Electron-ion collision frequencies were calculated for the summer months of the years 1959-1963 by studying the deviative absorption of radio waves in the F2-region at Waltair (7-3°N geomagnetic latitude), India. These collision frequencies were utilized in deducing the electron temperature in the F2-region. It is shown that the electron temperature has a linear relationship with the sunspot number, though such a relationship was not obvious for the collision frequencies, because of the electron density variations.

**Introduction**

The study of the ionospheric charged particle density has a long history, but the measurement of charged particle temperatures is of more recent origin. The most accurate methods as yet for temperature measurements are probably the in situ Langmuir probe and the incoherent back-scatter techniques. It will be impractical to study long-term temperature variations with solar activity by in situ probes, while the back-scatter establishments are limited to a very few locations in the world and it is impossible to obtain a global picture. However, it has been pointed out that by using the empirical relations developed by Anderson and Goldstein from laboratory experiments, the electron temperature in the F2-region can be derived from the deviative absorption measurements. The expression for deviative absorption of radio waves in the ionosphere can be derived from the Appleton-Hartree magneto-ionic theory and it has been shown that the total deviative absorption can be expressed by the relation

\[ Kds = \frac{v}{2c} \left( P' - P \right) \]  

where \( K \) is the absorption coefficient in the deviating zone, \( v \) is the mean collision frequency in the deviating zone, \( c \) the velocity of light and \( P \) and \( P' \) the phase and group paths respectively. Appleton has shown that this can be conveniently transformed into a more practical form as

\[ \frac{v}{c} = \int \frac{d(\log \, \rho)}{d\theta} \]  

where \( f \) is the operating frequency, \( \log \, \rho \) is the deviative absorption and \( \theta \) is the equivalent height of reflection in the \( A_{\nu} \) technique. The collision frequencies thus derived have been used, as discussed in a later section, for deducing the F2-region electron temperatures.

**Experiments and Calculations**

There have been very detailed reports on the theory of absorption and the techniques of measurement and also on the various sources of error and the methods of minimizing them. We will not go into any details of the equipment or the method of absorption measurement since the equipment consists of conventional pulse sounding system and the method of measurement is by the constant gain technique such as described by Piggot et al. However, it may be mentioned that a detailed description of the equipment and the various precautions taken for these measurements are documented elsewhere.

In addition to routine \( A_{\nu} \) absorption measurements, many experiments were conducted to measure the collision frequency in the \( D \) and \( E \)-regions between 1959 and 1963 at Waltair (17-6°N, 83-3°E, 7-3°N geomagnetic latitude), India. We will limit ourselves in this communication to the F2-region measurements. On at least four magnetically quiet days in every month absorption measurements were taken at frequencies close to the critical penetration frequency of the F2-layer. Only those observations around midday were chosen so that the non-deviative absorption in the \( D \) and \( E \)-regions remained practically constant throughout each experiment. Simultaneously, virtual height versus frequency observations also were taken and the true heights were calculated by assuming a parabolic distribution with an estimated error of \( ±\,5 \) km. The values of \( \theta \) were plotted against \( -\,\log \, P \). The gradient of the curve in each case for a particular value of \( \theta \) corresponding to a particular value of \( f \) is determined, and the values of collisional frequencies are calculated using Eq. (2).

It should be mentioned in this connection that Whitehead has estimated the error in the measured collisional frequency consequent to assuming \( P' \) in Eq. (1) to be equal to \( 2\,\cos \,\theta \,d\,P \). The expression for the error was

\[ \frac{d(\log \, \rho)}{d\theta} \]

where \( \theta \) is the angle between the imposed magnetic field and the direction of propagation of the radio waves, and \( P \) the actual path traversed. For Waltair, the error is only about \( 2\times\,10^4/\sec \). However, those measurements where the reflection coefficients were not obtained by
Comparing the first and second echoes were corrected for this error.

To avoid seasonal effects in the study of variation of \(v\) with solar activity, measurements in the three summer months of May, June and July were used for the years 1960-1963 and the months of July and August were used for 1959, since the measurements were started only in July 1959. On each of the four days in a month, the experiment was conducted about six times continuously and the collision frequency calculated for each of these experiments. The average of all the 24 measurements thus obtained in a month was taken and tabulated against the average sunspot number of the four particular days.

**Results and Discussion**

Fig. 1 shows a plot of the electron collision frequencies against the sunspot number for the period July 1959 to July 1963. As mentioned earlier, each point represents the average of about 24 independent measurements in a particular month and the error indicated for each point is the standard deviation of the measurements represented by that point rather than the estimated error. Throughout the data shown in Fig. 1, the true height of reflection varied from 290 to 330 km. Since most of the deiative absorption occurs very close to the F2 peak, the \(v\) values in Fig. 1 do not pertain to a particular height, but represent the electron collisional frequencies at the F2 peak while its height varies from 290 to 330 km. The increase of collision frequency with sunspot activity, as may be noted from Fig. 1, is not commensurate with the increase in electron density. This is due to the increase in electron temperature which tends to reduce the collision frequency.

The collision frequency and the electron temperatur in the F2-region are related to the electron collision frequency at the F2 peak while its height varies from 290 to 330 km. Since most of the deiative absorption occurs very close to the F2 peak, the \(v\) values in Fig. 1 do not pertain to a particular height, but represent the electron collisional frequencies at the F2 peak while its height varies from 290 to 330 km. The increase of collision frequency with sunspot activity, as may be noted from Fig. 1, is not commensurate with the increase in electron density. This is due to the increase in electron temperature which tends to reduce the collision frequency.

The collision frequency and the electron temperature in the F2-region are related as

\[
v_{e,i} = \left[ 34 + 8.36 \log_{10} \frac{N^i_T}{n_{e0}} \right] n_e T_e^{3/2} \quad \ldots (3)
\]

where \(v_{e,i}\) is the collision frequency of the electron with ions (which essentially is the total collisional frequency of the electron in the F2-region); \(T_e\) the electron temperature; and \(n_e\) the electron/ion density. The temperature of the positive ions, which may be different from that of the electrons, is also involved to some extent in the above expression (in the log term). This has been ignored since the effect is too small to affect our results.

Employing Eq. (3) and using the measured values of \(n_e\) corresponding to the individual experiments, the values of \(T_e\) were deduced for the same data shown in Fig. 1. A plot of these temperatures against the Zurich sunspot number is shown in Fig. 2. Since a linear relationship is obvious, a straight line was fitted by the method of least squares and is of the form

\[
(T_e)_R = (T_e)_0(1 + \alpha R) \quad \ldots (4)
\]

where \((T_e)_R\) is the electron temperature when the sunspot number is \(R\) and \((T_e)_0\) is the temperature for zero sunspot number. The values of \((T_e)_0\) and \(\alpha\) are 1194°K and 0.0034 respectively. The value of \((T_e)_0\) which is the change in \(T_e\) per unit change in \(R\) is 4.1°K.

There have been many direct measurements of electron temperature recently, but measurements around the magnetic equator in the F3-region are scarce. For low sunspot activity (30 < \(R\) < 40), Bowen et al. reported a value of about 1100°K for the electron temperature at 400 km at 10°N magnetic latitude from Ariel 1 satellite, while Brace et al. reported a value of about 1400°K at about the same height and latitude. The latter value compares very well with that from Fig. 2 for \(R = 35\) which is 1340°K.

Some studies have been made of the solar activity variations of electron temperature by using satellite data at 1000 km, but no study was available near the F2 peak. The incoherent scatter data of charged particle temperatures at Arecibo (geomag, 139...
latitude 30°N have also been used to study their variations with the 10.7 cm solar flux. While the ion temperatures and the night-time electron temperatures showed a definite increasing trend with the solar flux, no such relationship was obvious for the day-time electron temperature.

Several attempts have been made earlier to deduce electron temperatures from the deviative absorption in the F-layer, though most of them employed the cosmic noise \( A_2 \) technique measurements. The general trend in a majority of these observations has been that the electron temperatures thus deduced are too low, hardly exceeding the expected neutral temperatures. One problem in utilizing \( A_2 \) technique measurements for deducing F-region temperatures is that since the operating frequency has to be considerably higher than the \( f_{F2} \) (to avoid large 'window' effects), the percentage of deviative absorption is rather low. However, some results at low geomagnetic latitudes have shown good agreement with direct measurements. It was also shown theoretically that electron temperature variations with solar activity at F-region levels are highly latitude sensitive and the pattern of change reverses from mid-latitudes to low latitudes.

Conclusion

The deduction of electron temperatures from absorption measurements is rather indirect and the interpretation of absorption data is very complex because of various effects like focusing, fading and dispersion. However, these effects were minimized by increasing the pulse width and increasing the number of observations for better statistics. Though this method cannot be a substitute for direct measurements, it can be applied with very little additional expense at the routine ground stations at least in low latitudes where the effect of the magnetic field on the measurements is very small.

Acknowledgement

The help rendered by J. H. Sayler of Goddard Space Flight Center, USA, in reducing the mass of observational data with the help of a computer is gratefully acknowledged.

References

1. NICOLET, M., Physics Fluids, 2 (1959), 95.