PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Properties of the Upper Atmosphere Determined from Satellite Orbits

L. G. Jacchia

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IV. THE UPPER ATMOSPHERE

Properties of the upper atmosphere determined from satellite orbits

By L. G. Jacchia

Smithsonian Astrophysical Observatory, Cambridge, Massachusetts, 02138, *U.S.A.*

1. Satellites and the atmosphere

Irregularities in the Earth's gravitational potential perturb the orbits of artificial satellites in a great many ways. They cannot, however, change the mean value of the major axis of an orbit, which determines the period of revolution. To change the orbital period a dissipative force is required, such as the drag exerted on the satellite by the Earth's atmosphere. Solar radiation pressure does not affect the period of a satellite provided the satellite does not cross the shadow cone of the Earth. If the orbit is all in daylight, the effect of the force cancels out after one revolution. If, however, the satellite goes in and out of the Earth's shadow, and the orbit is not circular, the effect does not cancel out and radiation pressure will cause a change in the period.

Atmospheric drag and solar radiation pressure are the only major forces that are known to affect the period of a satellite. Other forces, such as the interaction of an electrically charged satellite with atmospheric ions or with the magnetic field of the Earth, are undoubtedly present, but they are generally quite small. For low-orbiting satellites, with perigees below 300 km, the effect of atmospheric drag on the orbital period is so much larger than that of solar radiation pressure, that the latter can be neglected for all practical purposes. Above 400 km, however, radiation pressure makes itself felt, and above 700 km it may become more important than atmospheric drag. Actually, these figures vary a great deal with the phase of the solar cycle, since the atmosphere expands or contracts with solar activity. At sunspot minimum the effect of radiation pressure becomes comparable with that of atmospheric drag at about 600 km, while at sunspot maximum it does not become so below 1100 km.

If the orbit of a satellite is sufficiently elongated, most of the drag occurs around perigee, so we can, with appropriate formulas and assumptions, use the drag to compute atmospheric densities at perigee height or thereabouts; if solar radiation pressure is important, its effect must be subtracted from the observed drag.

The first property of the upper atmosphere that was discovered when satellites were launched is its great variability. In 1958 the Sun was very active and the atmospheric drag of the Vanguard 1 satellite—whose perigee height was then, and still is, about 650 km—wildly fluctuated back and forth, often by as much as a factor of 2 in a matter of a week or two, following the appearance and disappearance of spots on the solar disk.

2. Sunspots and the atmosphere

The variation of the atmosphere with sunspot activity is interpreted as being caused by variations in the intensity of emission of extreme ultraviolet radiation. Ever since spectrographs mounted on rockets had been sent aloft, shortly after the end of World War II, it had been found that in the ultraviolet spectrum of the Sun there are numerous emission lines, extending well beyond the region where the photospheric continuum fades to invisibility. These lines, which come from highly ionized atoms (Fe XIV, Fe XV, Si IX, Si X, He II, etc.) such as are found in the lower solar corona, are absorbed by the Earth's atmosphere, as Hinteregger (1962) has shown, at heights between 100 and 200 km. This is precisely the region in which the temperature of the atmosphere shows a tremendous increase with height, so it was logical to assume that the heating of the upper atmosphere was mainly a result of the absorption of radiation emitted in the e.u.v. lines. The inferred variability of the e.u.v. radiation indicated that it came from coronal regions above sunspots—and this was brilliantly confirmed by the first Orbiting Solar Observatory (Oso 1), which showed that the intensity of most e.u.v. lines, integrated over the whole disk of the Sun, varies in phase with the number or the area of sunspots.

Sunspot activity is often measured by the so-called Wolf number, which is arrived at by combining a great number of sunspot observations made all over the world. It usually takes several months before definitive Wolf numbers are published, and in view of the variable shape and configuration of sunspots, it cannot be expected to be more than a coarse, semiquantitative index of solar activity. There is, however, another solar quantity that varies with sunspot activity and is readily available as soon as it is measured—and that is the solar flux at decimetric wavelengths. The 10·7-cm flux, observed daily with a radio telescope at Ottawa, is generally used as a serviceable index of solar activity, and the parallelism between its variations and those of the upper atmosphere is remarkable.

Early satellite observations also showed that, in addition to varying with sunspot activity, the Earth's atmosphere reacts to magnetic storms. As is known, intense magnetic storms occur when clouds of charged particles, ejected from the Sun in the course of a solar flare, collide with the Earth's magnetosphere. A solar flare is a short-lived phenomenon, which generally lasts an hour or less. Although a great deal of ultraviolet radiation is emitted by the flare region, no reaction has been observed in the atmosphere that can be directly connected with this enhanced radiation. This does not mean that there is no heating of the atmosphere during a flare: only, the heating is too small and of too short duration to be detected from the motion of satellites. If a magnetic storm follows a flare, it does so after approximately 1 day, and it generally lasts the better part of 24 h, or even longer. It is then that the atmosphere is noticeably heated and expands; the duration of the atmospheric perturbations matches that of the magnetic storm, but lags some 6 or 7 h behind it. More recently it has been found that not only magnetic storms but even the smallest variations in the magnetic field of the Earth, such as are observed during magnetically quiet days, are reflected in temperature and density variations in the upper atmosphere.

3. Structure of the upper atmosphere

Other types of atmospheric variation have been detected by satellites, such as the diurnal and the semi-annual variations, and in a moment we shall examine each type of variation in greater detail. Before we do that, however, let us see what satellites have taught us about the general structure of the atmosphere. Figure 1 shows four atmospheric-density profiles in logarithmic scale; they represent the variation with height of the daytime

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

maximum and the night-time minimum density, respectively, for two extremes of solar activity. The first thing that strikes our attention is the tremendous range of the density variation at heights above 300 km: at 600 km the possible range reaches a factor of 300. Another striking feature of the diagram is that in all profiles the slope decreases with increasing height. If the atmosphere were isothermal and of homogeneous composition, the gas laws tell us that the density would decay exponentially with height; in a logarithmic scale all density profiles would be straight lines. Clearly this is not the situation. What,

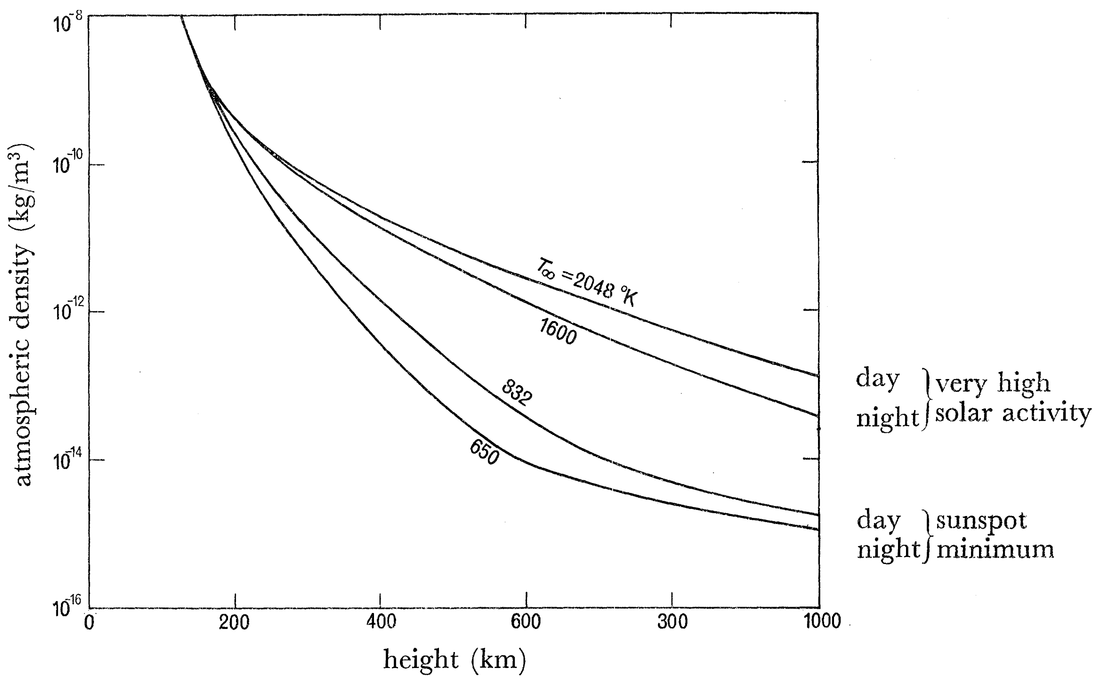

FIGURE 1. Day and night density profiles in the upper atmosphere at sunspot maximum and at sunspot minimum. The profiles were computed from a model atmosphere (Jacchia 1965), assuming a maximum day temperature 28 % higher than the corresponding night-time minimum.

then, varies with height? Is it the temperature, is it the composition, or both of them? The answer was given by Nicolet (1960), who showed that above 250 km or so the observed density profiles could be satisfactorily reproduced if for each of them the temperature was assumed to be a different constant and the composition varied with height according to the law of diffusion in a gravitational field. The constant temperatures above 250 km range from 650 °K to about 2000 °K, or maybe even a little higher, according to solar activity and hour of the day. These temperatures are all much higher than the 200 °K that is found at the height of 100 km, so there must be a sharp increase in temperature in the region between 100 and 250 km. This is exactly as it should be, since the e.u.v. radiation from the Sun is absorbed just in that region. Figure 2 shows three temperature profiles corresponding to three different levels of solar activity. The region from the beginning of the temperature rise, at about 90 km, to where the rise stops, is called the *thermosphere*; the height at which the rise stops is called the *thermopause*. As can be seen, the thermopause is shifted higher and higher with increasing solar activity.

From sea level to a height of about 90 km mixing keeps the atmosphere homogeneous in composition; this region is called the *homosphere*. As everybody knows, the atmosphere in this region is 78 % nitrogen and 21 % oxygen, both in molecular form, plus 1 % argon and traces of various other natural and unnatural gases. Proceeding to heights above 90 km we have a first change in composition owing to the dissociation of molecular oxygen operated by solar e.u.v. and the consequent production of atomic oxygen. When we reach 100 km, diffusion sets in and further contributes to change atmospheric composition;

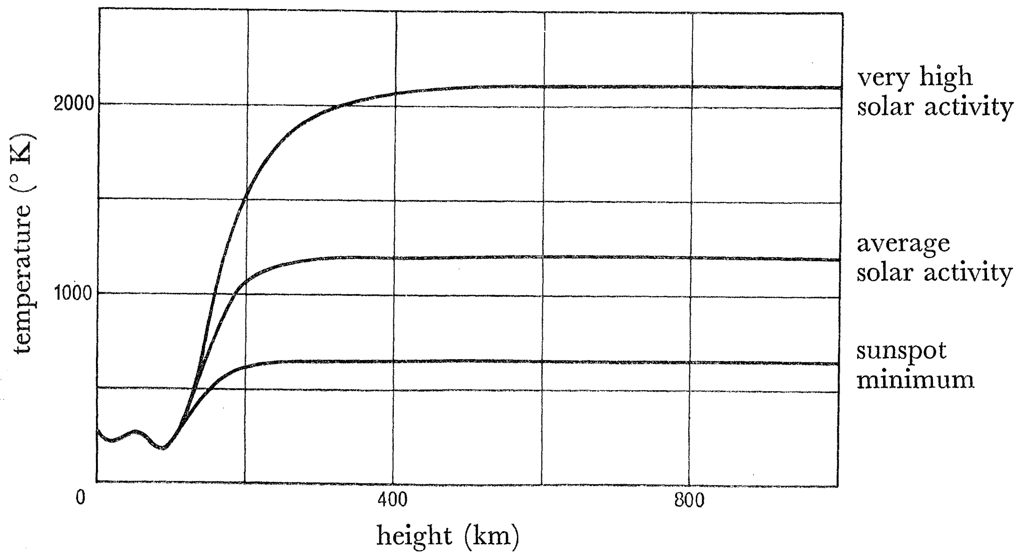

FIGURE 2. Atmospheric temperature profiles for three stages of solar activity.

above 120 km the atmosphere can be considered, in a first approximation, to be in diffusion equilibrium, a condition in which the density variation with height of each atmospheric constituent is independently governed by gravity and temperature, as though it were the only constituent. This region, in which atmospheric constituents behave differently from each other, is called the *heterosphere*. The thermosphere covers the lower part of the heterosphere. The overlap of the two regions should not cause any confusion, because in one case the division is made according to temperature and in the other according to composition.

As we proceed to greater and greater heights, we leave all the heavy constituents behind. Molecular oxygen becomes unimportant above 250 km and nitrogen above 400 or 500 km, until we are left with an atmosphere of atomic oxygen. If we proceed further up, we find that even atomic oxygen gives way to lighter constituents such as helium and hydrogen, which were only trace impurities at sea level, and above 1000 km hydrogen, the lightest of all gases, emerges as the lone survivor. Actually, all these heights depend very much on solar-activity conditions, as can be seen from figure 3, which shows how the concentration of the major atmospheric constituents varies with height for three levels of solar activity.

When the density of the atmosphere is about 10^{-15} g/cm^3, i.e. 10^{-12} of that at sea level, the mean free path of atmospheric particles is of the same order of magnitude as the scale height. The height at which this occurs is often taken as the base of the *exosphere*; at times of low sunspot activity it can be as low as 350 or 400 km, but at sunspot maximum it goes up to 700 and even 900 km.

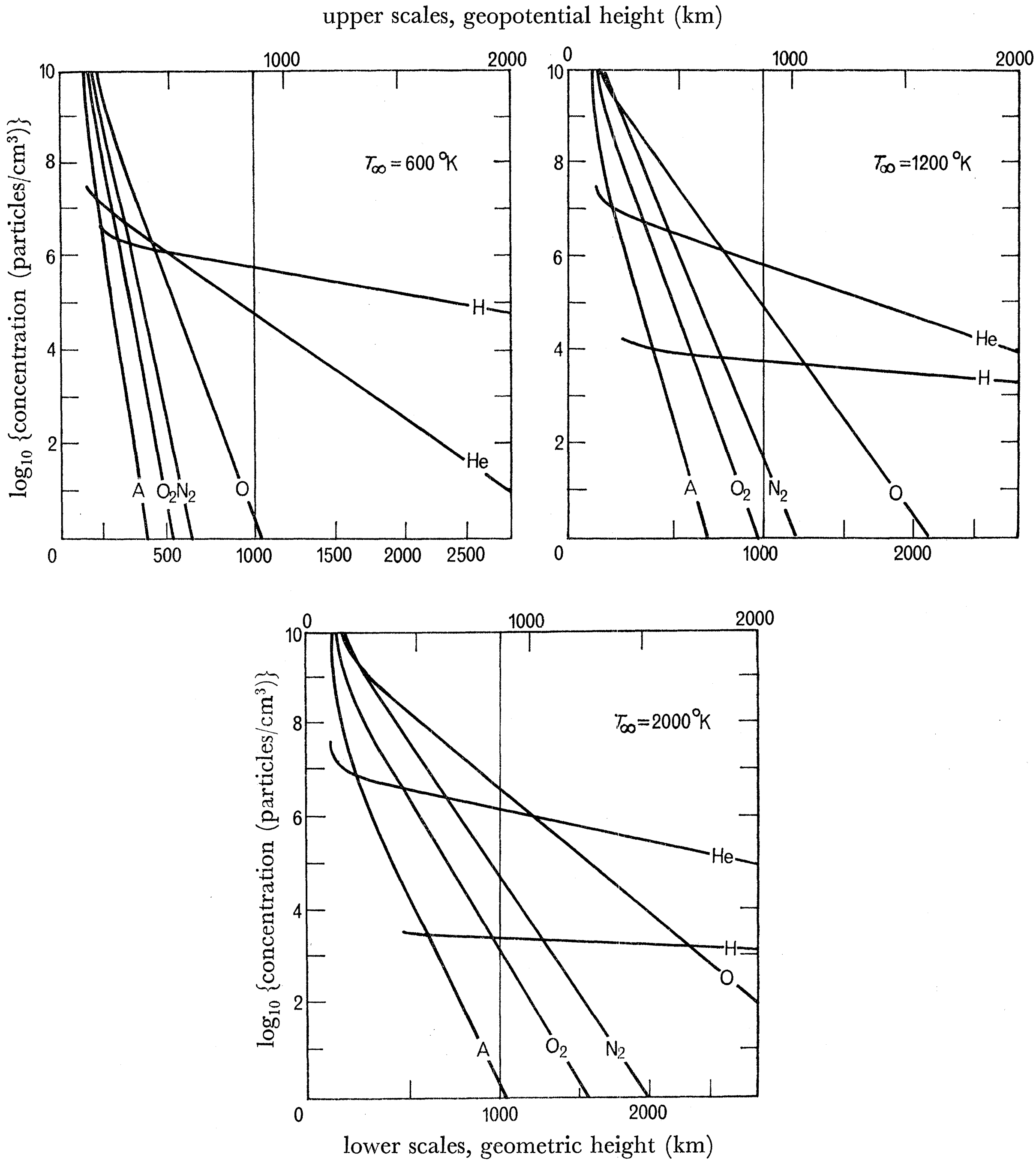

FIGURE 3. Concentration of the principal atmospheric constituents as a function of height for three exospheric temperatures.

If we assume that the atmosphere is essentially in diffusion equilibrium above 120 km, we can construct atmospheric models for different temperature profiles, provided we know what the temperature and the composition are at 120 km. Although there still remains considerable uncertainty about such boundary conditions, various atmospheric

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

models have been constructed in this fashion (Nicolet 1963; Harris & Priester 1962; Jacchia 1965). They are useful in the analysis of atmospheric variations, because with their aid we can convert density variations into temperature variations, which can be intercompared much more easily. Also, we cannot have an understanding of atmospheric phenomena unless we are able to analyse the temperature variations that underlie them. Any variation of solar energy will result in a temperature variation in the atmosphere; density variations are only a consequence. As can be seen from figure 1, a change of 350 degC in the temperature can change the density by a factor of 10 at 600 km; at 200 km, however, it will change the density by less than a factor of 2, or even not at all if the temperature is high enough.

Present-day atmospheric models are much less than perfect. Their greatest weakness comes from the lack of adequate data on temperature, density, and composition—and their variations with solar activity—at the base of the heterosphere, around 120 km. It is hoped that the situation will be somewhat improved during the coming rise of solar activity, through experiments with instrumented rockets, falling spheres, chemical releases, radio sounding, etc. Another difficulty arises at greater heights where helium and hydrogen become important, because the concentrations of these gases are not accurately known and depend, especially that of hydrogen, on their escape rate, which varies enormously with temperature.

4. Variations with solar activity

Let us now go back to upper-atmosphere variations. Today we recognize four distinct types of variation, namely: (1) a variation with solar activity, (2) a variation with geomagnetic activity, (3) a semi-annual variation, and (4) a diurnal variation.

In the variation with solar activity we must distinguish between the slow variation with the 11 y solar cycle and the day-to-day variation. The latter is caused not only by the forming and dissolving of sunspots, but also by their appearing and disappearing on the solar disk owing to the Sun's rotation with a period of 27 days. If we take the values of the temperature above the thermopause—let us call it the 'exospheric' temperature—that were derived from satellite drag from 1958 to 1964, from sunspot maximum to sunspot minimum, and plot them against the corresponding values of the 10·7 cm solar flux, we find that they fall approximately on a straight line. To be more exact, we find a linear correlation for the maximum temperature, which occurs in the daytime, and another linear correlation for the minimum temperature, which occurs at night (figure 4), from which we derive that the temperature increases 3·6 degC per unit flux at night and 4·6 degC in daytime. If, on the other hand, we try to derive the relations between solar flux and exospheric temperature from a much shorter time interval, comparable with the 27-day period of the solar rotation, the temperature variation per unit flux turns out to be only about one-half of what we had obtained before. The difference is not surprising, because the e.u.v. radiation that heats the atmosphere comes not only from sunspots, but also from the whole disk of the Sun, and by analogy with the decimetric solar flux we must expect also the disk component to vary with the solar cycle.

Sunspots often have the tendency to cluster in one long-lasting, active area, leaving the rest of the solar surface relatively free of spots. When that happens, the number of sunspots on the visible disk shows a strong 27-day variation, as the rotation of the sun periodically brings the active area into view from the Earth; sometimes this 27-day periodicity can be followed uninterruptedly for as long as 2 years, as in 1960–62. In such cases the same periodicity is found in the 10·7 cm solar flux and in the temperature and density of the upper atmosphere (see figure 5).

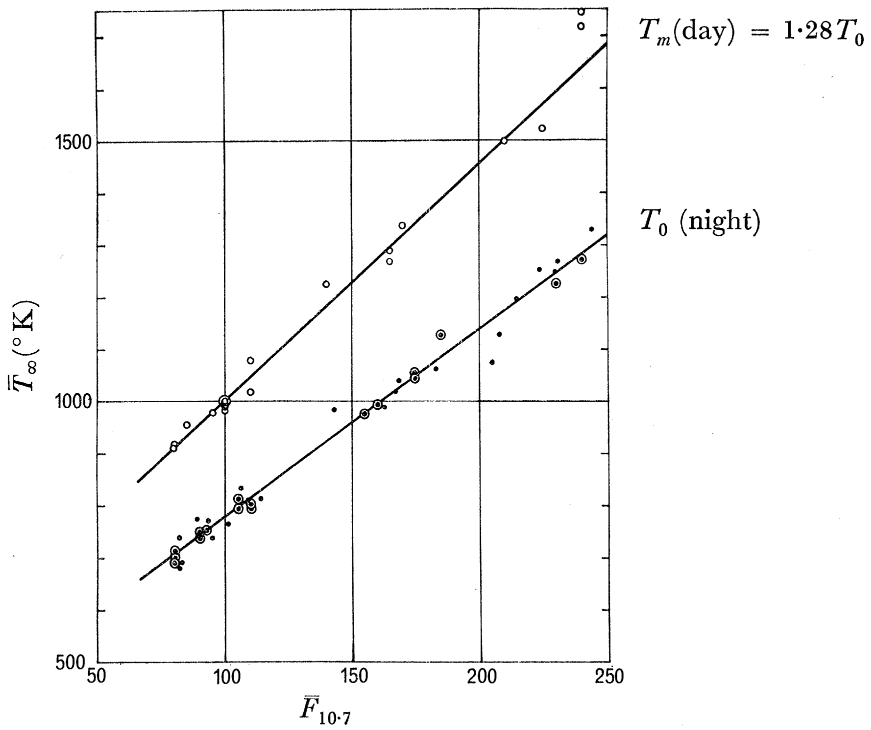

FIGURE 4. Day and night exospheric temperatures as a function of the 10·7 cm solar flux. Temperatures and fluxes are mean values, from which the effect of the '27-day' oscillations has been removed by smoothing. The temperatures were computed from the densities derived from satellite drag by use of atmospheric models (Jacchia 1965).

5. VARIATIONS WITH GEOMAGNETIC ACTIVITY

As we said before, the density variations with sunspot activity can be satisfactorily explained by variable heating in the thermosphere caused by changes in solar e.u.v. radiation. No such ready explanation is found for the variations with geomagnetic activity. The amplitude of the density variation during geomagnetic perturbations varies with height in approximately the same manner as that of the solar-activity effect, so we think that also here we have to deal mostly with thermospheric heating. The question is: What mechanism causes the heating? Ion currents and hydromagnetic waves have been variously singled out as possible heating agents, but the truth of the matter is that we are still waiting for a good explanation.

In the meantime let us see what we know about the phenomenon. Satellite-drag data have shown that the atmospheric perturbation lags some 6 or 7 h behind the geomagnetic disturbance. This is likely to be due to conduction time, if the heat is generated in the lower thermosphere, where conduction time is high. Since observations have shown that the atmospheric perturbation can be detected as an increase in density at heights as low as

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

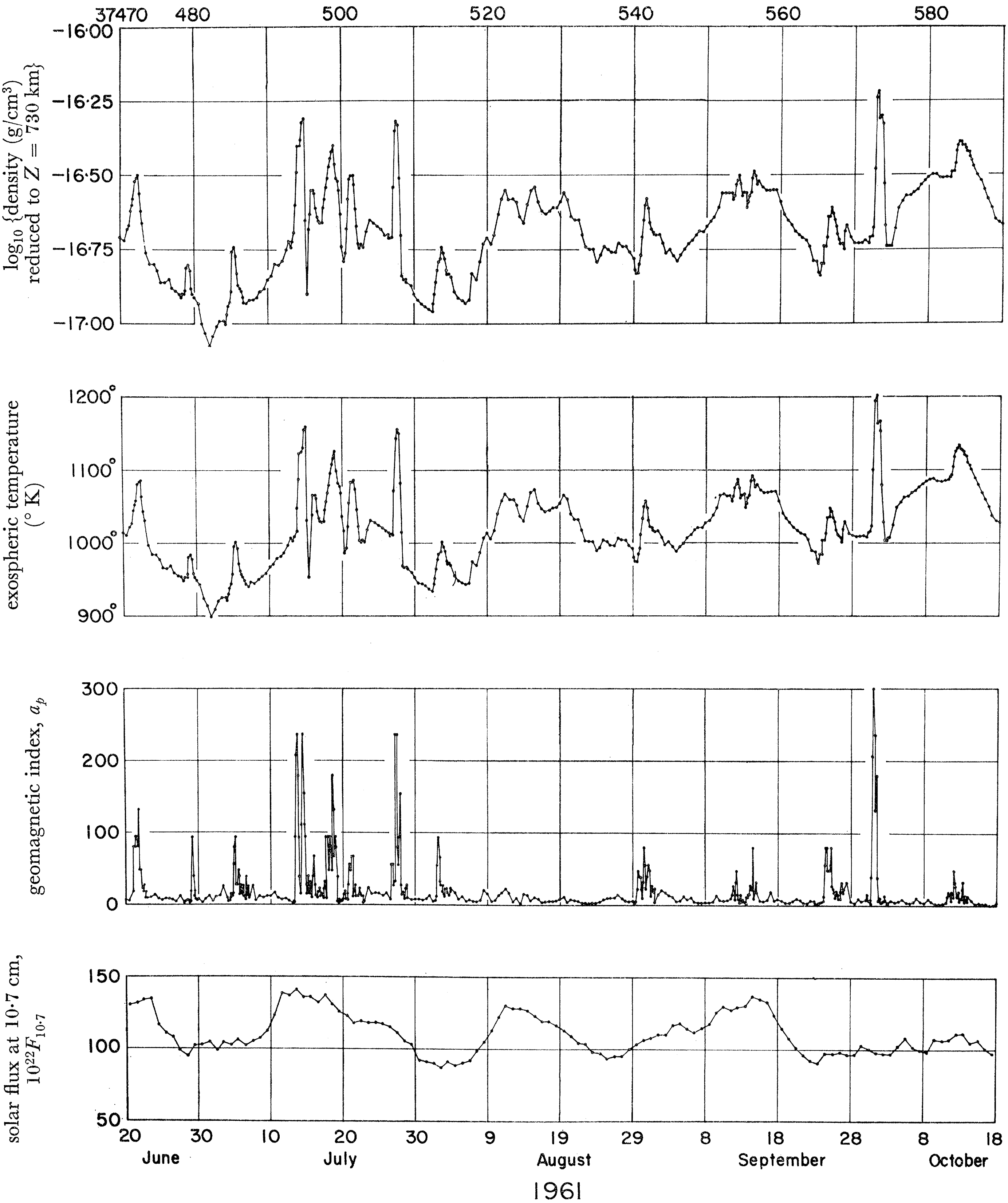

FIGURE 5. Atmospheric densities and temperatures derived from the drag of the Explorer 9 satellite (1961 δ1), compared with the geomagnetic index a_p and the 10·7 cm solar flux. The drag was determined from precise position measurements on photographs taken with the Baker-Nunn cameras. The abscissa is the Modified Julian Day (J.D. minus 2400000·5).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

160 km, we must conclude that the heating occurs at even lower heights, confirming the point. The observed time lag is 7 h at low and middle latitudes, but seems to be a little smaller, about 6 h, in the auroral zones. Also, in the auroral zones the atmospheric perturbation appears to be somewhat enhanced, by some 20% on the average, although occasional enhancements by a factor of 2 or more are not to be excluded on the basis of observations.

If we convert the observed density variations to temperature variations on the basis of existing atmospheric models—a procedure that is not entirely correct, because the models are valid for quiet geomagnetic conditions and assume equilibrium, but is the best we can do—we find that during magnetic storms the temperature increases by about 1 degC for every unit increase of the 3 h geomagnetic planetary index a_p. This index is proportional to the amplitude of the variation of the geomagnetic field during a 3 h interval and varies from zero to a maximum of 400. Outside magnetic storms the Earth's magnetic field also varies a little, mirroring the variations in the solar wind impinging on the magnetosphere, as was proved by the instruments aboard the Mariner 2 probe and the Imp satellites. During these periods of comparative calm, however, the temperature change per unit a_p is considerably greater: for example, when a_p increases from 0 to 10, the temperature increases by about 65 degC, which gives a rate of change 6·5 times greater than at the time of a storm. While for values of a_p larger than 50 the temperature seems to be linearly related to a_p, for smaller values it seems to be linearly related to the K_p index, which is a logarithmic function of a_p (see figure 6). It almost looks as though the process through which the ordinary solar wind heats the atmosphere were different from the one that operates during magnetic storms proper.

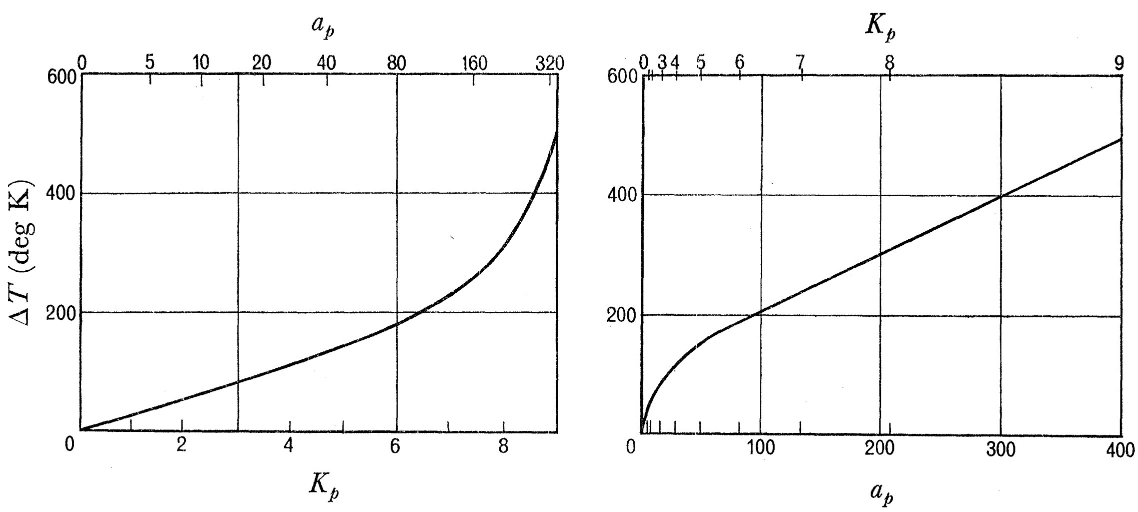

FIGURE 6. Atmospheric heating ΔT as a function of the 3 h geomagnetic indexes K_p (above) and a_p (below).

If the geomagnetic effect in the atmosphere is caused by the interaction of the solar wind with the Earth's magnetosphere, we have an interesting problem. From Mariner 2 measurements we know that the K_p index is related to the solar-wind velocity (km/s) by the relation

$$v = 330 + 67 \cdot 5 K_p.$$

When $K_p = 0$ the variation of the magnetic field is zero, but not the solar-wind velocity, which then is down to its minimum value of 330 km/s. Under such conditions is there no contribution to the heating of the atmosphere from the solar wind, or is there a background residual heating from it? This question may have some bearing on the semi-annual effect, as we shall see.

6. The semi-annual variation

The semi-annual variation is the least understood of all. Of the variations with sunspot activity we know the primary cause and we think we know the mechanism that produces them. Of the geomagnetic effect we know what the primary cause is, but we do not know the mechanism. Of the semi-annual effect we know neither the cause nor the mechanism.

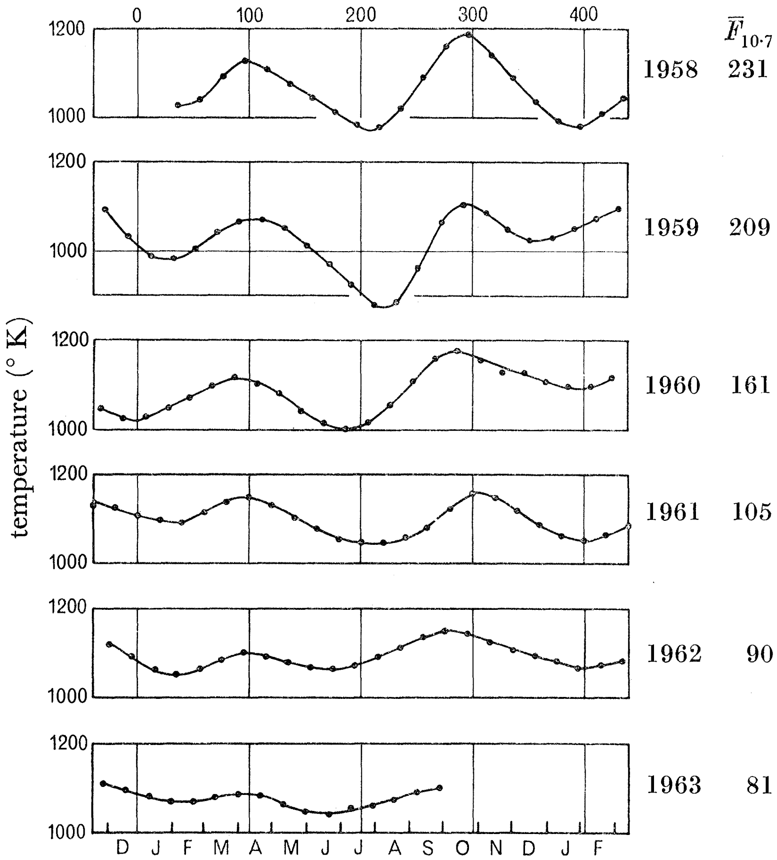

Figure 7. The semi-annual variation in the night-time exospheric temperature from 1958 to 1963, as derived from the drag of five satellites. Days after 1 January at the top of the figure. Plotted are night-time temperatures reduced to a standard 10·7 cm solar flux value of 175. The average of $F_{10\cdot7}$ is given for each year.

The density of the atmosphere at satellite levels shows a deep minimum in July followed by a high maximum in October. In January we have a secondary minimum, followed by a secondary maximum in April. The maxima follow the equinoxes by 3 or 4 weeks, and the minima follow the solstices by the same time interval. The amplitude of the variation is quite large at sunspot maximum, but decreases toward sunspot minimum (figure 7).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

A semi-annual variation with essentially the same characteristics is observed in the ion density of the F_2 layer at mid-latitudes. Those who study the neutral atmosphere suspect that the cause of the semi-annual oscillation is to be sought in the variation of ion densities, while the ionosphere people suspect that the variation of the neutral atmosphere must be at the base of the ion-density variation. Even if we find out who is right, however, we will still not know why a semi-annual variation is there at all.

Hypotheses have been advanced, of course, and the primary cause has been variously sought in a change with latitude in the emission of the solar wind, in the seasonal change of tilt of the Earth's magnetic dipole with respect to the solar wind, and in seasonal variations in the planetary circulation at thermospheric levels.

The first hypothesis requires the Sun to emit more corpuscular radiation in the bands of heliographic latitudes where the sunspot areas are located. As the heliographic latitude of the Earth changes, we would then experience a variation of the solar wind with maxima around the equinoxes. The trouble is that the magnitude of the observed variation would require the corpuscular radiation to occur in unlikely narrow beams. It is true that around the equinoxes magnetic storms are more frequent; we do not, however, observe the sustained higher level of geomagnetic activity that would explain a smooth semi-annual variation. As a way out, it has been suggested that some of the magnetic-storm particles might be trapped for longer periods in the Earth's magnetic field, giving rise to a smoothly varying component in the population of the radiation belts, which in turn would be responsible for heating the atmosphere.

The second hypothesis starts from the fact that the interaction between the solar wind and the magnetosphere, for some unknown reason as we saw, causes a heating of the atmosphere. As the Earth moves around the Sun, the tilt of the magnetic axis of the Earth changes and this causes a slight change of shape in the boundary of the magnetosphere. During one-half of the year the tilt repeats the variation of the other half, except for an inversion of the poles, so it stands to reason that if this variation has any effect at all on atmospheric heating, the effect should have a semi-annual periodicity.

The third hypothesis requires air to move at thermospheric levels from the summer pole to the winter pole, where it would sink and dissipate its heat content into the cold mesosphere, the region between 50 and 90 km. Through this process the thermosphere would be cooled around the solstices, but not around the equinoxes, when the atmosphere above the two poles should have the same temperature.

Interesting results have been recently obtained by Cook & Scott (1966) from the drag of the Echo 2 satellite. At the height of this satellite, about 1100 km, the amplitude of the semi-annual density variation is enormous, reaching a factor of 3 near sunspot minimum. If the variation were caused only by temperature changes in the thermosphere, the resulting amplitude in the helium and hydrogen atmosphere at 1100 km should be smaller, not greater, than the amplitude observed at lower heights. Cook (1967) suggests that the semi-annual variations in the thermosphere may be accompanied by a change in the level at which the diffusion process for helium starts. Since the concentration of helium at any given height is very sensitive to a change in this level, we could have an amplification of the semi-annual effect at heights where helium is the main atmospheric constituent.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

7. The diurnal variation

If solar e.u.v. radiation is a major source of upper-atmospheric heating, the temperature will go up after sunrise and fall at night, and atmospheric densities will do the same. Satellites show the effect very conspicuously (figure 8). As the perigee of a satellite orbit slowly moves from daylight into the shadow of the Earth and back into daylight again, with a period that usually amounts to a few hundred days, the drag rises and falls with the same period. From this change we can deduce that atmospheric densities reach a minimum around 4 a.m. and a maximum around 2 p.m. The temperature range is large at the equator and progressively decreases towards the poles, as it logically should.

While the range in density at any given height can be determined quite accurately, it is not so simple to find out what the underlying temperature range is. The reason for this uncertainty is that the atmospheric models that are used to convert density variations into temperature variations presuppose equilibrium conditions, which are not realized when we have to deal with 24 h oscillations. If we were to trust static temperature models, we would obtain a daily temperature increase on the equator by a factor of 1·28 over the minimum night-time temperature. The only dynamic models in existence are the Harris-Priester models, which form the basis of the Cospar 1965 atmosphere, but it is questionable whether they give the right answer regarding the temperature, considering the artificial assumptions that had to be made to reproduce the observed density variations. In any case, these models give a temperature range by a factor of 1·50. Recent nitrogen scale heights obtained by Spencer, Taeusch & Carignan (1966) from rocket-borne mass spectrometers would indicate that the diurnal temperature factor is not greater than 1·25. Preliminary experiments we are now making at the Smithsonian Astrophysical Observatory with dynamic models that take into account lateral conduction and diffusion give a factor of 1·35 or so.

If we consider surfaces of equal atmospheric density above the Earth, we find that these surfaces bulge out where the temperature is higher, in the sunlit hemisphere. For this reason one often speaks of a 'diurnal bulge' in the upper atmosphere. If e.u.v. absorption and conduction were the only factors governing the diurnal variation, we would expect the diurnal bulge to move in latitude with the seasons following the migration of the subsolar point. Moreover, we would expect that at the equinoxes, when days and nights are of equal length everywhere on Earth, the temperature would decrease from the centre of the bulge outward by the same rate in all directions. Recent observations of high-inclination satellites with perigees above 500 km have shown that at those heights things might be different. The diurnal bulge seems to move but little from the equator, and it appears to be elongated in the north–south direction. The picture is reminiscent of the ion-density distribution in the F_2 layer, which shows two maxima, one on either side of the geomagnetic equator, around 2 or 3 p.m. local time. If the similarity is more than a matter of pure coincidence, we may well suspect the ions having something to do with it. Forced to move in the magnetic field of the Earth, ions may drag along enough neutral gas to cause winds that could appreciably alter the temperature distribution in the upper atmosphere. Winds should be there in any case, even without the benefit of ion motion, because of the pressure gradients engendered by the diurnal variation. The winds resulting from the interaction of ions driven along magnetic

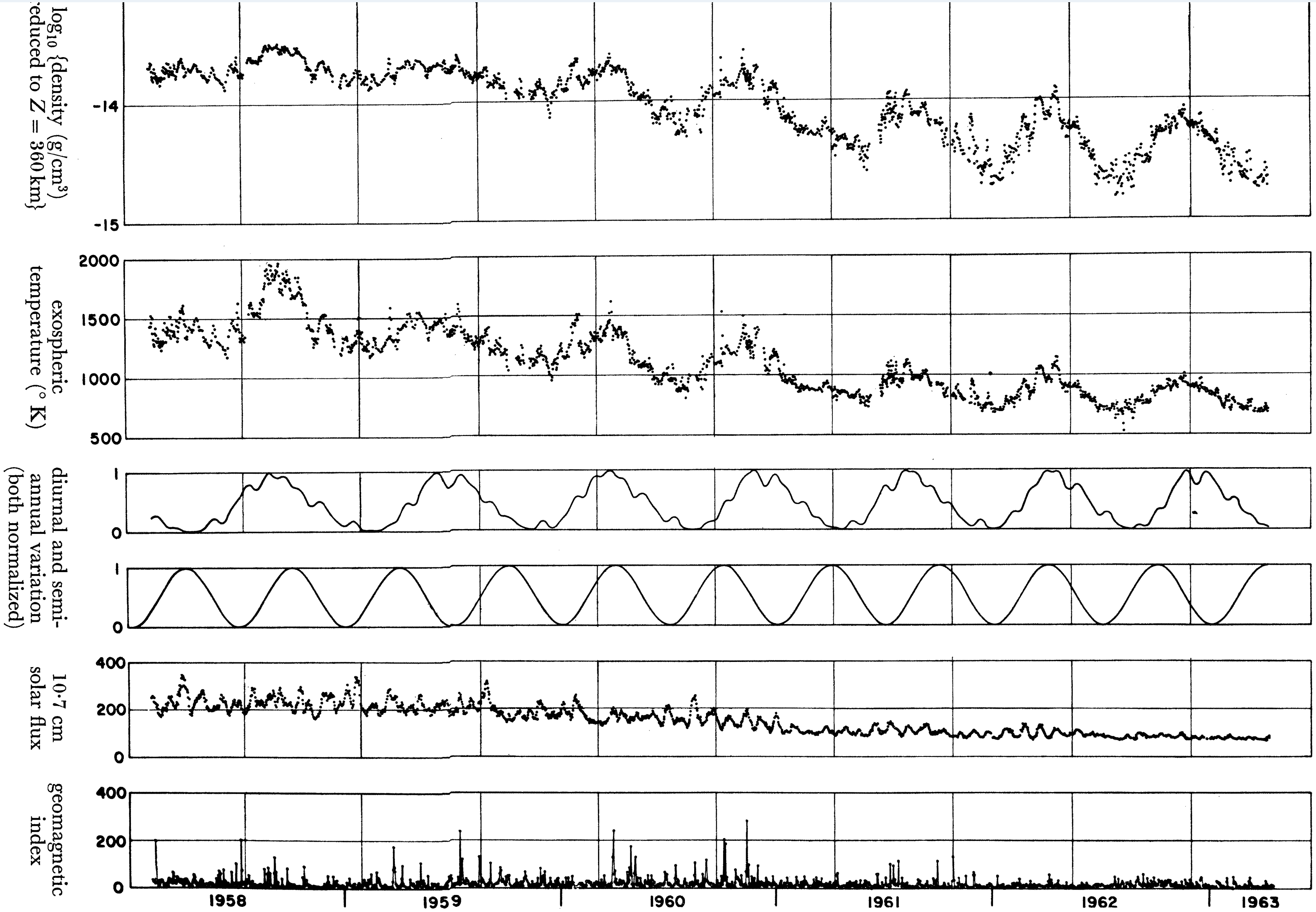

FIGURE 8. Densities and temperatures derived from the drag of the Explorer 1 satellite (1958 α), compared with solar and geomagnetic parameters. The diurnal-variation curve, with constant amplitude, is shown for reference, as well as a constant-amplitude semi-annual curve with maxima and minima roughly coincident with those of the temperature variation. The 'wiggles' in the diurnal-variation curve are due to the rapid oscillations in latitude of the satellite's perigee; the perigee approaches the diurnal bulge from the morning side. Notice how the response in the density curve to temperature variations increases as the temperature decreases. The abscissa is the Modified Julian Day (J.D. minus 2400000·5) (Jacchia 1965).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

lines of force and neutral gas impelled by pressure gradients and deflected by Coriolis forces have recently been computed by Kohl & King (1966), who find for them velocities that can reach 35 m/s at sunspot maximum and 100 m/s at sunspot minimum; they conclude that the magnitude of these velocities is such that winds cannot be neglected in any dynamical model of the atmosphere.

Winds of a systematic nature blowing at 100 m/s from west to east are postulated by King-Hele & Scott (1966) to explain the observed secular decrease in the orbital inclination of satellites. Whether the diurnal temperature variation can provide such winds is rather questionable.

8. Conclusion

As we can see, at every step in our journey we seem to have ion clouds above our horizon, although we do not quite know what exactly they are doing there, whether they affect the temperature or whether they are merely decorative like fair-weather clouds. Or, rather, in one instance, in the geomagnetic effect, we know they must be more than decorative; in the semi-annual and the diurnal effects we can only suspect that their presence has something to do with what we observe. We have not mentioned ions in the variation with solar activity—but, since we are at it, we might just as well ask ourselves whether that is the only variation from which the effect of ions is excluded. It is true that much of the observed variation can be ascribed to variations in solar e.u.v. radiation, because we know it is there. But could not the solar wind also have an 11 y variation whose effect on atmospheric temperature is superimposed on, and nearly indistinguishable from, that of the e.u.v. radiation? This is not only possible, but actually very probable. Cosmic-ray records show an 11 y fluctuation attributable to a variation in the density of the interplanetary plasma with the solar cycle. In addition, we know that the variation in the solar e.u.v. radiation causes a change in the ion density of the ionosphere, and this in turn may effect the temperature of the neutral gas.

By analysing the drag of artificial satellites, we have learned a great many facts about the upper atmosphere. Since none of the satellites launched before 1961, and only six since then, were intended for the exploration of the neutral atmosphere, the knowledge acquired from satellite drag can be considered as a welcome, but unintended, dividend of the space effort. As knowledge of facts has accumulated, a few problems have been clarified, but many more have been raised. We will doubtless find some clues to a few of these problems by monitoring the atmosphere through more precise drag analysis, using satellites in a greater variety of orbits. It seems safe to predict, however, that the solution of the problems will come only by combining the knowledge acquired from observations and experiments of many different types, both inside the atmosphere and outside.

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