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STABLE MID-LATITUDE RED ARCS: OBSERVATIONS AND THEORY

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I. INTRODUCTION

The stable mid-latitude red arc (SAR-arc) was first observed in the night sky by Barbier in 1957 from Haute Province in southern France (Barbier, 1958, 1960). During a geomagnetic storm he noted that the 6300 Å photometer, while performing almucanter scans at a fixed angle above the horizon, occasionally showed two conspicuous regions of enhanced brightness. The enhanced brightness was caused by what appeared to be a homogeneous arc of 6300 Å emission, roughly aligned in an east-west direction. The arcs were unusual because they occurred at mid-latitudes, well south of the auroral zones; they were also stable and persisted throughout the night, quite unlike the more common aurora. Soon after this discovery, observers in Australia and the United States (Roach, Barbier, and Duncan, 1962) confirmed the existence and world-wide extent of these arcs.

The purpose of this paper is to review the relevant observations and theories and to summarize the present-day understanding of mid-latitude red arcs. The observed features of the arcs will be outlined in Section II, the ionospheric behavior in the region of an arc will be given in Section III, and the various theories for red arc formation will be discussed in Section IV.

II. OBSERVED FEATURES OF RED ARCS

The observed features of red arcs have been reported by numerous authors (Roach and Roach, 1963; Megill and Carleton, 1964; Cole, 1965, 1967; Cruz, et al., 1965; Marovich, 1966; Hoch, Marovich, and Clark, 1968; Roble, Hays, and Nagy, 1970; Hoch and Clark, 1970). A summary of the general properties given by these authors is outlined in this section.

A. The enhanced emission observed in the arcs is the forbidden line of atomic oxygen $OI(^1D - {}^3P)$ at 6300 Å. The other major auroral and airglow emission lines are not enhanced in the arc. In particular, the 5577 Å emission caused by the transition from the $OI(^1S)$ metastable state to the $OI(^1D)$ metastable state does not appear to be enhanced within the arc region. The excitation energies of the $OI(^1D)$ and $OI(^1S)$ states are 1.96 ev and 4.17 ev, respectively; therefore, the lack of 5577 Å emission implies that a low-energy source must be responsible for the arc formation.

B. The absolute intensity of the arc ranges from a few hundred rayleighs to tens of kilorayleighs. During the last solar cycle maximum the mean intensity was about 6 KR (Roach and Roach, 1963); on the other hand, the intensity of the arcs observed so far during the present solar cycle maximum is considerably lower (Hoch, Marovich, and Clark, 1968; Ichakawa and Kim, 1969; Roble, Hays, and Nagy, 1970; Hoch and Clark, 1970).

C. The arcs generally occur in mid-latitudes, as shown in Fig. 1 (Roach and Roach, 1963), and are observed to be homogeneous and stable. They are several hundred kilometers wide in the meridional direction and current evidence

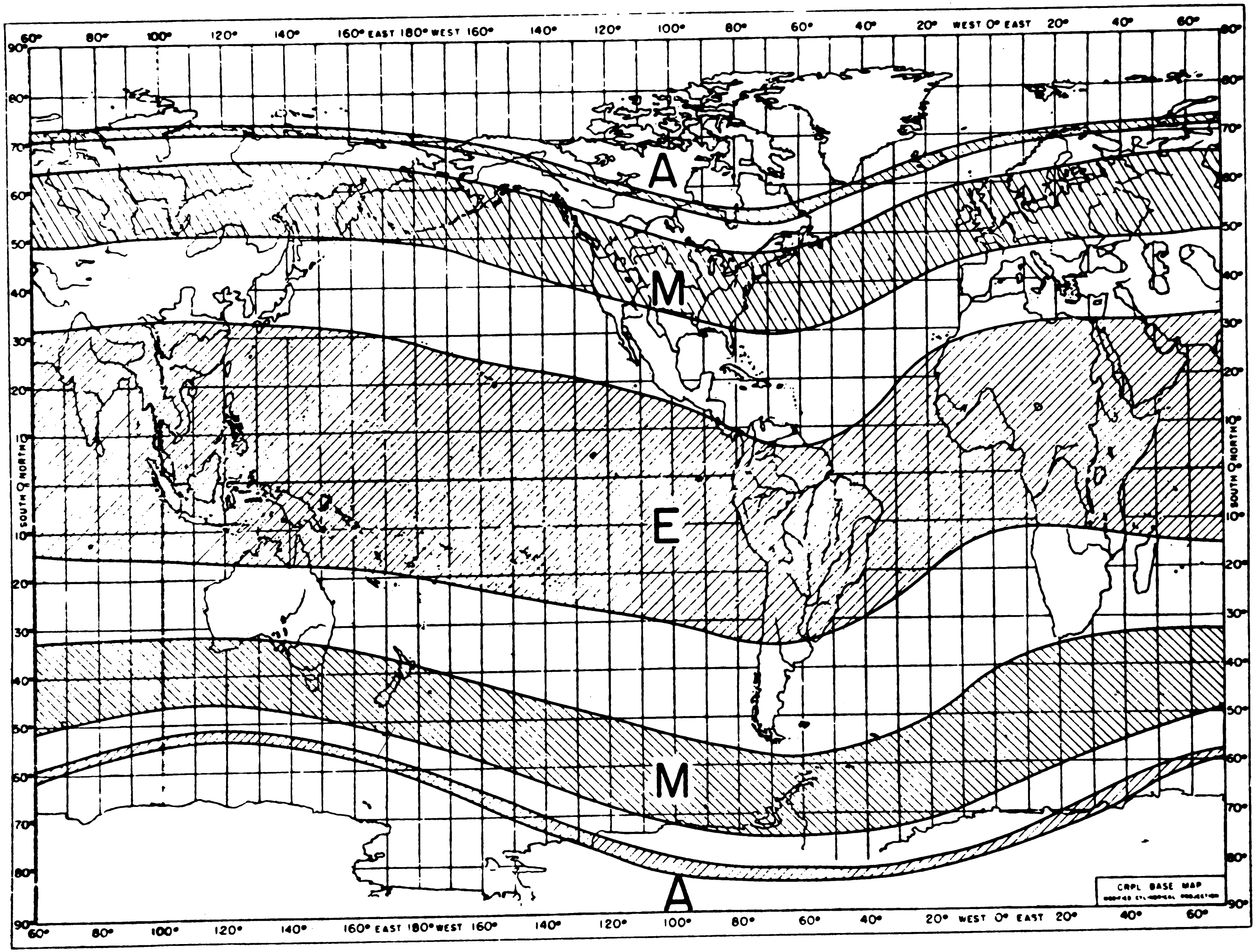

Fig. 1. Zones of characteristic 6300 Å activity; M region corresponds to Stable Mid-Latitude Red Arc (Roach and Roach, 1963).

indicates that the arcs extend in longitude around the nightside of the globe (Roach, Barbier, and Duncan, 1962; Marovich and Roach, 1963; Reed and Blamont, 1968). A meridional cross-section of the normalized 6300 Å intensity contours for a typical SAR-arc is shown in Fig. 2 (Tohmatsu and Roach, 1962). In their longitudinal extent the arcs are at times slightly tilted with respect to constant L shells. Satellite observations (Reed and Blamont, 1968) indicate that arcs occur simultaneously in both the northern and southern hemispheres, approximately along conjugate latitudes.

D. The mean height of the peak intensity occurs near 400 km. The height of an individual arc is determined from triangulation measurements, performed simultaneously from two or more observing stations (Roach, *et al.*, 1960; Moore and Odercrantz, 1961; Hoch, Marovich, and Clark, 1968. Using a method of obtaining both height and geographical position from a single station, Rees (1963), studied 9 SAR-arcs observed at Fritz Peak, Colorado, and found heights varying from 390 to 560 km with an indication of greater heights for the more northerly arcs.

E. The red arc, once it forms, generally persists throughout the night with a lifetime of 10 hours or longer.

F. In the northern hemisphere the arc usually moves north to south at rates between 4 and 50 m/sec with the maximum observed rate at about 87 m/sec (Roach and Roach, 1963). In certain cases multiple arcs form along different magnetic invariant latitudes and in these cases the southerly arcs are more stable.

G. The frequency of arc occurrence appears to follow the solar cycle.

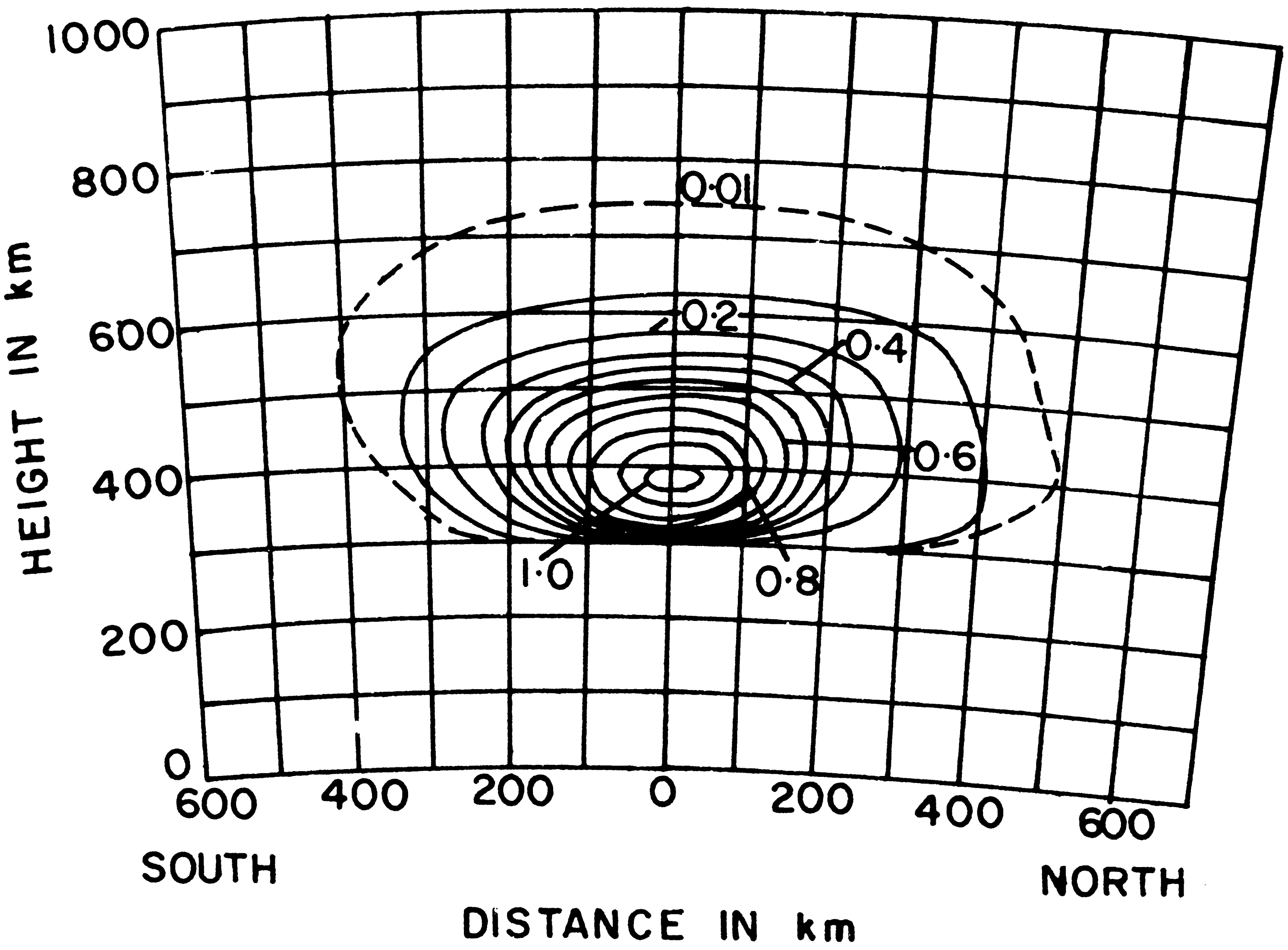

Fig. 2. Normalized 6300 Å isophotal representation of a SAR-arc cross-section (Tohmatsu and Roach, 1962).

The arcs are observed only during periods of increased magnetic activity. During the last solar cycle a good correlation was found between arc intensity and magnetic indices, as shown in Fig. 3. This correlation is strikingly modified for the current solar cycle maximum period. In general, fewer arcs have been observed and the intensity of the arcs which have been observed is considerably lower, as shown in Fig. 3. It should be noted that Rees and Akasofu (1963) have shown a positive correlation between the SAR-arc intensity and the magnetic atoms parameter D_{st}. This effect has not been investigated for the arcs observed in the current solar cycle.

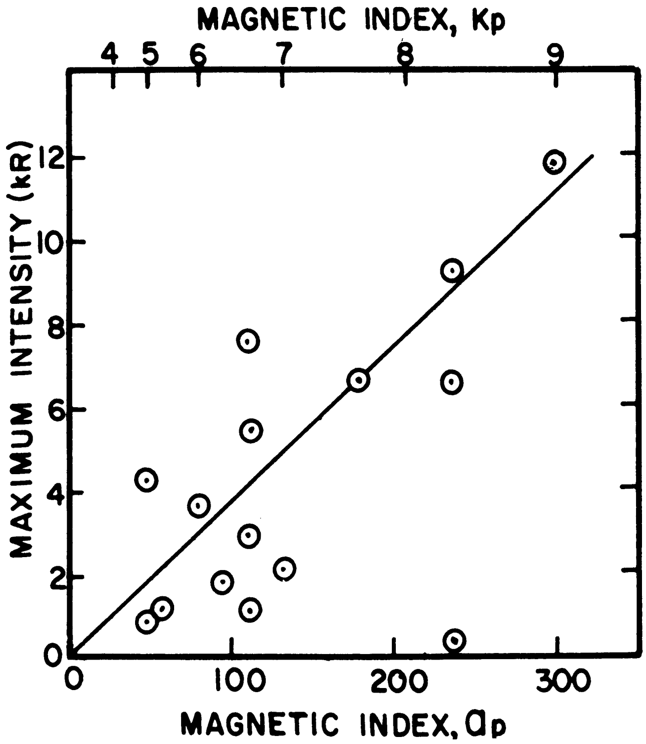

Fig. 3a. Correlation between the maximum intensity of SAR-arcs and the magnetic indices K_p and a_p during the period 1958-1963 (Roach and Roach, 1963).

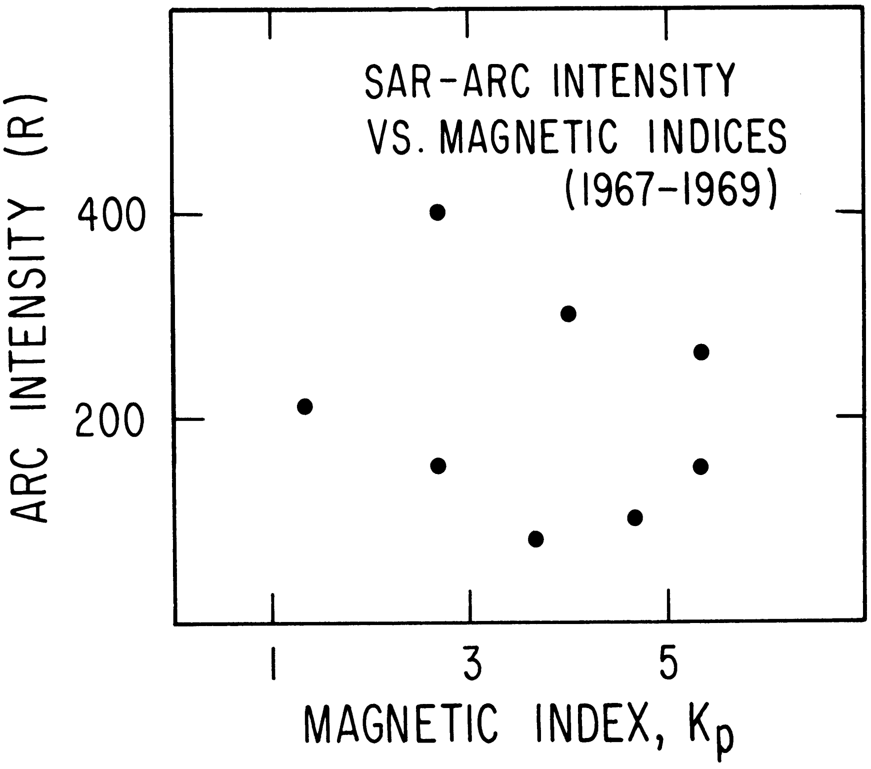

Fig. 3b. Correlation between SAR-arc intensity and the magnetic index K_p, during the period 1967-1969 (Hoch and Clark, 1970).

III. IONOSPHERIC BEHAVIOR IN THE REGION OF A RED ARC

During the last solar cycle maximum, when most of the SAR-arc observations were made, electron density height profiles within the SAR-arc could only be determined from ionosonde data. In general, the ionograms obtained during times of the SAR-arc were difficult to analyze due to spread-F, indications of more than one layer, oblique echoes, and generally confusing traces. In spite of these difficulties, King and Roach (1961) and Walker and Rees (1968) were able to deduce electron density profiles for several SAR-arcs.

King and Roach (1961) were able to obtain an electron density profile for the arc which appeared on November 28/29, 1959. The arc was centered some 200 km north of the ionosonde station, but by comparing the vertical reflections and the oblique echo, which were received from a large irregularity in the F-layer near the region of the arc, they were able to conclude that: (a) the critical frequency for the oblique echo was lower than for the overhead reflection, indicating a lower peak electron density in the arc than in the ionosphere adjacent to the arc, and (b) the spread of the oblique echo was greater, suggesting that the reflection is due not to a simple reflecting layer but rather to a complex irregular region.

Walker and Rees (1968) have taken advantage of the proximity of the Fritz Peak Airglow Observatory to the Boulder ionosonde station to examine six ionograms obtained when SAR-arcs were directly overhead. Their analysis shows that the bottomside ionograms for faint SAR-arcs yielded maximum electron densities which were not significantly different from undisturbed conditions, although there is some suggestion that the altitude of the maximum is usually high in the arcs. As a result of their study, they established an electron density profile representative of a faint SAR-arc (< 1 KR) by using ionogram readings between 260-400 km, an average nighttime profile below 260 km, and an extrapolated profile above 400 km with an appropriate scale height. The resulting profile is shown in Fig. 4.

The features of the SAR-arc listed above were determined from ground-based measurements of arcs which occurred during the last solar cycle maximum. The satellites in orbit at that time were not equipped with the proper instruments to effectively probe the topside structure of the arc. There are now a number of satellites in orbit which have the capability to determine the topside ionospheric structure in the neighborhood of an SAR-arc, but very few results have been published so far.

Norton and Marovich (1969) obtained topside soundings from both the Alouette I and II satellites during the SAR-arc which occurred on September 28/29, 1967. They found an electron density depression in the vicinity of a SAR-arc while passing over it in a north-south direction, as shown in Fig. 5 (Clark, et al., 1969). The topside ionogram also showed traces which could be interpreted as oblique echoes from slant electron density gradients. Norton and Findlay (1969) have also observed a significant increase in the electron temperature at 1800 km measured by the Alouette II satellite as it passed over an arc (Fig. 6). The region of the increased electron temperature was directly over the SAR-arc and it was broad enough to overlap the electron density depression. Satellite passes occurring before and after the observed SAR-arc do not reveal the increased

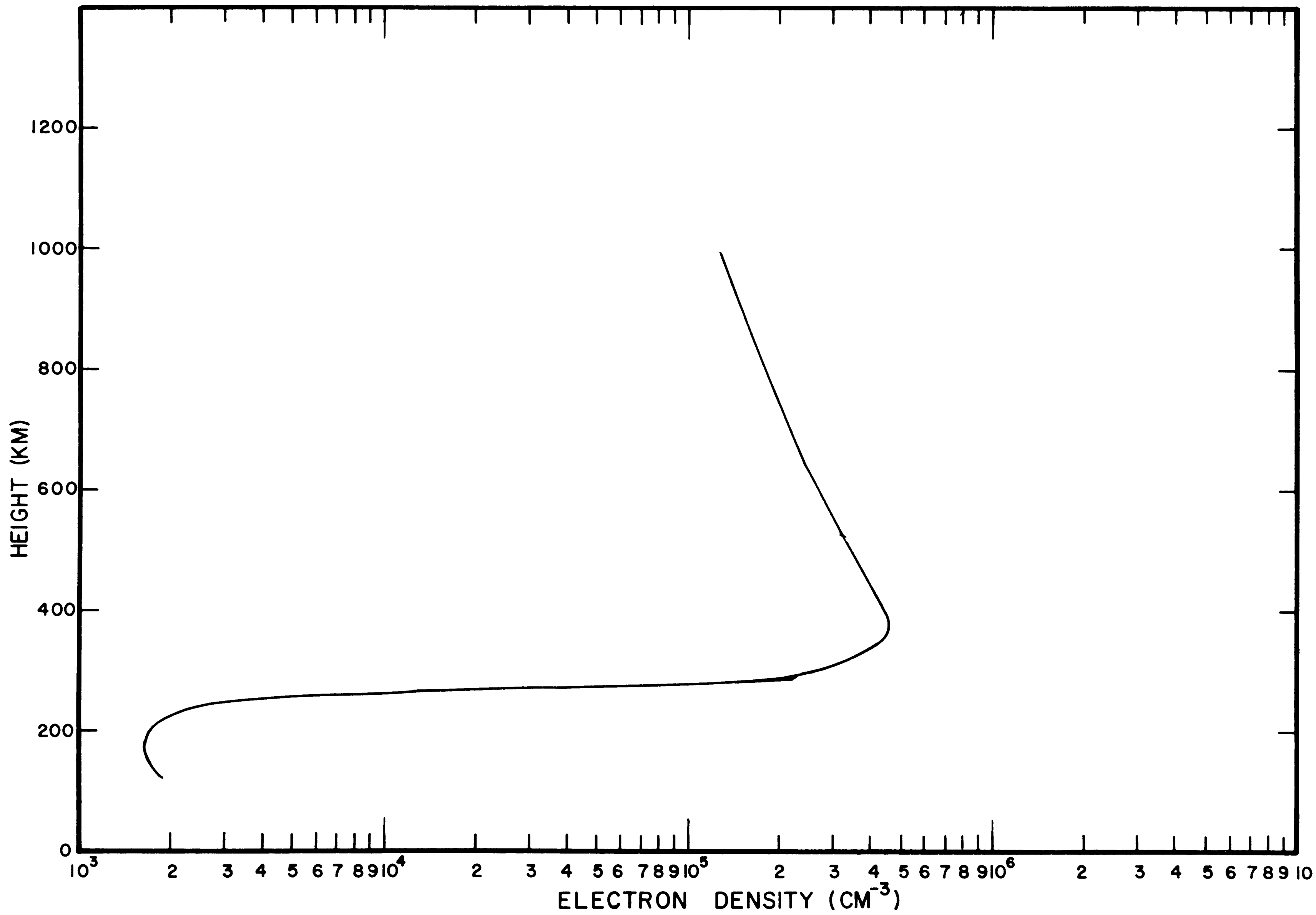

Fig. 4. Typical electron density height profile for a weak SAR-arc (Walker and Rees, 1968).

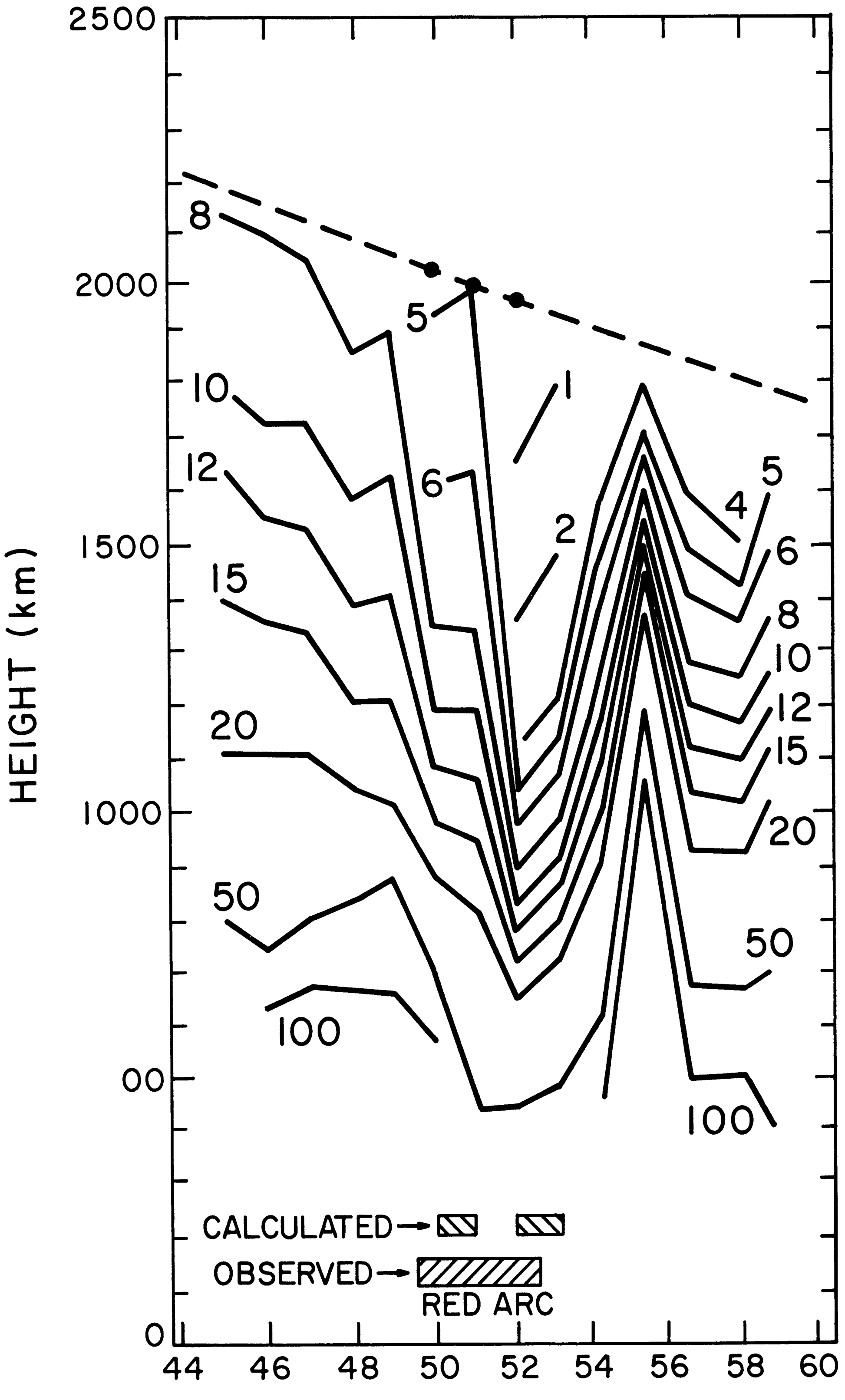

Fig. 5. Contours of the electron density determined from the data of the Alouette II topside sounder, at the time of a weak SAR-arc (Clark, <u>et</u> <u>al</u>., 1969).

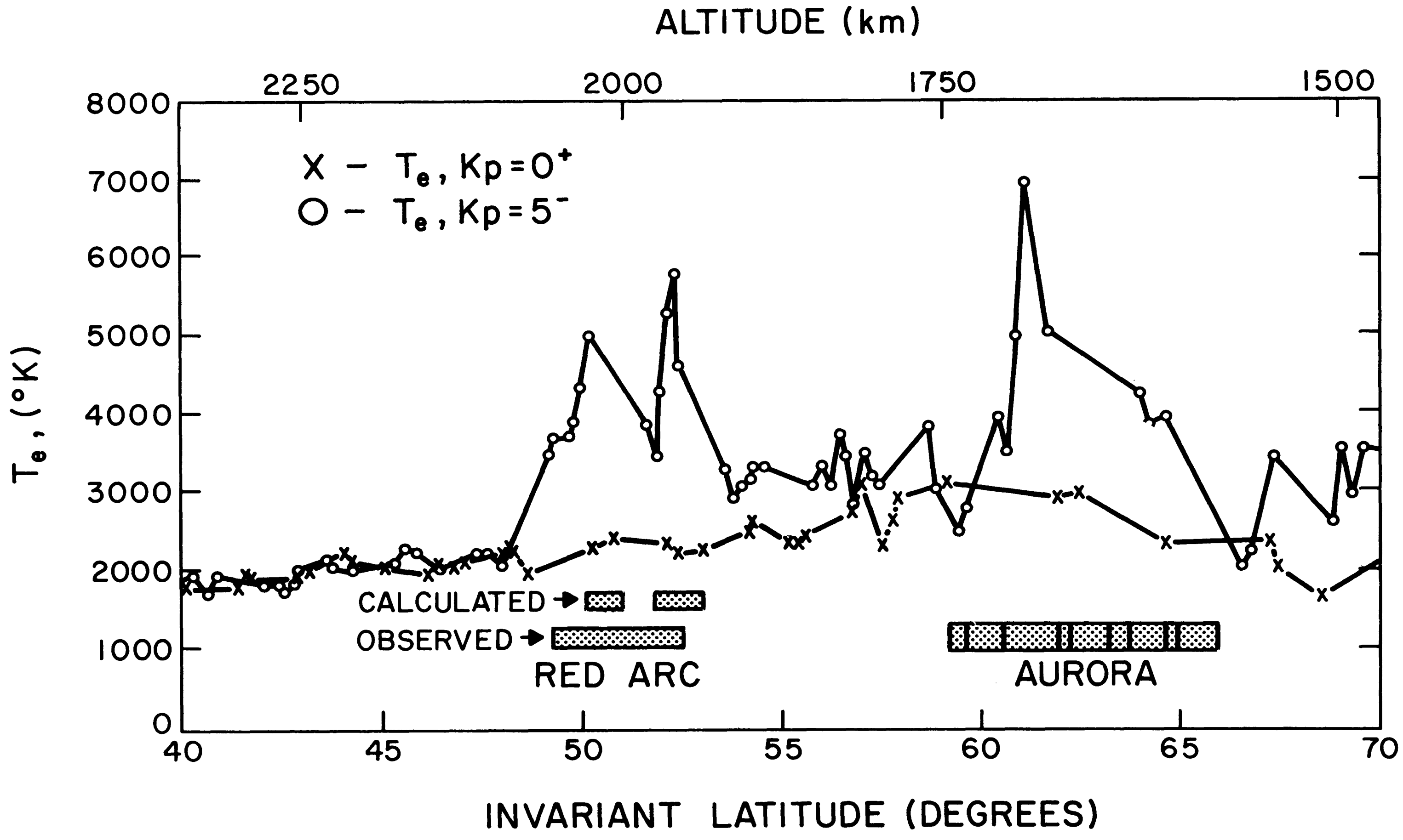

Fig. 6. Electron temperature in the neighborhood of the Alouette II satellites as a function of magnetic latitude (Norton and Findlay, 1969).

electron temperature. Therefore, it appears likely that the increased electron temperature is related to the SAR-arc excitation mechanism.

No ion temperature observations in the region of a red arc have yet been reported. Ground-based observations of the neutral gas temperature inside and outside of a red arc region have been carried out (Hays, Nagy, and Roble, 1969; Roble, Hays, and Nagy, 1970) by measuring the Doppler broadening of the 6300 Å emission line. Hays, Nagy, and Roble (1969) observed the red arc of October 31/November 1, 1968, which occurred during a very intense magnetic storm. The Doppler temperature observations indicated no neutral gas temperature increase inside the arc when compared to the region outside of the red arc in the normal nightglow layer. A general increase in the overall exospheric temperature, however, was measured and the temperature increase was in agreement with model atmosphere predictions (e.g., Jacchia, 1965).

There is some experimental evidence bearing on the relation between red arcs and the plasmapause. The southern edge of the well known topside ionization troughs are believed to define the position of the plasmapause (Bowman, 1969; Burnell and Rycroft, 1969). The satellite observations of Norton and Findlay (1969) found that the trough began just north of the observed arc, indicating that the arc forms just inside the plasmasphere. Both the September 28/29, 1967, and the October 31/November 1, 1968, arc, which were widely observed, show a northwest-southeast tilt with respect to constant L shells; a tilt is in the same sense as that of the mean plasmapause (Carpenter, 1966). Preliminary whistler results (Carpenter, 1970) and satellite ion spectrometer data (Chappell, Harris, and Sharp, 1970b) show very good agreement between these red arcs and the plasmapause position. Glass, *et al.* (1970), observed and tracked with an aircraft a red arc over Australia, and found that the arc was also tilted with respect to the L shell in accordance with the expected plasmapause position.

IV. REVIEW OF VARIOUS PROPOSED EXCITATION MECHANISMS

A. DISSOCIATIVE RECOMBINATION HYPOTHESIS

King and Roach (1961) attributed the production of the red arc to enhanced recombination of NO^+ ions. However, Rees (1961) has shown that the time constants for recombination and the arc lifetime are inconsistent and Dalgarno and Walker (1964) have noted that the reaction for dissociative recombination of NO^+ ions is spin forbidden. In view of these difficulties, enhanced dissociative recombination appears unlikely as a significant excitation mechanism of the red arc.

B. ELECTRIC FIELD HYPOTHESIS

Rees (1961), Megill, Rees, and Droppleman (1963), Megill and Carleton (1964), and Walker and Rees (1968) have all examined the mechanism of an electric field acting orthogonal to the geomagnetic field as an excitation source for the SAR-arc. In this mechanism an electric field perpendicular to the geomagnetic field lines provides sufficient energy either directly or via the ions, to the ambient electrons in the ionosphere to excite the SAR-arc through collisions with atomic oxygen. The source of the electric field is not clear; however, it could conceivably be generated through the interaction of the magnetosphere with the solar wind. The high conductivity along the magnetic field lines provides a good connection between the ionosphere and the magnetosphere, so that a transverse electric field applied anywhere across a given magnetic shell will also appear in the ionosphere.

Several mechanisms have been suggested by Megill and Carleton (1964) for the production of the electric field, and each requires a steady transport of charge perpendicular to the magnetic shells. The convective motions in the magnetosphere which cause the charge separation responsible for the electric field are not well defined and therefore, most authors assume that an electric field exists and they proceed to calculate the electron energy distribution function and the excitation rates of the atmospheric gases resulting from this field.

Rees and Walker (1968) have made a detailed study of the heating of ionospheric electrons by an electric field normal to the magnetic field, and later (Walker and Rees, 1969) applied the results to the question of the excitation of the SAR-arc. They have shown that, although there is some direct heating of the electrons, the major heating mechanism is caused by elastic collisions of ions with electrons. The perpendicular electric fields heat the ions much more efficiently than the electrons, so that the ion temperature rises above the electron temperature over much of the lower ionosphere. Walker and Rees (1968) have solved the coupled electron temperature—ion temperature problem with allowance for heat conduction in the electron gas, but not the ion gas. The calculated electron and ion temperature profiles are shown in Fig. 7 for a range of assumed electric field strengths. This figure indicates extremely large ion temperatures, especially at the lower altitudes. Since the ions transfer their energy to the neutrals through elastic and inelastic collisions, the high ion temperature implies a significant neutral heating which should cause a large perturbation in the neutral atmosphere. Walker and Rees (1968)

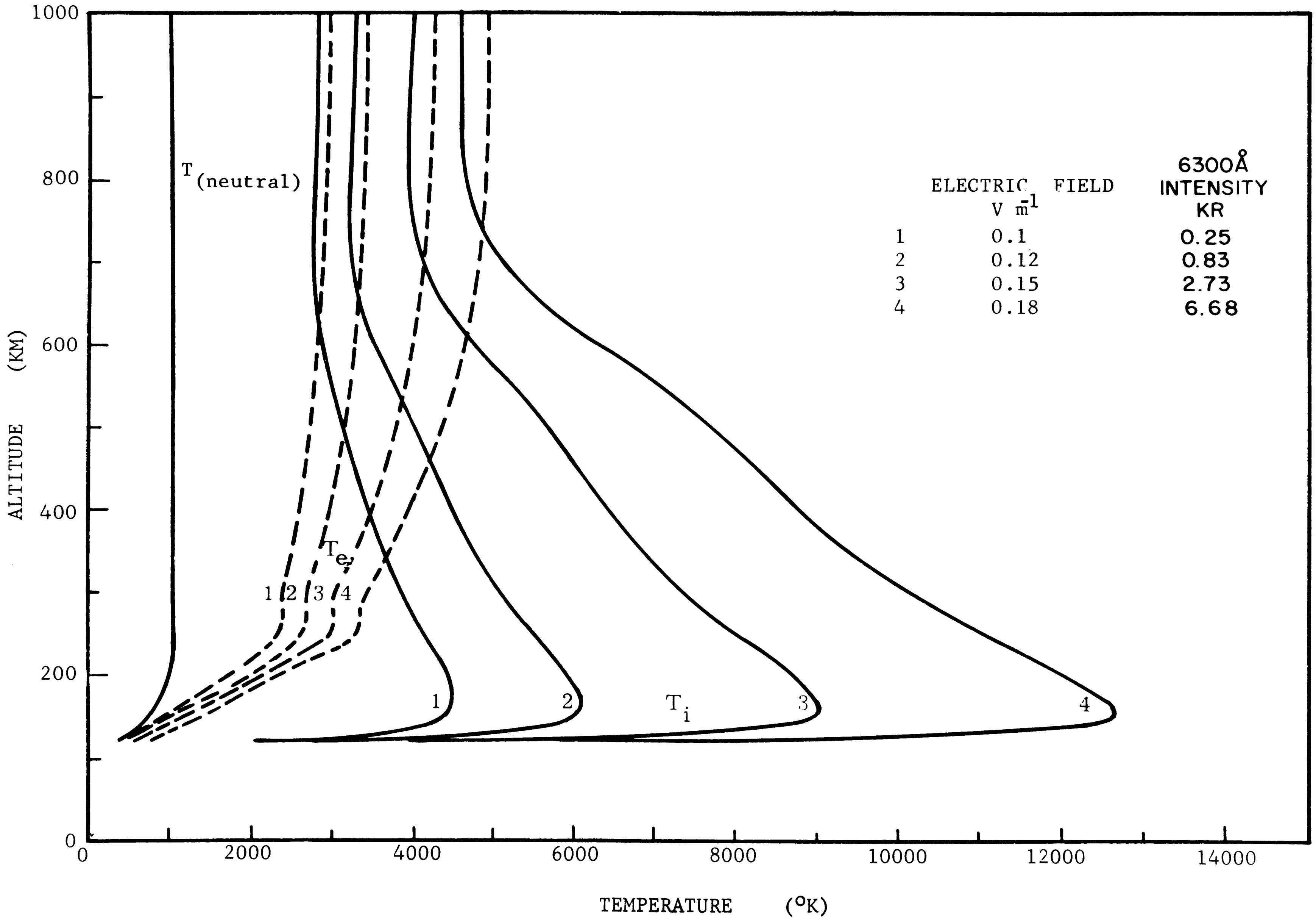

Fig. 7. Electron and ion temperature profiles which result from heating by a range of elec fields perpendicular to the magnetic field (Walker and Rees, 1968).

have also shown that the volume emission rate height profiles, due to electric field heating, have a maximum near 350 km, independent of the magnitude of the field. This height is somewhat lower than the average height determined from observational data.

Cole (1965) has examined the data for some 19 SAR-arcs and found that the average time interval in which the atmosphere magnetically conjugate to the station observing the SAR-arc was sunlit is 3 hours and 5 minutes. During this time the sunlit conjugate E-region had considerably more ionization than the nighttime ionosphere of the station observing the SAR-arc. As a result, the electrical conductivity in the conjugate ionosphere is at least 400 times greater. An electric field of about 1 mv/cm is capable of exciting a small SAR-arc in the night hemisphere and, because of the good conductivity along the geomagnetic field lines, this electric field is also present in the conjugate hemisphere. Such a field would according to Cole (1965), give rise to a magnetic bay of about 1400 γ in the conjugate geomagnetic field, whereas in the nighttime ionosphere, where the SAR-arc is present, a magnetic bay of 3 - 4 γ would occur. It appears unlikely that a magnetic bay of 1400 γ in the sunlit hemisphere would go unnoticed, yet no observation has been reported of such a disturbance occurring simultaneously with a SAR-arc. Current observational evidence does not support the atmospheric and ionospheric effects which would be caused by an electric field, although the means of detecting the high ion temperatures were not available during the last solar cycle. As mentioned in the previous section, no relevant ion temperature observations have been reported for this solar cycle either. The Doppler temperature observations of Hays, Nagy, and Roble (1969) and Roble, Hays, and Nagy (1970) indicated no neutral gas temperature increase inside the arc region. However, if transverse electric fields are responsible for the arc formation, the very high ion temperatures are likely to cause an observable perturbation in the neutral atmosphere. In view of the arguments presented here, it is unlikely that transverse electric fields play a direct role in the creation of SAR-arcs.

C. SOFT ELECTRON FLUX HYPOTHESIS

Dalgarno (1964) has postulated that an incident flux of electrons with an energy of about 400 ev is responsible for the type A red aurora and it is conceivable that a soft electron flux may also excite the SAR-arc. Walker and Rees (1968) have examined this mechanism in detail and found that a sufficiently soft electron flux can provide enough heat to the ambient F-region electron gas to excite the 6300 Å emission line of atomic oxygen by thermal impact, and yet not excite the other optical emissions normally present in an aurora. Because of the predominant 6300 Å emission within SAR-arcs, they had to set an upper limit of 15 ev on the initial energy of the bombarding electrons. Also, in order to excite the SAR-arc to any measurable degree, an electron flux of the order of 10^9 electrons cm^{-2} sec^{-1} or more is required and this flux must be active over the 10 hour lifetime of the SAR-arc. This soft flux of electrons, with energies of a few ev or less, may turn out to be equivalent to a special form of magnetospheric thermal conduction which is discussed in the next section.

D. THERMAL CONDUCTION

Cole (1965) postulated that the SAR-arc is excited by electron impact of heat ambient F-region electrons with atomic oxygen. The F-region electron gas is kept hot by the conduction of heat from the magnetosphere, along geomagnetic field lines, into the ionosphere. Cole (1965) showed that an electron temperature of only 3200°K in the F-region was sufficient to excite a 10 KR red arc, but not the other common atmospheric emission lines. He has also shown that the magnetospheric ambient electron temperature, for this particular SAR-arc, has to be of the order of 10,000 - 15,000°K in order to maintain a flow of heat along the geomagnetic field lines into the ionosphere to excite the SAR-arc to the 10 KR level. This temperature corresponds to an average energy per thermalized particle of 1 to 1.5 ev. Because of the low electron density in the magnetospheric plasma, thermal conduction may depart from its conventional meaning and the energy flow may appear as a soft electron flux flowing down the geomagnetic field lines into the ionosphere. In this sense the soft electron flux and thermal conduction hypothesis are equivalent.

The heat conduction hypothesis appears to be the most acceptable of the mechanisms outlined in this section; therefore, the energy sources and requirements, the corresponding ionospheric conditions, and a comparison between the theoretically predicted and observed features of a red arc, created in this manner, will be given in the next section.

V. DISCUSSION

According to the thermal conduction model of the SAR-arc proposed by Cole (1965), energy from the hot magnetospheric plasma is conducted down along the geomagnetic field lines, heating the F-region electrons. This heating causes the electron temperature to rise above its normal value, resulting in sufficient numbers of electrons in the Maxwellian tail to excite the ^1D state ($E > 1.96$ ev) but not the ^1S state ($E > 4.17$ ev) of atomic oxygen.

Thermal conduction in the F-region electron gas has been considered by a large number of authors (Geisler and Bowhill, 1965; Dalgarno, McElroy, and Walker, 1967; Nagy and Walker, 1967; Walker and Rees, 1968; Dalgarno, et al., 1968; Hanson, et al., 1969; Nagy, et al., 1969) who have shown that electron thermal conduction is very important in determining the electron temperature profile in this region. Banks (1967a, 1967b) has shown that ion thermal conduction does not play a significant role below about 600 km. DaRosa (1966) studied the time dependent electron energy equation and found that the F-region ionosphere accommodates itself fast enough to changing conditions so that it is, in effect, in a "thermal quasisteady state." The above metioned works justify the use of the one-dimensional steady state energy equation, taking into account the electron but not the ion thermal conduction, to study the electron and ion temperature behavior in a red arc, as done by Walker and Rees (1968) and Roble (1969).

The results of Roble (1969), who considered a range of energy flows into the ionosphere from the magnetosphere and calculated the resulting electron temperature, ion temperature, and 6300 Å emission rate profiles are shown in Figs. 8 and 9. The ionosphere model used in these calculations was the one given by Walker and Rees (1968) shown in Fig. 4; and the neutral atmosphere model used was that of Jacchia (1965), with an exospheric temperature of 1500°K. Figure 8 indicates that heat flows from the magnetosphere in excess of about 10^{10} ev cm^{-2} sec^{-1} will cause detectable red arcs and the emission rate profiles of Fig. 9 show that predicted peak emission heights are in the 400 km region, in agreement with the observations. These calculations indicate very clearly that for a given heat flow the red arc will form in the region of low electron densities.

It is quite feasible that in the latitude region of significant heat inflow from the magnetosphere, and corresponding high electron temperature, an increase in the vibrational temperature of the nitrogen molecules will take place (Walker, 1968; Walker, Stolarski, and Nagy, 1969). The high N_2 vibrational temperature results in an increased recombination coefficient (Schmeltekopf, Fehsenfeld, Gilman, and Ferguson, 1967; Schmeltekopf, Ferguson, and Fehsenfeld, 1968) which in turn causes a decrease in the F-region electron densities, thus providing more suitable conditions for red arc formation.

Electron density and temperature measurements in the region of the September 28/29, 1967, SAR-arc were obtained by the Alouette I and II satellites (Norton and Findlay, 1969) (i.e., Figs. 5 and 6). Roble, Hays, and Nagy (1970) used the data obtained from these satellites to calculate the shape and intensity of the red arc and compared the theoretical results with ground-based measurements. They carried out these calculations by using the measured electron

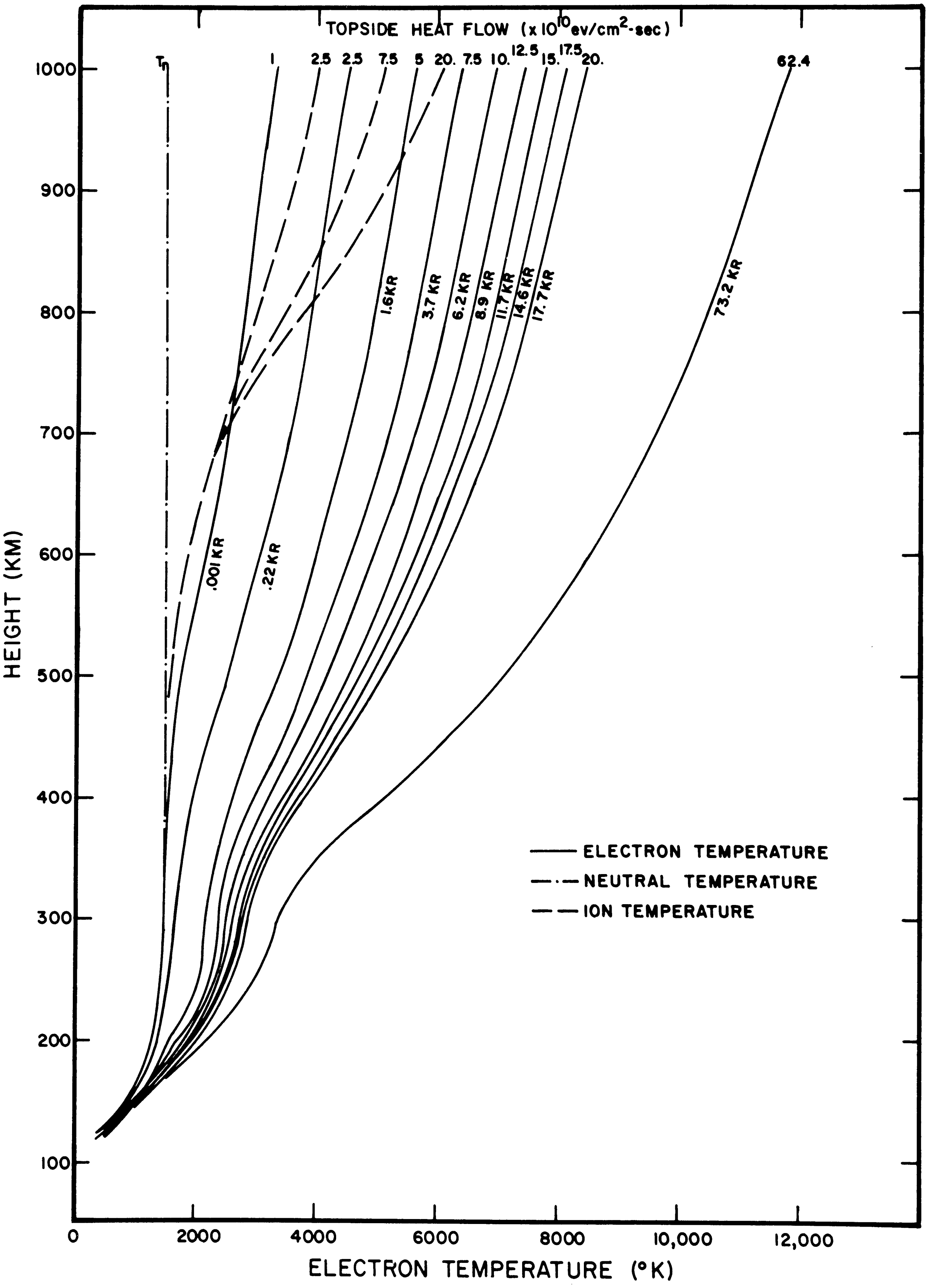

Fig. 8. Calculated electron and ion temperature height profiles for a range of SAR-arc intensities (Roble, 1969).

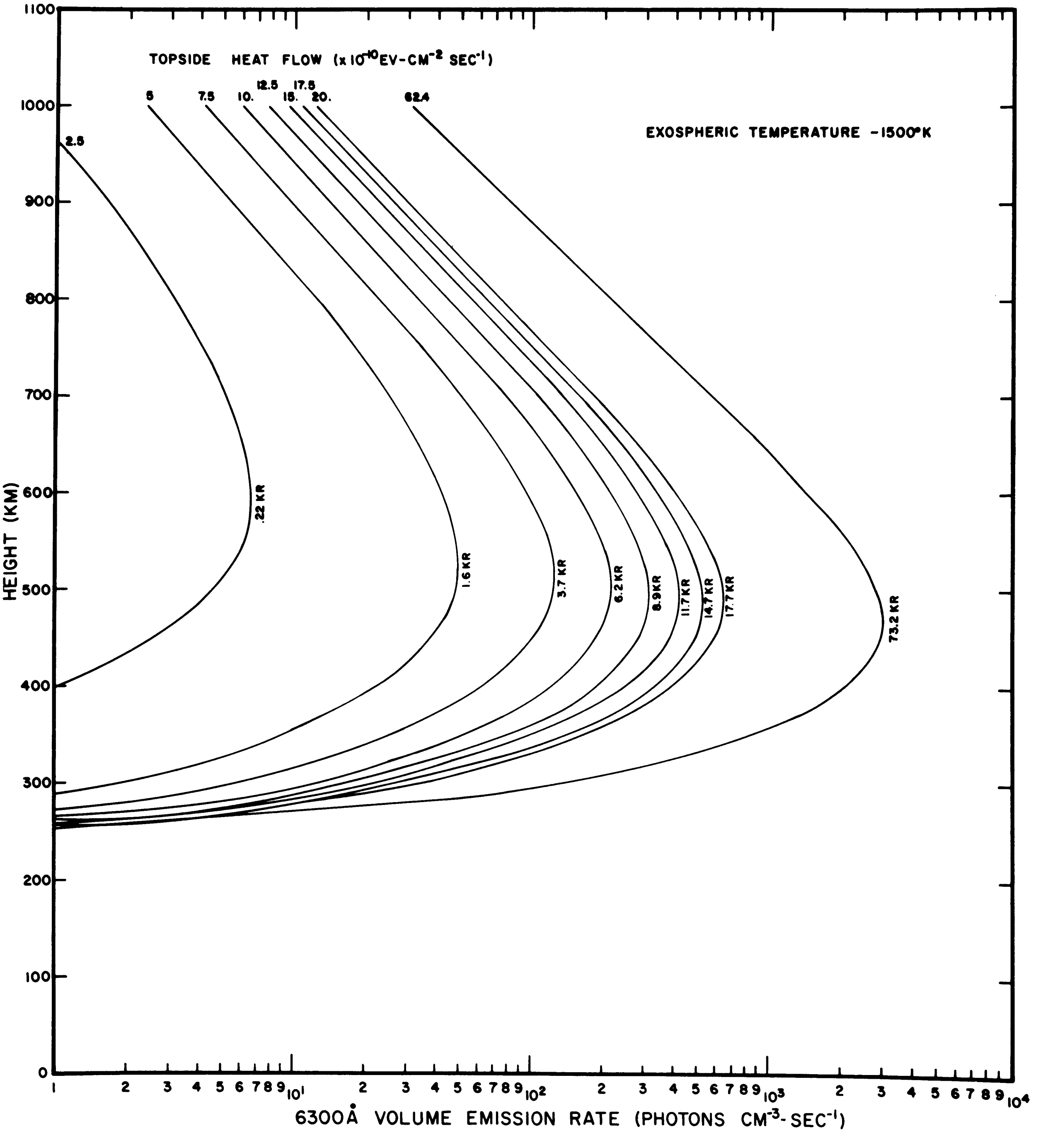

Fig. 9. Calculated 6300 Å volume emission rate height profiles for a range of SAR-arc intensities (Roble, 1969).

density profiles and adjusted the top heat flows to fit the calculated electron temperatures at 1800 km to those measured by the satellite. (Electron temperature measurements were obtained only at the satellite altitude.) The calculated electron temperatures and top heat flows are shown in Figs. 10 and 11, respectively. The calculated contours of the arc and volume emission rates are shown in Fig. 12. The zenith intensity of the arc was calculated to be 314 R which is in reasonable agreement with the measured value of 170 R. The calculated peak altitude and position of the arc was also found to be in good agreement with the observations.

The pressure forces originating from the red arc heating drive a thermal cell with upward motion in the red arc region and a slow subsidence over a much greater area outside the arc. The adiabatic warming and cooling by these motions significantly reduce the calculated neutral temperature increase within the red arc from the value obtained in the absence of motions. These motions also enlarge the horizontal scale of the region of temperature increase.

A significant amount of energy is transferred from the hot electrons and ions to the neutral gas within an arc (Roble, 1969). Roble and Dickinson (1970) have examined the question of atmospheric response to this heating and found that very little heating of the neutral gas actually occurs. These results also show that the large thermospheric heating of about 450°K, observed during the red arc of October 31/November 1 (Roble, Hays, and Nagy, 1970) is not a direct consequence of the energy inflow responsible for the arc itself.

The average shape of the plasmapause (Carpenter, 1966) indicates a decreasing L value from dusk to dawn. This tilt is in the same sense as those observed

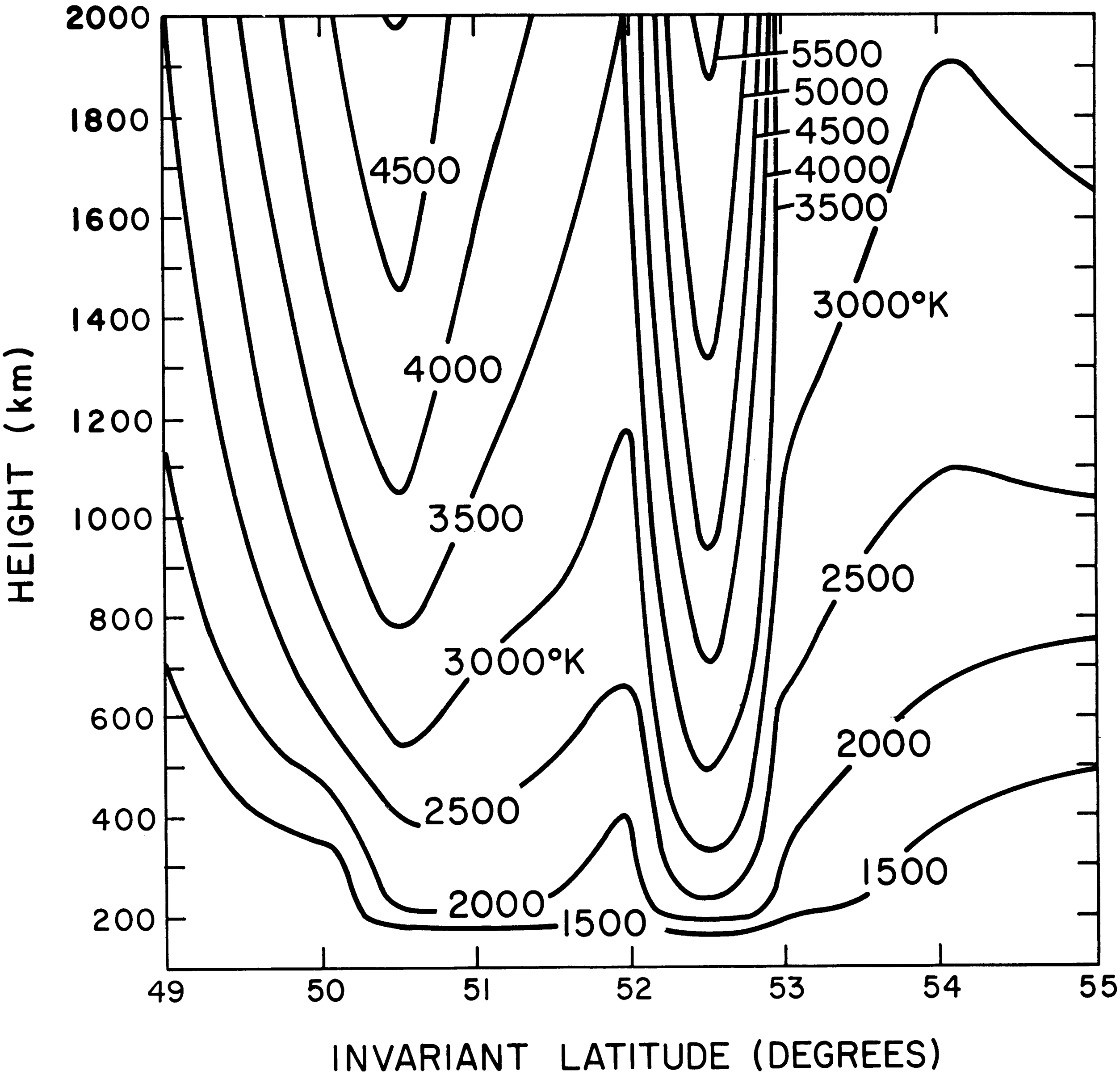

Fig. 10. Calculated electron temperature contours for the September 28-29, 1967, SAR-arc (Roble, Hays, and Nagy, 1970).

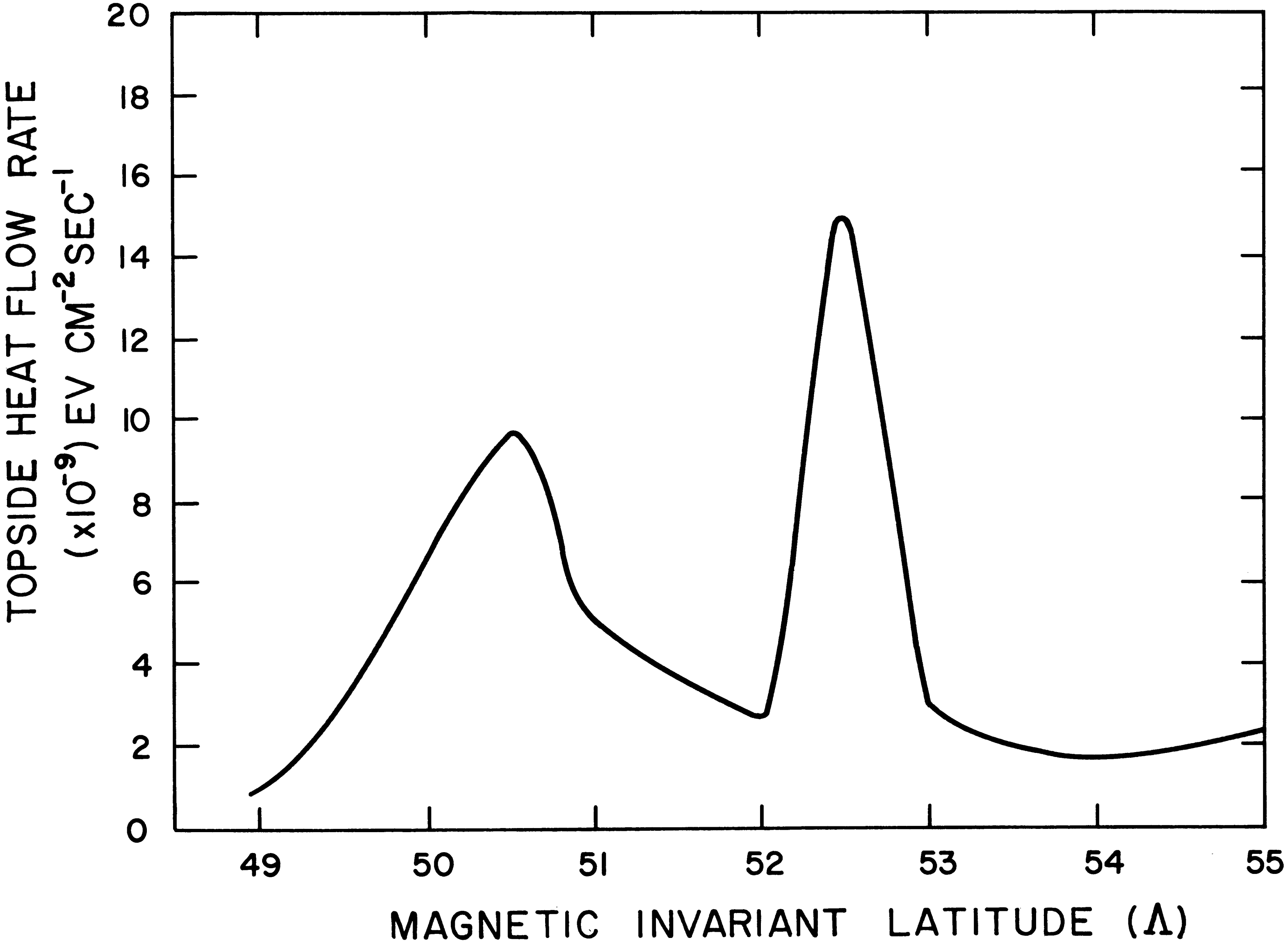

Fig. 11. Calculated topside heat flow for the September 28-29, 1967, SAR-arc (Roble, Hays, and Nagy, 1970).

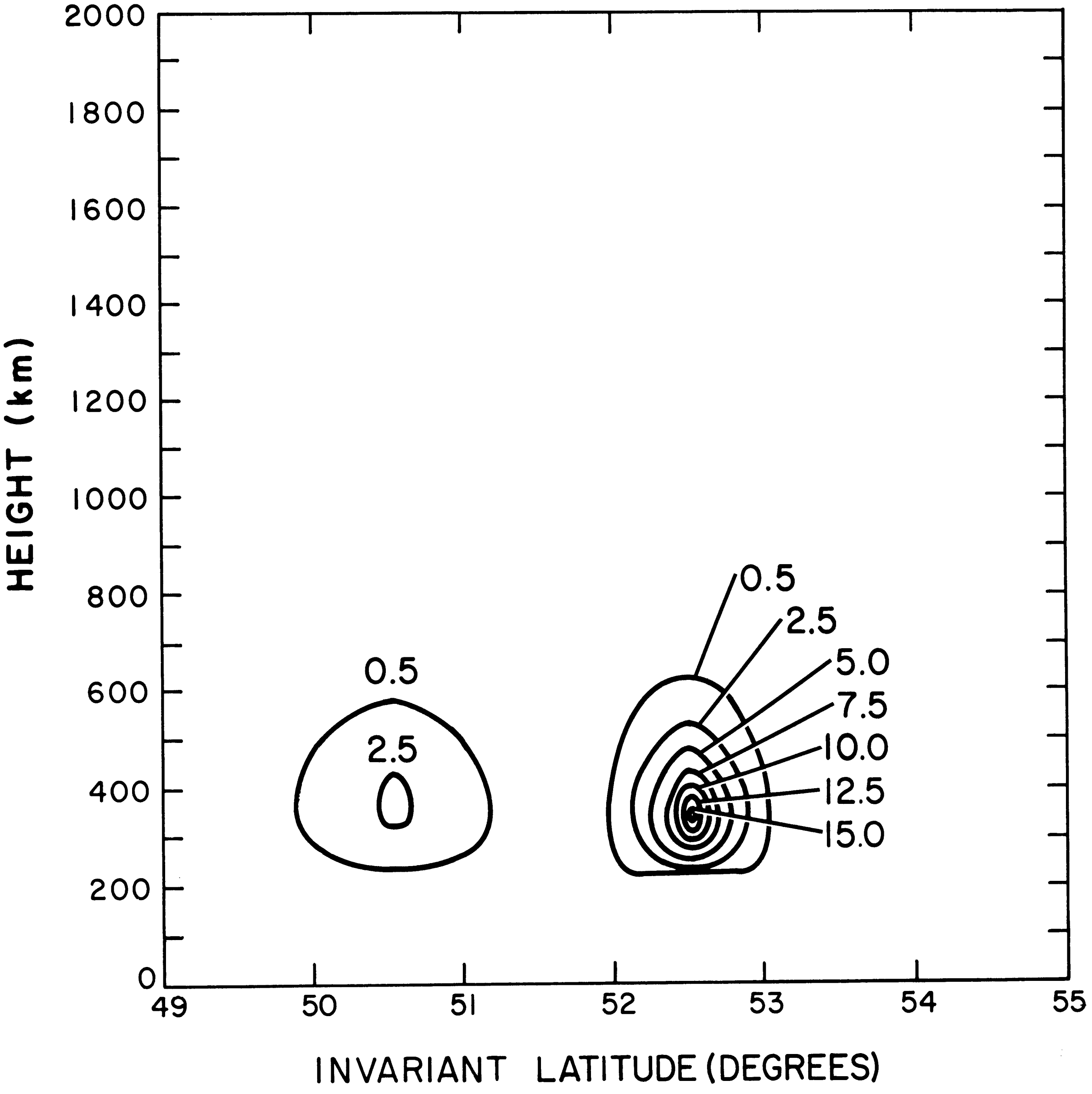

Fig. 12. Calculated 6300 Å volume emission rate contours for the September 28-29, 1967, SAR-arc (Roble, Hays, and Nagy, 1970).

in recent SAR-arcs. Glass, et al. (1970), suggested that the apparent motion of SAR-arcs is largely due to the fact that they are tilted with respect to the L shells. A ground-based observing station will see an apparent equatorward motion of the arc, due to the rotation of the earth, as long as the plasmapause and the arc are stationary. If the plasmapause is not stationary and is moving the arc along with it during the observations, an additional red arc motion will be apparent. This is a plausible explanation for the general but not universal equatorward motion of the arcs; if for example, the plasmasphere is expanding, as would be the case during a recovery, the apparent arc motion could drop to zero or even turn around.

So far in this discussion nothing has been said about where the energy flowing down into the ionosphere originates. A connection between the magnetospheric ring current and SAR-arc has been pointed out by Cole (1965, 1967, 1969). Cole (1967) suggested that "the hot plasma resident in the outer geomagnetic field during quiet times acts as a source of plasma which, by the action of random electrostatic fields, is pumped deep into the geomagnetic field and energized during storms." He showed that during an interchange of two tubes of unit flux, the energy of the particles increases by a factor of about $(R_2/R_1)^{8/3}$, where R is the radial distance of the respective field tubes. Such a redistribution would result in an average increase of energy of the order of ten; therefore the 10-100 ev ambient plasma observed by Serbu (1964) in the outer magnetosphere would have the 200-2000 dv energy required for the ring current (Cole, 1967) when pumped deeper into the magnetosphere during a storm. Collision among the low-energy thermal particles inside the plasmapause and these 200-

2000 ev particles would heat the electrons to very high temperatures, resulting in energy to be conducted down into the ionosphere. This heat flow would provide the energy needed to explain red arc formation by the thermal conduction hypothesis.

Cole (1965) has also carried out an energy balance calculation of a magnetic storm and compared the energy in the magnetospheric ring current to the energy required to sustain the SAR-arc. He considered the case of a geomagnetic storm with a 100 - γ main phase decrease in the equator. According to Parker (1962) a storm of this magnitude requires a change of about 3×10^{22} ergs in the kinetic energy of the trapped magnetospheric particles. Cole (1965) has calculated an electron temperature of 3200°K to excite a 10 KR SAR-arc and when the rate of cooling of the electrons was integrated over the three-dimensional volume of the arc, the total loss rate was found to be between 4×10^{16} to 2×10^{17} ergs $\sec^{-1}$. The energy lost in 6300 Å radiation for the SAR-arc was approximately 10^{15} ergs $\sec^{-1}$. Therefore, if the 3×10^{22} ergs stored in the ring current of the geomagnetic storm was conducted to the ionosphere in about 10^5 seconds, the order of the lifetime of the SAR-arc, the energy loss rate is of the order of 3×10^{17} ergs $\sec^{-1}$ in apparent agreement with the energy required to sustain the arc.

The narrow meridional extent of the red arcs indicate that the energy deposition must take place in a very narrow region just inside the plasmasphere. Satellite observations by Frank (1967) did find a rather narrow region of soft particles just inside the plasmasphere. Cornwall, Coroniti, and Thorne (1970) suggest that during the main phase of a geomagnetic storm ring current protons

(< 50 kev) diffuse rapidly via Bohm diffusion, across the plasmapause. Once inside the plasmasphere these protons will generate ion cyclotron waves, which are subject to Landau damping. Thermal electrons within the plasmasphere are the only important Landau particles, since their thermal speed is comparable to the Alfvén speed of the wave. Therefore, it is quite feasible that a fraction of the proton energy is transferred to the thermal electrons, and this energy will be transported either via thermal conduction or convection down into the ionosphere to cause the red arcs. Calculations by Cornwall, Coroniti, and Thorne (1970) show that this proton population only extends about 2/3 Re into the plasmasphere in rough agreement with the soft particle observations of Frank (1967) and the narrowness of red arcs. The Bohm diffusion may depend on the temperature and density gradients at the plasmapause which are known to be highly variable (e.g., Chappell, Harris, and Sharp, 1970a) and this may explain why red arcs are formed during some storms and not others. The major difficulty of this proposed mechanism is that the strong injection region of ring current protons is believed to be in the midnight to dusk region, thus the energy deposition would not be a constant for the complete night sector; this is in contrast with the fact that SAR-arc intensities are fairly constant throughout the night.

VI. SUMMARY

The observational features of the arc are fairly well established. At present, the thermal conduction model appears to explain the red arc features most consistently, but it must be noted that a soft electron flux would give very similar results. Ion temperature measurements in the vicinity of an arc, which should be forthcoming in the very near future, can establish conclusively whether transverse electric fields play any important role in the formation of the arcs. Accepting the assumption that the arcs are the result of energy flowing down from the plasmasphere, the major remaining question is: where does the energy come from and how does it get into the plasmasphere? The variouus proposed mechanisms discussed in the previous chapter appear feasible, but much work needs to be done before this problem is completely resolved.

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