COMMENT ON ION AND ELECTRON TEMPERATURES IN THE MARTIAN UPPER ATMOSPHERE

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Abstract. Ion temperature profiles measured by the retarding potential analyzers on Viking I and II are examined. It is found that the thermal conduction must be modified by other transport processes or by the presence of magnetic fields to account for the observed profiles. Such processes also affect the electron temperature profile, which, however, was not measured. Estimates of the magnetic field parameters are obtained assuming the magnetic field is the dominant effect.

Introduction

The retarding potential analyzers (RPA) on the Viking landers obtained the first in situ measurements of ion densities and temperatures in another planetary atmosphere. Hanson et al. (1977) have considered a chemical model which roughly reproduces the measured ion density distributions as a function of altitude. The altitude dependence of the ion temperature was not considered, except to note that the ion temperature increased rapidly with altitude above 200 km. Chen et al. (1978) add to the above model a description of the heating and cooling processes for the ionspheric plasma. They find that the altitude dependence of the ion temperature cannot be reproduced even if a heat flux of 300 km, implied by the slope in the ion temperature profile, is included. As changes in particle densities and thermal conduction coefficient did not improve this situation markedly, they suggest that in addition to a heat source at high altitudes, presumably the solar wind, some volume heating mechanism may be responsible for the observed temperature.

In this letter we first consider the magnitudes of those processes that contribute to the heating and cooling of the atmosphere ions. In agreement with Chen et al. (1978), it is found that the usual heating and cooling terms cannot be used to account for the observed temperature profile. The principle difficulty is shown to be the significant heating caused by vertical conduction. The existence, however, of magnetic fields in the planetary ionosphere, which are expected to accompany the solar wind impact on the ionosphere (cf. Daniel and Cloutier, 1977), or which would be present if Mars had a permanent magnetic moment (cf. Dolginov, 1978), would modify the conduction considerably. The effect of such fields on the ion temperature is examined and limits on the magnetic fields are obtained which are consistent with the average behavior of the Viking I ion temperature profile. The electron temperature is then considered. A quantity of importance in any attempt to model the chemistry of the upper atmosphere.

Ion Temperature Profile

Though the ion temperature profiles in Fig. (1) show considerable structure, particularly for Viking II, the predominant feature at higher altitudes is a rapid increase in temperature with increasing altitude. One notes, neglecting the structure, that the two profiles exhibit a roughly exponential behavior, above 175 km for Viking I and 165 km for Viking II, with the average profiles shifted by about 10 km. Approximate equilibrium with the neutrals occurs below these altitudes, with the ions apparently remaining about 10% hotter than the neutrals. Chen et al. (1978) suggest this effect may be due to Joule heating by the ion currents which were observed down to 120 km in the Viking RPA experiment. These ion currents, indicative of the presence of electric fields in the atmosphere, show a significant fluctuation with altitude (Hanson et al., 1977), and may in fact be related to the structure seen in the temperature profile. Here we note only that the average altitude dependence of the ion temperature is quite similar for the two measured profiles, indicative of an average, downward heat flux at high altitudes. In the following all comparisons and calculations are based on the Viking I data.

The energy balance of the ionspheric plasma is described by the following equation (Banks and Kockarts, 1973)

\[ \frac{\partial T_i}{\partial t} = -n_i k T_i \nabla \cdot \vec{U}_i + \frac{1}{\gamma - 1} n_i k T_i \nabla \cdot \vec{U}_i + \frac{Q_i}{L_i} \]

where \( T_i \) is the ion temperature, \( n_i \) the number density, \( \vec{U}_i \) the bulk velocity, \( \gamma \) the ratio of specific heats, \( \phi \) the heat flux and \( (Q_i - L_i) \) are the heating and cooling terms. The heat flux, \( \phi \), contains contributions due to both molecular heat conduction and other non-bulk transport heating and cooling mechanisms. In Table 1 we use the average profile of Fig. 1 to calculate the downward heat flow, \( \phi_d \), for Viking I at a few altitudes and the rate of heat deposition by vertical conduction, \( -d\phi/dz \). Both of these quantities will be sensitive to the assumed average profile and therefore can be relied upon for order of magnitude estimates only, which is sufficient for our purposes. The downward energy flux in Table 1, though significant, is seen to be a small fraction of the incident solar wind flux of approximately 0.5 ergs/cm²/sec, which is predominantly deflected around the planet (cf. Daniel and Cloutier, 1977). The vertical heat conduction is seen, from Table 1, to be a significant source of heat at all altitudes considered. That is, not only is a downward heat flow implied, but a large amount of heat would be deposited at all altitudes. In Table 2 we give estimates of the principle transport and cooling

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TABLE 1. Vertical Conduction

<table>
<thead>
<tr>
<th>Altitude</th>
<th>$\phi_z = K_1 \frac{d}{dz} T_i$</th>
<th>$- \frac{d}{dz} \phi_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>$-7 \times 10^{-4}$ (ergs/cm²/s)</td>
<td>$3 \times 10^{-10}$ (ergs/cm²/s)</td>
</tr>
<tr>
<td>250</td>
<td>$-1.5 \times 10^{-4}$</td>
<td>$7 \times 10^{-11}$</td>
</tr>
<tr>
<td>200</td>
<td>$-3 \times 10^{-6}$</td>
<td>$1 \times 10^{-12}$</td>
</tr>
</tbody>
</table>

[Estimates for Viking I using $K_1$ as the field free ion-neutral conduction at 300 km and plasma conduction at 250 and 200.]

terms calculated using Viking I data for densities (Nier and McElroy, 1977, and Hanson et al., 1977). It is seen that all the terms considered are significantly smaller than the heat conduction term in Table 1. A possible exception to this which is not shown is radiative cooling, if, for instance, some mechanism rapidly populates low-lying vibrational states. Reasonable estimates for this mechanism and the horizontal transport of heat suggest these also do not compare to the heating by vertical conduction implied in Table 1. It is noteworthy that heating by the electrons, which is often responsible for the ion temperature differing significantly from that of the neutrals is a small effect at all altitudes considered.

As the equilibrium ion temperature is obtained by equating the heating and cooling terms in Eq. (1), what is missing in the description of the ion temperature profile is not a heat source, but rather, in the absence of a compensating loss mechanism, a process which reduces the heat deposition by conduction. The conductive heating could be modified by competing transport processes or the presence of fields. The velocities used in Table 2 are the bulk velocities induced directly by the solar wind (R. E. Daniel, Jr., unpublished results, 1977). The incorporation of other transport processes is attractive because of the average exponential nature of the observed temperature profiles. However, the solar wind interaction with the atmosphere is thought to produce a roughly horizontal magnetic field in the ionosphere tending to restrict the transport of ions and electrons (Butler and Stolarski, 1978).

Such a field would mitigate the effect of these vertical transport processes on heat conduction. These fields will, however, in the same manner, modify the molecular heat conduction. Based on the calculations for Venus (Daniel and Cloutier, 1977) the horizontal magnetic field is relatively constant down to the ion maximum. The vertical conduction coefficient $K_z$ in the presence of a magnetic field (Hochstim and Massel, 1969)

$$K_z = \left( \frac{V \cdot k}{\mu \cdot h} \right)^2 + \sin^2 \theta \cdot K.$$  \hspace{1cm} (2)

Here $K$ is the conduction coefficient parallel to the field, $I$ is the magnetic dip angle, $w$ the gyrofrequency and $v$ the collision frequency which depends on particle densities. The second order correction factors $g$ and $h$, for conduction in a plasma, vary slowly with the ratio $V/w$. Here we assume they are constants which are reasonable averages over the altitude range considered.

To determine the effect of the magnetic field on the ion temperature profile we calculate the equilibrium ion temperature using the conduction coefficient in Eq. (2) for a fixed field at all altitudes. A finite difference scheme was used to solve Eq. (1) with $\beta f_T = 0$, and a corresponding equation for the electron temperature discussed below. Included in Eq. (1) are the vertical heat conduction, ion-neutral cooling and electron-ion heating (Banks and Kockarts, 1973). The calculation is confined to that altitude region, 130 km to 250 km, where $K$ in Eq. (2) can be accurately described by the plasma conduction coefficient and $v$ the Coulomb collision frequency for the ions (Banks and Kockarts, 1973), the neutrals are predominantly CO$_2$ or O and the ions predominantly O$_2^+$ and O$^-$. At higher altitudes ion-neutral collisions affect conduction, the lighter ions begin to play a role (Chen et al., 1978) and the solar wind terms in Table 2 become important.

Viking I observations are used for the densities with the amount of O taken from the calculation of Hanson et al. (1977). We chose to fix the temperature at the upper boundary to agree with the average exponential temperature in Fig. 1 for Viking I. The same conclusions are obtained fixing the slope.

In Fig. (2) it is seen that for a horizontal magnetic field above a few gammas ($10^{-5}$ gauss) the effect on the conduction is significant in this altitude range. The shape of the profiles does not agree closely with the assumed average profile, but a field of about $6 \gamma$ gives a reasonable, average fit. Based on the solar wind model for Venus, the fields considered here are not unreasonable (Daniel and Cloutier, 1977). If the field is assumed to be quite large, varying the inclination angle essentially reduces the conduction coefficient by a constant factor. That such changes can affect the ion temperature profile is seen from Fig. (3). Again, the agreement is not good overall; however, an angle of around 6° gives about the right slope at the higher altitudes. From Fig. (4) it is seen that a small, non-horizontal field can be used to reproduce the average profile reasonably accurately over the altitude range considered. For Viking I, a field of $12 \gamma$ and an angle of $12^\circ$ gives about the right average altitude dependence for the ion temperature based on our choice of the average profile.

TABLE 2. Heating and Cooling Rates (ergs/cm³/s)

<table>
<thead>
<tr>
<th>Altitude</th>
<th>Joule Heating</th>
<th>Neutral Cooling</th>
<th>Electron-Ion Heating</th>
<th>Bulk Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>$10^{-12}$</td>
<td>$-10^{-13}$</td>
<td>$10^{-15}$</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td>250</td>
<td>$10^{-13}$</td>
<td>$-10^{-12}$</td>
<td>$10^{-14}$</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td>200</td>
<td>$10^{-14}$</td>
<td>$-10^{-11}$</td>
<td>$10^{-12}$</td>
<td>---</td>
</tr>
</tbody>
</table>

[Bulk motion due to solar wind driven currents and Joule heating by solar wind are due to R. E. Daniel, Jr. (unpublished works, 1977). For the electron-ion heating we assumed $T_e = 2T_i$ to obtain the maximum heating rate.]
This corresponds to a heat flux at 250 km which is about 7% of that in Table 1. The sizes of the fields and angles considered are sufficient to largely suppress the thermal effects of other transport processes below 250 km. Therefore the model used here, though not unique, is self-consistent, as well as plausible. The structure observed in the ion temperature profile which we discussed earlier can in principle be explained by the presence of electric fields in the ionosphere as these fields also have a small effect on the conduction (Bulter and Stolarski, 1978). Further, it is likely that the magnetic field will vary somewhat over this altitude range.

If the modification of the conduction by the magnetic field is the dominant effect in determining the ion temperature profiles, that is, other transport processes are not important, then purely horizontal fields will essentially eliminate conduction in the electron gas because of its correspondingly larger gyrofrequency. In Fig. (5) we present estimates of the electron temperature calculated with varying dip angle for the conduction coefficient in Eq. (2). These calculations were carried out in parallel with the ion temperature calculations including the electron-ion cooling, using photoelectron
heating rates for the electrons calculated by Mantas and Hanson (1978), and loss rates to 0 and CO2 as estimated by Hoegy (1976) and Morrison and Green (1978), respectively. In all cases, heating by the solar wind is neglected; that is, we chose zero slope at 250 km, and K in Eq. (2) is the plasma conduction coefficient (Banks and Kockarts, 1973). If the conduction is totally suppressed, the electron temperatures are seen to be high due to heating by photo-electrons. The differences between electron temperature profiles in Fig. (6), will have a significant effect on the electron-ion recombination rate for O2 + e, and therefore a bearing on models used to calculate ion density profiles.

Conclusions

The calculations presented show it is possible to describe the principle behavior of the ion temperature profile by assuming a heat source at high altitudes, presumably the solar wind, and nearly horizontal magnetic fields, which are expected to accompany the solar wind impact on the upper atmosphere. It has also been suggested that Mars may have permanent magnetic moment (cf. Dolginov, 1978), which would be an alternative source for the field that does not depend on zenith angle. The data available cannot distinguish between these sources. The model considered here is, clearly, not the only possible explanation of the temperature profile. It does not, however, require new heating or cooling mechanisms and it allows limits to be placed on the size and dip angle of the magnetic field.

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References


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