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Density of the Ionized Upper Atmosphere to 5500 Kilometers ‡

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One of the instruments carried on the Scout Vehicle (NASA, ST-II) which was launched from Wallops Island, Virginia, at U.T. 15:23 on 4 October 1960 was a four-grid ion probe (Hale, 1961). The preliminary ion probe data which Hale presented in 1961 were used in some later calculations pertaining to the composition of the ionized upper atmosphere (Hanson, 1962). The manner in which the scale height of the ion density increased with increasing altitude was interpreted by Hanson as indicating that the ionized upper atmosphere changed from predominantly O^+ between 550 and 1000 km., to predominantly He^+ between 1000 and 2200 km. following Nicolet's suggestion (1961), and to predominantly H^+ above 2200 km. The fact that Hale's preliminary density data also showed that the density began to increase with increasing altitude above 4200 km. giving a negative scale height from 4200 km. up at least to the limit of the measurements at 5500 km. was neither noted or explained.

Because of the possibly great significance of the change to a negative scale height, laboratory calibrations of the ion probe and a re-evaluation of the 1960 flight data were undertaken at North Carolina State in 1962. These studies have been completed and show that the rate of increase of density with increasing altitude is greater than previously supposed, and that the negative scale height is probably real.

The ion probe consists of four parallel knitted wire grids and a shielded collector plate arranged as shown in Figure 1.

In making the measurements in the upper atmosphere, the upper grid, P, was grounded to the vehicle. The next two grids, Q and R, were both connected to the same saw-tooth ion-retarding potential swept from -2 volts to +30 volts every 2.5 seconds. The fourth grid S was held at 30 volts negative with respect to the vehicle, in order to turn back all incoming electrons and to suppress secondary and photo-emission from the collector plate, T. The collector plate was connected to an amplifier U which held the collector near the potential of the vehicle, except for contact potential differences to be discussed later.

The equipment used in calibrating the ion probe is illustrated in Figure 2. An evacuated glass cylinder A is used, the inside surface of which is made electrically conducting while remaining transparent, using a process which has previously been described (Bennett, 1959, 1963). The ion probe B is mounted on an arm C which can be rotated without breaking vacuum in order to measure the response of the ion probe at various aspect angles with respect to the direction of motion of the vehicle. The chamber is evacuated through D while any desired gas can be admitted directly into the main part of the chamber through tube E.

An ion source is located at F and is illustrated in greater detail in Figure 3. The ion source uses knitted tungsten wire grids and is a modification of the ion source in the non-magnetic mass spectrometer used for measuring the neutral composition of the upper atmosphere (Townsend, 1952).

In the present application, the gas in the chamber is maintained at about 3.10^{-5} Torr. Electrons from a filament G are accelerated at 45 volts through the electrode H which is called the cage and which uses three interconnected grids as shown. The grid J is held at a potential of 20 volts negative with respect to the cage H. The grid doublet K is held at a potential of 22.5 volts negative with respect to the cathode, thus turning back all of the electrons from the cathode. Ions which have been produced by the electrons ionizing the gas in the cage are accelerated downward by the negative potentials on grids J and K. The ions emerging through grid K have a wide spread in energy corresponding to the spread in potential of the various positions between H and K at which the ions are produced. A grid doublet L held at 2.5 volts negative with respect to the cage turns back all ions except those which have very nearly the same kind of velocity distribution as was observed with the ion probe in the flight at Wallops Island. A grid M is grounded to the test chamber in order to insure that the only electric fields in the test chamber will be those due to contact potential differences. The average energy of the ions projected downward into the test chamber from the ion source is about 1.5 e.v. less than the potential difference between the test chamber and the cage H.

In Figure 4 is shown the energy distribution as measured with the retarding potential applied in each of three different ways. The dotted curve shows the characteristic when the retarding potential is applied to the third grid only while the second

and first grids are both grounded to the shell. The solid curve shows the characteristic when the retarding potential is applied to both the second and third grids interconnected to act as a grid doublet. A comparison of these two curves shows that the use of a single grid introduces an unacceptably large error in the measured ion energies and also distorts the velocity distribution at the lower ion energies. Some of the aluminum with the same composition as the skin of the rocket was substituted for the nichrome V collector plate in the ion probe. The velocity distribution obtained by applying the retarding potential to the collector is shown with the dashed curve. Comparison of the latter two curves shows that there was a contact potential difference of 0.5 volts between the skin of the rocket and the retarding grid doublet; that is, if the rocket were uncharged, a retarding potential must be applied to the tungsten wire grid doublet which is 0.5 volts greater than the kinetic energy of the incoming ions in electron volts in order to just stop the ions from reaching the collector.

The ion probe was rotated to measure directly the change in characteristic due to change in aspect angle. The results are shown in Figure 5. By using these calibration curves, it has been possible to apply the proper corrections to the measurements made in flight when the direction of motion had turned away from the normal to the ion probe grids by substantial amounts at the higher altitudes.

Measurements in the Upper Atmosphere

In order to cover the very wide range in ion currents to be found between 550 km. and 5500 km., the

amplifier used in flight was allowed to approach saturation for currents above 2.5×10^{-9} amperes as seen in the calibration curve plotted in Figure 6. The output from the amplifier was linear for currents smaller than 2.5×10^{-9} amperes, that is, for all of the measurements above 2000 km.

The ion density was computed for each characteristic from the maximum current and vehicle velocity by applying corrections for the aspect angle as found from Figure 5. The resulting curve is given in Figure 7 where the logarithm of the numerical density of ions is plotted against an altitude scale in which the geo-potential increases linearly, in order that a density variation with constant positive scale height will have a constant negative slope. The actual altitude is shown in the scale at the right hand side of Figure 7. Dashed lines are also shown for predominantly O^+ from 550 to 1200 km., He^+ from 1800 to 2600 km. and H^+ above 2900 km. The curve definitely breaks away from the dashed curve and has a negative scale height from 4200 km. up to the limit of the measurements at 5500 km.

If the temperature is assumed to be approximately $2000^\circ K$ and the charged particle density to be about 2000 per cubic centimeter, the Debye length in the medium is smaller than the diameter of the end of the ion probe mounting. For this reason, it is not believed that the contact potential difference between the outer tungsten wire grid and the skin of the rocket has any important effect on the ion currents collected in these measurements.

Discussion

The onset of the negative scale height lies in the Van Allen radiation belt whose best known components are energetic protons and electrons, (Bame, et. al., 1963; Hess, 1963). These high energy particles are mixed with lower energy ions and electrons whose densities increase exponentially with decreasing energy (Freeman, 1962; Pizzella, 1963) down at least to about 1 Mev. for protons and about 40 Kev. for electrons. Little has been reported about the densities of protons with energies below 100 Kev. and electrons below 10 Kev. (Davis, et. al., 1964).

The density of the neutral gases at the altitude of the inner radiation belt has been estimated to be of the order of 1000 hydrogen and helium atoms per cubic centimeter (Hanson, 1962). The rate of production of magnetically trapped low energy ions is proportional to the densities of the energetic particles which produce the ions by ionizing the residual neutral gas. The density of trapped low energy ions is not of course reduced by charge exchange with neutrals. The cross section for direct re-combination with electrons is quite negligible compared with the cross sections for scattering and for ionization. The principal way in which the trapped low energy ions can escape is by being scattered by collisions into escape cones of solid angle through which the ions can descend into the denser part of the upper atmosphere and be absorbed. The collision cross-sections for deflection into the escape cones are several orders of magnitude smaller than the ionization cross sections. The density of trapped low energy ions should, therefore, be several orders of magnitude greater than the density of neutral atoms.

Conclusion

The measurements suggest that the radiation belts containing magnetically trapped high energy particles should also contain substantially increased densities of trapped low energy ions and electrons.

The fact that such trapping can produce increased densities of low energy ionized matter suggests further that measurements should be made in the outer part of the outer radiation belt. The continual collision of ionized matter from the sun with trapped matter in the outer belt may well scatter incoming material into trapped orbits without scattering trapped material into free orbits in equal amount. This would produce increased densities of ionized material in the outer belt.

The authors wish to express their gratitude to Dr. Richard F. Taschek and to Dr. Harold Argo for their continued support and encouragement throughout this investigation.

8

Figure Captions

- Figure 1. Arrangement of electrodes in ion probe. The actual separation of grids is less than shown in this schematic drawing.
- Figure 2. Test chamber.
- Figure 3. Ion source used with test chamber.
- Figure 4. Measurements of velocity distribution by the ion probe in the test chamber by applying the retarding potential in various ways.
- Figure 5. Effect of turning the perpendicular to the ion probe electrode away from the direction of the velocity of the rocket upon the observed velocity distribution, as found by rotating the ion probe in the test chamber.
- Figure 6. Calibration curve for the amplifier used in flight.
- Figure 7. Dependence of ion density upon altitude after corrections have been applied for aspect angle.

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FIGURE 1

FIGURE 2

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FIGURE 4

FIGURE 5

FIGURE 6

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