Testing the star formation scaling relations in the clumps of the North American and Pelican cloud complexes

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1 INTRODUCTION

Molecular clouds are the dense regions of the interstellar medium (ISM), which supplies all the raw materials for the formation of stars. Star-formation is a multi-stage process in which the dense part of molecular clouds undergo gravitational collapse and set footprints for the formation of new stars. Though tremendous progress has been achieved in recent decades, the understanding of complete episodes of star-formation is still under debate. This is a fundamental issue in the field of astrophysics.

The process which regulates the conversion of gas into stars is still least understood. Schmidt (1959) was the first who proposed a SFR-gas relation (popularly known as “Schmidt Relation”) in the form of a power law, in which the star-formation rate (SFR) surface density is proportional to the square of volume density. Later star-formation properties of many spiral and starbursts galaxies were studied by Kennicutt (1998) using both atomic (H\textsubscript{I}) and molecular (H\textsubscript{2}) gas for the estimation of $\Sigma_{\text{gas}}$ in the entire galaxies. He proposed a power law between the star-formation...
rate density ($\Sigma_{\text{SFR}}$) and gas surface density ($\Sigma_{\text{gas}}$) in the form of $\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}$. This scaling relation is called as the “Kennicutt–Schmidt relation”, where $N = 1.4$. Using sensitive observations with sub-kpc resolution, Bigiel et al. (2008) studied the atomic and molecular gas in 18 nearby galaxies and obtained a linear relation between $\Sigma_{\text{SFR}}$ and molecular gas density, for values above $10^2$ M$_{\odot}$ pc$^{-2}$. According to this study, the value of $N$ is $1.0 \pm 0.02$. Liu, Gao & Greve (2015) have analyzed 181 galaxies, out of which 115 are normal spiral galaxies, and 66 are IR galaxies. These authors reported a tighter correlation between $\Sigma_{\text{gas}}$ (traced by HCN) and $\Sigma_{\text{SFR}}$, with $N = 1.01 \pm 0.02$. In a recent study, de los Reyes & Kennicutt (2019) examined 109 spiral and 138 dwarf galaxies. These authors found that spiral galaxies define a tight relation between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{gas}}$ (estimated from both atomic H I and molecular H$_2$) with value of $N = 1.41 \pm 0.07$. According to this study, the $\Sigma_{\text{SFR}}$ are only weakly correlated with H I surface densities, but exhibit a stronger and roughly linear correlation with H$_2$ surface densities. The value of $N$ was found generally to be in between 1 – 2 from observations of several galaxies carried out in last two decades (Suzuki et al. 2010; Boissier et al. 2003; Martin & Kennicutt 2001; Heyer et al. 2004; Komugi et al. 2005; Schuster et al. 2007).

Most of the above results are based on studies of either resolved observations of galaxies or the complete galaxies. However, many studies have been carried out to test the relation of $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{gas}}$ in Milky Way clouds and compare them with the extragalactic relations. Wu et al. (2005) have observed dense cores using HCN, both in external galaxies and in our Galaxy, and found a tight SFR-gas relationship, which was earlier observed by Gao & Solomon (2004) towards a sample of IR galaxies. Evans et al. (2009) have examined several regions from Spitzer 2d survey and found that the SFR-gas relation for the Galactic clouds lie above the relations of Kennicutt (1998) and Bigiel et al. (2008), but lie slightly above the relation of Wu et al. (2005). Evans et al. (2009) found that the $\Sigma_{\text{SFR}}$ of Galactic clouds are higher by a factor $\sim 20$ compared to the values obtained using the relation of Kennicutt (1998). Heiderman et al. (2010) examined seven 2d regions and 13 regions from the Gould Belt (GB) survey and extended the comparisons of Galactic SFR-gas relations with the extragalactic relations. They also found a similar conclusion as obtained by Evans et al. (2009). Heiderman et al. (2010) reported that their $\Sigma_{\text{SFR}}$ is higher by a factor of $\sim 30$ compared to the values obtained using relation of Kennicutt (1998). This discrepancy is mainly due to the fact that the Kennicutt–Schmidt relation (Kennicutt 1998) is derived over large regions such as galaxies, where the diffused clouds within the galaxies, have no role in active star-formation. Heiderman et al. (2010) also derived a relation similar to that of Wu et al. (2005).

The simple Kennicutt–Schmidt relation shows a large scatter between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{gas}}$. Many discussions found in literature, for the search of a better correlation between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{gas}}$. Heiderman et al. (2010) have suggested that above a certain threshold gas surface density, the star formation rate and the cloud mass are better correlated. From their studies, $A_V \sim 8$ mag found to be the threshold level, which was also confirmed independently by Lada, Lombardi & Alves (2010). However, later on, some studies have questioned the existence of a density threshold in molecular clouds (Burkert & Hartmann 2013; Clark & Glover 2014). To reduce the scatter between the SFR-gas variance observed in Kennicutt–Schmidt relation, Krumholz, Dekel & McKee (2012) have proposed the volumetric star-formation relation which is a congruity between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{gas}}/t_{\text{ff}}$, where $t_{\text{ff}}$ is the free-fall time scale. According to these authors, the volumetric star-formation relation is able to reduce the high scatter seen in SFR-gas variance observed by Kennicutt (1998). This relation has been examined extensively by Krumholz, Dekel & McKee (2012) and Federrath (2013). In these works, the free-fall time scale is estimated over the average density of the cloud. Evans, Heiderman & Vutisalchavakul (2014) tested this relation and found that the free-fall model did not work well for nearby clouds. It is suggested that due to the clumpy nature of molecular clouds, the typical free-fall time scale of star-formation should not be the average time scale of the cloud. Rather it is the density-dependent time scale of the substructures which collapse to form stars (Salim, Federrath & Kewley 2015). This is called the multi-free-fall time concept (Hennebelle & Chabrier 2011, 2013; Chabrier, Hennebelle & Charlot 2014) in which the variation of $\Sigma_{\text{SFR}}$ with $\Sigma_{\text{gas}}/t_{\text{multi},-ff}$ is examined. A relation of $\Sigma_{\text{SFR}}$ with $\Sigma_{\text{gas}}$ evaluated over the orbital time scale is suggested by Kennicutt (1998). In this case, it is proposed that the star-formation is affected by galactic spiral arms and bars. These large scale radial processes affect the star-formation occurring from molecular gas over an orbital time scale (Wyse & Silk 1989; Kennicutt 1998). Star-formation evolved over several cloud crossing time scales have been studied in detail by Elmegreen (2000). In this study, it was suggested that the star-formation process is rapid in dense regions, and it finishes in several cloud crossing time scales. In summary, there exists a handful of star formation scaling relations to explain the star formation processes in molecular clouds. The North American and Pelican Nebulae complexes are young, massive, and is a nearby Galactic star-forming region. For this region, deep multi-wavelength data is available to make a complete census of young stellar objects (YSOs). This motivates us to analyze the various star-formation relations in dust clumps associated with North American and Pelican Nebulae complexes. We have explained various star-formation scaling relations in more detail in later sections, while we test them towards our region. This work has been presented in the following way. In Section 2, we discuss details about the target. In Section 3, we discuss the details of the data sets used in this study. In Section 4, we discuss various analysis and results, and section 5 summarizes the results.

### 2 DETAILS / CHARACTERISTICS OF THE TARGET

Our analysis covers the region associated with North American Nebula (NGC 7000) and the Pelican Nebula (IC 5070). Both the regions are part of the large H II region called W80 (Morgan, Strömgren & Johnson 1955; Westerhout 1958). We call the whole region covered by both the nebulae as “NAN” complex (Rebull et al. 2011; Zhang, Xu & Yang 2014). This is a nearby molecular cloud complex and associated with many massive stars. Dis-
Figure 1. Color-composite image of the NAN complex made using WISE 12 μm (red), 4.6 μm (green), and 3.6 μm (blue) images. This image shows the complete NAN complex along with the locations of NGC 7000 and IC 5070. Warm dust emission is seen at 12 μm, and the other two bands show the stellar population. The dashed line shows the outline of the six sub-regions within the complex identified by Zhang, Xu & Yang (2014). Names of all the regions are also given. Blue plus sign (“+”) marks the location of ionizing star (Comerón & Pasquali 2005). The reddened O-type stars (Straižys & Laugalys 2008) are shown as red cross (“×”) marks. The white arrows point towards the locations of the Bright-rimmed clouds within the complex.

NAN is a well studied star-forming region at near-infrared (NIR), mid-infrared (MIR), and also in millimeter (mm) and sub-mm wavebands of molecular line data. Using the 2MASS photometry, Comerón & Pasquali (2005) have identified an O5V star (2MASS J205551.25 + 435224.6) as the ionizing source of the NAN complex. A few more reddened O-type stars are also identified by Straizys & Laugalys (2008), which might play a role in ionizing the hydrogen gas in the NAN region. Using MIR data Guié et al. (2009) and Rebull et al. (2011) have identified a total of 2082 YSOs in the complex. These YSOs are identified from the IRAC and MIPS observations of Spitzer Space Telescope, covering a region of ∼ 7 deg² centred at α = 20 : 54 : 18.0 and δ = +44 : 05 : 00.0. From the analysis of molecular line data (Bally & Scoville 1980; Dobashi et al. 1994) and NIR extinction (Cambrésy et al. 2002), it has been found that a large amount of molecular gas is located toward the Dark Nebula LDN 935 (Lynds 1962), which bisects the North American and Pelican nebulae. The latest analysis of NAN complex using 12CO, 13CO, and C18O molecular line data by Zhang, Xu & Yang (2014) have identified filamentary structures and investigated the star-formation properties within them. These authors have identified several dense clouds of surface density over 500 M☉ pc⁻². The mean H₂ column densities are 5.8, 3.4, and 11.9×10¹¹ cm⁻² for 12CO, 13CO, and C18O, respectively and total mass of the complex is estimated to be 5.4×10⁴, 2.0×10⁴, and 6.1×10³ M☉ from 12CO, 13CO, and C18O, respectively. This indicates the different forms of gas traced by the molecules. The mass traced by the 18CO and C18O lines are ∼ 36% and ∼ 11% of the mass traced by the 12CO. In their analysis, Zhang, Xu & Yang (2014) have identified 611 small scale dense cores from the 18CO map. However, in our analysis, we are interested in large scale molecular cloud clumps and probe the star-formation properties within them. Using GAIA astrometry, the clustering and kinematics of the YSOs and associated molecular gas have been analyzed by Kuhn et al. (2020). This work has focused only on a small area around the star-forming complex consisting of some clusters. The latest spectroscopic analysis on the NAN complex by Fang et al. (2020) suggests a sequential history of star formation in the NAN region.

In this work, we aim to probe the SFR and star formation efficiency (SFE) of dense clouds located in the NAN complex. These are two important parameters to study the star-formation activity of a star-forming complex. SFR is defined as the amount of mass converted into stars per unit
time, whereas SFE is defined as the ratio of the stellar mass of star-forming region to the total stellar and gas mass of the parental cloud. Using molecular line and photometric data in deep NIR and MIR bands, we analyze the SFR and SFE of the entire NAN complex. In Figure 1, we show the whole field of view of the NAN complex in MIR bands. Based on the spatial distribution of molecules, Zhang, Xu & Yang (2014) have visually identified the boundaries of the six star-forming regions identified in Rebull et al. (2011) and their respective names are marked in Figure 1, along with their boundaries. The WISE\(^1\) color composite image shows the presence of warm dust emission traced by the 12 \(\mu\)m band. The warm dust emission appears to be distributed along the border of two broken bubbles. Bright-rimmed clouds (BRCs) are located on the border of the bubbles (Ogura, Sugitani & Pickles 2002) (see Figure 1). The lower bubble is located in the region of the Gulf of Mexico, and the upper bubble is distributed within regions of the Caribbean Islands, Pelican’s Neck, and Pelican’s Hat. A dark filament is seen within the Gulf of Mexico, which could be due to the early stage of the cloud. Four O-type stars are located within the Gulf of Mexico. The complete NAN complex is active in star formation, which is clear from the presence of various outflows, H\(_2\) jets, HH objects and H\(_\alpha\) emission line stars and bright rimmed clouds (Bally & Reipurth 2003; Comerón & Pasquali 2005; Armond et al. 2011; Bally et al. 2014).

3 DATA USED IN THIS STUDY

3.1 Spitzer MIR data

We use the MIR photometric data obtained from Spitzer Space Telescope (Werner et al. 2004) with Infrared Array Camera (IRAC; Warren et al. 2007). The region towards the NAN complex studied in four IRAC bands by Guieu et al. (2009) and in three bands of Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) by Rebull et al. (2011). In our analysis, we obtained the photometric data in 3.6 and 4.5 \(\mu\)m IRAC bands used in Guieu et al. (2009) and Rebull et al. (2011) (private communication). To ensure all sources are of good photometric quality, we use only those sources with error less than 0.2 mag. The IRAC and deep JHK photometry data are used to identify and classify the extra YSOs and to study the star formation properties in the NAN complex.

3.2 NIR data from UKIDSS

In this work, we retrieve NIR photometric data in J, H, and K bands from the UKIDSS (Lawrence et al. 2007) Galactic Plane Survey (GPS; Lucas et al. 2008). This survey was carried out with the UKIRT Wide Field Camera (WFCAM; Casali et al. 2007). The survey has a resolution of \(\sim 1\)\(^{\prime}\), and 5\(\sigma\) magnitude limits are 19.77, 19.00, and 18.05 in J, H, and K band, respectively (Warren et al. 2007). In our analysis, we use sources with an error less than 0.2 mag in all the three bands. This ensures the good photometric quality of the sources. Using deep NIR and MIR data, we identify the extra YSOs along with the YSOs identified by Guieu et al. (2009) and Rebull et al. (2011) in the NAN complex. These YSO candidates are used to quantify the star formation properties such as SFR and SFE within the NAN complex.

3.3 Molecular line data

Properties of molecular cloud associated with the NAN complex have been analyzed using J = 1 – 0 transition lines of \(^{12}\)CO (115.271204 Hz) and \(^{13}\)CO (110.201353 Hz) by Zhang, Xu & Yang (2014). Details regarding the molecular line observations and data reduction can be found in Zhang, Xu & Yang (2014). The \(^{12}\)CO and \(^{13}\)CO maps have velocity resolutions of 0.16 and 0.17 km s\(^{-1}\), respectively. Our analysis uses the same molecular line data to probe the gas properties in the NAN complex.

4 ANALYSIS AND RESULTS

4.1 Results from NIR and MIR data

4.1.1 Completeness of NIR and MIR data

We analyse the completeness limits of NIR and MIR bands within an area of 2.5\(^{\circ}\) x 2.5\(^{\circ}\) centred at \(\alpha = 20 : 54 : 59.05\) and \(\delta = +44 : 03 : 08.58\), using histogram distributions.

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\(^{1}\) This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration.
Histograms in all these bands are shown in Figure 2. The turnover point in the source count is considered as 90% completeness of the photometry (Winston et al. 2007; Jose et al. 2013; Samal et al. 2015; Jose et al. 2016). The completeness limits in all the NIR and MIR bands obtained from the histogram distribution are listed in Table 1. This analysis shows the completeness limits of the NIR and MIR photometry within the entire NAN region. However, we caution that the local completeness may vary due to the non-uniform extinction present in the region.

### 4.1.2 Additional YSOs in NAN complex

Selection of candidate YSO towards the NAN region have been carried out by Guieu et al. (2009) and Rebull et al. (2011) using the photometric data from Spitzer IRAC and MIPS observations. A total of 2082 YSOs have been retrieved by these authors along with 114 YSOs found in literature which are detected using various techniques. Out of these, 1286 YSOs are from the IRAC and MIPS photometric data (see tables 3 and 4 of Rebull et al. 2011). 796 YSOs are only from IRAC photometric data, which do not have MIPS counterparts (see Table 8 of Rebull et al. 2011) and remaining 114 are previously suggested YSOs in literatures which are not recovered by IRAC or MIPS (see Table 9 of Rebull et al. 2011). In this study, we attempt to identify the additional YSOs associated with NAN region using the deeper JHK photometric data from UKIRT combining with the photometry in 3.6 and 4.5 μm of Spitzer IRAC. Before identifying the YSOs, we have merged the UKIRT and Spitzer catalogs, with a cross-matched radius of 1″. The merged catalog includes 342586 sources within an area of 2.5° × 2.5° centred at α = 20 : 54 : 59.05 and δ = +44 : 03 : 08.58.

To identify and classify the YSOs, we used the intrinsic K-3.6 vs. 3.6-4.5 color-color (CC) cut off criteria given in Gutermuth et al. (2009). To obtain the intrinsic colors of the sources, we made a K-band extinction map of the region based on the (H-K) color excess of the background sources (See Jose et al. 2016, 2017 for details). Here we caution that the systematic errors associated with the adopted extinction laws may lead to an uncertainty in A_v measurements of dense clouds by ~20% (Jose et al. 2016).

Using the extinction map, we deredden all the sources using the extinction laws described in Flaherty et al. (2007). Following Gutermuth et al. (2009) criteria, we are able to identify 2162 YSOs within the NAN complex. We also have adopted the criteria that all the Class II YSOs must have [3.6]_0 < 14.5 mag, and all protostars must have [3.6]_0 < 15 mag. These magnitude cut-off assures removal of the contaminants such as dim extragalactic sources (Gutermuth et al. 2009).

By comparing our YSO list with the list of Rebull et al. (2011), we obtain 1063 YSOs as common sources, and 1099 YSOs are additional detections. The color-color plot of ([3.6] − [4.5])_0 vs. ([K] − [3.6])_0 in Figure 3 shows the distribution of 2162 YSOs in NAN complex, in which the additional 1099 YSOs identified in this study are highlighted.

In order to remove any possible contaminants in the additional YSO list, we use [K]−[4.5] vs. [H]−[K] CC diagram, which is a well known technique (Chavarría et al. 2008; Winston et al. 2007; Samal et al. 2014) to identify YSOs with genuine IR excess emission. We plot all the additional 1099 YSOs on the [K]−[4.5] vs. [H]−[K] CC diagram and is shown in Figure 4. The blue curve is the locus of the M-dwarf stars (Pecaut & Mamajek 2013), in which the color values in H-K and K-W2 (K band minus the WISE band 2) are given. Here we assume the K-W2 is equivalent to K-4.5 since the WISE band 2 and IRAC band 2 have similar central wavelengths. The long arrow is the reddening vector drawn using extinction laws of Flaherty et al. (2007), which starts from the tip of M5 dwarf. The IR excess sources are expected to lie rightward at least 1σ away from the reddening vector. Of the additional 1099 YSOs, we find that ~77% (842 YSOs) lie 1σ away to the rightward of the reddening vector. We are unable to retrieve the nature of sources falling leftward of the reddening vector. The majority of these non IR-excess sources are highly reddened with H-K color > 1 mag, which corresponds to to Av > 15 mag, and they show distinct distribution from the majority of the YSOs, and hence they could be the reddened background sources. To be more confident of our detected YSO sample free from any background contaminants, we consider only those YSOs which lie rightward of the reddening vector in Figure 4. Hence, including this conservative constraint into this analysis, we are left with 842 additional YSOs. Figure 4 displays the 1099 candidate YSOs identified in this work as small gray dots, and the 842 YSOs with confirmed IR excess are overplotted in black color.

We observe that the Class I YSOs are very less compared to the Class II YSOs, as it is clear from Figure 3. Also, we find that these Class I sources are mostly distributed at the location of the Spitzer, and MIPS identified Class II sources in the H-K vs. 3.6-4.5 CC space, and moreover, we have identified them only using near-infrared photometry (i.e., 2.16 to 4.5 μm). Hence in this analysis, we consider all the additional YSOs as Class II sources. However, we note that, even if some are true Class I YSOs, it will not affect our results as we are generally interested in the total number of YSOs in this study.

### 4.1.3 Final YSO catalog and classification

To make the final YSO list, we used all YSOs (2190) listed in Rebull et al. (2011) along with the extra 842 YSOs detected in this study (see section 4.1.2). Hence after excluding the common sources, the NAN complex is found to be associated with 3038 candidate YSOs. In this section, we obtain the evolutionary stage of the YSOs. Out of the 1286

| Band | Total No. Sources | 90% Completeness Limit (mag) |
|------|-------------------|-------------------------------|
| J    | 1792215           | 19.5                          |
| H    | 1792215           | 18.5                          |
| K    | 1792215           | 18.0                          |
| I1   | 450560            | 16.0                          |
| I2   | 450978            | 15.5                          |
| I3   | 189723            | 15.0                          |
| I4   | 72417             | 14                            |
| M1   | 3932              | 8.5                           |
Guieu et al. lists additional 796 YSOs without any evolutionary class, which are not recovered by their YSO classification scheme. These 796 YSOs are a subset of the 1657 YSOs originally detected by Guieu et al. (2009) using the four IRAC bands photometry and detection criteria of Gutermuth et al. (2008b). This detection mechanism uses several combinations of color and magnitude cuts using the IRAC bands for identification of YSOs and for the removal of contaminants such as PAH dominated galaxies, AGNs and sources excited with shock emission. To classify the YSOs, Guieu et al. (2009) adopt the classification scheme of Lada (1987) and André (1994). In this scheme, the YSOs are classified into different classes based on their IRAC spectral index value. Since the evolutionary classes of the 796 YSOs are not mentioned either by Guieu et al. (2009) or by Rebull et al. (2011), we have classified the YSOs following the same classification scheme used by Guieu et al. (2009). Out of these 796 YSOs, we find that 58 are Class I, 510 are Class II, 162 are Class III, and 66 are flat-spectrum sources. Finally, we inspected 114 YSOs listed in Table 9 of Rebull et al. (2011), which were detected based on various techniques in the literature. Out of these 114 YSOs, 67 have photometry in all four IRAC bands (Rebull et al. 2011). Based on the criteria adopted by Guieu et al. (2009), 3 are retrieved as Class I, 58 are Class II, and 3 are flat spectrum YSOs. We cross-checked the remaining 47 sources with the YSOs detection technique adopted by us. We retrieve 5 as Class II YSOs, and the rest are assumed to be unknown class.

In summary, from the Rebull et al. (2011), Guieu et al. (2009) catalogs, and additional YSOs from our deep JHK and IRAC based data, 3038 YSOs have been identified in the entire complex. Of these, we retrieved 334 as Class I, 341 as flat spectrum, 1964 as Class II, 332 as Class III, and 67 as unknown class YSOs. This is the most complete and updated list of YSOs detected towards the NAN region to date. The full list of 3038 YSOs, along with their evolutionary class, is presented in Table A.

In this work, we do not include the Class III sources as these sources are largely incomplete, like the case in Gould Belt (GB) clouds (Dunham et al. 2015) and represent only 2% of the total YSO population. To obtain a full census of Class III objects, an in-depth X-ray survey would be needed (Forbrich et al. 2010; Pillitteri, Walk & Megeath 2016). However, the missing YSOs may not have a significant effect on the star-forming properties of clumps estimated in this analysis as in the dense regions such as in molecular clumps, majority of the stars might not have reached the Class III phase (Gutermuth et al. 2008a; Samal et al. 2015), while their exclusion may underestimate the global SFR and SFE of the entire complex.

4.1.4 Mass completeness limit of YSOs

As discussed in the previous section, we identified a set of additional YSOs to make the YSO sample more complete. However, the different bands' sensitivities will play a significant role in the identification of the YSOs. In this section, we attempt to determine the mass completeness limit of our detected YSOs following discussions given in Jose et al. (2016) and Dutta et al. (2018). Mass completeness limit varies as a function of extinction of the complex as well as crowding of sources listed in Tables 3 and 4 of Rebull et al. (2011), 273 sources are Class I, 604 are Class II, 112 are Class III, 272 are flat spectrum, and 25 are of unknown type sources. Rebull et al. (2011) used [3.6] vs. [3.6]-[24] color-magnitude diagram as the primary mechanism for YSO selection, with adequate care for the removal of contaminants. Table 8 of

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Color-color diagram of [3.6]-[4.5] vs. [K]-[3.6] color-color diagram showing the distribution of all the YSOs in NAN complex. The highlighted sources in green color are the additional candidate YSOs identified from this study.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Color-color diagram of [K]-[4.5] vs. [H]-[K] to check the YSOs with IR excess. The blue curve shows the locus of late-type M-dwarf stars adopted from Pecaut & Mamajek (2013). The long black arrow displays the reddening vector plotted using the extinction laws of Flaherty et al. (2007), starting from the tip of M5 dwarf. All the additional 1099 YSOs are plotted as gray dots, and the 842 IR excess YSOs are overplotted as black dots. A typical length of the reddening vector for $A_K = 1$ mag is also shown on the plot.}
\end{figure}
the region (see Damian et al. 2020 for details). In order to estimate the average value of $A_V$ within the NAN complex, in Figure 5, we show the histogram of $A_V$ values of the NAN complex. We find that the NAN complex is associated with a mean $A_V$ value of $\sim 6 \pm 3.4$ mag.

As discussed in Section 4.1.1, we see that 90% completeness limits of UKIRT JHK photometry are 19.5, 18.5, 18.0 mag, respectively. For the Spitzer 3.6 and 4.5 μm photometry, the completeness limits are 16.0 and 15.5 mag, respectively. We use the 4.5 μm band to determine the mass completeness limit of YSOs, since this band is shallow compared to other bands. Assuming an extinction range of $A_V = 6 - 10$ mag, distance of 800 pc, and considering the pre-main sequence isochrone of 2 Myr (Baraffe et al. 2015)\(^2\) (details regarding age of 2 Myr is discussed in section 4.3.1), the magnitude limit of 4.5 μm photometry (i.e., 15.5 mag) corresponds to stellar mass limits of 0.03 – 0.08 M⊙. This shows that with our deep photometry analysis, we are able to identify the YSOs down to the brown dwarf regime. However, we do not exclude the fact the whole NAN complex suffers from variable extinction. So the local extinction may play a role in the local mass completeness of the YSOs.

4.1.5 Distribution of YSOs

The spatial distribution of YSOs on the hydrogen column density image is displayed in Figure 6. Class I (red), flat spectrum (green), and Class II (blue) are shown in the figure. The YSOs are mostly diagonally distributed from north-west to the south-east. The Class II YSOs dominate towards the north-west region. The south-east shows an overpopulation of Class I and flat-spectrum YSOs. The distribution of YSOs indicates the presence of many sub-clustering, as suggested in the previous studies (Cambrésy et al. 2002; Guieu et al. 2009; Rebull et al. 2011).

In Figure 6, the contours represent the distribution of hydrogen column densities (N(H\(_2\)) of different values. The association of YSOs to different column density levels is seen from this figure. As expected most of the YSOs are located above the N(H\(_2\)) of $2.2 \times 10^{21}$ cm\(^{-2}\). A large fraction of YSOs is distributed above $4.5 \times 10^{21}$ cm\(^{-2}\) shows the association of YSOs with dense clumps, suggesting the active star-formation activity within the clumps. Above $8.5 \times 10^{21}$ cm\(^{-2}\) very less fraction of total YSOs are located towards the densest part of the cloud. Among the total YSOs ∼ 7%, 5%, 6%, 20% Class I, flat-spectrum, Class II, and Class III YSOs, respectively lie outside the CO mapped region. Thus the majority of projected sources lie inside the cloud area. This also implies that the contamination level of non-YSOs to our Class I to Class II sample may be at the level of 5 to 7%.

4.2 Emission from cold dust component

4.2.1 Column density from \(^{12}\)CO and \(^{13}\)CO

In molecular clouds, star-formation depends on the properties of gas (Krumholz & McKee 2005; Krumholz, McKee & Tumlinson 2009; Elmegreen 2007). To quantify the properties of the cold dust emission and star-formation, associated with the NAN complex, we have generated the H\(_2\) column density map. We estimate the molecular hydrogen column density (N(H\(_2\)) from the \(^{12}\)CO (I\(^{12}\)CO) and \(^{13}\)CO (I\(^{13}\)CO) integrated intensity maps. \(^{12}\)CO traces the diffuse part of the molecular cloud, whereas the \(^{13}\)CO traces the dense regions of the molecular cloud. Using both the CO maps, we will be able to get a more accurate estimation of the hydrogen column density. At first, we estimate N\(_{H_2}\) from \(^{12}\)CO map. The CO-to-H\(_2\) conversion factor X\(_{CO}\) can be expressed by the following equation (Rebolledo et al. 2016).

$$\frac{N_{H_2}(^{12}CO)}{cm^2} = \frac{X_{CO}}{cm^{-2} K km s^{-1}} \times \frac{I_{^{12}CO}}{K km s^{-1}} (1)$$

The typical value of the conversion factor X\(_{CO}\) in Milky Way is $2 \times 10^{20}$ (Bolatto, Wolfire & Leroy 2013). In our analysis, we use the same value to convert \(^{12}\)CO to H\(_2\) column density. Further, we estimate N\(_{H_2}\) from \(^{13}\)CO using the conversion factor (\(^{12}\)CO/\(^{13}\)CO) $\times 2.0 \times 10^{20}$. We use the \(^{12}\)CO/\(^{13}\)CO (mean intensity ratio) to be 3 (Bolatto, Wolfire & Leroy 2013). The final N\(_{H_2}\) map is obtained by pixel-wise matching of individual maps generated from the \(^{12}\)CO and \(^{13}\)CO maps. In the pixel-wise match, we retain the maximum pixel value for the final map. For example, for a particular pixel, if the column density from the \(^{13}\)CO is higher than the \(^{12}\)CO, then we retain the higher value. This ensures the contribution from both \(^{12}\)CO, which traces the diffuse emission and \(^{13}\)CO, which traces the dense part of the molecular cloud. The final column density map is shown in Figure 7. Background value of the column density map is ~ $1.5 \times 10^{21}$ cm\(^{-2}\). We estimate the background level by averaging the N(H\(_2\)) values over a few regions free from diffused emission of the column density map. Zhang, Xu & Yang (2014) find that the lowest contour level of their \(^{12}\)CO map to be 10 K km s\(^{-1}\), which corresponds to

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\(^2\) The models described in the paper are available online at http://perso.ens-lyon.fr/isabelle.baraffe/BHAC15dir.


\[
\Sigma N(H_2) \approx 1.8 \times 10^{22} \text{ cm}^{-2}
\]

which is similar to our estimated background value of the column density map. The column density map displays several high density clumpy regions. The peak column density value \((\sim 4 \times 10^{23} \text{ cm}^{-2})\) is located towards the Pelican’s Neck region. The average value of column density is \(\sim 3.6 \times 10^{23} \text{ cm}^{-2}\).

We have also estimated the column density from \(^{13}\text{CO}\) map assuming a local thermodynamic equilibrium (LTE) following the method explained by Nagahama et al. (1998). As explained above, we combine the column density maps generated from \(^{12}\text{CO}\) and \(^{13}\text{CO}\) to prepare the final column density map. The average and peak column density values of this column density map are similar to the column density map generated earlier. This shows that the column density map produced assuming LTE is similar to the map generated in the earlier method. We also found that the mass of the clumps and the entire cloud is in agreement with the estimations of the first approach within 3 to 8 % label.

4.2.3 Physical parameters of clumps

We derive several physical parameters such as radius, mass, hydrogen volume number density, and surface density of the star-forming clumps. Using the clump apertures retrieved from astrodendro, we estimate the physical sizes of the clumps \((r = (A/\pi)^{1/2}; \text{Kauffmann \& Pillai 2010})\). Mass of the clumps are calculated using the following equation

\[
M_{\text{clump}} = \mu_{H_2} n_{H} A_{\text{pixel}} \Sigma N(H_2)
\]

where, \(n_{H}\) is the mass of hydrogen, \(A_{\text{pixel}}\) is the pixel area in cm\(^2\), \(\mu_{H_2}\) is the mean molecular weight which is assumed to be 2.8 (Kauffmann et al. 2008), and \(\Sigma N(H_2)\) is the integrated column density. The hydrogen volume number density is derived as, \(n_{H} = 3M_{\text{clump}}/4\pi r^3 \mu_{H_2} n_{H}\), \(r\) being the radius. Surface density is derived as, \(\Sigma_{\text{gas}} = M_{\text{clump}}/\pi r^2\). All the derived physical parameters of the clumps along with the mean, median, and standard deviation are listed in Table 2.

We estimate the same physical properties for the entire NAN complex for the area shown in Figure 7. Mass, radius, volume density, and gas surface density of the NAN complex are \((7.5 \pm 0.1) \times 10^4 \text{ M}_\odot, 17.2 \pm 1.0 \text{ pc}, (0.05 \pm 0.01) \times 10^3 \text{ cm}^{-3}, \) and \(81.3 \pm 0.1 \text{ M}_\odot \text{ pc}^{-2}\) or \(0.02 \pm 0.0001 \text{ gm cm}^{-2}\), respectively. We compare the physical parameters of the whole NAN region with other nearby Galactic clouds studied by Evans, Heiderman \& Vutisalchavakul (2014). Compared to the Galactic clouds, the whole NAN complex is

\[\text{(cyan)}, \text{respectively.}\]
Table 2. Physical parameters of the cold clumps associated with the NAN region. The peak position of column density, radius, mean column density, total column density, mass, volume density, and gas surface density are listed.

| Complex          | Clump No. | RA (J2000) | DEC (J2000) | Radius (pc) | Mean \(N(H_2)\) \((\times 10^{21}\text{cm}^{-2})\) | \(\sum N(H_2)\) \((\times 10^{24}\text{cm}^{-2})\) | Mass \((M_\odot)\) | \(n_H2\) \((\times 10^3\text{cm}^{-3})\) | \(\Sigma_{gas}\) \((M_\odot\text{pc}^{-2})\) |
|------------------|------------|------------|-------------|-------------|---------------------------------|---------------------------------|-------------------|-------------------|-------------------|
| Pelican’s Hat    | 1          | 20:52:36.26 | 44:47:48.47 | 0.9±0.05    | 5.3                                  | 10.1                             | 306±2.2          | 1.4±0.2          | 117±2.0 (0.02 0.0001) |
|                  | 2          | 20:51:06.58 | 44:39:40.11 | 1.2±0.06    | 5.2                                  | 15.9                             | 487±2.8          | 1.1±0.2          | 117±1.0 (0.02 0.0001) |
| Caribbean Islands | 3          | 20:51:33.74 | 44:32:21.67 | 1.7±0.08    | 7.2                                  | 47.2                             | 1427±15.8        | 1.19±0.2         | 163±4.7 (0.02 0.0002) |
|                  | 4          | 20:52:06.41 | 44:22:16.22 | 0.7±0.03    | 5.4                                  | 5.3                              | 161±1.1          | 2.0±0.3          | 120±0.2 (1.0 0.00003) |
|                  | 5          | 20:50:56.04 | 44:25:38.18 | 2.0±0.10    | 8.4                                  | 80.4                             | 2429±8.6         | 1.0±0.2          | 187±6.8 (0.02 0.00002) |
| Caribbean Islands | 6          | 20:54:59.85 | 44:17:28.45 | 1.6±0.08    | 8.1                                  | 45.8                             | 1382±2.6         | 1.3±0.2          | 181±4.8 (0.04 0.00002) |
|                  | 7          | 20:52:08.83 | 44:07:40.51 | 1.5±0.08    | 7.1                                  | 38.9                             | 1178±5.0         | 1.1±0.2          | 176±4.5 (0.03 0.00003) |
| Pelican’s Peak   | 8          | 20:51:42.94 | 44:34:44.10 | 0.5±0.03    | 5.4                                  | 3.7                              | 111±1.3          | 2.4±0.4          | 120±0.1 (1.0 0.00003) |
| Caribbean Islands | 9          | 20:51:16.37 | 44:35:22.84 | 1.0±0.05    | 8.8                                  | 19.1                             | 577±2.4          | 2.2±0.5          | 196±5.2 (0.04 0.00002) |
| Caribbean Islands | 10         | 20:55:07.92 | 44:33:53.86 | 1.2±0.06    | 9.6                                  | 31.7                             | 959±2.5          | 2.0±0.3          | 213±4.2 (1.0 0.00002) |
| Gulf of Mexico   | 11         | 20:57:32.10 | 44:37:45.16 | 2.3±0.11    | 8.1                                  | 97.5                             | 2962±8.6         | 0.9±0.1          | 181±2.0 (0.04 0.00002) |
| Caribbean Sea    | 12         | 20:52:33.10 | 44:31:18.37 | 1.8±0.10    | 5.7                                  | 44.1                             | 1335±2.4         | 0.8±0.2          | 127±2.0 (0.03 0.00002) |
| Gulf of Mexico   | 13         | 20:58:25.72 | 43:19:09.70 | 0.7±0.04    | 6.3                                  | 7.3                              | 219±2.2          | 2.2±0.3          | 139±7.1 (0.03 0.00003) |
| Gulf of Mexico   | 14         | 20:55:59.73 | 43:04:21.98 | 0.8±0.04    | 5.5                                  | 8.5                              | 256±2.1          | 1.7±0.2          | 122±1.1 (0.03 0.00002) |

Mean 1.3 6.7 32.5 985 1.5 153.4 (0.08) |
Median 1.2 6.7 25.4 768 1.4 149.4 (0.03) |
N/d 0.5 1.5 27.8 843 0.5 32.8 (0.007) |

1 Values of gas surface density \((\Sigma_{gas})\) in parenthesis has unit gas cm\(^{-2}\).

4.3 Measurement of Star-formation rate and efficiency

In this section, we derive the SFR and SFE of the cold dust clumps located towards the NAN region. These parameters will help us to understand the ongoing star-formation activities within the molecular clumps. Using these parameters we test the various star-formation relations in subsequent sections.

4.3.1 Star-formation rate

We derive the SFR for all the dense clumps using the following relation

\[
\text{SFR} = \frac{M_\star}{\tau}
\]

where, \(M_\star\) is the total stellar mass within a molecular clump, and \(\tau\) is the average age of the molecular clump. To estimate the SFR, the two important parameters required are age and stellar mass within the star-forming clump.

For the estimation of age, we follow the discussion made in Evans et al. (2009) and Heiderman et al. (2010). While carrying out a similar analysis, Evans et al. (2009) have assumed an age of 2 Myr, which is an estimate of the time taken to pass the Class II phase. This assumption is made because the study is complete towards the Class II YSOs, or these YSOs are dominant among all the other identified YSOs. As discussed in Section 4.1.3, we have seen a dominance of Class II YSOs (~65% of total YSOs) over all other YSO classes in NAN region. Hence we assume an age of 2 Myr in our analysis. Various uncertainties of SFR estimation in this assumption are discussed by Heiderman et al. (2010).

The next important parameter in the analyses is the estimation of stellar mass within the dense clumps. Many studies have considered the total mass of YSOs as the stellar mass (Evans et al. 2009; Heiderman et al. 2010; Jose et al. 2016). In our analysis we assume a mean mass of 0.5 \(M_\odot\) for YSOs, consistent with the studies of IMF (Chabrier 2003; Kroupa 2002; Ninkovic & Trajkovska 2006). Then the total stellar mass is estimated by multiplying the total number of YSOs with 0.5 \(M_\odot\).

The derived SFR of the individual star-forming complexes, along with their mean, median, and standard deviation, are listed in Table 3. The uncertainties in the SFR calculations are mainly associated with the YSO counts and we estimate them following the method of Evans, Heiderman & Vutisalchavakul (2014). The SFR values from clump to clump varies in the range of 0.5 ± 0.4 – 78.3 ± 4.4 \(M_\odot\) Myr\(^{-1}\). Clump 11 has maximum SFR, and Clumps 13 and 14 have minimum SFR. The mean

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of SFR is \(\sim 14 \pm 0.5 \ M_\odot \ \text{Myr}^{-1}\). The SFR surface density values of the different clumps vary in the range of \(0.2 \pm 0.1 - 4.8 \pm 0.5 \ M_\odot \ \text{yr}^{-1} \ \text{kpc}^{-2}\). Clump 11 has the maximum SFR surface density, and Clump 14 has the minimum SFR surface density.

For all the 14 clumps, the mean, median, and standard deviation of \(\Sigma_{\text{SFR}}\) are 1.5, 1.0, and 1.2 \(M_\odot \ \text{yr}^{-1} \ \text{kpc}^{-2}\), respectively. Also for the complete NAN complex the value of \(\Sigma_{\text{SFR}}\) is 0.6 \(\pm 0.1 M_\odot \ \text{yr}^{-1} \ \text{kpc}^{-2}\). For the nearby Galactic clouds the mean, median, and standard deviation values of \(\Sigma_{\text{SFR}}\) estimated by Evans, Heiderman & Vutisalchavakul (2014) are 0.89, 0.48, and 0.99 \(M_\odot \ \text{yr}^{-1} \ \text{kpc}^{-2}\), respectively. Within standard deviation we have derived the mean, median, and standard deviation values of \(\Sigma_{\text{SFR}}\) estimated by Evans, Heiderman & Vutisalchavakul (2014). These clumps have less SFR, taking a longer time to deplete gas. The depletion time is expressed as

\[
\text{t}_{\text{dep}} = \frac{M_{\text{gas}}}{\dot{M}_*}
\]

where \(M_*\) is the total YSO mass within the clump, and \(M_{\text{gas}}\) is the total mass of clump. The derived SFE of all clumps are listed in Table 3. SFE of all clumps are in the range of \(0.4 \pm 0.003 - 5.0 \pm 0.003\%\), and for the whole NAN complex, SFE obtained 1.6 \pm 0.004\%. The mean, median, and standard deviation values of SFE estimated for all the 14 clumps are 2.0, 1.5, and 1.6\%, respectively. These values of SFE are consistent with the values obtained for other molecular clouds (Evans et al. 2009; Lada, Lombardi & Alves 2010; Federrath & Klessen 2013; Jose et al. 2016).

To further study the properties of molecular clouds, we calculate the depletion time for the molecular cloud. The depletion time is expressed as

\[
\text{t}_{\text{dep}} = \frac{M_{\text{gas}}}{\dot{M}_*}
\]

where \(\dot{M}_*\) is the star-formation rate. The derived depletion time for the clouds are listed in Table 3. We find that the depletion time varies in the range of \(\sim 38 - 548\) Myr. Clumps 1, 2, 7, 8, 9, 10, 12, 13, and 14 have \(t_{\text{dep}}\) more than 100 Myr. These clumps have less SFR, taking a longer time to deplete the gas. For the remaining clumps, \(t_{\text{dep}}\) are in the range of \(\sim 38 - 76\) Myr. The mean, median, and standard deviation of \(t_{\text{dep}}\) estimated over all the 14 clumps are 218, 132, and 182 Myr, respectively, and for the entire NAN complex, \(t_{\text{dep}}\) is 119.6 \pm 2.4 Myr. Within the standard deviation, our values agree with the depletion time obtained for the nearby Galactic clouds by Evans, Heiderman & Vutisalchavakul (2014). Their mean, median, and standard deviation of \(t_{\text{dep}}\) are 201, 106, and 240 Myr, respectively.

### 4.3.3 Speed of star formation in clumps

The amount of matter that converts into stars over a free-fall time has been addressed by Krumholz & Tan (2007). They have reported that the conversion of matter into stars follows a slow process, converting only \(\sim 1\%\) of gas to stars over a free-fall time. The star-formation rate per free-fall time is defined as the fraction of mass of objects converted into stars in a free-fall time at the object’s peak density (Krumholz & McKee 2005). We have derived the star-formation rate per free-fall time (SFRff) of the 14 dust clumps of the NAN complex using the relation given below.

\[
\text{SFR}_{ff} = \frac{M_* \cdot t_{ff}}{M_{\text{gas}}} = \frac{t_{ff}}{t_{\text{dep}}}
\]

For each clump, we have derived \(t_{ff}\) (explained in Section 4.4.2), \(t_{\text{dep}}\), and SFRff are listed in Table 3. The SFRff of all clumps varies in a range of 0.004 – 0.029, and for the whole NAN complex the value of SFRff is 0.0003. Mean, median, and the standard deviation of SFRff derived for all the 14 clumps are 0.009, 0.006, and 0.008, respectively. The mean SFRff of clumps within NAN complex are comparable to the values obtained by Krumholz & Tan (2007) and the values obtained by the theoretical predictions by Krumholz & McKee (2005).

Evans, Heiderman & Vutisalchavakul (2014) derived the mean, median, and standard deviation of SFRff for the nearby star-forming regions to be 0.018, 0.016, and 0.013, respectively. The mean value of SFRff for the 14 clumps obtained by us and the mean value of nearby star-forming regions obtained by Evans, Heiderman & Vutisalchavakul (2014) agree within standard deviation. This suggests that the clumps within the NAN complex and the regions studied by Evans, Heiderman & Vutisalchavakul (2014) are equally efficient in converting matter into stars over their free-fall time.

Krumholz, McKee & Bland -Hawthorn (2019) reviewed the values of SFRff estimated based on different studies. They reported that the value of SFRff estimated from YSO counting and HCN analysis is \(\approx 0.01\), with a study-to-study dispersion of \(\sim 0.3\) dex and dispersion of 0.3-0.5 dex within a single study, which is summarized in their figure 10. Our derived median value of SFRff is 0.006 or -2.2 dex, which is based on YSO counting, matches with other analysis within a dispersion of \(\sim 0.3\) dex.

### 4.4 Test of star-formation relations

#### 4.4.1 Test of Kennicutt-Schmidt relation

The derived value of SFR surface density for the individual molecular clumps towards the NAN complex can be compared with other Galactic star-forming regions and also with other galaxies. We calculate the theoretical value of SFR surface density for all clumps by using the Kennicutt-Schmidt relation, which has been given for other galaxies (Kennicutt 1998) as,

\[
\Sigma_{\text{SFR}} (M_\odot \ \text{Myr}^{-1} \ \text{pc}^{-2}) = (2.5 \pm 0.7) \times 10^{-4} \Sigma_{\text{gas}}/1 \ M_\odot \ \text{pc}^{-2})^{1.4 \pm 0.15}
\]

where \(\Sigma_{\text{SFR}}\) is the SFR surface density and \(\Sigma_{\text{gas}}\) is the gas surface density. In our analyses the gas surface density values for all the clumps are listed in Table 2. The predicted values of \(\Sigma_{\text{SFR}}\) for clumps using equation 7 lie in range of 0.2
Figure 8 displays the plot between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{gas}}$. On the plot, the black filled circles represent our dust clumps, and the red filled star symbol represents the value observed over the entire NANC complex. The average value over all clumps shown as the blue filled star. The relation from Kennicutt (1998) is shown as a blue solid line. The green box on the plot is for the sources of Evans et al. (2009) adopted from their Figure 4. In Figure 8, we have plotted SFR-gas relations from Bigiel et al. (2008) and Wu et al. (2005). Bigiel et al. (2008) have studied the molecular and atomic gas with the sub-kpc resolution of many nearby galaxies and derived the linear relation between the $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{gas}}$. Wu et al. (2005) have derived their relation by observing dense gas traced from both Galactic star-forming regions and external galaxies using HCN as a tracer. Heiderman et al. (2010) have also studied many nearby star-forming regions in the solar neighbourhood and derived a relation between the $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{gas}}$.

In Figure 8, compared to the 14 clumps in NANC, the value of the entire NANC complex lies towards the low $\Sigma_{\text{gas}}$ and its position lie among the other Galactic star-forming regions (Evans et al. 2009; Evans, Heiderman & Vutisalchavakul 2014). Our clumps as well as the sources of Evans et al. (2009) and Evans, Heiderman & Vutisalchavakul (2014) lie close to the extrapolated relation of Wu et al. (2005) and Heiderman et al. (2010). However, all the points are lying above the relation of Kennicutt (1998). This is likely due to the fact that the relation of Kennicutt (1998) and its coefficient, and exponents are derived by averaging larger regions such as galaxies, where most of the area might be filled with diffused gas without active star formation. This relation might not help to explain the underlying process going on within the star-forming regions of the denser gas of smaller scales. For more details see Evans et al. (2009).

4.4.2 Test of Volumetric star-formation relation

In previous section, we check the Kennicutt-Schmidt relation. Krumholz, Dekel & McKee (2012) have argued that the $\Sigma_{\text{SFR}}$ is better correlated with $\Sigma_{\text{gas}}/t_{\text{ff}}$ than $\Sigma_{\text{gas}}$ itself, where $t_{\text{ff}}$ is the free-fall time scale. This relation between $\Sigma_{\text{gas}}/t_{\text{ff}}$ and $\Sigma_{\text{SFR}}$ is called the volumetric star-formation
relation. According to this relation, a fraction of the molecular gas is converted into stars over a free-fall time period. The general form of the relation is expressed as follows (Krumholz, Dekel & McKee 2012)

$$\Sigma_{\text{SFR}} = \epsilon \frac{\Sigma_{\text{gas}}}{t_{\text{ff}}}$$

(8)

where $\epsilon$ is a dimensionless measure of the SFR, and it is a constant quantity. Federrath (2013) defined the quantity $\epsilon_{\text{ff}} = \epsilon \times \text{SFE}$, where $\epsilon_{\text{ff}}$ is the local core-to-star efficiency and $\epsilon$ is the fraction of infalling gas, that is accreted by the star.

To test this star-formation relation, we estimate the free-fall time scale of the 14 dust clumps using the following relation

$$t_{\text{ff}} = \left( \frac{3 \pi}{32 G m_H n_L} \right)^{1/2}$$

(9)

where, $m = 2.8$, $m_H$ is the mass of the hydrogen atom, and $n_L$ is the volume number density of each clump, and $G$ is the Gravitational constant. For each clump, the volume number density is listed in Table 2. Importing these values into above equation, we calculate $t_{\text{ff}}$ and are listed in Table 3. Mean, median, and standard deviation of $\Sigma_{\text{gas}}/t_{\text{ff}}$ for the 14 clumps are 189.2, 174.0, and 54.4 $M_\odot$ yr$^{-1}$ kpc$^{-2}$, respectively. Value of $\Sigma_{\text{gas}}/t_{\text{ff}}$ obtained over entire NAN region is $14.1 \pm 2.8$ $M_\odot$ yr$^{-1}$ kpc$^{-2}$.

In Figure 9, we show the variation of $\Sigma_{\text{SFR}}$ with $\Sigma_{\text{gas}}/t_{\text{ff}}$.

4.4.3 Test of Orbital time model

Kennicutt (1998) has proposed an empirical star-formation relation, which shows that the SFR of the galaxies depends on the galactic orbital dynamics. This relation can be expressed as follows

$$\Sigma_{\text{SFR}} = \epsilon_{\text{orb}} \frac{\Sigma_{\text{gas}}}{t_{\text{orb}}}$$

(10)

where $\Sigma_{\text{gas}}/t_{\text{orb}} = \Omega$ is the angular rotation speed, $t_{\text{orb}}$ is the orbital rotation speed, and $\epsilon_{\text{orb}}$ is the efficiency of star-formation. This relation also called as the Gas – $\Omega$ relation. From the galaxy samples, Kennicutt (1998) has estimated $\epsilon_{\text{orb}} = 0.017$, which means that the SFR is $\sim 10\%$ of the available gas mass per orbit. This large scale process, which regulates the formation of stars by affecting the gas over an orbital time period, has been observed towards many galaxies (Tan 2000; Suwannajak, Tan & Leroy 2014).
In this analysis, we test this star-formation relation towards the 14 dust clumps of the NAN complex. Whether a large scale effect plays any role on the star-formation process in a Galactic star-forming region can be verified by testing this relation. We calculate the orbital time period of the clumps by using the following relation

\[ t_{\text{orb}} = \frac{2\pi R_G}{V_\theta} \]  \hspace{1cm} (11)

where, \( R_G \) is the Galactic radius, and \( V_\theta \) is the azimuthal velocity for a flat rotation curve. We used \( V_\theta = 254 \text{ km s}^{-1} \) from Reid et al. (2009). Using the relation from Xue et al. (2008), we have estimated the Galactic radius towards the NAN region to be 8 kpc. Since all the dust clumps are associated with the NAN complex, so the orbital time period will be same for all, which is estimated to be 193.7±30.0 Myr. We derived the mean, median, and standard deviation of \( \Sigma_{\text{gas}}/t_{\text{orb}} \) for the clumps and the values are 0.8, 0.8, and 0.2 \( M_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \), respectively and for the entire NAN complex the \( \Sigma_{\text{gas}}/t_{\text{orb}} \) is 0.4±0.02 \( M_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \).

Figure 10 shows the variation of \( \Sigma_{\text{gas}}/t_{\text{orb}} \) for \( \Sigma_{\text{gas}}/t_{\text{orb}} \). The black solid lines on the plot correspond to \( t_{\text{orb}} = 1.0 \) (top) and \( t_{\text{orb}} = 0.1 \) (bottom). All our dust clumps are shown as black dots, and the value obtained over the entire NAN is shown as the red star. The average value obtained overall clumps is shown as the blue star. We have also shown the sources studied by Evans, Heiderman & Vutisalchavakul (2014) as magenta dots. For their sources, at first, we estimate the value of \( R_G \) and then \( t_{\text{orb}} \). We used the Galactic latitudes and longitudes of the sources and the relation of Xue et al. (2008) to estimate the value of \( R_G \). For all the sources of Evans, Heiderman & Vutisalchavakul (2014), we estimate \( R_G \) to be \( \sim 8 \) kpc, similar to the value used by Heyer et al. (2016). The values of \( t_{\text{orb}} \) for sources of Evans, Heiderman & Vutisalchavakul (2014) lie within a range of 185 – 204 Myr. Mean, median, and standard deviation of \( t_{\text{orb}} \) for sources of Evans, Heiderman & Vutisalchavakul (2014) are 193, 191, and 4 Myr, respectively.

In Figure 10, we see that all our dust clumps distributed around the efficiency of \( t_{\text{orb}} = 1.0 \), which is higher than the value of \( t_{\text{orb}} = 0.1 \) estimated by Kennicutt (1998) for disk galaxies. Similar results are also seen by Heyer et al. (2016), for their ATLASGAL sources. This implies that the large scale processes might play a significant role on the formation of molecular clouds from the ISM (Koda, Scoville & Heyer 2016; Heyer et al. 2016). However, this has no impact on the star-formation processes happening within small-scale regions, like the molecular dust clumps.

4.4.4 Test of Crossing time model

The crossing time scale is defined as the time taken by the disturbance to cross the entire cloud traveling at a turbulent equivalent of mean speed (Evans, Heiderman & Vutisalchavakul 2014). We calculate the crossing time for each clumps using the following relation

\[ t_{\text{cross}} = \frac{2 r_{\text{cl}}}{\sigma_v} \]  \hspace{1cm} (12)

where, \( r_{\text{cl}} \) is the radius of clump and \( \sigma_v \) is the dispersion velocity. Radius of all clumps are listed in Table 2. We estimate \( \sigma_v \) from the line width measured by averaging over the clumps from our \(^{13}\)CO map. The estimated \( t_{\text{cross}} \) for all the clumps are listed in Table 3. We derived the mean, median, and standard deviation of \( \Sigma_{\text{gas}}/t_{\text{cross}} \) for the clumps as 11.4, 11.5, and 5.1 \( M_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \), respectively and for the entire NAN complex the value of \( \Sigma_{\text{gas}}/t_{\text{cross}} \) is 0.5±0.1 \( M_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \).

The variation of \( \Sigma_{\text{SFR}} \) with \( \Sigma_{\text{gas}}/t_{\text{cross}} \) is shown in Figure 11. The black dots show the clumps’ locations, and the value of entire NAN is displayed as the red star. The blue star represents the average value obtained for all the clumps. For comparison, we have also plotted the sources from Evans, Heiderman & Vutisalchavakul (2014) as magenta dots on the plot. In this Figure, we do not see any correlation between \( \Sigma_{\text{SFR}} \) and \( \Sigma_{\text{gas}}/t_{\text{cross}} \).

The relevance of crossing time scale on the star-formation process in molecular clouds is analyzed by Elmegreen (2000). This study reported that the formation of stars within the molecular cloud begins by condensing the material, and the process gets completed over several crossing times. They also observed that the star formation in large scale structures is slower than in small scale regions. However, in our clumps, we do not find any evidence of the effect of crossing time scale on the star formation process. Similar conclusion have also been made for nearby sources studied by Evans, Heiderman & Vutisalchavakul (2014).

4.4.5 Test of multi free-fall time model

The basic idea of the multi free-fall time scale concept is discussed in Section 1. The earlier studies (Krumholz, Dekel & McKee 2012; Federrath 2013) have large scatter for relation between \( \Sigma_{\text{SFR}} \) with \( \Sigma_{\text{gas}}/t_{\text{ff}} \), where \( t_{\text{ff}} \) is considered as the \( t_{\text{single-free}} \) by Salim, Federrath & Kewley (2015). To reduce
the scatter and formulate a more precise relation. Salim, Federrath & Kewley (2015) proposed the equation relating $\Sigma_{\text{SFR}}$ with $\Sigma_{\text{gas}}/t_{\text{multi-ff}}$. In this case they assume that the gas densities (PDF) follow the log-normal distribution as the initial condition of star-formation. The log-normal form of PDF is expressed as follows

$$p(s)ds = \frac{1}{\sqrt{2\pi} \sigma^2} \exp\left(-\frac{(s - \sigma_0)^2}{2\sigma^2}\right) ds$$  \hspace{1cm} (13)

where, $s = \ln(\rho/\rho_0)$ is the mean density, $\sigma$ is the variance, which related to the mean density as $\sigma_0 = -\sigma^2/2$ (Vazquez-Semadeni 1994). The quantity $\Sigma_{\text{gas}}/t_{\text{multi-ff}}$ is the maximum gas consumption rate or multi-freefall gas consumption rate (MGCR). The equation of $\Sigma_{\text{gas}}/t_{\text{multi-ff}}$ related to $\sigma_s$ is given as follows (Salim, Federrath & Kewley 2015)

$$\Sigma_{\text{gas}}/t_{\text{multi-ff}} = (\Sigma_{\text{gas}}/t_{\text{ff}}) \exp\left(\frac{3}{8} \sigma_s^2\right)$$  \hspace{1cm} (14)

According to Padoan & Nordlund (2011) and Molina et al. (2012) the logarithmic dispersion has the following expression

$$\sigma_s^2 = \ln\left(1 + b^2 M^2 \frac{\beta}{\beta + 1}\right)$$  \hspace{1cm} (15)

where $M$ is the sonic Mach number, $b$ is the turbulent driving parameter (Federrath, Klessen & Schmidt 2008; Federrath et al. 2010), and $\beta$ is the ratio of thermal to magnetic pressure plasma.

Using the above equations, it is possible to derive the expression for the multi-freefall correction factor (Salim, Federrath & Kewley 2015),

$$C_{\text{multi-ff}} = \frac{(\Sigma_{\text{gas}}/t_{\text{multi-ff}})}{(\Sigma_{\text{gas}}/t_{\text{single-ff}})} = \left(1 + b^2 M^2 \frac{\beta}{\beta + 1}\right)^{3/8}$$  \hspace{1cm} (16)

To get an estimate of the logarithmic dispersion we fit the log-normal equation of PDF and fit it to the actual gas density (Figure 12). In this plot, we estimate $\rho_0$ from the column density map averaging over the entire NAN complex. From the fitting we obtain the value of $\sigma_s = 0.67346 \pm 0.01695$. In our analysis we use the value of $b=0.4$ and $\beta \rightarrow \inf$ (Salim, Federrath & Kewley 2015; Brunt 2010). The use of $\beta \rightarrow \inf$ means that we assume magnetic field to be zero. Importing these parameters into equation 15, we derive the value of sonic Mach number $M = 2$, and the multi-freefall correction factor $C_{\text{multi-ff}} = 0.6$ for the entire NAN complex. For the 14 clumps associated with NAN, we derive the $\Sigma_{\text{gas}}/t_{\text{multi-ff}}$ and are listed in Table 3.

The mean, median, and standard deviation values of $\Sigma_{\text{gas}}/t_{\text{multi-ff}}$ estimated for the clumps are 224.3, 206.2, and 64.4 $M_\odot$ yr$^{-1}$ kpc$^{-2}$, respectively and for the entire NAN complex the derived value of $\Sigma_{\text{gas}}/t_{\text{multi-ff}}$ is $22.1 \pm 2.2$ $M_\odot$ yr$^{-1}$ kpc$^{-2}$. In Figure 13, we display the variation of $\Sigma_{\text{SFR}}$ with $\Sigma_{\text{gas}}/t_{\text{multi-ff}}$ for all the 14 dust clumps. From this plot, we could see a similar distribution as we see in Figure 9, where we show $\Sigma_{\text{SFR}}$ with $\Sigma_{\text{gas}}/t_{\text{ff}}$, which is considered as single free-fall time. This relation received support from recent analysis of few starburst galaxies (Sharda et al. 2018, 2019). However, in our case we did not find any significant difference between the variations of $\Sigma_{\text{SFR}}$ with respect to $\Sigma_{\text{gas}}/t_{\text{multi-ff}}$ and $\Sigma_{\text{gas}}/t_{\text{ff}}$. This relation also shows a good correlation for regions of large scale compared to smaller star-forming regions.
Figure 14. Clumps detected above N(H$_2$) = 7.5 × 10^{21} \text{ cm}^{-2} displayed on the column density map. The clump numbers are also given. Scaling of column density map starts with 7.5 × 10^{21} \text{ cm}^{-2} to highlight only the dense parts of the NAN complex.

4.4.6 Test of star formation rate and dense gas mass

Several studies reported a better and tight correlation between the SFR and the mass of dense gas. Gao & Solomon (2004) first observed this tight SFR and dense gas relation towards a sample of IR galaxies, and later this has been observed towards the Galactic dense clouds by Wu et al. (2005). The idea that the molecular clouds form stars efficiently above a certain threshold has been discussed by many authors (Goldsmith et al. 2008; Lada, Lombardi & Alves 2010; Heiderman et al. 2010). It has been suggested that the SFR is better correlated to the dense mass (Lada, Lombardi & Alves 2010; Heiderman et al. 2010). This correlation between SFR and dense gas has been observed in many star-formation studies (Lada et al. 2012; Evans, Heiderman & Vutisalchavakul 2014; Vutisalchavakul, Evans & Heyer 2016; Evans et al. 2020).

In this work, we test this model towards the dense clumps associated with the NAN complex. We detect these dense clumps from the column density map following a similar procedure mentioned in section 4.2.2, with a threshold value of 7.5 × 10^{21} \text{ cm}^{-2}. We identify seven clumps which lie above this high column density value. Figure 14 shows the distribution of these clumps on the column density map. For all these dense clumps, we derive mass, which are listed in Table 4. We call the mass of these clumps as the dense mass. To derive the SFR of the clumps, we count only the Class I YSOs within the clumps and use the age as 0.55 Myr, typically a crossover time of Class I YSOs. The derived SFR values of the clumps are listed in Table 4.

In Figure 15(a), we display the relation between the mass of the clumps and their SFR. The linear fit indicates a relatively poor correlation between SFR and dense gas mass of the clumps. In Figure 15(b), we plot the dense mass versus SFR of the complete NAN complex (which is equivalent to the sum of the seven clumps) along with the other Galactic star-forming regions found in literature (Evans, Heiderman & Vutisalchavakul 2014; Vutisalchavakul, Evans & Heyer 2016). For the complete NAN region, mass of dense gas and SFR are estimated to be $7186 \pm 14 \text{ M}_\odot$, and $104.6 \pm 9.7 \text{ M}_\odot \text{ Myr}^{-1}$, respectively. In Figure 15(b), the green box represents the coverage of sources taken from Evans, Heiderman & Vutisalchavakul (2014) and the magenta box represents the sources from Vutisalchavakul, Evans & Heyer (2016). The dotted magenta line displays the linear least-square fit adopted from Vutisalchavakul, Evans & Heyer (2016). The red star on the plot represents the NAN complex, and the solid black line is the dense gas relation suggested by Lada et al. (2012) drawn using equation 9 of Evans, Heiderman & Vutisalchavakul (2014). From this plot, it is clear that the NAN complex lies among the other Galactic star-forming regions, where the tight relation between SFR and dense gas have already been observed. We agree with the previous analysis of a tight relationship between SFR and dense gas, which is also observed towards the whole NAN region. The dense gas mass is better to predict the SFR of the entire NAN complex rather than for the individual clumps.

4.4.7 Testing star-formation relations for the entire NAN complex

In above sections, we tested several star-formation scaling relations for the dust clumps within the NAN complex. All the star-formation relations show scatter for the 14 dust clumps. Similar scatter was also seen for the nearby star-forming regions analysed by Evans, Heiderman & Vutisalchavakul (2014). However, the ATLASGAL clumps studied by Heyer et al. (2016) produced a linear correlation of $\Sigma_{\text{SFR}}$ with $\Sigma_{\text{gas}}$/tff and $\Sigma_{\text{gas}}$/t_{cross}. Does the relations differ for star-forming regions of different sizes? A more precise relation between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{gas}}$ would help to explain the star-formation processes within regions of small size.

In this section, we test the star-formation relations for the complete NAN complex and compare it with the other Galactic regions. Salim, Federrath & Kewley (2015) have compared the three star formation relations, the Kennicutt–Schmidt relation, single free-fall time scale model, and the multiple free-fall time scale model. They study these relations for several Galactic regions and galaxies and is presented in Figure 2 of Salim, Federrath & Kewley (2015). The different panels of the Figure 16 provides a comparison of the three major star-formation relations. Here, we use all the sources analyzed by Salim, Federrath & Kewley (2015) shown as black squares and the NAN complex shown as the red star. The solid black lines are adopted from Salim, Federrath & Kewley (2015). The location of NAN matches with other Galactic star-forming regions, but with a larger offset from that of Salim, Federrath & Kewley (2015) in the multi free-fall time model. Salim, Federrath & Kewley (2015) obtained the scatter in multi free-fall time scale model to be 1.0, which is less by a factor of 3 – 4 than the other two star-formation relations implying that this relation is the better to predict SFR. A recent similar analysis by Sharda et al. (2018) and Sharda et al. (2019) also leads to a similar conclusion. This is because the multi free-fall time scale model accounts for the physical effects.
such as turbulence and magnetic field along with the effect of gravity. These physical factors play an important role in the formation of stars (Padoan & Nordlund 2011; Federrath & Klessen 2012).

5 DISCUSSION

We test several star-formation relations in clumps associated with the NAN complex. Here we attempt to find out which star-formation relation is better to predict the SFR. An easy and efficient way is to measure the spread among the data points and check which relation shows the best result. For this purpose, we plot the quantity $X$ versus $SFR/X$ in the logarithmic scale. The quantity $X$ is different for different star-formation relations. Then we check which relation is better performing based on their dispersion.

For the Kennicutt-Schmidt relation, $X = M_{\text{gas}}$, which is mass of each clump. In the case of volumetric star-formation relation, $X = M_{\text{gas}}/t_{\text{ff}}$. For the orbital time model, crossing time model, and multi free-fall time model, $X = M_{\text{gas}}/t_{\text{orb}}$, $M_{\text{gas}}/t_{\text{cross}}$, and $M_{\text{gas}}/t_{\text{multi-ff}}$, respectively. For the test of SFR versus dense gas mass, $X = M_{\text{dense}}$, which is estimated above $N(H_2) = 7.5 \times 10^{21} \text{ cm}^{-2}$. In Figure 17, we show the variation of $X$ versus $SFR/X$. We put all our clumps and compare with nearby Galactic star-forming regions (Evans, Heiderman & Vutisalchavakul 2014), wherever possible. The estimated mean and standard deviation of the variable $SFR/X$ are listed in Table 5.

We observe that for all the relations, the standard deviation in $SFR/X$ is $0.5$ dex. The crossing time model displays a maximum dispersion of $0.6$ dex. We obtained minimum dispersion to be $0.4$ dex for the Kennicutt-Schmidt relation and the orbital time scale model. However, it is difficult to make any strong conclusion based on this small number of clumps, about which relation is better to predict the SFR in clumps. Vutisalchavakul, Evans & Heyer (2016) have also derived the mean and standard deviation for three star-formation relations (Kennicutt-Schmidt relation, volumetric star-formation relation and for SFR versus dense mass). So we compared the estimation made by us for the clumps with the nearby cloud sample of Evans, Heiderman & Vutisalchavakul (2014) and Galactic Plane clouds of Vutisalchavakul, Evans & Heyer (2016). In

Table 4. Physical parameters of the clumps associated with dense regions. The peak position of column density, radius, mass, gas surface density are listed along with associated YSOs (Class I), densities, and star formation rate.

| Clump No. | RA (2000) | DEC (2000) | Radius (pc) | Mass ($M_\odot$) | $\Sigma_{\text{gas}}$ ($M_\odot$ pc$^{-2}$) | N (YSOs) | N/Area (pc$^{-2}$) | SFR ($M_\odot$ yr$^{-1}$) | SFR/Area ($M_\odot$ yr$^{-1}$ kpc$^{-2}$) |
|-----------|-----------|-----------|-------------|---------------|-----------------|----------|----------------|-----------------|-----------------|
| 1         | 20:53:35.74 | 44:32:21.67 | 0.9 ± 0.05 | 611.2 ± 15 | 213.8 ± 1.5 (0.04 ± 0.0002) | 9        | 3.2 | 8.2 ± 0.7 | 2.9 ± 1.0 |
| 2         | 20:50:50.64 | 44:23:38.18 | 1.6 ± 0.08 | 570 ± 27    | 209.8 ± 1.0 (0.03 ± 0.0002) | 19       | 2.3 | 17.3 ± 3.9 | 2.1 ± 0.5 |
| 3         | 20:54:59.85 | 44:17:22.84 | 1.3 ± 0.06 | 937 ± 25    | 192.3 ± 1.0 (0.04 ± 0.0003) | 5        | 1.0 | 4.6 ± 0.2 | 0.9 ± 0.4 |
| 4         | 20:52:09.83 | 44:47:46.51 | 0.8 ± 0.04 | 372 ± 23    | 185.4 ± 1.5 (0.02 ± 0.0002) | 1        | 0.5 | 1.0 ± 0.2 | 0.5 ± 0.4 |
| 5         | 20:55:16.37 | 43:51:22.64 | 7.0 ± 0.05 | 577 ± 24    | 198.3 ± 1.4 (0.04 ± 0.0004) | 1        | 0.3 | 1.6 ± 0.8 | 0.3 ± 0.3 |
| 6         | 20:57:32.10 | 43:47:45.16 | 1.6 ± 0.09 | 197 ± 27    | 192.4 ± 1.7 (0.05 ± 0.0006) | 79       | 7.7 | 73.8 ± 8.1 | 7.9 ± 1.0 |
| 7         | 20:55:07.92 | 43:33:52.86 | 1.2 ± 0.06 | 580 ± 25    | 212.4 ± 1.2 (0.04 ± 0.0002) | 1        | 0.2 | 0.9 ± 0.8 | 0.2 ± 0.2 |

$^\dagger$ Gas surface density ($\Sigma_{\text{gas}}$) in parenthesis has unit gm cm$^{-2}$. 

Figure 15. (a) Variation of dense mass with SFR for all the clumps detected above $N(H_2) = 7.5 \times 10^{21} \text{ cm}^{-2}$. The red line is the linear fit considering all the clumps. (b) Variation of dense mass with SFR for the complete NAN complex, which is shown as the red star. Green box demarcates the region covering sources of Vutisalchavakul, Evans & Heyer (2016) adopted from Figure 8 of their paper. Similarly, the magenta box demarcates the region for sources of Vutisalchavakul, Evans & Heyer (2016) adopted from Figure 4 of their paper. The dotted magenta line is the linear least-square fit adopted from Figure 4 of Vutisalchavakul, Evans & Heyer (2016). The prediction of Lada et al. (2012) is plotted as a solid black line. We draw this line using equation 9 of Evans, Heiderman & Vutisalchavakul (2014).
all these studies the standard deviation is similar and of the order of ~0.5 dex. However, the mean value differs among the analysis and also among the different predictors. The possible reasons could be the non-uniformity in the various methods used for the estimation of SFR and the uncertainties associated with the assumption that all the clumps are at a similar evolutionary stage that have already produced the majority of the stars.

6 SUMMARY

In this work, we have analyzed the entire region of NAN complex for an area of $2.5^\circ \times 2.5^\circ$ and test various star-formation scaling relations in the dust clumps. The major outcome of the work are the following.

(i) We use the deep NIR data of UKIDSS WFCAM and MIR data in 3.6 and 4.5 μm bands of Spitzer IRAC to identify additional 842 YSOs located in the NAN region. Combining this additional YSOs with the previously detected YSOs by Rebull et al. (2011) and Guieu et al. (2009), a total of 3038 YSOs are found to be associated with NAN. This is the deepest and most complete YSO list detected towards the NAN region to date. Out of 3038 YSOs, 334 are Class I, 1964 are Class II, 332 are Class III, 341 are Flat-spectrum, and 67 are unknown type YSOs. The YSOs are complete down to a mass range of $0.03 - 0.08 M_\odot$, for the extinction range $A_V$ of 5 – 10 mag at a distance of 800 pc and for the average age of ~2 Myr.

(ii) Most of the YSOs display a spatial distribution along the diagonal region extending from north-west to south-east. Class II YSOs seem to be dominating the north-west region.

(iii) Using the $^{12}$CO and $^{13}$CO molecular line data, we generate the column density map. Using the astrodendro algorithm, 14 dust clumps have been identified. Physical properties of all the dust clumps are derived.

(iv) We derive the SFR and SFE of all the dust clumps and compare the $\Sigma_{\text{SFR}}$ with $\Sigma_{\text{gas}}$ of all the dust clumps. The SFR and SFE of clumps lies in range of $0.5 \pm 0.4 – 78.3 \pm 4.4 M_\odot$ Myr$^{-1}$ and $0.4 \pm 0.003 – 5.0 \pm 0.003\%$, respectively. The estimated $\Sigma_{\text{SFR}}$ are in range of $0.2 \pm 0.1 – 4.8 \pm 0.5 M_\odot$ yr$^{-1}$ kpc$^{-2}$.

(v) We test the Kennicutt-Schmidt relation for all the dust clumps. All the clumps lie above the Kennicutt-Schmidt relation. This implies that the relation proposed based on the observations towards galaxies is unable to explain the star-formation processes within local clumps.

(vi) From volumetric star-formation relation, we see a large scatter among the clumps. All clumps lie above the efficiency level of 0.001. For this relation, we observe a high scatter among the clumps associated with the NAN complex.

(vii) We use the orbital time period model to understand the underlying process of star-formation within the clumps. However, this has no impact on the star-formation process happening within the small scale regions, like the molecular dust clumps.

(viii) We test the crossing time scale model in all the dust clumps. However, in our clumps, we did not find any evi-

Figure 16. This plot shows the variation of $\Sigma_{\text{SFR}}$ with $\Sigma_{\text{gas}}$, $\Sigma_{\text{gas}}/t_{\text{single}}$, and $\Sigma_{\text{gas}}/t_{\text{multi}}$. The black squares are the sources from Salim, Federrath & Kewley (2015) and the solid lines are from Figure 2 of Salim, Federrath & Kewley (2015). The red star represents the location of NAN complex.
Figure 17. Variation of $\log(\text{SFR}/M_{\text{gas}})$ with $\log(M_{\text{gas}})$ (a), $\log(\text{SFR}/(M_{\text{gas}}/t_{\text{ff}}))$ with $\log(M_{\text{gas}}/t_{\text{ff}})$ (b), $\log(\text{SFR}/(M_{\text{gas}}/t_{\text{orb}}))$ with $\log(M_{\text{gas}}/t_{\text{orb}})$ (c), $\log(\text{SFR}/(M_{\text{gas}}/t_{\text{cross}}))$ with $\log(M_{\text{gas}}/t_{\text{cross}})$ (d), $\log(\text{SFR}/(M_{\text{gas}}/t_{\text{multi-ff}}))$ with $\log(M_{\text{gas}}/t_{\text{multi-ff}})$ (e), and $\log(\text{SFR}/M_{\text{dense}})$ with $\log(M_{\text{dense}})$ (f). On all the plots, the black dots are for clumps associated with NaN complex and the magenta dots are for the nearby star-forming regions taken from Evans, Heiderman & Vutisalchavakul (2014). The black and magenta solid lines represent the mean values.
dence of the effect of crossing time scale on the star formation process.

(ix) The multi free-fall time model has also been tested. Similar to other relations, we did not find any evidence of multi free-fall time on the star-formation within the clumps.

(x) Our test of SFR versus the dense gas mass does not reveal a tight SFR gas relation for the clumps associated with dense gas, which could be due to low statistics of our sample. However, for the whole NAN complex, a tight relation is observed.

(xi) We test the star-formation relations for the entire NAN complex. We conclude that these star-formation relations have less scatter dealing with galaxies or large scale structures. While for small scale regions, they have large scatter.

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DATA AVAILABILITY

Table of the list of YSOs is provided as online material. The other data underlying this article will be shared on reasonable request to the corresponding author.

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| Variable | NAN Clumps | Evans 14 |
|----------|------------|----------|
|          | Mean | SD | Mean | SD |
| log(M_{gas}[Myr^{-1}]) | -2.16 | 0.41 | -2.07 | 0.43 |
| log(M_{gas}/t_{ff}[M_{\odot}Myr^{-1}]) | -2.24 | 0.46 | -1.90 | 0.44 |
| log(M_{gas}/t_{orb}[M_{\odot}Myr^{-1}]) | 0.13 | 0.41 | 0.28 | 0.40 |
| log(M_{gas}/t_{cross}[M_{\odot}Myr^{-1}]) | 1.00 | 0.60 | 1.50 | 0.48 |
| log(M_{gas}/M_{dense}[Myr^{-1}]) | -2.32 | 0.46 | – | – |
| log(SFR/M_{dense}[Myr^{-1}]) | -2.29 | 0.52 | – | – |
Table A1: List of all the 3038 YSOs associated with NAN complex.

| YSO | RA (J2000) | DEC (J2000) | J  | H  | K  | 3.6 | 4.5 | 5.8 | 8.0 | 24.0 | Class |
|-----|-------------|-------------|----|----|----|-----|-----|-----|-----|-------|-------|
|     | (h m s) | (° ' '') | (mag) | (mag) | (mag) | (mag) | (mag) | (mag) | (mag) | (mag) |       |
| 1   | 20:46:24.98 | 44:55:45.83 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 4.84±0.04 | Unknown |
| 2   | 20:46:36.80 | 44:44:34.94 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 9.67±0.05 | 0.00±0.00 | 9.15±0.05 | 0.00±0.00 | 0.00±0.00 | Unknown |
| 3   | 20:46:41.54 | 44:36:48.56 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 11.64±0.05 | 0.00±0.00 | 11.31±0.06 | 0.00±0.00 | 0.00±0.00 | Unknown |
| 4   | 20:46:45.64 | 44:35:11.43 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 8.15±0.05 | 0.00±0.00 | 6.53±0.05 | 0.00±0.00 | 0.00±0.00 | Unknown |
| 5   | 20:47:17.51 | 44:37:49.85 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 12.37±0.05 | 11.99±0.06 | 11.64±0.06 | 11.10±0.06 | 0.00±0.00 | Class II |
| 6   | 20:47:21.51 | 44:10:25.14 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 13.04±0.06 | 0.00±0.00 | 12.16±0.06 | 0.00±0.00 | 7.52±0.05 | Flat |
| 7   | 20:47:22.69 | 43:50:11.09 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 11.86±0.05 | 11.65±0.05 | 11.47±0.06 | 10.71±0.06 | 0.00±0.00 | Class II |
| 8   | 20:47:23.59 | 43:44:39.57 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 7.61±0.05 | 7.17±0.05 | 6.62±0.05 | 5.46±0.05 | 0.00±0.00 | Class II |
| 9   | 20:47:25.20 | 43:48:32.05 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 10.01±0.05 | 9.47±0.05 | 9.03±0.05 | 8.13±0.05 | 0.00±0.00 | Class II |
| 10  | 20:47:26.01 | 43:49:8.99  | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 14.13±0.06 | 13.84±0.06 | 13.63±0.10 | 12.98±0.11 | 0.00±0.00 | Class II |
| 11  | 20:47:27.03 | 43:49:12.71 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 13.78±0.06 | 13.57±0.06 | 13.34±0.09 | 13.01±0.14 | 0.00±0.00 | Class III |
| 12  | 20:47:27.89 | 43:50:22.71 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 13.61±0.06 | 13.38±0.06 | 13.04±0.07 | 12.62±0.08 | 0.00±0.00 | Class III |
| 13  | 20:47:28.17 | 44:57:11.49 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 7.32±0.05 | Unknown |
| 14  | 20:47:30.40 | 43:46:12.19 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 11.10±0.05 | 10.43±0.05 | 9.94±0.06 | 9.46±0.06 | 0.00±0.00 | Class II |
| 15  | 20:47:34.19 | 43:47:23.92 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 11.53±0.06 | 11.14±0.06 | 10.50±0.06 | 9.74±0.06 | 0.00±0.00 | Class II |
| 16  | 20:47:35.34 | 43:44:46.04 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 13.83±0.06 | 13.56±0.06 | 13.25±0.08 | 12.47±0.09 | 0.00±0.00 | Class II |
| 17  | 20:47:36.09 | 44:29:29.97 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 10.10±0.05 | 0.00±0.00 | 9.88±0.06 | 0.00±0.00 | 7.99±0.05 | Class III |
| 18  | 20:47:37.47 | 43:47:24.81 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 6.62±0.00 | 6.10±0.00 | 3.97±0.05 | 3.52±0.00 | 0.00±0.00 | Unknown |
| 19  | 20:47:37.62 | 43:43:37.74 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 10.94±0.05 | 10.47±0.05 | 10.10±0.06 | 9.31±0.06 | 0.00±0.00 | Class II |
| 20  | 20:47:38.03 | 43:49:28.11 | 0.00±0.00 | 0.00±0.00 | 0.00±0.00 | 12.09±0.05 | 11.76±0.05 | 11.58±0.06 | 10.59±0.06 | 0.00±0.00 | Class II |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)