Chapter 1

Introduction

1.1 Millimeter-wave Astronomy

Millimeter radio astronomy as an important branch of astronomy was born with the discovery in 1971 of carbon monoxide in the interstellar medium at 115 GHz by Wilson et *al.*(1971). In the two decades since this discovery, over 60 molecules have been detected in the ISM. Some of the organic molecules identified are quite complex containing as many as 13 atoms. Line radiation from molecules in the ISM has given us a wealth of new information. Molecular line studies are about the only way to probe the cold, dense regions where new stars are believed to be born. These studies have led to the discovery of the Giant Molecular Clouds, the most massive structures in the galaxy, the unexpected outflow phase of young stars, the circumstellar and interstellar masers, and a variety of chemical species.

Molecular clouds are mainly made up of H_2. Being a homomorphic molecule H_2 has coincident charge and mass centers. Consequently it has no permanent dipole moment and so does not radiate in its lower rotational transitions. Molecular hydrogen has been studied, however, through its vibrational-rotational quadrupole transitions. These lines fall in the IR region requiring higher energies to be excited restricting the direct study of H_2 to shock excited regions with temperatures $\sim$1000K. H_2 has also been observed through its UV absorption lines but obviously only along selected lines of sight. In essence, direct observation of H_2 in the cold interstellar medium is not possible. Fortunately the next most abundant molecule **CO** has a permanent diplole moment leading to conveniently observable radio lines. The lowest rotational transition (J=1 $\rightarrow$ 0) of CO at 115.271 GHz corresponds to an $h\nu/k = 5.5$K. This transition is easily excited by collisions with molecular hydrogen even in clouds with very low kinetic temperature. The minimum density required is $\sim$ 100 cm^{-3}. Therefore CO is widely used as a tracer of H_2 in cold interstellar clouds. The less abundant species. ^{13}CO, is used to overcome difficulties posed by the high optical depth of ^{12}CO in probing deeper into molecular clouds. Molecules with different dipole moments and formation chemistry are used to study regions of different physical conditions and activities.

Advances in millimeter-wave radio astronomy were limited by developments in antenna and receiver technology. During the eighties, many large telescopes some with surface accuracy high enough to go upto 1000 GHz have been built and receiver technology has matured sufficiently to permit routine observations.

1.2 Molecular Clouds

Over the past decade several ^{12}CO and ^{13}CO surveys have been undertaken on the galactic scale which have led to the realisation that most of the molecular gas is concentrated in Giant Molecular Cloud complexes. GMCs are at the high end of the molecular cloud aggregates. In order of magnitude their masses are $\sim 10^6 M_\odot$ and sizes are ~100pc. They are the birth sites of high mass stars but they also form low mass stars. The dark cloud complexes like Taurus and Ophiucus are smaller with masses in the range 10^{3-4} $M_\odot$ and mainly form low mass stars. Towards the lower end of the molecular cloud distribution we have the dust globules, which are further discussed below.

It was first suggested by Bok and Reilly(1947) that dark dust globules are probable sites of star formation. For a long time no direct evidence was forthcoming to support this claim. The first evidence was provided by Schwartz(1977) when he discovered star formation in a globule in the Gum Nebula (GDC 1). This globule has turned out to be very interesting: It has an embedded young star, the Herbig-Haro object HH46-47; and is a strong case for star formation caused by external mechanisms (Schwartz 1977). Globules have been grouped into four classes based on their optical morphology (Leung 1985). They are: (a) the elephant trunk globules, (b) globular filaments, (c) isolated dark globules, and (d) cometary globules. Elephant trunk globules are long tongues of obscuring gas and dust seen in projection against bright HII regions. Their sizes are ~ 0.01 - 0.5 pc, and their masses are in the range ~ 5-10 $M_\odot$ and densities ~ 10^{3-4} cm^{-3}. The best examples of elephant trunks are found in the Rosette Nebula. Globular filaments are dark nebulae with elongated filamentary structure. Isolated dark globules are also known as Bok globules. They have sharp boundaries and are not near HII regions or bright nebulosities. Well studied examples are B68 and B335. Cometary globules (CGs) have a cometary morphology: a dusty head with a luminous tail on one side and bright rims on the other side. They are discussed in more detail in the rest of this chapter.

1.3 Cometary Globules

Bright rimmed globules, many of which have cometary structure, have been subject of study since the thirties. Pottasch(1965) studied a number of bright rims and concluded that they are ionised hydrogen regions caused by nearby O-type stars. Interest in cometary globules was revived with the discovery of HH46-47 and a sizable population of CGs in the Gum-Vela region. The CGs in the Gum-Vela region were first noted by Hawarden and Brand(1976) and Sandqvist(1976). Later, Zealey *et al.* (1983, hereafter referred to as Z83) and Reipurth(1983) independently found, a total of 38 CGs in a surveys of the SERC IIIa-J and ESO B plates of which 32 were in the Gum-Vela region. Figure 1.1 shows a photograph of CG 15, a typical CG. The Gum globules have the following characteristics (see figure 1.1):

- A compact dusty head
- A long faintly luminous tail extending from one side of the head; the other side has a sharp edge with narrow bright rims.
- The tails of these CGs point away from a general center.
- Sometimes the heads have embedded young stars in them.

It is now well established that many bright rimmed globules found in association with HII regions are sites of on-going low mass star formation (Dibai 1963, Sugitani *et al.* 1989, Sugitani, Fukui and Ogura 1991. Cernicharo *et al.* 1992, Duvert *et al.* 1992). The earliest example of such star formation is the discovery of HH 46-47 in the cloud GDC 1 (ESO 210-6A) in the Gum Nebula mentioned earlier. GDC 1 has characteristics similar to the cometary globules. It is now known that CGs are not restricted to the Gum Nebula. The original list contains CGs in Orion and recently CGs have also been found in the Rosette Nebula (Block,1990). Carbon monoxide maps of molecular clouds in Orion show cometary structure with tails pointing away from the Ori OB1 Association (Bally *et al.* 1991). It is believed that the cometary globules are formed by the effect of UV radiation from young stars, stellar winds, and supernova shocks on nearby molecular clouds.

The globules in the Gum Nebula arc in a complicated setting (see figure 1.2). This nebula is a large shell like structure (radius—18°) seen in Hα (Gum, 1952;1955). The estimated distance of $\sim$ 400 pc implies a radius of 125 pc (Brandt *et al.* 1971). In the general direction of the centre of the nebula are the Vela SNR (age $\sim 10^4$ yrs), the Pup A SNR (age $\sim$ 3700 yrs), ζ Pup (O4f), the most luminous star in the southern sky, the Wolf-Rayet binary γ^2 Vel (WC8+O9), and a possible B Association. These objects together represent a significant source of ionising radiation and stellar wind. Various models have been proposed for the Gum Nebula in which some of these objects play an important role (see, for example, Bruhweiler, 1983). Whether the Gum Nebula is expanding or not has been a point of controversy in the past, but latest studies indicate expansion at 10 kms^{-1} (Srinivasan *et al.*. 1987). In the central region of the Gum Nebula the CGs are distributed non-uniformly over a

Figure 1.1: An optical image of CG 15, a typical cometary globule reproduced from the SERC survey plate (what is shown is a negative image). The obscuring head is seen as a white patch whereas the tail and the bright rim are black.

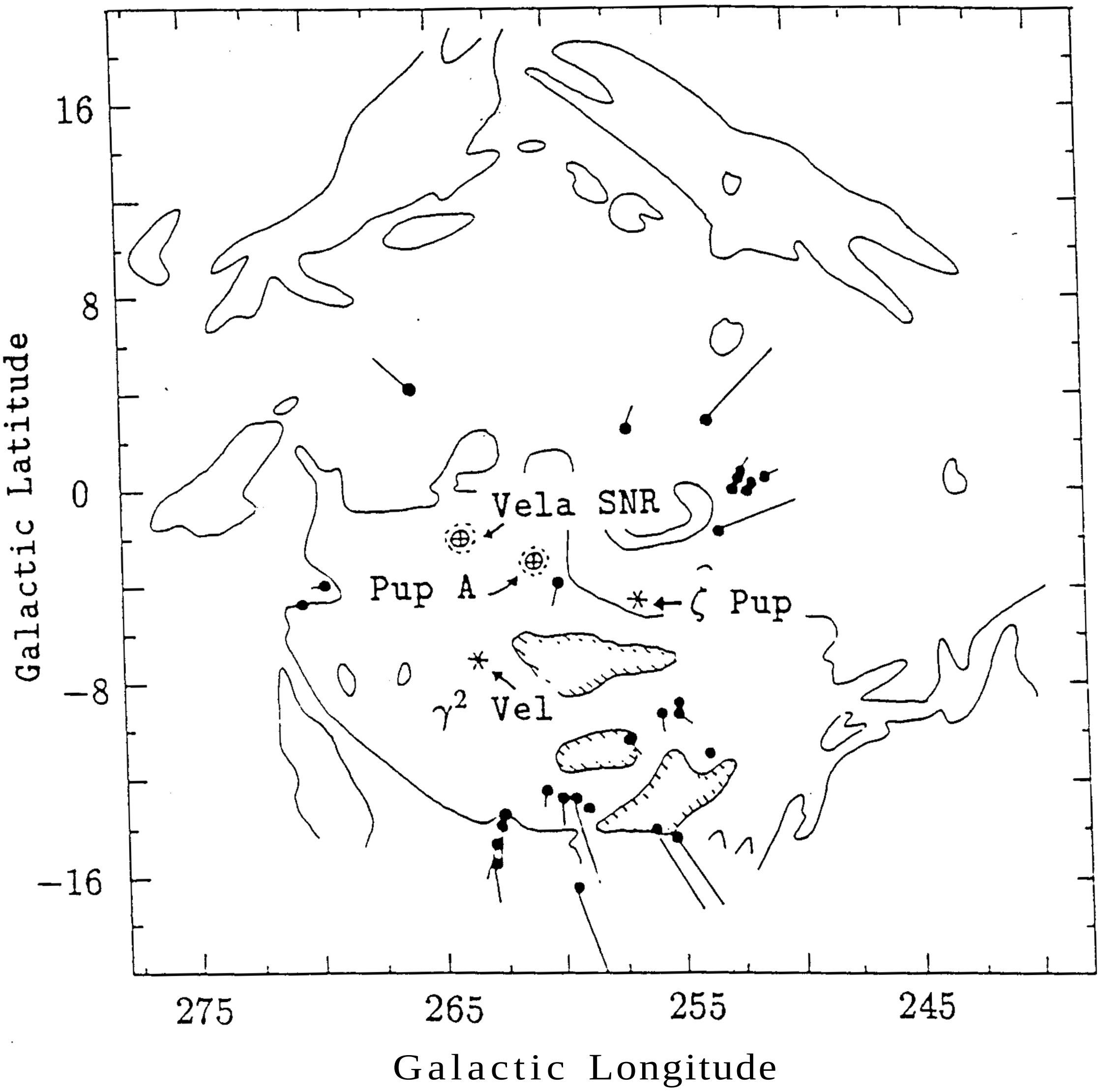

Figure 1.2: The Gum-Vela region. The solid lines mark the regions of Hα emission. The cometary globules are shown as filled circles, with tails scaled up 10 times for clarity. The locations of objects in this figure are approximate (adapted from Pettersson 1991).

rough *annulus* whose center is close to the place from which the tails point away. This *morphological center* is offset from the approximate center of the Gum Nebula by about 4°. The best fit circle to the distribution of CGs has a radius of $\approx 9.5°$. There is firm evidence for star formation in some of the CGs as well as some of the other dark clouds in the Gum-Vela region (Schwartz 1977; Bok 1978; Reipurth 1983; Pettersson, 1987,1991; Graham 1986; Graham and Heyer 1989)

Soon after the discovery of HH46-47, it was suggested that low mass star formation in the Gum Nebula may have been triggered by external events (Schwartz 1977), quite possibly the events responsible for the origin of the Gum Nebula itself (Brand *et* al.. 1983). Stellar winds, SN shocks. and shocks associated with the expansion of HII regions can compress small globules into gravitational instability leading to star formation. Numerical studies of such processes give credence to this idea (Woodward 1976;1979). Reipurth(1983) has argued in favor of UV radiation from young stars being the cause for the origin of CGs as well as star formation in them. There have also been studies of radiation driven implosion as a mechanism for star formation (Sandford,Whitaker and Klein 1982, Bertoldi and McKee 1990). Specifically, Bertoldi and McKee have shown that clouds exposed to UV radiation will acquire a cometary structure.

1.4 Previous Studies

The first systematic study of the cometray globules in the Gum Nebula was done by Zealey *et. al.*(1983). They made 4 cm formaldehyde absorption observations of 9 CGs with the Parkes 210 foot telescope. 01113' CGs big enough to have a good chance of detection with the 4.4' beam were observed. Goss *et al.*(1980) had observed some of the CGs in an independent survey. Radial velocities for a total of 10 CGs were thus obtained. Z83 concluded from this data that the radial velocities were consistent with rotation of the system about an axis perpendicular to the galactic plane. They suggested that the orientation of this axis implied that the kinematics of the CGs is dominated by galactic rotation. In addition they found that in an $l-v$ plot the CGs lined up on a straight line parallel to the HI data for the region, but offset in l. They took this to mean that the observed velocities of the CG complex are wholly due to large scale effects of the local spiral structure. Assuming that such a line represented galactic rotation effects they studied the deviations from the straight line fit to look for expansion or rotation. Their conclusion was that the CGs may be on a shell expanding with velocities upto 5 kms^{-1}. [We find this surprising since the residuals (i.e. the deviations from their straight line fit) were only ± 2 $\mathrm{kms^{-1}}$]. In addition, from a study of the tails seen in optical photographs they identified two *centers* from where maximum number of tails pointed away.

1.5 Present Study

In this thesis we present a study of the system of cometary globules in the Gum Nebula using mainly the 10.4m millimeter-wave radio telescope at the Raman Research Institute, Bangalore.The thesis is organised in three parts:

(1) The first part deals with the development of a wide-band mechanically tuned local oscillator using the Gunn diode for use with the 10.4m millimeter-wave radio telescope at the Raman Research Institute. This is described in chapter 2.

(2) The second part is devoted to a study of the cometary globules in the Gum-Vela region. As mentioned earlier, there has been no satisfactory study of the system of CGs in the Gum Nebula. A detailed study of the system was therefore undertaken using the mm-wave rotational transitions ($J=1 \rightarrow 0$) of the molecules ^{12}CO and ^{13}CO. The observations consist of a ^{12}CO survey of the heads and the *tails* of the CGs, and mapping one of them viz., CG22 in ^{12}CO and ^{13}CO. The aim of the survey was to study the kinematics of the CGs and gas motions along the tails. The main objective was to make a more complete study of the *kinematics* of the system than was possible before. As mentioned above, in previous attempts the velocity information was available only for 10 out of the more than 30 CGs. Since our beam size was 1' we could detect even the smaller clouds that were not detected in the previous surveys. The mapping of one of the globules was done primarily for estimating its mass. The telescope and observations are described in chapter 3. The analysis of the survey data is the subject of chapter 4 and chapter 5 deals with the maps of CG 22.

(3) The third part of the thesis, presented in chapter 6, deals with an analysis of the locations of embedded young stellar objects (YSOs) inside the dark clouds in the Gum Nebula region. The aim of this study was to look for evidence for externally triggered star formation in these clouds. We have used the far-infrared point sources from the IRAS PSC (with suitable flux criteria) to identify embedded YSOs. By simple statistical methods we show that the YSOs have higher tendency to fall on the side of the clouds facing the morphological center than the far side.

In chapter 7 we discuss the results and present an overall view of the system of CGs in the Gum Nebula.

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