SU-SEL-65-103

Lunar Radar Measurements of the Diurnal Exchange of Ionization Between the Ionosphere and the Magnetosphere

by

Philip Yoh

December 1965

Scientific Report No. 14

Prepared under
National Aeronautics and Space Administration
Grant NsG-377

RADIOSCIENCE LABORATORY

STANFORD ELECTRONICS LABORATORIES

STANFORD UNIVERSITY • STANFORD, CALIFORNIA

SEL-65-103

LUNAR RADAR MEASUREMENTS OF THE DIURNAL EXCHANGE OF IONIZATION BETWEEN THE IONOSPHERE AND THE MAGNETOSPHERE

by

Philip Yoh

December 1965

Scientific Report No. 14

Prepared under
National Astronautics and Space Administration
Grant NsG-377

Radioscience Laboratory
Stanford Electronics Laboratories
Stanford University Stanford, California

ABSTRACT

During the period from December 1963 to April 1964 a large number of simultaneous measurements of the Faraday polarization rotation and the Doppler excess frequency of radar echoes were made at Stanford, California. The experimental results showed a large temporal variation of the electron content above the earth's ionosphere. This variation of the electron content is attributed to an exchange of ionization between the ionosphere and the lower magnetosphere. A net upward electron flux of about 3.7×10^{12} m^{-2} sec^{-1} is found in the morning; the corresponding number for downward flow in the afternoon is about 2.8×10^{12} m^{-2} sec^{-1}. If a diffusive-equilibrium model is assumed, it can be demonstrated that the cause of this flow is the change of temperature in the region of the upper ionosphere and lower magnetosphere.

Introduction. Since the first contact of the moon by radio waves [De Witt and Stodola, 1949], a considerable amount of effort has been concentrated on studying the dynamic characteristics of the ionized cislunar medium. The first such study measured the number of Faraday polarization rotations between the earth and moon (Browne et al, 1956). This particular type of measurement gives the total electron content of the earth's ionosphere. Recently, another type of measurement, Doppler excess frequency, was made by Howard et al [1964a]. This measurement provides the average time rate of change of the electron content along the entire radar path. On the occasion of the July 20, 1963 solar eclipse, simultaneous measurements of Doppler excess frequency and Faraday polarization rotations were made at Stanford, California [Howard et al, 1964b]. The results of the latter experiment showed a large depression of the electron content above the ionosphere.

This paper presents the daytime results of simultaneous measurements of Doppler excess frequency and Faraday polarization rotation on lunar radar echoes that were obtained daily over a period of five months (December 1963 to April 1964). Analysis of the data shows a large diurnal change of ionization density content above the ionosphere--the amount of change of electron content is about 4×10^{16} el/m^2. In the light of these results, it is suggested here that the change of ionization occurs in the lower magnetosphere. A diffusive-equilibrium model of the electron density distribution is assumed, and this model requires appropriate changes in temperature of the diffusive-equilibrium region which could account for such a large observed change of the ionization content.

Experiment. The experiment described by Howard et al [1964a, b, c] was conducted daily for one to three hours around local lunar transit time. Two harmonically related frequencies, near 25 and 50 Mc, were transmitted with linear polarization from an array of 48 log-periodic antennas and one 150-foot dish respectively. These transmitting antennas were also used for receiving radar echoes during the Doppler excess frequency measurements. A 60-foot dish was used as a receiving antenna to measure the Faraday polarization rotation at 50 Mc.

Theory. The amount of Faraday polarization rotation (Faraday rotation) for a linearly polarized wave passing through a magnetoionic medium is given as (Howard et al, 1964b)

$$\phi_F = \frac{\overline{f_0^2 f_L}}{2f^2} T_0 \quad (1)$$

where ϕ_F is the number of cycles of Faraday rotation, f_0 is the plasma frequency ($f_0^2 = 80.6\ N$ in mks units, where N is the electron density), f_L is the longitudinal electron gyrofrequency, f is the operating frequency, and the radar path length is T_0 sec times the vacuum velocity of light. The bar denotes the mean value of $f_0^2 f_L$ along the path. The electron content I_F along the radar path deduced from Faraday rotation is then given as

$$I_F = \frac{1}{40.3} \frac{f^2 c}{f_L} \phi_F \quad (2)$$

The value f_L is taken at the height of 400 km at the subionospheric point.

The Doppler excess frequency is the time rate of change of the rf phase. Thus the time integral of Doppler excess frequency gives the change in the number of cycles. The number of cycles ϕ_{DE} is given by

$$\phi_{DE} = \frac{f_0^2}{2f} T_0 \quad (3)$$

The relative electron content I_D can be expressed as

$$I_D = \frac{1}{40.3} fc \, \phi_{DE} \tag{4}$$

Results. The average relative electron contents measured by the Faraday-polarization and Doppler-excess-frequency methods are plotted in Fig. 1.

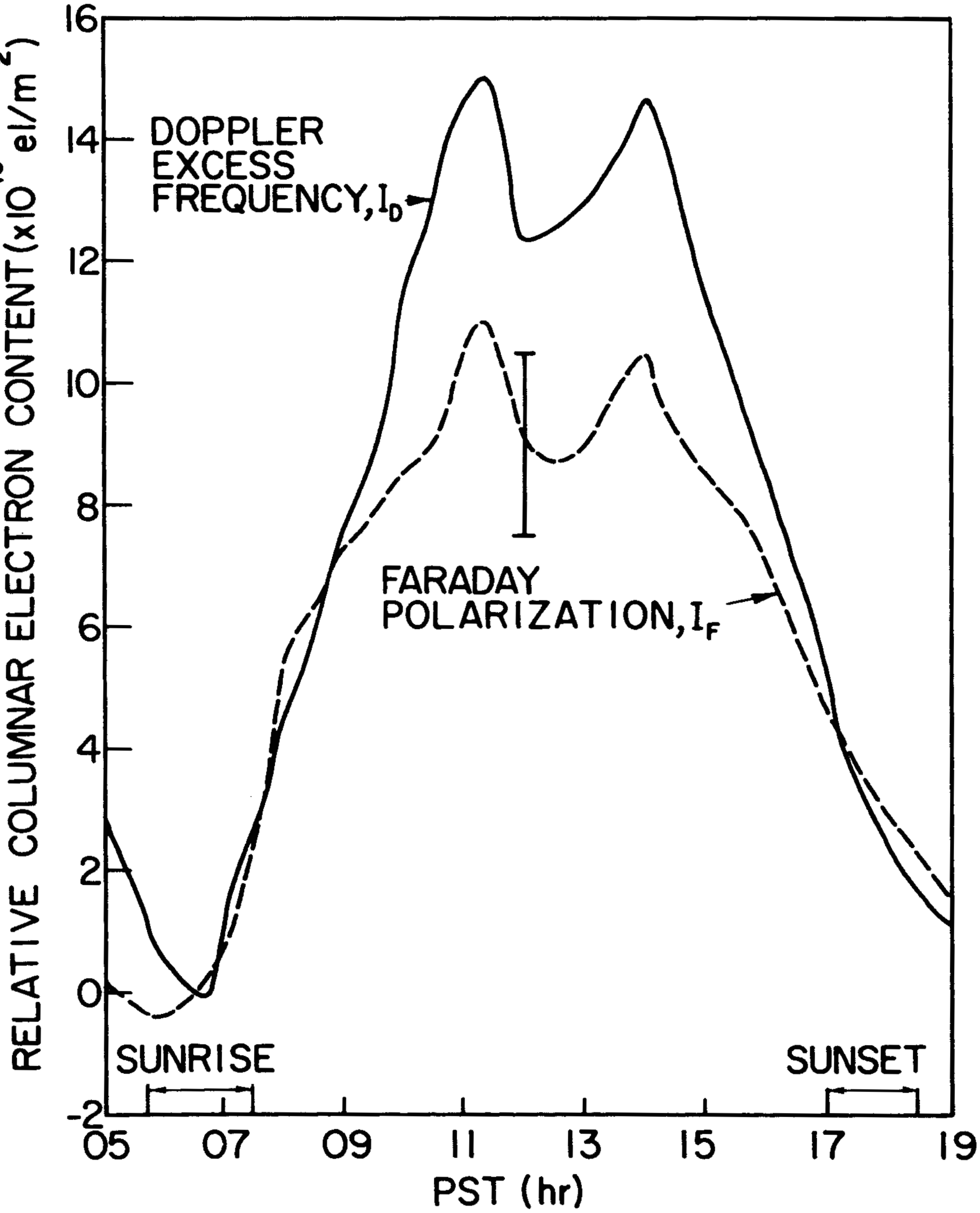

FIG. 1. AVERAGED DAYTIME RESULTS OF RELATIVE ELECTRON CONTENT MEASURED BY FARADAY POLARIZATION AND DOPPLER EXCESS FREQUENCY.

It is clear that the Doppler method detects a much larger change of ionization content. Figure 2 represents the difference between the two curves, $I_D - I_F$, the greatest difference being about 4×10^{16} el/m^2.

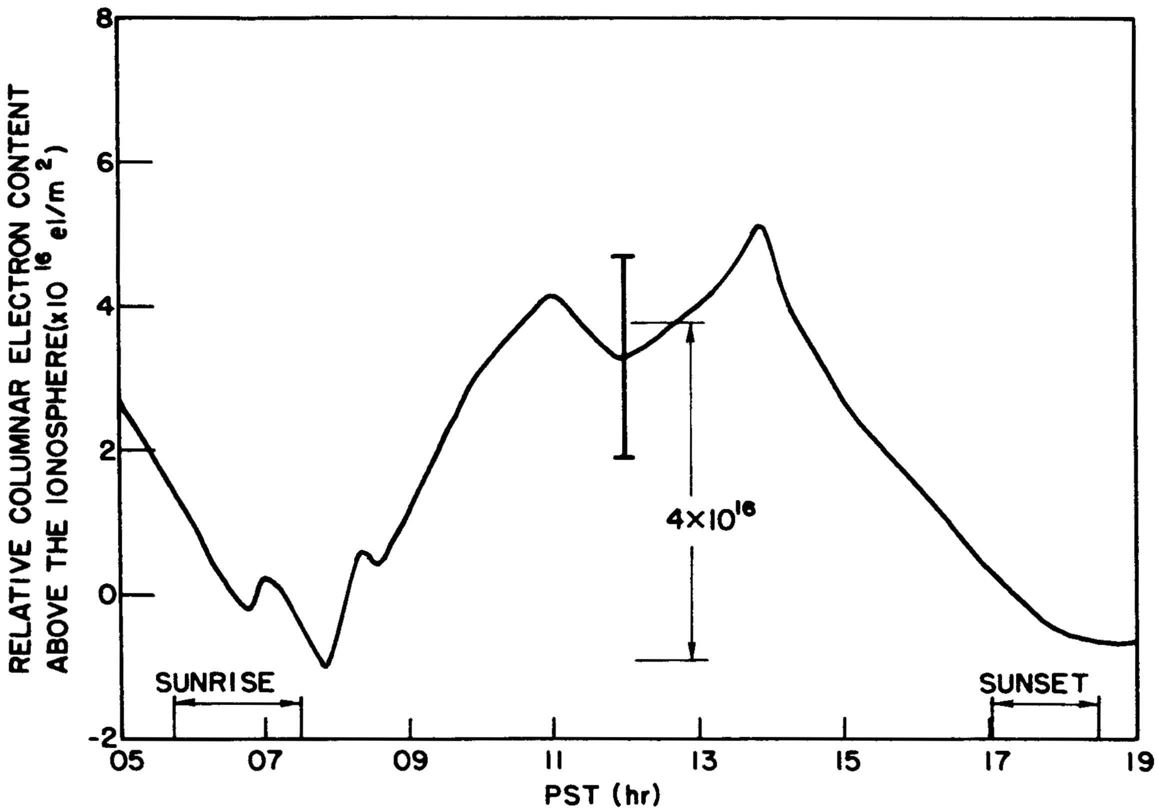

FIG. 2. DIFFERENCE OF AVERAGED DAYTIME RESULTS OF LUNAR MEASUREMENTS.

It is seen that the rate of increase of ionization content in the morning is slightly higher than the rate of decrease in the afternoon. In the morning the period of increasing ionization is about 3 hours (0800 to 1100), and in the afternoon the period of decaying ionization is about 4 hours (1400 to 1800). Hence the average rate of change of columnar electron content can be calculated as

	Average Rate of Change of Columnar Electron Content
Morning hours	3.7×10^{12} el/m^2/sec
Afternoon hours	2.8×10^{12} el/m^2/sec

The decrease of ionization content detected by the Doppler method during predawn hours has been treated in a separate paper [Yoh et al, 1966].

Finally, the shape of the change of ionization above the ionosphere is similar to that of the ionospheric change (i.e., a rapid increase of ionization after sunrise reaches its maximum value about noon; it starts to decay in the early afternoon and continues until after sunset).

Discussion. The cislunar medium contains several different regions--the ionosphere, the inner and outer magnetospheres, the transition region, and the solar-wind region--which are characterized by their different magnetic fields, high- and low-energy, density distributions, and plasma-flow parameters. Figure 3 represents the plane of the lunar orbit, looking from the north celestial pole. The dashed line of the magnetopause is an extrapolation from the IMP-I magnetometer measurements [Ness et al, 1964]. The shock front in the antisolar hemisphere was derived by Yoh et al [1966]. The transition region lies between the boundaries of the shock front and the magnetopause. The outer magnetosphere is the region between the magnetopause and the "knee," and the inner magnetosphere is the region between the boundaries of the knee and the top of the ionosphere. (Carpenter and Jewell [1965] recently reported on the position of the knee around the earth.)

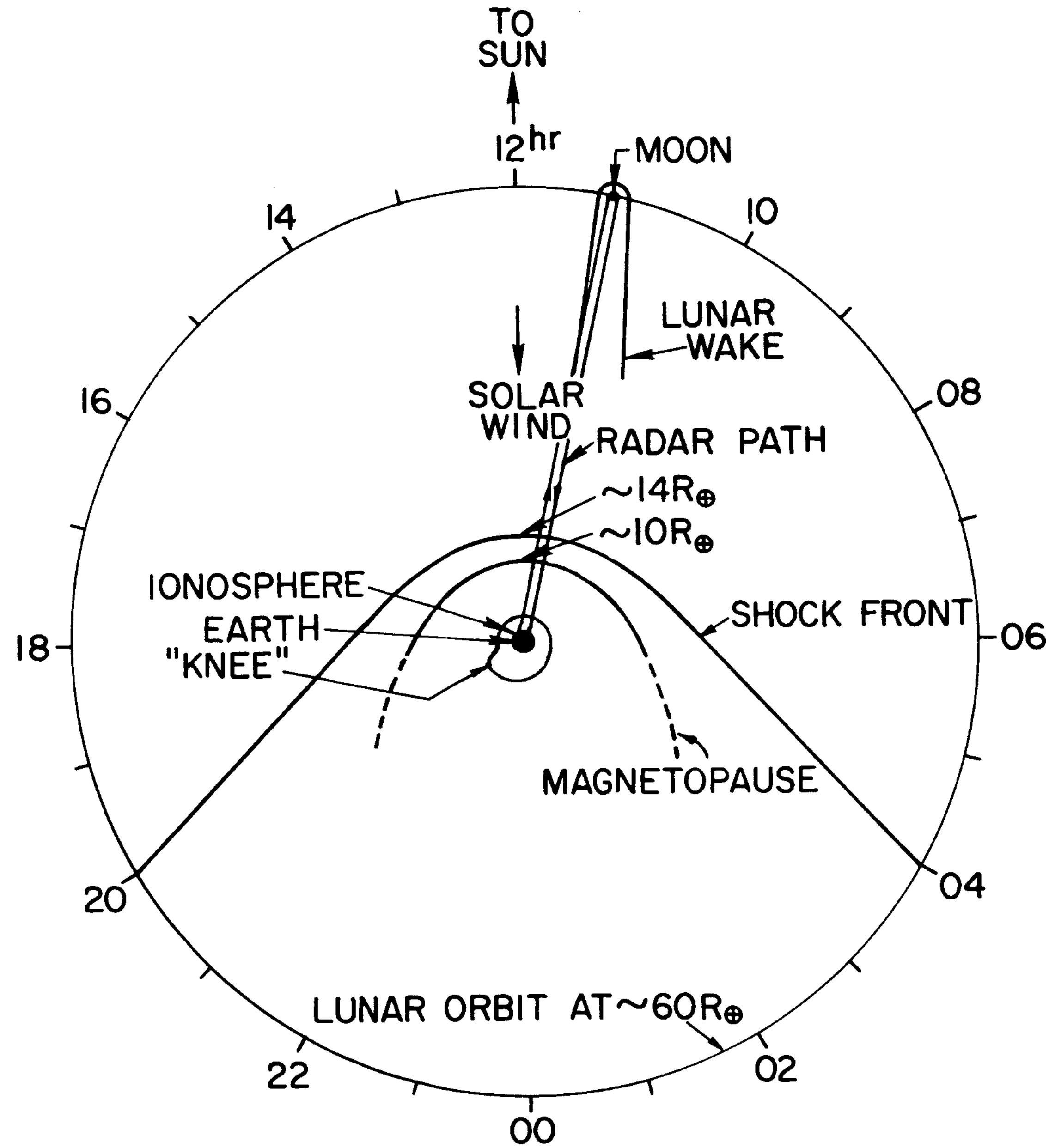

FIG. 3. REGIONS IN THE CISLUNAR MEDIUM SHOWING EXAMPLE OF RADAR PATH.

It can be seen in Fig. 3 that the radar path lengths in different regions depend on the position of the moon: during daylight hours they do not change by any significant amount, but during nighttime hours there is a significant change in the solar-wind region and inside the shock front. Since the measurements are taken near the lunar transit time, the moon is always in the solar direction for the daytime measurements.

Figure 4 shows the order of magnitude of the electron content in different regions on the daytime side. Since the observed change of ionization content is beyond the ionosphere [Yoh, 1965], it is concluded that the only region that can possibly support the diurnal vaviation of 4×10^{16} el/m^2 is the inner magnetosphere. This conclusion is supported

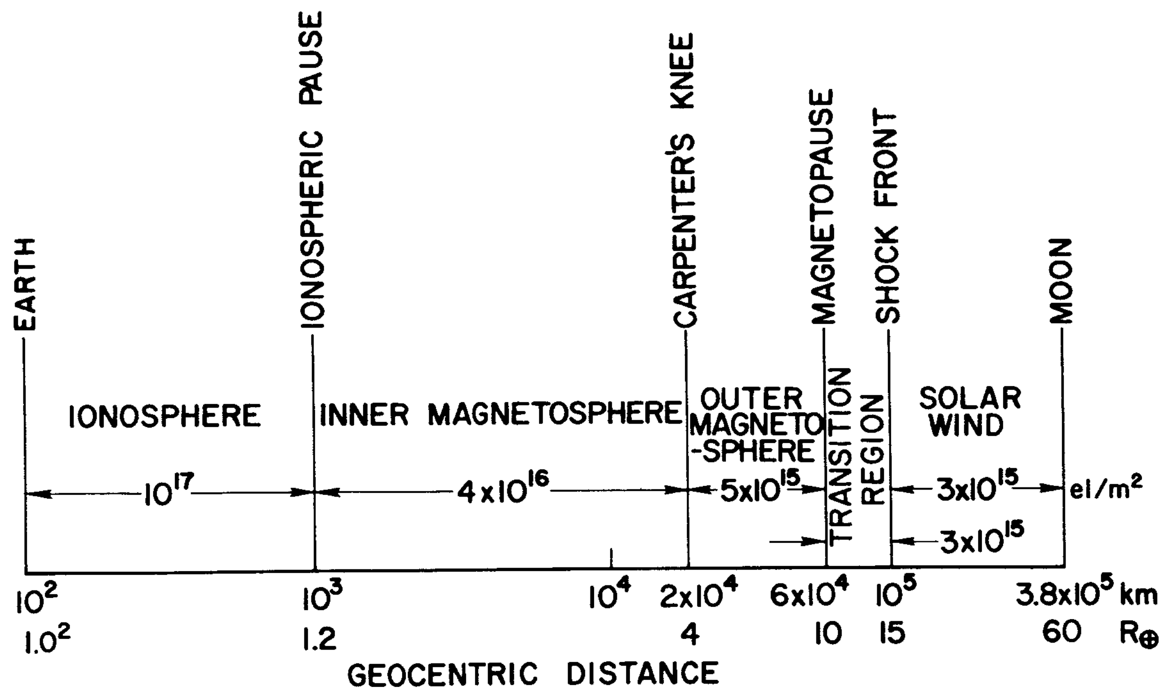

FIG. 4. AVERAGED ELECTRON CONTENT IN THE DIFFERENT REGIONS IN THE CISLUNAR MEDIUM IN THE SOLAR DIRECTION.

by the fact that the total sum of electron contents from the other three regions--outer magnetosphere, transition region, and solar-wind region--cannot account for the observed value of change of ionization content.

A diffusive-equilibrium model, based on the following assumptions, was constructed to explain the results shown in Fig. 2:

1. It is isothermal--i.e., temperature is independent of height.
2. The ion temperature T_i is equal to the electron temperature T_e.
3. The base of its diffusive-equilibrium region is taken at 500 km.
4. It has three ionic constituents: O^+, He^+, and H^+.

The electron-density distribution can be expressed as [Bauer, 1962]

$$N_e = N_0 \left[\frac{\exp(-A'/h_1) + \eta_{12} \exp(-A'/h_2) + \eta_{13} \exp(-A'/h_3)}{1 + \eta_{12} + \eta_{13}}\right]^{1/2} \qquad (5)$$

where the subscripts 1, 2, and 3 refer to O^+, He^+, and H^+ respectively, and where

N_0 = electron density at the base level

h_s = scale height expressed as $h_s = k(T_e + T_i)/mg$, where m is ion mass and g is acceleration of gravity

A' = "reduced" altitude, defined as

$$A' = \frac{h - h_o}{(1 + h/R_\oplus)(1 - h_o/R_\oplus)}$$

where h is true height measured from the ground, h_o is the height of base level, and $R_{\oplus}$ is earth's radius, 6370 km

η_{ij} = ratio of ion densities at base level, defined as $\eta_{ij} \equiv N_j/N_i\big|_{500\ km}$

Equation (5) states that the electron-density profile depends on the temperatures and ion compositions at the base level. If one of the paremeters should change, the shape of the electron-density distribution would be changed.

In considering the electron-density distributions it is helpful to first consider a simple expression for determining the height of transition levels of different ionic species. The expression for a single ion species is

$$N_i = N_{io} \exp\left[-\int_{h_o}^{h} \frac{m_i g}{kT_i}\, dh + \int_{h_o}^{h} \frac{g m_+ M_+}{k(T_e + T_i)}\, dh\right] \qquad (6)$$

where N_{io} is the density of the i^{th} ion species at base level and M_+ is the mean ionic mass. At the transition level,

$$N_i = N_j \qquad (7)$$

substitution of Eq. (6) in Eq. (7) yields

$$N_{io} \exp\left[-\int_{h_o}^{h} \frac{m_i g}{kT_i}\, dh + \int_{h_o}^{h} \frac{M_+ g}{k(T_e + T_i)}\, dh\right]$$

$$= N_{jo} \exp\left[-\int_{h_o}^{h} \frac{m_j g}{kT_j}\, dh + \int_{h_o}^{h} \frac{M_+ g}{k(T_e + T_j)}\, dh\right] \tag{8}$$

Assuming that all ionic constituents have the same temperature yields $T_i = T_j = T$, and Eq. (8) then reduces to

$$\frac{N_{io}}{N_{jo}} = \exp\left[-\int_{h_o}^{h} \left(\frac{m_j g}{kT} - \frac{m_i g}{kT}\right) dh\right] \tag{9}$$

Let the upper limit of the integral be the height of the transition level L of the i^{th} and j^{th} ionic constituents. Equation (9) then becomes

$$\ell n \frac{N_{jo}}{N_{io}} = \int_{h_o}^{h} \frac{(m_i - m_j)g}{kT}\, dh \tag{10}$$

Let $a = \ell n(N_{jo}/N_{io})$ and $b = (m_i - m_j)/kT$. Since the term $(m_i - m_j)/kT$ is constant, the integral requires a simple integration,

$$\frac{a}{b} = \int_{h_o}^{h} g \, dh \qquad \text{and} \qquad g = g_o \left(\frac{R_+}{h + R_+} \right)^2 ,$$

where g_o is the acceleration of gravity at the earth's surface. After integration and some algebraic manipulation, the expression for L is given as

$$L = \frac{bh_o + a[1 + (h_o/R_+)]}{b - (a/R_+)[1 + (h_o/R_+)]} . \tag{11}$$

The transition level is a function of both ion temperature and the composition of ionic constituents at the base level. The transition level of the two species does not depend on the third component. However, the ionic distribution of any particular species depends not only on the third species but also on the electron temperature. A family of curves is plotted in Figs. 5 and 6 to show the transition levels of He^+ and O^+ and of H^+ and He^+ as functions of ion temperature.

If the transition levels and the temperature are known, one can find the ionic composition at the base level. Hence the electron-density profile can be calculated from Eq. (5). Evans [1965] has measured a large change of electron temperature above the peak of electron density in the F2 layer during the daytime. The electron temperature at a height of about 700 km reaches as high as 3000 ^oK near noon and less than 2000 ^oK near sunrise and sunset. The ion temperature approaches the electron temperature at a high altitude, which has been measured by

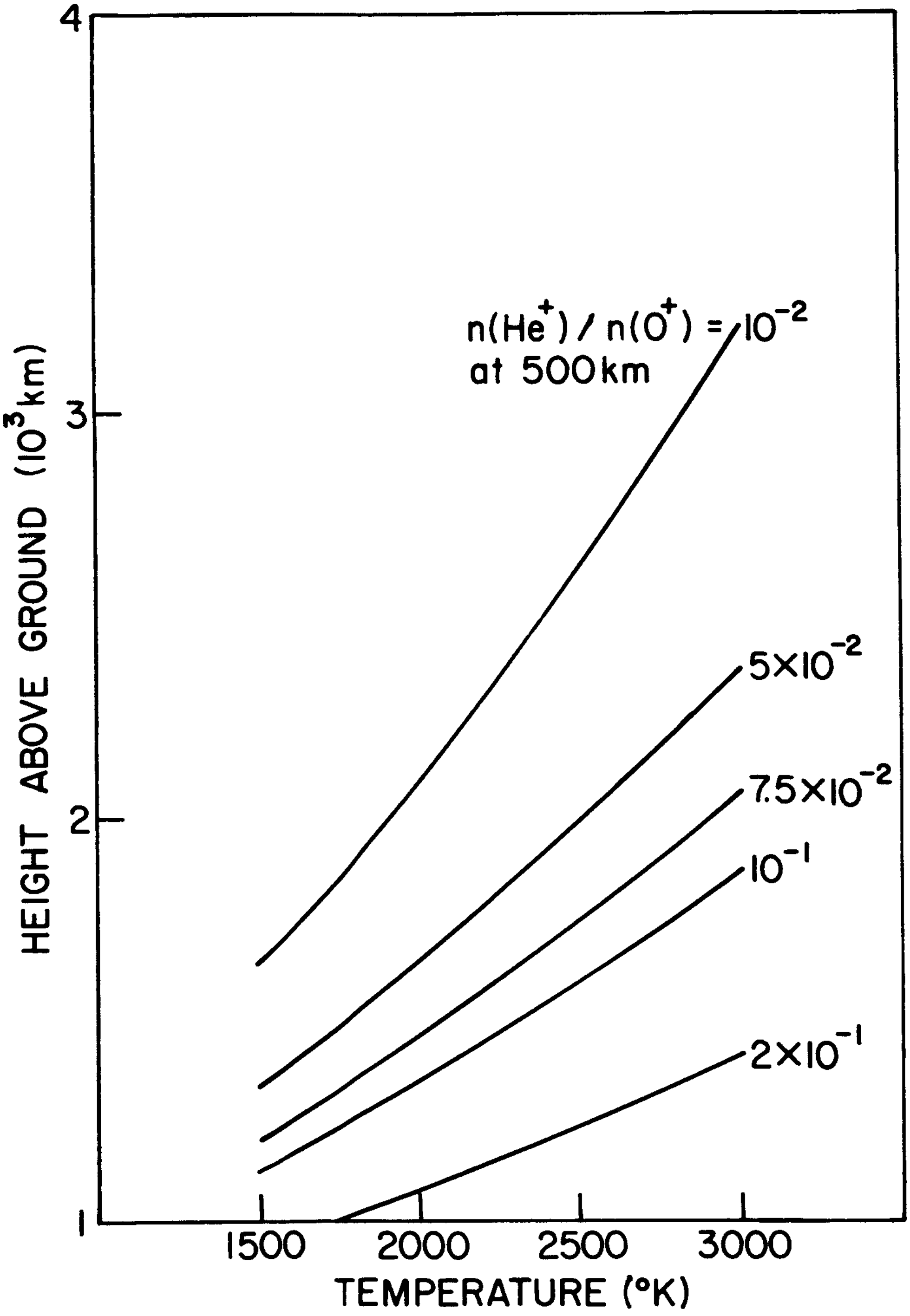

FIG. 5. TRANSITION LEVELS BETWEEN He^+ AND O^+ FOR DIFFERENT COMPOSITIONS AT THE BASE LEVEL (500 KM).

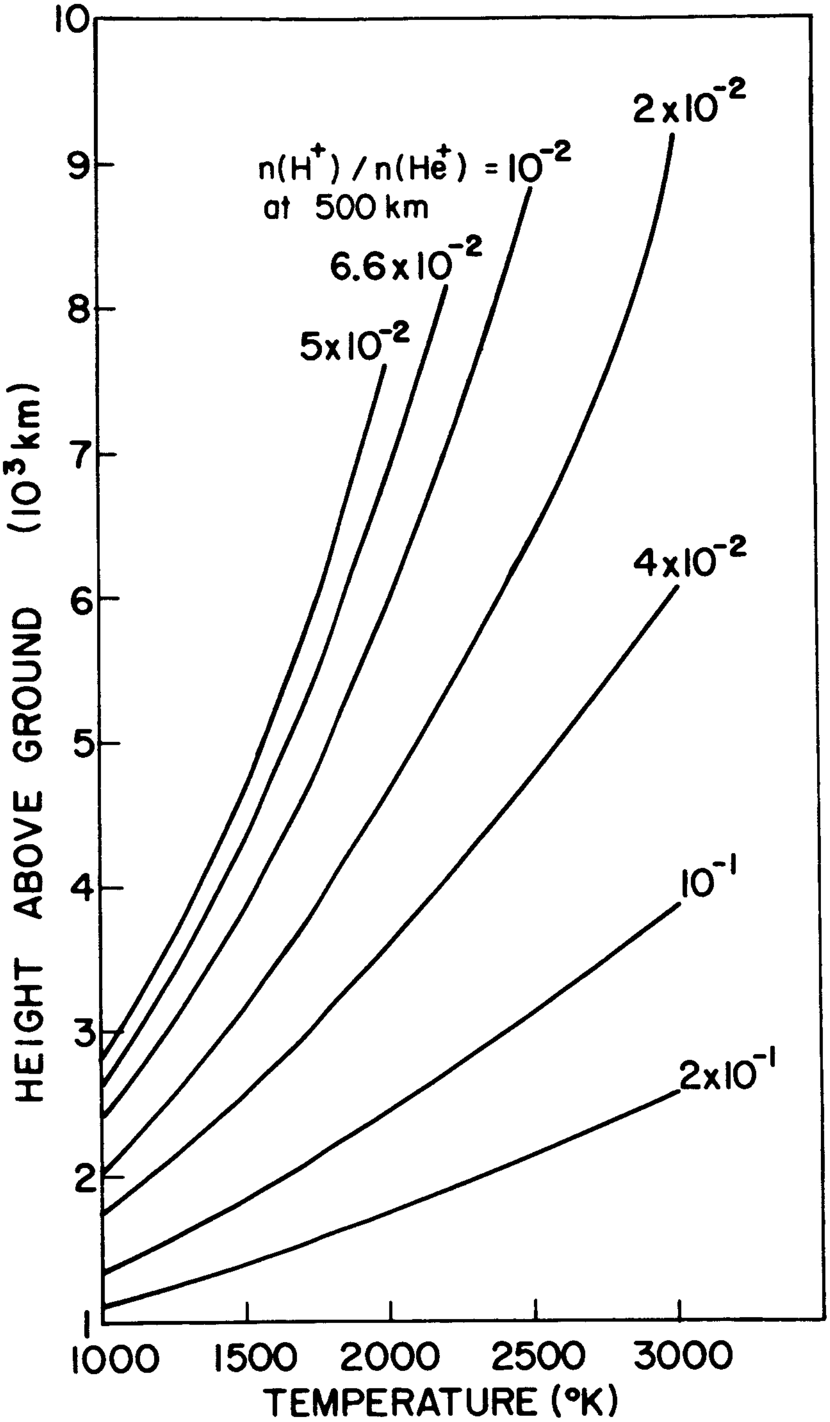

FIG. 6. TRANSITION LEVELS BETWEEN H^+ AND He^+ FOR DIFFERENT COMPOSITIONS AT BASE LEVEL (500 KM).

Evans and Loewenthal [1964] and predicted by theories of Hanson [1963] and Dalgarno et al [1963]. Hence the assumption that the ion temperature and the electron temperature are the same is a reasonable one. The results of the Ariel satellite measurements [Bowen et al, 1964] on the transition levels show that during daytime hours the transition between He^+ and O^+ is above 1000 km and can be as high as 1400 km at mid-latitudes. The transition level between He^+ and H^+ cannot be detected by the satellite because of its low orbit.

A sample calculation of integrated normalized electron content is given below:

Height Range (km)	Integrated Electron Content Normalized at Base Level 2500 °K	1500 °K
500 - 1,000	3.0×10^5	2.4×10^5
1,000 - 4,000	3.5×10^5	2.1×10^5
4,000 - 10,000	2.5×10^5	1.3×10^5

The ionic compositions at 500 km are chosen in such a way that the transition level between He^+ and O^+ remains fairly constant above 1000 km and between He^+ and H^+ is about 3000 km, as suggested by Bowen et al [1964]. Thus,

$$\eta_{12} = 0.1 \qquad \text{and} \qquad \eta_{23} = 0.4$$

An illustration of the shape of electron-density distribution with different temperatures is shown in Fig. 7. It is clear that the changes of temperature affect the percentage the most at high altitudes.

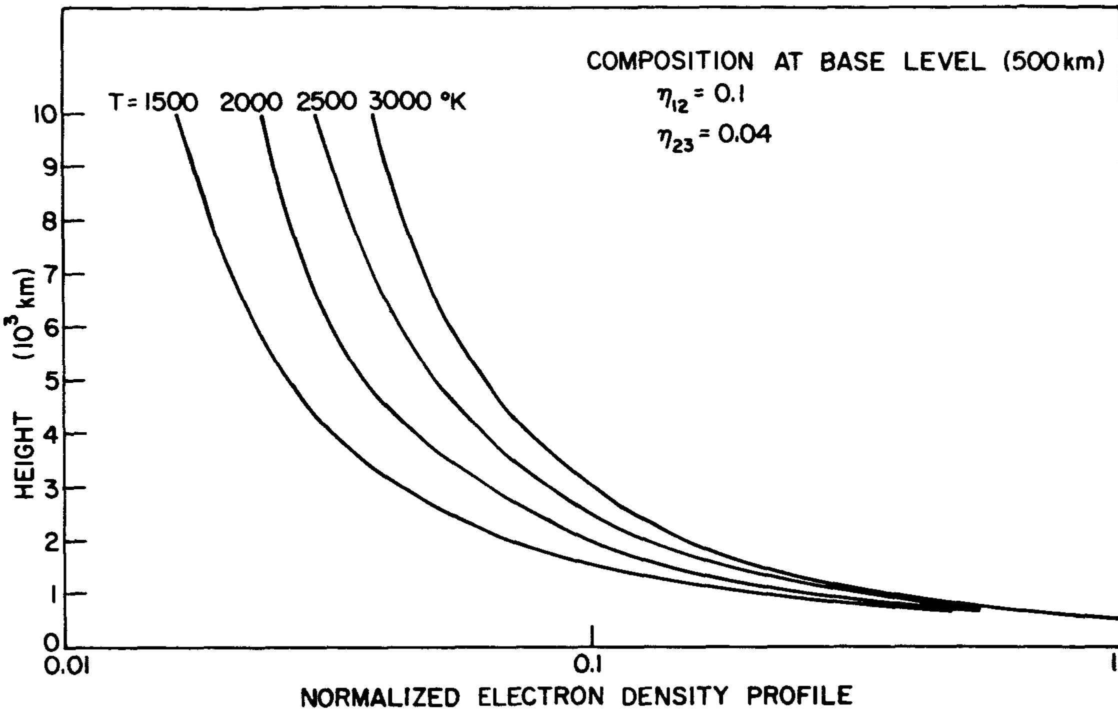

FIG. 7. NORMALIZED ELECTRON-DENSITY PROFILE ABOVE BASE LEVEL FOR DIFFERENT TEMPERATURES.

Now it is desirable to estimate the value of N_{eo} at 500 km for noon and sunset or sunrise. During the entire period of the lunar radar experiment, the bottomside ionosonde was operated every 15 minutes at Stanford and the average diurnal variation of the maximum electron density was thus obtained. Figure 8 shows the variation of N_{max}, which increases rapidly after sunrise, reaches its maximum value near noon, and starts to decay in the afternoon until after sunset. The nighttime value of N_{max} remains fairly constant. If the density at 500 km is assumed to vary in the same fashion as N_{max}, a large change of electron density at 500 km between noon and sunset or sunrise would be expected. If it is assumed that the density at 500 km is about one-tenth of N_{max}, the

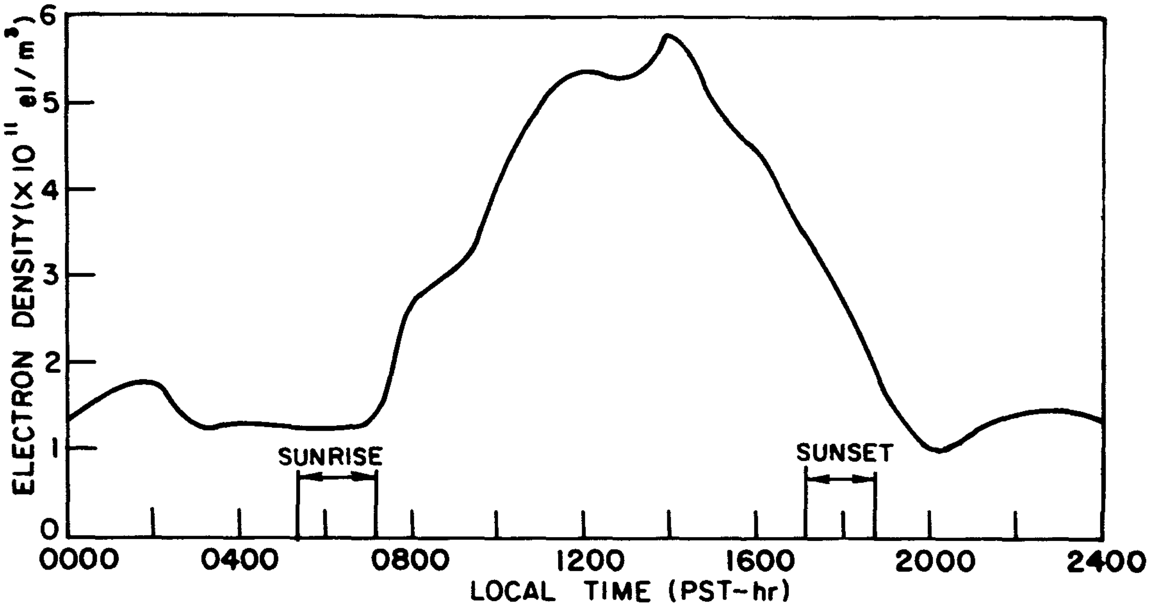

FIG. 8. AVERAGED MAXIMUM ELECTRON DENSITY, N_{max}, MEASURED AT STANFORD DURING THE LUNAR-RADAR-ECHO EXPERIMENT.

density at 500 km would vary from 5.5×10^{10} m^{-3} to 2.5×10^{10} m^{-3}. The net changes of electron content for the different height ranges, using the high value of density for 2500 ^oK and the low value for 1500 ^oK, are shown below:

Height Range (km)	Change of Electron Content (el/m^2)
500 - 1,000	1.0×10^{16}
1,000 - 4,000	1.4×10^{16}
4,000 - 10,000	1.0×10^{16}

It is clear from the above that, with a fairly large change of temperature, the change of electron content in the high-altitude region has the same order of magnitude of change as was observed for the lunar radar echoes.

The Doppler method measures the net change of electron content, 3.4×10^{16} el/m^2. The amount of change of electron content computed by the Faraday method is about 1.2×10^{16} el/m^2. Subtracting the two values gives a net difference of change of electron content of 2.2×10^{16} el/m^2.

Since local ionization production does not occur above 1000 km, the amount of increase and decrease of ionization at the high altitudes or lower magnetosphere must be restored or removed from somewhere else. It is therefore logical to deduce that the ionosphere serves as the source as well as the sink and that the electron-flux flow between the ionosphere and the lower magnetosphere does exist.

The results of other workers support this idea of electron-flux flow. For example, Evans [1965a], using radar backscatter, detected a large downward drift of the ionization from above 500 km during the 20 July 1963 eclipse. The results of his measurements showed, at the beginning of the eclipse, a large depression of the ionization at heights above 500 km and an increase of ionization near the density peak of the F2 region. The amount of density depression at the high altitudes was about half of the pre-eclipse value. Evans again observed an increase of ionization near the peak during normal afternoon hours [1965b]. This evidence agreed with the lunar-radar measurement of the downward flow of ionization in the afternoon hours.

The results of both Ariel [Willmore, 1964] and Explorer XVII [Brace et al, 1965] satellite measurements on electron temperatures and ion density in the upper ionosphere and part of the lower magnetosphere indicate an upward flow of ionized flux. The value of the upward flux is on the order of 10^{12} m^{-2} sec^{-1}, which agrees well with the value suggested by the lunar-radar experiment. Hanson [1963] has predicted theoretically the amount of fast photoelectron drifting upward to be about 10^{12} m^{-2} sec^{-1}.

REFERENCES

1. Bauer, S. J., "On the Structure of the Topside Ionosphere," J. Atmos. Sci., 16, 1962, pp. 276-278.

2. Bowen, P. J., et al, "Ion Composition of the Upper F-Region," Proc. Roy. Soc. (London), 281, 1964, pp. 504-514.

3. Brace, L. H., N. W. Spencer, and A. Dalgarno, "Detailed Behavior of the Mid-Latitude Ionosphere from the Explorer XVII Satellite," Planet. Space Sci., 13, 7, Jul 1965, pp. 647-666.

4. Browne, I. C., J. V. Evans, J. K. Hargreaves, and W. A. S. Murray, Radio echoes from the moon, Proc. Phys. Soc. London, 8, 69, 901-920, 1956.

5. Carpenter, D. L., and T. R. Jewell, "Temporal and Spatial Variations of the "knee" in the Magnetospheric Electron Density Profile," paper presented at Spring 1965 URSI meeting, Washington, D.C.

6. Dalgarno, A., M. B. McElroy, and R. J. Moffett, "Electron Temperatures in the Ionosphere," Planet. Space Sci., 11, 1963, pp. 463-484.

7. De Witt, J. M., Jr. and E. K. S. Stodola, Detection of radio signals reflected from the moon, Proc. IRE, 37, 229-242, 1949.

8. Evans, J. V., "Cause of the Mid-Latitude Evening Increase in f_o F2," J. Geophys. Res., 70, 1965b, pp. 1175-1186.

9. Evans, J. V., and M. Loewenthal, "Ionospheric Backscatter Observations," Planet. Space Sci., 12, 1964, pp. 915-944.

10. Evans, J. V., "An F-Region Eclipse," J. Geophys. Res., 70, 1965a, pp. 131-142.

11. Hanson, H. B., "Electron Temperatures in the Upper Atmosphere," Space Research, Vol. III, edited by W. Priester, North-Holland Publishing Co., Amsterdam, Netherlands, 1963, pp. 282-302.

12. Howard, H. T., P. Yoh, and V. R. Eshleman, Radar doppler measurements of the cislunar medium, J. Geophys. Res., 69, 535-539, 1964a.

13. Howard, H. T., B. B. Lusignan, P. Yoh, and V. R. Eshleman, Radar Doppler and Faraday polarization measurements of the cislunar medium during the July 20, 1963 solar eclipse, J. Geophys. Res., 69, 540-544, 1964b.

14. Howard, H. T., B. B. Lusignan, and V. R. Eshleman, Radar astronomy and propagation research, SEL-64-114, Final Rpt. AF contract AF19(604-7436, Stanford Electronics Labs., Stanford, California, September 1964c.

15. Ness, N. F., C. S. Scearce, and J. B. Seek, "Initial Results of the IMP-I Magnetic Field Experiment," J. Geophys. Res., 69, 1964, pp. 3531-3570.

16. Willmore, A. P., "Energy Sources for the Ionospheric Electrons," Nature, 202, 1964, pp. 41-42.

17. Yoh, P., H. T. Howard, B. B. Lusignan, and V. R. Eshleman, "Lunar Radar Measurements of the Earth's Magnetospheric Wake," J. of Geophy. Res., 71, Jan 1966.

18. Yoh, Philip, "Radar Studies of the Cislunar Medium," Rept. SEL-65-091 (Scientific Rept. No. 12), Stanford Electronics Laboratories, Stanford, Calif., Dec 65.