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Nocturnal Thermal Disequilibrium of the $F_2$ Region Ionosphere at Middle Latitudes

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Incoherent scatter measurements performed above St. Santin (44°3'N, 2°15'E) in the $F_2$ region over the period 1971–1972 have revealed the existence of a small systematic temperature difference (10–20 K) between the electrons and the ions at night, the former being the colder. However small, this effect cannot be accounted for by statistical or systematical errors. This temperature difference reflects the tendency of the electron gas to cool faster than the ion and neutral gases and the absence of any $F_2$ region electron heat source (such as the downward flow of energy from the protonosphere) at night.

INTRODUCTION

As opposed to the daytime behavior for which cascading of energy from the photoelectrons to the electrons and to ions leads to generally higher electron temperatures, nighttime incoherent scatter observations performed above St. Santin (44°3'N, 2°15'E) show systematic departures of the ionospheric plasma from thermal equilibrium around 300 km (10–20 K).

The experimental evidence for a few selected cases is presented in the first part and is discussed in the light of the statistical errors attached to the data.

A statistical analysis of the data gathered during the years 1971–1972 is also presented. The energy budget of the plasma is discussed in the second part.

OBSERVATIONS

Figures 1a and 1b present two examples of nighttime ion and electron temperature variations at 300 km. In both cases the ion temperature is consistently larger than the electron temperature by some 20–50 K. This difference is only slightly larger than the statistical error (~15 K) assigned to it. However, the statistical nature of the errors and the constancy of the sign of the difference from one measurement to the next are an indication of the reality of the effect. The possibility that this is caused by a systematic error has been investigated. The most likely cause for such an error was found to be an erroneous estimate of the electron concentration, which would lead to an improper least squares fitting of the experimental incoherent scatter spectrum. However, simulations of such an effect for larger departures of the electron concentration (25%) than those which can be anticipated on the basis of comparison with ionograms only led to changes in the difference of one third.

In addition, errors in the estimate of the electron density are observed to fluctuate, so that increases or decreases of the difference are equally probable.

While the temperature difference in the two cases seems to remain roughly constant, a significant temperature variation is observed, exhibiting a temperature minimum around 0000 and 0200 hours LT in Figures 1a and 1b, respectively, followed by an enhancement. These features simply reflect the coupling of the plasma to the underlying thermosphere. This coupling will be discussed in the following section; the minimum is linked to the semidiurnal variation of the exospheric temperature [Alcaydé, 1974; Harper, 1973].

Figure 2 is a composite of the observations performed at 300 km above St. Santin during the years 1971 and 1972 between 2200 and 0100 hours LT.

In spite of the scatter of the data points, a definite tendency for larger ion temperatures is clearly evident. On the assumption that each night of data constitutes one measurement of the temperature difference a weighted average according to individual error bars was performed so as to give the mean value of the temperature difference. Figure 3 shows the corresponding distribution of the estimates of the temperature difference and the
The energy budget of the plasma for these particular conditions has been studied in detail by Mazaudier [1974]. The dominant terms in the ion energy balance equation are the heating of the ions by friction induced by the relative motion of the ions and neutrals and the collisional cooling of the ions by the neutrals associated with a small temperature difference,

$$\frac{3}{2}k(T_n - T_i) = \frac{1}{2}m_n(v_i - v_n)^2$$

(1)

where $T_n$ and $T_i$ are the neutral and ion temperatures, $m_n$ the mass of the neutral particle, $(v_i - v_n)$ the relative ion neutral velocity, and $k$ Boltzmann's constant. Determinations of the ion-neutral relative velocity based on ion drift measurements and a model of the neutral atmosphere [Amayenc, 1975] lead to an estimate of the order of 10 K for the temperature difference between the ions and the neutrals for normal conditions.

Note that the collision term with electrons which play a dominant role during daytime has become negligible for the electron ion temperature differences encountered at night in this region.

On the other hand, in the energy balance equation for the electrons, collisions with the ions are the dominant form of heat loss and must be balanced by heat conduction.

$$\sin h \frac{\partial}{\partial z} \left[ -\sin hK_e(\partial T_e/\partial z) \right] = L_{ei}$$

(2)

where $z$ is the altitude, $K_e$ the electron thermal conductivity, $h$ the dip angle between the horizontal and the magnetic field, $T_e$ the electron temperature, and $L_{ei}$ the rate of energy transfer from the electrons to the ions.

$$L_{ei}(O^+) = -4.8 \times 10^{-7} \cdot T_e^{-3/2}(T_e - T)N_e^2 \text{ eV cm}^{-3} \text{ s}^{-1}$$

(3)

Energy exchange through the fine structure levels of atomic oxygen and through the vibrational levels of molecular nitrogen for these particular conditions is generally more than 1 order of magnitude smaller. Figure 4 shows schematically the energy budget of the three gases (neutrals, ions, and electrons) at night: The ions are strongly coupled to the neutrals, while the electrons are strongly coupled to the ions.

Therefore to first order, the three gases are strongly tied together with the following consequences: (1) any change in the neutral temperature is reflected in a change of the ion temperature and in turn in the change of the electron temperature; and (2) the three gases tend to be distributed similarly; i.e., they tend to exhibit the vertical distribution on the neutral gas temperature.

To second order, this latter effect has interesting consequences for the electron energy balance. The tendency for the electron gas to follow the neutral gas temperature distribution via coupling with the ion gas implies a progressive downward increase in the temperature gradient, i.e., following approximately a Bates [1959] type profile. Since the heat conductivity is comparatively much higher for the electron gas than for the two other gases, this results in a large downward heat flow for the electron gas. A new equilibrium is reached when the extra electron heat loss rate is compensated by energy provided by the slightly warmer ions.

It must be noted, however, that this holds true only in the $F$ region, where the electron density is sufficiently large and the neutral density sufficiently small. Lower down the combination of increased neutral concentration and decreased electron density leads to a large decrease of the electron thermal conductivity, as was pointed out by Banks [1966].

It is now necessary to verify quantitatively the efficiency of the process mentioned above. For that purpose we have compared the integrated ion to electron energy transfer rate between 275 and 350 km averaged over the

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**Fig. 1b.** Same as Figure 1a for the night of October 3-4, 1972.

**Fig. 2.** Nighttime ion and electron temperature differences at 300 km above St. Santin during experiments performed in 1971 (circles) and 1972 (crosses). Each symbol corresponds to one data point.

**Fig. 3.** Nighttime averages of ion and electron temperature differences at 300 km above St. Santin during experiments performed in 1971 (crosses) and 1972 (circles). The statistical error associated with each average is indicated.
Fig. 4. Energy budget of the nighttime ionosphere plasma. The period 2100-0300 LT to the increased heat conduction flux between 350 and 275 km averaged over the same time period. Since small temperature gradients are involved, we have used the following method: the ion temperature profiles were first fitted in a least squares sense to the Bates type profile \[\text{[Bauer et al., 1970]}\]. The shape parameters so obtained were then used to determine the variation in temperature gradient. This method is, in fact, equivalent to assuming that the electron temperature gradient is negligible at the upper limit and therefore any heat conducted down from the protonosphere has been absorbed through collisions above 350 km. This will be discussed later but in most cases seems consistent with the observations. The errors involved in the computations of the energy losses and the change in electron heat conduction for individual vertical profiles are quite large (of the order of 100%); however, the averaging procedure and the need to obtain only an order of magnitude estimate make these errors acceptable. The results for 1972 and 1971 are presented in Table 1, which gives the ratio of the integrated ion to electron loss rates over the increase in heat conduction flux over the same altitude range. The same data are also presented in Figure 5, which indicates for each night the corresponding heat conduction fluxes and integrated ion to electron energy transfer rates. The least squares fitting of a straight line to the data points gives

\[K_e \langle dT_e / dz \rangle = 0.09 + 0.6 \int L_{el} \, dz\]

For 70% of the cases the ratio lies within 0.35 and 4, which considering the errors involved seems to indicate that for these cases a balance between the two processes is realized. It can therefore be stated that generally the lower electron temperatures observed are required to provide the heat flux associated with the downward increase in temperature gradient associated with the temperature profile of the neutral gas (which drives the other gases). For 30% of the cases, however, the disagreement seems to be larger than can be accounted for by errors involved. In five cases the ratio is too small or negative, which indicates that the ions supply less energy than the energy conducted downward by the electrons (or even gather energy from the electrons); these correspond to cases for which the electron energy is directly provided by conduction from the protonosphere either because of a small energy absorption in the upper F region associated with small electron densities or because of an extra protonospheric heating associated with a magnetic disturbance. This is illustrated in Figures 6a and 6b, which correspond to a small ratio and a ratio close to one, respectively. The first case (night of February 24-25, 1972) is characterized by a significant magnetic activity (\(Kp \approx 4\)) and shows large electron temperature gradients around 350 km, indicating a departure from a neutral gas temperature profile and the presence of a downward flux of

### Table 1. Experimental Results

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*The four sets of values represent Kp indices taken every 3 hours between 1800 and 0600 LT.*
energy from the protonosphere. The second case (night of October 3-4, 1972) exhibits very small electron temperature gradients at 350 km. However, the transparency of the upper ionosphere to the protonospheric electron heat flow appears to be an important parameter, and this may explain why the four other cases of deficiency in the ion energy transfer rate occurred during low magnetic activity, while three cases in which there was a good balance of the ion to electron energy transfer rate and of the heat conduction flux at 275 km occurred during magnetic disturbances. In two cases there appears to be too large an ion to electron energy transfer rate (January 4-5, 1972, and August 3-4, 1971). We have found no simple explanations for these.

**CONCLUSION**

To first order, electron, ion, and neutral gases are in thermal equilibrium in the nighttime middle-latitude F region (275-350 km). However, a small systematic temperature difference has been observed between the ions and the electrons, the latter being the cooler (10-20 K). This temperature difference arises from the fact that the small temperature gradient of the three gases leads, because of the high electron thermal conductivity, to a more rapid cooling of the electron gas; in the absence of energy coming from the protonosphere the extra energy is provided to the electrons by the ions through collisions and proportionally to the electron and ion temperature difference. This situation seems to prevail for 70% of the time above St. Santin (44°N, 2°E).

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**REFERENCES**


Fig. 6a. Electron temperature profiles above St. Santin for the night of February 24-25, 1972.

Fig. 6b. Same as Figure 6a for the night of October 3-4, 1972.


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