Techniques of measurements of neutral and plasma parameters

As discussed in Chapter 1, the equatorial spread F (ESF), is known to be due to the generation of irregularities in electron and ion densities and as well in the electric fields. In order to investigate the role of plasma and neutral dynamics in the causative mechanism of ESF, it is essential to know the basic neutral and plasma parameters at the onset time of equatorial spread F. However, most of the earlier insitu measurements have been concentrated on the well developed phase of the phenomenon, essentially to study the spectral characteristics of the plasma irregularities. Direct measurements at the onset time of ESF are indeed not available. Coordinated measurements on neutral winds and temperature alongwith plasma densities and irregularities were planned and conducted at the onset time of ESF. Five RH-560 rockets were launched from Sriharikota, (5.5° dip latitude) India during 1981-82. Three of them were launched on geomagnetically quiet days while the other two happened to be on a disturbed day. The complete details of the launchings along with the geophysical conditions are given in Table 2.1.

Artificial vapour clouds were released in the upper atmosphere to measure neutral winds (both horizontal and vertical components) and temperatures. The ionized portion of the released barium clouds was used to measure the electric fields. Rockets containing Langmuir probe and ion mass spectrometer were flown to measure plasma parameters such as
### Table 2.1

<table>
<thead>
<tr>
<th>Date</th>
<th>Flight</th>
<th>Payload</th>
<th>Launch Time (IST)</th>
<th>Elevation</th>
<th>Azimuth</th>
<th>Solar Flux</th>
<th>$A_p$</th>
<th>$K_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 Mar 1981</td>
<td>RH560-20</td>
<td>Ba-Sr clouds</td>
<td>1849</td>
<td>84.5°</td>
<td>72°</td>
<td>224.0</td>
<td>17</td>
<td>2</td>
</tr>
<tr>
<td>16 Feb. 1982</td>
<td>ASV 19</td>
<td>Ba-Sr clouds</td>
<td>184314</td>
<td>82.2°</td>
<td>56°</td>
<td>1843</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>16 Feb. 1982</td>
<td>ASV 26</td>
<td>LP+RFMS</td>
<td>1909</td>
<td>82.1°</td>
<td>71.8°</td>
<td>170.5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>1 Mar 1982</td>
<td>ASV 31</td>
<td>Na cloud</td>
<td>1842</td>
<td>82.3°</td>
<td>75.8°</td>
<td>162.2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1 Mar 1982</td>
<td>ASV 30</td>
<td>LP+RFMS</td>
<td>1905</td>
<td>82.5°</td>
<td>110.8°</td>
<td>231.3</td>
<td>68</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1:- Details of the rocket experiments, launch settings and the geophysical conditions.
densities and the irregularities in them. In this chapter the techniques used in the insitu measurements of neutral and plasma parameters such as winds, temperatures, electric fields and plasma densities are described. The procedures adopted to analyse the data are briefly presented.

2.1 Neutral parameters by artificial vapour clouds:

It was first suggested by Bates (1950) that chemical clouds released in the upper atmosphere could be used as tracer to study atmospheric parameters. The first chemical release was a continuous trail of sodium vapour during evening twilight (Edward et al., 1956).

The technique involves the release of suitable chemicals in vapour phase using rockets. In a few seconds, the released clouds attain the ambient temperature and pressure and move with the ambient winds. The clouds can be released all along the trajectory of the rocket either as a trail or as blobs (puffs) at the predetermined altitudes. The trail releases can be used to measure continuously the altitude profiles of horizontal winds and temperatures. However, the trail releases cannot be used to measure vertical motions as it is difficult to find any clearly identifiable points along the trail. The blob releases are used to measure all the three components (north-south, east-west and vertical) of the velocities at discrete altitudes. The measurements are possible during different times of the day by releasing suitable chemicals and detecting with proper instruments. Rosenberg et al., (1963a,b) suggested that the trimethyl aluminium (TMA) can be used as tracers from 80 to 150 km
altitude region during nighttime. The released TMA gas reacts chemically with atmospheric oxygen and becomes chemiluminescent. This cloud gives rise to a band of emissions ranging from 4500\(\text{A}^{\circ}\) to 6500\(\text{A}^{\circ}\). These chemiluminescent clouds with ground based photographic techniques can be used to measure the atmospheric parameters. Alkali metal vapours whose resonance line emissions fall in the visible region of the electromagnetic spectrum are normally used during day and twilight measurements. These clouds resonantly scatter the solar radiation. As the releases are in vapour phase, the chemicals which have low boiling points are preferred. The materials are chosen in such a way that the excitation potentials fall well within the range of the available solar photon energy and the excitation time scales are shorter than diffusion time scales. Table 2.2 consists of a list of materials and the relevant parameters of substances which are generally used as tracers. The resonantly scattered solar radiation cannot be photographed from ground stations during day time because of the strong background sky. However, the possibility of taking photographs of the released clouds during daytime from an aircraft flying above 40,000 feet with cameras fitted with 10\(\text{A}^{\circ}\) bandwidth filter are reported in the literature (Bedinger, 1973). The daytime releases can be detected using groundbased photometers employing different techniques (Bedinger 1970; Best 1970a,b; Rees et al. 1972b; Desai et al 1979). Release of lithium clouds which have a resonant line at 7608\(\text{A}^{\circ}\) is normally preferred for daytime experiments mainly because, the solar continuum present around
<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
<th>Resonance emission line (Å)</th>
<th>Ionisation potential (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barium</td>
<td>Ba I</td>
<td>5535</td>
<td>5.21</td>
</tr>
<tr>
<td></td>
<td>Ba II</td>
<td>4554</td>
<td></td>
</tr>
<tr>
<td>Lithium</td>
<td>Li I</td>
<td>6708</td>
<td>5.38</td>
</tr>
<tr>
<td>Sodium</td>
<td>Na I</td>
<td>5890</td>
<td>5.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5896</td>
<td></td>
</tr>
<tr>
<td>Strontium</td>
<td>Sr I</td>
<td>4607</td>
<td>5.69</td>
</tr>
</tbody>
</table>

I and II correspond to neutral and ionised states respectively.

Table 2.2: Alkali metals used in vapour release experiments and their respective resonance emission lines along with their ionisation potentials.
this wavelength is about one half of that of the sodium D lines. Lithium can also be used in twilight conditions. However, being a lighter species, the diffusion rates are faster than that of sodium and hence is not employed commonly. In twilight conditions, the upper atmosphere is in the sunlit region while the camera stations are situated in the Earth's shadow. Under this condition, ground based camera stations can photograph the resonantly scattered solar radiation by the released alkali metals. During twilight times, sodium, barium, strontium etc can be released as blobs. Photographs taken simultaneously from more than one station with background stars are used to triangulate the clouds and obtain their coordinates at a particular instant. The time sequence of these photographs taken in synchronisation from different locations on ground are used to derive the atmospheric motions. The advantage of Ba-Sr clouds is that the barium clouds get ionised by solar ultra violet radiation above the altitude 150 km. The motion of the ion clouds are used to derive the ambient electric fields. As the clouds attain the ambient temperature and pressure immediately after the release (within 100 sec.), their expansion rate in the later phase can be used to measure the molecular diffusion coefficients from which the neutral temperatures can be inferred. These aspects are discussed in detail in this chapter.

2.2 Vapour releases in the present study:

In the present study, three rockets containing vapour clouds as payloads were launched from Sriharikota (SHAR 5.5°
dip. latitude). Out of these, two rockets were launched with Ba-Sr vapour payloads which were released as blobs at preset altitudes. The other rocket was launched with a sodium vapour payload which was released in the form of trails. These payloads were fabricated by the Pyrotechnic Laboratory in Vikram Sarabhai Space Centre (VSSC), Thumba, India. The clouds were photographed simultaneously from four ground stations Gudiwada, Kavali, Tirupati and Pondicherry situated on the eastern coast of the southern India as shown in figure 2.1. During the first rocket flight (28 March, 1981) however, the photographs were taken from Kakinada instead of Gudiwada station, while the remaining stations are the same for all the three launchings. It is to be noted that the error in determining the cloud coordinates is minimum when the distance of the clouds to the base of triangle (formed by joining the centre of cloud and the two stations) is the same as the base length of triangle (Anandarao 1977). The release altitudes were from 90 km to 300 km and hence four stations were set up. The clouds were photographed using K-24 and Hasselblad cameras. Kodak 2485 film with usable frame size of 5" x 5" was used in K-24 cameras while 70 mm size of the same film was used in the Hasselblad cameras. More than two cameras were operated from each station to cover the complete extent of the clouds. An electronic control unit was used to control the cameras for automatic simultaneous exposures. A sequence of exposures and gaps were programmed beforehand. One minute after the launch, the control units were synchronised thus ensuring simultaneous recording of the photographic frames.
Fig. 2.1: The locations of the camera stations Gudiwada, Kakinada, Kavali, Tirupati and Pondicherry in Southern India surrounding the launch site Sriharikota (SHAR).
from all the camera stations. In the present study, all the three releases were conducted during evening twilight time and hence the background stars were also photographed along with the clouds. These star fields were used as a reference to find out the camera axis.

2.3 Analysis Procedure for blob releases:

The methods used for the analysis of the blob and trail releases are different. For blob releases, the triangulation method described by Smith (1963) is adopted. The method of analysis is described briefly.

To deduce the motions from the cloud photographs, it is essential to find the position co-ordinates of the cloud at different times after the release. A cartesian coordinate system (X,Y,Z) is chosen in which X axis is towards east, Y axis towards north and Z axis vertically upward. In this system, the cloud co-ordinates \((X_c, Y_c, Z_c)\) are defined as follows:

\[
\begin{align*}
X_c &= R \cos E \sin A \\
Y_c &= R \sin E \cos A \\
Z_c &= R \sin E
\end{align*}
\]  

where \(R\), \(E\), and \(A\) are the slant range, elevation and azimuth of the cloud centre respectively. The azimuth is measured from north along east. These three quantities are essential to deduce the cloud position at a given time and are obtained by the determination of (1) the accurate look angles of the camera centres, (2) the look angles of different clouds as seen from two or more stations and (3) the slant ranges of the cloud centres using the look angles obtained from two
In order to accomplish these steps the positions of the cloud centres and stars are read from all the frame sequences photographed from different stations, in arbitrary coordinate systems using a travelling microscope (least count .001 cm). These coordinates are translated into standard coordinate system using the position coordinates of 3 or more stars following the method of Smith (1963).

The accurate look angles of each camera are determined by using the celestial co-ordinates (right ascension and declination) of at least three or more identified stars on the photographs from a camera station. For this procedure, the position coordinates of the camera station (latitude and longitudes) sidereal time of the launch and the approximate look angles of the cameras are required. The latitudes and longitudes of the camera stations were determined by monitoring the United States Navy Navigation Satellite (US-NNSS) passes from corresponding locations of the stations with a geo-receiver system. By this method, the latitude and longitudes are determined with an accuracy of ± 3 arc sec.

The slant ranges of the clouds are determined using triangulation method which is illustrated in the figure 2.2. $S_1$ and $S_2$ are the two camera stations whose position vectors $Y_1$ and $Y_2$ with respect to the launch station A are known. $C_1$ and $C_2$ are the centres of the clouds as seen from $S_1$ and $S_2$ respectively. Ideally these centres $C_1$ and $C_2$ must coincide but in practice due to experimental and numerical errors the distance $C_1C_2$ is non-zero. $R_A$ and $R_B$ are vectors connecting
Fig. 2.2: Illustration of the triangulation procedure for the blob release. $C_1$ and $C_2$ denote the centres of the blob as seen from the two camera stations $S_1$ and $S_2$. $C$ is the mid-point of $C_1C_2$. $A$ is an arbitrary point (usually launch site) on the surface of earth with respect to which the spatial coordinates of $C$ are computed (based on Smith 1963).

Fig. 2.3: Illustration of the triangulation procedure for the trail release. The straight lines intersecting the trail as seen from station $S_2$ are the transformations of the points shown by arrows on the trail as seen from the station $S_1$ to the frame of camera 2 (Desai et al., 1975).
the cloud centres \((C_1\text{ and } C_2)\) and the respective stations \(S_1\) and \(S_2\). Though the magnitude of \(R_A\) and \(R_B\) are not known, the direction cosines of these vectors are known from which the unit vectors \(n_1\) and \(n_2\) are obtained. The direction cosines of the cloud centre whose elevation and Azimuth are \(E_1\) and \(A_1\) as seen from station \(S_1\), are defined as

\[
\begin{align*}
\cos \alpha_1 &= \cos E_1 \sin A_1 \\
\cos \beta_1 &= \cos E_1 \cos A_1 \\
\cos \gamma_1 &= \sin E_1
\end{align*}
\tag{2.2}
\]

Similarly the direction cosines of the cloud centre as seen from station \(S_2\) are obtained by replacing the subscripts 1 by 2 in the above equation.

The slant range \(R\) is shown to be as (Smith 1963)

\[
R = \frac{1}{2} (\gamma_1 + \gamma_2) + \frac{1}{2|\vec{n}_1 \times \vec{n}_2|^2} \left\{ \vec{n}_1(\gamma_2 - \gamma_1) \cdot \left[ \vec{n}_1 - \vec{n}_2 (\vec{n}_1 \cdot \vec{n}_2) \right] \right. \\
\left. + \vec{n}_2(\gamma_1 - \gamma_2) \cdot \left[ \vec{n}_2 - \vec{n}_1 (\vec{n}_2 \cdot \vec{n}_1) \right] \right\} \tag{2.3}
\]

The various sources of errors are discussed by earlier workers (Smith 1963; Rao 1966; Narayanan 1973; Anandarao 1977). The principal error is due to cloud centres not coinciding from different observational sites. This error is obtained by determining the minimum perpendicular distance \((C_1C_2)\) between the lines \(C_1S_1\) and \(C_2S_2\):

\[
C_1C_2 = \begin{vmatrix}
\begin{array}{cccc}
1 & x_1 & x_2 & \cos \alpha_1 & \cos \alpha_2 \\
Y_1 & Y_2 & \cos \beta_1 & \cos \beta_2 \\
Z_1 & Z_2 & \cos \gamma_1 & \cos \gamma_2 \\
1 & 1 & 0 & 0
\end{array}
\end{vmatrix} \times K \tag{2.4}
\]
where \[ K = \left\{ \sum (\cos \beta \cos \gamma - \cos \beta \cos \gamma) \right\}^{1/2} \] (2.5)

Here \((X_1, Y_1, Z_1)\) and \((X_2, Y_2, Z_2)\) are the cartesian coordinates of the stations \(S_1\) and \(S_2\) respectively. The components of errors in each direction are evaluated from this vector. The errors in the position coordinates are translated into errors in velocities.

The other source of errors is due to the possibility of the identified centres not being the same in every pair of photographs taken at different times. The coordinates of these cloud points against time after the launch showed little scatter on plotting. Hence this error is usually neglected compared to the above mentioned error (equation 2.4).

2.4 **Determination of vertical velocities:**

After an initial free expansion phase the duration of which is normally depending on the altitude of release, the cloud attains into diffusive equilibrium with the surrounding atmosphere. Because of the weight ratio of the released atoms and the mean molecular weight of the surrounding atmosphere, the cloud sedimentates under the action of gravity (Rieger 1974). The difference between the observed motion of the cloud and the sedimentation velocity of the cloud is attributed to the ambient vertical motion (Rieger 1974). The sedimentation velocities of the clouds are determined by:
where $M_n$ and $M_a$ are the molecular weights of the released neutral atoms and those of the ambient atmosphere respectively. Here $D$ and $H$ represent the intermolecular diffusion coefficient of the released vapour and the scale height of the atmosphere respectively. The measured molecular diffusion coefficients and the inferred temperatures are used in determining the sedimentation velocities, thus accounting for the sedimentation effects in the determination of vertical velocities.

2.5 **Analysis procedure for the trail releases:**

The centre of the cloud can easily be identified as a common point for the blob releases. However in the case of the trail releases the method of identification of the common point on the clouds as photographed from different stations is difficult. Hence a modified procedure developed by Desai et al (1975) is used in the present analysis. The method of obtaining the azimuth and elevation of a point on the trail with respect to the star background remains the same as that described earlier. Approximate range values are assumed from one camera station $S_1$ for that point on the trail. The position coordinates of this point are transformed to the other station $S_2$ using a transformation matrix which depends upon the latitudes and longitudes of the triangulating stations. These transformed points are plotted in the azimuth and elevation plane as shown in the figure 2.3. The locus of the transformed points which happens to be a straight line for
different values of ranges assumed, crosses over the trail as seen from the other station $S_2$. The range corresponding to the crossover point is taken to be the slant range for the point chosen on the trail photographed from $S_1$. The same procedure is adopted for determining the position coordinates of different points on the entire photograph of the trail from $S_1$. This is counterchecked with the available photographs from a third station $S_3$. The position coordinates of the trail points at different times are then obtained from which the horizontal wind components are derived.

2.6 Determination of molecular diffusion:

Manring et al (1961), Golomb and MacLeod (1965) have dealt the mechanism of diffusion of the released chemicals in the ambient atmosphere. As the releases are usually of explosive type, the released atoms initially (i.e. within 20 secs.) move with very high radial velocities of the order of $1 \text{ km s}^{-1}$. After the initial expansion, the released cloud attains the ambient temperature and pressure. The further expansion of the cloud is due to molecular diffusion processes. The initial forced expansion followed by molecular diffusion of the clouds for various emission lines are shown in the figure 2.4 (Stoffregen et al 1971). Lloyd and Sheppard (1966) pointed out that the process governing the growth rate of the cloud diameter above 120 km is mainly due to molecular diffusion. In general the cloud released below about 100 km is distorted rapidly because of turbulence. The expansion velocity of the cloud in this region is due to eddy diffusion and is a complicated function of the atmospheric parameters. In the
Fig. 2.4: Typical intensity variation of three barium lines during the first minute after release (Stoffregen et al, 1971).
present investigation, only the molecular diffusion rates are studied.

Several investigators (Manring et al. 1961; Rees 1967; Lloyd and Sheppard 1966) have used different methods for the determination of molecular diffusion rates by measuring the expansion rate of the vapour release. Various methods of determining the diffusion coefficients and sources of errors are discussed by earlier workers (Narayanan 1973; Ranjan Gupta 1985). Desai and Narayanan (1970) developed a method for the determination of diffusion coefficients wherein, they had eliminated the errors due to the presence of bright sky background during twilight conditions. This method which involves the calibration of the photographic films is used in the present study. The calibration is done by exposing a standard wedge transparency for known exposure timings, before developing the films. The negative of the films containing the image of the wedge transparencies are scanned by a microphotodensitometer. Figure 2.5 depicts the calibration curve of the film wherein the photographic densities (p) versus the logarithm of the exposure (Intensity x time) are plotted. The slope of the linear portion is generally known as '1' of the film. During twilight conditions, the varying background contributions in each frames are to be eliminated to obtain correct diffusion rates. The cloud and its adjoining region (to correct for the background brightness), in the photographic films taken at different times, are scanned in two perpendicular directions by a micro-photodensitometer. The measured densities from the cloud and background regions are
EXPOSURE = INTENSITY X TIME
DENSITY = $\log_{10} \left( \frac{1}{\text{TRANSparency}} \right)$

$\gamma = \text{SLOPE} = 0.97$

Fig.2.5: Calibration curve of Kodak 2485 film used in Gudiwada camera station on 16th February, 1982.
converted into their corresponding intensities using the characteristic curves of films and the exposure times. Thus the brightness only due to the released clouds (after subtracting the background contribution in the brightness domain) versus the radial distances on the negative of the film are obtained. These radial distances are converted to actual distances of the cloud in space by multiplying with the ratio of the slant range of the cloud to the focal length of the camera lens. The triangulation method described earlier yields the slant range information. Hence the cloud brightness versus the actual radius of the cloud in space are evaluated at different times. As the molecular diffusion is isotropic, the brightness distribution is gaussian in shape. The radius at which the brightness corresponds to 1/e times the peak central value is determined as \( r_e \). The slope of the plot \( r_e \) versus time (t) is determined to give 4D where D is molecular diffusion coefficient (\( D_{12} \)).

These values correspond to the intermolecular diffusion of the released atoms through the ambient air. To obtain the diffusion coefficient of the ambient atmosphere (\( D_{11} \)), the measured coefficients (\( D_{12} \)) have to be multiplied by a factor in the following way.

\[
D_{11} = D_{12} \left( \frac{\sigma_{12}}{\sigma_{11}} \right)^2 \left( \frac{\mu_{12}}{\mu_{11}} \right)^{1/2}
\]

(2.7)

where \( \sigma \) and \( \mu \) are the mean collisional diameter and the reduced mass of the inter diffusing molecules. The subscripts '11' and '12' stand for the ambient atmospheric species and
the released species through the ambient atmosphere respectively. Since the experimental values of $\sigma$ are not available, they are assumed to be proportional to the cube root of molecular mass (Golomb and Maclaeod 1965).

Various sources of error in the determination of the effective radius ($r_e$) are principally due to the photographic grain size, non uniformity of film emulsion and signal to noise ratio of the image. Besides, the errors in determining the range as discussed earlier, along with the instrumental errors of the microdensitometer and camera are to be included. The estimations of these sources of errors were made following Narayanan (1973).

2.7 Neutral temperatures from Diffusion Profile:

Several investigators (Golomb et al 1967, 1968, 1969; Rees 1968, Rees et al 1969) have reported simultaneous measurements of diffusion coefficients and spectroscopically determined temperatures in the altitude region of 120 - 250 Km. Lloyd and Sheppard (1966) have discussed the determination of the temperature profile from the molecular diffusion profile. This method is heavily dependent on the model parameters used in it. Desai and Narayanan (1970) have developed a new procedure for the same and have verified their method by making use of the simultaneously measured profiles of both molecular diffusion and temperatures (Rees et al 1969). In the present study, the temperatures are derived from the diffusion profile using their procedure as discussed below.

The inter-diffusion of two dissimilar species (denoted by subscripts 1 and 2) is given by the expression (Hirschfelder
et al., 1954)

\[ D_{12} = \frac{2.628 \times 10^{-7}}{\rho \sigma_{12}^2} \left( \frac{T^3}{2f_{12}} \right)^{1/2} \]  

Here \( P \) and \( T \) are the pressure in atmosphere and temperature in kelvin. \( m_{12} \) is the reduced molecular weight given by \( \frac{m_1 m_2}{m_1 + m_2} \) where \( m_1 \) and \( m_2 \) are the molecular weight of species. \( \sigma_{12}^2 \) is the collisional cross-section and its temperature dependence is calculated from the intermolecular interaction. For an assumed analytical model of the intermolecular potential function of the values of \( \sigma_{12}^2 \) are obtained from tables given by Hirschfelder et al (1954).

Above 100 km, different molecular species undergo diffusive separation and consequently their number densities are distributed according to

\[ n_i = n_i^o \left( \frac{\frac{T_o}{T_h}} \right) \left[ \exp \left( - \int_{h_o}^{h} \frac{m_i g}{kT} dh \right) \right] \]  

\( T_o \) and \( T_h \) are the temperatures at heights \( h_o \) and \( h \) respectively and corresponding number densities are denoted by \( n_i^o \) and \( n_i \). Here the subscript 'i' denotes the different molecular species whose masses are denoted by \( m_i \).

Differentiation of equation (2.8) with respect to height and substituting (2.9),

\[ \frac{1}{D_{12}} \frac{dD_{12}}{dh} = \frac{g}{kT} \sum n_i^o m_i \exp \left[ \int_{h_o}^{h} \frac{-m_i g}{kT} dh \right] + \frac{\Sigma}{2} \frac{M_i}{M(M + M_i)} \frac{dM}{dh} \]

\[ \frac{dT}{dh} = \frac{3}{2T} \left( 1 - G(T) \right) \]  

\( \frac{1}{D_{12}} \frac{dD_{12}}{dh} = \frac{g}{kT} \sum n_i^o m_i \exp \left[ \int_{h_o}^{h} \frac{-m_i g}{kT} dh \right] + \frac{\Sigma}{2} \frac{M_i}{M(M + M_i)} \frac{dM}{dh} \]

\[ \frac{dT}{dh} = \frac{3}{2T} \left( 1 - G(T) \right) \]
where \( M' \) and \( M \) are molecular weights of vapour and the ambient atmospheric molecules respectively. The term \( G(T) \) takes into account the temperature variations of the collision cross section and is obtained from the tables given in Hirschfelder et al (1954). Temperatures are determined by integrating equations (2.9) and (2.10) simultaneously. Here the model atmospheric temperature and molecular weight preferably at the highest altitude are used as the initial values in the numerical integration. The integration is carried from higher to lower altitudes in steps of 1 km. The procedure simultaneously calculates the molecular weight. Thus the temperature profiles are derived from the measured diffusion profiles.

2.8 Temperature measurements by a Fabry-Perot Spectrometer:

A high resolution pressure scanned Fabry-Perot spectrometer was operated from one of the camera stations (Gudiwada) during the sodium trail vapour release experiment. By monitoring the Doppler broadening of the resonantly scattered sodium D1 line (\( \lambda_0 \)), the neutral temperatures were determined at three different altitudes. The instrumental profile was obtained using a Laser, just after the completion of the experiment. This instrumental profile was deconvolved from the observed profile to get the source profile. The
temperatures were derived from the full width at half maximum \((\Delta \lambda)\) of the source profile using the expression given in equation (2.11). The details of the instrument were discussed by Ranjan Gupta (1985). As the duration of the illumination of the cloud was limited, measurements were possible only at three altitudes which were determined from the look angles of spectrometer and the slant ranges obtained from the photographic triangulation.

\[
\Delta \lambda = 7.16 \times 10^{-7} \lambda_0 \frac{I}{M}
\]  

(2.11)

2.9 Measurements of electric fields from Ba-Sr releases:

The barium strontium (Ba-Sr) vapour payload technique was first developed in Max Planck Institute at Garching, Munich, by Foppl et al. (1965, 1967). The importance of this release is that the barium cloud gets ionised to yield the information about the ambient electric field. The strontium which is present as an impurity in the barium has a high efficiency of evaporation. Hence it gives intense resonance emission and remains neutral throughout the observational time (about 30 mts.) at the ionospheric altitudes. Hence the Ba-Sr releases give information on both winds and plasma motions simultaneously. This technique of releasing Ba-Sr was acquired by the Indian Scientists with the initial help from the Max Planck Institute and such payloads have been fabricated in the Pyrotechnique division of Vikram Sarabhai Space Centre, Trivandrum (Oommen et al., 1976).

The energy (96.3 K Cal/gm mole) from the following
exothermic reaction between the part of the barium with a suitable oxidising agent such as cupric oxide, is used to vaporise the rest of the barium and release it in the form of a blob.

\[(1 + n) \text{Ba} + \text{CuO} \rightarrow \text{BaO} + \text{Cu} + n\text{Ba}_\text{vapour} \quad (2\text{12})\]

Cupric oxide whose heat of formation is low (37.1 K cal/gm mole) is chosen as the oxidising agent to give more exothermic energy. The details of these payloads are discussed extensively by Foppl et al., (1965, 1967) and Oommen et al (1976).

The processes of ionisation of barium are extensively studied by earlier workers (Haser 1967; Stoffregen et al 1971). The thermal ionisation process of alkali metals was dealt by Pressman et al (1959). The calculated ion density by this process is less by a factor of $10^5$ than the observed density making it insignificant. This is confirmed by the absence of the formation of an ion cloud in the Earth's ultraviolet shadow region (Haser 1967). According to the calculation by Foppl et al (1965) the probability of photoionisation of barium from ground state is $5.1 \times 10^{-4}$ sec$^{-1}$. However, the observations revealed that sufficient ionisation took place in about 23 sec. Therefore, Haser (1967) concluded that the ionization must take place in a two step process: i) the resonance absorption ($5535\text{\AA}$) to populate the metastable state by spontaneous transition and ii) photoionization by absorption of solar UV radiations from the metastable state. Figure 2.6 depicts the typical spectral
Fig. 2.6: Energy-level diagrams of neutral (Ba I) and ionised (Ba II) barium (Haser 1967).
configuration of neutral(BaI) and ionised barium (BaII) clouds. It was experimentally found that many spectral lines could be observed from metastable levels 5d\(^1\)D and 5d\(^3\)D. These metastable levels are populated during the initial phase (~20 sec. after the release) by the high temperatures associated with the release and in the later phase by spontaneous transition. Those clouds which are released below 130 km get oxidised as the rate of oxidation is faster than that of the ionisation rate.

The Sr and Ba energy level diagrams are similar. There are two levels (4d\(^1\)D and 4d\(^3\)D) in Sr similar to Ba levels 5d\(^1\)D and 5d\(^3\)D. However, the 4d\(^1\)D state is not populated efficiently and the 4d\(^3\)D state is not a metastable state. Hence Sr clouds remain neutral throughout the observational time at the ionospheric altitudes.

Haerendel et al(1967) studied the motion of these artificial ion clouds and related it to the ambient electric field. They considered the ionised cloud as a homogenous cylinder of finite length and solved the equation of motion of these ion clouds with the following assumptions.

1) The rapid changes in the initial expansion phase (~20 sec. after the release) were neglected. 2) The atmospheric scale heights were assumed to be larger than the cloud extension in height and hence the effect of gravity was neglected. 3) The magnetic field(B) was taken to be homogenous and constant with time (4) The ion electron collisions were considerably less than the ion neutral collision. (5) The shears and temporal changes in the neutral winds(W\(_n\)) were
neglected. The following expression for the ionospheric electric field \( \mathbf{E} \) perpendicular to magnetic field was derived.

\[
\mathbf{E}_\perp = \frac{1+\alpha}{2} \frac{B}{c} \left[ \mathbf{e}_B \times \mathbf{v}_\perp + \frac{1}{k_i} \left( \mathbf{v}_\perp - \mathbf{w}_\perp \right) + \frac{\lambda^* - 1}{\lambda^* + 1} \mathbf{w}_\perp \times \mathbf{e}_B \right]
\]

where \( \lambda^* \) is the ratio of the integrated pederson conductivities inside the cloud, to the ambient ionosphere; \( k_i \) being the ratio of gyrofrequency of Ba\(^+\) to collisional frequency; \( \mathbf{e}_B \) being the unit vector along the magnetic field whose magnitude is \( B \); \( c \) is the velocity of light; \( \mathbf{v}_\perp \) and \( \mathbf{w}_\perp \) are the velocities of the ion and neutral clouds perpendicular to the magnetic field direction. Hence to obtain the values of the ambient electric field, the neutral winds, ambient electron density and density inside the clouds are required. Normally the quantities of Ba vapour released at different altitudes are to be taken in such a way that the value of \( \lambda^* \) reaches nearly unity well within the observational time. However, the amount of release must provide sufficient visibility in order to be photographed. About 500 gm of CuO + Ba mixture is to be released at lower altitudes of 150 - 160 km and progressively increased to 2.5 kg at 300 km altitude, because of higher diffusion rate at higher altitude. Table 2.3 gives the details of the amount of the mixture released in two flights. It is to be noted that the spectroscopically determined yield is only 6 to 7% of the mixture due to condensation in the nozzle of the release mechanism (Foppl et al 1967; Stoffregen et al 1971). The exact amount of releases
### Table 2.3

<table>
<thead>
<tr>
<th>Date</th>
<th>Blob No.</th>
<th>Amount of Ba + CuO mixture in gm.</th>
<th>Planned Km</th>
<th>Actual Km</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>28th March</td>
<td>I</td>
<td>500</td>
<td>100</td>
<td>81</td>
<td></td>
</tr>
<tr>
<td>1981</td>
<td>II</td>
<td>500</td>
<td>150</td>
<td>119</td>
<td>*Rocket under-performed</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>750</td>
<td>225</td>
<td>138</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>2000</td>
<td>260</td>
<td>194</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>2500</td>
<td>335</td>
<td>235</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3: Details of the amount of mixture used in both the flights 28th March 1981 and 16th Feb. 1982 along with the actual altitudes of release.
is dependent on the efficiency of the releasing mechanism. Hence the precise determination of the magnitude of the ion cloud movement is limited to the extent of the uncertainty in λ. This aspect of λ greater than unity will be discussed in Chapter 3 where results are presented. The errors in the determination of velocities of ion clouds due to triangulation are translated as the errors in the determination of electric fields.

2.10 Measurements of Electron density by Langmuir probe:

In order to measure the plasma parameters in the laboratory discharge, a probe was developed by Irwing Langmuir in 1926 and the subsequent probes developed using this principle are named after him. The output current is collected from a metallic sensor by applying an appropriate voltage to it and exposing it into the medium of interest. Depending upon the operating voltage of the sensor in the current-voltage characteristic of the probe, the plasma parameters such as electron and ion densities and electron temperatures are determined. This technique has been successfully used by several groups (Ichimiya et al 1960; Spencer et al 1962; Smith 1964; Brace and Spencer 1964) to study the ionospheric plasma parameters. A modified version of the LP system which works on a single floating battery was designed and developed in the Physical Research Laboratory (Prakash and Subbaraya, 1967). This design facilitates the reduction of internal leakage current and permits more thorough prelaunch checkouts. This probe has been used in different rocket flights by applying a suitable operating voltage to the sensor with respect to the
body of the rocket. Complete details about the system (Gupta 1970; Sinha 1976; Subbaraya et al., 1983) and unique measurements obtained using these probes (Prakash et al., 1971) are available in literature. In the present study, the data obtained using this probe from the rocket flights conducted from Sriharikota are used in the present investigation on ESF.

The probe can be operated at the same potential of the ambient plasma (usually negative) where the current collected is entirely due to thermal motions of the charged particles. Since the average thermal motion of the electrons are much larger than those of ions (due to the inertia) the probe at the plasma potential can be used to measure electron densities if the electron temperature is known and vice versa. The probe can also be operated at large negative potential, or slightly retarding but linearly varying and/or accelerating potentials with respect to the medium to measure ion density, or electron temperature and/or electron density respectively. In the present study the probe was operated in the accelerating potential regime. The voltage of the sensor was kept at 4 volts with respects to body of the rocket. It was operated in a fixed bias mode and hence the entire data were used for the determination of electron density and the irregularities in it.

In this regime the output current depends upon the shape of the sensor. An ogive shaped sensor at the tip of the rocket nose was used. The effective area of cross section of the above shaped sensor viewed from any direction is the same.
Measurements of electron density with such a shaped sensor do not depend on the aspect of the vehicle (Smith 1969). The sensor is made up of an electrical conductor (stainless steel) which can also withstand the heating due to aerodynamical effects. In order to measure electron density in the plasma the size of the sensor must be less than that of the Debye length. The probe used in this study was of 2.5 cm diameter, and the perpendicular distance between the tip and the base of ogive shape is also 2.5 cm. A guard electrode made up of stainless steel was used to render electric fields near the sensor normal to its surface and hence used as an electrical insulator between the sensor and the rest of the system. Two insulating materials were provided, one between the guard electrode and sensor and the other between the guard electrode and the rest of the rocket body. When the probe collects one type of charge the reference electrode collects the opposite type of charge. Here, the body of the rocket was used as the reference electrode whose area was much larger than the area of the sensor which ensured a stable reference. The probe is useful only above 80 km where the electrons are captured before collision. The probe can be considered to be at rest, even with a typical velocity of the rocket of few hundred meters to about a kilometer per sec., compared to the thermal velocities of the electrons which is of the order of 100 km per sec.

The probe described above, mounted on a rocket body along with proper electronics measured the electron current which was converted into analog voltage. The basic data telemetered
back to ground were recorded on magnetic tapes and photographic charts.

The output voltages are proportional to electron densities. The constant of proportionality is established on the basis of intercomparison with plasma resonance probe and ground based ionosonde carried out on several occasion from Thumba. The uncertainties in the absolute densities and the relative changes are estimated to be 15% and 5% respectively.

2.11 Ion Mass Spectrometer:

A Mass spectrometer is a system consisting of number of elements (ion source, analyser, detector and Vacuum system) designed to carry out the determination of mass charge ratio along with their intensities. The mass-charge ratio enables to identify the species, while the intensities enable to determine the abundance of the species. In the upper atmospheric ion composition studies, the ion source and the Vacuum system are provided by the atmosphere itself (above 100 km). While making the neutral measurements, the ion source is to be incorporated along with the system. The mass spectrometers are classified into static and dynamic type of instruments. In the first type, the mass analysis is accomplished by static fields (electric and/or magnetic fields). The momentum and energy dispersion properties are used for the mass separation. In dynamic type, the mass analysis is accomplished by time varying fields or ion movement. The basic principle of mass separation in these types of instruments is the time dispersion of the ion motion.
There are several static and dynamic types of instruments. Only a few instruments have been successfully used for upper atmospheric studies, while the rest of instruments being more suitable to ground-based laboratory studies. The instrument chosen for the upper atmospheric studies should in general satisfy the following criterion: light weight, rugged, high current efficiency, large collecting area, repeatability and simplicity. The dynamic instruments satisfy these criterion and have found extensive usage as rocket and satellite payloads. One such dynamic mass spectrometers namely Bennett type radio frequency mass spectrometer has been built in PRL for measuring upper atmospheric composition (Shirke et al 1977; Sridharan 1981, 1983). In the present investigation, in order to measure the ion composition, a three stage Bennett radio frequency mass spectrometer was flown along with LP payload on both occasions. The principle of this mass spectrometer is briefly discussed in the following paragraph.

When the mass spectrometer is exposed to the atmosphere, the ambient ions pass through a fixed voltage before entering into a three stage resonance accelerator. Each stage consists of three grids and to the middle one in each case an rf potential is applied. As the acceleration experienced by an ion in each stage depends upon its velocity and phase with which it enters, the three stages are placed such that ions with one particular initial velocity (which depends on the mass) and phase experience more acceleration than do the others. As the ions pass through the three stage resonance accelerator, some will gain energy from and some will lose
energy to the rf field. A stopping potential adjusted to be close to the maximum energy gain derived from the rf is applied before the collector plate, so that only those ions which have gained near maximum energy are collected. Thus, the mass selection is achieved in this instrument. By varying the d-c accelerating voltage in the form of a linear sweep at the rate of 1 scan/sec the instrument is operated in a spectrometer mode.

The ion mass spectrometer used in the present study is represented schematically in figure 2.7. \( G_1 \) and \( G_2 \) are ion accelerating grids and are given potential of the order \(-8\)V and \(-80\)V respectively. This ensures fairly uniform energy distribution of the ambient ions. '\( G_3 \)' is the first grid in the first stage of the analyser to which a dc accelerating voltage, in the form of a sweep is applied. The repetition rate of the sweep being 1.2 to 1.5 sec (-80 to -500 volts). To the centre grid is applied a radio frequency of 5 MHz with a peak to peak amplitude of 10 volts superposed over the dc sweep. The distance in terms of rf cycle between the centre grid of the first stage to that of the second stage is 7 cycles while the third stage separated by 5 cycles distance from the second stage. The integral numbers between stages are so selected as to avoid any appreciable overlap of the harmonic peaks apart from the central resonant peak. In order to make the drift space equipotential the first grid \((G_6)\) of the second stage is connected to \(G_5\) of the first stage. Similarly the grids of second stage \((G_8)\) is connected with \(G_9\) of the third stage. Succeeding the third stage, a set of
Fig.2.7: Schematic representation of a 3-stage Bennett mass spectrometer along with the associated electronic blocks (Sridharan 1983).
stopping potential grids are provided. Three such grids ($G_{12}$, $G_{13}$ and $G_{14}$) kept at the same potential (+30V) enable a very sharp cutoff. This is followed by a suppressor grid (-550V) and a Faraday Cage collector. The collector plate is kept in a cage completely shielded and floating. The plate is well insulated from the surrounding cage with the insulation resistance of $>10^{12}$. The whole structure is kept in a stainless steel enclosure and all the electrode leads are brought out by suitable vacuum feed through. The grid rings are made up of stainless steel to which very well stretched gold plated tungsten mesh (50 x 50), is spot welded. The optical transparency of the grid is well over 90%. The grid thus prepared provides a good approximation for an equipotential surface. The spectrometer had a resolving power of 20. Usually the signal amplitudes due to various ionic constituents are summed up and normalised to the Langmuir probe electron densities ($\sum i N_i = N_e$) in order to obtain the absolute ion densities.

Unfortunately no useful data on ion composition could be obtained in both the flights due to some technical problems.