Chapter 4

Photometry of the bright rim of the Cometary Globule CG 22

4.1 Introduction

In Chapters 2 and 3, the system of dark clouds seen in the Gum-Vela region called the Cometary Globules (CGs) were discussed. These clouds are seen to have a head-tail morphology with the tails generally pointing away from a central region. Further, this system of clouds is also known to be expanding about this center. The "heads" of the CGs show bright rims, which have been associated with diffuse emission rather than reflection nebulae (Struve 1937). Pottasch (1956, 1958) studied a number of these rims and suggested that they are diffuse HII regions, ionized by nearby O stars. The influence of nearby bright stars on the CGs manifests in other ways as well. In Chapter 2 we argued that the CGs form part of an expanding Shell of gas and dust with a mass of $\sim 10^5$ $M_\odot$ and radius of $\sim$ 80 to 90 parsecs, powered by the centrally located OB association Vela OB2. The velocities of the CG system in the Gum Nebula could arise in part from the "rocket effect" of the ionizing radiation from the nearby O star ζ Puppis (Sridharan 1992). In Chapter 3, we studied the magnetic field in one of the globules, CG 22. The morphology of the field seems to show some influence of an external source. The Cometary Globules are part of a larger family of dark globules which include elephant trunk globules, globular filaments and isolated dark globules (Bok Globules). Star formation is known to occur in at least some classes of small dark clouds including the CGs at enhanced efficiencies. These results are in general agreement with the theory developed by Bertoldi (1989) and Bertoldi and McKee (1990) for clouds exposed to ionizing radiation, again suggesting the influence of nearby stars. In the Gum Nebula, ζ Puppis and γ^2

Velorum (a Wolf-Rayet - O star binary) are two of the hot stars to which the ionization seen in the Nebula is primarily attributed (Reynolds 1976a, 1976b).

In Chapter 2 we touched upon the controversy sorrounding the nature of the Gum Nebula and its relation to the IRAS Vela Shell, Vela OB2, ζ Puppis and γ^2 Velorum. We concluded that it is most likely that the Cometary Globules and the IRAS Vela Shell were inter-related and their distances were similar to that of the Gum Nebula itself. This picture differs from the earlier conclusions of Sahu (1992). In support of these arguments we presented the new Hipparcos distance estimates for both ζ Puppis and γ^2 Velorum. In this chapter, we attempt to strengthen the causal connection between the Cometary Globules and ζ Puppis. As mentioned earlier, although the Cometary Globules seem to form part of a larger expanding molecular Shell, their morphology and *bright rims* certainly set them apart. It is therefore important that one assesses the role of the 041f giant, ζ Puppis, in the formation and evolution of the CGs. In the light of the new distance estimate to this star, one would be able to improve the distance estimate to the CGs themselves and in turn their association with IRAS Vela Shell if one firmly establishes that ζ Puppis is the main ionizing source.

In this chapter we describe a photometric study in Ha of the ionized rim of the Cometary Globule CG 22, the largest of the CGs in this region. The objective was to arrive at a quantitative estimate for the intensity of the Ha emission line and hence the number of recombinations per second within the rim. We also aimed to estimate the rim temperature from the line to continuum ratio. The estimate of the rate of recombinations can be used to determine whether the required ionizing radiation is consistent with that expected from the nearby stars, in particular ζ Puppis. This question is one of considerable relevance to the nature and evolution of the CGs as well as the IRAS Vela Shell. ζ Puppis and γ^2 Velorum are thought to play an important part in the ionization of the entire Gum Nebula and the question of their location has implications for the nature of this controversial giant HII region as well. We also discuss our results in the light of the new estimates to the distances of ζ Puppis, γ^2 Velorum and the OB association Vela OB2, arrived at through the measurements by the Hipparcos satellite.

To summarize, the basic motivation behind this experiment was to:

1. *Study the physical conditions prevailing in the rim.*

2. *Establish the role of ζ Puppis in its formation.*

4.2 Observations

The observations were done with the 2.3m (90") telescope at the Vainu Bappu Observatory, Kavalur on the night of December 3 1994 . The CG rim was imaged at the prime focus with an Astromed cooled CCD, giving a corrected field of view of $\sim$ 6' x 4', with a pixel size corresponding to $\sim$ 45". The "head" region of CG 22 is approximately 6' by 6' in size and the frame encompassed most of the rim. We imaged in two filters. "On-line" images were taken using an Ha (λ6563Å) filter with a passband of 100 Å. To estimate the continuum and isolate the line emission, we used an image taken with a broad band filter centered approximately on the line. For this purpose we used an R-band filter (λ6550Å) having a bandwidth of 1300 Å. For calibration we used the stars Hiltner 600 and HD 19445 (Oke and Gunn 1983). Each exposure in the Ha filter was limited to a maximum of 30 minutes to limit the number of cosmic ray events in the frame. The calibrators were observed for a similar period. The broad band frames were of $\sim$ 5 minutes duration each. The total exposure time on the rim was $\sim$ 90 minutes for the Ha images. Fig 4.1 shows an optical picture of CG 22 (from SERC 'J' survey plates). The dotted lines show the boundaries of the image that was taken in the Ha filter.

4.3 Data Reduction

The CCD frames were put through the standard processing steps of dark and bias removal and flat fielding. The flat fielding was done using sky flats. In order to estimate continuum and isolate line emission, we used a technique described by Waller (1990) and briefly summarized below.

The detected count rates through the two filters are

$$R_0(W) = \eta(W)[f(line) + \Delta\lambda(W)f_\lambda(cont)] \tag{4.1}$$

$$R_0(N) = \eta(N)[f(line) + \Delta\lambda(N)f_\lambda(cont)] \tag{4.2}$$

where W denotes the wide R-band and N the narrow (Ha) band filters, R_0 is the count rate from the imaging instrument (analog-to-digital units or ADUs per second), AX is the bandwidth of the respective filters, f_λ(cont) is the spectral flux density for the continuum and f(line) is the flux in line emission. The slope in the source spectrum across the wide band was neglected.

Using a calibrator star which has *no* line emission one can scale the broad band images to the narrow band images by equalizing count rates in the two, so

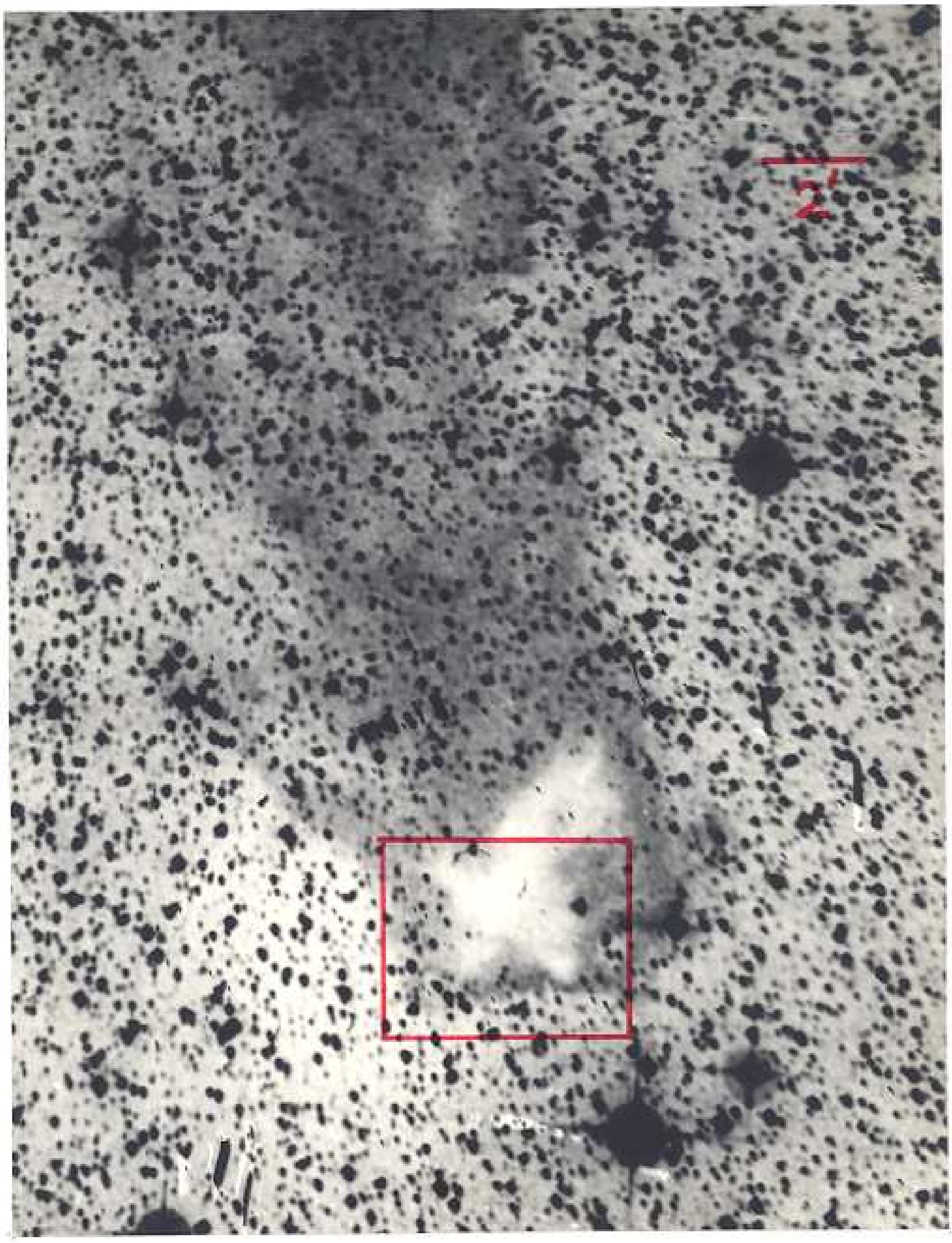

Figure 4.1: The head and part of the tail of the cometary globule CG 22 from the SERC 'J' plate. The box shows the approximate location of the frame used to estimate Hα emission. The approximate scale is indicated at the top right corner. The co-ordinates for the head are (RA,DEC) ~ (8h 26m 48.0s, -33° 34' 12.0")

that

$$R_0(N) - cR_0(W) = 0 \tag{4.3}$$

where the scaling factor is

$$c = \frac{\eta(N)\Delta\lambda(N)}{\eta(W)\Delta\lambda(W)} \tag{4.4}$$

After the scaling and subtraction of the continuum has been applied to the line images, the line flux is estimated from eqns: 4.1, 4.2 and 4.4 as

$$\mathrm{f\,(line)} = \frac{R_0(N) - cR_0(W)}{\eta(N)[1 - \Delta\lambda(N)/\Delta\lambda(W)]} \tag{4.5}$$

Once the wide and narrow band images are flux calibrated, f(line) is given by

$$f(line) = \frac{[f_\lambda(N) - f_\lambda(W)]\Delta\lambda(N)}{[1 - \Delta\lambda(N)/\Delta\lambda(W)]} \tag{4.6}$$

In similar fashion the continuum flux can be isolated from the line emission to give

$$f(cont) = \frac{f_\lambda(W) - [f_\lambda(N)\Delta\lambda(N)]}{[1 - \Delta\lambda(N)/\Delta\lambda(W)]} \tag{4.7}$$

The data reduction was done using the IRAF package from NOAO. Flux calibration, and scaling of broad band to narrow band were done using the magnitudes estimated from HD 19445, and repeated on Hiltner 600. The error on the magnitude estimates were $\sim$ 0.2 magnitude. The count rates in the above formulae have to be corrected for atmospheric extinction. However our estimate for the atmospheric opacity yielded values negligible when compared to the intrinsic errors in the magnitude estimation and therefore we neglected the extinction correction in our calculation.

4.4 Results

4.4.1 Ha! intensity and the Recombination rate

The intensity I, of the Hα emission line is given by

$$I_\alpha = \frac{h\nu}{4\pi} \int \epsilon\ \alpha_H\ n_e^2\ e^{-\tau} ds \tag{4.8}$$

where ϵ is the probability of an Hα photon being emitted per recombination, α_H is the effective recombination rate of hydrogen, n_e is the electron density, and τ is the optical depth to Ha photons of energy $h\nu$. The integral is over a pathlength s.

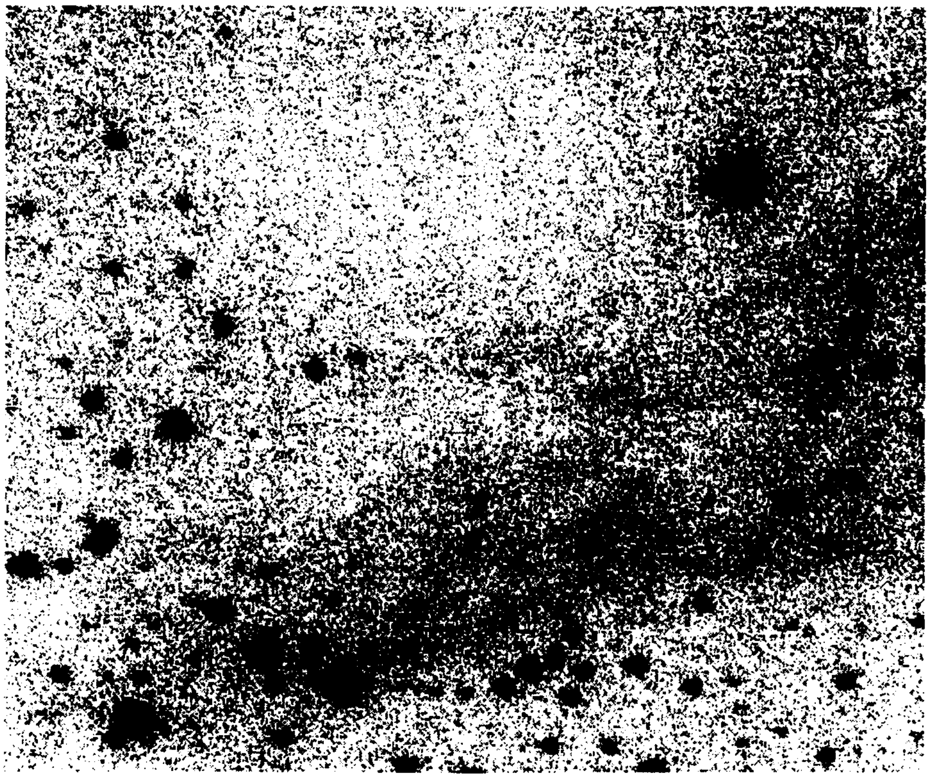

Figure **4.2:** A negative of the image taken with the H a filter of the bright rim of the cometary globule CG **22.** The region shown here is indicated by a box in Fig 4.1. The total exposure time for this frame was $\sim$ 90 minutes. Each individual exposure was limited to less than **30** minutes. The continuum flux has not been removed. The images of several bright stars are seen to be saturated.

Given the integrated emission $I_\alpha(tot)$ from the rim (i.e over the solid angle subtended by it) the number R of recombinations per second within the gas can be obtained from

$$R = 4\pi d^2 \frac{e^\tau}{\epsilon h\nu} I_\alpha(tot). \tag{4.9}$$

where d is the distance to the emitting gas. Fig **4.2** shows the image of the rim (this frame is marked on the SERC survey plate in Fig 4.1) taken with the H a filter. The continuum flux has not been removed. The rim is seen as the bright region (for ease of production, we have shown the negative images). Fig **4.3** shows CG **22** rim in H a emission after removal of the continuum emission. The line emission was isolated by scaling and subtracting the flux calibrated R-band frame from the calibrated H a image (equation **4.6).** Before subtraction the two images were aligned with reference to the bright stars present in them. A comparison of Fig **4.3** with Fig **4.2** shows the efficacy of removal of continuum

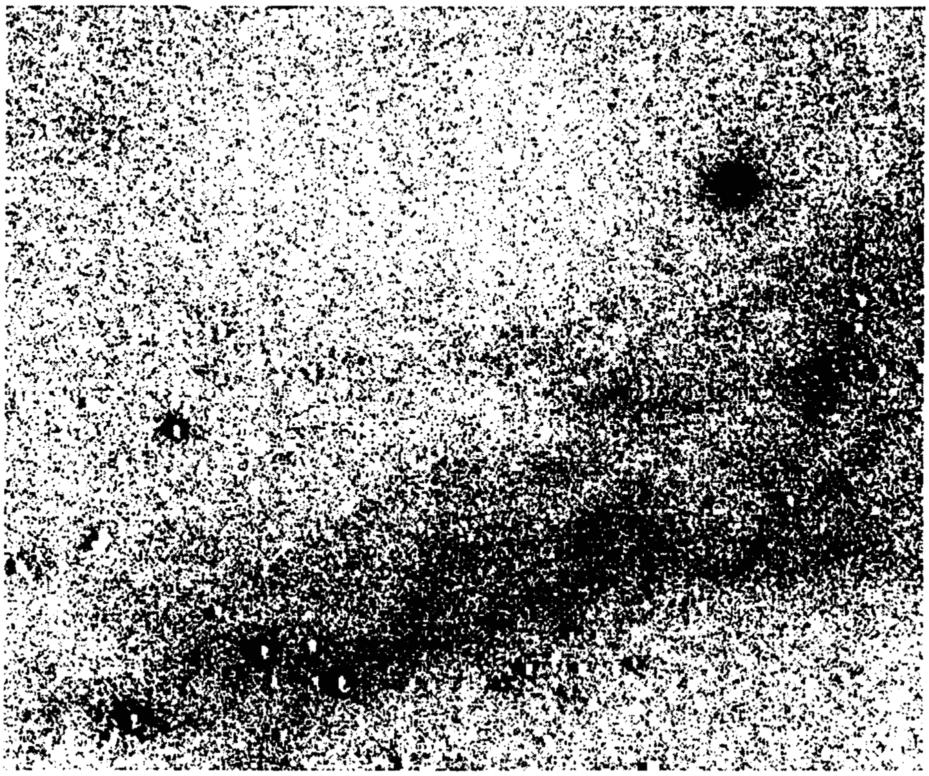

Figure 4.3: The rim of CG 22, as seen in Hα emission, after removal of the continuum emission. The continuum removal **was** done by subtracting a scaled R band image from the frame shown in Fig 4.2. The unsaturated stars seen in Fig 4.2 have disappeared, indicating the efficacy of this procedure. The subtraction does not remove the saturated stars, since the scaling is no longer applicable.

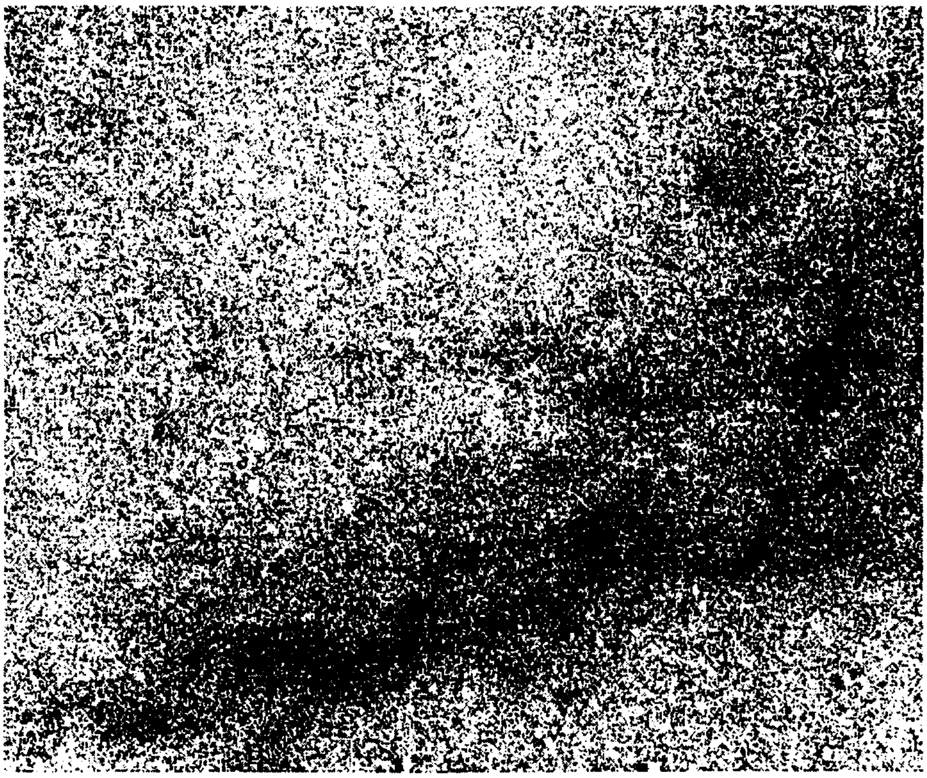

Figure 4.4: The rim of CG 22, as seen. in **Ha** emission, after removal of the continuum emission and editing out the saturated star images in the frame.

emission. The disappearance of the unsaturated stars in the $H\alpha$ frame can be used to gauge the extent of elimination of continuum light.

Before estimating the **Ha** flux from the rim, the saturated stars in the frame were removed by editing the image and the "holes" filled in with background flux levels estimated from the sorrounding regions. Fig 4.4 shows the rim after this was done.

Fig 4.5 shows the contour plot of the rim in $H\alpha$ emission after removal of the saturated stars. The contours are in flux units with a scaling factor of 7.75×10^{-18}.

The contours in Fig 4.5 envelopes all of the rim as seen in emission. The **Ha** flux estimate over this region is

$$f(\mathrm{Ha}) = (1.0 \pm 0.2)\ \mathrm{x}\ 10^{-11}\mathrm{ergs\ cm^{-2}\ s^{-1}}$$

the error being estimated from the measured magnitudes of the standard stars over the night.

From equation 4.9 the recombination rate within the bright rim is estimated

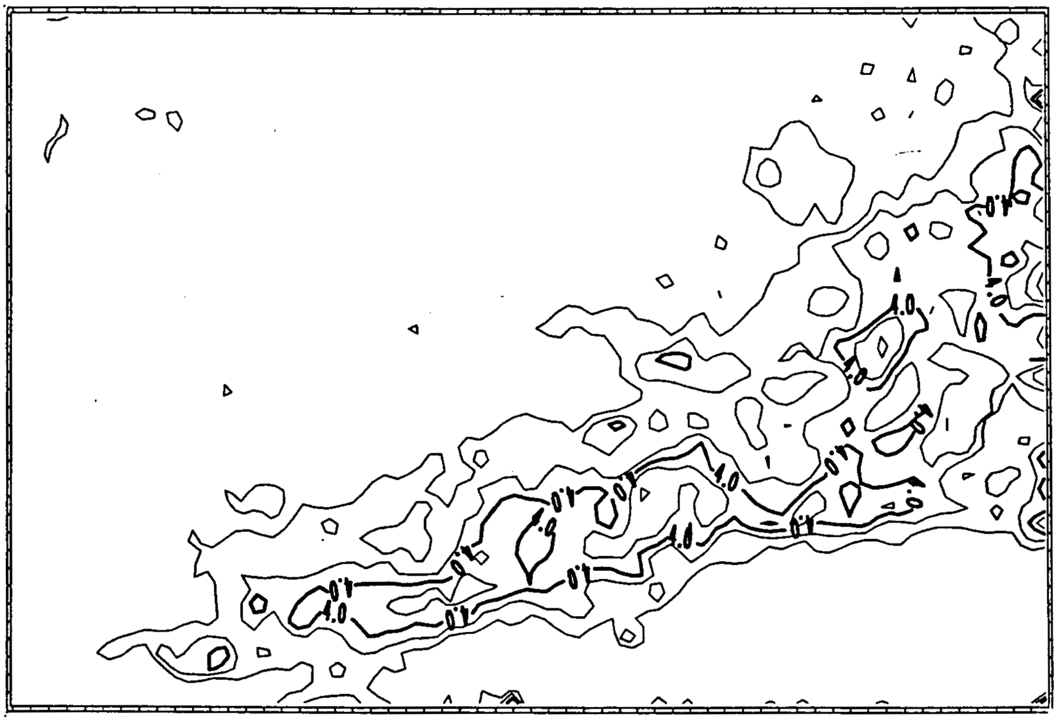

Figure 4.5: Contour plot of the $H\alpha$ flux seen in Fig 4.4. The contours are in flux units of ergs cm^{-2}s^{-1} with a scaling factor of 7.75×10^{-18}.

to be

$$R = 18.3 \times 10^{43} s^{-1}$$

The assumed values for the various quantities are:

1 d, the distance to the CG system = 450 pc. (Sridharan 1992, Sahu 1992).

2 ϵ, the Ha photon emission probability = 0.5 (Spitzer 1978).

3 τ, the optical depth to Ha photons = 0.15. This is from the estimated visual extinction A, of 0.19 towards ζ Puppis (Reynolds 1976a).

4.4.2 Is the Bright Rim caused by ζ Puppis?

The image scale for the 2.3m telescope is 45" per pixel. The angular size of the rim as included in the box shown in Fig 4.1 is 4'. Assuming a distance of 450 pc to the CG system, the linear size of the imaged section of the rim is 0.52 pc. The size of the head of CG 22 is $\sim$ 5' (0.65 pc at 450 pc) as estimated by Sridharan (1992). This is consistent with the size of the head as it appears in Fig 4.1. The rim faces ζ Puppis which is to the south and west of the globule. The projected area of the imaged section of the rim facing ζ Puppis is therefore $\sim 0.52 \times 0.65 = 0.43 \mathrm{pc}^2$. ζ Puppis is at a projected distance of 64 pc from the rim of CG 22, again assuming a distance of 450 pc for both the star and the globule (Sahu 1992). Assuming this to be the distance from ζ Puppis to the rim, and taking into account the number of ionizing photons intercepted by the rim at this distance, the required flux of ionizing photons ($h\nu > 13.6$ ev) from the star to produce the measured recombination rate is $\sim 2.8\times 10^{49}$ photons per second. Given the uncertainty in the surface temperature of ζ Puppis the flux of Lyman contimuun photons from this star is difficult to estimate. However for an estimated surface temperature of 42,000 K (Holm and Cassinelli 1977), the ionizing flux would be $\sim$ 5.9 x 10^{49} photons per second. This value is also consistent with that required for the ionization observed in the whole of the Gum Nebula (Chanot and Sivan 1983). Assuming this photon flux from ζ Puppis, this bright O star is clearly capable of providing the required number of ionizing photons to explain the observed ionization in the bright rim. The only other alternative source of ionizing photons in the region is γ^2 Velorum. This is a binary with an 091 star and a Wolf-Rayet (WC8) (the classification of the O star is now thought to be O8.5III, van der Hucht et *al.*, 1997; or 08111, Schaerer, Schmutz and Grenon, 1997; based on Hipparcos distance estimates.) The projected distance of this binary from CG 22 is about 1.8 times that of ζ Puppis. This would then require an ionizing photon flux of $\sim 8.9 \times 10^{49}$ per second, about 3 times that required from ζ Puppis. Neglecting the flux from the WC 8 companion , the estimates for the Lyman continuum flux from γ^2 Velorum is $\sim 1.32\times 10^{49}$ photons per second (Panagia 1973). This falls short of the minimum required flux by a factor of $\sim$ 7.

The Hipparcos distance estimate

Since we carried out this study, the distances to ζ Puppis and γ^2 Velorum have been measured by the Hipparcos satellite (van der Hucht et *al.*1997). The distance estimate to ζ Puppis is 429^{+120}_{-77} parsec. Vela OB2 also has been studied using the satellite. de Zeeuw et *al.*(1997) derive a mean distance of 415±10 parsec to this OB association. This important result confirms that ζ Puppis is in the vicinity of Vela OB2. The distance estimate also agrees with the previous estimates for the CG distances (Pettersson 1987; Brand et *al.*1983).

4.5 Conclusions and Discussion

We have obtained calibrated Ha intensity towards the bright rim of the Cometary Globule CG 22. We find that the recombination rate within the ionized rim of CG 22 globule is consistent with the ionizing source being the bright (O4If) star ζ Puppis. γ^2 Velorum, the other bright (binary) star in the region cannot account for all the observed ionized material in the CG rim, although it may contribute to the ionization. This finding *confirms* the association of ζ *Puppis* with the *system* of Cometary Globules. The system of CGs is known to be expanding, as discussed in Chapter 2. In a study of this system in molecular lines, Sridharan(1992) had conjectured that the observed expansion could be influenced by ionizing radiation from ζ Puppis. Our findings support this claim inasmuch as the star is situated near the CG system. The IRAS Vela Shell is an expanding shell of gas seen in the region with which the CGs seem to be associated. The entire Shell is seen to be expanding and the presence of ζ Puppis in this region can definitely influence the evolution of the IRAS Vela Shell as well. We had conjectured that the CGs are part of the larger Shell and that they differed (bright rims and head-tail morphology) from the other clouds in the Shell because of their proximity to ζ Puppis. In this Chapter we have been able to confirm this conjecture by showing quantitatively that the bright rim of ionized hydrogen in the globule CG 22 can only be caused by ζ Puppis.

There is some additional indication that the CG rims are presently ionized by ζ Puppis. ζ Puppis has a large proper motion and is classified as a runaway star presumably as a result of the disruption of a massive binary by a supernova explosion. The tails of the CGs are estimated to be ~ 3 Myrs old from the velocity gradients seen in CO. The tail formation therefore is a more gradual process compared to the lifetime of the rim (i.e, time required for the ionized hydrogen in the rim to recombine) and is likely to be from the combined influence of the stars in Vela OB2, as well as ζ Puppis, over a period of the order of a million years or so. The bright rims on the other hand are caused by ζ Puppis at its *present position.* Support for this comes from the fact that CG **31 A,** one of the globules closest to ζ Puppis shows a rim *on the side facing ζ Puppis in its present position, while the tail points to the Vela OB2 association where ζ Puppis presumably originated.* The Hipparcos distances show that Vela OB2 and ζ Puppis are at similar distances. Thus, since the CGs have to be in the proximity of ζ Puppis to explain their bright rims, they are also in the vicinity of these objects. The locations of these objects are consistent with the scenario we put forward in Chapter 2, namely that the CGs are part of a large Shell of gas expanding under the influence of Vela OB2. Their bright rims (and to some extent their tails also) are caused by ζ Puppis. γ^2 Velorum is at a distance of 258^{+41}_{-31} from Hipparcos measurements. This places it in the foreground of the other objects.

The temperature of the diffuse nebula associated with the rim can be estimated from the line flux to continuum flux ratio. However, our initial estimates yield values which are very low compared to the estimated temperatures for the rest of the Gum Nebula. We plan to improve on the continuum estimate to examine this inconsistency. The temperatures of such bright rims is an important handle on the origin and evolution of isolated clouds exposed to strong radiation fields. We also aim to map the tail of CG 22 in Hα to estimate the amount of ionized gas, if any. This would provide an important clue to the origin of the tail.

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An overall Summary of the main Results and Conclusions

Chapter 1

In the first chapter we described an observational effort to detect absorption in the 21 cm line radiation of neutral hydrogen from interstellar clouds which had earlier been detected through the absorption lines of Na and Ca^+. The major aim of this investigation was to establish a one-to-one correspondence between clouds seen in optical absorption towards bright stars and those seen in 21 cm absorption and emission in general Galactic surveys. The sample of stars chosen was such that in their line of sight optical spectra showed evidence of both low and high velocity clouds. In our opinion, the main contributions contained in this chapter are the following:

1. *This is the first 21 cm absorption study of the interstellar gas in the line of sight towards bright stars* which have been extensively probed earlier in optical absorption.
2. Twenty four fields were investigated. This yielded nearly fifty HI absorption spectra due to the fortuitous circumstance that in some fields there was more than one radio source.
3. *In most cases, the velocity of the HI absorption feature agreed with the corresponding low velocity optical absorption feature.*
4. In those lines of sight where HI emission data was available, it was found that the *emission and absorption velocities matched.*
5. *This enabled us to determine for the first time, the optical depths and spin temperatures of these clouds.*
6. The derived spin temperatures, optical depths, and absorption widths enabled us to identify for the first time that *the low velocity clouds seen in*

optical absorption are a subset of the general population of diffuse HI clouds seen both in 21 cm emision and absorption.

7. In our observations, *we failed to detect HI absorption corresponding to the high velocity optical absorption features* (our experimant was sensitive to an optical depth limit of ~ 0.1).
8. Since earlier HI emission studies also failed to detect hydrogen gas at the higher velocities, this provides an extremely important clue to the origin of the velocities of clouds.
9. We have advanced arguments that *the gas seen in optical absorption cannot be "circumstellar" in origin* – as had been conjectured earlier.
10. **A** scenario suggested earlier for the high velocity optical absorption features was that they arise in relic supernova shells. We have argued that if one takes careful account of the pressure of the compressed magnetic field in the supernova shells, as well as the pressure of the cosmic rays accelerated in situ, the interstellar gas swept up by the supernova blast waves will never get compressed to the kind of densities required to explain the observed absorption lines. Thus according to us, the scenario that optical absorption is produced by relic supernova shells is not viable.
11. *We have advanced detailed arguments to support the hypothesis that the high velocity optical absorption features arise in interstellar clouds which have been shocked and accelerated by supernova remnants in their late phases of evolution.* Such a mechanism would naturally result in the higher velocity clouds being warmer and also of lesser column density compared to the low velocity clouds.
12. *The above conclusion is fully consistent with the absence of high velocity 21 cm absorption features in our experiment.* Supporting evidence for this argument also comes from ultraviolet absorption studies towards bright stars.

Chapter 2

In this chapter we described a study of the molecular gas associated with a shell-like object in the Gum-Vela region delineated by its infrared emission. The main results and conclusions of this chapter are:

1. *We have established for the first time the presence of a substantial amount of molecular gas associated with the infrared Shell.* Previously, the only evidence for molecular gas was circmstantial and it hinged on the system of a few Cometary Globules, in which molecular gas had been detected, being physically associated with the infrared Shell.

2. *We have been able to demonstrate that this molecular Shell is in expansion about a common centre with a velocity of the order of* $12\ km\ s^{-1}$.

3. The fact that the system of Cometary Globules is also expanding with roughly the same velocity, and with respect to roughly the same location, provides evidence for the first time that the *Cometary Globules are in fact physically associated with the infrared and molecular Shell.*

4. We have also convincingly demonstrated that a subset of the so called "Southern Dark Clouds" are also part of the expanding Shell.

5. According to our estimate, *the total mass of the expanding Shell is of the order of* $10^5\ M_\odot$.

6. Based on the morphology of the Shell, its clumpiness, its expansion, and the presence of the Vela OB2 association of stars in the interior, we have advanced arguments that *the expanding Shell is most likely the remnant of the parent Giant Molecular Cloud* from which the Vela OB2 association formed; *the birth of the association resulted in the fragmentation of this cloud.* Till recently, it was a matter of controversy as to whether the Vela OB2 stars are part of a genuine association; the distance to these stars were also uncertain. The recent results from the Hipparcos satellite have laid to rest both these doubts.

7. Based on the Hipparcos estimate for the distance to ζ Puppis, we have advanced arguments that the system of Cometary Globules are energised by this luminous star.

8. We have also argued that the Gum Nebula is in the immediate foreground of the molecular Shell, and that it is a Stromgren sphere in the interstellar medium maintained by ζ Puppis.

9. We have attempted to place this expanding Shell of molecular gas in the context of other prominent structures one encounters in the interstellar medium such as "super shells". In our opinion, *this expanding shell of molecular gas discovered by us will, in* $\sim 10^7$ *years develop into a classical neutral hydrogen super shell. After another* 10^7 *years or so, the swept up shell will undergo* instabilities resulting in secondary massive star formation such as we witness in the Gould's Belt.

Chapter 3

In this chapter we reported some measurements of optical polarisation of light from stars within, and seen through, the Cometary Globule CG 22. The aim of this experiment was to detect and determine the orientation of the magnetic field in this globule. The main results were:

1. Thirteen stars within and just outside the Cometary Globules were targetted.

2. *We have detected linear polarisation of the order of 1% for stars within the boundary of CG 22, with the polarisation vector parallel to the cometary tail.* In the case of stars outside the boundary of the globule, either no polarisation was detected or a small degree of polarisation parallel to the Galactic plane.

3. *From the direction of polarisation we conclude that the magnetic field in CG 22 is oriented parallel to its tail.*

4. Based on a rough estimate of the strength of the field we have argued that it may be dynamically important.

5. We conclude that the alignment of the field parallel to the tail may be causally connected with the process of the formation of the tail itself.

Chapter 4

In chapter 4 we presented a photometric observation of the Ha emission from the bright rim of the Cometary Globule CG 22. The objective was to establish the physical conditions prevailing in the rim.

1. *We have presented the **first** ever quantitative estimate of the total $H\alpha$ **flux** from the ionised gas in the bright rim of a cometary globule.*

2. Our results clearly indicate that the primary agent responsible for the bright rim is ζ **Puppis**. We have ruled out the possibility that the other bright star in the region y^2 Velorum also plays an important part.

3. In chapter 2 we had established that the Cometary Globules are associated with the Shell sorrounding the Vela OB2 association. The recent Hipparcos measurement places ζ **Puppis** at roughly the same distance as the Vela OB2 association. *Thus it should be taken as firmly established that ζ **Puppis** plays an important role in producing the cometary morphology of the globules.*