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Solar Activity Effect and Diurnal Variation in the Upper Atmosphere

W. PRIESTER[1]

Institute for Space Studies
New York 27, New York

Abstract. It has been shown that the relation between density variations in the upper atmosphere derived from satellite drag measurements and the solar flux in the decimeter range can be given by $\rho \sim S^m$ where ρ is the density, S the solar flux, and the exponent m is a function of altitude and local time. This function has been derived for the altitudes 350, 650, and 1300 km (Figs. 1, 2, and Table 1). Further, the temperature variation at 650 km as function of solar activity, measured by the 20- or 10.7-cm flux, has been calculated for the diurnal maximum (14 h LT) and minimum (5 h LT). To explain the calculated temperature-variation, it is suggested that in addition to the heating of the F layer by solar extreme ultraviolet radiation, another important energy source must be present that also increases toward the maximum of the solar cycle.

Comparison of the fluctuations in the orbital period of the satellite 1957β (Sputnik 2), given by *Jacchia* [1958], with the fluxes of the solar 20-cm radiation, measured by the Heinrich-Hertz-Institute, Berlin, revealed a striking correlation [*Priester*, 1958, 1959], which was brilliantly confirmed by *Jacchia* [1959*a*, *b*] in satellites 1957β, 1958β_2 and 1958δ_1, using the 10.7-cm solar flux measured at Ottawa, and by *Priester and Martin* [1960] in satellites 1958β_2, 1958α, 1958$\delta_{1,2}$. The perigee heights of these satellites lie in the range of 200 to 660 km above earth's surface. The correlation was later also confirmed for greater heights (1000 to 1600 km) from the analysis of the orbital elements of the satellite 1960ι_1 (Echo I) by *Roemer* [1961], *Zadunaisky, Shapiro, and Jones* [1961], and by R. Bryant (unpublished data). The fluctuations occur almost rythmically, having periods of between 24 and 37 days. This variation is commonly referred to as the '27-day period.' As early as 1958 Jacchia suggested that the cause of the fluctuations might be a variable radiation from the sun [*Jacchia and Briggs*, 1958]. In addition, a close correlation between the fluctuations of satellite periods and the sunspot numbers was found by *Paetzold* [1959].

The fluctuations of these periods are obviously caused by density variations in the upper atmosphere. Of course, it was clear in advance that solar decimeter radiation could not be the physical cause for the fluctuations in the atmospheric density, but should merely be considered as an index of it. In our first paper on this matter [*Priester*, 1958, 1959], it was pointed out that the cause of the fluctuations in density could be seen in the heating of the atmosphere by variable X radiation of the sun, which, according to *Elwert* [1956] is mainly absorbed in the ionospheric E layer. During the Symposium on Space Research held in Nice, January, 1960, it became clear from a paper by *Hinteregger, Damon, Hiroux, and Hall* [1960], who have measured the extreme ultraviolet spectrum of the sun, that the major source of the heating of the upper atmosphere is the absorption of EUV radiation, which mainly occurs in the altitude range 150 to 250 km. Most important seems to be the 304 A line of ionized helium. For theoretical reasons, we can expect a very close correlation between the so-called 'slowly varying component' of the solar radiation in the 3- to 30-cm range, which, according to *Waldmeier and Mueller* [1950], is due to thermal emission by coronal condensations and both the X rays and the 304 A line that should also originate in these condensations.

From the first rough analysis [*Priester and Martin*, 1960] it turned out that this correlation between air density and the solar decimeter

[1] National Academy of Sciences, National Research Council Research Associate with National Aeronautics and Space Administration, on leave from Bonn University Observatory.

radiation [3–30 cm], which we called the 'solar activity effect,' is, as a first approximation, represented by $\rho \sim S$, where ρ is the density and S the flux of the 20-cm or the 10.7-cm radiation. This proportionality between density and flux was also used and confirmed by *Jacchia* [1960]. It is the main concern of the present paper to give a more sophisticated relation between density and solar flux.

But first we have to consider another strong effect in the upper air densities, which is closely related physically to the 'solar activity effect': the diurnal variation of density. This reaches its peak at about 14 h local time, followed by a decline until sunset. During the night, the density continues to decline, though more slowly. After sunrise, the curve begins to rise steeply until it reaches the peak. The amplitude of the variation increases with increasing altitude. At 200 km, it is only a few per cent, contrary to the solar activity effect which yields quite pronounced density variations even at this altitude. But at about 300 km the diurnal variations become the most important characteristic of the density fluctuations, which reach an amplitude of about a factor of 10 at 650 km. This effect was found nearly at the same time and separately by *Wyatt* [1959], *Jacchia* [1959*b*], *Priester and Martin* [1960] and *Paetzold and Zschoerner* [1960]. Detailed results for the heights 210, 562, and 660 km were given by *Priester, Martin, and Kramp* [1960] and by *Jacchia* [1960].

There are three further effects causing density variations in the upper atmosphere. One of these, correlated with large magnetic storms, was found by *Jacchia* [1959*c*]. He confirmed this result by analyzing the changes of period of seven satellites during the November 1960 event [*Jacchia*, 1961]. It was also confirmed by *Jastrow and Bryant* [1961] on the data of Echo I. This effect is believed to result from the solar corpuscular radiation. A possible mechanism, proposed by *Dessler* [1959], consists of heating the upper atmosphere by means of hydromagnetic waves. They arise at heights between 3×10^4 and 6×10^4 km as a result of instability, which occurs when the stream of solar particles interacts with the earth's magnetic field. The dissipation of the energy of these waves would occur at a height of approximately 150 to 200 km and heat the F_1 layer. From this we might expect that in general the quiet-day solar wind makes a nonnegligible contribution to the heating of the F layer.

The second effect has a semiannual period. It was found by *Paetzold and Zschoerner* [1960, 1961]. This phenomenon is characterized by a general decrease in density during the months of June, July and January. A similar effect exists in the frequency of occurrence of auroras and in the general variation of the geomagnetic indices when they are averaged over many years [*Bartels*, 1932]. This supports the suggestion that the semiannual effect is also due to solar corpuscular streams.

The third effect was recently found by *Rasool* [1961]. It is a correlation between density variations in the upper atmosphere and the occurrence of large meteor showers. But this effect is generally small and therefore not very significant. It yields density increases of about 5 per cent, which last for a few days, as a statistical analysis of the density data obtained during the occurrence of fifteen showers has shown. In this study, Rasool used the density data derived by *Martin* [1961]. These data are reduced to a standard level of solar activity (solar 20-cm flux $S = 170.10^{-22}$w/m^2 c/s) and also reduced to the mean perigee height. Further, the required density scale heights for the individual local times of perigee were taken from the atmospheric model of *Priester, Martin, and Kramp* [1960]. The orbital elements were mainly taken from the papers by *Jacchia* [1959] and *Zadunaisky* [1960]. As the magnetic storm effect and the meteoritic effect, however, are rather transient, they will not influence our statistics on the solar activity effect and on the diurnal variation, since the few disturbed days can simply be omitted.

During the course of the investigation of the solar activity effect it turned out that the density variation can be given by

$$\rho \sim S^m \qquad (1)$$

where ρ is the density and S the solar flux. The empirical quantity m is derived from the satellite drag measurements. Preliminary values of m as a function of height were previously given by *Martin, Neveling, Priester, and Roemer* [1961]. *Paetzold and Zschoerner* [1961] also give the variation of the solar activity effect with heights up to 650 km. Their numerical values are in satisfactory agreement with our results. From our present knowledge of the heating of the upper atmosphere owing to absorption of solar extreme ultraviolet radiation and the theory of heat conduction in the thermosphere and exosphere, we are led to suppose that the exponent m is not only a function that increases with altitude but also depends on the local time. In order to derive these functions, we used the atmospheric densities calculated by Martin for the altitudes 350 and 650 km and the densities obtained by *Roemer* [1961] and by R. Bryant (unpublished data, 1961) from the orbital elements of satellite 1960ι_1 (Echo 1) for altitudes between 1000 and 1600 km. The successive maxima and minima of the 27-day density variation were correlated with the corresponding extremes of the 20-cm and the 10.7-cm solar flux. In order to avoid the possible influence of other effects that also change the density at a given height, the amplitude of each maximum was calculated by taking the difference between the maximum density and the average of the two adjacent minimum values, and vice versa, for determining the amplitude of a minimum. The same procedure was followed in determining the amplitudes for the extremes of the solar flux. In this way the exponents were calculated using the formula

$$m = \frac{\log \rho_{\max} - \log \rho_{\min}}{\log S_{\max} - \log S_{\min}} \qquad (2)$$

The results for 650 km, derived from Vanguard I, and for 350 km, derived from Explorer I, are plotted in Figures 1 and 2 as functions of local time. Despite the fact that we used the best satellite data available at present, the scattering of the values of m is very large, because m has to be derived as a quotient of two small numbers. Plotted are only those values for which the denominator in formula 2 was larger than 0.100. In order to see how much scatter is the result of the uncertainty in the radio fluxes, we used both the 10.7-cm and the 20-cm fluxes. For the altitude range between 1000 and 1600 km, data from satellite Echo I were only available for the interval of local time between 12 and 20 h. For this reason only an average value of m can be given for this time interval. We found for 1300 km $m = 2.0 \pm 0.4$. Despite the large scatter in Figure 1, a diurnal variation of m at an altitude of 650 km can be seen, with $m = 1.2 \pm 0.3$ at 14 h local time and $m = 3.0 \pm 0.4$ at about 5 h local time. A preliminary curve has been drawn to fit the points considering their individual accuracy. It turns out that the relative amplitude of the density variations due to the solar activity effect is greater at dawn than

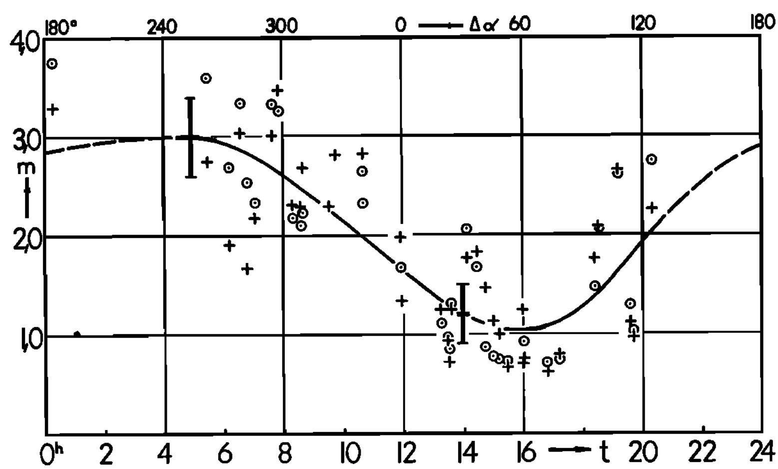

Fig. 1. Variation of the exponent m with local time t for an altitude of 650 km, derived from the satellite Vanguard I; m is defined by $\rho \sim S^m$ where ρ is the atmospheric density and S the solar flux. In deriving m we used the 20-cm flux (circles) and the 10.7-cm flux (crosses) in order to diminish the uncertainty of the results due to the scatter of the radio data. The upper line gives $\Delta\alpha = \alpha_\pi - \alpha_\odot$ where α_π is the right ascension of the satellite perigee, $\alpha_\odot$ the right ascension of the sun. The large crosses at 14 hours and 5h 20m mark the values used in the further calculations (see Table 1).

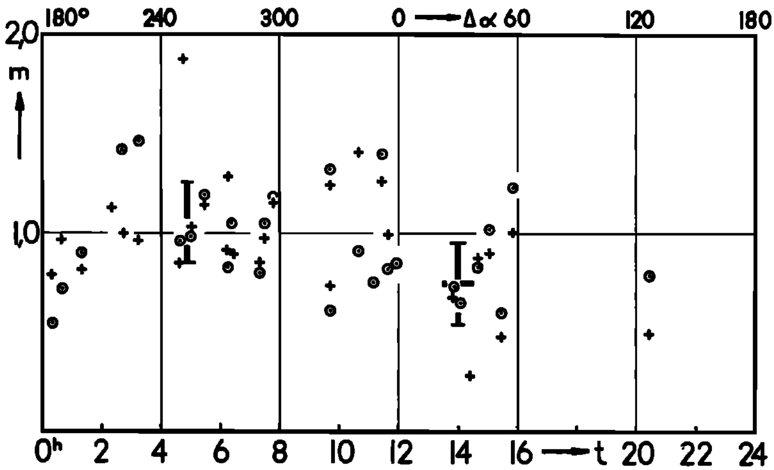

Fig. 2. Variation of the exponent m with local time for an altitude of 350 km, derived from the satellite Explorer I. The scales and the symbols are the same as in Figure 1.

early in the afternoon. Obviously this is caused by the combined effects of the heating owing to absorption of solar EUV radiation during daytime and the heat conduction. It would be of interest to derive the temperature variation in this part of the lower exosphere as a function of local time and solar activity. To do this we need a model of the upper atmosphere that fits the satellite data and gives the physical properties as a function of height, local time, and solar activity. We used a model whose main characteristic is a linearly increasing pressure-scale-height H_p. In this model the gradient dH_p/dh, where h is the altitude, is a function of local time and solar activity; this dependence was derived from the satellite data. A model of this kind was calculated by *Nicolet* [1960]. A similar model, which we have now derived (Priester, unpublished data, 1961) has been shown to give an excellent representation of the densities derived from satellites in the range from 350 to 1600 km.

TABLE 1. The Exponent m as Function of Altitude and Local Time

Altitude	14 h LT	5 h LT	Remarks
km			
350	$m = 0.55$	$m = 1.05$	Calculated
350	$m = 0.75 \pm 0.2$	$m = 1.05 \pm 0.2$	Observed
650	$m = 1.2 \pm 0.3$	$m = 3.0 \pm 0.4$	Observed
1300	$m = 2.2$	...	Calculated
1300	$m = 2.0 \pm 0.4$	...	Observed

Using this model and the two m values calculated for 650 km for 14 h and 5 h LT we were able at first to derive m as a function of local time and altitude and to check these results with the findings plotted in Figure 2 for 350 km and with the result for 1300 km described above. We found a satisfactory agreement between calculated and observed m values (see Table 1).

Furthermore, it was easy to calculate the variation of T/M as a function of local time and solar activity, where T is the temperature and M the mean molecular weight. The data for an altitude of 650 km are plotted in Figure 3. Unfortunately it is not possible to derive the variation of T only, because the absolute value of the mean molecular weight and its variation with time and solar activity are not known with accuracy. But from the fact that the atmosphere is shifted upward during the daytime, yielding a bulge near the subsolar point, we can make some reasonable estimates of the variation of M. We used a linear relation between M and dH_p/dh where M varies from 13.8 at just before dawn and at minimum solar activity to 16.0 as 14 h local time and maximum solar activity. With this estimate, it was possible to derive prelimnary representation of the temperature variation as a function of solar activity, indicated by the 20- or the 10.7-cm flux, for both the diurnal maximum at 14 h local time and the diurnal minimum at about 5 h local time. The

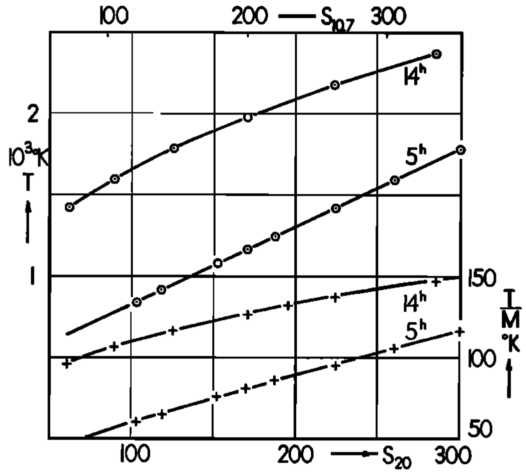

Fig. 3. Variation of temperature T (upper two curves) and of T/M (lower two curves) with solar activity, measured by the 20-cm solar flux (lower scale) and the 10.7-cm flux (upper scale). Both fluxes are expressed in units of 10^{-22} w/m² c/s. M is the mean molecular weight. The data refer to an altitude of 650 km and the two curves show the variations at 14 h and 5 h local time, respectively.

results are plotted in the upper part of Figure 3. We can see the expected increase of temperature with solar activity for both diurnal maximum and minimum. But from the viewpoint of only heat conduction and absorption of EUV radiation, it is difficult to understand why the difference in temperature for the diurnal extremes is almost constant, or is even decreasing with increasing solar flux. This can also be seen in the T/M values and holds for any reasonable estimate of the variation in M. The most plausible explanation seems to be to assume an additional heating process which is available during both day and night and which also increases with solar activity. It is reasonable to suppose that this mechanism involves the solar wind, also invoked to explain the seminannual variation and the magnetic storm effect. Only very rough estimates of the fraction of heating due to solar wind can be given from the temperature variation in Figure 3. We should expect that this effect alone is able to maintain the exosphere during the night at a temperature level of about 1000°K during maximum solar activity when the 20-cm flux is greater than 250 in the usual units. In addition, at solar minimum the contribution of this effect to the temperature should be smaller than 300°. When we compare the density variations in the upper atmosphere calculated from formula 1 using the m values derived from the 27-day variations with the mean densities given by *King-Hele and Walker* [1961] for 1958, 1959, 1960, we find a slightly larger variation in the latter data. This perhaps can also be explained by the additional heating process mentioned above.

The conclusions must be considered as very preliminary, but investigation of the solar activity effect and the diurnal variation during the present solar cycle seems to offer a possibility of getting better insight into the energy balance of the upper atmosphere. For this, however, it is necessary to have very accurate satellite data.

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