CHAPTER 2

INSTRUMENTATION AND OBSERVATION

This chapter describes the instrumentation used for the observations in the present work. The Instrumentation involved a) installing a 14 inch telescope and setting up a mini-observatory at Gurushikhar Mt. Abu, India and b) designing, fabricating and testing of the two high resolution Fabry-Perot Spectrometers (FPS) used respectively in imaging and scanning modes. Most of the observation were carried out from Gurushikhar using the imaging Fabry-Perot system. The 1 meter telescope of Vainu Bappu Observatory, Kavalur, S. India was used with the piezo-electrically scanning FPS to obtain the line profiles of certain cometary emissions during the few nights of allotted telescope time in April 1986.

2.1 Selection of the parameters of Fabry-Perot Spectrometers

A Comet is an extended object with the emission lines and bands embedded in a strong continuum. A particular advantage of the Fabry-Perot system is its ability to discriminate the line and continuum sharply. Combined with its high light gathering power or etendue, it is thus a very
useful and powerful instrument for studying comets. The present instrumentation is optimized for both imaging in the cometary emissions with an intensifier camera.

2.1.1 Flux collecting power(L)

The flux collecting power, light gathering power or luminosity or etendue "L" of a spectrometer is defined as

\[ L = \epsilon A \Omega \]

where \( \epsilon \) = transmission factor, \( A \) = area of the dispersing element, \( \Omega \) = acceptance solid angle of the spectrometer. Since comet is an extended object, increasing \( \Omega \) would result in higher \( L \) upto the angular extent of the comet. Jacquinot (1954, 1960) showed that for each class of spectrometers the product \( L \times R \) is a constant, where \( R \) is the resolving power of the spectrometer. For an interferometric device like a Fabry-Perot which works on the principle of division of amplitude, possessing a circular symmetry, \( L \) is higher by a factor of 30 to 100 compared to grating spectrometer and 300 to 1500 compared to prism devices (Meaburn 1976). Since \( A \) is nearly the same for different types of spectrometers, for a given resolving power an F.P. can collect light over a wider solid angle; and hence it is advantageous to use for observing an extended object.

2.1.2 Choice of emission lines

The choice of emission lines for the present study and
suitable filters are based on two criteria.

(a) One of the major aims was to study the kinematics of the plasma and neutrals in the Coma and tail by measuring the Doppler shifts. Guided by the previous work of Huppler et al (1975) one of the lines selected was at Hα 6563 Å in the wings of which H₂O⁺ rotational line feature (0, 7, 0) is present. The [01] line at 6300 Å was also selected to study the neutrals, since oxygen is one of the important water group atoms in the coma. These lines have less crowded spectra in comparison to other emission lines of H and O and are suitable for a study with a Fabry-Perot. They were also the emissions for which narrow band filters were readily available. Study of these lines would also help to understand the nature of the parents of H & O.

The C₂ (0-0) Swan band at 5165 Å is uncontaminated by the emission from NH₂ unlike at other visible wavebands. Hence it was decided to use this band to obtain the FP interferogram for C₂.

Since the cometary spectra is rich in emission lines and bands all over the visible spectrum, it is necessary to use narrow band pre-filters to avoid the inter order overlapping. Proper choice of free spectral range (FSR) is also a crucial aspect, which will be discussed in chapter 4. Table 2.1a gives the details of the narrow band filters used for the interferometric work.
### TABLE 2.1a

**Characteristics of Narrow Band Interference Filters**

<table>
<thead>
<tr>
<th>Emission</th>
<th>λ (\text{A}^\circ)</th>
<th>(\Delta \lambda \text{A}^\circ)</th>
<th>Peak Trans (%)</th>
<th>Size (diameter)</th>
<th>Temperature coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>6563 at 20°C</td>
<td>5</td>
<td>40</td>
<td>50 mm</td>
<td>0.15 (\text{A}^\circ/\circ)C size towards red</td>
</tr>
<tr>
<td>[O I]</td>
<td>6300 at 20°C</td>
<td>3</td>
<td>40</td>
<td>50 mm</td>
<td>&quot;</td>
</tr>
<tr>
<td>Na</td>
<td>5890</td>
<td>30</td>
<td>40</td>
<td>50 mm</td>
<td>&quot;</td>
</tr>
</tbody>
</table>
(b) For obtaining the cometary images in several emission and continuum wave bands a number of interference filters were selected to isolate the spectral features. These relatively broad band filters were procured from the International Halley Watch (IHW). Table 2.1b gives the detailed characteristics of these filters.

Figure 2.1 gives a typical cometary spectrum and the filter bandwidths used in the present work.

2.1.3 The exposure time:

The near nucleus images of Comet Halley in white light, Kodak Wratten filters and IHW filters were obtained with short exposures of $< 1^s - 3^m$. The short exposures of this type have the advantage of removing the smear due to the internal motion of cometary material. Typical exposures were

White light $< 10^s$
Wratten filters $< 30^s$
IHW filters $< 2^m$

It is to be noted that the relatively small exposure times on the comet was made possible mainly due to the use of an image intensifier with a quoted gain $\sim 30,000$. 
TABLE 2.1 b

Characteristics of IHW filters

<table>
<thead>
<tr>
<th>Emission</th>
<th>$\lambda$</th>
<th>$\Delta \lambda$</th>
<th>Peak Trans (%)</th>
<th>size (diameter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CN</td>
<td>3874</td>
<td>50</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>$C_3$</td>
<td>4060</td>
<td>73</td>
<td>44.5</td>
<td>25</td>
</tr>
<tr>
<td>$C^+$</td>
<td>4260</td>
<td>70</td>
<td>42</td>
<td>25</td>
</tr>
<tr>
<td>Cont.</td>
<td>4850</td>
<td>65</td>
<td>70</td>
<td>25</td>
</tr>
<tr>
<td>$C_2$</td>
<td>5135</td>
<td>90</td>
<td>61</td>
<td>25</td>
</tr>
<tr>
<td>Cont.</td>
<td>6840</td>
<td>98</td>
<td>74</td>
<td>25</td>
</tr>
<tr>
<td>$H_2O^+$</td>
<td>7000</td>
<td>175</td>
<td>77</td>
<td>25</td>
</tr>
</tbody>
</table>
Figure 2.1 A typical cometary spectrum. On the top, indicated the band widths of the filters used.
2.2 Fabry-Perot Spectrometers

A number of good books and reviews are available on Fabry-Perot spectrometers, the most recent being by G. Hernandez (1986). The practical use of the device in interferogram mode and scanning mode are nicely described by T. Chandrasekhar (1982) and K.C. Sahu (1985). Apart from several other reviews by Vaughan (1967), Meaburn (1970) and others, J.N. Desai (1984) summarizes the use of F.P. Spectroscopy in studying various aspects of space science. Here a few basic equations, useful for the present discussion will be given.

2.2.1 The basic equations:

A F-P etalon is essentially a pair of optical flat $\lambda/200$ fused silica plates, held parallelly (~ $\lambda/100$) at a distance $t$. To avoid the absorption loss, the facing surfaces of the plates are coated with high reflectivity (~ 95%) multilayer dielectric coating. The transmission profile of an ideal F-P is described by Airy function (a function of transmission light of wavelength $\lambda$, through a F-P etalon).

\[ I = I_0 \left( \frac{T}{1-R} \right)^2 \left( 1 + \frac{4 \pi}{(1-R)^2} \frac{\sin^2 \theta/2}{\Delta} \right) \quad \cdots 2.2 \]

where \( \Delta = \frac{2\pi}{\lambda} \left[ 2 \mu \frac{t \cos \theta}{\lambda} - 2\pi/\lambda \right] \quad \cdots 2.3 \]


T and R = Transmission and Reflectivities of etalon flats.
r = Phase change on reflection.
\( n \) = Refractive index of the medium between the plates.
\( \Theta \) = Angle of incidence.
\( \lambda \) = Wavelength of incident light.

Since \( r \) is negligible for visual wavelengths, it follows from above equations that the Airy function peaks when,

\[
2 \mu t \cos \Theta = n \lambda
\]

...2.4

where \( n \) is an integer called the order number. This shows that the wavelength separation between the two successive orders of a given line can be expressed as

\[
\Delta \lambda = \frac{\lambda^2}{2 \mu t}
\]

...2.5

\( \Delta \lambda \) is called free spectral range (FSR). The full width at half maximum of the Airy function (2.2) is known as the resolution limit and given as,

\[
\delta \lambda = \frac{\lambda^2 (1 - R)}{2 \mu t \pi \sqrt{R}}
\]

...2.6

Where \( \frac{\pi \sqrt{R}}{1 - R} (= N_R) \) is called the reflective finesse.

Hence for the higher finesse higher the resolution of the instrument. In actual practice, however, the effective finesse is decided not only by the reflectivity of the plates but
also from several other sources as described in the next section.

2.2.2 Instrumental broadening:

The instrumental profile is the convolution of five basic functions i.e. Airy (AI), spherical plate defect (PD), Misalignment (MI), Microsmoothness (MS) and aperture (AP) and expressed as,

\[ I = AI \ast PD \ast MI \ast MS \ast AP \]
(* symbol for convolution)

The resultant width becomes more than expected from eqn. (2.6) due to the deterioration of finesse by several factors listed above. The nature of these functions are described in detail by Hernandez (1986). The detailed derivation of these functions and in particular the misalignment function is summarized by Ranjan Gupta (1985). A brief summary of constructing the synthetic line profile is given in the appendix 2.1. Table 2.2 summarizes the contribution of different functions towards the finesse of the instrument. The synthetic profiles by convolving these functions were carried out by the author with the parameters of the spectrometer and given in section 3 and 4.

2.3 Imaging Fabry-Perot Spectrometer
### TABLE 2.2
Five Basic Functions Contributing to the Instrumental Broadening

<table>
<thead>
<tr>
<th>Source</th>
<th>Function</th>
<th>Width</th>
<th>Finesse</th>
<th>Note</th>
</tr>
</thead>
</table>
| Microscopic flatness        | Gaussian       | $\frac{\Delta \lambda}{M} / 4.7$ | $MG/4.7$    | $\lambda/\lambda_{MG}$=
| imperfection                |                |                          |             | surface defect            |
| Spherical plate defect      | rectangular    | $\frac{\Delta \lambda}{Ms/2}$ | $MS/2$      | $\lambda/Ms$ = Plate defect |
| Misalignment                | Inverted       | $\frac{\Delta \lambda}{MP/\sqrt{N}}$ | $MP/\sqrt{N}$ | $\lambda/MP$ = departure from parallelism |
| parabola                    |                |                          |             |                           |
| Aperture                    | rectangular    | $\frac{\lambda}{2 \pi} \frac{\Omega}{n \pi}$ | $2 \pi n \Omega$ | $\Omega$=Solid angle subtended by the aperture at the etalon |
| Airy                        | Airy           | $\frac{\Delta \lambda}{NR}$ | $NR= \frac{R+R}{1-R}$ | $R$=Reflectivity of the etalon plates |
Each point on the FP fringe corresponds to a definite direction of incident flux and hence to a definite location on the object under study. Hence an interferogram is an imaging spectra of the source. This property of the FP has been extensively used in various fields such as for studying the dynamics of Solar Corona (T. Chandrasekhar et al., 1981), determination of the velocity field and turbulent structure of gaseous nebula (Deharveng 1973) and gas dynamics in galaxies (Vaucouleurs et al., 1980).

2.3.1 Mode selection:

The basic principle involved in this method is the "Spatial Scanning" consisting of varying the order number (n) of eq. 2.4 by changing the value of the angle $\theta$ for a given wavelength $\lambda$. On each fringe of a given order, $\theta$ can be varied in small increments to scan in $\lambda$, thereby constructing the line profile.

In general there are two ways of accomplishing i.e. (1) varying the effective radius of an angular aperture and its width in a controlled manner in the image plane of the etalon fringe or (2) using a 2-dimensional detector array for recording the fringe pattern. A detailed account of the various modes of operation is described by Hernandez (1986). The advent of two-dimensional imaging solid-state detector arrays have made it possible to use the later method widely. In practice this is realised in two modes, namely
telecentric or non-classical and classical. The telecentric mode has the advantages of perfect smearing over a selected area of the source, thereby removing the contribution due to sharp intensity gradients. Telecentric mode however sacrifices spatial resolution, which can be retrieved to a limited extent by using insect eye camera lens. The other advantage of this method is the improvement of finesse, because of using a small area of FP, which may not be so effective due to the availability of high quality etalons. However, it can be seen from eqn 2.1 that the disadvantage of this method is the low effective etandue (because of using smaller part of the etalon). The spatial resolution is also sacrificed.

In the present case the intensity gradient in the coma is not a serious problem. The more important problem is correctly assessing the contribution of the continuum and correcting for it. The columnar intensity due to neutral species such as C₂ is expected to follow a power law i.e. \( r^{-1} \). H α or [OI] emissions also do not have sharp gradients in the coma. Hence the spatial smearing has no advantage in this case. It would be advantageous to obtain spatially resolved information. The available finesse of the etalon was sufficient for the present work. Therefore it was decided to use the classical mode of obtaining the interferograms.

2.3.2 The Etalon
The alignment and the spacing control between the two plates of the etalon are achieved by the optical contacting technique. This method has the advantage of stability (required under exacting field conditions) over several other methods employing the mechanical stress as described by Hernandez (1986). Though this is a passive method of control, usually very high stability is achieved throughout the operation.

For the present work the entire visible range from 4500 Å to 6700 Å was covered by using two airspaced optically controlled etalons. The etalon parameters are given in table 2.3. Each of the two etalons is mounted in a ring that can be rotated to offset the fringe centre from the optic axis of the system. The off-axis mode is useful in varying the spectro-spatial resolution across the extended source. For instance, in this mode a single fringe can be positioned over most of a comet tail to provide spatially continuous line profiles.

2.3.3 The image intensifier:

Since exposures as short as possible were derived to avoid the smearing due the internal motion of cometary material, the problems of telescope drive and rapidly varying sky conditions (while working at the zenith angles
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Green etalon</th>
<th>Red etalon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral coverage</td>
<td>4500 Å to 5500 Å</td>
<td>5700 Å to 6700 Å</td>
</tr>
<tr>
<td>Spacer value</td>
<td>300 µm</td>
<td>1000 µm</td>
</tr>
<tr>
<td>Usable aperture</td>
<td>40 mm</td>
<td>24 mm</td>
</tr>
<tr>
<td>Free spectral range</td>
<td>4.17 Å (at λ = 5000 Å)</td>
<td>2.15 Å (at λ = 6563 Å)</td>
</tr>
<tr>
<td>Effective finesse</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>Effective instrumental width</td>
<td>0.30 Å</td>
<td>0.11 Å</td>
</tr>
<tr>
<td>Plate flatness</td>
<td>λ/100</td>
<td>λ/100</td>
</tr>
</tbody>
</table>
close to $90^\circ$), a high gain second generation (Gen II) image intensifier was used. The working principle of this device is simple. The optical image is converted into an electron image using a S-20 type photocathode, which is then passed through a micro-channel plate producing an intensified electron image. This electron image falls on a phosphor screen of p39 type (having long time constant, advantages for longer integration) to produce an optical image with again of $\sim 3 \times 10^4$. A "zero-thickness" optical fibre glass plate is used to transfer the image from phosphor screen to any detector (a photographic film in the present case). The Gen II image intensifiers have the ergonomic advantage over earlier generations, due to the use of microchannel plates and the built in power supply, which is desirable for the field experiments.

The scale size at the phosphor end of the intensifier was determined by measuring the separation of a binary system of stars ("Mizar" in Ursa Major in the present case) with known angular separation. The calibration interferograms were also used to determine the magnification. It was established that the magnification of the image intensifier was 1.2. The phosphor background was seen to be uniform over more than 95% of the area in the image plane. The essential parameters of the image intensifier used are listed in table 2.4.

The image intensifier was found to perform
<table>
<thead>
<tr>
<th>Image intensifier parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective diameter of multialkali photocathode</td>
</tr>
<tr>
<td>Spectral range</td>
</tr>
<tr>
<td>Wavelength of peak response</td>
</tr>
<tr>
<td>Limiting spatial resolution at center at 5% MTF level</td>
</tr>
<tr>
<td>Maximum image distortion near edge compared to center</td>
</tr>
<tr>
<td>Equivalent background input minimum detectable flux</td>
</tr>
<tr>
<td>Gain (variable by potentiometric control)</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>External power supply</td>
</tr>
</tbody>
</table>
satisfactorily under field conditions. It was however found to exhibit small spots distributed over the image plane, which can be readily recognized. At times flashes of light were also noticed near the edges, which did not significantly impair the observations.

2.3.4 The optical layout:

Figure 2.2 is a schematic of the interferometer. The light from the comet was collected by the telescope mirror P and S. The collimation of the image formed at the Cassegrain focus of the telescope was accomplished by an 80 mm focal length f/1.2 special camera lens L. It is convenient and accurate to carry out the collimation adjustment with just the front end of the instrument coupled to the telescope and with a bright star, e.g. Sirius as the source. The adjustment was found to be stable over a period of several weeks with the instrument coupled to the telescope. The collimated light passed through the FP etalon E and filter F (several filters as given in Table 2.1a) focused by a 50 mm focal length f/1.2 Nikkor camera lens O onto the photocathode of the image intensifier.

2.3.5 The camera and data recording:

To record the image, the film plane has to be flush with the fiber optic output plate. This arrangement poses a few problems since commercially available 35 mm cameras are
Figure 2.2. Schematic of the imaging Fabry-Perot interferometer optics.

S = Secondary mirror of the telescope
P = Primary mirror of the telescope
V = Visual port  M = Flip mirror assembly
A = Entrance aperture  L = Collimator lens
E = Fabry-Perot etalon  F = Narrow band filter
O = Camera lens  I = Image intensifier
B = Battery supply  C = Camera.
usually single lens reflex (SLR), in which the film plane is inaccessible from the front end. Reimaging the phosphor output onto the film by a short focus lens is difficult and involves loss of light. This problem was overcome by modifying an old 35 mm non-SLR camera. Two slots were made on the front side of the camera body to bring out the film and make it slide smoothly over a velvet-lined metallic projection. Thus when fitted to the image intensifier, the film remains in contact with the fiber optic window, being pressed by the projection. A pin and slot arrangement made for attaching the camera to the intensifier ensures easy coupling in the dark. In operation, the phosphor screen is viewed by a high power eye-piece and the star field is focussed. The eye-piece is then removed and the camera is coupled to the intensifier. The film movement is reasonably smooth, and no serious problem of film scratch was encountered.

2.3.6 The film and calibration:

A high contrast, microscopic grain (~ 320 lines/mm with D 19 developer) Kodak's technical pan 2415 film in 35 mm format, with extended red sensitivity was used in proximity contact with the phosphor screen of intensifier to record the comet images and interferograms. We have obtained the image of Crab nebula (M1) which is of 8.6 magnitude with the exposure of 30 sec.
However, feeble night airglow feature at 6300[Å] could be recorded only on a faster emulsion Kodak 2485. For comet work 2415 emulsion was found to be satisfactory.

For converting the photographic densities to relative intensity, a step wedge (with 7 steps) impression was invariably taken on each film using a wedge sensitometer shown in figure 2.3. The calibration curve was constructed by measuring the photographic density steps in the wedge impressed on the film and \((D = - \log_{10} T)\) and the corresponding diffuse densities \((\log_{10} E)\), both measured in the laboratory with a microdensitometer. The typical characteristics curves are given in the following chapters. The film is subject to low intensity reciprocity failure. This effect was not serious, wherever the morphological structures were considered. However for intensity estimation and profile width measurements, proper care has been taken as will be discussed in later chapters.

For the spectroscopic calibrations the He-Ne (6328 Å) Na (5890 and 5896 Å) and Hg (5461 Å) interferograms were taken on each observing session. Fig.8 gives a typical laser interferogram. The analysis and results of the calibration interferogram is given in sec 3.8.

2.3.7 Interferometric and imaging mode of operation:

This instrument was used both in interferometric and
Figure 2.3. Schematic diagram of the wedge sensitometer.
imaging mode. The interferometric mode was realised with the optical scheme shown in Fig. 2.2. By removing the narrow band filter, the same instrument could be used in imaging mode. On removing the narrow band filter, the interferometer samples the spectrum every free spectral range, \( \sim 2 \text{ A}^\circ \) for red etalon and \( \sim 4 \text{ A}^\circ \) for the green etalon, at each point of the extended object, within the spectral range of the etalon. It then acts as a comb filter, and the net effect is a nearly white light image. There is of course large flux loss due to etalon reflection \( \sim 90\% \) but with the intensifier this did not pose a problem with broad band filters. The interferometric optics results in an effective f/no of \( f/7 \), hence reducing the exposure time by a factor of \( \sim 2.5 \) compared to the \( f/11 \) system. The image scale size and the field of view on the film were 67 arc sec/mm and 21 arc min in the plane of sky respectively.

At times, the image intensifier camera system was attached with a commercial telecompressor and filter slide assembly to obtain the comet images at higher f/Nos. In this case the image scale size and field of view were 83 arc sec/mm and 28 arc min respectively.

2.3.8 Performance of the instrument:

Fig. 2.4 show the laboratory assembly of the interferometer. The instrument weighs \( \sim 6 \text{ kg} \) and is \( \sim 66 \text{ cm} \) long. Fig 2.5 show the field assembly of the instrument with
Figure 2.4. The laboratory assembly of the imaging Fabry-Perot interferometer.
Figure 2.5: The imaging interferometer coupled to C-14 telescope at Gurushikhar, Mt. Abu.
the C-14 telescope. The off centered laser/spectral lamp fringe system were routinely taken (at times with superimposed comet images) for locating the fringe centre and defining the instrumental profile. Fig 2.6 a, b show the laser and Na lamp interferogram. The observed instrumental profile was obtained by scanning a typical region of the calibration interferogram and constructing a wavelength \( \lambda \) vs relative intensity plot.

The stability of the instrument was determined in the following way. Three laser fringes, the second in the beginning, one at the middle and the third at the end of the observing session, were selected (observation lasted for 8 months from October 1985 to May 1986). The difference between the radii of successive orders i.e.

\[
(R^2_{n2} - R^2_{n1}) = 2F^2\lambda/2\mu t
\]

was found to be constant over this long period with a maximum variation of +5 \( \mu \) m from the quoted value, within the measurement errors. This implies \( \mu t \) was stable upto 2% all through the observations. The slight variation can be expected due to the change in \( \mu \) and \( t \). However for each night of observation \( \mu t \) was determined to use for analysing the data of that night, reducing further the error due to this source.

The test results for the instrument were obtained on
the Orion nebula. Fig 2.7 show the interferogram taken in the \([\text{OIII}]\) line (5007/10 Å) and \(\text{H}\alpha (6563/5 \ \text{Å})\). The line profile analysis from these interferograms give the internal velocities consistent with the results obtained by earlier observations. An important point to note here is the case of operation and short exposure times needed for obtaining spatially resolved observations from a relatively faint nebulosity.

2.4. Servo Controlled Piezo-Electric Scanning Fabry-Perot Interferometer

In order to obtain the photoelectric line profiles of \([\text{OI}], \text{H}\alpha \text{ and } \text{H}_2\text{O}^+\) emissions, a central aperture scanning Fabry-Perot spectrometer with higher finesse and stability was developed. Unlike the instrument described in the earlier section, this instrument has active control of the gap and parallelism and the scanning is achieved at the etalon proper. Unlike the interferometer described above which was a light weight device specially designed to go with C 14 telescope the scanning F.P was designed to operate on a 1 meter Cassegrain telescope and was a much more sophisticated instrument.

2.4.1 Choice of the device

Cometary spectra is rich in closely spaced emission bands and lines throughout the visible spectrum. Moreover
Figure 2.7. Interferogram of Orion Nebula taken in [OIII] (5007/10 Å).
Figure 2. Interferogram of Orion Nebula taken in H-alpha (6563/5 Å).
the feable emissions are embedded in a strong continuum background. In the coma the continuum brightness varies as \(1/\mathcal{R}\), where \(\mathcal{R}\) is the projected distance from the nucleus. The emission lines such as [OI], \(\text{NH}_2\) etc. are confined very strongly towards the nuclear region. Therefore the noise introduced due to the tracking error or atmospheric scintillation is considerable in this case.

To obtain the line profiles under the conditions described above, it is essential to design a spectrometer with a large free spectral range, so that the two orders of a given line are well separated in wavelength and the filter band width need not be too narrow. Care also must be taken so that other orders of a different emission line do not overlap. To obtain a large spectral resolution with a wide free spectral range, it is necessary to have as high finesse as possible. Coadding several scans of the same spectral region can improve the S/N, which needs a highly stable system.

Since the optical finesse of the plates presently available are high (\(\sim \sqrt{\lambda}/200\)), the overall finesse of a etalon is limited by the control of alignment and spacing. Essentially there are two ways of achieving the alignment and spacing control, i.e., passive and active. In the passive method, after the alignment is reached, the etalon spacer and support combination are supposed to remain stable while the observations are on. In the optically contacted etalon used
in the previous instrument the passive alignment is maintained to a high degree of accuracy by the optical banding the FP plates at the time of manufacture. In optically contacted system at best parallelism upto $\lambda/20$ may be achieved. In the present case however an active method was employed. The active method can be realized in many ways. One way is to monitor of Brewstar white light or monochromatic light fringes formed by double passing the etalon at opposite ends of two perpendicular diameters from an auxiliary source. (Ramsey, 1962, 66). The fall in intensity level in the resulting fringe pattern in the measure of the degradation of the parallelism, which is restored by using the piezo-electric transducers. However this method has two drawbacks of introducing the light. The breakthrough in FP servo control came about with the development of capacitance micrometry by Hicks et al (1974) and Jones and Richards (1973) Piezo-electric transducers and capacitance micrometry have been used in the present instrument, which will be discussed in the section 4.4.

As it can be seen from equation 2.4 wavelength scanning is achieved by changing the optical spacing $\mu \cdot t$ of the etalon.

This can be realised by changing $\mu$ or $t$. Changing is achieved by changing the pressure of the chamber or using the electro-optic materials. The range of scanning is also limited in pressure scanned devices. For e.g. a spectral
range of \( \sim 4 \) \( \text{Å} \) at \( H \alpha \) would require a pressure variation of over 2 atmospheres in air. Hence a more stable method of "mechanical scanning" was employed in the present case. Again mechanical scanning can be accomplished by several techniques as described by Hernandez (1986). The most successful method to attain mechanical scanning has been associated with the use of the piezo-electric materials which is used in this device. In section 4.4, this will be discussed in detail.

2.4.2 Optical system:

The optical layout and the electronics of the piezo-electrically controlled central aperture scanning Fabry-Perot Spectrometer is shown schematically in Fig. 2.9. The f/13 Cassegrain beam from the telescope is focussed on to an aperture wheel has different entrance apertures ranging from 8" to 160" in the sky. A fixed aperture of \( \sim 50" \) was used during the observations. A flip mirror system is provided for viewing the star field to ensure that the object of interest is properly centred on the cross wire. A post focal plane flip mirror-eye piece system is also provided to actually verify that the object is on the optic axis and is properly focused. The same flip mirror arrangement also permits light from a He-Ne laser or a suitable calibration source like a low pressure, spectral lamp to be diverted into the system for evaluating the instrumental profile. The light from the telescope is
Figure 2.9. The optical layout and electronics of the piezo-electrically central aperture scanning Fabry-Perot spectrometer.
collimated, passed through the ET 85 etalon and focused by the camera lens onto the exit aperture. A Fabry lens then images the telescope primary onto the photomultiplier cathode and prevents small seeing effects or photocathode sensitivity variations from affecting the line profile. Just in front of the camera lens another flip mirror is provided to view the fringe system from a calibration source like the laser. This visual check on the alignment of the etalon was found to be very useful in the initial adjustments when the exact setting of electronic control were not known. The optical parameters are summarized in table 2.5.

2.4.3 Mechanical system:

The mechanical system consists of several aluminium tubes which are all threaded on the inside. The optical elements enclosed in brass or aluminium casings are mounted inside these tubes and can be moved along the threads for fine adjustment.

The etalon is housed in a thermocol padded enclosure so that it is not subject to rapid temperature variations. There is a provision for enclosing the interference filters in metallic rings and heating them by passing a current through a coil embedded in the rings. A well-calibrated thermistor serves as a temperature sensor which can be adjusted to a value to tune the filter for the peak of the spectral line under investigation. The temperature
TABLE 2.5

**Optical parameters**

Entrance apertures available: 8, 16, 32, 48, 64, 80 and 160 arc. sec. in the sky with f/13 beam and 1 m telescope.

<table>
<thead>
<tr>
<th>Collimating lens</th>
<th>Focal length (mm)</th>
<th>Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>290</td>
<td>50</td>
</tr>
<tr>
<td>Camera lens</td>
<td>180</td>
<td>57.5</td>
</tr>
<tr>
<td>Fabry lens</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

**Interference filter**

- Size: 50 mm diameter
- Peak wavelength: 6563 Å at 20°C
- Bandwidth (FWHM): 5 Å
- Temperature coefficient: 0.15 Å/°C rise towards red
- Peak transmission: 40%
coefficient of a multilayer dielectric filter is typically ~ 0.15 Å° shift towards red per degree centigrade rise of temperature. A typical 10°C range of the temperature control unit, employed in the present instrument, provides a wavelength tuning range of ~ 1.5 Å° which is generally adequate.

There is a special provision for permanently mounting and aligning a He-Ne laser through the first flip mirror for monitoring the performance of the piezo-electric system at any position of the telescope. In actual operation this arrangement was found to be very convenient in deriving the instrumental function.

The photomultiplier with its thermo-electric cooling unit and the preamplifier circuit is also attached to the main system. Four thick Aluminium rods (12 mm thick) run through the entire system providing the necessary structural strength at all orientations. The FP spectrometer system including the optics, coupling Cassegrain plate, PMT housing and connecting cables weighs 72 kg and is a little more than 1 metre in length. The laboratory assembly of the instrument along with the associated electronics is shown in Fig. 2.10. Fig. 2.11 show the instrument attached to 1 m telescope.

2.4.4 Electronics:
Figure 2. The piezo-electrically central aperture scanning Fabry-Perot spectrometer coupled to 1 meter f/13 telescope.
The electronics associated with the instrumentation consists of three parts, namely (1) Servo control of the etalon (2) Wavelength scanning (3) Control and the data acquisition system.

(1) Servo control of the etalon:

The servo system for maintaining the parallelism between the plates of the etalon consists of the sensors which are capacitance micrometers and piezo-electric transducers. The deviation from parallelism detected by micrometers are compensated by giving appropriate voltages to the piezo-transducers.

A. The Sensor:

In order to sense the deviation from the parallelism or the prescribed inter plate gap, very small displacements are to be detected. For example, in an FP system of finesse ~ 50, a scan over one FWHM of instrumental profile would require a plate movement of,

$$t \sim \frac{\lambda}{100}$$

If the tolerance in this movement is taken at 1% level then sensor should be able to detect changes $\sim \frac{\lambda}{10^4} \sim 0.5 \text{ Å}$
(at 5000 Å). The capacitance micrometers can detect length variations down to $10^{-12}$ m. Further in this method, no optical beam is needed and hence the problem of scattered light does not arise. (The rapid response of the sensor (~0.03 ms) and the fast loop response permits a fast servo-control of plate parallelism to be developed).

Although ET 85 system (which was used in the present device) is a commercial equipment supplied by Queensgate Inc. a brief description of the system here would not be out of place.

B. The piezo-electric etalon:

The characteristics of a piezo-electric etalon ET85 (Queensgate Instruments Inc) used by us is shown in table 2.6. The etalon has five capacitors $CX_1, CX_2, CY_1, CY_2$ and $CZ$ formed by evaporating gold pads on to one of the interferometer plates and fused silica pillars optically contacted to the etalon base plate. Parallelism information along X axis is obtained by comparing $CX_1$ with $CX_2$ and similarity along Y axis by comparing $CY_1$ with $CY_2$. $CZ$ measures the actual spacing of the etalon in comparison with a fixed reference capacitor. The error signal derived from the capacitor is fed to three piezo-electric transducer elements (PZT-5 H vernitron) with a net coefficient of 2.6 m/750 V for maintaining parallelism. The details of etalon mounting, derivation of the error signal
### TABLE 2.6

**Piezo-electric etalon**

<table>
<thead>
<tr>
<th>Type</th>
<th>ET 85 (Queensgate Instruments Inc).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td>5500 - 6700 Å</td>
</tr>
<tr>
<td>Usable Aperture</td>
<td>85 mm</td>
</tr>
<tr>
<td>Plate flatness</td>
<td>~ λ/100</td>
</tr>
<tr>
<td>Plate separation</td>
<td>496 ± 3 μm</td>
</tr>
<tr>
<td>Peak Reflectivity</td>
<td>95% at 6000 Å</td>
</tr>
<tr>
<td></td>
<td>93% at 6560 Å</td>
</tr>
<tr>
<td>Reflective finesse</td>
<td>43 at 6563 Å</td>
</tr>
<tr>
<td>Material</td>
<td>Spectrosil B</td>
</tr>
<tr>
<td>Free spectral range (F.S.R.)</td>
<td>4.0 Å (6300 Å)</td>
</tr>
</tbody>
</table>
and the control system (i.e. CS100) electronics are discussed by Hicks et al (1984).

(2) Scanning

The scanning of the ET-85 piezo-electric etalon is also governed by CS100 system. Scanning is achieved by applying the same step voltages to all the piezo stacks through the Z offset input of the CS100 unit. Z offset is a 12 bit binary number giving a range -2048 to +2047 units corresponding to the maximum separation of the etalon plates of +1 \( \mu \text{m} \). The smallest increment in the spacing is thus \( \sim 5 \text{ A}^\circ \) which results in a wavelength sampling interval of \( \delta \lambda = (\delta t/t)\lambda = \lambda/10^6 \). An eight step increment would result in a sampling interval of \( \sim 0.053 \text{ A}^\circ \) giving for one free spectral range at 6328 \( \text{A}^\circ \) 76.1 increments. The full range of \( \pm 1 \mu \text{m} \) of the plate separation would result in a scan range spanning 6 orders at H\( \alpha \). The Z input voltage and piezo expansion are not in general linearly related because of hysteresis and thermal drifts. The closed loop nature of the control system, however, takes care of the above effects to give a scan wherein the CS100 step is linear to better than 0.1% with the scan wavelength.

(3) Control

A 8085 based microcomputer was employed for controlling the scan and recording the data. Through an RS-232 interface
it transmits the sequence of numbers to CS100 unit for varying the plate separation. For a scan (at laser wavelength of 6328 Å) of one order, the etalon the plate gap should change by \( \frac{\lambda}{2} \approx 3164 \text{ Å} \sim 76.1 \) increments of 8 steps each - each wavelength increment corresponding to 0.053 Å. In order to analyze a profile, a scan range of 2 FSR locating two adjacent order peaks distinctly in the scan is necessary. At each increment the data can be integrated over a time which can be varied from 1-99s. In normal operation the specifications were for a scan range of over 3 FSR, a step size of 8 and an integration time of 1 or 2 seconds for increment. The total time of a scan for 1 second integration time is \( \sim 4 \) minutes.

(4) Photon detector:

The detection system incorporates a photon counting photomultiplier tube (EMI 9863B/350 type) whose characteristics are given in table 2.7. The photomultiplier is housed in a thermoelectrically cooled enclosure (FACT-50 MK chamber) which can reach a temperature of -20°C.

The output photoelectron pulses from the photomultiplier tube are amplified and subsequently discriminated against the background noise by an integrated hybrid charge sensitive preamplifier, discriminator and pulse shaper (Model A-101 PAD, Amptek Inc). The TTL output of the PAD circuit is compatible with any photon counter input.
<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>EMI-9863/350 photon counting type</td>
</tr>
<tr>
<td>Surface</td>
<td>S-20, 14 stages</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>(6300 %) ~ 7%</td>
</tr>
<tr>
<td>Effective aperture</td>
<td>9 mm</td>
</tr>
<tr>
<td>Dark counts</td>
<td>450 count/s (25°C)</td>
</tr>
<tr>
<td></td>
<td>&lt; 10 count/s (-15°C)</td>
</tr>
<tr>
<td>Photomultiplier gain</td>
<td>$2.7 \times 10^7$</td>
</tr>
</tbody>
</table>
(5) Recording

The photon counts and the step numbers which are proportional to the optical gap and hence the scan wavelength are continuously displayed on a computer terminal and also recorded through an interface on a dot matrix printer for hard copy. An X-Y plotter provides a useful analog version for visual check of the data being recorded.

2.4.5 Performance

The instrument has been fully assembled in the laboratory and tested. Fig. 2.1Q shows the Laboratory assembly of the instruments for testing. The instrument was used with 1 m telescope at Vainu Bappu Observatory, Kavalur for observing Comet Halley for 5 nights in April 1986.

Finesse: Figure 2.12 shows the profile of 5 basic functions described in 2.2 and their convolved resultant synthetic profile, superimposed with He-Ne laser profile at 6328 Å. The free spectral range of 4.04 Å is scanned in 76.1 steps. One resolution element (1 FWHM) is therefore 0.144 Å giving an effective finesse of 28. The effective finesse deduced theoretically is \( \approx 30 \) which shows that the system performance is optimum.
Figure 2.19. Instrumental profile of scanning Fabry-Perot spectrometer. Five basic functions contributing to the instrumental profile and the convoluted resultant function along with the laser profile.
Stability: The stability of the etalon and associated electronics was determined by taking laser calibration scans of the system several times during a night of observation. The departure of the laser peak from its original value is a measure of the stability. It was found that in a typical 6 hour period the maximum departure corresponds to ~2.5 elementary steps or 0.016 Å in wavelength at 6328 Å or a relative velocity resolution of 0.76 km/s. The line profiles of several standard astronomical objects such as Orion nebula, M8 and NGC 2440 were taken in order to check the instrumental performance. Fig. 2.13 gives the line profiles of Orion nebula and M8. The line width are consistent with the published results.

Owing to the limited time, (5 nights allotted) on the 1 meter telescope for observations and tests observations on Halley with the above spectrometer were somewhat limited. The [OI] and NH₂ profiles derived from these observations are discussed in detail in Chapter 4.

2.5. The Telescope at Gurushikhar

For most of the period, Halley observation were carried out with a 35 cm telescope from Gurushikhar Mt. Abu. Main feature of the telescope and site are described below.
Figure 2.13. Line profile of the standard astronomical objects obtained with the piezo-electrically scanning Fabry-Perot spectrometer.

a. Orion Nebula  
b. M8.
2.5.1 The Drive Corrector

The 35 mm aperture telescope was mounted on a special Gaussian equatorial mount (Byers Co Ltd) and housed in a makeshift enclosure during the 8 month period of Halley observations. Special care was taken to achieve the polar alignment precisely and balance the telescope with counter weights against the instrument. However the most serious problem with the commercial drive used on C-14 was gear periodic error which amounted to several tens of arcseconds in peak to peak amplitude. We devised a special corrector mechanism to overcome these errors. Employing a specially developed drive corrector (Ashok et al., 1987) the drive stability of the telescope was achieved to a level ~ 5" or better.

In principle the drive corrector senses the periodic error in phase by a suitably coupled four-quadrant potentiometer to the shaft of the erroring gear. The error voltage, so obtained is frequency converted and fed in antiphase to the drive motor. Fig. 2.14 schematically shows this method of error correction.

In practice a four-quadrant potentiometer has a continuous value of resistance from 0- to 5 K and back to 0- varying linearly with the rotation of 360°. By suitably biasing the potentiometer a triangular shaped error voltage $V_e$ was generated, the amplitude of which was
Figure 2.14 Schematic diagram of the drive corrector.
determined by the magnitude of the error. The amplitude $V_e$ formed one input to the summing amplifier while the mean tracking voltage $V_m$ derived from a potential divider network formed the other. The summing voltage was frequency converted at a rate of 10 KHZ/v. The varying output of V/F converter was suitably amplified to give 30 W power for the telescope's drive motor.

The observed peak-to-peak deviation from mean tracking rate was around 50" which was successfully brought down to about 5" (Fig. 2.15 a,b). However for comet observations, the error was slightly more, as long integration times were used. The average error, however, does not exceed ~ 20". Nevertheless, for analysis only those images were chosen, which had minimum tracking error (Judged from the star trails). Since for interferograms no spatial information can be obtained in the inter fringe gap, the spatial resolution is not stringent. Error due to these sources will be discussed in detail in the following chapters.

2.6. The Observing Sites

The observations were made mainly from Gurushikhar, Mt. Abu, India and for five nights at Vainu Bappu Observatory, Kavalur. Table 2.8 gives the geographical co-ordinates of these sites. In general the sky conditions were excellent at both places during the observations. On several occasions at Mt. Abu the Fabry-Perot interferograms were recorded in
Figure 2.15 Star trailing before (a) and after (b) the use of drive corrector.
### TABLE 2.8
Observing site details

<table>
<thead>
<tr>
<th></th>
<th>Kavalur</th>
<th>Gurushikhar (Mt. Abu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>+12° 34' 35&quot;</td>
<td>+24° 39'</td>
</tr>
<tr>
<td>Longitude</td>
<td>78° 49' 45&quot;E</td>
<td>72° 43' E</td>
</tr>
<tr>
<td>Altitude</td>
<td>725 m</td>
<td>1700 m</td>
</tr>
</tbody>
</table>
Na $D_1$ $D_2$ (5890,5896) lines with varied intensity as shown in Fig. 2.16. These fringes are associated with night airglow due to their extent and not with the comet.

2.7. The Observations and Data

The Comet P/Halley 1982i was first recorded by us on 16 Oct. 1985, when the comet was at 2.14 AU, with an estimated magnitude of $\sim 11$. Comparing the star field of Oct 15 and 16 the comet was unambiguously identified. Figure 2.17 a,b show the comet field on three successive days. Soon after recovering the comet the IHW filter photograph in $C_2$ (5140/90 Å) and blue continuum (4845/65 Å) were successively taken on Oct. 20, 1985 (Fig. 2.18 a,b). A complete set of photographs of Comet Halley in all the IHW filters on a single day is given in Fig. 2.19. The observations were continued upto 15 Jan. 1986 ($\gamma = 0.8$ AU) in the pre-perihelion period. In the post perihelion the observations were taken from 8 March 1986 ($\gamma = 0.82$ AU) till 7 May 1986 ($\gamma = 1.72$ AU).

Around 200 frames of good quality including 100 frames of white light images of the inner coma have been obtained. Six interferograms have been recorded. The statistics of the data is given in table 2.9.

Appendix 2.1
Construction of Instrumental Profile

The instrumental profile of a Fabry-Perot spectrometer is the convolution of five basic functions given in table 2.2. In order to construct the instrumental profile for the instruments used in the present work the individual functions were generated by a FORTRAN programme through the computer with the manufacturer's specified data on the etalon. Since the parallelism between the two plates was achieved by adjusting the voltages in piezo-electric transducers and minimizing the "breathing effect" of the casing fringes, the half width of the profile due to misalignment was kept variable. Varying misalignment was function several convoluted instrumental functions were generated and the best fit with the observed laser profile was chosen. The resultant instrumental width was found to be $=0.14 \, \AA^0$ and the finesse 20. The effective finesse deduced theoretically for the scanning Fabry-Perot spectrometers is $\sim 30$ which shows that the system performance is optimum. Similar exercise was carried out for the imaging Fabry-Perot spectrometer.
Figure 2.16. Atmospheric Na line fringes.
Figure 2.17. Comet field in successive days i.e. (a) 16 Oct. 1986, (b) 18 Oct. 1986. Note the changing position of the comet with respect to the star field.
Figure 2.18. Image of comet Halley in $C_2$ and continuum emission bands taken on Oct 10, 1985.
Figure 2.19. IHW filter photographs taken on 23 March 1986.
Figure 2.19. IHW filter photographs taken on 23 March 1986.
Figure 2.19. IHW filter photographs taken on 23 March 1986.
Figure 2.19. IHW filter photographs taken on 23 March 1986.
**Gurushikhar Observations Statistics of Data**

**Mode 1 (Filter Imagery)**

<table>
<thead>
<tr>
<th>Emission</th>
<th>No. of frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₂</td>
<td>46</td>
</tr>
<tr>
<td>C0⁺</td>
<td>30</td>
</tr>
<tr>
<td>H₂O⁺</td>
<td>25</td>
</tr>
<tr>
<td>CN</td>
<td>2</td>
</tr>
<tr>
<td>White light</td>
<td>111</td>
</tr>
<tr>
<td>Comet + laser</td>
<td>27</td>
</tr>
</tbody>
</table>

**Mode 2 (Interferograms)**

<table>
<thead>
<tr>
<th>Emission</th>
<th>Date</th>
<th>Heliocentric Distance in AU</th>
<th>Exposure time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₂</td>
<td>1986 Jan 12.604</td>
<td>0.84</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1986 Mar 22.985</td>
<td>1.04</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1986 May 1.965</td>
<td>1.63</td>
<td>30</td>
</tr>
<tr>
<td>H₅ (6563 Å)</td>
<td>1986 Mar 13.0</td>
<td>0.89</td>
<td>11</td>
</tr>
<tr>
<td>Na(5890 / 5896Å)</td>
<td>1986 Mar 22.999</td>
<td>1.04</td>
<td>10</td>
</tr>
<tr>
<td>[O I] (6300 Å)</td>
<td>1986 Mar 15.994</td>
<td>0.92</td>
<td>15</td>
</tr>
</tbody>
</table>

Note: Comet + laser frames were taken to determine the position of the centre of the fringe pattern in the interferograms.