Chapter 7

Discussion

7.1 Introduction

The main results obtained from the study presented in the previous chapters are the following:

(i) The system of cometary globules in the Gum Nebula appears to be expanding from a common center. The *expansion age* is $\lesssim$ 6 Myr.
(ii) The observed velocity gradients along the tails of the globules suggest a *stretching age* for the tails of $\sim$ 3 Myr.
(iii) The mass of a typical globule is $\sim$ 20 $M_\odot$
(iv) Star formation triggered by external mechanisms appears to be going on in this region

In this chapter we discuss several scenarios that may have a bearing on the above results.

The rough agreement between the expansion age and the ages of the tails suggests that both the formation of the tails and the expansion of the globules may be due to a common cause. The presence of young stars in this region with estimated ages ranging from 10^5 to a few 10^6 years may be an important clue. Some of these are embedded in the heads of the CGs, while others are isolated. CG1 has an embedded star with age $\sim$ 10' yrs (Brand *ef al.*1983, Reipurth 1983), and the embedded IR source CG30IRS4 in CG30 has an age $\sim 10^6$ yrs (Pettersson, 1984). The bipolar molecular outflows associated with HH46-47, HH120 and HH56-57 have dynamical ages of $\sim 10^5$ yrs (Olberg *ef al.*1988). As already mentioned the study of the distribution of IHAS sources indicates that star formation triggered by external means is indeed going on in this region. All these strongly point to the possibility that the processes responsible for the expansion of the globules, as well as their cometary appearance, have also triggered star formation in some of them. The various possible mechanisms are (i) supernova explosion(s), (ii) radiation from massive stars found in the central region, and (iii) stellar wind from these massive stars. Before discussing each of these scenarios it would be useful to have an estimate of the kinetic energy of a typical globule and its momentum. Assuming a typical CG mass $\sim 20 M_\odot$ (see chapter 5 and Harju *et al.* 1990) and an expansion velocity of 12 kms^{-1}, the kinetic energy is $\sim$ 3 x 10'" ergs per globule, and its momentum $\sim 5 \times 10^{40}$ gm cm s^{-1}. We now proceed to make simple estimates for energy and momentum that can be imparted to a globule from each of the processes mentioned above.

7.2.1 Supernova explosions

According to prevalent opinion, the Gum Nebula is an old supernova remnant with an age $\sim$ **10'** yrs (Reynolds, 1976; Leahy, Nousek and Garmire **1992).** Therefore it is natural to ask if the original explosion that created the Gum Nebula could itself be responsible for the observed properties of the system of CGs. The energy and momentum intercepted by a globule are given by

$$E = 3.1 \times 10^{48} \left(\frac{E_{SNE}}{5 \times 10^{51} ergs}\right) \left(\frac{r}{0.25pc}\right)^{2} \left(\frac{d}{5pc}\right)^{-2} \tag{7.1}$$

$$P = 8 \times 10^{39} \left(\frac{E_{SNE}}{5 \times 10^{51} ergs}\right)^{0.5} \left(\frac{M_{ej}}{8M_{\odot}}\right)^{0.5} \left(\frac{r}{0.25pc}\right)^{2} \left(\frac{d}{5pc}\right)^{-2} \tag{7.2}$$

where E_{SNE} is the energy of explosion of the SNE, M_{ej} is the ejected mass and r and d are the radius of a globule and its distance from the explosion center at the time of explosion. Assuming an ejected mass of $8M_{\odot}$, an energy of explosion equal to 5 x 10^{51} ergs, and a typical size of **0.5** pc for the CGs, we estimate that a typical CG has to be not more than a few parsec from the explosion center in order to. intercept sufficient momentum.

This is a plausible scenario but it should be pointed out that the center of the Gum Nebula shell is 4.5° north of the *morphological center* derived from the tail directions of the CGs. However, we would not like to over-stress this point because of the inherent difficulties in determining the center of explosion of such an old SNR. A more serious difficulty is the following: Although the original explosion could have caused the expansion of the system of CGs and the observed tail structures, the presently observed ionised bright rims cannot be attributed to it, as argued before in chapter 4 in a similar context, viz., that the bright rims have a recombination time scale $\sim$ 1000 years and so cannot survive for **10'** years.

7.2.2 Radiation pressure

The most massive star in the region is ζ Pup (O If)and therefore is the most significant source of photons for exerting radiation pressure. Its luminosity is **9** $\times 10^5$ $L_{\odot}$ (Bohannan *et al.* 1986). Models suggest that this star may have just finished or is in the final stages of core hydrogen burning. Its ZAMS mass is believed to be $\sim$ 60 $M_{\odot}$. This implies that ζ Pup is a few million years old. It is reasonable to assume that its average luminosity over the past few million years was the same as its present luminosity. The CG closest to ζ Pup is at a distance of **40** pc from it.

a globule and its distance from the star respectively. The stellar wind from ζ Pup has a terminal velocity of 2600 $\mathrm{kms^{-1}}$ and the mass loss rate is 5×10^{-6} $\mathrm{M_{\odot}yr^{-1}}$ (Bohannan ***et al.*** 1986). We estimate the energy and momentum intercepted by a typical globule from the wind from ζ Pup to be $\sim$ 6 x 10[illegible] ergs and $\sim$ 10^{38} gm $\mathrm{cms^{-1}}$, respectively, over 6 million years. Stellar wind from γ^2 Vel and the companion of ζ Pup will increase these numbers by a factor of four, and the momentum available will still be less by an order of magnitude (even given the assumed 100% efficiency of conversion of the stellar wind momentum to cloud momentum).

7.2.4 Rocket effect

Finally, we consider the rocket effect which results from the anisotropic expansion of the hot ionised gas from the bright rims. When a neutral cloud is exposed to ionising radiation from a star, an ionisation front is driven into the cloud. The ionised hydrogen produced on the side of the cloud facing the star is at a much higher pressure than the gas outside because of its high density. This gas then expands towards the star forming a dense cloud of ionised gas between star and the cloud. Making the simplifying assumption that this gas expands into vacuum, the expansion velocity will be close to the velocity of sound in the ionised region. It is this expanding layer of gas that is seen as the bright rim. The effect of this streaming of gas in the bright rim produces a recoil on the cloud accelerating it away from the star. It also leads to evaporation of the cloud. This process has been called the ***rocket*** effect and was first proposed by Oort and Spitzer(1955) for accelerating interstellar clouds.

We estimate below the velocity that the CGs can acquire as a result of such a rocket effect. The temperature and density at the bright rim of CG30 has been measured by Pettersson(1984) to be $\sim$ 10^4K and $\sim$100$\mathrm{cm^{-3}}$. Reipurth(1983) has estimated that ζ Pup alone can easily account for the observed ionisation level ($n_e \sim 100$ $\mathrm{cm^{-3}}$) at the bright rims. Using mass loss rates of $\sim$ 9$\times$ 10^{-5} $\mathrm{M_{\odot}yr^{-1}}$ as derived by Reipurth(1983), and an expansion velocity of the hot gas —10 $\mathrm{kms^{-1}}$ (velocity of sound in the bright rim), we estimate the total momentum acquired by a typical globule due to the rocket effect operating for 6 million years to be $\sim$ 10^{42} gm $\mathrm{cms^{-1}}$. This should be compared with the required momentum $\sim$ 5 x 10^{40} gm $\mathrm{cms^{-1}}$. If we include the former companion of ζ Pup, γ^2 Vel and the other B stars, the clouds can be easily accelerated to the observed velocities even with larger initial masses. From the above discussion it appears that the only plausible mechanism which can explain *both* the bright rims and the expansion velocities is the heating caused by radiation (and possibly stellar wind) from the stars in the central region, and the consequent rocket effect. We have not yet attempted to explain the tail structures. It is conceivable that a part of the expanding ionised gas will be swept back by the radiation and stellar wind from the central stars forming the tail. This flow should also entrain some neutral material to account for the CO emission from the tails. The ionisation front may also dislodge neutral material from the periphery of the globule (as compared to the center of the globule, where a large column of gas is present) which can then flow along the tail. In larger globules shadowing by the head may be important. We hope to investigate this in detail in the near future. We wish to mention in passing that Bertoldi and McKee(1990) have shown that UV radiation and stellar wind can result in molecular clouds developing tail-like structures.

7.3 The proper motion of ζ Pup

The star ζ Pup is very remarkable from several view points. First of all, it is a very massive star. It is tlie most luminous star in the southern sky. It has a large proper motion of .033" (-0.031" in α and 0.012" in δ)(SAO star catalog 1966), translating to a transverse velocity of 74.3 $\mathrm{kms^{-1}}$ at the assumed 450 pc distance. It was proposed very early that ζ Pup must be a *runaway star* resulting from tlie explosion of its binary companion (Reynolds 1976). It was also suggested that the Gum Nebula is the remnant of this explosion. If, indeed, ζ Pup is a runaway star. its companion which exploded must have been more massive to have evolved faster to explode first. Also, if the explosion is spherically symmetric then the binary will disrupt only if the mass ejected is greater than half the total mass. This means that tlie companion of ζ Pup must have been the more massive star *even at the time of explosion.* This suggests that the region where we now find the CGs there were atleast five massive stars a million years back (including the progenitor of the Vela pulsar and γ^2 Vel).

We have shown in figure 7.1, the proper motion of ζ Pup and its past trajectory. The path passes very close to the morphological *center* of the system of CGs. As can be seen it was closest to the *center* half a million years back. We suggest that this is the original site of the binary whose disruption resulted in the present large proper motion of ζ Pup. It is possible that the Vela progenitor, the proposed ζ Pup binary and γ^2 Vel are all part of the Vela OB3 association found by Brandt *et. al.*(1971). Such *a* scheme naturally accounts for the lack of any object of significance near the *center* at present. The ζ Pup binary would have been the dominant object in the region causing most of the tails which have grown over a few million years to point away from it.

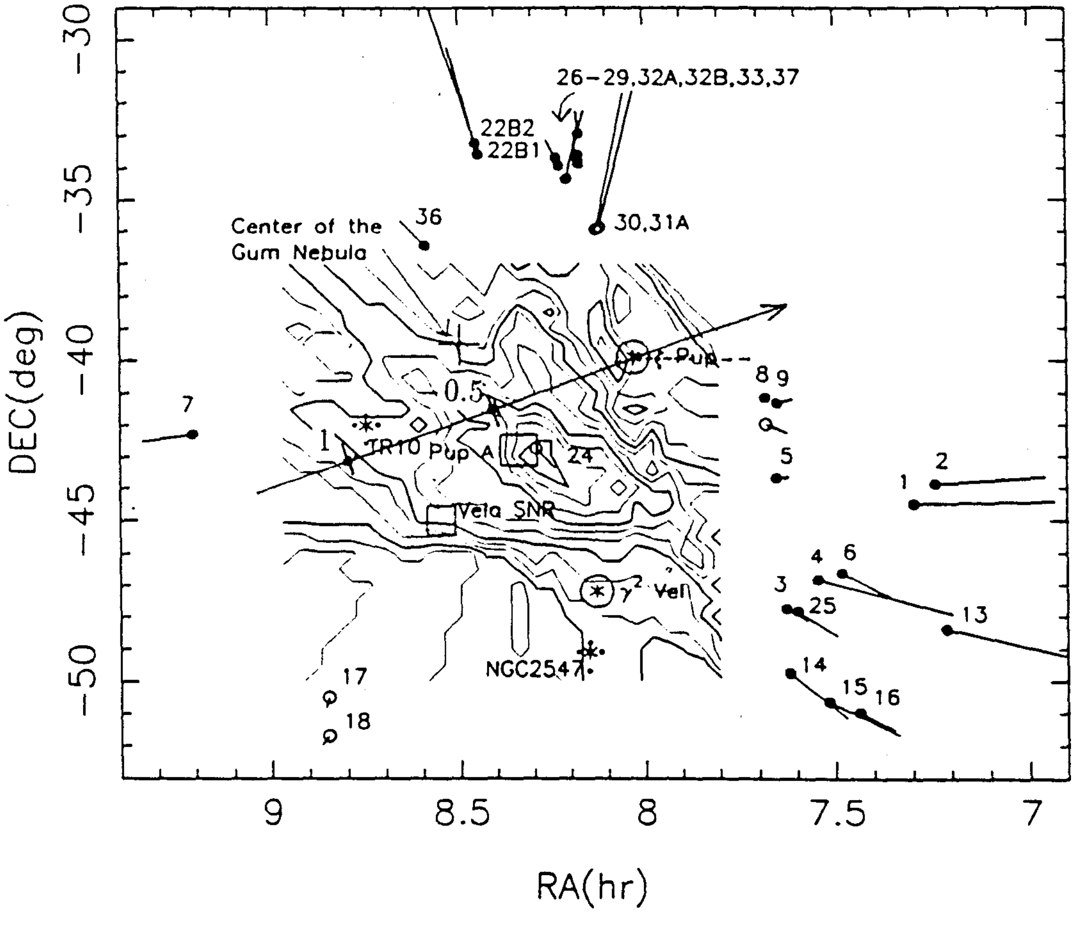

Figure 7.1: Diagram showing the proper motion of ζ Pup extrapolated back in time. The past trajectory is graduated in millions of years. The star would have been close to the *morpohological center* half a million years back.

As we have already mentioned the bright rims of the of the CGs are short lived and therefore should reflect the effects of the changing position of ζ Pup. An examination of the orientation of the bright rim of CG 31A the CG closest to ζ Pup (in projection) shows that this indeed is the case. This is shown in figure 7.2 where the CG 30-31 complex is shown with the directions to ζ Pup and the *center* marked. The bright rim is normal to the vector pointing to ζ Pup whereas the tail is along the direction to the *center*.

7.4 The Gum Nebula

Based on the above discussion we propose the following qualitative model for the Gum Nebula. We have shown in figure 7.3 tlie region including the H a emission regions collectively called tlie Gum Nebula. The region to the south is more intense in H a and tlie CGs are distributed over this region. The location of the original ζ Pup binary is in the southern part of tlie Gum Nebula. We propose that this region of enhanced $H\alpha$ emission is tlie remnant of the explosion of tlie companion of ζ Pup (the two northern filaments may be also connected with this explosion; but this would require a highly asymmetric expansion of tlie SNR). This picture can be tested by the analysis of the radial velocities of the $H\alpha$ filaments with respect to the *center*. One might also look for soft X-ray emission from the interior of the remnant which should be restricted to the southern part. There is already an indication that this may be the case from the HEAO X-ray data (Leahy, Nousek and Garmire 1992). This study is incomplete as the coverage of the nebula is poor. Data from ROSAT should definitely throw much light on this picture.

We propose the following picture for the Gum-Vela region: The stars ζ Pup, its past companion, the progenitor of the Vela pulsar/SNR, the binary γ^2 Vel, all formed around the same time, a few million years ago, from the same molecular cloud, and were part of the Vela OBR association. The parent molecular cloud from which these stars formed was-slowly evaporated away by the UV radiation and stellar winds from these stars. The denser regions in this molecular cloud were not destroyed completely, although they lost a significant part of their original mass due to the harsh environment. These surviving pieces of the original molecular cloud may be what are now seen as the cometary globules. About half a million years ago the companion of ζ Pup exploded whose ejecta and swept up material is probably what is seen in H a in the Gum Nebula. The ionisation in the nebula is now maintained by the other stars in the region. This explosion resulted in the disruption of the binary giving ζ Pup its large proper motion.The expansion of the system of cometary globules is largely caused by the rocket effect and the tails are partly the ablated material flowing down-stream. The effect of the UV radiation, stellar winds and the SN shock compressed the clouds leading to star formation as evidenced by the IRAS sources.

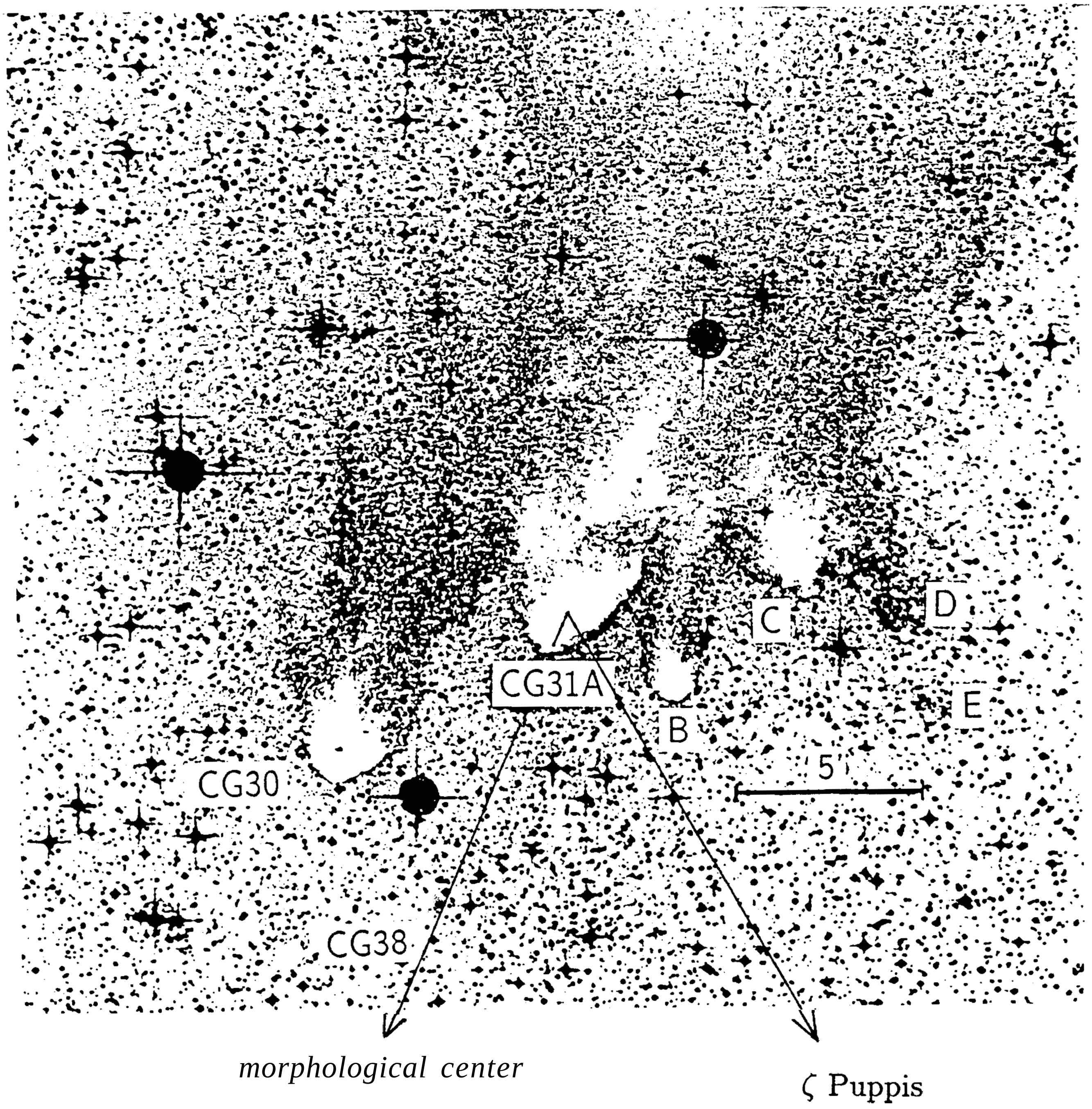

Figure 7.2: The orientation of the bright rim of CG31A with respect to the tail directions in this region. The directions to ζ **Puppis** and the morphological center are marked. The tails point away from the morphological center whereas the bright rim is perpendicular to the direction to ζ **Puppis**.

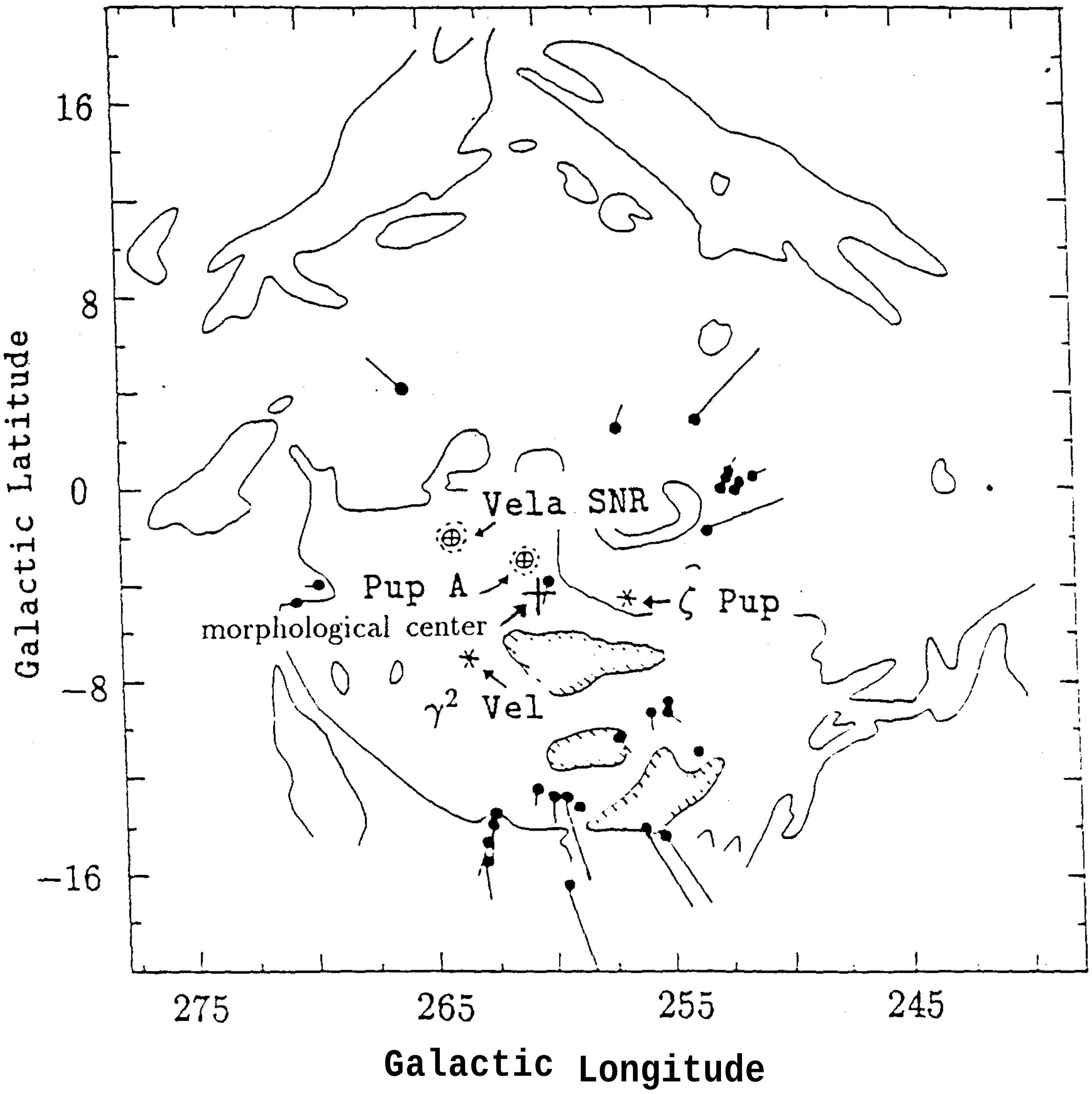

Figure 7.3: Overall picture of the Gum-Vela region showing the H_α emission as solid lines, the CGs as filled circles with tails (scaled up 10 times for clarity), the *morphological center* derived from the tails and other important objects in the region. The locations of objects shown are approximate (adapted from Pettersson 1991).

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Appendix A

In this appendix we derive formulae for obtaining the physical parameters of a molecular cloud from the observed J=1→0 transition lines of ^{12}CO and ^{13}CO. We basically follow the procedure outlined by Dickman(1978).

The assumptions made in the derivation are: (1) The excitation temperature of the J=1→0 transition is constant along the line of sight. (2) Both ^{12}CO and ^{13}CO have the same excitation temperatures for the J=1→0 transition and this temperature is equal to the kinetic temperature of the gas. (3) The J=1→0 transition of ^{12}CO is optically thick.

The specific intensity obtained after background subtraction and calibration is given by

$$I_\nu = [B_\nu(T_{ex}) - B_\nu(T_{bg})]\left(1 - e^{-\tau_\nu}\right) \tag{A.1}$$

The measured line temperature after all corrections is related, bydefinition, to I, as

$$I_\nu = 2kT_R^* \nu^2/c^2 \tag{A.2}$$

Keeping in mind that at 11.5 GHz $h\nu \ll kT$ is not valid and using T_{bg}=2.7K, the cosmic microwave background radiation temperature, one gets from equations A.1 and A.2,

$$T_R^* = [J_\nu(T_{ex}) - J_\nu(2.7)]\left(1 - e^{-\tau_\nu}\right) \tag{A.3}$$

where $J_\nu(T) = T_\nu/(e^{T_\nu/T} - 1)$ and $T_\nu = h\nu/k$. We derive below, the formulae for various physical parameters.

A.1 Temperature

For the optically thick line center of the ^{12}CO line, A.3 reduces to

$$T_R^* = T_{Lp} = J_\nu(T_{ex}) - J_\nu(2.7) \tag{A.4}$$

where T_{Lp} is the peak line temperature. Putting in numbers, we get, with the assumption that $T_{ex} = T_{kin}$,

$$T_{kin} = T_{ex} = \frac{5.532}{\ln(1 + \frac{5.532}{T_{Lp}+0.8182})} \tag{A.5}$$

A.2 Optical Depth

Assuming the excitation temperature for ^{13}CO to be same as that for ^{12}CO we derive from A.3 and A.5

$$\tau_{13} = -\ln\left[1 - \frac{T_{13}}{5.289}\left\{\left[e^{\frac{5.289}{T_{ex}}} - 1\right]^{-1} - 0.1642\right\}^{-1}\right] \tag{A.6}$$

where T_{13} is the T_R^* measured for ^{13}CO.

A.3 Column Density

We can relate the optical depth to the column densities of molecules $\mathcal{N}_0$ and $\mathcal{N}_1$ in the J=0 and J=1 rotational states respectively as

$$\tau_\nu = (h\nu/c)(B_{01}\mathcal{N}_0 - B_{10}\mathcal{N}_1)\phi_\nu \tag{A.7}$$

where B_{01} and B_{10} are the Einstein's co-efficients and ϕ_ν is the line profile function satisfying the condition $\int \phi_\nu d\nu = 1$. Using

$$\frac{\mathcal{N}_1}{\mathcal{N}_0} = \frac{g_1}{g_0} e^{-h\nu/kT_{ex}} \tag{A.8}$$

and

$$B_{01} = \frac{g_1}{g_0} A_{10} \frac{c^3}{8\pi h\nu^3} \tag{A.9}$$

and integrating over the line, we obtain

$$\int \tau_\nu d\nu = \mathcal{N}_0 \frac{c^2}{8\pi\nu^2} \frac{g_1}{g_0} A_{10} \left(1 - e^{-h\nu/kT_{ex}}\right) \tag{A.10}$$

The total column density $\mathcal{N}_{13}$ of ^{13}CO including all levels is obtained using the partition function Q for linear molecules (Dickman 1978),

$$\frac{\mathcal{N}_{tot}}{\mathcal{N}_0} = Q = 2T_{ex}/T_0 \tag{A.11}$$

With $A_{10} = 7.4$ x 10^{-8} s^{-1} one gets

$$\mathcal{N}_{^{13}CO} = 2.42 \times 10^{14} \frac{T_{ex} \int \tau_{13} dv}{(1 - e^{-5.289/T_{ex}})} \qquad \text{(A.12)}$$

where we have used $\int \tau_\nu d\nu = (\nu/c) \int \tau_v dv$.

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