REFERENCES


Dolginov Sh. Sh., Geomagn. and Aero. 12, 611, (1972).


Gruenberg R.C., Hand Bk. of Tele. and Remote Controls, (1967).


JOULE HEATING DUE TO THE EQUATORIAL ELECTROJET
AS OBSERVED BY ROCKETBORNE PROBES

S. SAMPATH*, T. S. G. SASTRY*, K. OTAMA* and K. HIROAO*

* Physical Research Laboratory, Ahmedabad, India
** Institute of Space and Aeronautical Science, University of Tokyo, Tokyo, Japan

A Nike-Apache rocket carrying a proton precession magnetometer and an electron temperature probe was launched on a magnetically quiet day, near noon, from Thumba, India. The purpose of the experiment was to study Joule heating in the E region of the ionosphere, due to the equatorial electrojet current. The current density \( J \) profile derived from the magnetometer data, the electron temperature \( T_e \) profile obtained from the electron temperature probe and the neutral temperature \( T_n \) profile from the CIRA model are used to study the Joule heating effect. The excess of electron temperature over that of the neutrals \( T_e - T_n \), which is a consequence of Joule heating, correlates well with the current density \( J \). To relate \( J \) and \( T_e - T_n \), quantitatively the Cowling conductivity \( \sigma_3 \) profile and the calculated profile of mean fractional energy loss per collision \( \xi \) of electrons with the neutrals are used.

The energy needed to give the observed increase in temperature, \( T_e - T_n \), has also been calculated theoretically and compared with the energy delivered by the electrojet.

1. Introduction

The electron temperature distribution under equilibrium conditions is determined by the rate of heat input to the ambient electron gas and the rate of energy loss by various loss processes. A general heating is produced by the absorption of solar radiation. Much of the absorbed energy appears as kinetic energy of photoelectrons. The energetic photoelectrons lose their energy to the ambient electrons, ions and neutrals. It is assumed that the ambient electrons suffer frequent elastic collisions among themselves and attain a Maxwellian distribution, characterized by the electron temperature \( T_e \). The ions and neutrals, except in the upper F region, attain equilibrium amongst themselves and are considered to have a common temperature \( T_\infty \). The electron gas cools by collisions with neutrals and ions. The heat loss to positive ions is important only above 200 km, while below this height the heat loss to neutrals is more important.

Theoretical electron temperature profiles based on the above mentioned assumptions have been derived by various workers [1–4]. It is found that the electron temperature increases with height throughout the ionosphere. \( T_e \) is equal to \( T_\infty \) below 150 km, above which \( T_e \) exceeds \( T_\infty \). The difference \( T_e - T_\infty \) increases above 150 km and reaches a maximum near 250 km. According to these findings there is no thermal non-equilibrium below 150 km. These conclusions are based upon the assumption that radiation from the sun is the only source of heat energy...
and that local heating effects such as Joule heating are negligible. However, for calculating the temperature distribution in the equatorial and auroral ionospheres Joule heating effects have to be taken into account.

Joule heating in the equatorial E region due to the electrojet has been studied theoretically by Kato [5]. Joule heating affects the thermal equilibrium, by raising $T_e$ above $T_s$ in a way similar to the heating produced by the absorption of solar radiation. In the present discussion, the energy produced by Joule heating is related to the observed increase in $T_e$ over $T_s$ under the assumption that the energy loss of electrons by collisions with neutrals is the only loss process.

2. Flight Data

A Nike-Apache rocket carrying a proton precession magnetometer, an electron temperature probe, a capacitance probe and a gyro-plasma probe, was launched on a magnetically quiet day, 25 April 1971 ($K_p = 2$) at noon from Thumba, near the magnetic dip equator. The proton magnetometer and the electron temperature probe gave satisfactory measurements during the ascent up to 160 km. The electron temperature probe used in this experiment is the same as that described in [6].

3. Flight Results

The proton magnetometer measured a difference field $dH$ of $\pm 110$ nT as it traversed the electrojet. The vertical distribution of electric current density is derived from the slope of the difference field by the usual method [7]. The electron temperatures measured by the temperature probe and the gas temperature given by the CIRA 1965 model have been used to derive the temperature difference

![Fig. 1. Vertical profiles of measured electron temperature $T_e$ and the CIRA 1965 model neutral gas temperature $T_g$.](image-url)
The current density $J$ derived from the magnetometer data and the difference temperature $T_e - T_g$ plotted as functions of altitude.

The profiles of Maeda and Matsumoto [9]. The vertical profile of the electron temperatures obtained from the measurements is shown in Fig. 1, together with the CIRA 1965 model gas temperature profile. The current density $J$ derived from the magnetometer is shown in Fig. 2.

4. Calculations

The power generated by the electrojet is calculated and correlated with the observed difference $T_e - T_g$. It is assumed that this difference $T_e - T_g$ is due to the electrojet currents only. The power $Q$ generated by Joule heating can be written as

$$Q = J^2/\sigma_2,$$  \hspace{1cm} (1)

The heat input by the electrojet $Q_h$ is obtained as a function of altitude, and is shown in Fig. 3.

If we consider that the loss of energy due to collisions alone is important, under equilibrium conditions, the balance between the heat input by Joule heating and power dissipation by collision with neutral particles is soon established. Following Kato [5] the energy input can be written

$$Q = \frac{3}{2} k n_e v_e \lambda (T_e - T_g)$$  \hspace{1cm} (2)

where $k$ is Boltzmann's constant, $n_e$ is the electron density, $v_e$ is the collision frequency of electrons with neutrals and $\lambda$ is the mean fractional energy loss per collision. From (1) and (2)

$$\lambda = \frac{2}{3} \frac{J^2}{\sigma_2} \frac{1}{k n_e v_e (T_e - T_g)}.$$

**Fig. 2.** The current density $J$ derived from the magnetometer data and the difference temperature $T_e - T_g$ plotted as functions of altitude.
By putting in the known values of $J$, $\sigma_e$, $T_e - T_g$, $n_e$ and $v_e$, the parameter $\lambda$ is calculated as function of altitude. This profile is shown in Fig. 3.

In order to obtain an estimate of Joule heating, the heat input needed to give the observed increase in temperature is calculated. Following Dalgarno et al. [2], if $Q_2$ is the energy transferred to the electron gas in unit time, at equilibrium,

$$Q_2 = \frac{3}{2} k n_e \left( \left( \frac{dT_e}{dt} \right)_o + \left( \frac{dT_e}{dt} \right)_{n_e} + \left( \frac{dT_e}{dt} \right)_{O_1} + \left( \frac{dT_e}{dt} \right)_{O_2} \right)$$

(4)

where $dT_e/dt$ is the rate of temperature change by the electrons in collision with the neutrals, the neutral species being denoted by subscripts. In the present case the last term, which denotes the loss due to collisions with positive ions, is neglected. The expressions adopted for these calculations are

$$\left( \frac{dT_e}{dt} \right)_o = -10^{-14} n(O) T_e^{1/2} (T_e - T_g)$$

(5)

$$\left( \frac{dT_e}{dt} \right)_{n_e} = -7.6 \times 10^{-15} T_e + \left( \frac{G P}{n(N_2) \text{rot}} \right) n(N_2) (T_e - T_g)$$

(6)

$$\left( \frac{dT_e}{dt} \right)_{O_1} = -4.7 \times 10^{-14} n(O_2) T_e (T_e - T_g).$$

(7)

$n$ is number of particles cm$^{-3}$, $T$ in $^\circ$K and $dT/dt$ in deg s$^{-1}$.

To evaluate Eqs. (5), (6) and (7), the number densities $n(O)$, $n(N_2)$ and $n(O_2)$ are taken from the CIRA 1965 model. The rotational loss parameter $(G P/n(N_2))$ in Eq. (6) is calculated according to Dalgarno and Moffett [10]. The energy $Q_2$ needed to maintain the observed temperature difference is then calculated, and is shown in Fig. 3.

5. Discussion

It is evident from Fig. 1 that the measured electron temperatures ($T_e$) are more than the CIRA model neutral gas temperatures throughout the E region. In Fig. 2, the $T_e - T_g$ and the current density, $J$, profiles are shown for comparison.

![Mean fractional energy loss](image-url)
It is seen that there is good correspondence between $T_e - T_g$ and $J$ throughout the main electrojet layer around 106 km. The $T_e - T_g$ profile shows a rather broad maximum compared with the current density maximum, implying that the heating is not localized, but extends slightly above the electrojet layer.

The $\lambda$ values shown in Fig. 3, are slightly higher than those used by Kato [5]. The calculated $\lambda$ values show that $\lambda > 2m_e/M$, where $m_e$ is the electronic mass ($9.1 \times 10^{-30}$ g) and $M$ is the mass of the heavy particle in collision ($5 \times 10^{-23}$ g). This implies that the collisions are inelastic in the region considered.

The vertical profile of $\lambda$ shows a large peak between 120 and 130 km. Part of this increase in $\lambda$ is due to the small increase in current $J$ in this altitude range. This increase in $J$ is due to a second current layer often seen in equatorial $J$ measurements [12]. The broad peak in $T_e - T_g$ around 110 km may partly be due to the effect of this second current layer. Even after removing the effects of this possible second current layer, $\lambda$ shows a peak around 125 km. The magnitude of this peak depends largely on the rate of fall of electrojet current with altitude above the peak of the electrojet at 107 km. Examining Eq. (3), $v_\infty$ falls rapidly with altitude and $(km_n \nu_0(T_g - T_e))^{-1}$ has large values beyond 115 km. Since $J^2/\sigma_0$ has significant values between 115 and 130 km, $\lambda$ shows large values in this region. This means that the electrons in this region attain large energies between collisions. Therefore, one can expect the energy transfer per collision of electrons with neutrals to be large in this region.

The $Q_T$ profile shows a slight deviation from its normal trend at 106 km. The $Q_T$ value at 106 km is nearly one third of the $Q_T$ value at the same altitude. This implies that the measured strength of the electrojet current $J$ can account for only one third of the observed difference in temperature $T_e - T_g$. The difference between $Q_e$ and $Q_T$ decreases above 106 km.

The discrepancy between the theory and the experiment can be attributed to the following factors: (i) The experimentally measured electron temperatures could be slightly higher than the actual temperatures in the region. (ii) The CIRA model gas temperatures $T_g$ used in the calculation may not represent the actual gas temperatures in this region. The measurements by Knudsen and Sharp [11] at mid-latitudes suggests that $T_y \approx T_g$ and that the measured $T_g$ values agree with the model gas temperatures up to 120 km. However, there are no direct gas temperature measurements over the equator. (iii) The dependence of $\nu_\infty$ on $T_e$ can increase the $\nu_\infty$ values used here by a factor $(T_e/T_y)^{1/2}$ which is of the order 1.6 around 106 km. This increase in $\nu_\infty$ will reduce the $\lambda$ values by a factor 0.6 near 106 km. The new $\lambda$ value thus obtained for the region around 106 km agree with the $\lambda$ value used by Kato [5] for a difference in temperature of 440 °K.

6. Conclusions

1. The pronounced peak of $T_e - T_g$ around 106 km is due to the Joule heating effect of the electrojet. 2. The electron temperatures measured are higher than the CIRA model gas temperatures all over the E region. 3. The observed electrojet strength $J$ can account for only one third of the observed temperature difference $T_e - T_g$. 4. The $\lambda$ values obtained show that in the region of the electrojet the collisions between electrons and neutrals are inelastic.

To obtain a good understanding of the phenomenon of Joule heating it is
necessary to measure $T_e$, $T_\mu$, $J$ and $n_e$ in simultaneous or near simultaneous flights. It is also necessary to confirm the above findings by further experiments over the equator.

References

A Digital Pressure Transducer

T. S. G. SASTRY, H. S. MAZUMDAR & S. SAMPATH
Physical Research Laboratory, Ahmedabad

Received 26 October 1974

A digital pressure gauge that can measure pressures from 1 atm down to 0.5 mm Hg was developed using indigenously available materials and components. The performance of these gauges was tested by flying them on Russian M-100 rockets and comparing their performance with the performance of conventional meteorological pressure gauges used in standard meteorological payloads. Details of instrumentation and results of test flights have been presented.

1. Introduction

The digital pressure gauge consists of an ionization chamber containing a radioactive source. The output of the chamber is connected to an electrometer which, in turn, is coupled to a blocking oscillator. The output of the oscillator is a series of pulses. At low pressures the number of molecules of air ionized in the chamber by the α emissions from the source is small resulting in a small electrometer current and a small pulse rate. At higher pressures, the pulse rate increases as larger current is detected by the electrometer tube. Low pressure gauges devised on this principle for laboratory purposes have been described by Downing and Mellen, Sibley and Roehrig; etc. The gauge described here is of the type devised by Vanderschmidt and Cambou et al.

2. Instrumentation

Gauges with different configurations were designed to measure atmospheric pressure up to 50 km altitude, by balloons as well as small and medium sized rockets. Fig. 1 shows some of these instruments. Gauges 1 (a) and 1 (b) use ionization chambers of conical shape cut out of rectangular blocks of brass. The conical chambers are similar in configuration to the chamber described by Cambou et al. Four elliptical windows cut in the cone ensures quick equalization of pressure inside the chamber and the environment whose pressure is to be measured. The collector electrode is a tungsten wire of 0.5 mm in diameter. It runs centrally inside the chamber and is held in position at the broad end of the cone by a brass disc sandwiched between a pair of teflon rings. These teflon rings insulate the central electrode from the body of the chamber. The radioactive source used is polonium 210 of strength 50 μ curie or americium 241 of strength of 30 μ curie. The radioactive material is electrochemically deposited on a silver coin of 15.5 mm diameter and 3 mm thickness. The coin bearing the radioactive material is enclosed in a brass cap and screwed on to the narrow end of the chamber. All brass parts are polished and silver plated. The dimensions of the chamber and the windows and the angle of the cone are optimized to obtain the desired linearity between the collector current and the ambient pressure.

The gauge shown at 1 (c) is made out of a rectangular aluminium block. A circular hole of 1 cm diameter cut at the centre of the block along its length forms the chamber. The silver coin bearing the radioactive source is fitted at one end of the chamber and the tungsten wire electrode is introduced axially from the opposite end. The tungsten wire electrode is held in position with teflon discs as in the conical chamber. A 1 cm diameter window is cut on one side of the block to ventilate the chamber to outside air. This chamber is easy to mount and is more compact compared to the conical chamber.

The electronic circuits used are shown in Fig. 2. The circuit 2 (a) uses an electrometer tube amplifier coupled to a blocking oscillator. It is similar to the one used by Vanderschmidt, except for a few changes to make the output compatible with the telemetry requirements.

A more versatile circuit was developed which is shown in Fig. 2 (b). The potential at the grid of the electrometer tube at any instant is a function of the chamber capacitance and the charge on the central electrode. If the chamber capacitance and stray capacitance at the input of the electrometer tube remains constant, the potential at the grid of the electrometer tube rises as the charge accumulates on the chamber collector electrode. This potential is amplified by the electrometer tube and is fed to a comparator P which is connected in feedback loop with the transistor Q, to form a mono. When the probe potential at the input of the EM tube increases above a certain limiting value due to charge...
accumulation at the grid, the mono generates a positive going pulse which is fed to the chamber through capacitor C. This pulse reaches the grid of the EM tube via the chamber capacitance and drives it to conduction, thus discharging the charge accumulated on the collector electrode of the chamber. At the end of the pulse from the mono, the central electrode is ready to collect the charges due to ionization in the chamber again and the process repeats.

The charging rate of the chamber is proportional to the ambient density of air and if the temperature of air in the chamber does not change appreciably, the mono gives a pulse output whose frequency is proportional to ambient pressure. These pulses are fed to telemetry through the driver transistor Q2. In this circuit it is possible to adjust the pulse rate appropriate to the ground pressure by adjusting the feedback. The sensitivity of the chamber depends on
the capacitance of the chamber and stray capacitance of the input circuit. These must be stable and made as small as possible.

3. Preflight Calibration

The pressure gauges made for rocket flights will have to be calibrated after potting the section in which the electronic circuits are enclosed. The potted unit is kept in a vacuum chamber fitted with a standard pressure gauge. The voltage for the chamber and the circuit is fed through vacuum feedthroughs. The output of the chamber is connected to a digital counter. The counting rate at normal ground pressure is adjusted between 600 and 700 pulses per second. The counting rates for different pressures are noted as the evacuation of the chamber proceeds. The calibration curve of pressure against counting rate for the unit flown on flight 08-106 is shown in Fig. 3. It is found that the curve is linear even up to fraction of a mm of pressure.

4. Flight Results

A Russian M-100 rocket (FL 08-106) carrying the digital pressure gauge was launched from Thumba on January 3, 1973 at 2120 hrs IST. Earlier the same day at 2000 hrs IST a standard meteorological payload (FL 08-105) was launched to measure atmospheric pressure, temperature and wind velocity. Both the rockets carried radar transponders to enable trajectory determination. The rocket FL 08-105 payload contained two Pirani (hot wire) manometers for measuring pressure from 50 to $5 \times 10^{-4}$ mm Hg and two membrane manometers operating in the range 5 to 250 mm Hg. Pressure measurements from 760 to 350 mm Hg were obtained by balloon borne meteorological payload which usually precedes a standard Met. M-100 flight. The procedure adopted to derive the pressure values from data sent by a standard Met. M-100 payload has been described by Narayanan. In Fig. 4 the pressure measurements from the digital pressure gauge of FL 08-106 have

Fig. 2—The electronic circuits used for the rocket-borne digital pressure gauges

(a)

(b)
been compared with the pressure values derived from the meteorological rocket (FL 08-105) and the balloon data. It is seen that the agreement between the atmospheric pressure measured by the two independent methods is good especially above 20 km altitude.

A second digital pressure gauge was flown on 11 January 1973 at 2142 hrs IST on M-100 FL 08-108. This rocket did not reach the full expected altitude of 88 km but data could be obtained both on ascent and descent. The data from this flight along with CIRA model pressure has been shown in Fig. 5. In the flight 08-106 launched on January 3, the pressure gauge was mounted in the cylindrical part of the nose cone where the effects of the wake on the measured pressure are least. In the flight FL 08-108 the gauge was located in the conical part of the nose cone where the effects of the wake are more. This appears to have affected the measured ambient pressure at the sensor.

5. Conclusions

The performance of the digital pressure gauge described here compares well with the performance of conventional meteorological pressure gauges. It has the added advantage that its output is digital and hence easy to transmit and count. It also has a wide dynamic range for pressure measurements. Its response to pressure changes, stability of calibration and accuracy of measurement compares well with similar gauges imported and flown in the first few rocket flights from Thumba. As a laboratory vacuum

---

**Fig. 3**—Preflight laboratory calibration curve of pressure against counting rate for a typical digital pressure gauge instrumented for a rocket payload.

**Fig. 4**—Comparison of pressure measurements obtained by the digital pressure gauge on FL 08-106 and those obtained from a standard meteorological payload of FL 08-105.