	
Temperature	356	370	377	384	
Density	2.97	2.82	2.83	2.85	$\times 10^{-11}$ $g.cm^{-3}$
Pressure	3.23	3.14	3.19	3.23	$\times 10^{-2}$ $dyn.cm^{-2}$
Scale height	11.5	11.8	11.9	12.0	km
Mean mol. weight	27.2	27.6	27.9	28.2	-
N_2-density	4.94	4.70	4.69	4.67	$\times 10^{11}$ cm^{-3}
O_2-density	8.90	9.40	10.2	11.4	$\times 10^{10}$
O-density	7.47	5.17	4.02	2.85	$\times 10^{10}$
He-density	2.53	1.21	0.69	0.31	$\times 10^{7}$
H-density	9.81	4.34	2.32	0.97	$\times 10^{4}$
$O:O_2$ ratio	0.84	0.55	0.40	0.25	
Average eddy diffusion coefficient (from Colgrove et al. 1965)	5.0	7.5	11.	16	$\times 10^{6}$ $cm^2 sec^{-1}$

It is evident from Fig. 3 and Table 2 that the increasing height of the mixtopause leads to an increase of the exospheric temperature while at 120 km the number densities of the elements with atomic weights much smaller than the mean molecular weight show a significant decrease.

As a result of this we find density profiles which are essentially invariant to height variations of the mixtopause level. This invariance prevails at altitudes up to about 700 km. That is the range where atomic oxygen is the dominant constituent. The invariance is caused by the compensating-effect of the increased exospheric temperatures and decreased atomic oxygen densities at 120 km. We believe that this compensating-effect is mainly responsible for the fact that the densities in the thermosphere follow the model predictions with such an astounding reliability and can be so well related to the incoming solar heat flux as represented by the decimeter radiation. Since it cannot be expected that the mixtopause level remains at a constant height in local time, latitude and longitude, it has always been puzzling that the density in the thermosphere was so rather easily predictable.

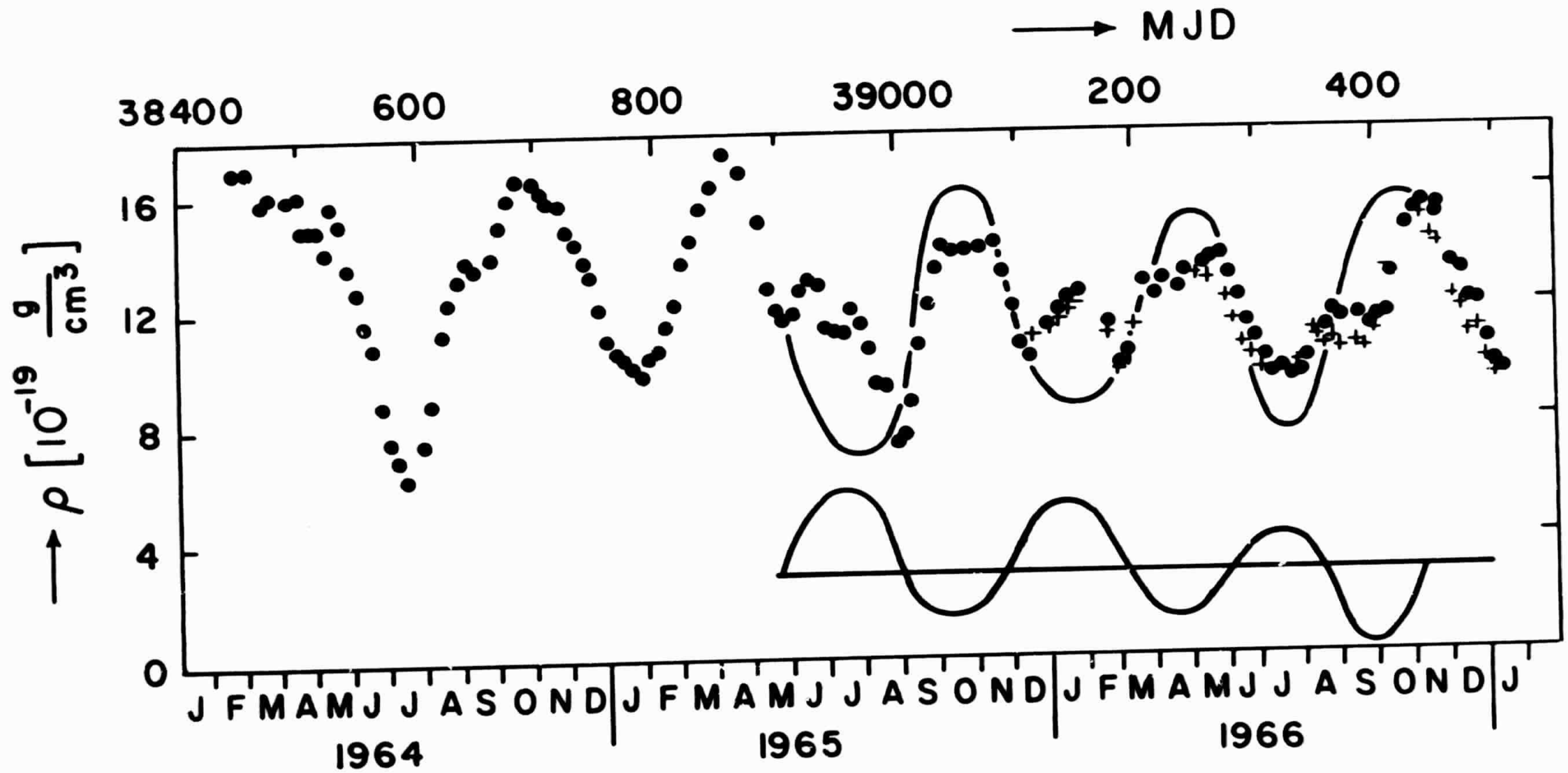
According to this behavior of the density it becomes immediately obvious, that a height variation of the mixtopause alone cannot be invoked to explain the basic features of the semiannual variation, since amplitudes as large as a factor of 1.5 to 2 for heights between 400 and 600 km cannot be produced this way. One would have to postulate rather severe variations in the boundary conditions of the models in order to produce the observed semiannual amplitude. This, for instance, could be a variation of the total density at 120 km as large as a factor of 1.5. This shows that there is an urgent need for more observational data on temperature, density and number densities in the lower thermosphere. The slight increase of the temperature at 120 km with increasing mixtopause heights (see Table 2) reveals one of the limitations of the scheme used in these calculations since only local dissipation of the absorbed solar energy is taken into account. The neglected downward heat transport by eddy diffusion would act against the increase of the temperature at 120 km. This will offset the invariance of the density in the upper thermosphere to some degree. A more detailed calculation will be attempted in a forthcoming paper. At the present, however, it is safe to state that the simple scheme of a height variation of the mixtopause with complete mixing below and diffusive equilibrium above that height cannot account for the semiannual variation in the range from 200 to 700 km.

At altitudes above 700 km where helium is the dominant constituent the expected strong dependence on the height of the mixtopause becomes apparent. It can be seen from Fig. 4 that the observed large semiannual amplitude at 1100km could be produced extirely by a change of the mixtopause height of 5 km. Since, however, only the excess of the amplitude ought to be explained here, a height variation of about 2 to 3 km would be fully sufficient.

5) Effect of a non-zero heat influx into the exosphere

The magnetosphere provides in general a very effective heat insulation between the earth's upper atmosphere and the solar wind. Thus, any heat flux conducted down from the hot solar wind plasma through the magnetosphere cannot be anything but very small. On the other hand, we are certain that during geomagnetic storms a considerable amount of energy is transferred from the solar wind region into the lower thermosphere, influencing the structure of the thermosphere in a very conspicuous way. We cannot be certain that this additional energy vanishes completely when the solar wind speed reduces to its quiet conditions (v=350 km/s). In addition, the fast electrons which are produced by photoionization in the ionosphere and are able to escape

into the lower magnetosphere, provide a non-negligible amount of energy, which will be finally conducted downwards. This might produce a heat flux in the lower exopshere in the order of 10^{-2} to 10^{-3} erg/cm^{2}sec (H. G. Mayr and H. E. Volland (1967), J. V. Evans (1967)). A similar amount of heat flux will be produced by fast hydrogen atoms, which enter the upper atmosphere with speeds in the range of 400 km/sec. These fast atoms are produced by charge transfer collisions, when neutral interstellar matter interacts with the solar wind (H. J. Fahr (1968)). There is even some probability that this heat flux shows a semiannual variation.


→ MJD
38400
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800
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→ ρ [10⁻¹⁹ g/cm³]
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1

For these reasons it seems worthwhile to evaluate how a small, but permanent heat flux into the exosphere affects the density profile of the thermosphere and exosphere. In our computer program for a diurnal structure of the upper atmosphere we incorporated an influx of 3.4×10^{-2} erg/cm^{2}sec.at the height of our upper boundary (800 km). This yields a temperature gradient of 0.1 $^{\circ}$K$\cdot$km^{-1} at 800 km. The diurnal average density profile then was compared with the calculated profile, when the exospheric heat influx was set to zero. In Fig. 5 the two density profiles are given. As representative for the diurnal average we have chosen data for 20:00 hours loc. time, since they provide the closest comparison with Cook's results for the semiannual amplitude at 1100 km. The rather large difference between the two curves demonstrates that a small heat flux into the exosphere with a semiannual amplitude in the order of 3.10^{-2} erg/cm^{2}sec could yield the required semiannual density variation. In contrast to Fig. 4 the amplitude in Fig. 5 remains rather large at lower altitudes. At 500 km the calculated value is 2.0, totally sufficient to account for the observed amplitude of 1.6 to 2.0 at 480 km (D. G. King-Hele (1968)). At a height of 300 km the calculated densities are 12.1 and 0.98×10^{-14} g/cm^3, respectively, with an amplitude of 1.25.

At 200 km, however, the amplitude has decreased to 1.07. The corresponding densities are 2.28 and 2.14×10^{13} g/cm^3.

This amplitude at 200 km is not sufficient to represent the recent observations at 190 km, where an amplitude of 1.45 has been found (D. G. King-Hele (1968)). As King-Hele points out there is even evidence of an appreciable amplitude at a height of 150 km (King-Hele and J. Hingston (1967)). Unfortunately, the results obtained from the exceptionally dense USSR-satellite 1966-101G at this altitude leave room for two different interpretations. The observed density amplitude is approximately 1.7, but this can be either the diurnal or the semiannual amplitude or a combination of both.

We might recall that even for very high solar activity, at the peak of the 1958 solar maximum, the densities derived from Sputnik 3 for a height of 215 km revealed a conspicuous minimum in summer 1958 (W. Priester and H. A. Martin (1960)) which with our present knowledge can only be interpreted as the semiannual minimum. Therefore we consider it likely that there is an observable semiannual variation even at heights as far down as 150 km. This could not be accounted for by any reasonable amount of heat conducted into the lower exosphere from above. Thus, observations of the semiannual effect in the lower thermosphere at altitudes around 150 km will decide whether the roots of the semiannual variation lie in the altitude range between 90 and 120 km.

6) Conclusions

In this paper we have investigated several possibilities which have been suggested for explaining the semiannual density variation in the thermosphere and exosphere:

1) a variation of the height of the mixtopause while the solar XUV-flux is kept constant, yields an appropriate density variation only at heights above 700 km, where helium becomes the dominant constituent. In the height range where atomic oxygen is dominant, the density is essentially invariant to the height change of the mixtopause. Thus, only the excess-amplitude observed in 1964-1965 at 1100 km can be explained this way. A variation of the mixtopause height by 2 to 3 km would be sufficient.

The mixtopause concept with complete mixing below and diffusive equilibrium above the height of the mixtopause has a limitation since only local dissipation of the absorbed solar radiation is considered. The downward heat transport by eddy diffusion at the bottom of the thermosphere is neglected. This will to some degree influence the invariance of the density in the upper thermosphere to changes of the mixtopause height, when the eddy diffusion processes are accounted for in a more complete way.

2) A small, permanent heat flux conducted into the lower exosphere from above causes a significant variation of the density structure of the upper thermosphere and lower exosphere. If such an hypothetical flux would undergo a semiannual variation with an amplitude of 3×10^{-2} erg/cm^{2}sec, then the resulting density variation would represent the observed data in the altitude range from 300 to 1100 km. This process, however, fails to explain the large amplitude of 1.45 observed at a height of 190 km.

3) In view of these calculations it is evident that observational data on the semiannual variation in the lower thermosphere (below 200 km) will become crucial for an understanding of this effect. This emphasizes the urgent need for more data in the lower thermosphere. All the evidence suggests that the roots of the semiannual effect must be sought at altitudes

below 120 km. With the computer programs available it will not be difficult to simulate the semiannual behavior of the thermospheric and exospheric density by ad hoc changes of the temperature and density at the lower boundary height (100 or 120 km). Without supporting measurements of these quantities, however, the procedure will remain unsatisfactory, since it will hardly give any further insight into the mechanism involved. Two proposals have been made, which have been recently discussed by R. E. Newell (1968). The proposal by F. S. Johnson invokes a large-scale meridional circulation which removes more heat from the lower thermosphere during the solstices than during the equinoxes. The second proposal is based on the Joule heating associated with the S_q-currents in the lower ionosphere. These currents have maxima at the time of the equinoxes. For a review of the Joule heating see K. D. Cole (1966). The observation that the absorption of long radio waves within the ionospheric D-region (E. A. Lauter et al. (1966)) exhibits strong semiannual variations shows again that the roots of the semiannual variation are at rather low altitudes.

On the other hand the sudden decrease of the semiannual amplitude at the beginning of a new solar cylce (compare section 3) indicates that the effect not only depends on the level of solar activity but also might depend on the time within the solar cycle. This would favor the Joule heating mechanism, since it is difficult to imagine how a circulation pattern could display the two fold dependence on solar activity. On the other some semiannual features which have been observed in the mesopheric wind system indicate a possible relationship between a global circulation and the semiannual variation. In order to substantiate this, further observational data on the semiannual effect, covering at least one complete solar cycle, are necessary.

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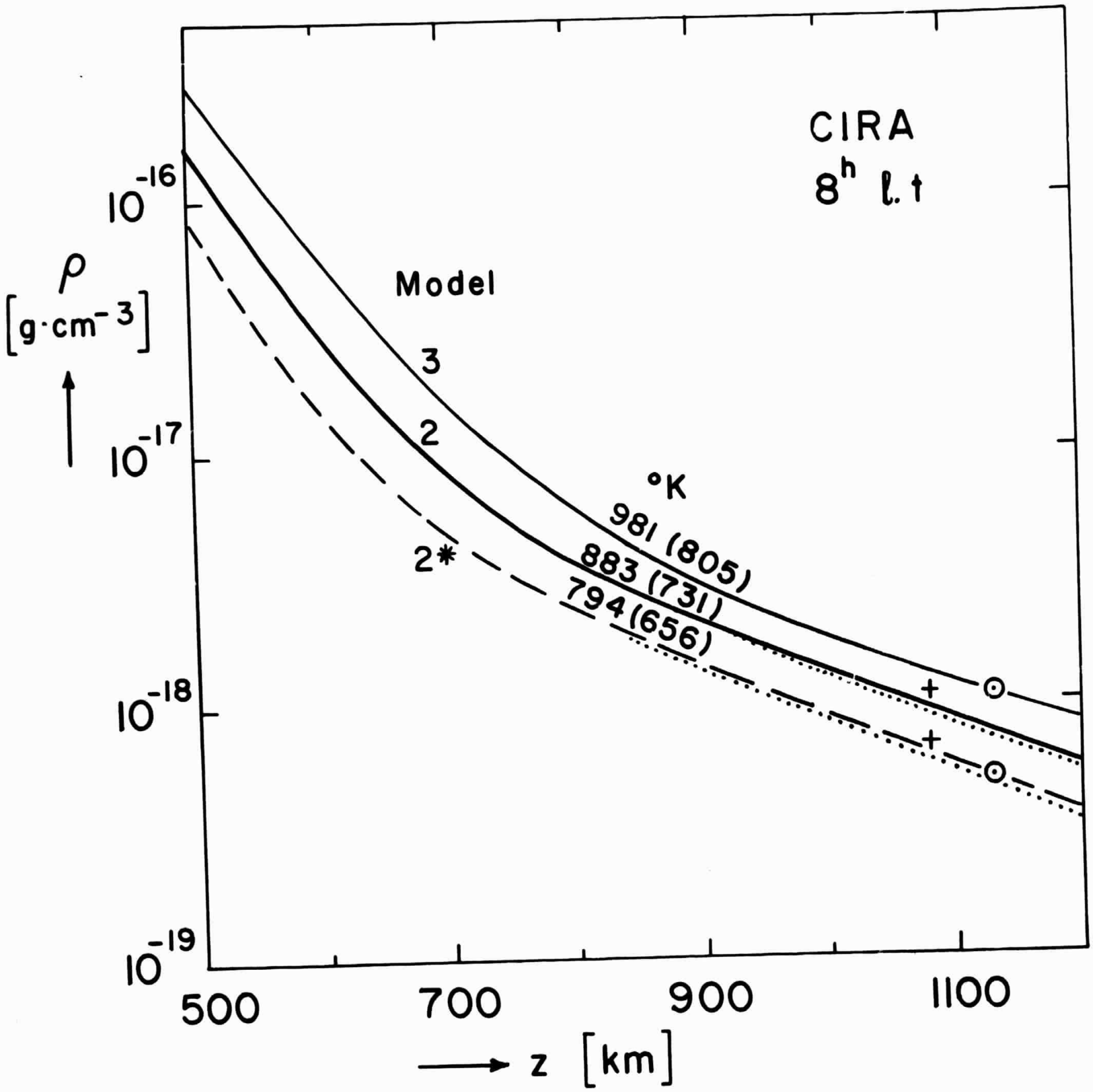
FIGURE CAPTIONS

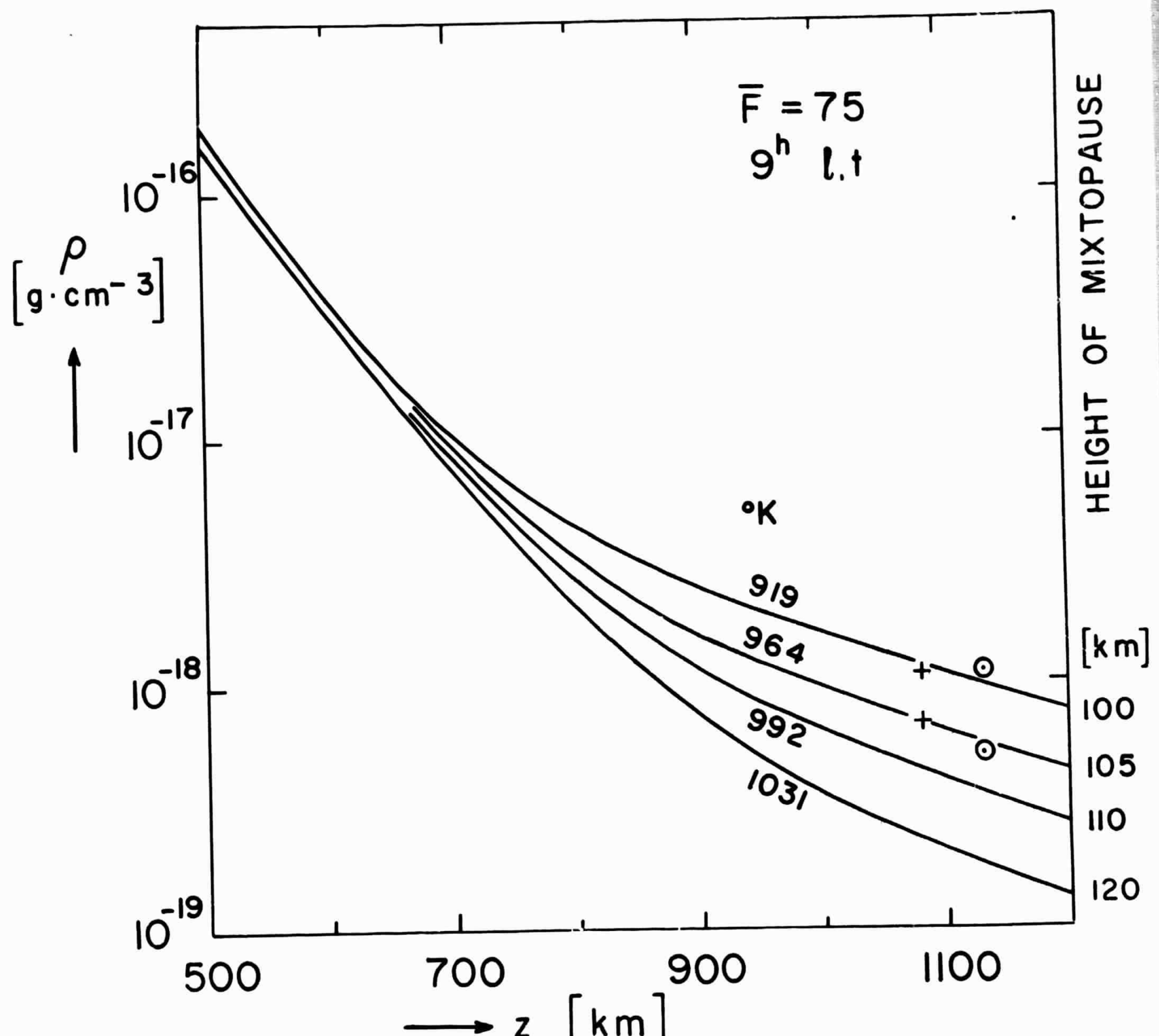
Fig. 1: Semiannual density variation at a height of 1130 km, derived from Echo 2 by G. E. Cook and D. W. Scott (1967). The data are adjusted to an average level of solar activity $\bar{F}$=100. The crosses are obtained if correction is made for a diurnal variation with an amplitude of a factor of 2. The curves are meant to illustrate a speculative interpretation of the sudden amplitude decrease at the beginning of the new solar cycle in 1965 (see text!)

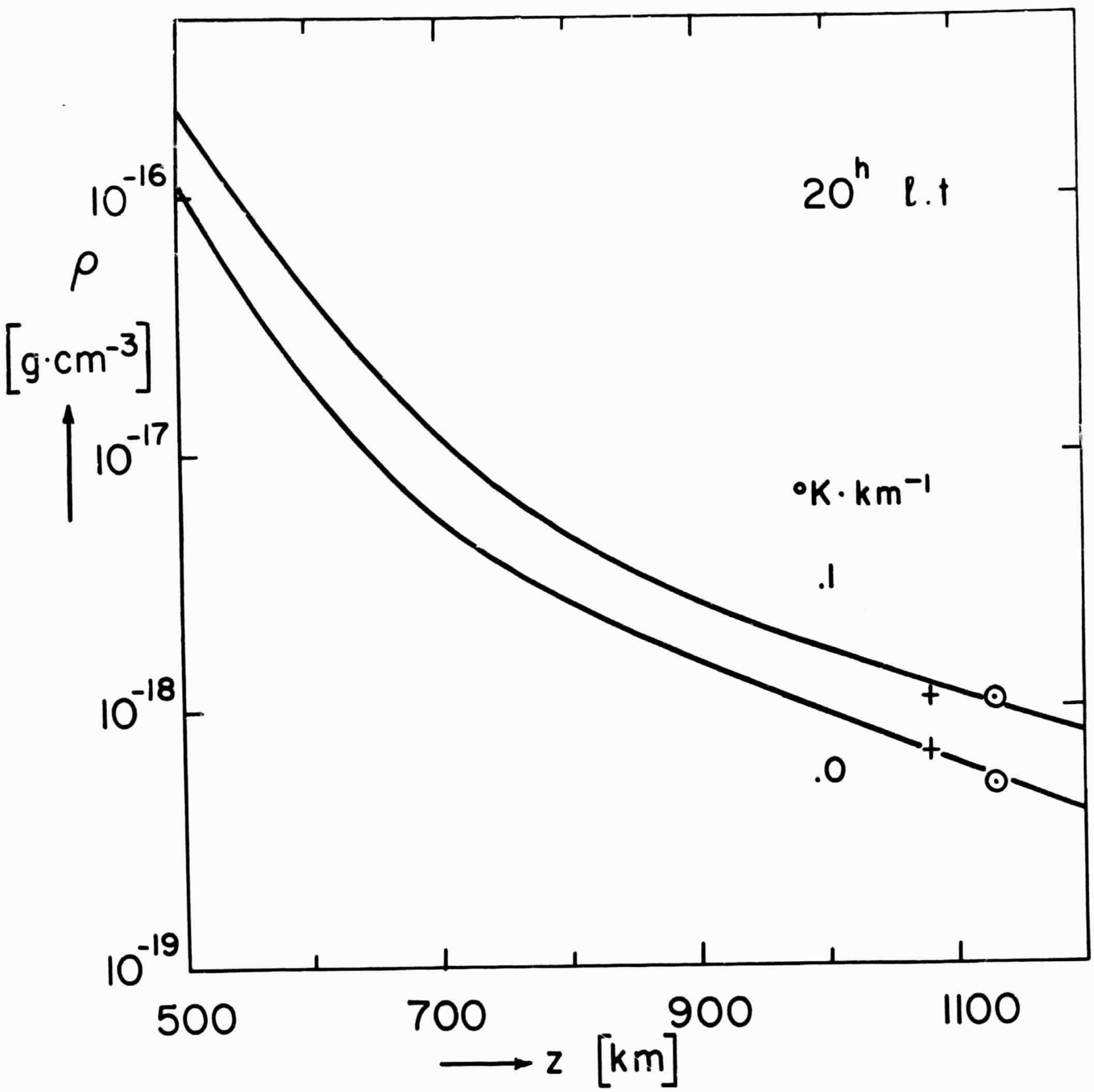
Fig. 2: Density profiles for the height range from 500 to 1200 km for CIRA 1965 models 2 and 3 for 8^h loc. time. The parameters give the exospheric temperatures with the nightime minimum temperatures in parentheses. In model 2* the exospheric temperature is 75°K lower than in model 2. The circles and crosses represent the semiannual extrema from Echo 2 and Calsphere 1, respectively (G. E. Cook (1967)). The data are adjusted to $\bar{F}$=75.

Fig. 3: Density profiles for the height range from 500 to 1200 km for $\bar{F}$=75 and 9^hloc. time for 4 different heights of the mixtopause, as given on the right hand side. The parameters of the curves are the resulting exospheric temperatures. The crosses and circles are the Echo 2 and Calsphere 1 data (see Fig. 3).

Fig. 4: Density profiles for the height range from 500 to 1200 km for the two exospheric temperature gradients 0.1 and 0.0 $^{o}K\ km^{-1}$, respectively. The circles and crosses are the same as in Fig. 3.


CIRA
8h l.t
Model
3
2
2*
°K
981 (805)
883 (731)
794 (656)
10^{-16}
10^{-17}
10^{-18}
10^{-19}
ρ [g·cm^{-3}]
500
700
900
1100
z [km]


F̄ = 75
9h l.t
HEIGHT OF MIXTOPAUSE
ρ [g·cm⁻³]
10^-16
10^-17
10^-18
10^-19
°K
919
964
992
1031
[km]
100
105
110
120
500
700
900
1100
z [km]



20h l.t
10^{-16}
10^{-17}
10^{-18}
10^{-19}
ρ
[g·cm⁻³]
°K·km⁻¹
.1
.0
500
700
900
1100
z [km]