Chapter 7

Conclusions and Future Work

7.1 Conclusions

The aim of this thesis has been to investigate the structure, evolution and kinematics of massive star forming regions. This has been undertaken by the study of few southern massive star forming regions through continuum and spectral line observations across a wide range of wavelength bands: from optical to radio wavelengths. The key findings from each of the chapters are summarised below.

The star formation activity of the southern filamentary IRDC G333.73+0.37 is analysed in Chapter 3. This region contains two distinct mid-infrared sources S1 and S2 connected by dark lanes of gas and dust. In order to study the properties of the molecular cloud, we created dust temperature and column density maps of this region. The 4700 M$_\odot$ filament is fragmented into 10 clumps. We have estimated the properties of these clumps such as temperature: 14.3 – 22.3 K and mass: 87 – 1530 M$_\odot$ by fitting a modified blackbody to the SED of each clump between 160 $\mu$m and 1.2 mm. The molecular line emission from the clump associated with infrared source S1 show infall signatures and we have modelled the infall profile of HCO$^+$ using the optically thin isotopologue H$^{13}$CO$^+$. From the low frequency radio continuum observations, we identify a shell-like H II region associated with S1. We also detect compact radio emission towards S2. The spectral types of these sources are consistent with late O or early B type stars. Photometric analysis of near and mid-infrared point sources unveil the YSO population associated with this cloud. Using the fragmentation analysis, we affirm the supercritical nature of this cloud. A large scale velocity gradient is observed along the filament that has likely origins due to an accretion flow. Our analysis reveal multiple objects in different evolutionary stages associated with this IRDC, such as millimeter cores, H II regions and YSOs. The expanding H II region S1 is in the process of dispersing the cloud in its immediate vicinity. According to the classification scheme of (Jackson et al., 2010), IRDC G333.73+0.37 is in intermediate phase compared to prestellar...
filamentary clouds and highly evolved regions that harbour massive star clusters in the Milky Way. Based on various estimates obtained for objects in different evolutionary stages, we find a lower limit to the age of this IRDC as $1 - 2$ Myr.

In Chapter 4, we investigated a relatively evolved star forming region IRAS 17256–3631. The low frequency radio continuum emission from this region exhibits a cometary morphology. Spectral type of the ionising source estimated from 1372 MHz radio map is O7-O7.5. The radio spectral index maps indicate the presence of thermal as well as non-thermal emission in this region. Narrow band Br$\gamma$ emission from the ionised gas at near-infrared wavelengths is also detected in this region and is consistent with radio emission. The narrow band H$_2$ image shows emission in the form of filamentary structures. These indicate the presence of highly excited molecular gas. We have identified a partially embedded infrared cluster associated with this region and the near-infrared spectroscopic study of the brightest star in the cluster, IRS-1, indicates that it is a late O or an early B-type star. Apart from the near-infrared cluster, we have also identified 18 mid-infrared YSO candidates in the region along with an extended green object: EGO-1, likely to be a massive protostellar candidate. The parent cloud is massive ($6700 \, M_\odot$) and is clumpy in nature. We have identified 18 cold dust clumps whose properties has been probed in detail. The temperature in these clumps range from 14.2 to 33.2 K whereas the mass ranges from 100 to 1200 $M_\odot$. Using various star formation tracers, we examined the evolutionary stages of these clumps. We have also analytically examined the origin of cometary morphology of the H II region. The radio emission is density bounded towards the north-west and is ionisation bounded towards south-west. Several high density clumps are located along the cometary head of the ionised emission. The morphology of IRAS 17256–3631 is explained with the champagne flow model.

The structure and kinematics of the H II region IRAS 17256–3631 and its neighbour IRAS 17258–3637 is probed using low frequency RRLs in Chapter 5. The latter is a bipolar H II region. The hydrogen H172$\alpha$ RRL from these regions are mapped using GMRT, India. We have also detected carbon (C172$\alpha$) RRL towards these regions. The effects of various line broadening mechanisms on the line width of H172$\alpha$ RRL has been carried out. The H172$\alpha$ RRL from both H II regions display the effects of pressure and dynamical broadening in the line profiles, with the dynamical broadening playing a major role in IRAS 17256–3631. The kinematics of ionised gas in IRAS 17256–3631 is compared with that of molecular cloud. For this, we have used molecular line
data from MALT90 pilot survey. A velocity gradient across the cometary axis of the 
H II region has been detected and the ionised gas at the cometary tail is blue shifted 
atleast 8 km s$^{-1}$ with respect to the molecular cloud, consistent with champagne flow 
model proposed in Chapter 4. The relative velocity of 5 km s$^{-1}$ detected between the 
northern and southern lobes of the bipolar H II region IRAS 17258–3637 is consistent 
with the premise that the bipolar morphology is a result of the expanding ionised gas 
lobes within a flat molecular cloud.

The large scale radio emission associated with the star forming complex comprising 
of the two H II regions IRAS 17256–3631 and IRAS 17258–3637 is analysed in Chapter 
6. We carried out low frequency wideband observations (bandwidth = 200 MHz) using 
upgraded GMRT to map the large scale diffuse emission from this region. Combining 
this with the optical, infrared and submillimeter data, we carried out a multiwavelength 
investigation of the diffuse emission to get a larger picture about the structure and evolu-
tion of this star forming complex. We detected a broken radio shell spanning a region 
$\sim 14'$, that encompasses the two H II regions. The radio spectral index of the shell is 
$-0.8$, indicating non-thermal emission. H$\alpha$ emission that mimics the morphology of 
the radio shell on a smaller scale is also detected here. We classify this radio shell and 
its optical counterpart as a previously unknown supernova remnant SNR G351.7–1.2. 
A $\gamma$-ray source detected by Fermi LAT (1FGLJ1729.1–3641c) is located towards the 
south-west of the radio shell and could have a possible origin in the interaction between 
high velocity particles from the SNR and the ambient molecular cloud.

From our detailed analysis on the evolution and structure of three star forming re-
gions, we arrive at the following conclusions. The analysis of star formation activity 
towards IRDC G333.73+0.37 and IRAS 17256–3631 has shown that the regions are 
currently undergoing a star formation flurry. The clumps in these regions range from 
active/evolved with ultracompact and compact H II regions and associated infrared clus-
ters to YSOs and EGOs prior to the formation of H II regions and to starless clumps 
that are devoid of any signatures of star formation. Of the 10 clumps in the IRDC 
G333.73, 40% are exhibiting signatures of star formation activity whereas 60% are qui-
escent clumps. In case of the cloud associated with the cometary H II region IRAS 
17256–3631, there are 18 identified clumps of which 33.3% are star forming clumps 
and 66.7% are quiescent clumps. The temperature of the dust clumps in these regions 
lie in the range 14 – 33 K and we find that the clump temperature changes with the
On the average, the temperatures of the active/evolved clumps are higher ($\Delta T \geq 5$ K) than that of the quiescent clumps. The average clump temperature in the IRDC G333.73 (17 K) is lower than that of the H$\text{II}$ region IRAS 17256–3631 (23 K). This is expected as the IRDC as a whole, is in an early evolutionary stage compared to the star forming region IRAS 17256–3631. The latter already harbour an infrared cluster that contain one or more massive stars. The radiation from the partially embedded cluster is heating up the ambient gas and dust and is in the process of dispersing the natal cloud. The typical column densities of the clumps in these regions are of the order of $10^{22}$ cm$^{-2}$ and the masses range from $\sim 100 - 1500$ $M_\odot$.

We have also probed the morphology and gas kinematics of the H$\text{II}$ regions associated with these regions. The origin of specific morphologies in H$\text{II}$ regions is still a matter of debate and several models are proposed to explain the diverse morphological classes. In this thesis, we study the morphology of three H$\text{II}$ regions: the cometary H$\text{II}$ region IRAS 17256–3631, bipolar H$\text{II}$ region IRAS 17258–3637 and shell-like H$\text{II}$ region S1 in the IRDC G333.73. Based on our analysis using continuum and spectral line data, we find that the effects of density gradients play a major role in IRAS 17256–3631 and IRAS 17258–3637 whereas in the case of S1, a combination of stellar wind and density gradient is responsible for the observed structure. Additionally, we also investigated the origin of mid-infrared arc-like emission around the compact radio source S2 and concluded that this is a result of stellar wind bow shock and density gradients. Irrespective of the morphological class, all of them show strong interaction with the ambient cloud. This is the first RRL mapping study of H$\text{II}$ regions at low frequency bands ($\nu \lesssim 1$ GHz). We emphasise on the importance of RRL and molecular line mapping studies to constrain the kinematic models of H$\text{II}$ regions that are in their early stages of evolution.

Using low frequency radio continuum observations and complementary archival data, we have identified a prospective SNR candidate SNR G351.7–1.2 interacting with the molecular cloud associated with the H$\text{II}$ regions IRAS 17256–3631 and IRAS 17256–3637. This is an important finding considering the fact that there are only a limited number of Galactic systems where there are SNR/molecular cloud interactions. Such systems are crucial in understanding the physics of shock/cloud interactions. The study also accentuates the importance of low frequency radio observations in identifying and segregating SNRs that are associated with H$\text{II}$ regions and molecular clouds.
The work provides a larger picture on the evolution of this star forming complex and how the shock waves from the dying massive star could affect the ambient medium and the formation of future massive stars.

### 7.2 Future work

We have used molecular line archival data to study the kinematics of a IRDC filament. Due to the limited resolution (∼1") of the surveys and lack of higher order transitions that better trace the kinematics of the cloud, we are not able to obtain an accurate picture of the velocity structure as well as the properties of this filament. It is therefore instructive to carry out follow up high resolution spectral line observations to sample the velocity structure of the entire filament while probing the infall and outflow activity of the central clump. As a continuation of the thesis work, we intend to carry out high resolution molecular line mapping towards a sample of IRDC filaments. At high angular resolutions, the sub-structures on these filaments at scales of cores (∼10,000 AU) can be probed in detail. Such investigations can reveal whether the cores in the filaments are likely to produce a single high-mass star or a cluster of low-mass stars. Furthermore, the high resolution molecular line data can trace the star forming activity of sub-parsec cores such as infalls/outflows. Molecular line mapping of these filaments will also provide insights on the chemistry and kinematics of these filaments and how it changes with evolution. The kinematic study is particularly important in the case of filaments having accretion flows within them. The high resolution millimeter observations can be complemented with radio frequency observations and archival data from various surveys.

Even though the combination of RRLs and submillimeter molecular line data is an efficient tool to probe the morphology and kinematics of H II regions, velocity mapping studies using RRLs remain limited. Hence, observational work towards a sample of H II regions with diverse morphologies are essential in perceiving the complex interaction mechanisms existing in massive star forming regions. A comparative study of the centimetre and millimeter RRLs originating from the same star forming region is helpful in analysing various effects of line broadening mechanisms and to detect the velocity difference between high and low density gas, if present. This is possible because high
frequency RRLs sample regions of high density whereas low frequency RRLs have contributions from both high and low density gas.