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ON THE VARIATIONS OF THE THERMOSPHERIC STRUCTURE

by W. Priester

Goddard Space Flight Center
Greenbelt, Md.

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ABSTRACT

The paper discusses the properties of the different effects which have been found to occur in the thermosphere and some conclusions which can be drawn with regard to the physics of the thermosphere.

In the discussion of the diurnal variation the emphasis is on the behavior of the diurnal amplitude in density during the solar cycle. At the height range between 200 and 300 km the amplitude has remarkably increased with decreasing solar activity.

The relation between atmospheric density and temperature and the solar EUV flux and the solar 10.7 cm flux—the latter serving as a convenient parameter—is discussed. The observational results for a phase shift between the variations in the EUV flux (or 10.7 cm flux) and the correlated variations in atmospheric temperature (or density) lie in the range between 0.5 and 2.3 days. During the solar minimum the atmospheric variations which parallel the 10.7 cm flux are far less pronounced than the variations correlated with geomagnetic activity. The phase shift derived from 45 geomagnetic storms and correlated density changes has been found to be 6 ± 3 (m.e.) hours.

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ON THE VARIATIONS OF THE THERMOSPHERIC STRUCTURE

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INTRODUCTION

The majority of the information on the time-dependent behavior of the thermosphere has been derived from satellite drag data which were obtained from the changes of orbital periods. These data are essentially limited to heights above 200 km, since the lifetimes of satellites with perigees below that height are usually too short. But a few limited conclusions about the thermospheric behavior below 200 km can be drawn from the knowledge of the atmospheric structure and its variations above that height.

If one combines this information with the results of rocket data on density, pressure, temperature and chemical composition obtained in the lower thermosphere, one will be able to present a self-consistent picture of the entire thermosphere, except for a few discrepancies which still remain at the present time.

THE DIURNAL VARIATION

In 1959 it was found—and since then often confirmed—that the density in the height range above 200 km undergoes a pronounced diurnal variation with a maximum at about 1400 hours local time and a minimum at about 0400 hours. This is understood as the consequence of a diurnal temperature variation in the thermosphere which in turn is essentially caused by absorption of solar energy and downward heat conduction acting as a smoothing process.

The observations for the decreasing phase of solar activity from 1958 through 1963 have shown that the time of maximum always remains at 1400 hours local time (Reference 1) within a range of uncertainty of about ±1 hour. In general, the amplitude of the diurnal density variation (that is, the ratio of the density at 1400 hours to the density at 0400 hours local time) increases with height.

At any given height the amplitude is dependent on the level of solar activity within the eleven-year solar cycle. This is particularly conspicuous in the height range around 200 km. In 1958 the

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observations of Sputnik 3 (1958 $\delta 2$) yielded a diurnal amplitude of only about 10 percent at a height of 200 km (Reference 2). In 1963, when the level of solar activity was already close to the minimum, the orbital analysis of several satellites by King-Hele and Quinn (Reference 3) revealed a density ratio of 1.7 at 200 km and the results on the satellites Cosmos 1 - 5 (1963 $\theta 1$, 1963 $\iota 1$, 1963 $\nu 1$, 1963 $\xi 1$, 1963 $\upsilon 1$) by Marov (Reference 4) suggest an even higher ratio of 1.9 at the same height. The drag data of Explorer 17 (1963 09A) (Reference 5) yielded a diurnal density ratio of 2.1 at 270 km for 1963. This ratio was only 1.5 in 1958-59 as can be shown from interpolation between data from Sputnik 3 and Explorer 1 (1958 $\alpha 1$) (Reference 6).

The increase of the diurnal amplitude at 200 km with decreasing solar activity can be understood if the heating of the thermosphere depends strongly on the level of solar activity. In diffusive equilibrium the reaction of the different constituents of the atmosphere on changes of the temperature depends on their molecular weights. The summation of the partial densities of the individual constituents is what we observe from the drag measurements.

The variation of the diurnal amplitude during the solar cycle was predicted by Harris and Priester (Reference 7) in their analysis of the time-dependent behavior of the upper atmosphere. They integrated the time-dependent heat conduction equation for an atmosphere which always remains in hydrostatic equilibrium. In order to account for different levels of solar activity within the eleven year cycle, the total heat input was taken proportional to the flux of the solar 10.7 cm radiation which had been proved to be a useful indicator of solar activity. Later on, the measurements from the OSO 1 (1962 $\zeta 1$) satellite on the solar EUV flux during March and April 1962 proved that there is an excellent proportionality between the EUV flux integrated from 50 to 400 A and the 10.7 cm radiation (Reference 8).

The analysis by Harris and Priester was based on fixed boundary conditions at a height of 120 km. Also, for the new edition of the COSPAR International Reference Atmosphere (Reference 9) it was decided to use constant boundary conditions at 120 km for temperature, density and chemical composition throughout the solar cycle, since no observational evidence on a significant variation at that height is available so far.

The comparison made by King-Hele and Quinn between their observational densities for 1963 and the CIRA Model 2 corresponding to the 1963-64 level of solar activity ($\overline{F} = 75$) revealed a good agreement if the densities are averaged over 24 hours. But the diurnal amplitude of the model at 200 km is given by a density ratio of 1.3 instead of 1.7 as revealed by the latest observations. For heights above 240 km, however, there is a good agreement between the model and the observations in both the average values and the diurnal amplitude. The differences between model densities and observational densities at those heights are less than 10 percent (see Figure 1).

Another slight discrepancy between the observed densities at 200 km and the new CIRA models occurs for times of very high solar activity (i.e. 1958). The model densities seem to be systematically too small by 10 to 15 percent (see Figure 2).

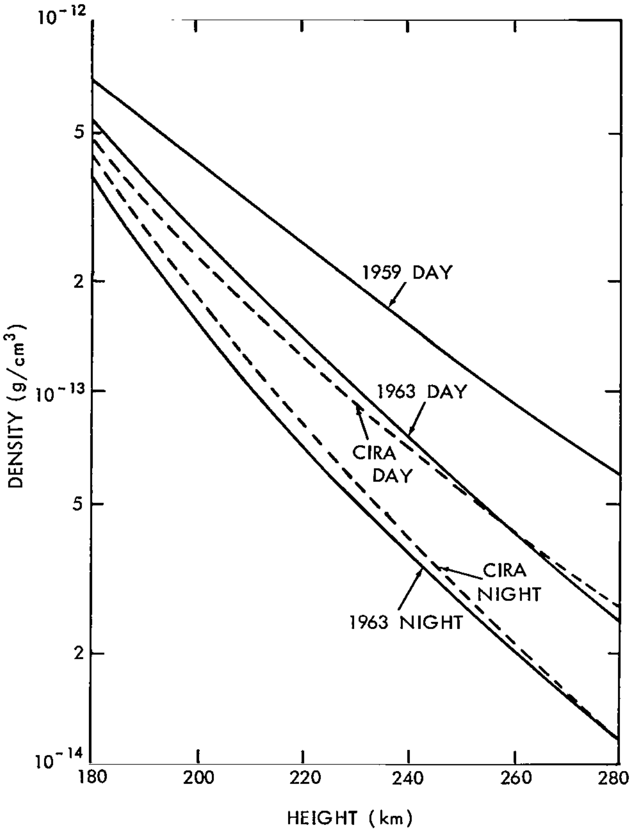

Figure 1—Diurnal variation of the density in the height range from 180 to 280 km for the year 1963 as determined by King-Hele and Quinn (Reference 3). Given are the daytime maximum and the nighttime minimum densities. They are compared with the corresponding CIRA Model 2 ($\bar{F}$ = 75) for 1400 and 0400 hours local time. In order to indicate the variation during the solar cycle, the observational daytime maximum densities for 1959 are also given.

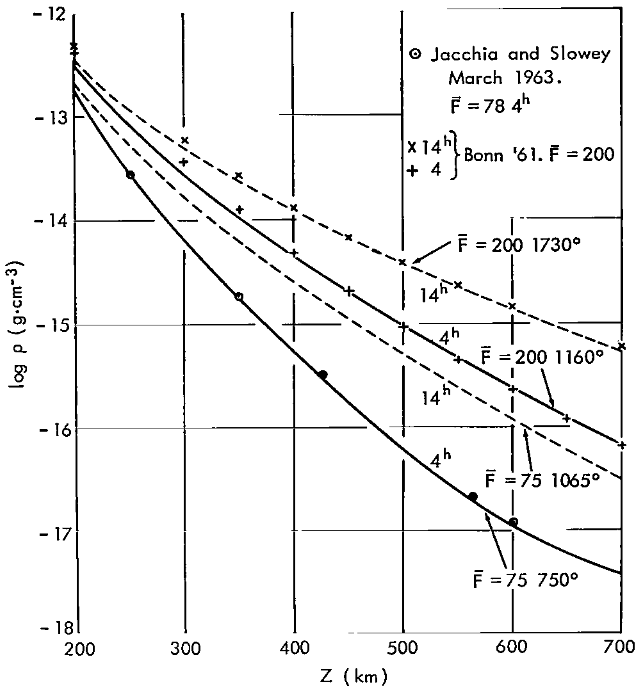

Figure 2—Comparison of CIRA model densities with data derived from satellite drag measurements (from CIRA, 1965). The models are for high solar activity (Model 7, $\bar{F}$ = 200) and very low solar activity (Model 2, $\bar{F}$ = 75). The observational data are the Bonn model 1961 for $\bar{F}$ = 200 (Reference 6) and the data derived by Jacchia and Slowey for March 1963 corresponding to $\bar{F}$ = 78 and 0400 hours local time from the 5 satellites Injun 3, Explorer 1, Explorer 8, Vanguard 2 and Explorer 9. The maximum and minimum exospheric temperatures are stated on the right.

All these small discrepancies provide a hint that the assumption of constant boundary conditions at a 120 km level throughout the solar cycle needs improvement. Unfortunately quantitative conclusions cannot be reached at present. Observational evidence on the correct temperature profile in the lower thermosphere and a highly accurate knowledge of the chemical composition is urgently needed. Variations of the temperature at 120 km over an eleven-year cycle with a range of 50 °K seem to be compatible with the available observational evidence. Also variations of the number densities at 120 km by as much as 30 per cent would be easily permissible.

The temperature measurements from cloud release experiments by Blamont (Reference 10) during the years 1960 to 1964 are compatible with a time-independent temperature at 120 km during that time interval. But this still allows a temperature variation of the order of 50 °K during the

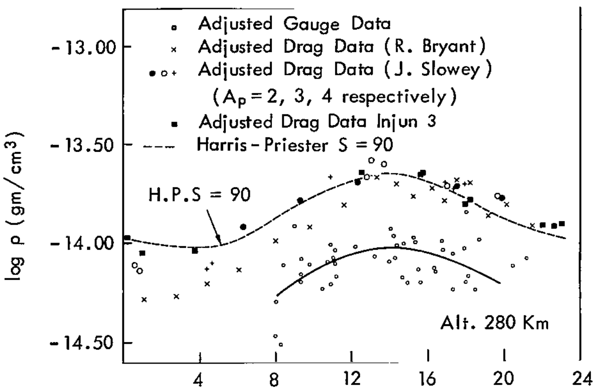

Figure 3—Comparison between gauge-measured densities and drag data, plotted as a function of local time. The gauge data are from an altitude range from 250 to 300 km and individually adjusted to $A_p = 2$ (see text). The drag data are selected for geomagnetically quiet conditions or adjusted to $A_p = 2$. All data are normalized to a height of 280 km above sea level.

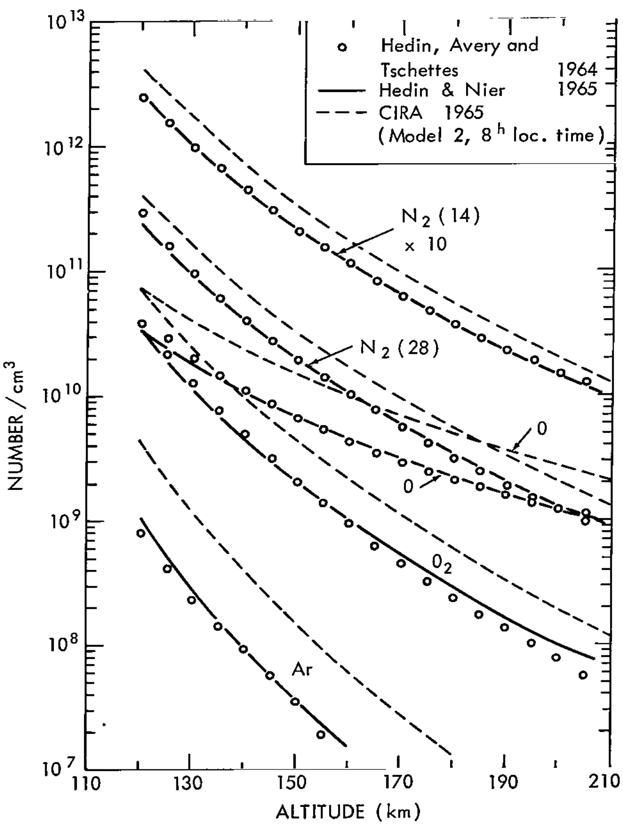

Figure 4—Number densities of N_2, O, O_2 and A from rocket-borne mass spectrometer measurements of June 6, 1963, 0730 MST (Reference 15) are compared with the corresponding CIRA Model 2 for 0800 hours local time. The higher densities in the model are necessary in order to reproduce the drag-determined densities above 200 km.

entire solar cycle. A series of rocket shots for measuring chemical compositions, temperatures, and densities over an entire solar cycle is urgently needed.

A curious discrepancy has been found between the recent direct measurements of atmospheric densities (total densities from pressure gauges and number densities from mass spectrometer measurements on board Explorer 17 and on rocket launchings) and the satellite drag measurements. This discrepancy amounts generally to a factor of about two in the sense that all drag derived values are larger than the directly measured values. This is illustrated in Figures 3 to 6. Here, for convenience, the comparison is partly made with the CIRA or the Harris-Priester models instead of the primary drag data. One should recall that the models are representative of the densities derived from drag measurements exclusively, since direct measurements were not available in sufficient numbers at the time when those models were constructed (1962 and 1964).

Figure 3 provides a comparison of the gauge-measured densities from Explorer 17 (Reference 11) and the drag-determined densities from the satellite Injun 3 (Reference 12) and Explorer 17 (References 5 and 13). The gauge data are from the altitude range of 256 to 300 km, normalized to a height of 280 km by using the Harris-Priester model S = 90 as a differential altitude transformer. The Injun 3 ($\beta_T 2$) data were selected for geomagnetically quiet conditions whenever $A_p \leq 2$.

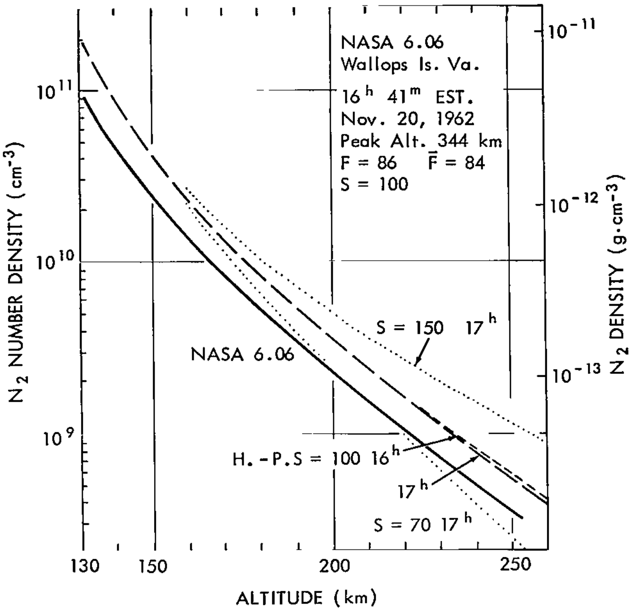

Figure 5—Number densities of N_2 for November 20, 1962 (Reference 16) compared with the appropriate Harris-Priester model S = 100 for 1700 hours local time. In order to demonstrate the solar cycle effect, the corresponding density curves for very low solar activity (model parameter S = 70) and for average solar activity (average of the 11-year cycle)(S = 150) are also given.

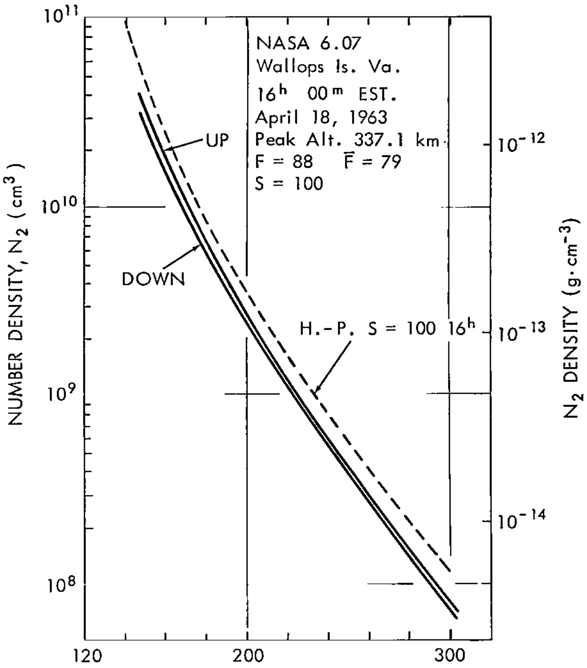

Figure 6—Number densities of N_2 from rocket-borne mass spectrometer measurements of April 18, 1963 (Reference 16) are compared with the N_2 values of the appropriate Harris-Priester model S = 100 for 1600 hours local time.

Slowey's Explorer 17 data were selected for $A_p = 2$, 3 or 4. All other data were adjusted to $A_p = 2$ by using the empirical relation derived by Newton, Horowitz and Priester (Reference 11).

The drag data and the corresponding Harris-Priester model densities are systematically higher than the gauge densities by a factor of two. This difference is greater than the combined uncertainties of both measurement techniques.

Figure 4 compares the number densities of N_2, O, O_2 and A obtained from mass spectrometer measurements by Hedin, Avery, and Tschetter (Reference 14), Hedin and Nier (Reference 15) (from an Aerobee flight launched at 0730 MST, 6 June 1963 at White Sands, New Mexico, carrying a magnetic mass spectrometer) with the appropriate CIRA Model 2 ($\overline{F}$ = 75) for 0800 hours local time. The 5-month average of the solar 10.7 cm flux for June 1963 is $\overline{F}$ = 81.4, sufficiently close to the model parameter used. The figure gives the direct mass spectrometer results (circles) and the calculated values (solid line), derived under the assumption of diffusive equilibrium from the temperature profile, which was obtained as a by-product from an analysis of the effect of the rocket rotation on the measured densities. The calculated number densities were normalized such as to yield the observed values at 150 km. The N_2 data were obtained from the mass 28 and also from the mass 14 peak. In the figure the latter values are multiplied by 10 for clarity.

The measured number densities for O and O_2 are lower by a factor of about two than those in the CIRA model. The model values are required to represent the satellite drag data above 200 km. For N_2 the factor is about 1.7. With regard to the temperature profile there is, however, good agreement between the data and the model. This can easily be seen from the fact that the curves are sufficiently parallel.

A similar discrepancy between observed and model number densities exists in the N_2 data obtained from NASA 6.06 and 6.07 launchings from Wallops Island, Virginia, on 20 November 1962 and 18 April 1963 (Reference 16, Figures 5 and 6). The solar activity parameter corresponding to these dates are $\bar{F} = 84$ and 81 (5-month averages). They are closely identical to the June 1963 value. Here the data are compared with the appropriate models of Harris and Priester (References 7 and 17) with a model parameter $S = 100$ corresponding to the given solar activity parameter. The model values are too large by a factor of about 1.5 to 1.7. Again there is good agreement for the temperature profiles. A comparison with the new CIRA models instead of the Harris-Priester models would reveal only a small discrepancy at the lower heights, since the boundary values for the new CIRA models were adjusted as closely as possible to these mass spectrometer results.

There is no explanation offered yet for the discrepancy between the drag data and the direct measurements. The several independent calibrations of the pressure gauges and also of the mass spectrometers seem to rule out a calibration error as large as a factor of two. If, however, the drag data are the ones which are to be improved, it would require an additional drag force which is equal to the aerodynamical drag. It does not seem to be possible to have an effective drag coefficient of about 4 instead of the value 2.2 which is usually taken in the 200 to 500 km range. Recently a careful reinvestigation of the drag coefficients has been undertaken by Cook (Reference 18). His findings are that the value of 2.2 should be correct within a ±10 percent limit in the altitude range from 200 to 500 km. On the other hand, a reduction of the drag-determined densities would immediately remove all the discrepancies and also would ease the high requirements on the absolute amount of heat available from the solar EUV radiation.

THE 27-DAY VARIATION, THE SOLAR CYCLE EFFECT, AND THE EFFECT OF GEOMAGNETIC ACTIVITY

The first effect which was found in the drag data was a variation with a period of approximately 27 days (Reference 19). These variations closely parallel the solar activity as measured in the decimeter flux (References 20 and 21).

It was, of course, evident from the beginning that the decimeter flux was only an index for the real heat source. The real source is obviously - at least to a large extent - the solar extreme ultraviolet radiation essentially below 911 A. About 50 percent of the energy between 100 and 900 A is, according to Hinteregger, Hall, and Schmidtke (Reference 22) contained in the emission lines; the remaining 50 percent is in the continuum.

From the correlation between density and decimeter flux, it was possible to predict that the EUV flux undergoes distinct variations in accordance with the decimeter flux. The correlation further implies that an important part of the EUV flux originates in the coronal condensations, since the slowly varying component of the decimeter flux comes from these areas of enhanced electron densities and temperatures in the solar corona. The close parallel of the He II 304 A line and several other lines in the wavelength range between 50 and 400 A with the 10.7 cm flux has been proved by the measurements with OSO I in March and April 1962 (Reference 23).

Despite the fact that the amplitudes of the 27-day variations in the density- and 10.7-centimeter flux curve match each other, it is evident that the general long-term trend in the thermospheric density curve is about twice as steep as in the flux curve. The long-term trend is the so-called solar cycle effect. A more detailed analysis of the different behavior of the 27-day variation and the long-term variation, which is believed to exhibit an eleven-year period, was carried out by Jacchia (Reference 24), Paetzold (Reference 25), Roemer (Reference 26) and Harris and Priester (Reference 7). Roemer showed that the best way to describe the phenomenon is to use a five-month average of the solar 10.7 cm flux, $\bar{F}$, as a solar cycle index and the daily flux values F for the 27-day variation. Thus the nighttime minimum temperature of the exosphere can be calculated from $\bar{F}$ and F in units of 10^{-22} W/m^2 (c/s):

$$T_{04} = 3.40\,\bar{F} + 460 + 1.9\,(F - \bar{F}) \quad [°K]$$

$$= 1.5\,\bar{F} + 1.9\,F + 460\,. \quad [°K]$$

These data represent the new CIRA tables. If one takes the Harris-Priester models as improved by Roemer, one obtains a very similar expression:

$$T_{04} = 3.46\,\bar{F} + 465 + 1.9\,(F - \bar{F})\,.$$

Jacchia's static diffusion models (1964) yield, for the exospheric nighttime minimum temperature:

$$T_4 = 3.60\,\bar{F} + 418 + 1.8\,(F - \bar{F})\,.$$

The differences between the formulas are negligible. They remain essentially smaller than 25 °K for the whole possible range of $\bar{F}$.

The formulas can be interpreted as follows: About 50 percent of the variable heat source parallels the daily decimeter flux. That means that the radiation which constitutes this part of the heat source originates in the coronal condensations. The remaining 50 per cent undergo a long-term variation but do not fluctuate within intervals of a few days. The latter displays the 11-year period in the structure of the solar corona.

Some caution should be exercized with regard to the numerical values of the percentages, since they depend somewhat on the particular choice of the solar activity parameter. Since, however, OSO I proved the close proportionality between the EUV flux in the spectral lines and the 10.7 cm flux, we feel even more confident about the extreme usefulness of the solar decimeter radiation until we have a continuous surveillance of the EUV flux from future satellites. Then we will be able to replace the auxiliary activity parameter by the directly measured EUV fluxes.

It is tempting to suggest which parts of the solar spectrum are to be identified with the different contributors to the heat source. At the present time these suggestions are, of course, highly speculative, and are also apt to oversimplify the situation. The part which parallels the 27-day variation might essentially consist of the lines in the EUV range according to the evidence from the OSO I measurements. In this context it is also interesting to compare the results from a theoretical investigation by Suemoto and Moriyama (Reference 27). The part with the long-term variation might be supposed to consist mostly of the EUV continuum. Direct measurements of the EUV spectrum over a period of an 11-year solar cycle will show whether this simplified picture is essentially correct, in the sense that the emission lines show a stronger variability with the daily changes of solar activity than the underlying continuum.

Since 1959 several investigations have been undertaken in order to find out whether there is a delay (phase shift) between the variations in the solar EUV flux (or its indicator, the decimeter flux) on one hand, and the response of the thermosphere, i.e., the change of density and temperature, on the other hand. How large is the delay and how can it be interpreted?

The situation is still somewhat obscure. The first finding on Sputnik 2 (1959 β1) seemed to show a hint for a delay of about 2 days. Therefore, in 1959 Priester and Martin investigated this problem on the basis of the statistical material then available. These data were essentially from 1958 β2 (Vanguard 1), 1957 β and 1958 δ2 (Sputnik 2 and 3) and 1958α (Explorer 1). The Vanguard 1 data are the dominant ones in the statistics. The perigee height of this satellite is about 650 km. Priester and Martin (Reference 2) presented their results from Vanguard 1 in a histogram of the individually observed delay times. In order to construct the histogram, the following data had been used: the times of maxima and minima in the density and in the solar 20 cm flux and the centers of adjacent "half-power" points in both curves. The result was a delay of 0.5 ± 0.5 days. The scatter of the data representing a Gaussian distribution with a 1/e halfwidth of 3 days is due to the rather poor time resolution of the satellite data at that time (2.5 days). This is superposed to the 20 cm flux data with a one-day resolution. This combines to about 3 days.

Then, in 1963 MacDonald analyzed the time delay from the drag data of the balloon satellites Explorer 9 (1963 δ1) and Echo 1 (1961 ι1). He found a statistically significant delay of 56 hours. Also a further investigation using the more recent and very accurate data of Explorer 9 again revealed a delay of slightly more than two days (Reference 28). He concluded from this that the 27-day variation results essentially from fluctuations in the solar wind. This conclusion, however, seems to be premature, since there are other explanations possible.

Bourdeau, Chandra and Neupert (Reference 8) have recently investigated the time correlation between the thermospheric temperature as revealed by Explorer 9 and the OSO measurements of the EUV from March until May 1962. There are only two maxima and two minima. The statistics with four data are, of course, very poor (Figure 7). Our figure has been adapted from their paper. It shows a comparison between the flux in the EUV lines (integrated flux) as measured by OSO 1 and the thermospheric temperature, T, from Explorer 9 (Reference 29) in the second line. Then the 10.7 cm flux follows. At the bottom the geomagnetic activity is given by Σ K_p.

With regard to the atmospheric temperatures derived from Explorer 9 it should be noted that the perigee of that satellite passed through the atmospheric bulge but remained close to the bulge center during March to May 1962. The bend-over of the dotted line connecting the Explorer 9 temperatures reflects the passage through the bulge.

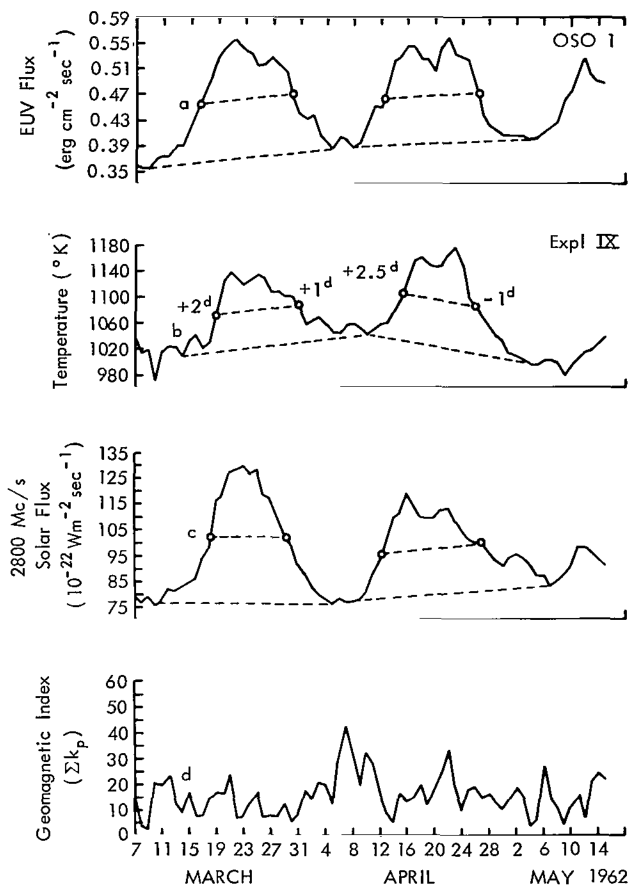

Figure 7—Comparison of the solar EUV flux from OSO 1 and the atmospheric temperature, derived from Explorer 9. Further, the solar 10.7 cm flux and the geomagnetic index Σ K_p is given. (Adapted from Bourdeau, Chandra and Neupert (Reference 8).

The delay between the EUV flux and the temperature is +2, +1, +2.5 and -1 days. This might be summarized as a delay of the order of one day. It surely needs more observational evidence before conclusions can be made. A delay time of the order of one day within the 27-day variation can be attributed to the reaction time of the thermosphere. From a theoretical investigation of this effect there is some preliminary evidence that the temperature at 120 km undergoes a 27-day variation with an amplitude of the order of 20°K.

For years of very low solar activity (1963, 1964), the 27-day variation is masked so highly by the geomagnetic activity effect, that a statistics of the phase shift is not feasible anymore. The geomagnetic activity effect, is a correlation between the geomagnetic index (K_p or A_p) and the density variations in the upper thermosphere. It was discovered by Jacchia in 1959. During the years with rather high solar activity this effect can be distinguished clearly only when a large magnetic storm occurs. The situation is reversed for the years of low solar activity, when the 27-day variation disappears in the stronger variations which are correlated with geomagnetic activity.

The superposition of the diurnal variation, the geomagnetic activity effect, and the 27-day variation is nicely displayed in the densities derived from Injun 3 (Figure 8) and from Explorer 17 (Figure 9). The data are plotted versus local time. Since the perigees move retrograde in local time, the dates (given on the top) increase toward the left side.

Figure 8 shows the density variations at an altitude of 250 km above sea level as a function of local time, t, as determined from accelerations of the satellite Injun 3 by Jacchia and Slowey (Reference 12) from December 15, 1962 through June 29, 1963. During this time the geographic latitude of the perigee covers the range from $+70^\circ$ to -60° as indicated by the numbers on the density curve. The solid and the dotted curve represent the Harris-Priester models for model parameters S = 90 and S = 100, respectively. The histograms in the upper part give the daily geomagnetic indices, A_p, and the solar 10.7 cm flux, F. At the top the dates of observations are given in the usual scale and in modified Julian dates (MJD). The black dots represent the densities during geomagnetically quiet days ($A_p \leq 2$).

No pronounced and unequivocal dependence of density on latitude can be seen, but density variations correlated even with small geomagnetic disturbances show up clearly. It seems that

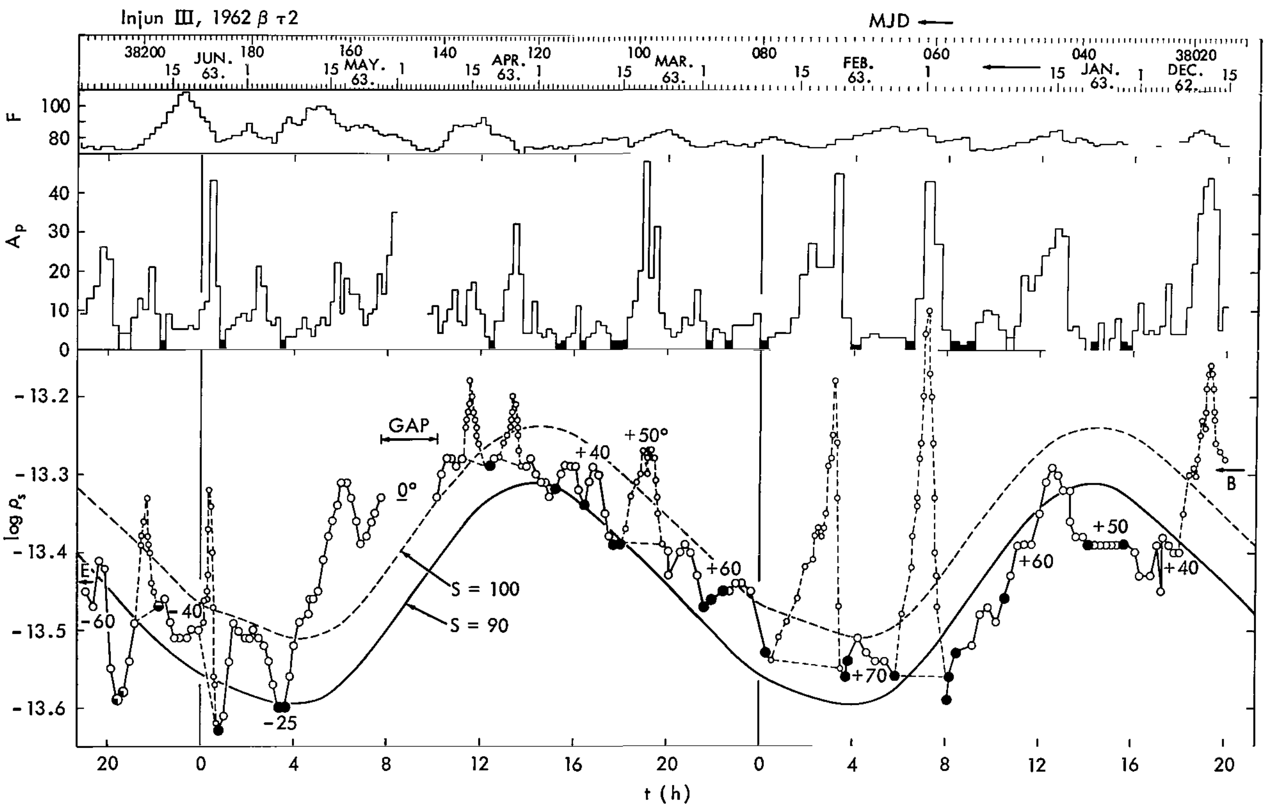

Figure 8—Densities at a height of 250 km above sea level derived from Injun 3 by Jacchia and Slowey for the time interval from December 15, 1962 through June 1963. The data are plotted as a function of local time of the perigee. The corresponding dates are given at the top, also as MJD (Modified Julian Dates). For comparison, the geomagnetic indices A_p and the solar 10.7 cm flux F are presented. The numbers on the densities indicate the geographic latitudes of the perigee. The curves represent the Harris-Priester models S = 90 and S = 100.

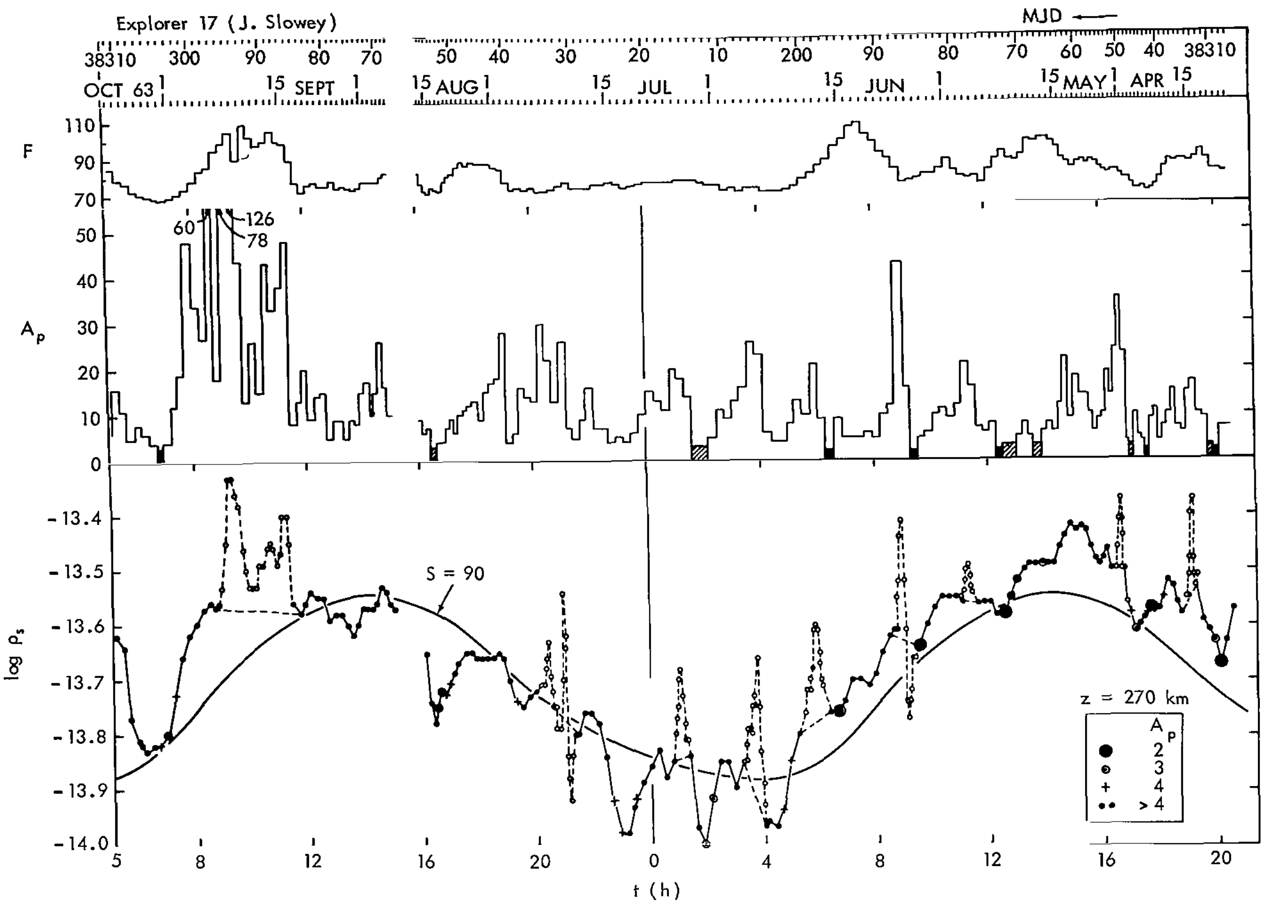

Figure 9—Densities at a height of 270 km derived from Explorer 17 by Slowey (Reference 5) for the time interval from April 8 to October 9, 1963. The data are compared with geomagnetic activity (A_p) and solar 10.7 cm flux F. The representation corresponds to Figure 8.

the reaction of the atmosphere to disturbances is greater at night and early morning than during daytime, in agreement with previous findings on atmospheric variations correlated with the 27-day variation of the solar 10.7 cm flux (Reference 26). Furthermore, there is an outstanding difference between the reaction of the atmosphere in and outside the auroral zone during geomagnetic storms as pointed out by Jacchia and Slowey. Storm-time density variations up to a factor of 3 can be seen while the satellite's perigee was at a latitude of $+70^\circ$.

The quiet-day diurnal density variation has an amplitude of a factor of 1.9, in good agreement with the appropriate theoretical model of Harris and Priester (Reference 7). As we pointed out already, the observed diurnal amplitude at 250 km for low solar activity is considerably larger than for times of high solar activity. The average solar 10.7 cm flux from December 1962 through June 1963 was $\bar{F} = 81$ in the usual units. This implies a model parameter of about $S = 100$ according to Harris and Priester, (Reference 17). This model fits the observed densities for slightly disturbed days ($4 < A_p < 10$).

For the extreme quiet days ($A_p \leq 2$) (black dots), a best fit is obtained with a model S = 90. The high precision in the density determinations requires one to account for the mean level of geomagnetic disturbance in addition to the average solar 10.7 cm flux when comparisons are made with the theoretical models.

Since we approach the solar minimum, the 27-day variations in density correlated with the daily solar 10.7 cm flux values can hardly be recognized anymore. The variations in the 10.7 cm flux normally cease completely during the solar minimum.

Figure 9 presents the densities at a height of 270 km for the time from 8 April 1963 to 9 October 1963 as determined by Slowey (Reference 5) from the drag on the Explorer 17 satellite. The graph presents the same quantities as Figure 8. The abscissa is the local time of the perigee.

Again the strong reaction of the density to increases in geomagnetic activity is very conspicuous. The deviation of the observed densities from the model values in late June and early July can be attributed to the well-known minimum of the semi-annual effect. This effect is described in Jacchia's review (Reference 1) and by Paetzold (Reference 30). The cause of this effect is not yet understood. It might be related to an energy source from the solar wind—a permanent component of the heat source which correlates with geomagnetic activity—or it might be caused by a global horizontal convective pattern.

The more recent statistics of the geomagnetic activity effect in the thermosphere revealed a very interesting feature (References 11 and 31). From the early statistics when only pronounced magnetic storms showed their effect in the thermospheric density and temperature, Jacchia found that the increase of the temperature is proportional to the geomagnetic index A_p:

$$\Delta T \sim A_p \ .$$

Now it became apparent that for A_p up to even as high as $A_p = 100$, a logarithmic approximation is a better representation:

$$\Delta T \sim \log A_p \ .$$

Jacchia and Slowey give an analytic expression which combines the two empirical relations. For instance, from the old formula it was expected that an increase in A_p from 2 to 10 would be accompanied by an increase of $\Delta T = 8^\circ K$ in the thermosphere. Now it was found that the increase is $\Delta T = 80^\circ K$, ten times as much as anticipated. It must be noted that between $A_p = 1$ and 0, the simple logarithmic approximation necessarily breaks down, since it would yield an infinite change in temperature. One might, however, wonder how large the contribution from this heat source to the total heating really is for extremely quiet geomagnetic conditions. The unsolved question is whether this heat source vanishes for $A_p = 0$ or whether a permanent "quiet" component exists.

The strong relation of the atmosphere to variations in geomagnetic activity suggests an investigation of the delay time between the atmospheric reaction and the maxima of the magnetic storms in a similar fashion as had been carried out for the 27-day variation. In Figure 10 the results are plotted using again the local time as the ordinate of the graph. The data from Explorer

9 were taken from the analysis of Jacchia and Slowey (Reference 29). For the analysis of Explorer 17 and Injun 3 the densities determined by Slowey (Reference 5) and by Jacchia and Slowey (Reference 12) were used. The three-hourly geomagnetic indices were adjusted to the time resolution of the satellite data. The phase shifts were then determined from a comparison of the curves of the density variation and the geomagnetic activity variation. The observed delay times are 6 ± 3 (m.e.) hours. There is no conspicuous dependence of the delay time on local time. Thus the atmospheric reaction occurs apparently worldwide at the same time on the day- and night-side of the earth. The statistics are, however, still poor and the conclusion might be subject to improvement when more data for afternoon and night times become available. Unfortunately it was not yet possible to investigate any dependence on latitude.

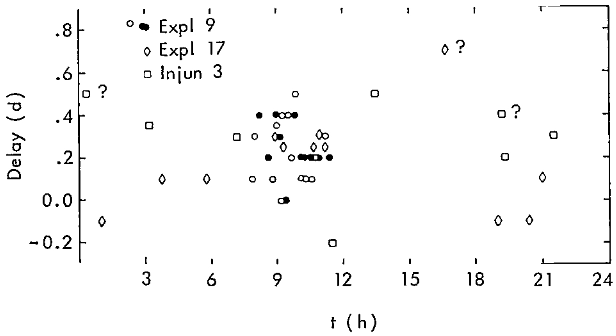

Figure 10—Phase shift between the storm time variations of geomagnetic activity and the related density variations in the thermosphere for 45 geomagnetic storms plotted as a function of local time of the satellites' perigee. On the average the density increase is 6 hours ± 3 (m.e.) hours behind the geomagnetic increase. The ordinate scale is given in parts of a day.

It can be hoped that the huge amount of data from satellite drag measurements and from direct experiments on board satellites and rockets will greatly contribute to a better understanding of the physics of the thermosphere.

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