Chapter 6

SUMMARY AND CONCLUSIONS

The present chapter gives the summary of the work done towards the thesis as presented in the foregoing chapters. At the end, we discuss some aspects on the work to be carried out in future.

The thesis basically comprises of two parts: I. Instrumentation II. Observations, results and discussion.

6.1 The Instrumentation

An imaging Fabry-Perot spectrometer (IFPS) is designed and constructed for the studies on kinematics of extended astronomical objects like HII regions, Planetary Nebulae and spiral galaxies. The IFPS employs a two dimensional imaging sensor called Imaging Photon Detector (IPD). This is the first time that such a detector is being used in the spectroscopic studies of astronomical objects. Also, this is the only instrument of its kind developed in India for the purpose of astronomical spectroscopy and one of the few in the world over. The instrument is designed to be used on the 1.2m telescope at Gurushikhar, Mt.Abu and on the 2.3m telescope at Kavalur, in South India. Also, a smaller version is designed for use on Celestron- 14 inch telescope at Mt.Abu. Present studies are made on the C-14 telescope with the smaller version. The IFPS is now being used successfully on the 2.3m telescope at Kavalur.

6.2 Observations and results on the kinematics of HII regions

6.2.1 Orion Nebula

The velocity field studies were made on the nearest HII region, the Orion Nebula, in [OIII] 5007 Å line. Line profiles were generated for about 2000 positions in a region $10.5' \times 10.5'$ on the nebula. Three type of studies were made on the data obtained: (i)general velocity flow (ii) high velocity flow and (iii)random or turbulent motions.

General velocity flow

The velocity field structure in the [OIII] 5007 Å line is obtained across different features (viz. 'bar' ionization front, dark 'bay'). The profiles showed an asymmetric or broad-winged shape and could be resolved in general into two gaussian components: The main results obtained after the analysis of the emission line profiles were as follows. (i) a narrow component with FWHM of around 20$\pm$ 3 km/sec and (ii) a broad component with FWHM of around 50$\pm$ 3 km/sec The two components could be interpreted as follows: The ionized gas from behind the trapezium is obstructed from flowing towards the molecular cloud and therefore the flow is directed towards the core region resulting in the interaction with the gas and neutral condensations present there which could give rise to secondary flows. These results are in general agreement with those of earlier results where line splitting (Wilson et al, 1959; Deharvang, 1979; Casteńada (1988)) in [OIII] 5007 Å line has been reported.

The iso-velocity contour map generated for both the components showed a decrease in the relative radial velocities from the Trapezium stars and are found to be blue-shifted from the centre outwards. This is in agreement with the champagne flow model suggested for the Orion cloud, according to which the ionized material is rushing towards the observer due to the pressure gradient established at the HI-HII interface.

Model Profile

A model emission line profile is constructed assuming a champagne flow and compared with the observed profile. The method involves calculating integrated sum of the radiation emitted by ions moving with different velocities along the line of sight with the assumption that thermal motions, turbulent motions and gradients in the velocity are the main source of line broadening. Assuming a temperature of $10^{4^{\circ}}$ K, the thermal broadening (FWHM) for [OIII] 5007 Å line was $\sim$ 5.3 km/s. The line profile was generated for a position on the nebula approximately $2'$ away from θ^1 Ori. The field of view considered for generating the line profile is $4''$ (corresponding to 2 pixels on our detector) and a velocity gradient of 1.73 km/s/pc was also assumed (from theoretical work of Yorke, 1986). Using a turbulent velocity of 9 km/s we find a reasonably good agreement between the generated profile and the narrow component of the observed profile.

Dark bay

The radial velocity was found to be low with no high velocity flow regions indicating that there is obstructing material to the expanding gas in this region.

Regions of high velocity flow

There are certain high velocity flows ($\sim$50 km/s) superimposed on the main flow observed in the narrow component. These high velocity flows are found to be either in the ionized regions near the stellar sources or in the molecular cloud regions. The mechanism proposed to explain these flows are either radiation pressure driven stellar winds or jets generated during the formation phase of Young Stellar Objects. The velocity map is compared with the density, temperature and intensity maps at optical as well as other wavelength regions (Infrared and radio) in order to look for the complimentary features and establish some correspondence. Some of the positions in the molecular cloud region do not seem to match with any of the peculiar features discovered before (viz. knots, jets and Harbig-Haro objects). A possibility is that these could be due to the shock waves generated by embedded outflows from young stellar objects or by supernova explosions or alternatively, it can be explained as due to the interaction of the ionized gas expanding from adjacent partially ionized globules.

Orion bar ionization front

Velocity profile was generated for the first time across the Orion 'bar' ionization front. A comparison with density profile (due to Pogge et al,1992) was made and Rankine-Hugoniot jump condition of mass flow across isothermal shock fronts is verified, according to which,

$$\rho_o v_o = \rho_1 v_1 \tag{6.1}$$

i.e., when velocity is high, density is low and vice versa. The high velocity flows are found only in certain clumps along the bar. This is in agreement with [OIII] map (Pogge et al, 1992) showing that the bar ionization front is found to be diffuse in [OIII] 5007 Å line in contrast to the sharp feature found in the bar in [NII], [SII] and [OII] lines. This is obvious from the fact that the doubly ionized oxygen arises in fully ionized zone (Ionization potential = 35.11 eV) whereas the singly ionized species, being sensitive to the sudden changes in the ionization, occur at the HI-HII interface.

Ionization mechanism

The actual velocity obtained by us around the bar ionization front is estimated to be more than 100 km/sec, indicating that O^{++} is produced by shock ionization (at least in part).

Turbulence

In order to study the random components in the flow, a statistical analysis is made from the large number of data points. A correlation function called structure function B(r) is used for the study of the fluctuations in the velocities. The standard Kolmogorov's law states that $B(r) \propto r^{2/3}$. But our analysis showed that the structure function $B(r) \propto r$; for a region about 100 arc seconds around θ^1 C Ori for both the narrow and the broad components. Thus, there is a deviation from the standard model of Kolmogorov. We interpret that this deviation is caused due to the presence of compressibily in the fluid (i.e., violation of one of the assumptions in Kolmogorov's model). The champagne flow of the material due to the expansion of the HII region indicates the possibility of the development of the Kelvin-Helmholtz instabilities (Blake 1972; Norman et al, 1982) in the cloud. The growth time of Kelvin-Helmholtz instabilities is found to be 1.9×10^4 yrs which is found to be less than the estimated age of the nebula ($\sim 10^6$ yrs). From this, we infer that Kelvin-Helmholtz instabilities could be the driving mechanism for turbulence in the Orion nebula.

The structure function around θ^2 Ori is found to be irregular in the case of narrow as well as broad components.

6.2.2 Trifid nebula

Velocity field studies were made for about 48 positions on the nebula in [OIII] 5007 Å line. The isovelocity map showed a picture of general expansion of the nebula in a region 2 arc minutes around HD 164492 with no high velocity flows. This indicates symmetric flow in velocities with no density gradients in this region as was observed in the case of Orion nebula. A general red-shift in the radial velocities is observed in the south west direction with a velocity change of 50 km/s. This indicates that the cloud is moving away from the observer. It is proposed that the red-shift corresponds to a champagne flow partly obscured by dust lanes. There is a symmetric localised flow with a red-shift velocity of 40 km/s observed about 2.3 arc minutes southwest of the central hot star HD 164492 corresponding to a bow shock feature adjoining a condensation. This could be explained in terms of Dyson's model (Dyson, 1975) where the ionized gas from the surface of a globule interacts with the stellar wind from the hot star resulting in the formation of bow shock. There is also a splitting in the line profile indicating the expansion of the partially ionized condensation.

6.3 Scope for future work

There are now high resolution images obtained by Hubble space telescope providing us with all finer details of the Orion nebula. Study of the velocity field structure across these features is required in order to understand the physical processes responsible for such structures. Such a study is required especially in lines arising from low-excitation ions, like [SII], [NII] and the neutral species such as [OI]. Therefore, we plan to study the kinematics of not only the Orion but also that of other diffuse nebulae, viz. Rosette, Lagoon etc. Further, in the case of Trifid, only a single interferogram was obtained, therefore a complete velocity map is required to be generated by scanning the etalon in one FSR and generating the velocity profile at each pixel position.

Apart from studies on the velocity field in the shocked regions, HH objects and neutral condensations, we plan to study the velocity field around the photodissociation regions (PDRs) using appropriate emission lines (eg., [OI] 6300 Å). This will help in understanding of the processes involved in the interaction of the ionized gas with the molecular cloud region.