X-621-68-11
PREPRINT

NASA TM X-63297

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JUNE 1968

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

To be published in the Journal of Atmospheric and Terrestrial Physics.

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DIURNAL VARIATION OF THE ION TEMPERATURE*

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ABSTRACT

Results on the diurnal variation of the ion temperature, obtained from the Thomson scatter spectra at Arecibo, in the height range 250-475 km are presented. At 250 km where the ion temperature (T_i) is expected to be nearly equal to the neutral temperature (T_n), T_i is generally observed to show diurnal maximum at 16 hr L.T. and diurnal minimum at 4 hr L.T., with no appreciable change in these times with solar activity. The average day to night T_i ratio at 250 km is found to be 1.45. These results are in apparent conflict with the satellite drag analysis in which T_n is found to have a diurnal maximum at 14 hr L.T. and day to night temperature ratio around 1.30. At 475 km where T_i is significantly above T_n, the diurnal behavior of T_i is observed to be different on different days. The day-to-day and hour-to-hour variations in T_i at this height are found to be due to the changes in the electron density and electron temperature and seem consistent in terms of an energy budget that includes heating of the ion gas by the hotter thermal electrons and cooling by the neutral atmosphere.

*This work was initiated at the Arecibo Ionospheric Observatory, Arecibo, Puerto Rico and completed at Goddard Space Flight Center

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I. INTRODUCTION

It was shown by Hanson (1963) that for altitudes below 300 km the energy transferred to the ion gas by the hotter electron gas would be rapidly lost to the neutral atmosphere and consequently the ion temperature (T_i) would be very nearly equal to the neutral temperature (T_n). At higher altitudes, due to substantial decrease in the neutral gas concentration, the ion gas can not efficiently loose the thermal energy (obtained from the electron gas) to the neutral gas without the existence of an appreciable difference between T_i and T_n. Hence a characteristic transitional behavior of T_i, increasing from T_n at 250 km towards the electron gas temperature (T_e) above 700 km is expected (Hanson, 1963; Geisler and Bowhill, 1965; Dalgarno et al., 1967; Banks, 1967). As such, experimentally observed T_i at altitudes below 300 km can provide information on the diurnal behavior of T_n and at higher altitudes can be used to examine the energy budget dealing with the heating and cooling of the ion gas. The purpose of this communication is to present results on the diurnal variation of T_i in this context. The ion temperatures to be reported are obtained from the Thomson scatter spectra observed in the height range 250 to 475 km at Arecibo during the period October 1965 through March 1967.

II. THE METHOD

The Arecibo facility and its operation for the ionospheric Thomson scatter measurements has been discussed by Gordon and Lalonde (1961) and by Carlson (1965). The power spectra of the Thomson scatter signal provide information on the electron and ion temperatures. In the present analysis, these have been collected with a 500μs pulse length (resulting in 75 km smearing) by using the digital autocorrelation technique developed by Perkins and Wand (1965). Temperatures from the spectra are derived by two methods. In one of these the half power width and the wing to center ratio of the power spectra are used (see e.g., Evans and Loewenthal, 1964). In the other, temperatures are determined from the first zero crossing and the depth of the first null of the autocorrelation functions (Perkins and Wand, 1965). A pure O^+ ion is assumed in interpreting the spectra. Temperatures used are the average of the two methods for any one observation. At times, in particular during the night, when temperatures by either of the two methods were not available (due to low signal to noise ratio or due to some inherent difficulties with the method), these times were not considered in the analysis.

III. THE RESULTS

Figures 1 and 2 are the diurnal plots of the ion temperature at heights of 250 and 325 km for several days during the period October 1965 through March 1967. The observations for each experiment, in general, start around 16 hr. L.T. on one day and end at about 20 hr. L.T. next evening and have a time resolution of about 30 minutes. Since T_i at 250 km is expected to be very nearly equal to T_n (Hanson, 1963; Geisler and Bowhill, 1965; Dalgarno et al., 1967: Banks, 1967), Fig. 1 should basically represent the diurnal behavior of T_n. While T_i can be more than T_n by a few tens of degrees at 325 km, the difference between T_i and T_n is not expected to change significantly with time during the day (Dalgarno et al., 1967). Nisbet (1967), in fact, has calculated T_n at 250 and 325 km from the Thomson scatter measurements of T_e, T_i and electron density (N_e) at Arecibo, by using the ion continuity equation. He has found T_n to be equal to T_i during the night at these heights. During the day he has estimated $T_i - T_n$ to be of the order of 25°K at 250 km and 100°K at 325 km with no appreciable variation in this value with the time of the day. As such Fig. 2 should also represent gross features of the diurnal behavior of T_n at these heights. The day-to-day changes in the value of T_i (at fixed times) are due to changes in the solar activity, as demonstrated in an earlier communication (Mahajan, 1967). The 'short term' hour-to-hour changes are generally within the uncertainty of the measurements (estimated to be about 5%). The diurnal maximum seems to occur most often around 16 hr L.T. (spread between 14 hr and 18 hr on other days) and is in disagreement with the 14 hr maximum evolved from the satellite drag data (see e.g. Jacchia, 1965). The time of the diurnal minimum is approximately before local sunrise.

The times of the occurrence of the diurnal maximum and minimum are more clearly demonstrated in Figs. 3 and 4, where the quantity T_i/T_{min} (T_i is the ion temperature at any time and T_{min} the minimum nighttime ion temperature for that day) is plotted against time for a height of 250 km for several geomagnetically undisturbed days. Due to minor fluctuations in the nighttime temperatures, some smoothing has been done to obtain T_{min}. Figure 3 includes observations on October 5-6, October 27-28, 1965 and January 31-February 1, February 28-March 1, 1966 during period of low solar activity. Figure 4 includes observations on August 16-17, November 12-13, 1966 and March 3-4, March 23-24, 1967 during periods of moderate solar activity. The daily and the 27-day average (centered at the day of observation) values of the 10.7 cm solar flux, reported by the National Research Council, Canada are given in Table 1. It can be noted from Figs. 3 and 4 that the average times of the diurnal maximum and minimum are respectively 16 hr L.T. and 4 hr L.T., both during the low and moderate solar activity. The average ratio T_{max}/T_{min} is 1.45 ±0.15 and is well above the value of 1.28 deduced from the satellite drag data (Jacchia, 1964), but is close to the COSPAR model (CIRA, 1965).

A comment that the 75 km smearing resulting from the long pulse length for the T_i measurements at 250km is in order. With the lower edge of the pulse in a region of heavier ions (NO^+ and O_2^+ in small quantities) and the possible increase of T_i with height in the region occupied by the pulse (i.e., 212.5 to 287.5 km), some errors in T_i measurements might be expected. While the errors due to temperature increase within the pulse length are expected to be negligible, (for nearly constant temperature gradient), as the measurements correspond to the center of the pulse, some underestimation in T_i is possible due to the presence of heavier ions near the lower edge of the pulse. It is however interesting to note that the T_i measurements are not very sensitive to the presence of heavier ions in small quantities. Wand (private communication) nas made some estimates of the error introduced due to the presence of heavier ions by comparing the theoretical autocorrelation functions with those experimentally observed from the 'double pulse' technique which gives 15 km resolution in height. He has found that the presence of 10% of the heavier ions throughout the pulse length underestimates T_i by no more than 2% and by less than 5% with 20% of the heavier ions. As the heavier ions for our long pulse measurements are present only in lowermost part of the pulse, the errors in this case are expected to be much smaller. Ion composition measurements during March 1966 (Brinton, private communication), a period closest to our observations, indicate about 20% of the heavier ions at the lower edge of the pulse, decreasing to about 1% at the upper edge. From these measurements one would estimate about 5% as an average amount of the heavier ions present throughout the pulse length. This would result in an underestimate of less than 2% in the T_i measurements. It is, however, pointed out that these errors are not expected to anyway affect the diurnal behavior of T_i at 250 km, as the errors will be systematic. Reasonable diurnal variation in the ionic composition will probably not significantly alter the results. Support to this conclusion also comes from T_i measurements at 325 km where the problem of long pulse is less serious (due to pure O^+ region). The diurnal behavior of T_i at 325 km follows very closely the T_i behavior at 250 km. Also, as the T_n calculated by Nisbet (1967), from the ion continuity equation, at 250 km is in reasonable agreement with that calculated at 325 km, our confidence in T_i measurements at 250 km all the more increases.

The diurnal behavior of the ion temperature at a height of 475 km, where T_i is observed to be significantly above T_n, is examined in Fig. 5. Here the daytime T_i is plotted against time for three observations. No nighttime data is used due to uncertainty in the ionic composition at this height during the night. The simultaneously measured T_e and N_e values for these observations are also plotted in Fig. 5 for comparison. The diurnal variation of T_i is not quite the same on all the three days and is very different from the T_i variation at 250 and 325 km shown in Figs. 1 and 2.

The day-to-day and hour-to-hour changes in T_i can be examined in terms of the energy budget dealing with the heating and cooling of the ion gas. The heat given to the ions by the hotter thermal electrons is given by:

$$Q_{ei} = \frac{7.7 \times 10^{-6} \; N_e \; N_i \; (T_e - T_i)}{A_i \; T_e^{3/2}} \tag{1}$$

where A_i is the ionic mass in atomic mass units and N_i is the ion density. Assuming oxygen atoms to be the major coolant for the ions at 475 km, then the heat given by the ions to the neutral gas is (Banks, 1967):

$$Q_{in} = 2.1 \times 10^{-15} \; N_e \; n(O) \; (T_i - T_n) \sqrt{T_i + T_n} \tag{2}$$

n(O) being the atomic oxygen concentration

If $Q_{ei} = Q_{in}$ and assuming $N_e = N_i$, then from equations (1) and (2):

$$\frac{T_i - T_n}{T_e - T_i} \; T_e^{3/2} \sqrt{T_i + T_n} \propto N_e \tag{3}$$

Thus one should expect a linear relation between N_e and the quantity on the R-H-S. of equation (3). This is examined in Fig. 6 where the experimentally observed N_e and $\frac{T_i - T_n}{T_e - T_i} T_e^{3/2}\sqrt{T_i + T_n}$ are plotted against each other for the three days shown in Fig. 5. Afternoon values between 12-16 hours have been used and T_n has been taken as the T_i measured at 250 km. There is a positive correlation between N_e and $\frac{T_i - T_n}{T_e - T_i} T_e^{3/2}\sqrt{T_i + T_n}$, thus indicating a reasonable agreement between the experimental observations and the theory. Ideally one should expect the points to lie on a straight line passing through the origin. This departure from the theory could be due to a variety of reasons; the major one being the accuracy of the quantity $\frac{T_i - T_n}{T_e - T_i}$. Although T_e and T_i are estimated to be correct within ±5%, these limits produce larger error in the ratio $\frac{T_i - T_n}{T_e - T_i}$. Variations in the number density of atomic oxygen would also add to the scatter.

IV. DISCUSSION

From above it is clear that the diurnal behavior of T_i at 250 km (and 325 km), where T_i is expected to be equal to T_n, is in conflict with the neutral temperature results derived from the satellite drag analysis. Assuming that the T_i values presented here are correct, this suggests that either T_i is not equal to T_n at 250 km or diurnal behavior of T_n deduced from satellite drag data is not reliable. As already pointed out, Nisbet (1967) has solved the ion continuity equation by using Thomson scatter measurements of T_i, T_e and N_e at Arecibo and has calculated that T_i is very nearly equal to T_n at 250 km. This would mean that the diurnal behavior of T_n derived for satellite drag data is probably questionable. It is, of course, well known that the satellite drag measurements do not provide continuous data throughout the day at one location. (See Priester et al., 1967, for a survey on Satellite drag analysis.) To construct a diurnal picture of the temperature, several days data corresponding to various latitudes, longitudes, altitudes, solar time, solar activity and magnetic activity might have to be used. The diurnal variation of the temperature is then evolved by adjusting the derived temperature for variations in the other parameters under suitable assumptions.

At this point it would, probably, be relevant to compare our experimental observations with some theoretical results. Harris and Priester (1962) have investigated the diurnal variation of the atmospheric temperature by integrating the time dependent heat conduction equation. They found that with EUV as the only heat source, the diurnal maximum should occur at 17 hr and have a maximum to minimum temperature ratio of 2.2. Although the time of the diurnal maximum is close to the time of T_i maximum (at 250 and 325 km) shown by our measurements, the amplitude is much higher. In the theoretical work of Harris and Priester, however, only the vertical expansion of the atmosphere in a column was considered. As is now, generally, believed that the horizontal movement of the air, giving rise to lateral heat transport, can significantly affect the phase and the amplitude of the diurnal maximum (Volland 1966, 1967), any value of the phase and the amplitude can be obtained by choosing suitable phase relations between the wind and the temperature.

V. CONCLUSIONS

In conclusion it can be said that the diurnal behavior of T_i at 250 km (and 325 km) is significantly different from the T_n results derived from satellite drag analysis. As T_i has been calculated to be nearly equal to T_n at 250 km by Nisbet (1967), it is concluded that the diurnal behavior of T_n evolved from satellite drag observations is questionable. The 16 hr L.T. diurnal maximum observed in the T_i measurements supports the recently reported Thomson scatter results of Carru et al. (1967) and Nisbet (1967). While the diurnal variation of T_i at 475 km can be different on different days, it seems consistent with the theory that assumes heating of the ion gas by the hotter electrons and cooling by the neutral atmosphere.

ACKNOWLEDGMENTS

I am thankful to Dr. H. C. Carlson and Mr. L. H. Brace for their helpful comments on the manuscript, to Dr. R. Wand for helpful discussions on the effects of long pulse smearing and to the National Academy of Sciences—National Research Council for the award of postdoctoral Resident Research Associateship at the Goddard Space Flight Center. The data used in this study were collected by the resident members of the Arecibo Ionosphere Group, under a regular observational program. The Arecibo Ionospheric Observatory is operated by Cornell University with the support of the Advanced Research Project Agency under a research contract with the Air Force Office of Scientific Research.

Table 1

Date	$S_{10.7}$ Daily Values	$\bar{S}_{10.7}$ 27 Day Average
Oct. 5-6, 1965	91, 85	81, 81
Oct. 27-28, 1965	78, 77	71, 71
Jan. 31-Feb. 1, 1966	78, 80	87, 86
Feb. 28-Mar. 1, 1966	86, 81	81, 81
Aug. 16-17, 1966	93, 94	104, 104
Nov. 12-13, 1966	129, 129	113, 114
Mar. 3-4, 1967	203, 215	162, 163
Mar. 23-24, 1967	151, 163	148, 148

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DALGARNO, A., McELROY, M. B. and WALKER, J. C. G.	1967	Planet Space Sci. 15, 331
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GEISLER, J. E. and BOWHILL, S. A.	1965	J. Atmosph. Terr. Phys. 27, 457
GORDON, W. E. and LALONDE, L. M.	1961	I.R.E. Trans. Antennas Propog. 9, 17
HANSON, W. B.	1963	Space Res. 3, 282
HARRIS, I. and PRIESTER, W.	1962	J. Atmosph. Sci. 19, 286
JACCHIA, L. J.	1965	Space Res. 5, 1152
MAHAJAN, K. K.	1967	J. Atmosph. Terr. Phys. 29, 1153
NISBET, J. S.	1967	J. Atmosph. Sci. 24, 586
PRIESTER, W., ROEMER, M. and VOLLAND, H.	1967	Space Sci. Rev. 6, 707

VOLLAND, H.	1966	J. Atmosph. Sci. 23, 799
VOLLAND, H.	1967	Space Res. 7, 1193

The following unpublished material is also referred to

CARLSON, H. C.	1965	Cornell University, CRSR Rep. 212
JACCHIA, L. J.	1964	Smithsonian Astrophys. Obs. Special Rept. No. 170
PERKINS, F. and WAND, R.	1965	Cornell University, CRSR Rep. 207

LEGENDS TO THE FIGURES

Fig. 1 Diurnal variation of T_i at 250 km for several days. The serial numbers are the codes for the experiment. The zero for T_i corresponding to each experiment is indicated on the vertical scale.

Fig. 2 Diurnal variation of T_i at 325 km for several days. The serial numbers are the codes for the experiment. The zero for T_i corresponding to each experiment is indicated on the vertical scale.

Fig. 3 Diurnal variation of the quantity T_i / T_{min} at a height of 250 km for 4 days during low solar activity.

Fig. 4 Diurnal variation of the quantity T_i / T_{min} at a height of 250 km for 4 days during moderate solar activity.

Fig. 5 Diurnal variation of T_i, T_e and N_e at 475 km for three days.

Fig. 6 A plot of N_e against $\frac{T_i - T_n}{T_e - T_i} T_e^{3/2} \sqrt{T_i + T_n}$ for observations shown in Fig. 5. Times between 12-16 hours have been used.

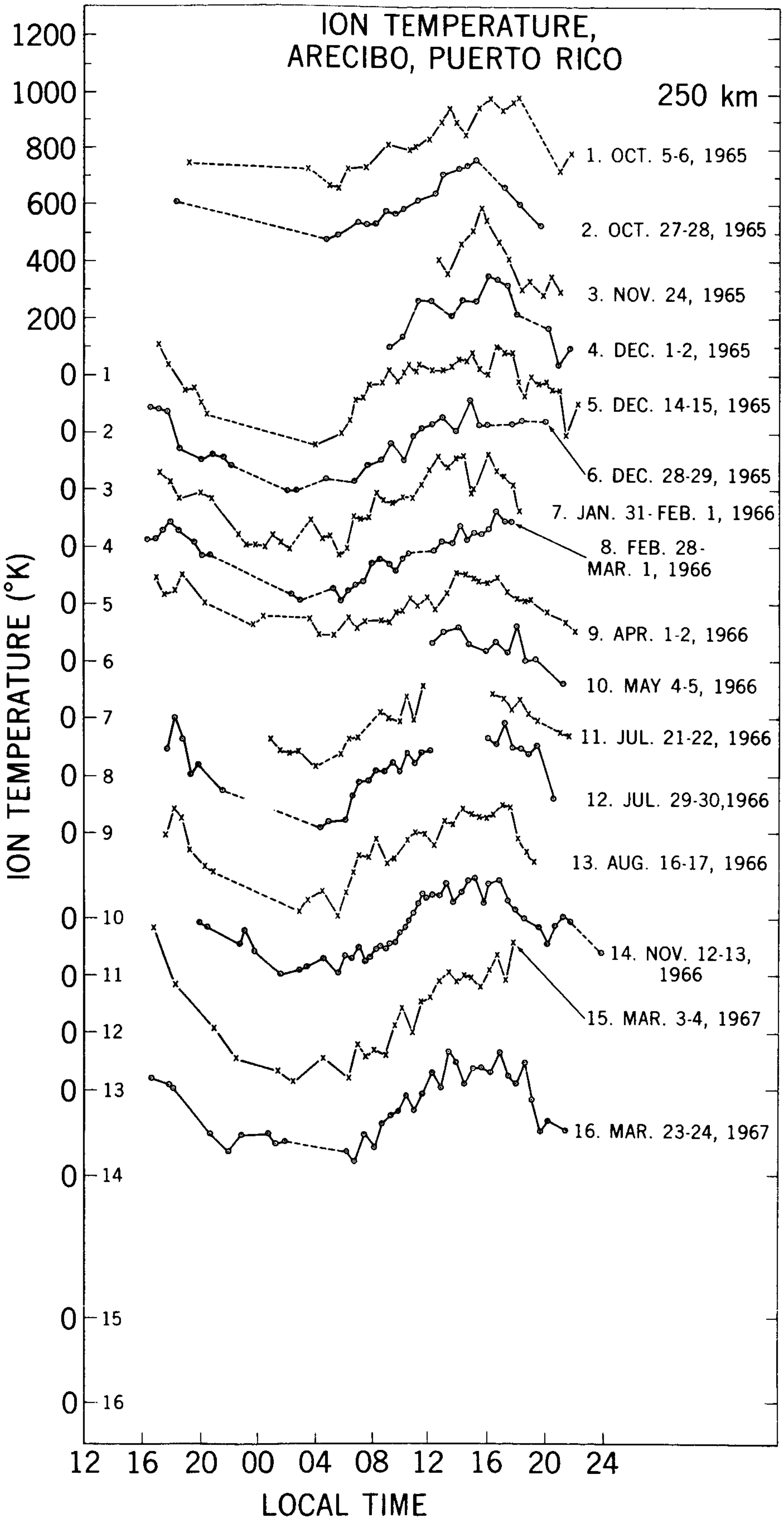
ION TEMPERATURE,
ARECIBO, PUERTO RICO
250 km
ION TEMPERATURE (°K)
1200
1000
800
600
400
200
0 - 1
0 - 2
0 - 3
0 - 4
0 - 5
0 - 6
0 - 7
0 - 8
0 - 9
0 - 10
0 - 11
0 - 12
0 - 13
0 - 14
0 - 15
0 - 16
1. OCT. 5-6, 1965
2. OCT. 27-28, 1965
3. NOV. 24, 1965
4. DEC. 1-2, 1965
5. DEC. 14-15, 1965
6. DEC. 28-29, 1965
7. JAN. 31-FEB. 1, 1966
8. FEB. 28-
MAR. 1, 1966
9. APR. 1-2, 1966
10. MAY 4-5, 1966
11. JUL. 21-22, 1966
12. JUL. 29-30,1966
13. AUG. 16-17, 1966
14. NOV. 12-13,
1966
15. MAR. 3-4, 1967
16. MAR. 23-24, 1967
12 16 20 00 04 08 12 16 20 24
LOCAL TIME

Figure 1

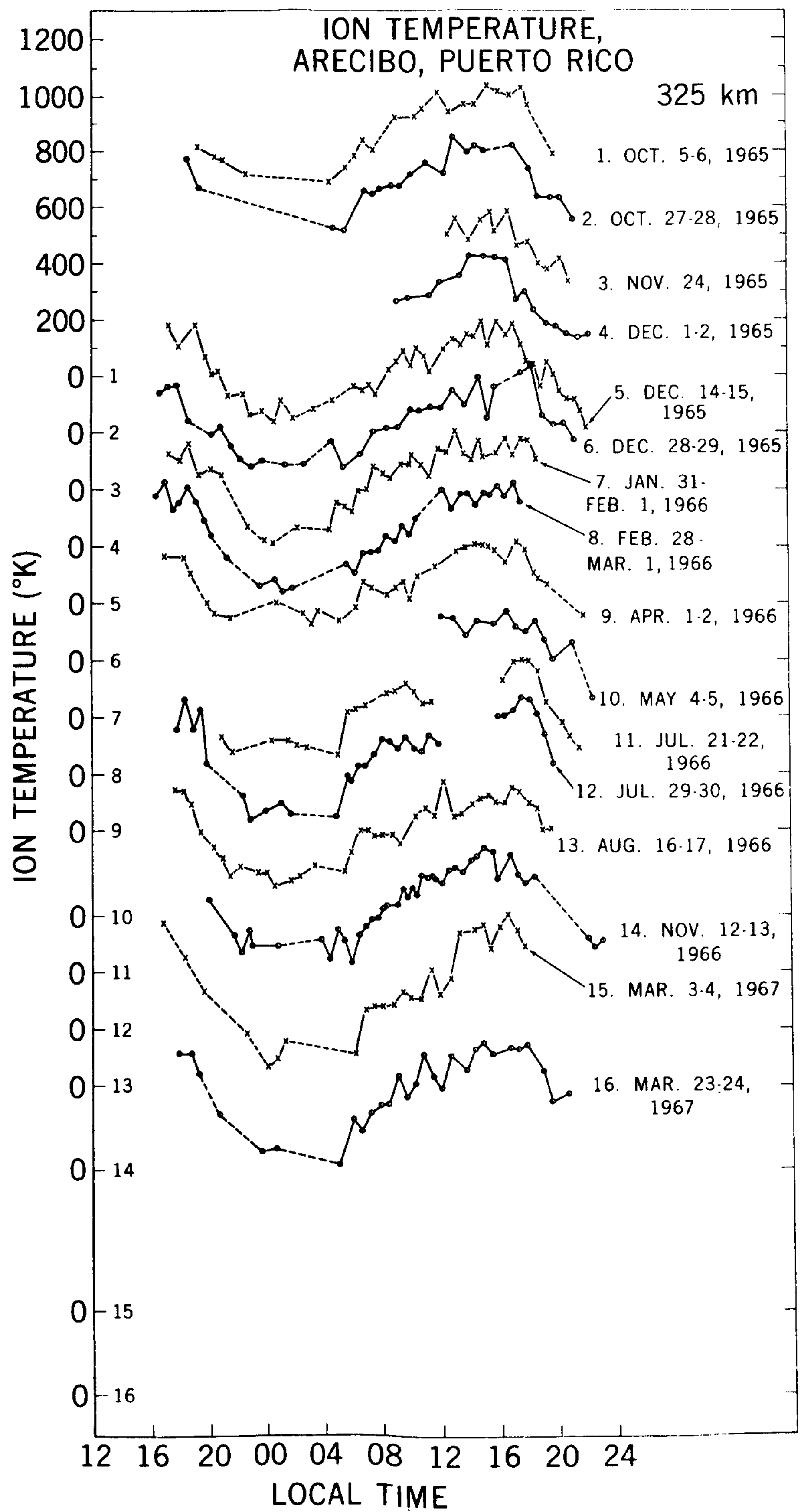
ION TEMPERATURE,
ARECIBO, PUERTO RICO
325 km
ION TEMPERATURE (°K)
LOCAL TIME
1. OCT. 5-6, 1965
2. OCT. 27-28, 1965
3. NOV. 24, 1965
4. DEC. 1-2, 1965
5. DEC. 14-15, 1965
6. DEC. 28-29, 1965
7. JAN. 31-FEB. 1, 1966
8. FEB. 28-MAR. 1, 1966
9. APR. 1-2, 1966
10. MAY 4-5, 1966
11. JUL. 21-22, 1966
12. JUL. 29-30, 1966
13. AUG. 16-17, 1966
14. NOV. 12-13, 1966
15. MAR. 3-4, 1967
16. MAR. 23-24, 1967

Figure 2

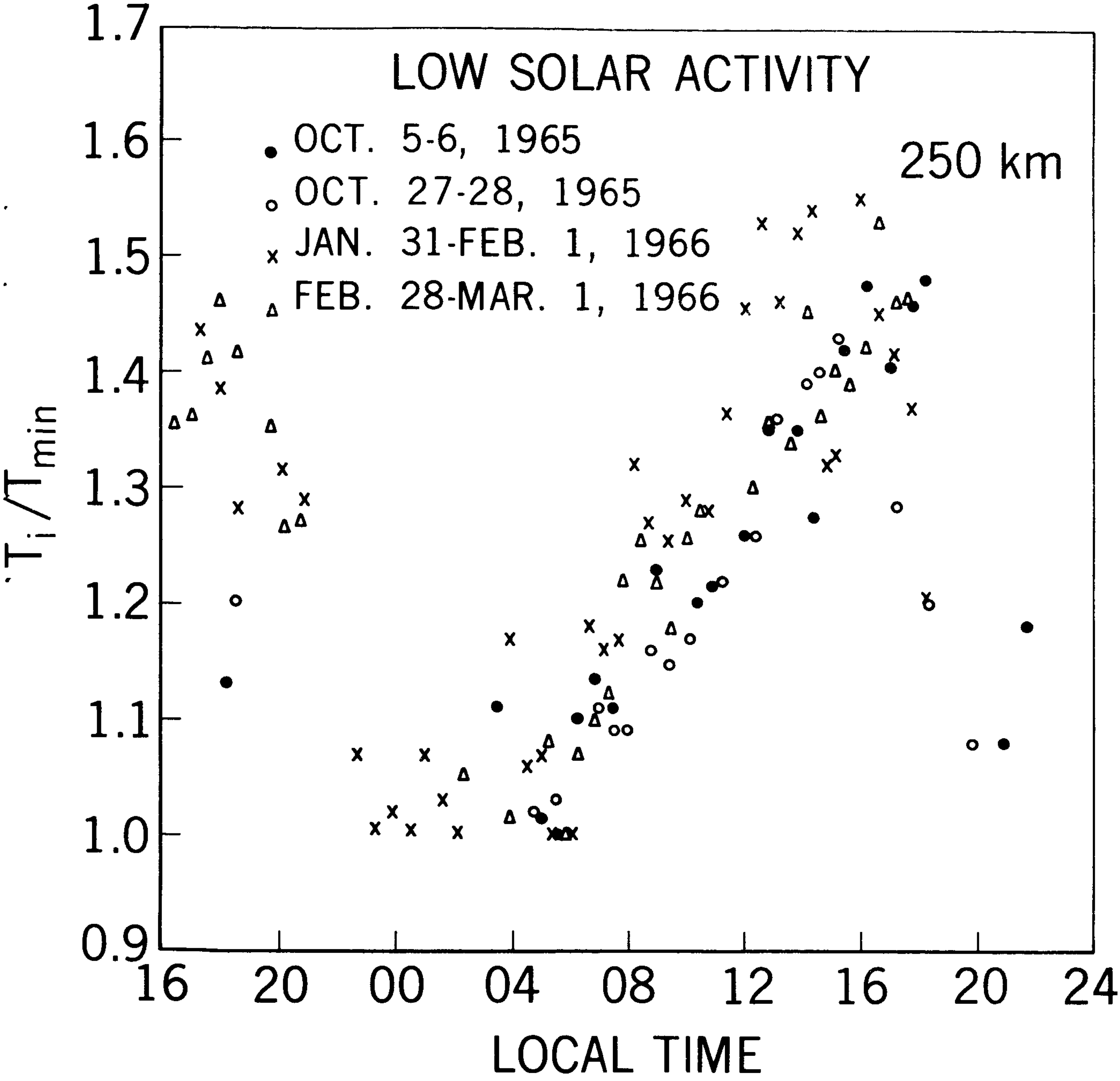
LOW SOLAR ACTIVITY
OCT. 5-6, 1965
OCT. 27-28, 1965
JAN. 31-FEB. 1, 1966
FEB. 28-MAR. 1, 1966
250 km
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
Ti /Tmin
16
20
00
04
08
12
16
20
24
LOCAL TIME

Figure 3

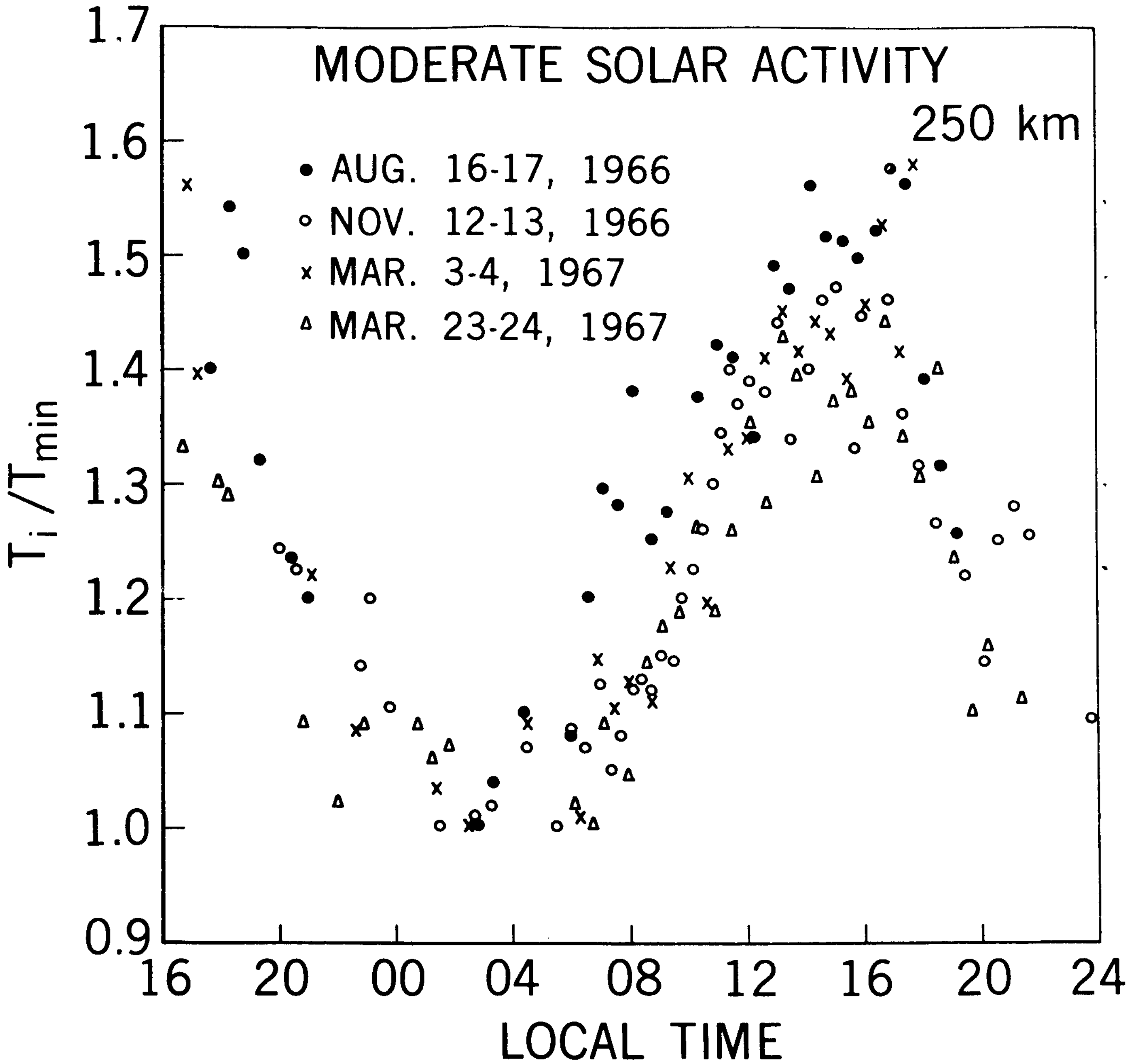
MODERATE SOLAR ACTIVITY
250 km
AUG. 16-17, 1966
NOV. 12-13, 1966
MAR. 3-4, 1967
MAR. 23-24, 1967
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
T_i / T_{min}
16
20
00
04
08
12
16
20
24
LOCAL TIME

Figure 4

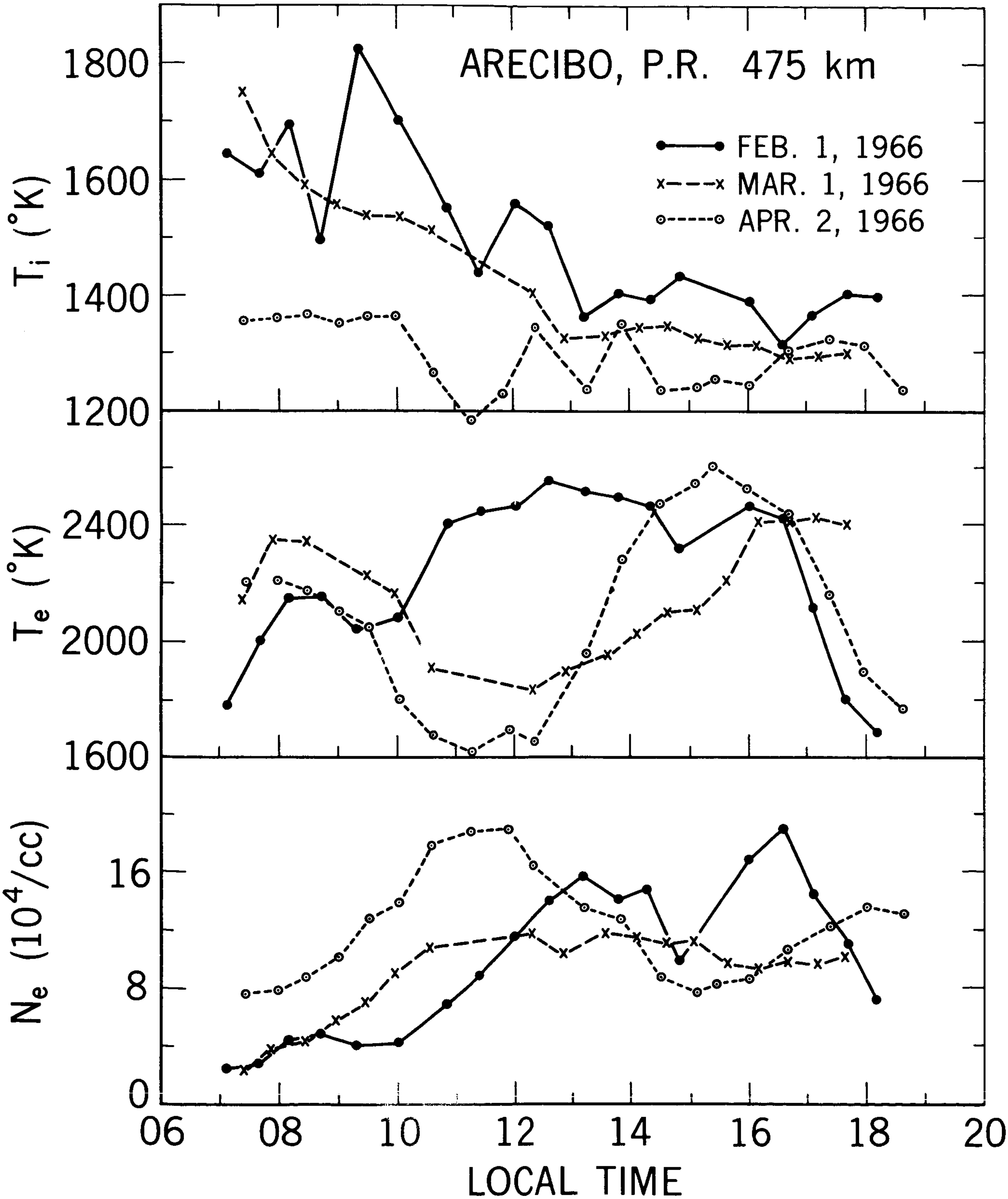
ARECIBO, P.R. 475 km
FEB. 1, 1966
MAR. 1, 1966
APR. 2, 1966
T_i (°K)
1800
1600
1400
1200
T_e (°K)
2400
2000
1600
N_e (10^4/cc)
16
8
0
06
08
10
12
14
16
18
20
LOCAL TIME

Figure 5

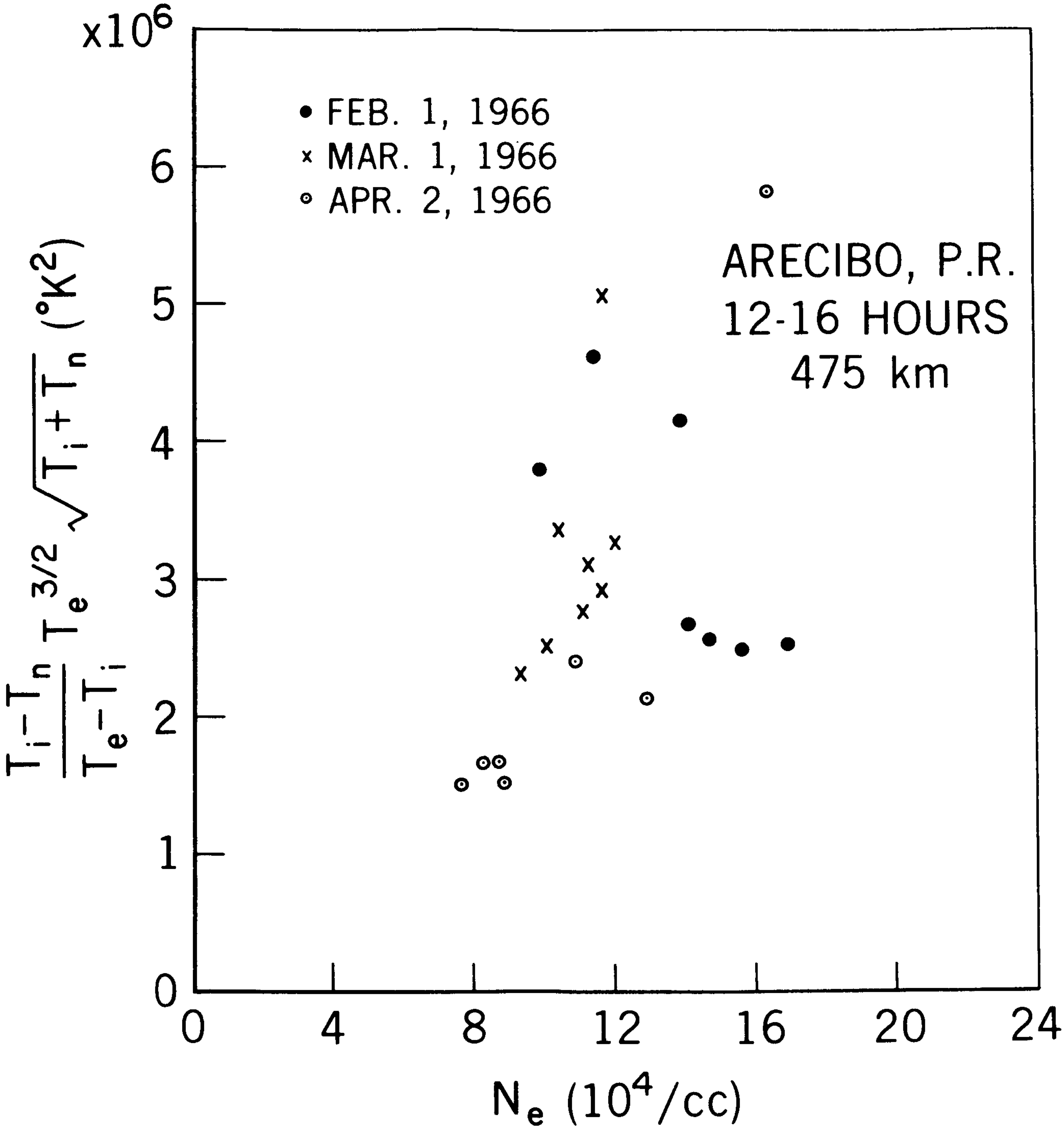
x10^6
FEB. 1, 1966
MAR. 1, 1966
APR. 2, 1966
ARECIBO, P.R.
12-16 HOURS
475 km
$\frac{T_i - T_n}{T_e - T_i} T_e^{3/2} \sqrt{T_i + T_n}$ (°K²)
0
1
2
3
4
5
6
0
4
8
12
16
20
24
N_e (10^4/cc)

Figure 6