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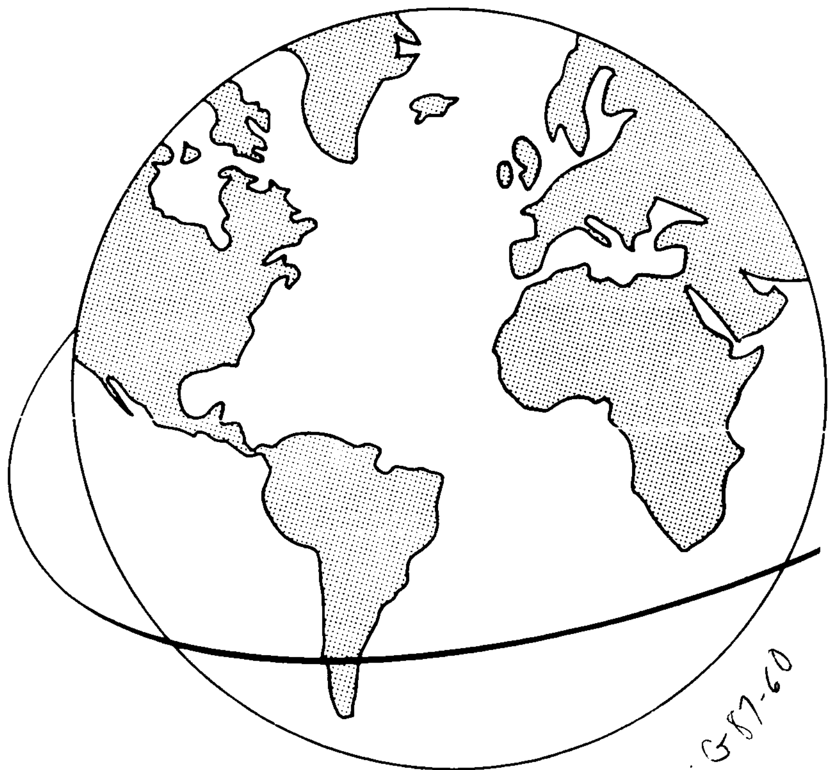
RECENT RESULTS IN THE ATMOSPHERIC REGION ABOVE 200 km AND COMPARISONS WITH CIRA 1965

L. G. JACCHIA



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ABSTRACT

At the Ninth COSPAR Meeting in Vienna, May 10-19, 1966, COSPAR Working Group IV (Properties of the Upper Atmosphere) adopted a proposal that for the following meeting, to be held in London in July 1967, several reviews should be compiled. They were to contain "comparisons of individual measurements with the COSPAR International Reference Atmosphere 1965, with emphasis on the IQSY data." The present paper was compiled in response to that request; it contains such comparisons and reviews the most important research developments in the region above 200 km during the past 2 years.

RÉSUMÉ

Au cours de la Neuvième Réunion, du 10 au 19 mai, 1966, à Vienne, du Comité sur la Recherche de l'Espace (COSPAR), L'Équipe IV du COSPAR (Propriétés de la Haute Atmosphère) a adopté la proposition que plusieurs compte-rendus soient compilés pour la prochaine réunion devant avoir lieu à Londres en juillet 1967. Ceux-ci devaient comprendre des "comparaisons de mesures individuelles avec l'atmosphère de référence internationale de 1965 du COSPAR, et faire ressortir les données de l'Année Internationale du Soleil Tranquille (IQSY)". La présente communication a été compilée en réponse à cette demande; elle contient de telles comparaisons et revoit les plus importants développements des recherches dans la région au-dessus de 200 km au cours des deux dernières années.

КОНСПЕКТ

На девятом съезде Комитета по исследованию космического пространства (COSPAR) имевшего место в Вене, 10-19 мая 1966 г., IV$^{\text{я}}$ Рабочая группа COSPAR (Свойства верхних слоев атмосферы) принял предложение о том чтобы несколько обзоров были подготовлены к следующему съезду в Лондоне, в июле 1967 года. Обзоры должны содержать „сравнения отдельных измерений с COSPAR Международной эталонной атмосферой 1965 г. с эмфазой на данные Международного года спокойного Солнца (IQSY)". Настоящая статья была подготовлена в ответ на это требование; она содержит таковые сравнения и рассматривает наиболее важные развития исследований за последние 2 года в области превышающей 200 км.

RECENT RESULTS IN THE ATMOSPHERIC REGION ABOVE 200 KM AND COMPARISONS WITH CIRA 1965

L. G. Jacchia

1. INTRODUCTION

Following is a brief review of the most important developments in upper atmosphere research in the region above 200 km since the compilation of the COSPAR International Reference Atmosphere (CIRA,1965). We shall limit ourselves to those developments and problems that have a direct bearing on the construction of atmospheric models.

This paper is to be presented at the Open Session of Working Group IV, Tenth Meeting of COSPAR, London, July 23-29, 1967. The work reported on here was supported in part by Grant No. NsG 87-60 from the National Aeronautics and Space Administration.

2. DENSITIES

The basic problem today, just as 3 years ago, is the lack of simultaneous observations of different atmospheric parameters, i. e., of density, temperature, and composition. Density is monitored systematically at heights from 200 to 700 km and sporadically to 1200 km and higher, by analyzing the orbital drag of artificial satellites. Densities obtained in this manner are quite reliable down to 10^{-17} g/cm^3, i. e., to a height of some 600 km at sunspot minimum and 1100 km at sunspot maximum; at greater heights, trouble arises from solar-radiation pressure, from possible changes in the drag coefficient, and from an increasing uncertainty in the density scale height and other atmospheric properties. Detailed density data from orbital drag over extensive periods of time have been published by Cook and Scott (1966), Jacchia and Slowey (1965), Jacchia and Verniani (1965), Jacobs (1967a), and Roemer (1966). Yearly averages of daytime and nighttime densities have been derived from the drag of many satellites by King-Hele (1965) and King-Hele and Quinn (1965, 1966). Fea (1965, 1966) has attempted to derive densities at 3500 km from the drag of Satellite 1963-30D. Densities from the nearly instantaneous drag measured by a dynamometer in the San Marco 1 Satellite have been published by Broglio (1967).

Densities are derived also from pressure gauges and mass spectrometers mounted on rockets and satellites. Although most of the measurements with rockets are made at heights below 200 km, a few Soviet rockets have pushed the measurements to 300 km. Surveys of density data obtained in this fashion are to be found in review papers by Mikhnevich (1965) and Horowitz (1966).

There has been considerable discussion on a possible discrepancy by a factor of nearly 2 between densities obtained by the orbital-drag method and those obtained from gauges in rockets and satellites. Critical reviews of the problem of satellite-drag coefficients have been published by Cook (1965, 1966a, b); the variation of the drag coefficient with height has also been considered by Izakov (1965). Friedman (1966) has discussed the density measurements by means of ionization gauges.

3. TEMPERATURES

Temperature determinations above 200 km, as we all know, are made by indirect methods and are more difficult to obtain and much less reliable than density determinations. Spencer, Brace, Carignan, Taeusch, and Niemann (1965), and Spencer, Taeusch, and Carignan (1966) have used rocket-borne, ejectable "thermosphere probes" to measure nitrogen density profiles from which neutral-gas temperatures can be deduced; in addition, the instruments in the probes measure the electron temperature. The electron temperatures showed a drop by a factor of 2 during the solar eclipse of July 20, 1963, proving that EUV is the major heat source in the F region In 1964 to 1965, during the quiet-sun period, the nighttime temperatures derived from the nitrogen profiles approached a constant value of about 725° K above 250 km, in good agreement with the CIRA tables and with the static models of Jacchia (1965a), which henceforth will be referred to as J65. The daytime temperatures were close to 825° K, considerably lower than the 1050° K predicted by CIRA, but in good agreement with J65, when the latitude of the observing site is taken into account.

Temperatures derived by Reber and Nicolet (1965) from mass-spectrometer data obtained from Explorer 17 in May and April 1963 show the same picture. The night temperatures, 650° to 700° K, are again in agreement with CIRA and J65, but the daytime temperature, 825° ± 75° K, while in agreement with J65, is some 250° lower than the CIRA value. The quasidynamic CIRA models require a temperature range nearly twice as large as the static J65 models to produce a given amplitude in the diurnal variation. Since in both models the relation between temperature and density is determined uniquely by the hydrostatic equation, the observational results from mass spectrometers, if taken at face value, would indicate that the diurnal temperature range of the CIRA tables is too large and that, paradoxically, the static models fit the observations better.

Pokhunkov (1966) has derived two temperature profiles from rocket-borne mass-spectrometer data. Both profiles show a temperature gradient between 120 and 150 km that is considerably smaller than that of the CIRA tables. Above 160 km, however, the situation is reversed, and in the profile of November 15, 1961, at 1600 local time, the temperature continues to rise and reaches 1470° K at 325 km, some 400° higher than the value given by the CIRA tables, i. e., with a discrepancy in the other direction with respect to the thermosphere probes and the Explorer 17.

Blamont and Chanin-Lory (1965) have published a survey of their determinations made between 1960 and 1964 using the thermal broadening of the D line emitted by resonance scattering from sodium clouds released by rockets.

4. COMPOSITION

Most of the mass-spectrometer data on atmospheric composition come from the 100- to 200-km region; the composition above 200 km in model atmospheres such as CIRA must be considered as a theoretical extrapolation of quantities observed at lower heights. Explorer 17, however, measured N_2 to nearly 500 km, oxygen to almost 700 km, and helium to 800 km (Reber and Nicolet, 1965). A comparison of the Explorer 17 data with the CIRA 1965 models shows the following. The observed N_2 density is some 50% higher at night, but low by a factor of 2 in daytime. Oxygen density, on the other hand, is lower than the tabular values, by a factor of 3 at night and by a factor of 5 to 10 in daytime. Helium is also lower than in the CIRA tables, by a factor of 2 at night and by a factor of 5 in daytime. For all three constituents the observed density variation from day to night is considerably smaller than the variation predicted by CIRA.

5. DIURNAL VARIATIONS

The CIRA tables represent the diurnal variation in the atmosphere at low latitudes; they are, however, unable to suggest what happens at higher latitudes. A worldwide, empirical model of the diurnal variation was given by Jacchia (1965b); in it the diurnal bulge was depicted as being almost radially symmetric and centered at the latitude of the subsolar point. Results from the two high-inclination satellites Explorer 19 and Explorer 24 seemed to cast some doubts about the validity of this model at high latitudes. Jacchia and Slowey (1967a) suggested that the bulge might be elongated in the north-south direction and permanently centered at the equator; Keating and Prior (1967a) found that the discrepancies in the results from the two Explorer satellites were minimized when the center of the bulge was shifted to the <u>winter</u> hemisphere.

To cast some light on the problem, Jacchia and Slowey (1967b) undertook a study of the diurnal variation using drag data on seven satellites from 1958 to 1966. The perigee of low-inclination satellites moves in latitude with a period much shorter than that of the day-to-night cycle. If, also, the bulge moves in latitude with the subsolar point, the two motions combined give origin to a complicated pattern of oscillations in the drag that is quite different from the pattern that would result if the bulge were stationary on the equator. The observed data show unmistakably that the original model of the bulge, nearly symmetrical and migrating in latitude with the subsolar point, is correct (see Figure 1). The discrepancies in high latitudes revealed by Explorers 19 and 24 are, apparently, caused by a winter helium bulge, which will be discussed later.

As we mentioned earlier, the diurnal variation of the exospheric temperature is much larger in CIRA than in J65, although in both models the ratio of the daytime maximum to the nighttime minimum is a constant: 1.50 for CIRA 1965 and 1.28 for J65. According to Jacchia and Slowey (1967b), this

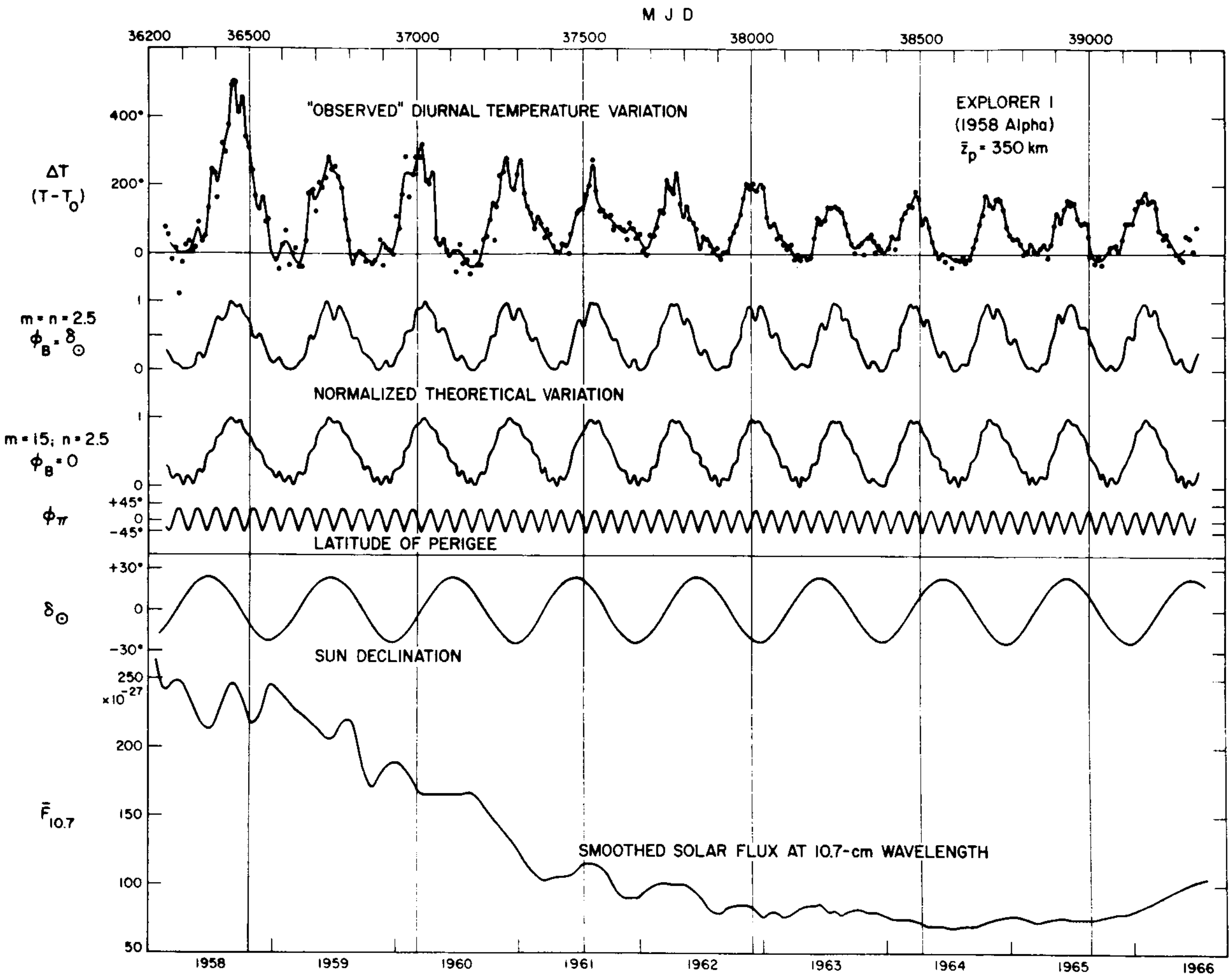

Figure 1. The diurnal temperature variation as derived from the drag of Explorer 1 using the static J65 models. The observed variations (top) are compared with the normalized theoretical variations according to the model of Jacchia (1965a), which assumes a migrating, nearly symmetrical diurnal bulge, and that of Jacchia and Slowey (1967a), in which the bulge is elongated and stationary. Curves of the latitude of perigee, the declination of the sun, and the smoothed 10.7-cm solar flux are added for reference. MJD in the abscissa is the Modified Julian Day (Julian Day minus 2 400 000.5).

ratio, when computed from the static models, is actually not quite constant. In 1958 to 1962 it was close to 1.32, but dropped rather suddenly to 1.26 in 1963 to 1966.

The diurnal density variations derived from the drag of four satellites, ranging in perigee height from 250 to 563 km, have been compared with predictions made with the CIRA and the J65 models on the basis of the 10.7-cm solar flux; the results are shown in Figure 2. An inspection of this figure reveals that:

1. The CIRA models represent fairly well the nighttime densities, although a systematic trend in the residuals with solar activity can be discerned.

2. The daytime densities in the CIRA models are systematically too high above 300 km, increasingly so as solar activity declines. This results in an exaggerated amplitude of the diurnal density variation. At 563 km around sunspot minimum the observed amplitude is only one-half of that predicted by CIRA.

3. The J65 models give the correct amplitude of the diurnal variation over the whole height range covered by the four satellites; both daytime and nighttime densities are correctly represented by the models above 350 km; hardly any dependence on solar activity can be discerned in the residuals.

4. At 250 km both sets of models predict densities that are a little too high: by 10% in CIRA and by 15% in J65.

As we saw before, not only is the amplitude of the diurnal density variation too large in CIRA above 300 km and for low solar activity, but so is that of the diurnal variations in temperature and composition. We are encountering the same difficulty in the three-dimensional model of the diurnal variation with which we are experimenting at the Smithsonian Astrophysical Observatory (Friedman, 1967). Since the discrepancies seem to be roughly proportional to the amplitude of the diurnal variation, and therefore to the density gradients, it may well be that lateral convection, so far neglected in all

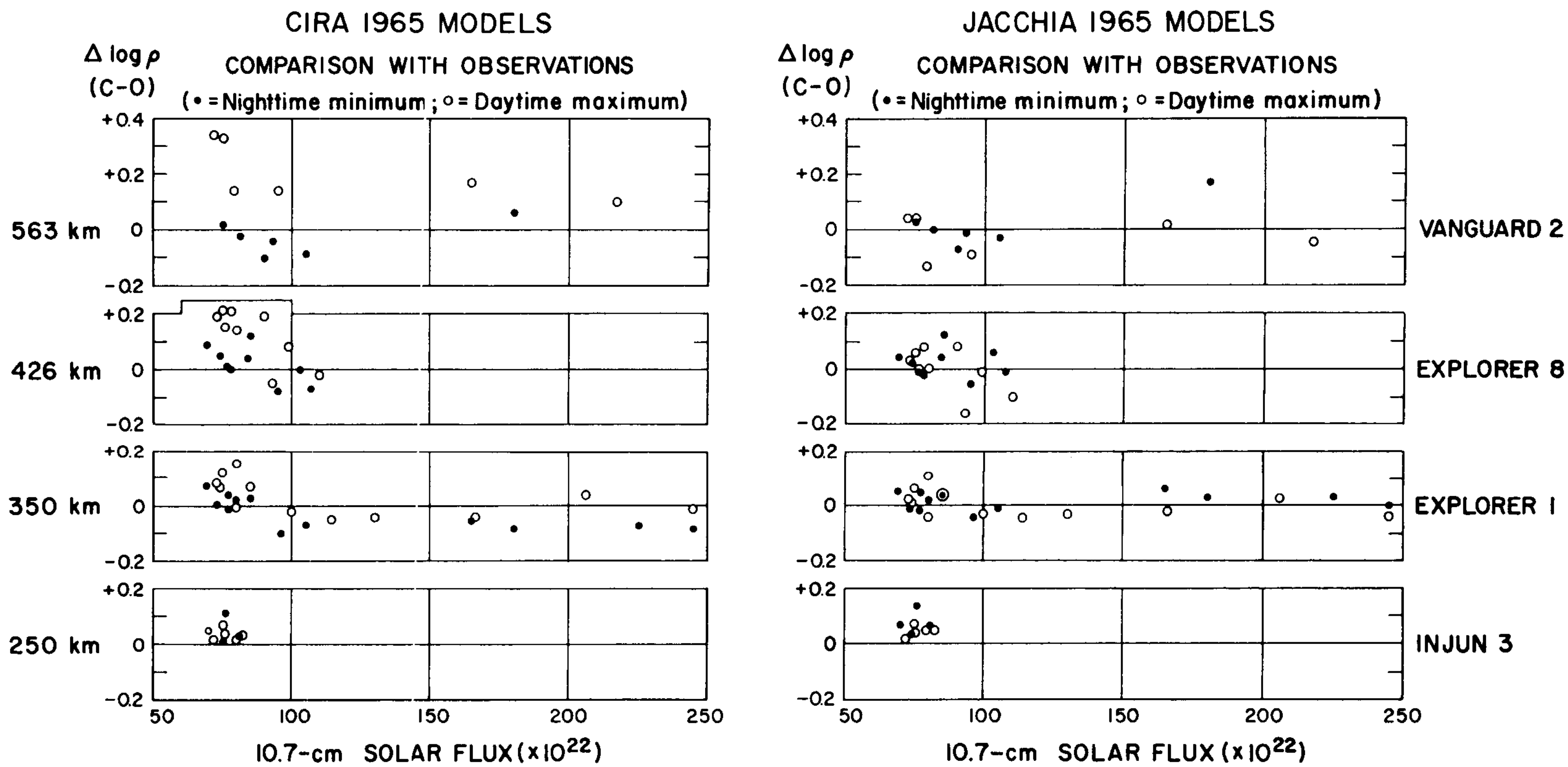

Figure 2. Comparison of the CIRA 1965 and J65 models with observations. Density residuals (computed minus observed) are shown as a function of the smoothed 10.7-cm solar flux for four satellites, arranged in decreasing order of perigee height. Daytime maxima are represented by open circles, nighttime minima by filled circles.

models, has something to do with the situation. The importance of winds at thermospheric levels, caused by pressure gradients originating with the diurnal variation, has been pointed out in a series of recently published papers (King and Kohl, 1965; Lindzen, 1966, 1967; Harris, 1966; Geisler, 1966). The effect of such winds would be, of course, to reduce the amplitude of the diurnal oscillation in all atmospheric parameters, including composition, inasmuch as horizontal winds with a diurnal cycle between regions of different compositions, such as the bright and the dark hemispheres, would provide a mechanism of nonturbulent mixing even at exospheric levels. In addition, we must not forget the systematic winds postulated by King-Hele and associates (King-Hele and Allan, 1966; King-Hele and Scott, 1966, 1967) to explain the excess in the secular decrease of the orbital inclination observed in artificial satellites.

Below 200 km the diurnal density variation as given by either CIRA or J65 seems to be too small. According to data obtained from the orbital drag of Cosmos rockets by King-Hele and Quinn (1966), in 1962 to 1965 at 200 km the relative amplitude was 1.7; J65 predicted 1.5, and CIRA, 1.4. At 180 km, according to the same source, the relative amplitude was 1.6, compared to 1.3 given by J65 and 1.2 by CIRA. Discrepancies in this direction were to be expected at low heights because of the assumed constancy of the boundary conditions at 120 km, and they had been observed in the density variations with solar activity (J65). It was because of these discrepancies at low heights that Bruce (1966) introduced a simple mathematical transformation of the J65 density profiles, whose effect is to increase the range of the density variation for heights below 250 km.

6. SOLAR-ACTIVITY EFFECT

The time lag of the so-called "27-day" atmospheric variation behind the variations of the 10.7-cm solar flux has been investigated by Roemer (1967), who finds for it an average value of 1.5 days. Actually, he finds a lag of 1.0 days near the center of the sunlit hemisphere — and this may be considered the reaction time of the atmosphere — and about 2 days in the dark hemisphere.

7. GEOMAGNETIC-ACTIVITY EFFECT

Jacchia, Slowey, and Verniani (1967) have investigated the atmospheric variations with geomagnetic activity using drag data on four high-inclination satellites. The time lag of the atmospheric variations behind those of the K_p or a_p index is found to increase from high to low latitudes: At 65° the lag is 5.8 ± 0.5 hours, and at 25° it is 7.2 ± 0.3 hours; De Vries, Friday, and Jones (1967) found a much larger variation with latitude, but their results are questionable because of the small orbital eccentricities of the satellites used in their study. Roemer (1966) found a lag of only 5.2 ± 0.4 hours at low latitudes from the drag of the Explorer 9 Satellite. This is in good agreement with the lag previously obtained from the same satellite by Jacchia and Slowey (1964), but differs by 2 hours from the more recent results we just mentioned. The problem of this discrepancy is being investigated by Roemer. The paper by Jacchia et al. (1967) confirms the enhancement of the atmospheric perturbations in the auroral zones (by some 15 to 25%) and the nonlinearity in the relation between temperature and K_p or a_p. This relation is expressed by the improved formula

$$\Delta T = 28^\circ \; K_p + 0\overset{\circ}{.}03 \exp(K_p)$$

or

$$\Delta T = 1\overset{\circ}{.}0 \; a_p + 100^\circ [1 - \exp(-0.08 \; a_p)] \quad .$$

Jacobs (1967b) found a 24-hour oscillation in the motion of low satellites in polar orbits and attributed it to an atmospheric heat bulge above the geomagnetic poles. Jacchia and Slowey (1967b) could find no trace of this bulge — the size of which should be quite spectacular, according to the oscillation that Jacobs observed to be by a factor as high as 1.7. They believe the cause of the oscillation must be nonatmospheric; 12- and 24-hour oscillations can easily appear in the motion of satellites when gravity anomalies and station positions contain even slight imperfections (see, for example, Jacchia and

Slowey, 1964, Figure 3). Even the smallest discernible oscillations with such small periods in the position residuals will result in large fluctuations in the second time derivative of the curve of residuals, from which the drag is computed.

8. THE SEMIANNUAL VARIATION; HELIUM AND HYDROGEN

An attempt by Anderson (1966a, b) to explain the semiannual variation in the atmosphere as an illusion caused by the motion in latitude of satellite perigees has been effectively disproved by King-Hele (1966a, b), who showed that the semiannual variation is conspicuously present even in the drag of polar satellites in circular orbits.

Cook and Scott (1966) and Cook (1967) have found that near sunspot minimum the amplitude of the semiannual density variation at 1100 km derived from the drag of the Echo 2 and the Calsphere satellites is larger than that predicted by the J65 models. The observed oscillation is by a factor of 2 for Echo 2, and 1.6 for Calsphere; J65 predicts only a factor of 1.06. Since at 1100 km the atmosphere at sunspot minimum consists largely of helium, and since the density of helium is very sensitive to the height at which diffusion begins, Cook theorized that a variation in this height with the semiannual cycle could result in an increased amplitude of this variation where helium is important. Priester (1967), however, found that the amplitude observed by Cook is not much larger, especially in the case of the Calsphere Satellite, than the variation predicted when the J65 formula is used in conjunction with the CIRA models. Part of the discrepancy between CIRA and J65 at 1100 km is to be traced to their different hydrogen concentrations at low temperatures, caused by a difference in the extrapolation to low temperatures of the hydrogen data computed by Kockarts and Nicolet (1962, 1963). Since the density of hydrogen decreases as the temperature increases, while helium does the opposite, a suitable combination of hydrogen and helium can reduce to zero any density variation of thermal origin when only these two components are present. This is just what happens in J65 at heights close to 1100 km, when the exospheric temperature is around 650° K; in the CIRA models for the same degree of solar activity the hydrogen concentration is one order of magnitude smaller, and is almost certainly more correct. If the hydrogen concentration in J65 is reduced to the level of the CIRA models, the predicted amplitude of the semiannual variation becomes 1.6, in perfect agreement with the Calsphere data.

In connection with hydrogen we can mention a recent review of hydrogen investigations by Donahue (1966) and two papers by Patterson (1966a, b), of which one deals with the concentration of hydrogen and the other with its diurnal variation. The last subject, the diurnal variation of hydrogen, is treated also in papers by Joseph and Venkateswaran (1965) and by Joseph (1966).

9. SEASONAL VARIATIONS IN HIGHER LATITUDES

The migrations in latitude in the course of the year involve a seasonal variation at any given geographic location; this variation, however, can be treated as an integral part of the diurnal variation considered on a global scale. A true seasonal variation at high latitudes has been revealed by the drag data of the Explorer 19 and Explorer 24 satellites (Jacchia and Slowey, 1967b). These data show that during the quiet-sun period there was an excess of density at high latitudes during the winter months at heights above 550 km. This greater density seems to be caused by an excess of helium and does not appear to be correlated to temperature variations at those heights. From the drag analysis of the same two Explorer satellites, Keating and Prior (1967b) reached similar conclusions concerning a helium bulge, except for the fact that they tried to connect it to the diurnal variation. The formation of a winter helium bulge over the poles could be explained by a seasonal subsidence of the level at which the diffusion of helium begins; the sensitivity of helium to the height of this level has been mentioned in Section 7. It appears difficult, however, to apply this explanation to a diurnal helium bulge, since the diurnal variation in winter is small at high latitudes — certainly much smaller, at turbopause level, than the seasonal variation observed by Champion (1966).

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NOTICE

This series of Special Reports was instituted under the supervision of Dr. F. L. Whipple, Director of the Astrophysical Observatory of the Smithsonian Institution, shortly after the launching of the first artificial earth satellite on October 4, 1957. Contributions come from the Staff of the Observatory.

First issued to ensure the immediate dissemination of data for satellite tracking, the reports have continued to provide a rapid distribution of catalogs of satellite observations, orbital information, and preliminary results of data analyses prior to formal publication in the appropriate journals. The Reports are also used extensively for the rapid publication of preliminary or special results in other fields of astrophysics.

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