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THERMOSPHERIC HYDROGEN: ABSOLUTE DENSITIES AND TEMPORAL VARIATIONS DEDUCED FROM IN SITU MEASUREMENTS

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

The concentration of atomic hydrogen at 350 km altitude has been derived from Explorer 32 measurements of ion composition and model n(O) values by consideration of the charge exchange equilibrium $O^+ + H \rightleftharpoons H^+ + O$. The measurements, made at northern temperate latitudes between June 1966 and January 1967, have made possible the first comprehensive study of thermospheric hydrogen density and its temporal variations based on in situ observations. During the period of measurement the average $F_{10.7}$ increased from 100 to 140, and n(H) varied between approximately 4×10^5 and 8×10^4 cm^{-3}, with a mean value of 2.3×10^5 cm^{-3}. The derived nighttime hydrogen densities are approximately a factor of 2.4 higher than the Kockarts-Nicolet model values, and the derived daytime values exceed the model by a factor of about 3.8. Employing the Jacchia formulation for the primary components of the exospheric temperature, parametric analysis has resolved the n(H) variations into contributions associated with temperature components due to solar activity, local time, geomagnetic activity, and the semi-annual effect. With one exception, the hydrogen concentration is observed to vary inversely with each of the model temperature components, as theoretically expected; the semi-annual variations in n(H), though small, appear to vary directly with temperature. The solar cycle effect accounts for a factor of 2.5 decrease in n(H) over the period of measurement, in reasonable agreement with a factor of 3 predicted by the Kockarts-Nicolet model; this suggests that n(H) varies by more than a factor of 10 over a solar cycle. The observations show, for the first time, that the 27-day variation in solar activity due to solar rotation is correlated with an inverse n(H) variation of as much as a factor of 1.3. The diurnal variation of n(H) is observed as approximately a factor of two increase in density between day and night (consistent with the models of Patterson and McAfee), with a daytime phase lag of two hours between model temperature and density, and a nighttime lag of four hours; furthermore, the magnitude of the n(H) diurnal variation is observed to increase with rising solar activity. It is concluded that while these results confirm individual features of several existing models, there appears to be, at present, no single theoretical model which fully describes the behavior of thermospheric hydrogen.

CONTENTS

1. Introduction

One of the long-standing questions in atmospheric research is that of the concentration and temporal behavior of thermospheric atomic hydrogen. The concentration of thermospheric hydrogen is governed by dissociation of water vapor in the lower atmosphere, diffusion, exospheric transport and thermal planetary escape. The escape mechanism is highly temperature-dependent, and since atmospheric temperature is, in turn, dependent on a number of geophysical and solar parameters, the hydrogen concentration varies with time in a complex manner.

A number of experimental techniques have been used, with only moderate success, to measure the hydrogen concentration and to determine its temporal behavior. Direct mass spectrometer measurements have proved difficult to interpret, due perhaps to instrumental effects [1-3]. Large uncertainties are also associated with the thermospheric hydrogen concentrations determined from airglow observations. These techniques all involve the measurement of integral intensities, requiring for the derivation of n(H) at a particular location the assumption of a model global hydrogen distribution. The interpretation of Lyman-α observations in terms of thermospheric hydrogen concentration, for example, is complicated by the effects of high-altitude scattering [4]. A better determination of thermospheric hydrogen variations can be made with ground-based Balmer-α observations [5], but the absolute concentrations derived are subject to uncertainties in the solar Lyman-β intensity and in the integrated hydrogen content in the direction of observation. Finally, satellite drag techniques are not useful for determining n(H) below 1000 km altitude because hydrogen is a minor constituent in this region.

This paper describes a correlative study of Explorer 32 data obtained in the period June 1966-January 1967, which has provided the first comprehensive determination of thermospheric hydrogen density and temporal behavior based on in situ measurements. The variation of n(H) at 350 km altitude, within a limited range of latitude and longitude, has been resolved into density contributions associated with the primary exospheric temperature components. This paper, which follows an early short report on the study [6], describes the derivation of the n(H) values, discusses the observed dependence of hydrogen on each of the exospheric temperature components, and compares our results with those obtained by other experimental techniques and with current theoretical models.

2. Explorer 32 orbit and instrumentation

The Explorer 32 satellite was launched on May 25, 1966, and its complement of aeronomy instruments obtained useful data until March, 1967. The orbit, with an inclination of 64.7°, perigee of 277 km, and apogee of 2725 km, provided measurements covering a full diurnal cycle at a selected altitude and geographic location in a period of approximately four months. This feature has made the satellite especially useful for study of the n(H) diurnal variation.

The instrument complement was designed to make in situ measurements of positive ion composition and concentration, electron concentration and temperature, and neutral particle composition, concentration and temperature. The present study, as described in § 3, is based upon correlation of data from several of the Explorer 32 instruments.

3. n(H) derivation technique

At thermospheric heights the charge-exchange reaction $O^+ + H \rightleftharpoons H^+ + O$ proceeds so rapidly that the H^+ distribution is governed by the chemical equilibrium relationship

$$n(H^+) = \frac{9}{8} \frac{n(O^+)\ n(H)}{n(O)} \tag{1a}$$

[7]. For the present study relation (1a) has been written in the form

$$n(H) = \frac{8}{9} \frac{n(H^+)}{n(O^+)}\ n(O) \tag{1b}$$

and n(H) has been derived from Explorer 32 measurements of the ion ratio and model n(O) values verified by Explorer 32 density gage results. (A more detailed discussion of this method of determining n(H) was presented in [8]). The measurements selected for analysis were made between June 1966 and January 1967, during perigee passes of the satellite over ground stations at Ft. Myers (Florida), Rosman (North Carolina), and Mojave (California). Figure 1 indicates the dates and altitudes of the measurements, and shows that with the exception of a few points at the end of the measurement period, all data were obtained in the altitude interval 280-400 km. By restricting the data to those obtained at the three selected ground stations, the geographic spread of the measurements was purposely limited in longitude (-65° to -124°) and latitude (23° to 47°). This restriction assures, as explained below, that the model n(O) values used in the n(H) derivation are valid, and that the deduced n(H) variations are free from any longitudinal effects that might be associated with longitudinal variations in the ion composition [9-11].

The $n(H^+)$ values were obtained from the Explorer 32 Bennett RF ion mass spectrometer (described in [12]). Due to amplifier saturation the accuracy of the ion spectrometer $n(O^+)$ measurements at F_{max} was degraded; the two companion cylindrical Langmuir probes [13] measured n_e at the time of each $n(H^+)$ observation however, and since to a close approximation $n_e = n(O^+)$ in this altitude range, the n_e values were used for $n(O^+)$ in relation (1b). Simultaneous with these determinations of $n(H^+)$ and $n(O^+)$, the Explorer 32 density gage experiment [14] provided measurements of atmospheric density, which at this altitude is predominantly atomic oxygen. Newton has reported [15] that the gage measurements at midlatitudes, for altitudes below 550 km, agree closely at all local times with the Jacchia 1965 model atmosphere [16, 17] density values. Figure 2 compares measured and model densities for Explorer 32 passes over Rosman, Mojave, and Ft. Myers during the period May-October 1966; the format of the figure is that used in [15], presenting versus local time, the ratio of measured to Jacchia model density on the right-hand vertical axis, and the logarithm of this ratio on the left. The demonstrated agreement between measured and Jacchia model densities affirms the validity of the model for the time period, altitude range, and geographic location of our $n(H^+)$ and n_e measurements. On this basis, the values of n(O) used in relation (1b) were obtained from the Jacchia

1965 model atmosphere, computed for the solar and geophysical conditions existing at the time of each $n(H^+)$ and n_e measurement. (The Jacchia 1970 model [18] includes n(O) values which, for the altitude range of our study, are at most 10% higher than those of the 1965 model.)

4. Hydrogen concentrations

The eight-month period of Explorer 32 measurements is shown in Figure 3 in the context of the long-term variation of solar activity. Our observations span an interval of rapidly increasing solar activity in which the mean 10.7 cm solar flux rose from a value of approximately 100 to approximately 140.

Our derived n(H) values are shown in the center panel of Figure 4, in which horizontal scales indicate the approximate day and local time of each observation (note that local time decreases from left to right, governed by the precession of the satellite orbit). To facilitate subsequent analysis we have normalized the hydrogen concentrations to an altitude of 350 km, assuming a scale height of 600 km which corresponds to a temperature of 900° K, the average of the day and night model values for the period of observation. The exospheric temperature, T_∞, for the time and location of each derived n(H) value has been calculated using the Jacchia 1965 model equations [16,17], and the variation of T_∞ with time is shown in the upper panel of Figure 4. The variations of the daily and 54-day mean values of the 10.7 cm solar flux for the period of our n(H) observations are shown in the lower panel.

Comparison of the three panels in Figure 4 reveals that the long-term increase in solar activity indicated by the rise in $F_{10.7}$ is correlated with (1) an overall increase in calculated exospheric temperature and (2) a corresponding decrease in the concentration of thermospheric hydrogen. Furthermore, comparison of the daily $F_{10.7}$ behavior with n(H) reveals a periodic n(H) variation which is inversely correlated with the 27-day variation of solar activity associated with solar rotation.

5. Analysis of n(H) variation

The complex variation of n(H) apparent in Figure 4 has been resolved by means of a least square analysis into a number of density components, each of which is associated with a primary component of the exospheric temperature, T_∞. The formulas for the temperature components are those of the Jacchia 1965 model, and include contributions associated with 11-year solar cycle, 27-day solar rotation, diurnal variation, geomagnetic activity, and semi-annual variation.

The solar activity components of the n(H) variation determined by this analysis are shown in Figure 5. The density component associated with the 11-year variation in solar activity is represented by the light solid line. The heavy line fitting the computed points (one point for each n(H) value in Figure 4) represents the sum of the density components associated with the 11-year solar cycle and the 27-day variation of solar activity associated with the sun's rotation. Figure 6 shows the sum (heavy line) of the components associated with the diurnal n(H) variation and the 11-year solar activity variation; the 11-year component alone is also shown (light line). The behavior of these n(H) contributions, and of those associated with the other exospheric temperature components, are discussed in the following section.

6. Discussion of n(H) components

6.1. Solar activity components of n(H) variation

The behavior of the solar cycle n(H) component in Figure 5 indicates that during the eight months of Explorer 32 measurements the thermospheric hydrogen concentration decreased by a factor of approximately 2.5 due to the long-term increase in atmospheric temperature which is associated with rising solar activity. Although our absolute n(H) values are higher than those given by the Kockarts and Nicolet theoretical model [19,20] (discussed in § 7), the observed decrease by a factor of 2.5 agrees well with the approximate factor of 3 decrease in n(H) at 350 km which is predicted by the model for an increase in thermopause temperature from approximately 780° to 920°K. These temperatures are the nighttime minimum values, for quiet magnetic conditions, calculated from the Jacchia 1965 model [16,17] for average $F_{10.7}$ values of 100 and 140, the activity levels at the beginning and end, respectively, of our measurement period. Our n(H) observations, then, indicate that the variation of thermospheric hydrogen concentration over a solar cycle will be large, perhaps well over a factor of ten as predicted by the Kockarts and Nicolet model.

The n(H) component associated with the 27-day variation in solar activity due to solar rotation modulates the long-term n(H) behavior in the manner shown by the heavy line in Figure 5. Our study has shown, for the first time, that this periodic component accounts for density variations of as much as a factor of 1.3, the hydrogen concentration again varying <u>inversely</u> with the related atmospheric temperature component. This result may have implications for the magnitude of the 27-day variation in solar Lyman-α flux deduced by Meier from airglow measurements [21], since the latter analysis assumed a constant geocoronal hydrogen density.

6.2. Diurnal component of n(H) variation

The heavy line in Figure 6 represents the sum of the n(H) contributions associated with the diurnal and solar cycle atmospheric temperature components (note that local time decreases from left to right). The diurnal variation of n(H) is observed as approximately a factor of two increase in concentration between day and night. Consideration of the diurnal component alone reveals that the n(H) diurnal variation, defined as the night-to-day density ratio, was larger for the second local time cycle covered by our observations than for the first cycle. This observed increase in the magnitude of the n(H) diurnal variation with increasing solar activity (and higher average exospheric temperature) is consistent with the behavior predicted by the Patterson [22] hydrogen model. A second characteristic of the n(H) diurnal component is an apparently variable phase lag between the Jacchia model exospheric temperature and hydrogen density. The error in our least square analysis is minimized when phase lags between model temperature and n(H) of two hours during daytime and four hours during nighttime are introduced; the phase lag was assumed to vary sinusoidally. Patterson's model predicts a phase lag of two hours at night, but no phase lag during day.

Characteristics of the n(H) diurnal variation determined from our Explorer 32 observations are compared in Table 1 with model predictions and with recently reported airglow results. (The models chosen are for low solar activity, $F_{10.7} \approx 100$.) The quantities compared are the night-to-day thermospheric hydrogen density ratio and the n(H) - model temperature phase lag. It is apparent that our in situ observations are in considerable disagreement with the COSPAR International Reference Atmosphere 1965 (CIRA, 1965) [23] and the Jacchia 1965 model [16,17] which is based on the theoretical model of Kockarts and Nicolet [19,20]. Our factor of two for the diurnal variation of n(H) is in excellent agreement, however, with the theoretical predictions of Patterson [22,24] and McAfee [25] whose models include the effect of lateral hydrogen transport. Tinsley has also deduced a factor of two from ground-based Balmer-α observations [5], and Meier and Mange have determined an upper limit of four for the diurnal density ratio from OGO-4 Lyman-α measurements [26]. The variable phase lag which we have observed between the diurnal variation of n(H) and the Jacchia model exospheric temperature is greater by two hours than that predicted by the Patterson model. The implications of this result are currently under study and will be discussed further in a later paper. As shown in the table, Tinsley has reported a nighttime phase lag of two hours. The hydrogen models used by Meier and Mange, however, include the assumption of azimuthal symmetry about the Earth - Sun line, and their data thus far apparently support a symmetrical hydrogen distribution [26].

6.3. Geomagnetic activity component of n(H) variation

By extending the data sample upon which our earlier report [6] was based to include n(H) values derived from measurements made on magnetically disturbed days, we have determined an inverse relationship between thermospheric hydrogen density and the Jacchia [16,17] geomagnetic activity temperature component. The measurement period, June 1966 - January 1967, was a time of generally low magnetic activity (average $a_p = 12$, $K_p = 3-$), and approximately 70% of our observations were made under conditions of $a_p \leq 10$ (reported in [6]). The remainder of our measurements were made under conditions of moderate-to-high magnetic activity, including periods in late August, early September, and January when a_p exceeded 150 for time periods of up to 15 hours. Our analysis reveals a consistent inverse relationship between thermospheric hydrogen concentration and the Jacchia temperature component derived from the value of a_p six hours prior to each n(H) observation.

6.4. Semi-annual component of n(H) variation

Unlike the four previously discussed components, the n(H) contribution associated with the Jacchia model semi-annual temperature component appears to vary directly with temperature. Although this result should at this time be considered preliminary, it may constitute further evidence that the atmospheric semi-annual effect is not explainable simply as a temperature phenomenon, but that in addition, neutral composition changes in the lower thermosphere should also be invoked [27-30]. Tinsley has drawn a similar conclusion from analysis of Balmer-α variations [5].

7. Discussion of absolute n(H) values

As discussed in §6.1 we have compared our derived hydrogen densities with the Kockarts and Nicolet model [19,20] values for appropriate exospheric temperatures. The average nighttime n(H) at 350 km derived from measurements made in June and October (Figure 4) was approximately 3.3×10^5 cm^{-3}. Based on the Jacchia model, the average nighttime minimum temperature in this period was approximately 820° K. For this temperature the Kockarts and Nicolet model predicts an n(H) of 1.4×10^5 cm^{-3}; thus, for nighttime, the model value is approximately a factor of 2.4 lower than our derived density. Similarly, the average daytime hydrogen density derived from measurements made in August and December was approximately 1.5×10^5 cm^{-3}, and the average model daytime temperature was about 980°K. For this temperature Kockarts and Nicolet predict an n(H) of 4×10^4 cm^{-3}, which is approximately a factor of 3.8 lower than our derived value. Thus, our derived hydrogen densities are higher than the Kockarts and Nicolet model values by an average (night and day) factor of about 3. It appears that these discrepancies result from (1) the neglect, in the model, of exospheric hydrogen transport, an effect which tends to damp the magnitude of the diurnal variation of n(H), and (2) the underestimation, in the model, of the hydrogen production rate or base level density at 100 km. It should be pointed out that Liwshitz, using Monte Carlo numerical techniques, has developed a hydrogen model [31] which predicts thermospheric hydrogen densities that are higher than the Kockarts and Nicolet values by a factor of 2-3 for an exospheric temperature of 1000° K.

Airglow investigations of the atmospheric hydrogen content have also led to the conclusion that the Kockarts and Nicolet n(H) values may be low. Meier and Mange [4,26] have found that their Fall, 1967 OGO-4 and OSO-4 Lyman-α observations are consistent with the Kockarts and Nicolet hydrogen model normalized upward by a factor of 3, to a density of 3×10^7 cm^{-3} at 100 km altitude. In reviewing Balmer-α observations made since 1958, Tinsley and Meier [32] report a large discrepancy between measured and theoretically expected Balmer-α intensities. They suggest that one way to resolve this difference is to invoke an atmospheric hydrogen abundance of up to ten times the Kockarts and Nicolet model value; they point out, however, that the discrepancy could also arise from the use of inappropriate solar Lyman-β flux values, or from neglect of the diurnal variation in n(H).

Prior [33] has derived two high-altitude n(H) values from satellite drag data obtained in the period March-May 1967. His densities, for altitudes of 2325 km and 2872 km and for local times near 0600 hours, exceed the Kockarts and Nicolet values by about a factor of three. This result is in good agreement with our nighttime thermosphere hydrogen density which is 2.4 times the Kockarts and Nicolet value.

8. Accuracy of results

The determination of relative n(H) variations by the method employed in this study is extremely accurate, since systematic errors associated with instrument calibration and inflight performance affect only the values of absolute hydrogen density. The primary sources of inaccuracy in the determination of relative n(H) variations are random factors such as instrument noise and data reading error. The amplitude of this small random error in the n(H) temporal variation, based on estimated uncertainties in n(H^+) and n_e, and substantiated by the results of our curve-fit analysis, is ±15%. This error has been filtered out of the n(H) components shown in Figures 5 and 6.

The uncertainty in our absolute hydrogen concentrations is primarily due to a possible inaccuracy of ±25% in the density gage verification of the Jacchia model n(O) values (Newton, personal communication). An inflight H^+ calibration of the ion spectrometer was performed using n_e data from the companion cylindrical Langmuir probes (the technique is described in [12]), thus eliminating possible errors due to mass discrimination in the spectrometer and to aerodynamic effects in the satellite sheath [34]. Further, any systematic error in the probe measurement of n_e cancels out, since it is the ratio n(H^+)/n(O^+) which is used in the determination of n(H). As pointed out by Banks [35] a small systematic error, of magnitude 0 to +10%, arises from the use of equation (1b) when the ion and gas temperatures are not equal. In summary, the uncertainty of our absolute n(H) values is (+35/-25)%.

9. Summary and conclusions

The concentration of atomic hydrogen at 350 km altitude has been derived from in situ measurements of ion composition and model n(O) values by consideration of the charge exchange equilibrium $O^+ + H \rightleftharpoons H^+ + O$. The uncertainty in the absolute values of n(H) is estimated to be (+35/-25)%, due primarily to the ±25% uncertainty in the n(O) values. The selected measurements were made within a limited geographic region, at northern temperate latitudes, between June 1966 and January 1967.

The average derived nighttime n(H) for the period June-October was approximately 3.3×10^5 cm^{-3}, a factor of 2.4 higher than the Kockarts and Nicolet model value for a temperature of 820° K (Jacchia model T_∞). The average derived daytime n(H) for the period August-December was approximately 1.5×10^5 cm^{-3}, a factor of 3.8 higher than the Kockarts and Nicolet value for T_∞ = 980°K. These discrepancies apparently result from the failure of the model to consider the effects of exospheric hydrogen transport, and from an underestimation of the hydrogen production rate or base level density at 100 km.

The variation of hydrogen concentration between approximately 4×10^5 and 8×10^4 cm^{-3} during the period of measurement has been resolved by a least square analysis into density contributions associated with the primary exospheric temperature components given by the Jacchia model. The results for each component are summarized below:

(1) Solar Cycle: The rise in average solar activity ($F_{10.7}$) from 100 to 140 between June 1966 and January 1967 and resultant atmospheric temperature increase caused the derived n(H) at 350 km to decrease by a factor of 2.5. This result agrees well with the factor of 3 decrease in n(H) predicted by the Kockarts and Nicolet model for the appropriate exospheric temperature rise, and indicates that the concentration of thermospheric hydrogen may vary during a solar cycle by considerably more than a factor of ten.

(2) Solar Rotation: Our results show, for the first time, that the 27-day variation in solar activity and the corresponding exospheric temperature component are correlated with an inverse n(H) variation of as much as a factor of 1.3.

(3) Diurnal: The derived concentration of thermospheric hydrogen increased by approximately a factor of two between day and night, with a nighttime phase lag of four hours between model exospheric temperature and n(H), and a daytime phase lag of two hours. The magnitude of the observed n(H) diurnal variation agrees with those predicted by the Patterson and McAfee models, which consider exospheric hydrogen transport, but our variable phase lag is greater by two hours than that given by Patterson.

Our observations also reveal an increase in the magnitude of the n(H) diurnal variation with rising solar activity.

(4) Geomagnetic activity: Our observations constitute the first evidence of an inverse relationship between geomagnetic activity, its associated exospheric temperature component, and thermospheric hydrogen density.

(5) Semi-annual: Unlike the four previous density components, the n(H) contribution associated with the model semi-annual temperature component, though small, appears to vary directly with temperature. This result may indicate that the semi-annual effect is not simply a temperature phenomenon, but that semi-annual changes in the neutral composition at low altitudes could also be important.

The results reported in this paper constitute the first comprehensive study of thermospheric hydrogen densities and temporal variations based on in situ measurements. Although individual features of several existing models are confirmed by our measurements, it appears that there is, at present, no single theoretical model which fully describes the behavior of thermospheric hydrogen and its response to changing solar and geophysical conditions.

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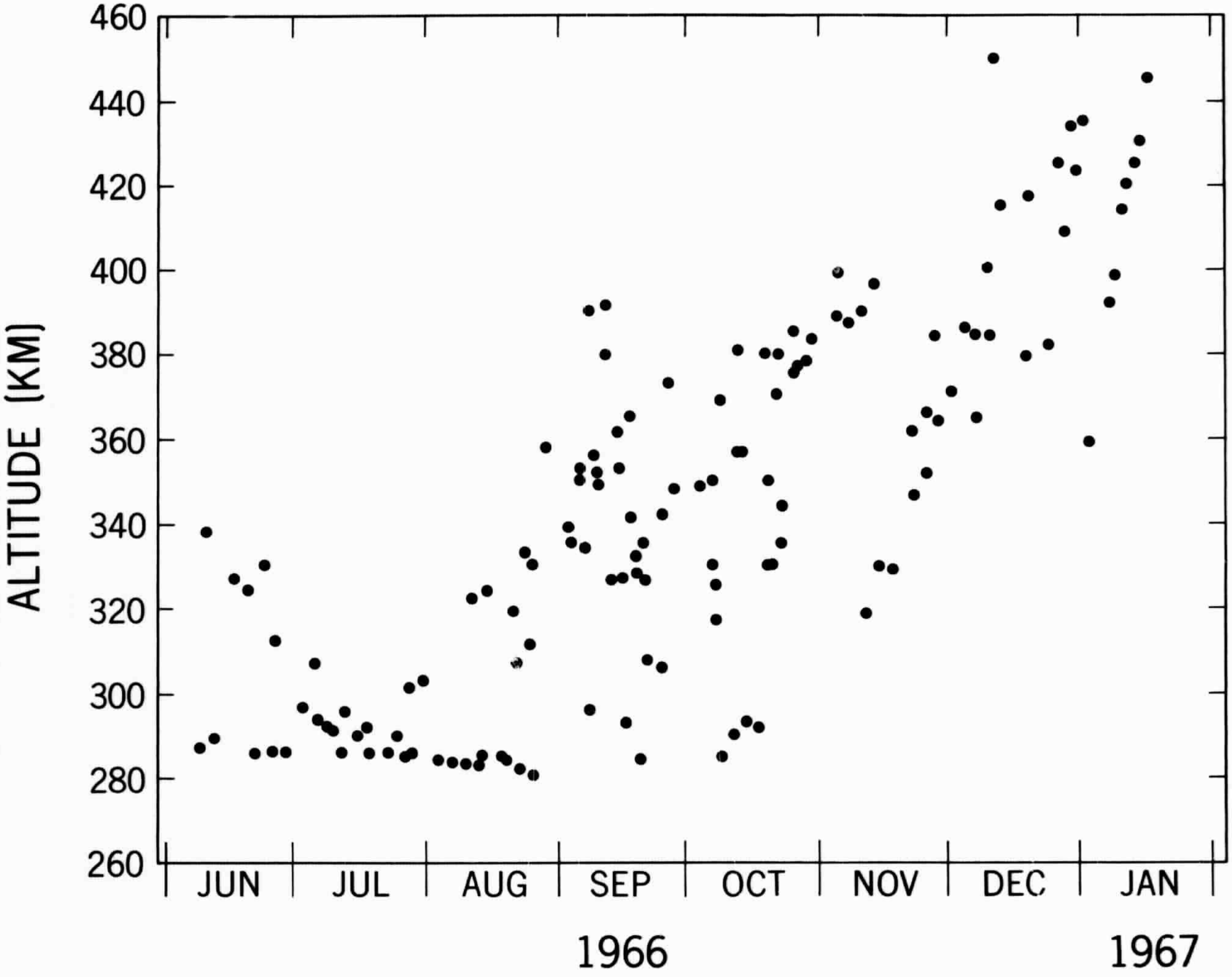

Figure 1. Plot of altitude versus date for Explorer 32 <u>in situ</u> measurements of $n(H^+)$ and n_e used in derivation of $n(H)$ values.

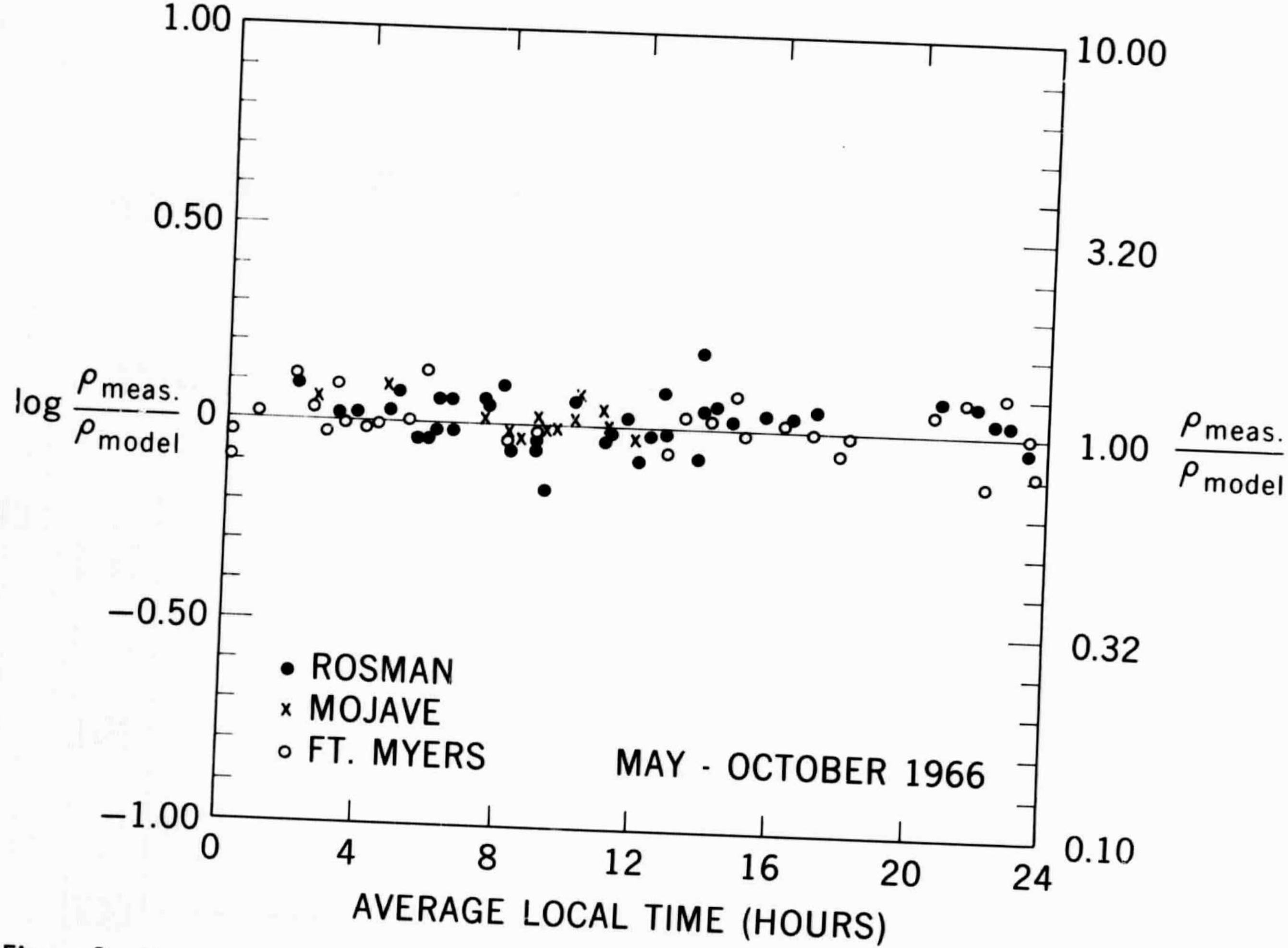

Figure 2. Comparison of Explorer 32 gage measurements of atmospheric density, obtained during perigee passes over selected ground stations, and Jacchia 1965 model values, demonstrating accuracy of the model (after Newton [15]). Ion composition data obtained at these locations have been combined with model n(O) values to derive n(H).

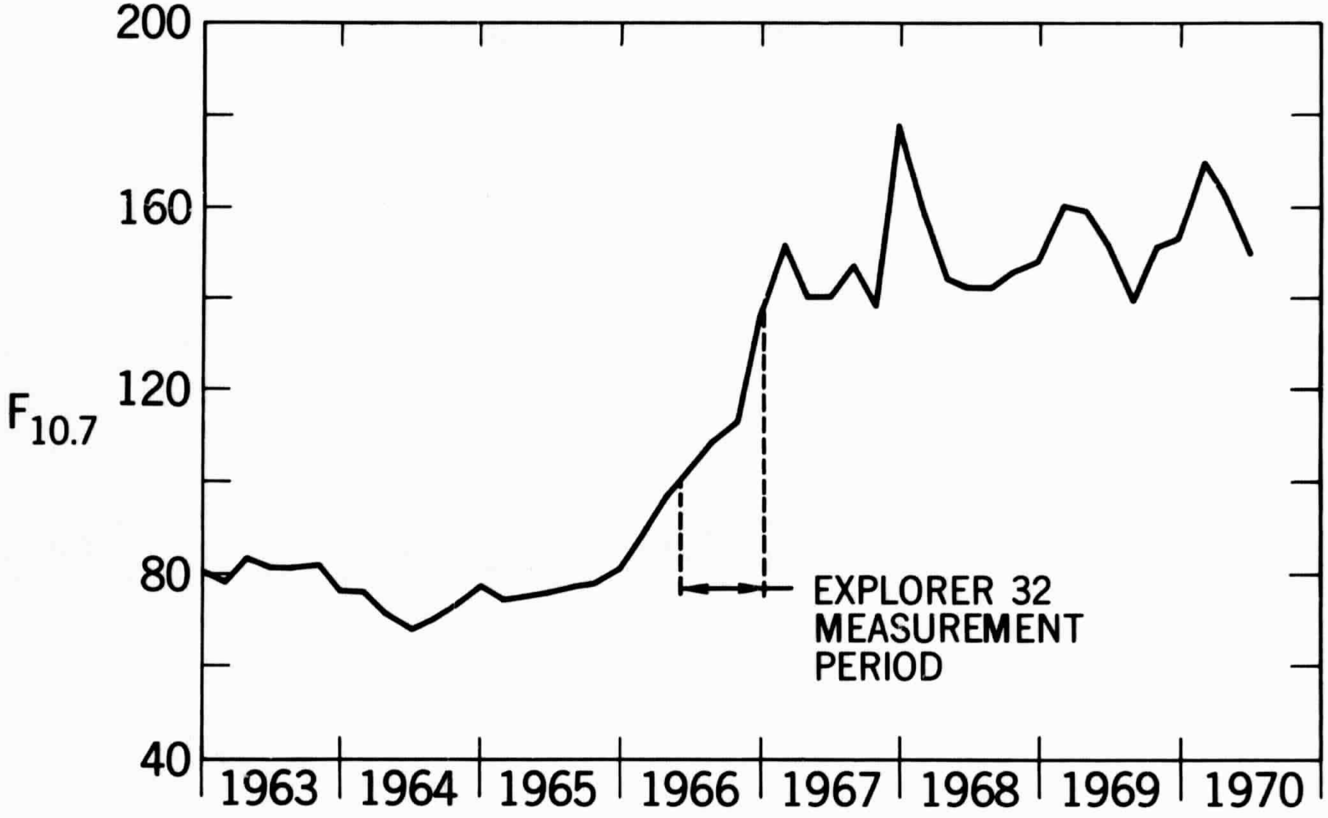

Figure 3. Period of Explorer 32 measurements shown in context of long-term variation of solar activity. (Plot is of 81-day running mean of 10.7 cm solar flux.)

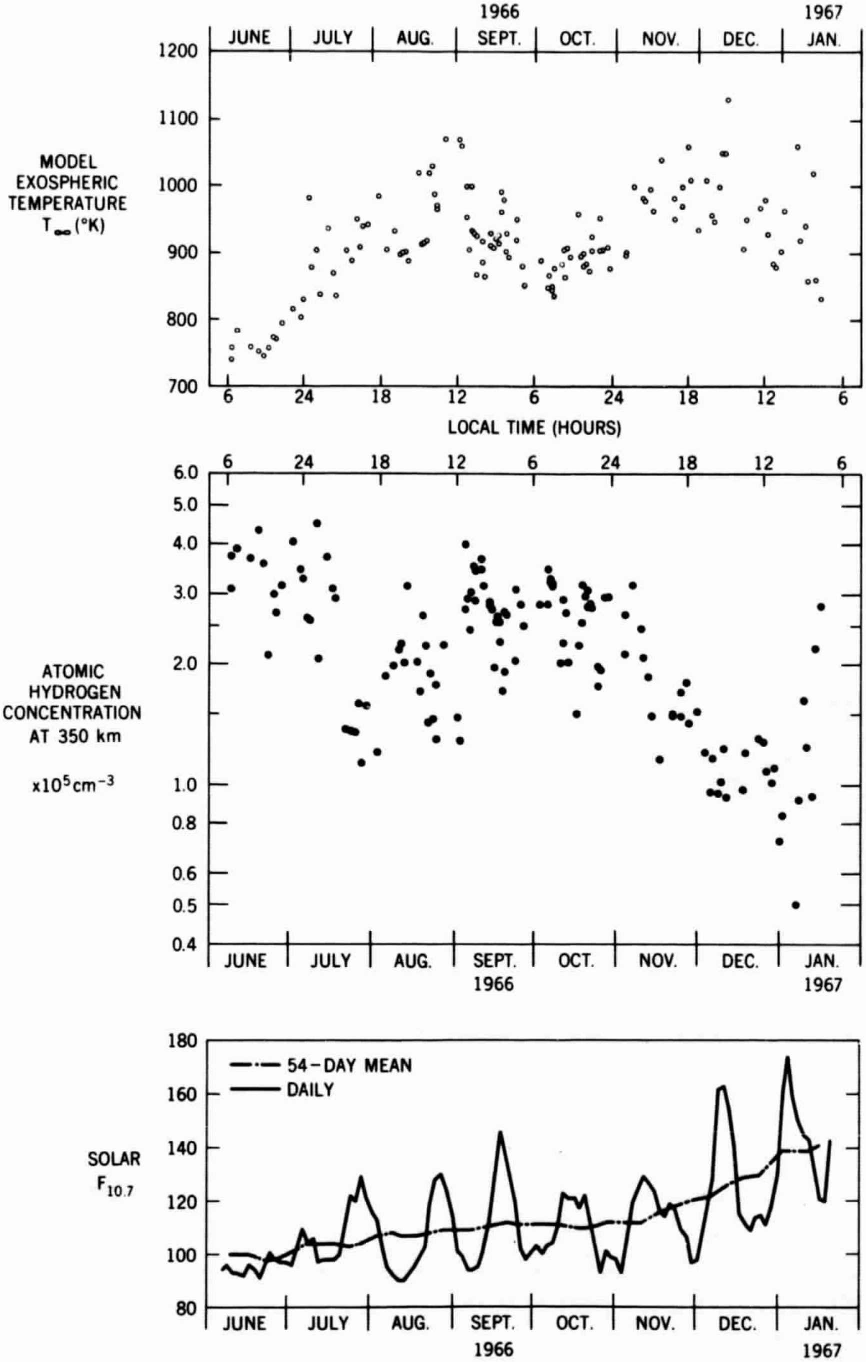

Figure 4. Concentration of atomic hydrogen at 350 km altitude, derived from in situ measurements of ion composition and Jacchia model n(O) values, for period June 1966–January 1967. Variations of model exospheric temperature (T_∞) and solar 10.7 cm flux during period of measurements are shown in upper and lower panels, respectively.

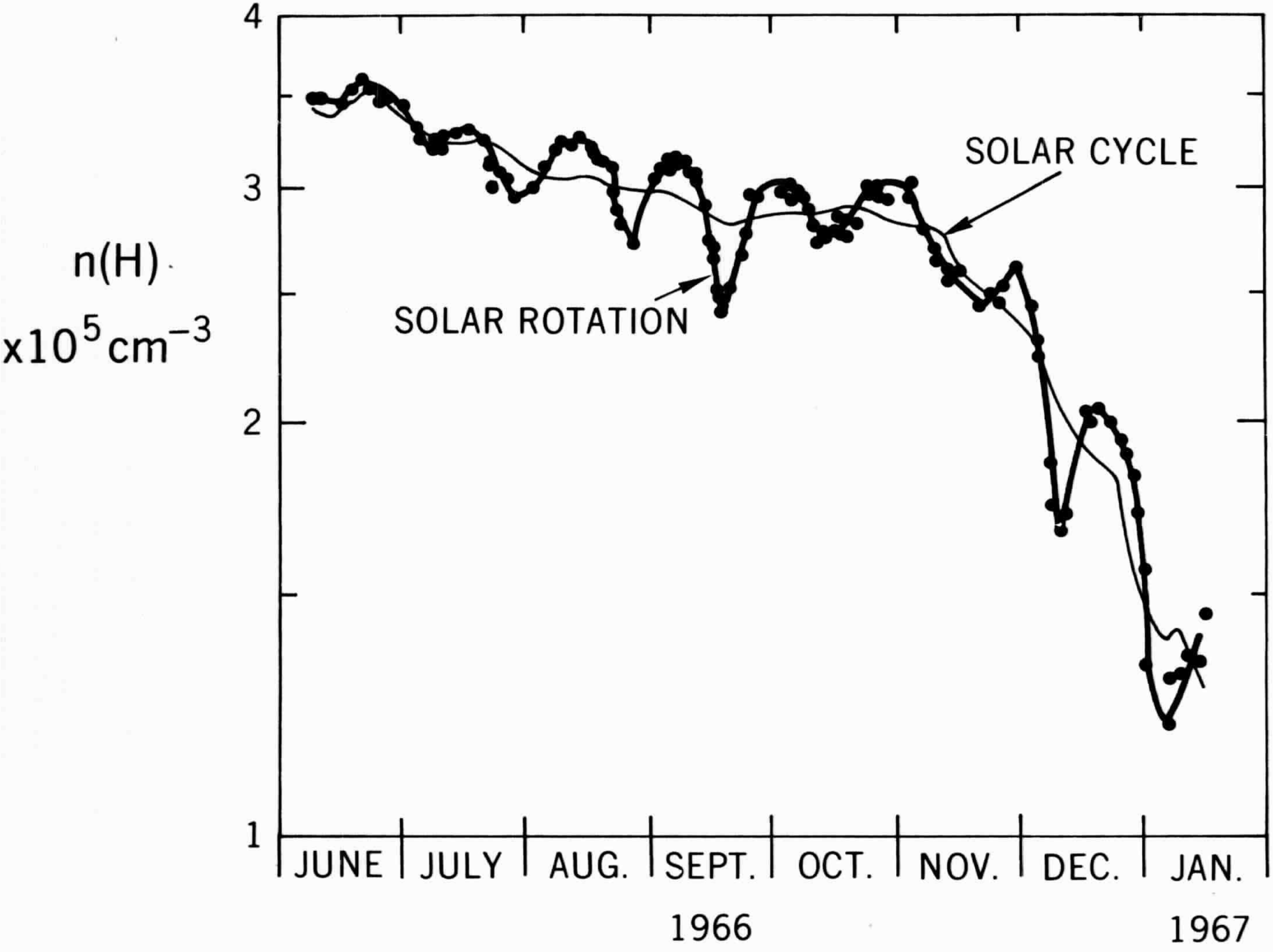

Figure 5. Sum of n(H) components associated with 27-day solar rotation and 11-year solar cycle (heavy line), and solar cycle component alone (light line).

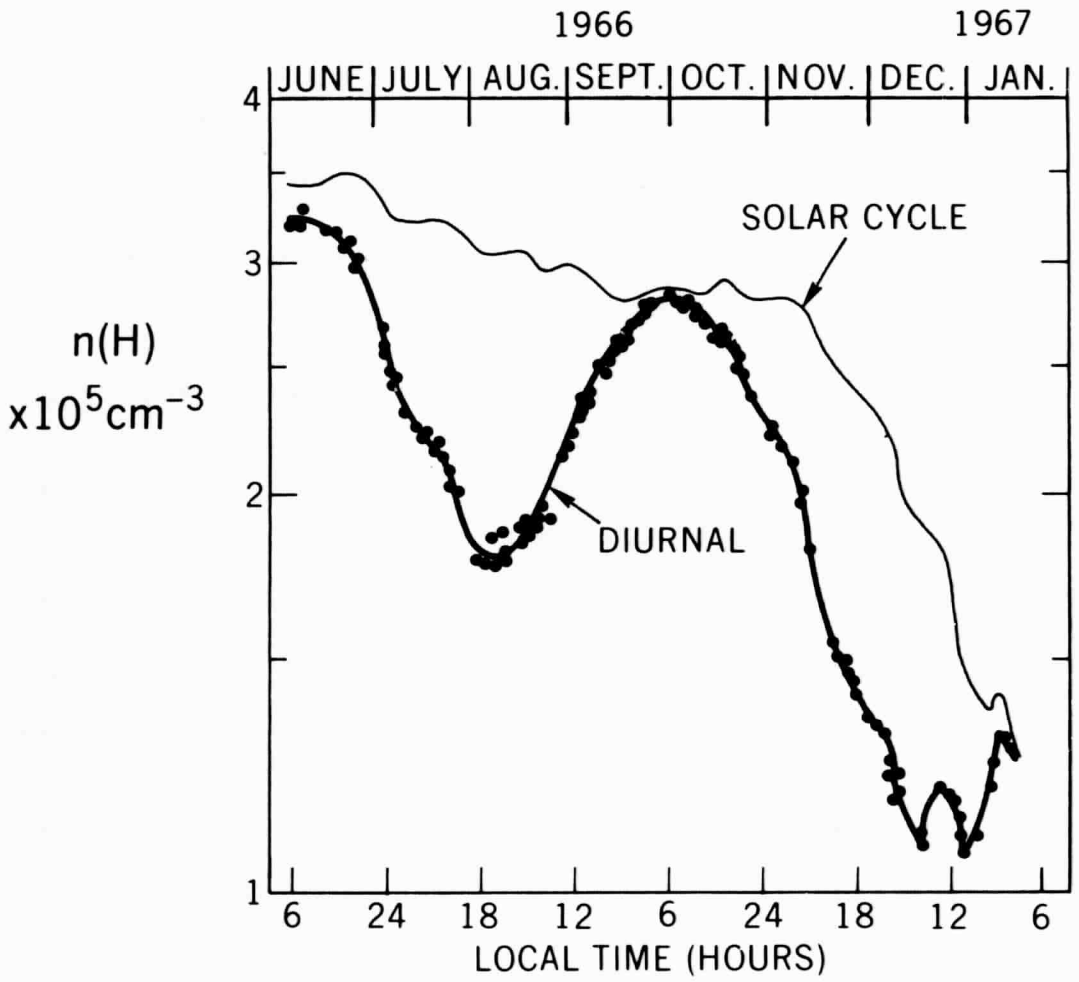

Figure 6. Sum of diurnal and solar cycle n(H) components (heavy line), and solar cycle component alone (light line). Note that local time decreases from left to right.

TABLE 1. DIURNAL VARIATION OF THERMOSPHERIC HYDROGEN CONCENTRATION

	$\frac{n(H)_{NIGHT}}{n(H)_{DAY}}$	n(H)—MODEL TEMP. PHASE LAG (HOURS)	
		DAY	NIGHT
CIRA 1965 MODEL	~ 1.1	0	0
JACCHIA 1965 MODEL (BASED ON KOCKARTS & NICOLET, 1962, 1963)	~ 4	0	0
McAFEE MODEL (1967)	~ 2		
PATTERSON MODEL (1966)	~ 2	0	~ 2
OGO-4 LYMAN-α (MEIER AND MANGE, 1970)	1–4		
GROUND-BASED BALMER-α (TINSLEY, 1970)	~ 2		~ 2
EXPLORER 32 IN SITU OBSERVATIONS (BRINTON AND MAYR, 1971)	~ 2	~ 2	~ 4