Kinematics of the Young Stellar Objects associated with the Cometary Globules in the Gum Nebula

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ABSTRACT

An analysis of proper motion measurements of the Young Stellar Objects (YSOs) associated with the Cometary Globules (CGs) in the Gum Nebula is presented. While earlier studies based on the radial velocity measurements of the CGs suggested expansion of the system of the CGs, the observed proper motion of the YSOs shows no evidence for expansion. In particular the kinematics of two YSOs embedded in CGs is inconsistent with the supernova explosion of the companion of ζ Pup about 1.5 Myr ago as the cause of the expansion of the CG system. YSOs associated with the CGs share the average proper motion of the member stars of the Vela OB2 association. A few YSOs that have relatively large proper motions are found to show relatively low infrared excesses.

Key words: stars: pre-main-sequence, kinematics - ISM: globules, clouds and HII regions:individual : Gum nebula

1 INTRODUCTION

The Gum Nebula, a prominent HII region of southern Milky Way, was discovered by (Gum 1952). The whole nebula is around 36° in diameter (Chanot & Sivan 1983). The true nature of the Gum Nebula is not very clear. Along with the two O type stars ζ Pup and γ^2 Velorum, two OB associations, Vela OB2 and Tr 10, have been found in the Gum Nebula region. There are also two supernova remnants (SNRs) in the direction of the Gum Nebula, Pup A and

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Vela SNR. However, Sridharan (1992) argued that the spatial coincidence of these two SNRs with the Gum Nebula is due to chance superposition. Chanot & Sivan (1983) described the Gum Nebula as an intermediate structure between classical HII region and typical supernova remnant.

About 30 cometary globules have been found in the Gum Nebula and they are distributed in a nearly circular pattern. They share common features of a compact, dusty head (sometimes with a bright-rim), and a comet-like tail. The tails of the globules generally point radially outwards from the centre of the Vela OB2 association. The axes of these CGs seem to converge on a very small area around at $l_{\parallel} \sim 261°$, $b_{\parallel} \sim$ - 5° e. g. Reipurth (1983), Zealey et al., (1983). The source of the CG complex is as yet still unclear. A single source may not be responsible for the formation and the evolution of the Gum Nebula complex. ζ Pup, and γ^2 Velorum and the two OB associations are considered as the probable source of the UV radiation and photoionisation of the nebula in the literature.

There are some uncertainties about the distances of ζ Pup and γ^2 Velorum. The estimated Hipparcos distance to the Wolf-Rayet WC8+O spectroscopic binary γ^2 Velorum is 258^{-31}_{+41} pc and to the O4I(n)f star ζ Pup it is 429^{-77}_{+120} pc (van der Hucht *et al.* 1997). However, Pozzo *et al.* (2000) argued that the distance to the γ^2 Velorum may be same as that for the Vela OB2 association. Again the estimated Hipparcos distance to the Vela OB2 association is 410 pc (de Zeeuw *et al.* 1999) and Woermann *et al.* (2001) estimated a distance of 500 pc to the expansion centre of the association. In this context an average distance to the CG system as 450 pc is reasonable as adopted by Sridharan (1992).

There have been several studies on the kinematics of the Gum Nebula region to determine whether the system is expanding or not, e. g. Yamaguchi *et al.* (1999) and references therein. Most of the studies concluded that the molecular material associated with the Gum Nebula is expanding though the expansion velocities obtained from various studies are different from each other. Zealey *et al.* (1983) and Sridharan (1992) studied the kinematics of the CGs in details and based on the radial velocity measurements concluded that the CGs are expanding and obtained the expansion velocity of the system as 5 and 12 km s^{-1} respectively. Woerman *et al.* (2001) investigated the kinematics of the neutral material around the Gum Nebula. They concluded that the Diffuse Molecular Clouds (DMCs) and Cometary Globules(CGs) form a single expanding shell centred on $l_{\parallel} = 261°$, $b_{\parallel} = $ -2.5°. According to their model the shell is asymmetric with the radii of the front and back faces as 130 and 70 pc respectively. They also obtained the expansion velocities of 14 and 8.5 km s^{-1} for front and back faces

respectively. They suggested the supernova explosion of the companion of ζ Pup about 1.5 Myr ago as the probable origin of the Gum Nebula and the expanding shell.

There have been no studies of the transverse (in the plane of the sky) motion of the Gum Nebula and the associated CGs. In this paper we have examined the proper motion measurements of stellar and young stellar objects (YSOs) in this region to study the expansion of the system of CGs and possible sources responsible for the triggered star formation in the CGs of Gum Nebula. In Section 2. and 3. we summarise the characteristics of the CGs in the Gum Nebula as well as the known YSOs in and around the CGs. We discuss the proper motions of the YSOs in Section 4. Results are discussed in Section 5. and conclusions are presented in Section 6.

2 COMETARY GLOBULES IN THE GUM NEBULA

Zealey *et al.* (1983) carried out an extensive study of the cometary globules in the Gum Nebula region. They found 29 CGs within a region of projected angular radius of 9.5°. They tabulated the coordinates, position angles, tail directions and measured H_2CO radial velocities of some of the CGs. They proposed the approximate centre of the CG complex based on the best fitting circle of the CG positions. Sridharan (1992) found some discrepancies in the coordinates of the CGs and redefined the coordinates of the individual CGs. Sridharan (1992) studied the kinematics of the cometary globules in the Gum Nebula using the transition lines of ^{12}CO and tabulated the V_{LSR} velocities of most of the CGs. We have adopted positions and velocities from Sridharan (1992) and the approximate centre of the system from Zealey *et al.* (1983). Reipurth (1983) suggested that the CGs are pointed towards the triangle formed by ζ Puppis, γ^2 Velorum and Vela Pulsar and estimated an average projected distance of 70 pc for the CGs from the centre of the triangle. It is possible that the two O type stars and the progenitor of the Vela Pulsar were the main energy source of the whole Gum Nebula region in the past. In Figure 1 we have plotted the respective CGs, members of the Vela OB2 association and the Young Stellar Objects(YSOs) around the CGs in the galactic coordinates together with the the probable energy sources γ^2 Velorum and ζ Pup. The adopted centre of the nebula from Zealey *et al.* (1983) is also plotted. The vectors associated with the CGs in the plot have lengths proportional to the tail-lengths of the CGs and also indicate their directions.

Various authors derived the centre of expansion of the CG complex, e. g. , Zealey *et al.*
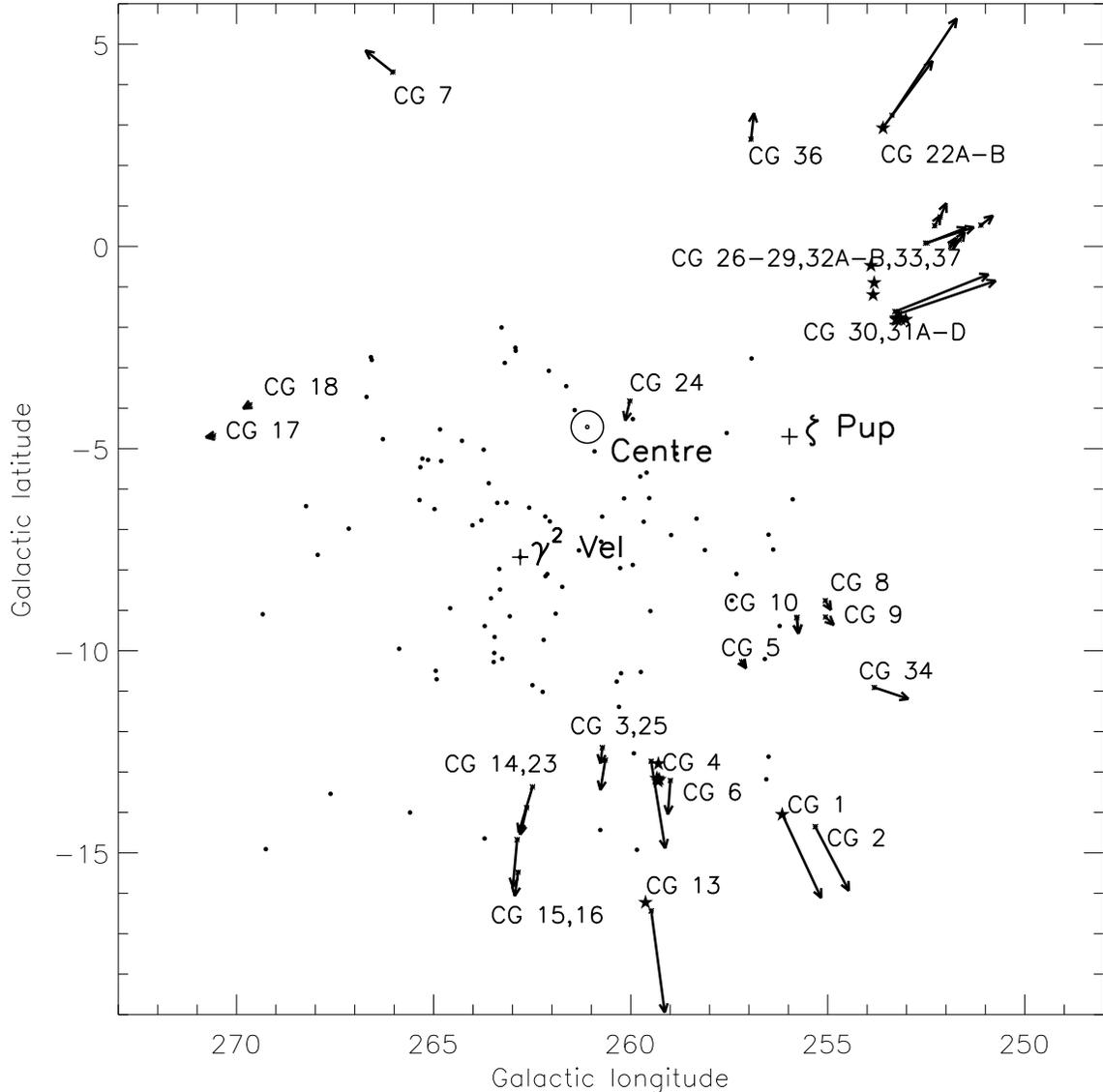
Figure 1. Distribution of CGs in the galactic coordinate. The tail vectors have lengths proportional to the tail lengths of the respective CGs. *Filled Circles* represent the members of the Vela OB2 association. *Stars* represent the Young Stellar Objects around the CGs. Positions of ζ Pup and γ^2 Velorum are also marked .

(1983), Reipurth (1983) and Sridharan (1992). In this paper we have adopted the position of the centre as suggested by Zealey *et al.* (1983) i. e., RA(2000) = $08^h19^m40.54^s$ Dec(2000) = - 44°09′30.8″ (l ~ 261.10°,   b ~ - 4.46°)   which is in good agreement with the centre coordinate (l ~ 261.5° ,   b ~ - 4.0°)   obtained by Woerman *et al.* (2001). We have also adopted the approximate centre of the Vela OB2 association as RA(2000) = $08^h07^m00.22^s$ Dec(2000) = - 46°41′53.8″ (l ~ 262.3°,   b ~ - 7.71°).

Reipurth (1983) proposed a mechanism for the formation and evolution of the CGs based on the interaction of the massive stars and their parent molecular cloud. Brand *et al.* (1983)

proposed that the cometary morphology has been created by the passing of shock wave through a spherical molecular cloud. They also suggested the possibility of star formation in the shocked molecular clouds. Analytical models (also known as the radiation driven implosion (RDI) models) have been developed by Bertoldi (1989) and Bertoldi & McKee (1990). Lefloch & Lazareff (1994) studied the evolution and morphology of the cometary globules by a 2-d hydrodynamic simulation. These models could not reproduce the details of triggered star formation by the UV radiation because they did not include the effect of self gravity. Miao *et al.* (2006) have shown the evolution of the cometary globules as well as the triggered star formation under the influence of the UV radiation of the massive stars by a 3-d smoothed particle hydrodynamics (SPH) simulation.

According to these models, when an OB association forms in a comparatively dense core of a clumpy Giant Molecular Cloud (GMC) its interaction with its parent molecular cloud can be destructive or constructive depending on the size and density distribution of the leftover clumps and cores of the parent GMC. The UV radiation from the massive young stars evaporates the gas and less dense material in its surroundings and creates an expanding Strömgren sphere. But it cannot evaporate the relatively dense cores of the clumpy parent cloud because of the recombination shielding of the front layer known as the ionised boundary layer [IBL] (Elmegreen 1976). However, the ionised gas starts to move towards the ionising source and due to momentum conservation the clumps also get a velocity radially outward from the central star. This mechanism is known as Rocket Effect (Oort & Spitzer 1950). The rocket effect pushes the loosely bound gaseous envelope much more effectively than the dense core. The expanding Strömgren sphere also creates a shock wave which interacts with the leftover remnant clumps and converts them into more dense regions. As a result a newly exposed dense core generally has a thin ionized layer and a tail in the opposite direction created by the leftover material of the parent GMC. At the same time the compression by the shock front can trigger the next generation star formation in the dense core. It thus provides the additional external pressure force to the gravity to collapse the clumps to form stars. This process of star formation is known as triggered star formation as opposed to the spontaneous star formation where only gravity is responsible for the collapse of the cloud core. Also the low mass stars which have formed in these globules simultaneously with the massive stars are exposed to photoevaporation.

Considerable evidence for current low mass star formation in the cometary globules of the Gum Nebula is discussed in the following section.

3   YOUNG STELLAR OBJECTS IN AND AROUND THE COMETRAY GLOBULES

Photometric and spectroscopic studies to investigate the low mass star formation in the Cometary Globules have been undertaken by Petterson (1987), Sahu (1992), Reipurth (1983, 1993), Kim (2005). Based on Hα emission line, Li absorption line and near IR infrared excesses, $\sim$ 30 YSOs have been identified in the direction of the Gum Nebula. There are confirmed signatures of the low mass star formation in the globules; e.g. CG 1(Reipurth, 1983), CG 22 [Sahu (1992), Reipurth (1983, 1993)], CG 30/31/38 complex [Reipurth (1983), Petterson (1987), Kim (2005)], CG 4/CG 6/Sa101 and CG 13 (Reipurth, 1993). We have tabulate the optical and near IR photometric measurements of the individual YSOs in the Table 1. We also include the spectral types and the measured Hα equivalent widths in the Table 1. Near IR magnitudes are taken from the 2MASS Point Source Catalog (Cutri, 2003). Except for NX Pup which is of spectral type A, the other YSOs found near the CGs are all late type stars with spectral types F, K and M. We also tabulate some useful parameters related to the known star forming CGs and dark clouds in Table 3.

Petterson (1987) made photometric, spectroscopic and infrared observations of 16 Hα emission line stars in the region near the cometary globules CG 30/31/38. They identified 9 T Tauri stars. They also found that except PHa 12 and PHa 44 all other spectroscopically confirmed YSOs are variable in V band. PHa 41 has shown optical variability of $\sim$ 3 mag. and PHa 15, PHa 21, PHa 34, PHa 41 have large (U-B) excesses.

Petterson & Reipurth (1993) surveyed five fields in the Gum Nebula for low mass emission line stars. They found 7 Hα emission line stars near the CG4/CG6/Sa 101 cloud complex and one more near CG 13. They confirmed the nature of the objects as the low-mass young stars [RP93] based on the low resolution spectra, optical and near IR photometry.

Kim *et al.* (2005) presented photometric and spectroscopic observations of low mass pre-main sequence stars in the cometary globules CG 30/31/38. They identified PMS stars in that direction by photometric and spectroscopic studies. They confirmed the youth of the PMS stars using the lithium abundances. They also measured the radial velocities of the PMS stars which are consistent with those of the cometary globules. However, Kim *et al.* (2005) also suggested that XRS 9, KWW 1055, KWW 1125, KWW 1333 and KWW 1806 are probably old field stars (50-100 Myr) with strong magnetic activity. We do not consider these objects in further discussion.

Table 1. Photometric and spectroscopic measurements of YSOs associated with CGs and Diffuse Molecular Clouds

No.	Name	V	Spectral Type	$W_\lambda(H\alpha)$ A°	J	H	K	Ref.[a]
1	NX Pup	10.61[1]	A0[1]	-44.0[5]	8.579 ±0.030	7.285±0.042	6.080 ±0.031	1,5
2	KWW 464	15.82	M3V	-2.8	12.126±0.024	11.392±0.026	11.173 ±0.026	2
3	KWW 1892/PHa 12	15.17	M1V	-26.6/-31.3	11.402±0.023	10.663±0.023	10.323 ±0.021	2,3
4	KWW 598	17.27	M2V	-11.5	12.150±0.024	11.519±0.023	11.281 ±0.023	2
5	KWW 1863	14.65	M1V	-2.8	10.873±0.028	10.194±0.033	9.940 ±0.024	2
6	KWW 1637	12.15	K6V	-2.4	9.529±0.023	8.880±0.022	8.708 ±0.024	2
7	KWW 873	13.81	K7V	-7.9	10.676±0.023	9.947±0.023	9.578 ±0.023	2
8	KWW 1043/PHa 15	16.61	M3V	–	11.925±0.028	11.135±0.025	10.628 ±0.024	2,3
9	KWW 975/Pha 14	15.56	M2V	-8.43	11.387±0.022	10.640±0.025	10.299 ±0.023	2,3
10	KWW 1302	15.76	M4V	-8.23	11.500±0.032	10.761±0.036	10.429 ±0.023	2
11	KWW 1953	15.58	M3V	-4.24/ -4.93	11.438±0.023	10.722±0.022	10.510 ±0.023	2
12	KWW 2205	16.20	M4V	-4.34	11.780±0.023	11.122±0.022	10.840 ±0.021	2
13	KWW XRS 9	–	G5V	3.23	9.783 ±0.021	9.464±0.022	9.346 ±0.023	2
14	KWW 1055	14.40	G2V	2.17	12.424±0.026	12.028±0.025	11.890 ±0.023	2
15	KWW 314	15.14	A3e	6.2	12.546±0.024	12.155±0.023	11.931 ±0.026	2
16	KWW 1125	12.35	<F8V	5.75	11.285±0.023	11.085±0.023	11.015 ±0.023	2
17	KWW 1333	13.64	<F8V	5.23	12.074±0.024	11.788±0.027	11.694 ±0.026	2
18	KWW 1806	13.99	<F8V	0.81	12.262±0.028	11.820±0.031	11.678 ±0.027	2
19	PHa 44	15.8	K7-M0	-50.7	12.996±0.028	12.175±0.027	11.713 ±0.019	3
20	PHa 51	15.7	K7-M0	-70.1	12.664±0.027	11.730±0.023	11.090 ±0.023	3
3	PHa 12	15.5	M1.5	-16.1	11.402±0.023	10.663±0.023	10.323 ±0.021	3,2
21	PHa 21	16.4	M4	-48.1	12.212±0.026	11.420±0.022	11.058 ±0.023	3
22	PHa 34	15.6	K3	-60.5	12.439±0.029	11.642±0.026	11.031 ±0.023	3
23	PHa 40	16.4	M0.5	-18.7	12.750±0.024	11.759±0.022	11.326 ±0.021	3
24	PHa 41	14.0	–	-98.6	10.775±0.024	9.806±0.022	8.914 ±0.024	3
8	PHa 15	16.9	M3	-130.5	11.925±0.028	11.135±0.025	10.628 ±0.024	3,2
9	PHa 14	16.4	M2	-22.0	11.387±0.022	10.640±0.025	10.299 ±0.023	3,2
25	PHa 92	13.38	K2	-35.4	10.573±0.023	9.692±0.024	9.044 ±0.021	3
26	[RP93] 1	>17	M3-4	-24.8	11.378±0.023	10.716±0.025	10.406 ±0.023	4
27	[RP93] 2	>17	M2	-266.5	12.855±0.021	11.932±0.021	11.404 ±0.020	4
28	[RP93] 3	14.99	K7	-27.0	11.204±0.022	10.218±0.021	9.582 ±0.020	4
29	[RP93] 4	14.59	K7-M0	-19.3	11.423±0.033	10.669±0.042	10.244 ±0.031	4
30	[RP93] 5	15.25	K2-5	-126.9	11.959±0.026	10.820±0.030	10.020 ±0.023	4
31	[RP93] 6	14.21	K7	-5.0	10.445±0.022	9.531±0.022	9.111 ±0.025	4
32	[RP93] 7	13.97	K5	-9.8	11.491±0.023	10.739±0.023	10.352 ±0.025	4
33	[RP93] 8	15.33	M1-2	-42.1	11.830±0.027	11.066±0.024	10.832 ±0.021	4

Notes:[a] 1: Hillenbrand *et al.* 1992, 2: Kim *et al.* 2005, 3: Petterson *et al.* 1987, 4:Reipurth *et al.* 1993, 5:Manoj *et al.* 2006 JHK measurements from the 2MASS ALL-Sky Release Point Source Catalog.

There are two YSOs, NX Pup and PHa 92, which are of some special interest. From the Figure 4 and Figure 5 it seems very likely that they are embedded in the heads of CG 1 and CG 22 respectively. Both the stars show associated reflection nebulosities, Hα emission line and near IR excess. Based on these observations Reipurth (1983) concluded that NX Pup is an YSO formed in CG 1. Sahu *et al.* (1992) also confirmed that PHa 92 is a T-Tauri star formed in CG 22. As these two YSOs are still associated with the respective CGs we can use the proper motion of the two stars as the transverse motion of the respective CGs. The formation and evolutionary models of the CGs predict a net radially outward motion . The CG tails are also directed radially outward. It should be noted that the tail formation is a relatively fast process and, therefore, the tail direction is determined by the current position of the cloud and the exciting star, while the direction of motion of the star born

Table 2. Statistics of proper motion of the YSOs and Vela OB2 members

Objects	$< \mu_\alpha \cos\delta >$ mas yr^{-1}	$\sigma(\mu_\alpha cos\delta)$ mas yr^{-1}	$< \mu_\delta >$ mas yr^{-1}	$\sigma(\mu_\delta)$ mas yr^{-1}
All YSOS	-8.39	5.12	10.25	7.53
High Velocity YSOs	-16.33	6.47	21.65	8.23
Normal Velocity YSOs	-6.27	1.38	7.20	3.37
Vela OB2 members	-6.42	2.45	8.13	1.93

in the CG would be determined by the initial velocity of the cloud (inertia) and prolonged acceleration, if any, due to the winds, radiation and supernova shocks of massive stars. Here we have used the proper motion measurements of the YSOs to study the kinematics of the CGs and effects of earlier events in the region on these objects, if any.

4   PROPER MOTION OF THE YOUNG STELLAR OBJECTS

We have collected the available proper motion data on the confirmed YSO candidates from the Naval Observatory Merged Astrometric Dataset (NOMAD) (Zacharias *et al.* , 2005) catalog. We have selected only those YSOs whose proper motion of at least one component is greater than the error of the measurements given in the catalog. We have also considered the catalog by Ducourant (2005) for the proper motion of the Pre Main Sequence (PMS) stars. The best measurements (smallest error) available in the two catalogs have been selected. However, (NOMAD) does not have the measurements for NX Pup. We have taken the proper motion measurements for NX Pup from Tycho 2 catalog (Hog *et al.* ,2000). For the stars taken from NOMAD catalog, we have converted their proper motion to the galactic coordinates by the formula as described by Mdzinarishvili (2005).

We tabulate the identification number, name, radial distance from the respective star to the NOMAD counterpart (r), equatorial coordinates, proper motion measurements and the associated errors in the respective columns of Table 4 . The observed differential proper motions of the YSOs with respect to the mean proper motion of the Vela OB2 are tabulated in Column (10) and Column (11). The proper motion measurements in galactic coordinates are included in Column (12) and Column (13) and the differential proper motion of the YSOs with respect to the mean proper motion of the Vela OB2 in galactic coordinate are tabulated in Column (14) and Column (15).

We have tabulated the mean proper motions of the YSOs from Table 4 and the member of the Vela OB2 association (de Zeewu *et al.* , 1999) from Tycho 2 Catalog (Hog, 2000). From Table 2 its quite clear that mean proper motion of all the YSOs is not similar to that
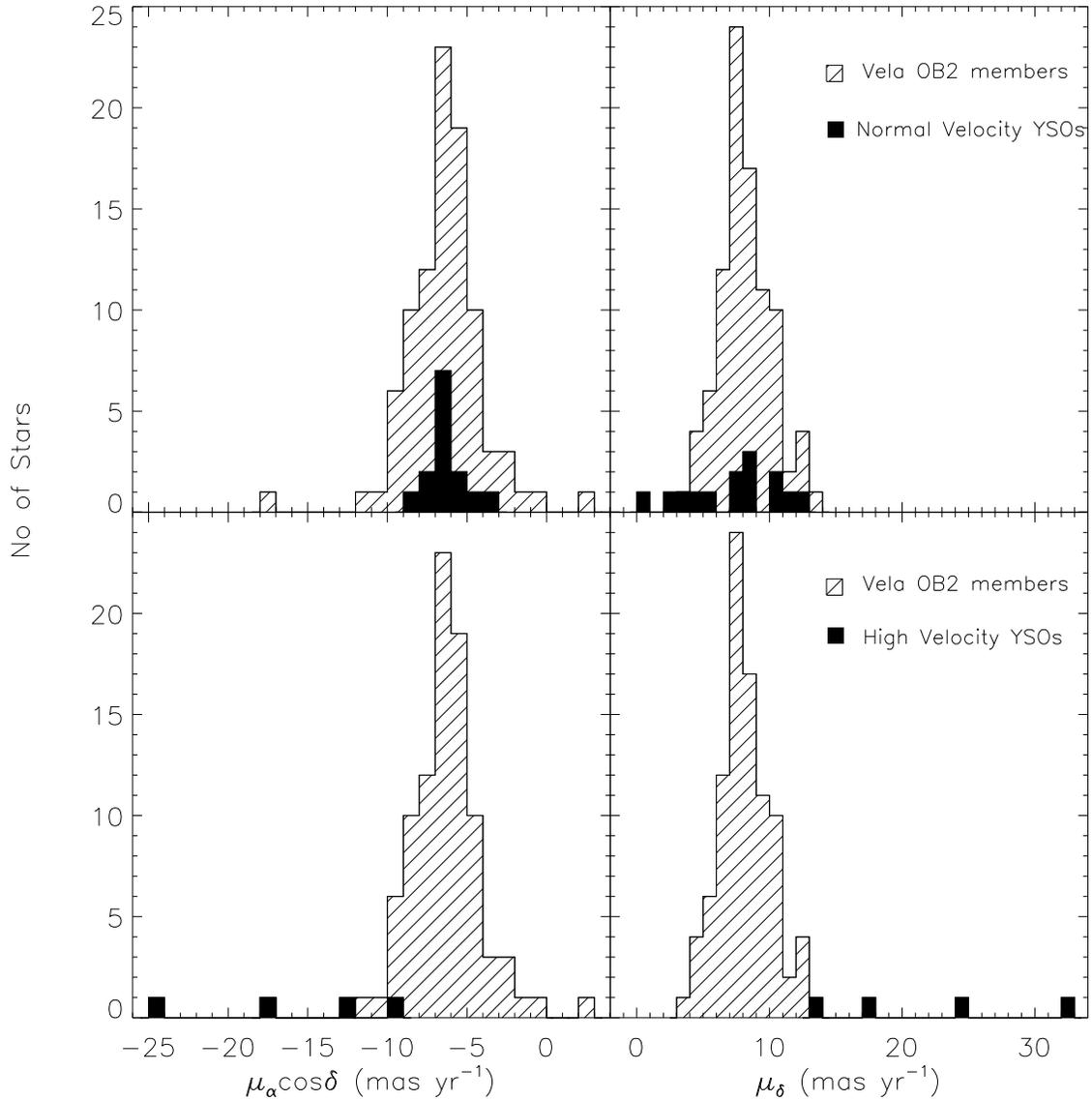
Figure 2. Proper motion histograms of *Normal Velocity YSOs*, *High Velocity YSOs*, and the members of Vela OB2 association. *Line-filled* histogram represent the members of the association and the *solid* histogram represent the YSOs.

of the Vela OB2 members. We consider YSOs 2, 4, 11 and 29 as *High Velocity YSOs* due to their proper motions being greater than 2σ from the mean in both the components. We discuss the properties of *High Velocity YSOs* in detail in the Section 5. Excluding the *High Veocity YSOs*, the rest of the YSOs are termed as *Normal Velocity YSOs*. The mean proper motion of the *Normal Velocity YSOs* is similar to the mean motion of the members of the Vela OB2 association within the error limit associated with the measurements of the proper motion. We have plotted the histogram of the proper motion of both *Normal Velocity YSOs* and *High Velocity YSOs* with the Vela OB2 association in Figure 2.

The heliocentric velocity of the association $V_{helio} = 18$ km s^{-1} (de Zeeuw*et al.* , 1999),

which is equivalent to V_{LSR} = 4 km s^{-1}. The radial velocities of the CGs and Diffuse Molecular Clouds (DMCs) are taken from Sridharan (1992), Woermann *et al.* (2001) and Otrupcek *et al.* (2000) respectively. The mean V_{LSR} ($< V_{LSR} >$) of the CGs is 1.74 km s^{-1} with $\sigma_{V_{LSR}}$ = 4.73. Among all the CGs, only CG 24 has radial velocity more than 2σ away from the mean. Excluding CG 24, $< V_{LSR} >$ for rest of the CGs is 2.13 with $\sigma_{V_{LSR}}$= 4.13. $< V_{LSR} >$ of the DMCs is 5 km s^{-1} with $\sigma_{V_{LSR}}$ = 6 km s^{-1}. Out of the 106, 96 DMCs have values within 2σ of the calculated mean. $< V_{LSR} >$ of these 96 DMCs is 3.5 km s^{-1} with $\sigma_{V_{LSR}}$= 4.52 km s^{-1} . These values indicate that there is a good coupling between the CGs, DMCs and the members of the Vela OB2 associations. All these systems of objects have the same average motion.

5   DISCUSSION

Woermann *et al.* (2001) have suggested that the supernova explosion of the massive binary companion of the ζ Pup is responsible for the origin of the Gum Nebula. They estimated that the explosion took place $\sim$1.5 Myr ago. They also suggested that the runaway O-star ζ Pup was within $< 0.5°$ of the expansion centre of the neutral shell $\sim$1.5 Myr ago. As a first order estimate we have traced back the proper motion of ζ Pup and Pha 92 and NX Pup (embedded YSOs) in galactic coordinates, and calculated their angular separations. The angular separation of PHa 92 and NX Pup from ζ Pup as a function of time in the past are plotted in Figure 3. We do not see any indication of convergence between all three in the last 1.5 Myr . This trend suggests that the supernova explosion of the companion of the ζ Pup did not give any radial motion to the stars NX Pup and PHa 92. So the supernova explosion was not responsible for the bulk motion of CG 1 and CG 22 associated with NX Pup and PHa 92 respectively.

Woermann *et al.* (2001) also gave a likely configuration of the Gum nebula. They suggested that most of the CGs and the Vela OB2 association are situated within the front face of the expanding shell. The expected transverse velocity components of the two stars based on the radial velocities of the CGs and the expansion velocity of the system can be calculated using the following formula $V_T = \sqrt{V_{exp}^2 - V_{radial}^2}$.

Considering V_{LSR} (CG 1) = +3.3 km s^{-1} and V_{LSR} (CG 22)= 6.65 km s^{-1} from Sridharan(1992) and V_{exp} = 14 km s^{-1} for the front face from Woermann *et al.* (2001) we obtained the expected transverse velocity components as V_T (CG 1)= 13.6 km s^{-1} and V_T (CG 22)=
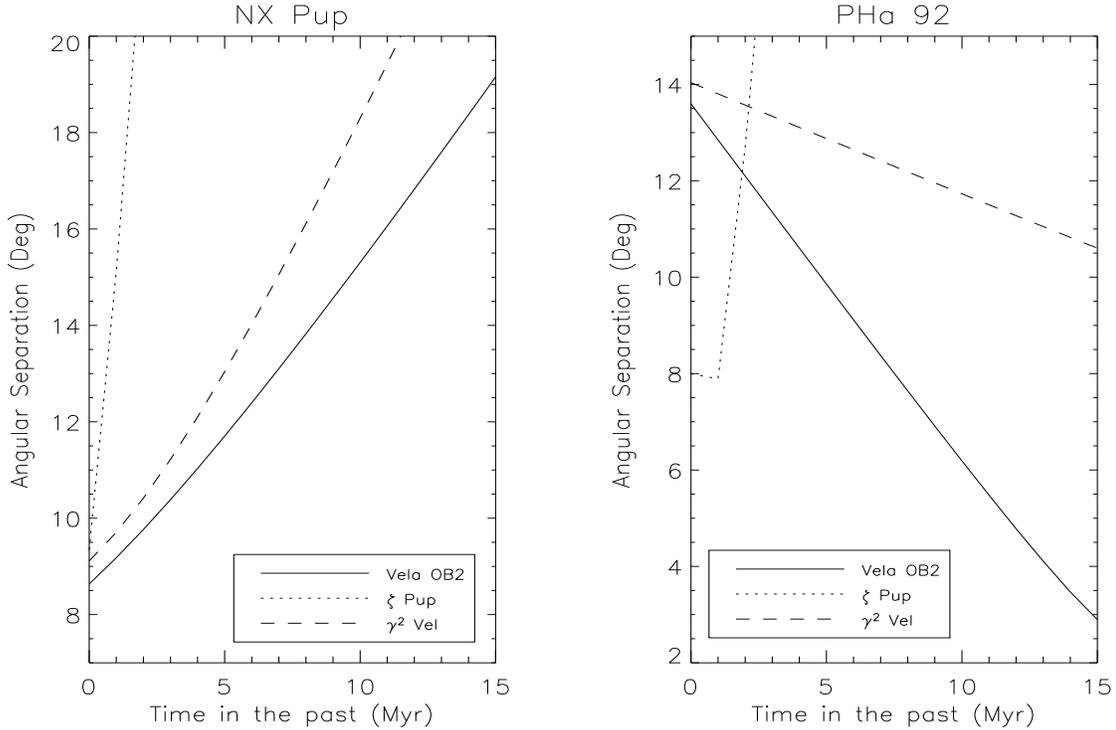
Figure 3. Angular separation of NX Pup and PHa 92 from ζ Pup, γ^2 Vel and Vela OB2 association in the past. The dotted, dashed and solid lines represent the angular separation from ζ Pup, γ^2 Vel and Vela OB2 association respectively.

12.32 km s^{-1}. These values corresponds to 5.78 and 6.38 mas yr^{-1} for CG 1 and CG 22 respectively with respect to the centre of explosion. Again, if CG 22 and CG 1 were close to the site of supernova explosion of the companion of ζ Pup 1.5 Myr ago then the proper motions of NX Pup and Pha 92 born in the respective CGs should be consistent with their motion from the site of the explosion to their present position. This would require a differential proper motion of NX Pup as $\Delta\mu_l cosb \sim$ - 30.09 mas yr^{-1}, $\quad \Delta\mu_b \sim$ - 36.23 mas yr^{-1} and PHa 92 as $\Delta\mu_l cosb \sim$ - 39.73 mas yr^{-1}, $\quad \Delta\mu_b \sim$ 1.01 mas yr^{-1}. At present we do not have the proper motion of the binary companion of ζ Pup which is the suggested centre of the expansion. But the other O type star γ^2 Vel shares a similar kind of motion as Vela OB2. So it is reasonable to adopt the mean proper motion of Vela OB2 for the motion of the centre. Considering the mean proper motion of the Vela OB2, the expected proper motion of NX Pup is $\mu_l cosb \sim$ - 40.49 mas yr^{-1}, $\quad \mu_b \sim$ - 41.03 mas yr^{-1} and for PHa 92 it is $\mu_l cosb$ $\sim$ - 50.13 mas yr^{-1}, $\quad \mu_b \sim$ 2.31 mas yr^{-1}.

Considering the earliest stars Yamaguchi (1999) suggested the age of the association as less than 10 Myr. We also traced back the proper motion of Pha 92 and NX Pup from the γ^2 Velorum and the mean proper motion of the Vela OB2 association up to 15 Myr. Figure 3 also shows the angular separations of NX Pup and PHa 92 from γ^2 Vel and Vela OB2

association. There is no indication of convergence of NX Pup with any of the sources (ζ Pup, γ^2 Velorum and Vela OB2) plotted in the diagram. However, the angular separation between the PHa 92 and the Vela OB2 association was shorter in the past than the present separation.

Adopting the proper motion of Vela OB2 for the motion of the centre, the observed differential proper motion of the stars with respect to the Vela OB2 association are estimated and tabulated in Table 4 (column 15 and 16). There is significant mismatch between the expected and observed differential proper motions of the YSOs with respect to the Vela OB association. For NX Pup the expected differential proper motion is $\Delta\mu_l cosb \sim$ -30.09 mas yr^{-1}, $\Delta\mu_b \sim$ -36.23 mas yr^{-1} while the observed differential proper motion is $\Delta\mu_l cosb \sim$ 3.32 mas yr^{-1}, $\Delta\mu_b \sim$ 0.04 mas yr^{-1}. For PHa 92 the expected differential proper motion is $\Delta\mu_l cosb \sim$ -39.73 mas yr^{-1}, $\Delta\mu_b \sim$ 1.01 mas yr^{-1} while the observed differential proper motion is $\Delta\mu_l cosb \sim$ 1.90 mas yr^{-1}, $\Delta\mu_b \sim$ 2.01 mas yr^{-1}. For other YSOs, the expected differential proper motion $|\Delta\mu| \sim$ 30 mas yr^{-1} while the observed differential proper motion is $|\Delta\mu| \sim$ 5 mas yr^{-1}.

The proper motion vector *P1* of NX Pup [Star identification No. 1 in Table 1] is plotted on the DSS image of CG 1 in Figure 4. The differential proper motion vector *D1* of NX Pup with respect to Vela OB2 association is also plotted Figure 4. The proper motion vector *P25* of PHa 92 [Star identification No. 25 in Table 1] is plotted on the DSS image of CG 22 in Figure 5. The differential proper motion vector *D25* of PHa 92 with respect to the Vela OB2 association is also plotted in Figure 5. The directions towards the Vela OB2 association and ζ Pup are also shown in Figure 4 and Figure 5. Within the errors associated with the proper motion measurements we do not find any clear evidence for the transverse motion for these two stars away from the site of supernova explosion of the companion of ζ Pup. For the objects which are not embedded in any CGs but supposed to be associated with the Gum Nebula, we get similar results. They also do not show any indication of expansion within the errors of proper motion measurements. This suggests that the system of CGs share the mean motion of Vela OB2 and do not show any systematic radial motions away from the centre.

We have also found 3 high velocity YSOs in CG 30 complex and one more in Sa 101. They have proper motion measurements more than 3σ away from the the mean proper motion of the Vela OB2. For the stars in the CG 30 complex Kim *et al.* (2005) have estimated an age of 2-5 Myr. These YSOs have Hα emission line as well as Li absorption line indicating
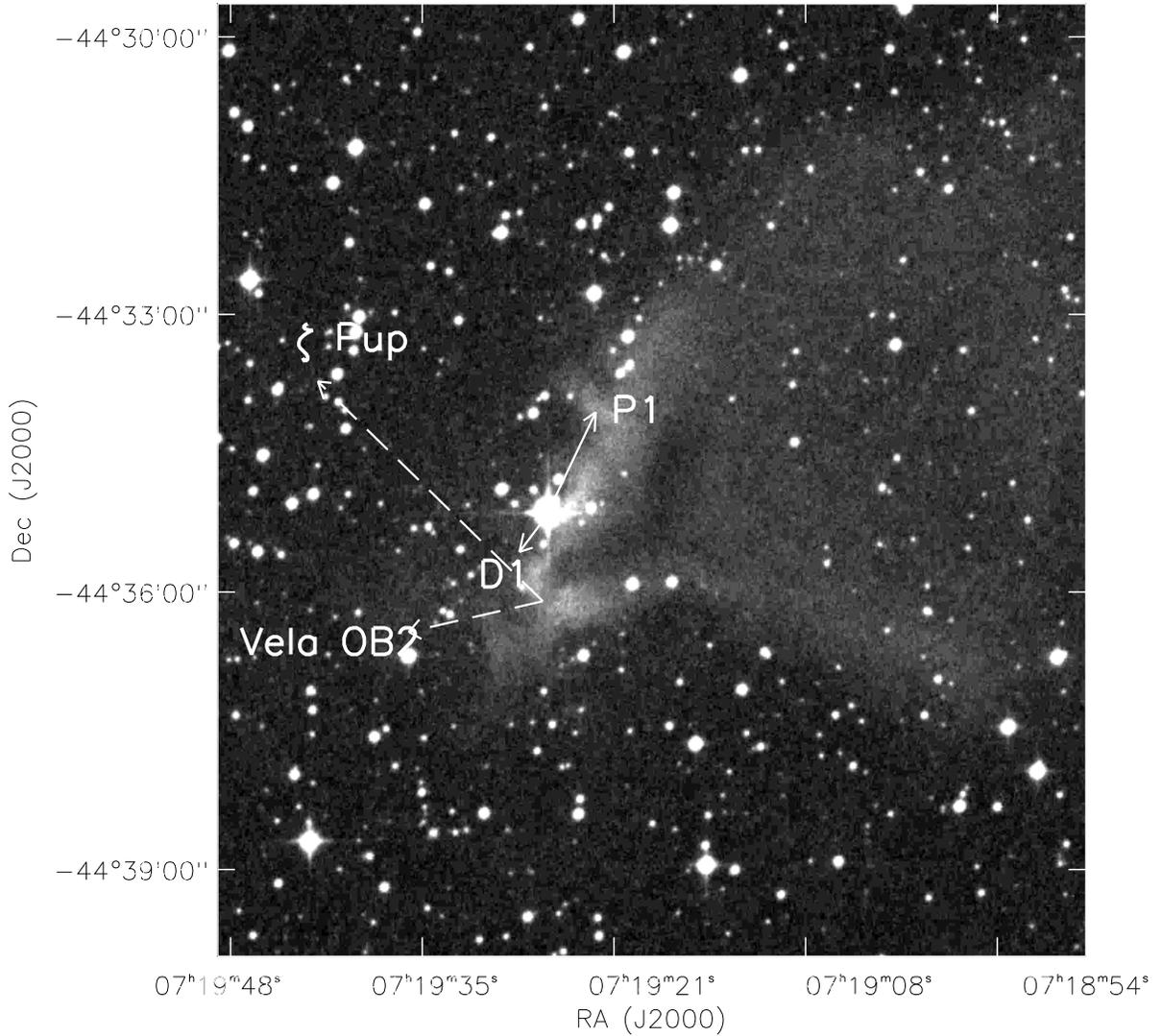
Figure 4. Proper motion vector *P1* of NX Pup plotted on the DSS image of CG 1. The directions towards the Vela OB2 association and ζ Pup are also shown by *dashed* lines. The differential proper motion vector *D1* is also plotted. Arrow lengths are proportional to the respective proper motion.

youth. Figure 6 gives a near IR J-H vs. H-K color-color (CC) diagram of the known YSOs in and around the CGs with reliable NIR photometry as given in Table 1. High velocity stars are marked with diamond and their corresponding identification number, as given in the Table 1. We exclude the high velocity star [RP93] 4 from the CC diagram due to poor measurements. The location of normal main-sequence and giant stars from Bessell & Brett (1988) are modified to the 2MASS photometry as suggested by Carpenter (2001) and plotted with solid and dash dot lines respectively. Points marked with *plus* on the dashed line are at an interval of $A_v = 5$ mag. Lee *et al.* (2005) have developed an empirical and effective set
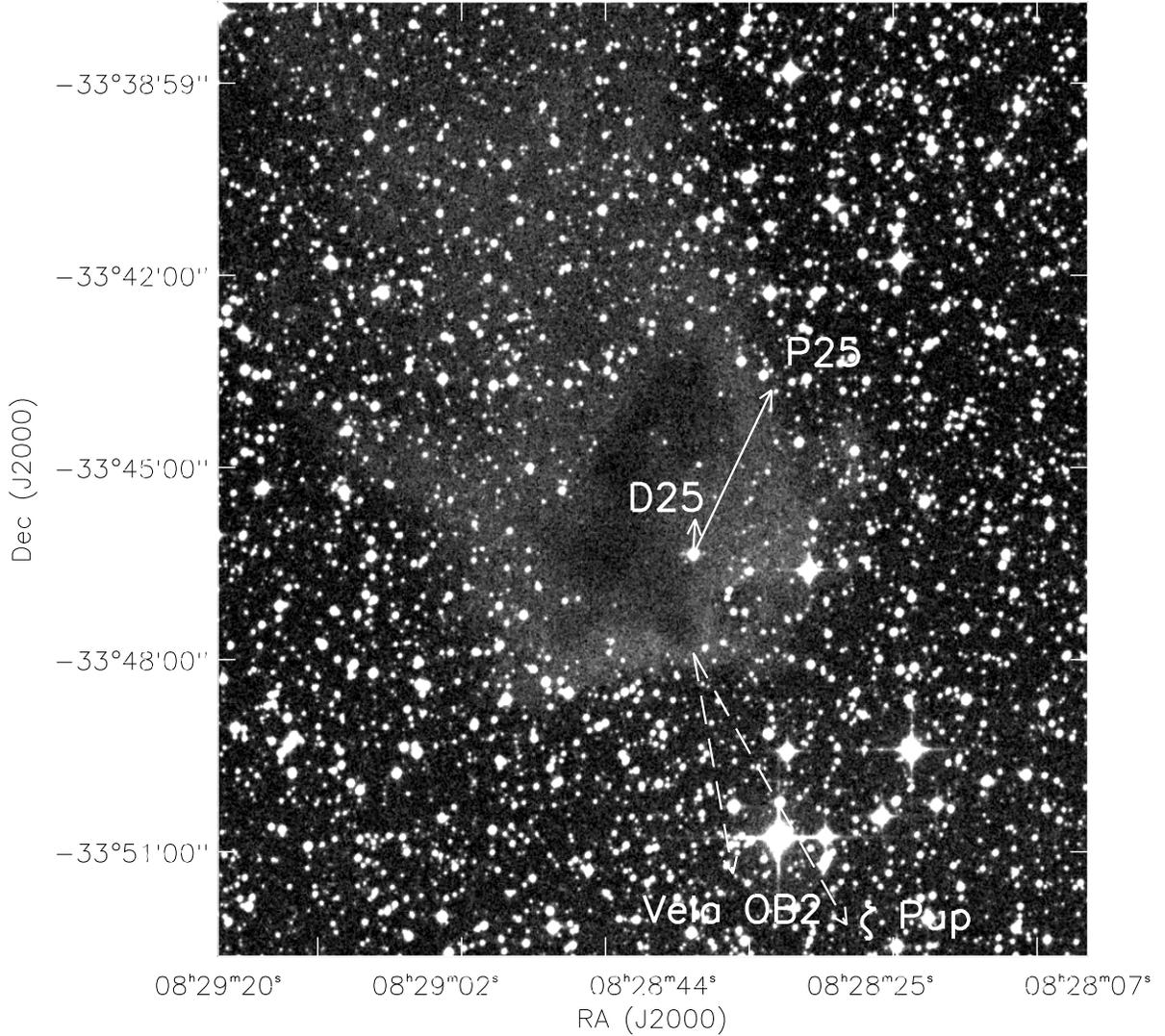
Figure 5. The proper motion vector *P25* of PHa 92 plotted on the DSS image of CG 22. The directions towards the Vela OB2 association and ζ Pup are also shown by *dashed* lines. The differential proper motion vector *D25* is also plotted. Arrow lengths are proportional to the respective proper motion.

of criteria, based on the 2MASS colors, to select candidate classical T Tauri stars (CTTSs). They found that the CTTS lie approximately between the two parallel dashed lines, defined empirically by $(j\_m - h\_m) - 1.7(h\_m - k\_m) + 0.0976 = 0$ and $(j\_m - h\_m) - 1.7(h\_m - k\_m) + 0.450 = 0$, where j_m, h_m, and k_m are 2MASS magnitudes, and the slope is specified by the interstellar reddening law (Rieke & Lebofsky 1985). The *dash dot dot* line in the CC diagram represents the dereddened CTTS locus (Meyer *et al.* 1997) , modified to the 2MASS photometry (Carpenter ,2001) with $(j\_m - h\_m) - 0.493(h\_m - k\_m) - 0.439 = 0$. The dashed parallel lines separate CTTS from Herbig Ae/Be and from reddened main sequence stars.
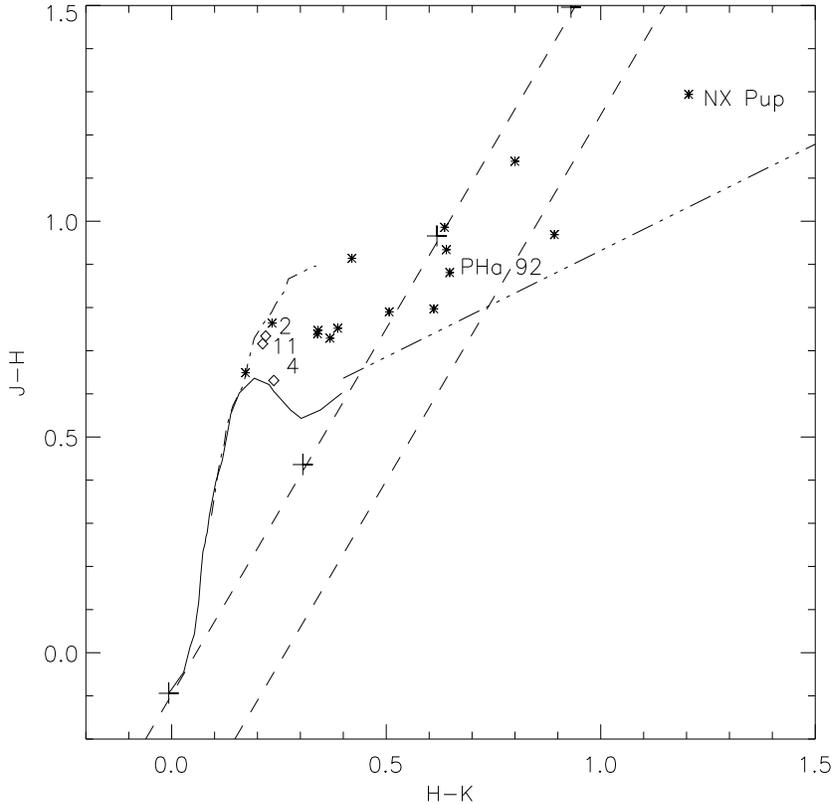
Figure 6. 2MASS JHK color-color diagram for the known YSOs in and around the CGs with reliable NIR photometry. High velocity stars are marked with diamond and their corresponding number from Table 1. *Solid* and *dash dot* curves are the locations of main-sequence and giant stars from Bessell & Brett (1988) converted into 2MASS as suggested by Carpenter (2001). The two *dashed* parallel lines, with the slope derived from interstellar reddening law (Rieke & Lebofsky 1985), separate CTTSs from Herbig Ae/Be and from reddened main-sequence stars (Lee *et al.* , 2000). The *dash dot dot* line is the dereddened CTTS locus (Meyer *et al.* , 1997). Points marked with plus on the dashed line are at an interval of $A_v = 5$ mag.

Positions occupied by the objects in the CC diagram give primary information about the nature of the YSOs. NX Pup (Herbig Ae) and PHa 92 (T Tauri) both have near IR excesses and their positions in the CC diagram also match with the criteria suggested by Lee *et al.* (2005). It is interesting to note that most of the YSOs which have similar proper motion as Vela OB2, show near IR excesses but all the three high velocity YSOs occupy similar positions in the CC diagram and they do not show near-infrared excesses. But there are no significant differences in Hα or Li equivalent widths and radial velocities of these objects compared with the other stars and the CGs (Kim *et al.* , 2005). If they are indeed associated with the CG 30 complex then they perhaps owe their high velocities to the process of star formation in the cloud which is not understood. It may also be possible that the cause of their high proper motion affected their circumstellar environment and as a result they do not have infrared excesses. There have been suggestions that during the star formation in binary or multiple systems YSOs can gain high velocities due to dynamical interactions [Sterzik *et*

al. (1995), Gorti & Bhatt (1996), Reipurth(2000)]. But CG 30 lies close to galactic plane . So it is also possible, but unlikely, that these objects are foreground YSOs moving with relatively higher velocities and large proper motions.

6   CONCLUSION

In the analysis presented above no clear evidence is found for the supernova explosion of the binary companion of ζ Pup causing expansion of the system of CGs in the Gum Nebula. We also do not find any systematic transverse expansion of the YSOs and the CGs in the Gum Nebula. It is possible that the CGs retain the initial velocities of their parent clumps inside the GMC characterised by a velocity dispersion as seen in the radial velocities. The energy sources in the Gum Nebula (stellar wind, radiation and supernova explosions) perhaps sweep out the diffuse material but not the relatively dense and massive CGs. The absence of CGs within some radius ($\sim$ 9 $^\circ$) of the OB association would then require destruction due to evaporation by the UV radiation (Reipurth, 1983) from the central energy sources. No clear evidence is found for transverse motion of YSOs and CGs as predicted by RDI models.

7   ACKNOWLEDGEMENT

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Table 3. Star forming CGs and Diffuse Molecular Clouds

CGs and the DMCs	l (°)	b (°)	V_{LSR} kms^{-1}	Vela OB2 Angular separation (°)	Vela OB2 Projected distance (pc)	γ^2 Vel Angular separation (°)	γ^2 Vel Projected distance (pc)	ζ Pup Angular separation (°)	ζ Pup Projected distance (pc)
CG 1	256.14	-14.07	3.3	8.6	67	9.11	71	9.35	73
CG 30/31/38	253.29	-1.61	5.8-7	10.67	84	11.3	89	4.11	32
CG 22	253.58	+2.96	6.5-6.8	13.54	106	14.1	110	7.97	63
CG 13	259.48	-16.43	3.7	9.03	71	9.29	73	12.22	96
CG4/CG6/Sa101	259.48	-12.73	0.9-1.7	5.98	47	6.38	50	9.03	71

Note: V_{LSR} from Sridharan (1992). Projected distances are at 450 pc .

Table 4. Proper Motion of the YSOs associated with Cometary Globules and Diffuse Molecular Clouds

No.	Name	r arcsec	RA (2000)	Dec (2000)	$\mu_\alpha cos\delta$ mas yr^{-1}	e mas yr^{-1}	μ_δ mas yr^{-1}	e mas yr^{-1}	$\Delta\mu_\alpha cos\delta$ mas yr^{-1}	$\Delta\mu_\delta$ mas yr^{-1}	$\mu_l cosb$ mas yr^{-1}	μ_b mas yr^{-1}	$\Delta\mu_l cosb$ mas yr^{-1}	$\Delta\mu_b$ mas yr^{-1}
1	NX Pup	0.123	07 19 28.26	-44 35 11.4	-4.2	2.0	6.1	1.9	2.22	-2.03	-7.08	-1.26	3.32	0.04
3	KWW 1892	0.101	08 08 22.15	-36 03 47.0	-6.5	4.8	7.7	4.7	-0.08	-0.43	-9.99	-1.29	0.41	0.01
6	KWW 1637	0.259	08 08 39.27	-36 05 01.7	-7.7	2.8	8.6	2.7	-1.28	0.47	-11.40	-1.81	1.00	-0.51
7	KWW 873	0.024	08 08 45.40	-36 08 40.2	-8.4	4.7	4.6	4.7	-1.98	-3.53	-8.42	-4.56	1.98	-3.26
8	KWW 1043	0.354	08 08 46.82	-36 07 52.8	-7.0	4.7	8.5	4.8	-0.58	0.37	-10.94	-1.27	0.54	0.03
9	KWW 975	0.099	08 08 33.87	-36 08 09.8	-5.9	4.8	12.3	4.8	0.52	4.17	-13.53	1.71	3.13	3.01
20	PHa 51	0.069	08 12 47.04	-36 19 17.9	-6.4	4.8	0.5	4.6	0.02	-7.63	-3.98	-5.03	2.59	-0.37
22	PHa 34	0.061	08 13 56.07	-36 08 02.1	-5.7	4.7	5.6	4.8	0.72	-2.53	-7.81	-1.67	4.06	-3.37
24	PHa 41	0.014	08 15 55.32	-35 57 58.1	-7.4	4.6	2.7	4.6	-0.98	-5.43	-6.34	-4.67	6.42	-3.73
25	PHa 92	0.041	08 28 40.70	-33 46 22.3	-6.6	4.6	10.4	4.6	-0.18	2.27	-12.30	0.71	1.90	2.01
28	[RP93] 3	0.987	07 31 10.81	-47 00 32.5	-6.7	5.0	10.9	4.9	-0.28	2.77	-12.73	-1.29	2.33	0.01
30	[RP93] 5	1.104	07 31 36.68	-47 00 13.2	-6.9	5.0	8.4	5.0	-0.48	0.27	-10.57	-2.54	0.17	-1.24
31	[RP93] 6	0.541	07 31 37.42	-47 00 21.5	-7.0	4.9	3.6	5.0	-0.58	-4.53	-6.29	-4.73	4.11	-3.43
32	[RP93] 7	1.501	07 33 26.86	-46 48 42.6	-3.2	4.9	11.1	4.9	3.22	2.97	-11.37	2.03	0.97	3.33
33	[RP93] 8	0.363	07 15 40.89	-48 31 27.3	-4.5	5.8	7.1	5.9	1.92	-1.03	-8.29	-1.39	2.11	-0.09
2	**KWW 464**	0.404	08 08 00.66	-35 57 33.3	-17.4	4.7	17.5	4.7	-10.98	9.37	-24.13	-5.17	-13.73	-3.87
4	**KWW 598**	1.089	08 08 37.60	-36 09 49.4	-10.0	18.0	24.0	5.0	-3.58	15.87	-25.59	4.61	-15.19	5.91
11	**KWW 1953**	0.103	08 08 26.93	-36 03 35.4	-13.0	4.9	13.1	5.0	-6.58	4.97	-18.05	-3.83	-7.65	-2.53
29	**[RP93] 4**	1.177	07 31 21.85	-46 57 43.9	-24.9	4.9	32.0	4.9	-18.48	23.87	-39.66	-8.47	-29.26	-7.17

Note: Differential proper motions are given with respect to Vela OB2 association. The *High Velocity YSOs* (2, 4, 11, 29) have been highlighted.