Vibrationally excited HC$_3$N emission in NGC 1068: Tracing the recent star formation in the starburst ring.

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ABSTRACT

Using ALMA data, we have studied the HC$_3$N and continuum emission in the starburst ring (SB ring) and the circumnuclear disc (CND) of the SB/AGN composite galaxy NGC 1068. We have detected emission from vibrationally excited HC$_3$N (HC$_3$N*) only towards one star-forming region of the SB ring. Remarkably, HC$_3$N* was not detected towards the CND despite its large HC$_3$N v = 0 column density. From LTE and non-LTE modelling of HC$_3$N*, we obtained a dust temperature of $T_{\text{dust}} \sim 250$ K and a density of $n_{\text{H}_2} = 6 \times 10^5$ cm$^{-3}$ for this star-forming region. The estimated IR luminosity of $5.8 \times 10^8$ L$_\odot$ is typical of proto-Super Star Clusters (proto-SSC) observed in the SB galaxy NGC 253. We use the continuum emissions at 147 GHz and 350 GHz, along with CO and Pa$\alpha$, to estimate the ages of other 14 SS Cs in the SB ring. We find the youngest SS Cs to be associated with the region connecting the nuclear bar with the SB ring, supporting the scenario of sequential star formation. For the CND, our analysis yields $T_{\text{dust}} \leq 100$ K and $n_{\text{H}_2} \sim (3 - 6) \times 10^5$ cm$^{-3}$. The very different dust temperatures found for the CND and the proto-SSC indicates that, while the dust in the proto-SSC is being efficiently heated from the inside by the radiation from massive proto-stars, the CND is being heated externally by the AGN, which in the IR optically thin case can only heat the dust to 56 K. We discuss the implications of the non-detection of HC$_3$N* near the luminous AGN in NGC 1068 on the interpretation of the HC$_3$N* emission observed in the SB/AGN composite galaxies NGC 4418 and Arp 220.

Key words: galaxies: individual: NGC 1068 – galaxies: Seyfert – galaxies: ISM – galaxies: star formation – galaxies: star clusters

1 INTRODUCTION

In many galaxies, both active galactic nucleus (AGN) and star formation (SF) activity contribute to a significant fraction of the total galaxy luminosity (Genzel et al. 1998). Discerning how much each one contributes to the galaxy luminosity can tell us the physical processes heating the gas and dust and thus evaluate their associated radiative and kinematic feedback in the context of galaxy evolution. In addition, establishing which is the dominating heating mechanism (AGN or SF) in extremely obscured nuclei remains a key problem in extragalactic astrophysics (Martín et al. 2016).

Due to the high extinction in these environments, observations in the IR or at shorter wavelengths only detect the outermost surface of the optically thick regions, where column densities of molecular gas can reach values of up to or even beyond $N(\text{H}_2) = 10^{25}$ cm$^{-2}$. With such large column densities, the AGN becomes Compton thick, preventing its identification even in the X-rays (e.g. González-Alfonso et al. 2012; Lusso et al. 2013; Costagliola et al. 2013).

In the last years it has been proposed that emission from
vibrationally excited molecules such as HCN or HC$_3$N in highly obscured galactic nuclei can be used as tracers of the nuclear activity in these obscured galaxy nuclei (Sakamoto et al. 2010; Costagliola & Aalto 2010; Martin et al. 2011; Martin et al. 2016; Aalto 2015; Imanishi et al. 2016, 2019; González-Alfonso & Sakamoto 2019). As the radiation from the obscured heating source is reprocessed by the dust into the IR, peaking in the mid-IR (10–50 μm), the IR photons efficiently pump these molecules into their vibrational excited states. On the other hand, the rotational levels from the vibrationally excited molecules emit radiation in the cm to sub-mm wavelength range, unaffected by dust extinction, making them powerful tools to probe the energetic processes taking place in the innermost regions of heavily obscured galactic nuclei.

In particular, vibrationally excited HC$_3$N (hereafter, HC$_3$N*) is very well suited for tracing energetic processes in highly obscured regions. In the Milky Way (MW), its emission is associated with warm, dense UV shielded and very compact regions around massive star-forming regions, named Hot Cores (HCs, e.g. Goldsmith et al. 1982; Wyrwoski et al. 1999; de Vicente et al. 2000, 2002; Martín-Pintado et al. 2005), where HC$_3$N* is tracing massive star formation in the early protostellar phases (hot core and circumstellar phases; Jiménez-Serra et al. 2009). However, HC$_3$N* emission is not detected in the circumnuclear disc (CND) surrounding the supermassive black hole (SMBH) of the MW since HC$_3$N is photodissociated by UV radiation (Costagliola & Aalto 2010; Martín et al. 2012; Costagliola et al. 2015) emitted from the central star cluster.

Outside the MW, HC$_3$N* has been observed in the nuclei of very active ULIRGs galaxies like NGC 4418 (Costagliola & Aalto 2010; Costagliola et al. 2015) and Arp 220 (Martin et al. 2011). More recently, in Rico-Villas et al. (2020) we detected HC$_3$N* emission in the prototypical starburst galaxy NGC 253. The emission is associated, like in the MW, with the very early phases of the formation of Super Star Clusters (i.e. proto Super Star Clusters, proto-SSCs hereafter). In contrast, we could not identify any HC$_3$N* emission associated with the strongest non thermal source (TH2, Turner & Ho 1985) nor its kinematical center (Müller-Sánchez et al. 2010), both proposed to host a SMBH in this galaxy. Unfortunately, the lack of observational evidence of the presence of an active SMBH in NGC 253 prevented us from studying its possible effects on the vibrational excitation of HC$_3$N. So far, all the observational data suggest that HC$_3$N* emission is mainly tracing the recent brief episodes of massive star formation in the very early stages of cluster formation. However, there is not any systematic study of the HC$_3$N* emission in nearby galaxies with AGN nuclear activity.

NGC 1068, one of the closest galaxies hosting spatially resolved AGN and starburst (SB) activities, offers a unique opportunity to study the effects of star formation and AGN activity from its ~ 107 M$_\odot$ SMBH (Davis et al. 2014; Combes et al. 2019) on the vibrational excitation of HC$_3$N. NGC 1068 is a prototypical Seyfert 2 barred galaxy, located at $D = 14.4$ Mpc (Bland-Hawthorn et al. 1997), with a luminosity of $L_{IR} = 3 \times 10^{11}$ L$_\odot$ (Telesco & Harper 1980). Its central region has been extensively observed to study the AGN activity and its effects of the SMBH on its surroundings, including fueling and associated feedback. NGC 1068 has an AGN driven outflow and bipolar radio jets that strongly interact with the ISM (García-Burillo et al. 2014). In particular, the elliptical ring with $r \sim 200$ pc, known as the CND, surrounding the SMBH is strongly affected by the AGN driven jets and outflow (Krips et al. 2006; García-Burillo et al. 2014, 2017, 2019; Viti et al. 2014). In addition to the AGN dominated central region, there is a SB ring where most of the recent massive SF of the galaxy concentrates, located at $r \sim 1.3$ kpc from the nucleus and arising from a two-armed spiral structure that starts at both ends of the central bar (García-Burillo et al. 2014).

García-Burillo et al. (2014) and Viti et al. (2014) analyzed the molecular emission from both the CND and the SB ring and found differences in the molecular line ratios (from CO, HCO$^+$, HCN and CS) between both regions, indicating that the radiative and mechanical feedback from the AGN has changed the physical conditions and the chemistry of the molecular gas in the CND. They found that, in general, more dense ($10^3$ cm$^{-3}$) and warmer ($T$ ~ 150 K) gas is found in the CND (Viti et al. 2014), although they only analyze one star-forming region as representative of the SB ring. Furthermore, the HC$_3$N abundance in the CND has been found to be enhanced likely due to the AGN induced chemistry (Viti et al. 2014), which offers a unique opportunity to study in detail the effects of the SMBH on the heating of its surroundings as traced by the HC$_3$N* emission.

In this paper we study the HC$_3$N emission in the CND and the SB ring of NGC 1068. Despite the bright HC$_3$N emission from the ground state observed in the CND, we find HC$_3$N vibrationally excited emission in only one condensation of the SB ring, revealing the presence of a Super Hot Core (SHC). We show that, contrary to massive proto-stars, the AGN is extremely efficient in heating the gas of the CND mainly through shocks originating in the jet/outflow system, but very inefficient in heating the dust by radiation, which is the requirement for HC$_3$N to be vibrationally excited for the derived H$_2$ densities.

2 DATA REDUCTION

To study the HC$_3$N emission from the SB ring and the CND of NGC 1068, we have used publicly available data from the ALMA science archive. The observations are summarized in Table 1. Additionally, we also made use of the HST NICMOS (NIC3) narrow-band (F187N, F190N) Pa$\alpha$ line emission image of NGC 1068 (for details on the calibration and imaging, see García-Burillo et al. 2014).

The ALMA data calibration and imaging was carried using the Common Astronomy Software Applications (CASA; McMullin et al. 2007) 4.2 version pipeline. Continuum emission maps were obtained by averaging line-free channels. Due to the large amount of molecular emission and the large velocity gradients between the CND and the SB ring data were not continuum subtracted in the uv-plane. For deconvolution we have used the CASA tclean task with Briggs weighting setting the robust parameter to 0.5. All the produced data cubes and continuum maps were corrected for the primary beam. The achieved synthesized beam sizes and resulting rms noise in the cubes, as well as the corresponding primary beam FWHM (FOV), are also listed in Table 1. Since most of the NGC 1068 observations are centered on the AGN po-

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sition, as we move to higher frequencies the observed field of view of the telescope primary beam is reduced, limiting the observations of the SB ring to the outer edge of the mapped area at ~ 220 GHz. As a consequence there is a decrease in sensitivity at the edges of the map where the SB ring is observed. Fortunately, project-ID 2011.0.00083.S (Martín et al. 2019) guarantees a flat spectral baseline in order to carry out the molecular line analysis.

3 RESULTS

3.1 Pa α and continuum emission

The left panel of Figure 1 shows the ALMA continuum emission maps obtained at 147 GHz and at 350 GHz overlaid on the Pa α emission. The figure also labels the main identified features in NGC 1068 discussed in this paper. As expected, the Pa α emission shows a spatial distribution different from the mm-submm continuum emission. This is partially due to the extinction of the Pa α lines by dust, and also because it traces a less embedded and more evolved stage in the process of massive star formation in the SB ring (Sánchez-García et al. in prep.).

From the continuum maps at 147 GHz and 350 GHz, we have identified 15 clumps (including the SHC) in the SB ring. We have also identified two representative sources that are bright in Pa α (Pa α 1 and Pa α 2) but do not have any associated 350 GHz emission. In addition, we have also included two CND positions, located East and West from the AGN. Their coordinates are listed in Table 2. To perform the analysis of the continuum emission, we have smoothed the Pa α and 350 GHz images to the same spatial resolution of the 147 GHz map (i.e. 0.62″ × 0.42″). We have then measured the peak continuum emission in the three maps at the location of the 147 GHz maximum (see Table 3).

Table 1. ALMA observations used in this work.

| Project-ID | Frequency (GHz) | Resolution (arcsec) | rms (mJy beam⁻¹) | FOV (arcsec) |
|------------|----------------|---------------------|------------------|--------------|
| 2013.1.00055.S | 85.37 – 100.99 | 0.73″ × 0.46″ | 0.67 | 62.49 |
| 2013.1.00021.S | 85.55 – 98.54 | 0.72″ × 0.46″ | 0.37 | 63.26 |
| 2013.1.00027.S | 88.61 – 104.30 | 0.67″ × 0.43″ | 0.54 | 60.37 |
| 2013.1.00047.S | 92.54 – 108.24 | 0.60″ × 0.38″ | 0.96 | 58.00 |
| 2013.1.00060.S | 96.25 – 110.05 | 0.155″ × 0.99″ | 0.62 | 56.45 |
| 2013.1.00221.S | 128.83 – 130.71 | 0.45″ × 0.35″ | 0.37 | 44.87 |
| 2015.1.01144.S | 143.62 – 159.44 | 0.65″ × 0.44″ | 0.62 | 38.43 |
| 2016.1.00023.S | 215.35 – 231.97 | 0.33″ × 0.26″ | 0.43 | 26.04 |
| 2011.0.00083.S | 342.27 – 357.92 | 0.42″ × 0.55″ | 3.48 | 48.69 |
| 2016.1.00023.S | 343.56 – 358.29 | 0.22″ × 0.19″ | 0.77 | 16.59 |

* Mosaic.

Table 2. Coordinates and velocities of the analyzed clumps.

| Location | RA (J2000) | Dec (J2000) | VLSR (km s⁻¹) |
|----------|------------|------------|---------------|
| SHC      | 00° 53′.49 | 11° 42′    | 1094.3 ± 0.3  |
| Cont. 1  | 00° 37′.48 | 11° 42′    | 1004.4 ± 1.2  |
| Cont. 2  | 00° 34′.97 | 11° 42′    | 1054.8 ± 1.1  |
| Cont. 3  | 00° 34′.64 | 11° 42′    | 1067.0 ± 2.3  |
| Cont. 4  | 00° 32′.66 | 11° 42′    | 1168.0 ± 0.9  |
| Cont. 5  | 00° 35′.75 | 11° 42′    | 1174.1 ± 1.1  |
| Cont. 6  | 00° 37′.75 | 11° 42′    | 1193.2 ± 0.6  |
| Cont. 7  | 00° 53′.12 | 11° 42′    | 1287.1 ± 0.3  |
| Cont. 8  | 00° 54′.96 | 11° 42′    | 1277.3 ± 0.4  |
| Cont. 9  | 00° 57′.88 | 11° 42′    | 1263.5 ± 0.3  |
| Cont. 10 | 00° 00′.76 | 11° 42′    | 1250.2 ± 1.0  |
| Cont. 11 | 00° 01′.64 | 11° 42′    | 1193.0 ± 0.5  |
| Cont. 12 | 00° 02′.85 | 11° 42′    | 1143.9 ± 0.7  |
| Cont. 13 | 00° 01′.61 | 11° 42′    | 1135.1 ± 1.6  |
| Cont. 14 | 00° 00′.95 | 11° 42′    | 1126.4 ± 1.5  |
| Pa α 1   | 00° 39′.37 | 11° 42′    | 1205.8 ± 0.8  |
| Pa α 2   | 00° 59′.28 | 11° 42′    | 1247.3 ± 0.9  |
| CND E.   | 00° 47′.84 | 11° 42′    | 1076.3 ± 0.6  |
| CND W.   | 00° 47′.64 | 11° 42′    | 1191.8 ± 1.1  |

* Velocity derived from CS since no HC3N was detected.

The continuum emission at 147 GHz in the CND is mainly dominated by the non-thermal synchrotron emission from the AGN and the bipolar radio jets interacting with the ISM and its AGN-driven outflow (García-Burillo et al. 2014). In the SB ring, the continuum emission at 147 GHz is expected to be mainly dominated by free-free emission. The flux at 8.4 GHz measured with the VLA with an angular resolution of 3.5″ × 2.9″ at the SHC is ~ 1.6 Jy (Anantharamaiah et al. 1993), which is consistent with optically thin free-free emission at 147 GHz as the spectral index between these frequencies is ~ −0.1. However, the beam sizes are rather different. We can also use the continuum emission at 350 GHz to estimate the possible contribution from dust emission to the 147 GHz continuum emission. Assuming that the dust emission measured at 350 GHz is optically thin and a typical dust emissivity spectral index of 1.5, the expected contribution of the dust emission to the 147 GHz flux will be only of about 20%, i.e. the 147 GHz continuum is dominated by the free-free emission. In the following discussion, we will consider that the continuum emission at 350 GHz is dominated by dust emission both toward the CND and the SB ring. Both continuum emissions coincide spatially on the SB ring, where they exhibit a clumpy structure associated to star-forming regions. Note that non-thermal emission dominates throughout the radio jet trajectory (which encloses the CND East knot; for a detailed analysis on the CND spectral indexes see García-Burillo et al. 2019).

3.2 HC3N emission

The right panel of Figure 1 shows the distribution of the HC3N ν = 0 (J = 16 – 15) and the CS (J = 3 – 2) velocity-integrated line emission overlaid on the 147 GHz continuum emission. This figure shows that the HC3N ν = 0 (J = 16 – 15) and CS (J = 3 – 2) lines trace the CND and the high density star formation clumps in the SB ring and closely follows...
the 147 GHz continuum in those regions. HC$_3$N emission is detected in sources with radio continuum and/or Pa$_\alpha$ emission, namely positions CND E., CND W., SHC and Cont. 6, 7, 8, 9 and 11. We have measured the velocity of the gas for the positions in Table 2 from HC$_3$N $v = 0$ (when detected) and from CS. Other molecules such as CO, HCN, HNCO, H$_2$CO or CH$_3$OH were also detected, but we will focus in this paper on the HC$_3$N emission on the selected positions.

In addition to the HC$_3$N emission from the ground vibrational state we have searched for HC$_3$N* emission from the SB ring and the CND. We have detected HC$_3$N* emission from the $v_1 = 1$ vibrationally excited state in the rotational transitions $J = 16 - 15$ ($E_{up} = 380$ K) and $J = 24 - 23$ ($E_{up} = 452$ K) towards only one condensation in the SB ring, hereafter the Super Hot Core (SHC). Integrated intensities in the SHC of rotational transitions from the $v_1 = 1$ vibrationally excited state are just below 1$\sigma$ and we treat them as undetected. Figure 2 displays the spectra of HC$_3$N from the rotational transitions $J = 16 - 15$, $J = 24 - 23$ and $J = 39 - 38$ in the ground, $v_1 = 1$ and $v_1 = 1$ vibrationally states towards the SHC. The lack of sensitivity prevented us from detecting HC$_3$N* emission towards any other position in the SB ring. It is remarkable that, in spite of the enhanced column density of HC$_3$N in the CND (see Sec. 4.2), we have not detected any emission of HC$_3$N* towards any of the CND positions. Like Figure 2, Figure 3 shows the spectra of the rotational transitions in the $v = 0$ and $v_1 = 1$ vibrational states towards CND East. The integrated fluxes for the observed HC$_3$N* transitions for the most relevant positions (SHC, Cont. 7, CND East and CND West) are listed in Table 4, with non-detected lines represented as upper limits with their corresponding $3\sigma$ integrated intensity values. It is worth noting the large contrast between the $v = 0$ and $v_1 = 1$ rotational lines.

4 ANALYSIS

4.1 Stellar and gas masses in the SB ring

We can use the Pa$_\alpha$ and the continuum emission at 147 GHz dominated by free-free emission to estimate the stellar mass of massive stars in the main sequence. Using the canonical values for an H II region of $T_e = 10^4$ K and electron density $n_e = 10^4$ cm$^{-3}$, the production rate of ionizing photons from the Pa$_\alpha$ peak emission, $Q_0^{\text{Pa}_\alpha}$ (Kennicutt 1998; Osterbrock & Ferland 2006):

$$Q_0^{\text{Pa}_\alpha} \, (s^{-1}) = 7.344 \times 10^{12} \cdot \left( \frac{L_{\text{Pa}_\alpha}}{\text{erg s}^{-1}} \right)$$

Figure 1. Left panel: (sub)millimiter continuum and Pa$_\alpha$ emission map of NGC 1068. The continuum map at 147 GHz is shown in blue, with contour levels 5$\times$, 10$\times$, 15$\times$, 50$\times$, 200$\times$, 600 $\times$ $\sigma_{147}$, with $\sigma_{147} = 0.025$ mJy beam$^{-1}$. The continuum map at 350 GHz is shown in red with contour levels 5$\times$, 10$\times$, 15$\times$, 50$\times$, 150$\times$ $\sigma_{350}$, with $\sigma_{350} = 0.10$ mJy beam$^{-1}$. Pa$_\alpha$ emission is shown in grey with contour levels 10$\times$, 20$\times$, 40$\times$, 80$\times$, 160$\times$, 320$\times$ $\sigma_{\text{Pa}_\alpha}$, with $\sigma_{\text{Pa}_\alpha} = 2 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$. Right panel: Integrated intensity map of HC$_3$N $v = 0$ (16 - 15) (in blue) and CS (3 - 2) (in red) line emission over the 147 GHz continuum map (in grey). The star marks the AGN position. Indicated are also the 14 continuum clumps identified on the SB ring, the Super Hot Core (SHC) position, the 2 positions with Pa$_\alpha$ emission but no 350 GHz continuum and the 2 CND positions studied. The beams of each map are shown on the lower left corner of each panel.
The values can change ~ 15% due to variations on the electron temperature within $T_e = 5000 - 20000 \, \text{K}$ and remain insensitive for electron density variations within $n_e = 10^2 - 10^6 \, \text{cm}^{-3}$ (Osterbrock & Ferland 2006; Piqueras López et al. 2016). We can also obtain the production rate of ionizing photons from the continuum emission at 147 GHz, $Q_{147}^0$, using the approach by Murphy et al. (2011) and assuming the same $T_e$ as for the determination of the $Q_{E-\text{iso}}^0$:

$$Q_{147}^0 (s^{-1}) = 10^{36} \left( \frac{T_e}{10^4 \, \text{K}} \right)^{-0.45} \left( \frac{\nu}{147 \, \text{GHz}} \right)^{0.1} \times \left( \frac{L_{147}}{\text{erg s}^{-1} \, \text{Hz}^{-1}} \right)$$

Finally, we convert the ionizing photons production rates to Zero Age Main Sequence (ZAMS) stellar masses ($M_*$) following Leroy et al. (2018):

$$M_*(M_\odot) \sim \frac{Q_{147}^0}{4 \times 10^{36}}$$

The ZAMS stellar masses derived from the ionizing photons production rates from Pa$\alpha$ and 147 GHz continuum emission ($M_*,\text{Pa}\alpha$ and $M_*,147$), are compared on Table 6. The mass of ZAMS stars in all condensations with radio continuum emission are a few $10^5 M_\odot$, typical of the Super Star Clusters (hereafter SSCs, young star clusters with stellar masses $\gtrsim 10^4 M_\odot$) found in NGC 253 (Rico-Villas et al. 2020), indicating that a substantial fraction of the star formation in the SB ring seems to be dominated by SSCs.

On the other hand, we can use the 350 GHz continuum emission to estimate the total gas mass from dust emission. Following Leroy et al. (2018), we first estimate the optical depth ($\tau_{350}$) by comparing the measured intensity peak ($I_{350}$) with that expected by assuming a dust temperature:

$$I_{350} = (1 - e^{-\tau_{350}}) B_\nu(T_{\text{dust}})$$

where $B_\nu$ is the blackbody intensity at 350 GHz for a given dust temperature. For our mass estimates we have assumed a dust temperature of 80 K (see Leroy et al. 2018, for SSCs in NGC 253). Changes in a factor of 2 in $T_{\text{dust}}$ will change the masses by a similar factor. Assuming a mass absorption coefficient $\kappa_{350} = 1.9 \, \text{cm}^2 \, \text{g}^{-1}$ (Leroy et al. 2018) and a standard dust-to-gas ratio (DGR) of 0.01 by mass (close to...
the value found by Wilson et al. (2008) for SB galaxies and similar to the 150 value commonly used for the Milky Way), we can convert $\tau_{350}$ into a gas surface density ($\Sigma_{\text{gas}}$) which is then converted into gas mass from the cloud surface area ($\theta^2$):

$$M_{\text{gas}}(M_\odot) = \Sigma_{\text{gas}} A = \frac{1}{DGR \cdot \theta^2_{350}}$$

(5)

The cloud surface areas have been derived from a two-dimensional Gaussian fitting to the 350 GHz continuum emission after deconvolution of the beam profile. The values of $\theta^2$ are listed in Table 3 and the gas masses in Table 6.

**Table 3.** Peak flux densities of the Paα and 147 GHz/350 GHz continuum emission measured toward the position of the 147 GHz continuum peak for each source. The three emission maps have been smoothed to a common resolution of 0.62″ × 0.42″ in order to measure the fluxes. Paα is measured in 10^{-17} erg cm^{-2} s^{-1}, while Cont. 147 and Cont. 350 in mJy beam^{-1}. \( \theta_{350}^2 \), in arcsec^2 (1″ = 70 pc), is the deconvolved surface area obtained from fitting a two-dimensional Gaussian to the 350 GHz continuum emission.

| Location | Paα (mJy beam^{-1}) | Cont. 147 (mJy beam^{-1}) | Cont. 350 (mJy beam^{-1}) |
|----------|---------------------|---------------------------|--------------------------|
| SCF      | 1.42 ± 0.01         | 1.37 ± 0.03               | 7.54 ± 0.12               |
| Cont. 1  | 1.96 ± 0.02         | 0.14 ± 0.02               | 0.65 ± 0.12               |
| Cont. 2  | 3.17 ± 0.02         | 0.21 ± 0.02               | 1.46 ± 0.12               |
| Cont. 3  | 0.83 ± 0.02         | 0.16 ± 0.02               | 1.20 ± 0.12               |
| Cont. 4  | 1.93 ± 0.02         | 0.25 ± 0.03               | 0.65 ± 0.09               |
| Cont. 5  | 0.71 ± 0.03         | 0.35 ± 0.03               | 1.47 ± 0.09               |
| Cont. 6  | 0.71 ± 0.02         | 0.72 ± 0.03               | 3.18 ± 0.09               |
| Cont. 7  | 3.50 ± 0.02         | 0.76 ± 0.03               | 5.34 ± 0.12               |
| Cont. 8  | 3.31 ± 0.02         | 0.72 ± 0.03               | 5.78 ± 0.13               |
| Cont. 9  | 1.03 ± 0.02         | 0.39 ± 0.03               | 2.51 ± 0.10               |
| Cont. 10 | 1.60 ± 0.01         | 0.25 ± 0.03               | 0.91 ± 0.11               |
| Cont. 11 | 1.21 ± 0.01         | 0.42 ± 0.03               | 3.28 ± 0.11               |
| Cont. 12 | 1.27 ± 0.01         | 0.21 ± 0.03               | 0.67 ± 0.11               |
| Cont. 13 | 1.71 ± 0.02         | 0.19 ± 0.03               | 1.22 ± 0.11               |
| Cont. 14 | 0.64 ± 0.02         | 0.18 ± 0.03               | 1.94 ± 0.11               |
| Paα 1    | 2.19 ± 0.03         | 0.18 ± 0.04               | ≤ 0.26                    |
| Paα 2    | 1.37 ± 0.02         | ≤ 0.13                    | ≤ 0.35                    |
| CND E    | 6.57 ± 0.01         | 0.65 ± 0.01               | 3.72 ± 0.08               |
| CND W    | 5.31 ± 0.03         | 0.12 ± 0.01               | 0.51 ± 0.08               |

**Table 4.** MADCUBA fitted integrated intensity for HC3N emission lines in mJy beam^{-1} km s^{-1} for the SHC, Cont. 7, CND East and CND West positions. Upper limits are 3σ.

| Transition | SHC | Cont. 7 | CND E | CND W |
|------------|-----|---------|-------|-------|
| $v = 0$    |     | 10-9    |       |       |
| $v = 0$    |     | 11-10   |       |       |
| $v = 0$    |     | 12-11   |       |       |
| $v = 0$    |     | 16-15   |       |       |
| $v = 0$    |     | 24-23   |       |       |
| $v = 0$    |     | 28-37   |       |       |
| $v = 0$    |     | 39-38   |       |       |
| $v = 0$    |     | 116-15  |       |       |
| $v = 0$    |     | 116-15  |       |       |
| $v = 0$    |     | 230-23  |       |       |
| $v = 0$    |     | 231-23  |       |       |

* Strongly blended with CO(3-2) due to the higher FWHMs in the CND (see Table 3).
* Blended with HCN(4-3) due to the higher FWHMs in the CND (see Table 3).

**4.2 Physical properties derived from HC3N**

Following the procedure used for NGC 253 in Rico-Villas et al. (2020), we have used both LTE and non-LTE multiline analysis of the HC3N emission from the $v = 0$ and the $v = 1$ vibrational states to derive the physical properties of the star-forming regions in the SB ring and the CND. We analyze the HC3N emission in sources where emission from the $v = 0$ is detected and we also include some positions with no HC3N emission for completeness (e.g. SSC 2, Paα 1 and Paα 2). The excitation of the HC3N can be dominated by different mechanisms: while its vibrational transitions are pumped mainly via absorption of mid-IR photons (IR pumping), the excitation of the rotational levels within a given vibrational state is usually dominated by collisions with H2 (Rico-Villas et al. 2020).

**4.2.1 LTE analysis**

To describe both types of excitation two different excitation temperatures are used, in LTE the vibrational temperature ($T_{\text{vib}}$) describing the excitation between vibrational levels,
and the rotational temperature ($T_{\text{rot}}$) describing the excitation between rotational levels within a vibrationally excited state. Usually, $T_{\text{vib}}$ reflects the dust temperature in the case of IR pumping (Rico-Villas et al. 2020).

The need of two excitation temperatures to describe the excitation of HC$_3$N is illustrated in the rotational diagram (Figure 4), which assumes optically thin emission (Goldsmith & Langer 1999). The upper and lower panels show the rotational diagram for the detected HC$_3$N* transitions toward the SHC and CND East condensation. The difference between the $T_{\text{rot}}$ and $T_{\text{vib}}$ is clearly illustrated by the dashed and color solid lines.

By fitting the transitions from the same rotational levels ($J = 16-15$ or $J = 24-23$) but different vibrational states, we estimate a vibrational temperature of $T_{\text{vib,16-15}} = 239 \pm 30$ K and $T_{\text{vib,24-23}} = 390 \pm 122$ K for the SHC. These temperatures are clearly higher than the lower rotational temperature $T_{\text{rot,v=0}} = 103 \pm 14$ K, obtained by fitting all the transitions observed from the ground state (Fig. 4). For the CND East, since no HC$_3$N* was detected, we derived an upper limit $T_{\text{vib,16-15}} \leq 122$ K from the $v_\gamma = 1$ $J = 16 - 15$ and a $T_{\text{rot,v=0}} = 42 \pm 10$ K. The errors have been obtained from bootstrapping using the uncertainties of the line fluxes. It is remarkable that the gas in the CND surrounding the SMBH seems to have lower excitation temperatures than the gas in the star-forming regions.

To fully account for the line profiles, opacity effects and line blending we have also carried out an LTE analysis of the HC$_3$N* emission using MADCUBA SLIM tool (Martín et al. 2019). Fig. 2 and 3 show the predicted SLIM line profiles superimposed on the observed spectra for the SHC and CND East, respectively. The fitted parameters with their associated errors are given in Table 5. For the SLIM fitting we have used a source size of 0.42", the smallest beam with HC$_3$N data that reproduces the observed $v = 0$ lines, although the emitting region of $v_\gamma = 1$ clearly must be smaller. We derive for the SHC $T_{\text{vib}} = 236 \pm 16$ K and $T_{\text{rot}} = 98 \pm 7$, similar to those derived from the rotational diagram. The derived line opacities are $< 0.01$, indicating that the optically thin assumption for the rotational diagram method is valid. For the CND positions, where HC$_3$N* emission is not detected despite the large HC$_3$N $v = 0$ column density, we have derived upper limits of $T_{\text{vib}} \lesssim 98$ and $\lesssim 117$ K for the East and West positions, respectively. The derived $T_{\text{rot}}$ from the emission of the $v = 0$ states in the CND is also much lower than in the SHC, reflecting lower excitation conditions (see below).

From the non-detection of HC$_3$N* in other star-forming regions of the SB ring we cannot completely rule out the presence of SHCs, since their upper limits to the emission from the $v_\gamma = 1$ lines are still consistent with $T_{\text{vib}} \sim 150 - 226$ K as derived from $J = 16 - 15$ HC$_3$N $v = 0$ and $v_\gamma = 1$ lines upper limits. Furthermore, SSC 7 and 8 have $T_{\text{rot,v=0}}$ very similar to the SHC, indicating similar physical conditions that are fully consistent with the presence of SHCs, i.e. internally heated. Conversely, SSC 6, 9 and 11 indicate $T_{\text{vib}} \lesssim 180$ K and $T_{\text{rot}} \sim 20 - 40$ K, which are much lower than in the SHC, pointing to a lack of SHCs associated with these condensations.

4.3 Non-LTE analysis

To derive the physical properties of the SHC and the CND and to properly account for the different excitation mechanisms of the vibrational and rotational HC$_3$N transitions, we have carried out a non-LTE radiative transfer modelling using the same code used in Rico-Villas et al. (2020) (described in detail in González-Alfonso & Cernicharo 1997, 1999; González-Alfonso & Sakamoto 2019), which includes

![Figure 4. Rotational diagram derived from the line intensities of HC$_3$N* for the SHC position (upper panel) and CND East position (lower panel). Transitions from the ground state $v = 0$ are marked with circles, $v_\gamma = 1$ with squares and $v_\delta = 1$ with triangles. The $J = 39 - 38$ transitions are highlighted in red, $J = 24 - 23$ in green and $J = 16 - 15$ in blue. Dashed grey lines represent the fit to all rotational transitions $J, J - 1$ from the ground state $v = 0$ (i.e. $T_{\text{rot,v=0}}$). The blue and green solid line represents the fit to the $J = 16 - 15$ and the $J = 24 - 23$ transitions from the $v = 0$ and $v_\gamma = 1$ states, respectively (i.e. $T_{\text{vib,16-15}}$ and $T_{\text{vib,24-23}}$). Errors have been obtained from bootstrapping.](image-url)
the HC$_3$N rotational transitions up to $J = 45$ in the $v = 0$, $v_2 = 1$ and $v_6 = 1$ vibrational states. As illustrated in Fig. 4 by Rico-Villas et al. (2020), the ratio between the $v_1 = 1$ and $v = 0$ rotational lines from the same rotational level is extremely sensitive to the dust temperature, and the ratio between lines from different rotational levels but from the same vibrational state are dependent on the $n_H$ density.

For NGC 1068, we consider the ratios of the $v = 0$ and $v_1 = 1$ $J = 24$ – 23 and $J = 16$ – 15 lines, since $J = 39 – 38$ are undetected except for the SHC position. Using the ratio between the $J = 16$ – 15 rotational transitions from the $v = 0$ and $v_1 = 1$ states ($v_0/v_1$), we find for the SHC a dust temperature of $T_d = 248 \pm 28$ K, very close to the derived $T_{\text{Vib}}$, and a density $n_H = (5.9 \pm 0.2) \times 10^3$ cm$^{-3}$.

For the other positions, since no $v_1 \neq 1$ line is detected, we only have a lower limit on the ratio $v_0/v_1$ and we assume the $T_{\text{Vib}}$ derived from LTE as their dust/kinetic temperature upper limit. To better constrain the dust temperatures and since the model also returns the SED, we also fit the observed continuum emission at 350 GHz. The obtained dust temperatures are similar to the $T_{\text{Vib}}$ derived from the LTE modelling.

In particular, for the CND East position, the derived parameters from the models are $T_d \lesssim 75$ K; a density $n_H = (5.9 \pm 0.3) \times 10^3$ cm$^{-3}$, and an HC$_3$N column density of $N_{\text{HC$_3$N}} = (9.5 \pm 2.9) \times 10^{15}$ cm$^{-2}$ with a fractional abundance of $X_{\text{HC$_3$N}} = (3.7 \pm 1.1) \times 10^{-9}$ (Table 5). It is worth noting that the dust temperatures toward the CND East and West positions are much lower than that derived for the SHC, despite the other parameters remaining similar to the SHC. The parameters for the CND are in agreement with those estimated by Viti et al. (2014), who derived densities for the CND (5 – 10) $\times 10^3$ cm$^{-3}$ and a kinetic temperature of 60 K and 100 – 150 K for the CND East and West positions, respectively. González-Alfonso et al. (2014), from modelling of the H$_2$O submillimeter emission, found a $T_d \sim 55$ K and high densities $n$(H$_2$) $\sim 10^6$ cm$^{-3}$, similar to the values we obtained.

### 4.3.1 Proto-Super Star Cluster in the SB ring: mass and luminosity

The physical conditions of the SHC (and also SSC 7 and 8) in NGC 1068, high $T_{\text{Vib}}$, and H$_2$ densities of few $10^3$ cm$^{-3}$, are similar to those found in the Super Hot Cores (SHCs) of NGC 253, where the IR emission from the dust heated by massive proto-stars vibrationally excites HC$_3$N. Rico-Villas et al. (2020) proposed that the SHCs trace the earliest phase of SSCs formation, the proto-SSC phase. Following the analysis presented in Rico-Villas et al. (2020), we have estimated the LTE and non-LTE luminosities of the condensations (clumps) studied in this work. For the LTE luminosities we have used the emission of a black body with a (dust) temperature of $T_{\text{Vib}}$ and the lower limit to the size of the SHC of 0.021" (1.41 pc) derived by assuming that the emission from the $v_0 = 1$ HC$_3$N $J = 16$ – 15 line is optically thin (see Rico-Villas et al. 2020). The same size is used to derive the upper limits for the other sources without detected HC$_3$N emission. The non-LTE luminosity is derived from the spectral energy distribution between 10 and 1200 $\mu$m predicted from the non-LTE models and assuming the same lower limit size as for the LTE estimate.

These estimates need to be corrected by the back warming/greenhouse effect (Donnison & Williams 1976; González-Alfonso & Sakamoto 2019), which appears in IR optically thick condensations when a fraction of the IR radiation returns to the source (back warming), achieving the thermal equilibrium at a higher dust temperature than expected for the optically thin case. For the $N_{\text{H$_2$}} \sim 10^{24}$ cm$^{-2}$ derived for the SHC, the apparent luminosities need to be corrected by a factor of 0.2 (Rico-Villas et al. 2020), i.e. the actual luminosities will be 5 times smaller than the directly estimated
from the analysis, obtaining for the SHC $5.8 \times 10^8 \, L_\odot$ and $5.9 \times 10^8 \, L_\odot$ from the LTE and non-LTE models, respectively. The luminosities corrected from back warming for all sources are listed in Table 5.

From these luminosities, we can make an estimate of the mass in proto-stars ($M_\star$) by assuming a luminosity-to-mass ratio of $10^3 \, L_\odot \, M_\odot^{-1}$ (similar to the luminosity-to-mass ratio typically assumed for ZAMS stars since the timescales for massive protostars to reach the ZAMS are short and expected to follow the ZAMS evolutionary track Hosokawa & Omukai 2009; Rico-Villas et al. 2020). The proto-star masses of the SSCs in NGC 1068 are given in Table 6. The luminosity and mass of proto-stars in the SSCs of NGC 1068 are similar to those found in NGC 253. The non detection of $HC_3N^*$ emission in the remaining SSCs prevents us from firmly establishing to what extent they are still undergoing the proto-SSC phase (see below), apart from the SHC clump.

5 DISCUSSION

5.1 On the heating of the SHC and the CND

As already mentioned, the excitation of $HC_3N$ can be dominated by two different mechanisms: IR radiation pumping by hot dust and/or collisions with $H_2$, which can be used to discriminate between different heating mechanisms. We have found a significant difference between the derived $T_{\text{vib}}$ for the CND East and West positions ($\lesssim 100 \, K$) and for the SHC ($\gtrsim 240 \, K$) and SSCs 7 and 8 ($\lesssim 220 \, K$). The same trend is also found for the rotational temperature ($T_{\text{rot}} = 41 \, K$ for the CND East, $29 \, K$ for CND West and $98 \, K$ for the SHC, with SSCs 7 and 8 having also high $T_{\text{rot}} \sim 80 \, K$). The derived $H_2$ densities for both the SHC and the CND positions are similar, but much lower than the critical density for collisional excitation of the vibrational levels ($> 10^7 \, \text{cm}^{-3}$, Wyrowski et al. 1999). Therefore, the excitation of the vibrational states must be through IR pumping by the hot dust and the excitation of the rotational levels by collisions with $H_2$.

The CND, located at $\sim 60 - 80 \, \text{pc}$ from the SMBH in NGC 1068, seems to be strongly affected by the AGN. Both radiative and mechanical effects have substantially changed its kinematics and physical and chemical properties (Tacconi et al. 1994; Usero et al. 2004; García-Burillo et al. 2010). X-rays from the AGN have been proposed to explain the specific chemical structure found in the CND (e.g. Sternberg et al. 1994; Usero et al. 2004; Aladro et al. 2012, 2013). Several studies have analyzed the influence of the AGN on the physical properties and chemical composition of the CND. Most of them disregarded the effects of the UV radiation and consider shocks and/or X-rays irradiation to be the most plausible mechanisms heating the CND (e.g. Galliano & Alloin 2002; Usero et al. 2004; Krips et al. 2011; Hailey-Dunsheath et al. 2012; Spingolo et al. 2012; Aladro et al. 2013; García-Burillo et al. 2014; Viti et al. 2014). The latter work, based on chemical modelling, have proposed that the CND can be characterized by a three-phase component ISM: two components with enhanced cosmic-ray ionization rates by a factor of 10 compared to the Milky Way, and/or X-rays, but with different densities ($10^5$ and $> 10^6 \, \text{cm}^{-3}$); and a third component dominated by shocks from the outflow driven by the AGN. Our derived $H_2$ density of $6 \times 10^5 \, \text{cm}^{-3}$ for the CND East and $4 \times 10^5 \, \text{cm}^{-3}$ for the CND West, are in agreement with the densities derived by Viti et al. (2014).

We have found significant lower vibrational temperatures $T_{\text{vib}} \lesssim 75 \, K$ and $\lesssim 114 \, K$ for the CND East and West positions than the gas kinetic temperatures of $80 - 160 \, K$ and $> 100 \, K$ derived by Viti et al. (2014) and that found in the SHC ($T_{\text{vib}} \sim 240 \, K$). Furthermore, the lower rotational temperature of the CND East and West positions, derived from the ground state (49 K and 21 K) than that for the SHC $T_{\text{rot}}$, is an indication of sub-thermal collisional excitation.

As discussed in Sec. 4.2, this clearly reflects that the IR pumping is not efficiently exciting $HC_3N^*$ on the CND. This could be due to a low dust optical depth at the wavelength of the vibrationally transitions ($45 \, \mu\text{m}$ for $\tau = 1$) or due to a low dust temperature, both effects indicate that the flux of IR photons being re-emitted (i.e. trapping) by dust at $45 \, \mu\text{m}$ is small and thus not enough to excite $HC_3N^*$. The first possibility can be ruled out since the $H_2$ column densities in the CND are $\sim 10^{24} \, \text{cm}^{-2}$ (see Table 5), which translates to dust opacities at $45 \, \mu\text{m}$ of $\tau \sim 16$. Then, the other option is a low dust temperature in the CND in spite of the large luminosity estimated from mid-IR $L_{\text{AGN}} = 1.1 \times 10^{44} \, L_\odot$ (Alonso-Herrero et al. 2011; García-Burillo et al. 2014). This indicates that the dust in the CND remains at a low temperature $< 100 \, K$ (García-Burillo et al. 2014), evidencing that the AGN is not effective at heating the dust in its surroundings. Indeed, as shown below, the upper limit to the dust temperature is consistent with the expected temperature for the heating from the AGN when considering that the dust in the CND is being heated externally. The CND is a condensation detached from the AGN located at a projected distance from the AGN of $\sim 75 \, \text{pc}$, the expected dust temperature for external heating will be $56 \, K$ taking into account the heating for the IR optically thin case using the Stefan-Boltzmann law (de Vicente et al. 2000):

$$T_d(K) = \left( \frac{L}{4\pi r^2 \pi \sigma} \right)^{1/4} = 15.222 \left( \frac{L(L_\odot)}{r(\text{cm})} \right)^{1/4} \quad (6)$$

This indicates that the dust in the CND not being efficiently heated by the AGN is due to being externally irradiated by the AGN (i.e. geometrical open system), where photon trapping in the IR is negligible and the temperature profile follows effectively the optically thin case. The opposite happens in geometrical closed systems, where the source is being internally irradiated and is optically thick in the IR. In this case, the greenhouse effect dramatically changes the dust temperature profile in the surrounding material, as observed in the SHC.

5.2 History of star formation in the SB ring of NGC 1068

5.2.1 Ages of SSCs

We can study the recent history of massive star formation in the SB ring of NGC 1068 by comparing the different tracers presented in this work. As discussed in Rico-Villas et al. (2020), the $HC_3N^*$ emission is thought to be tracing the proto-SSCs phase. The free-free radio continuum emission
at 147 GHz arises from Ultra Compact HII regions, an early phase in the evolution of massive ZAMS stars, but after the proto-SSC stage, as seen by their $\alpha$150−350 > 1 indexes. Finally, the Paα emission will trace a more evolved phase of massive ZAMS stars in the SSCs, as indicated by the lower mass ratio is expected to be close to 1 for no extinction, and it will increase as the extinction increases, since with the continuum emission at 147 GHz we are seeing a more embedded phase of star formation. This is indeed the trend found in the $M_{\alpha}/M_{\text{Paa}}$ ratio in Table 6. We can see that the SSCs with the lowest values of about 1, SSC 1, SSC 2, Paα 1 and Paα 2, almost do not show dust continuum emission at 350 GHz, as expected for low extinction. It is worth to remark that we are focusing on specific clumps in the SB ring where the dust continuum emission at 350 GHz, peaks (except for the Paα 1 and 2 sources) and the Paα emission is expected to suffer some extinction, although it seems to have no extinction outside these clumps (for a more detailed analysis on the Paα emission in the SB ring see Sánchez-Garcia et al. in prep). The highest values of the $M_{\alpha}/M_{\text{Paa}}$ ratios correspond to the proto-SSC (i.e. the SHC) and the SSC 6 located in the northern region of the SB ring. The high value found in the proto-SSC is consistent with the very early stage of the SSC formation. Following the procedure described by Rico-Villas et al. (2020), we can use the ratio of the mass in proto-stars ($M_{p*}$) to the mass in ZAMS stars ($M_{\alpha}$), to make an estimation of their age assuming that proto-stars have a timescale of $\lesssim 10^5$ yr with:

$$t_{\text{age}}(\text{yr}) \sim \frac{1}{1 + M_{p*}/M_{\alpha}} \times 10^5$$

(7)

The estimated age of the proto-SSC is $5.8 \times 10^4$ yr. For the more evolved SSCs without detected HC3N* emission, we can estimate their ages using the ratio $M_{\alpha}/M_{\text{Paa}}$. Assuming that the feedback from the SSCs removes the leftover material from cluster formation in $\lesssim 10^5$ yr (Dowell et al. 2008) and assuming a linear dependence of the gas removal with age, we can estimate the age as:

$$t_{\text{age,Paα}}(\text{yr}) = \frac{1}{1 + 13 \cdot (M_{\alpha}/M_{\text{Paa}} - 1)} \times 10^5$$

(8)

where 13 is a scale factor obtained from the SHC position. The ages obtained are listed on Table 6. We find that the youngest SSCs are the SHC and SSC 6 (ages of 6×10^4 years) located in the northern part of the SB ring, and SSC 7, 8, 9 and 11 (ages 2−4×10^5 years) in the southern part of the SB ring. It is remarkable that the youngest SSCs seem to be closely associated with the nuclear stellar bar and the beginning of the molecular spiral arms.

We can use the gas mass obtained from the 350 GHz continuum emission to make an estimation of the Star Formation Efficiency (SFE, Table 6) by assuming that the initial mass of the star-forming molecular clouds has not suffered significant mass losses. Since we only have upper limits for $M_{p*}$ for most of the SSCs, we will use only $M_{\alpha}$ and the expression:

$$SFE = \frac{1}{1 + M_{\text{gas}}/M_{\alpha}}$$

(9)

In case that mechanical feedback has played a significant role, like in the case of Paα 1 and 2, the SFE must be considered as an upper limit.

The SFE of the proto-SSC is only 0.2, suggesting that the star formation is very recent and still has a significant amount of gas available to convert into stars. SSCs 6, 7, 8, 9, and 11, with ages of few 10^5 yr, seem to be in a similar state to the SHC, where the latest star formation episode is just starting (or has just concluded). Unfortunately the
lack of sensitivity to detect HC$_3$N* does not allow to discriminate between the two possibilities. SSC 2 shows a relatively high gas mass and a relatively low SFE, but seems to be rather evolved as its $M_{*,147}/M_{\text{gas},147}$ ratio suggests. This could indicate that its star formation has been halted and a next generation of stars could be forming in an unrelated giant molecular cloud unresolved by our observations. On the other hand, SSC 1 has a SFE $\lesssim 0.5$ with low $M_{\text{gas}}$, indicating that it has already formed most of its stars.

5.2.2 Propagation of SSC formation in the ring

Using the ages in Table 6 ($t_{\text{age,Pa}}$) and the spatial distributions of the 147 GHz continuum and Pa$_\alpha$ emission, we can build a picture of the sequential star formation in the SB ring. The oldest SSCs, with ages of $\sim 10^7$ yr will be now visible on Pa$_\alpha$ (SSC 1 and 2 and Pa$_\alpha$ 1 and 2), then the next generation of SSCs, now in the ZAMS phase, are seen through the 147 GHz with moderate emission in the Pa$_\alpha$ with ages of $10^6$ yr and the most recent star formation (few $10^4$ yr) is taking place in the proto-SSC and SSC 6 (see Fig. 5).

Figure 5 shows the spatial distribution in the Pa$_\alpha$ and 147 GHz continuum emission along with the CO (1–0) emission to illustrate the structure and spatial segregation of these tracers in the spiral arms. In the regions close to the confluence between the bar and the SB pseudo-ring, especially in the southern part, there seems to be a trend in the spatial distribution of these tracers. Moving from the outer parts of the ring towards the AGN, the Pa$_\alpha$ emission is located downstream (at larger radii; better seen on the southern molecular arm), and the 147 and 350 GHz emission in the inner part. This might suggest an evolution/propagation in the star formation in the region where the SB pseudo-ring is closer to the bar, where gas is expected to be accumulated, and the youngest (most embedded) star formation episodes traced in this paper would be taking place.

We now consider if this spatial segregation of the different star formation tracers can be related to the kinematics and dynamics of NGC 1068. The main kinematic features of NGC 1068 are shown in Fig. 5. NGC 1068 rotates counter-clockwise with its spiral arms trailing. It has an outer oval structure that behaves like a large-scale bar of length $\sim 17$ kpc with an Inner Lindblad Resonance (ILR) region that corresponds to the SB pseudo-ring (Telesco & Decher 1988; Schinnerer et al. 2000). Inside the ILRs of the oval there is a nuclear bar detected at NIR wavelengths ($r \sim 1.3$ kpc and PA = 46°; Scoville et al. 1988; Schinnerer et al. 2000). The corotation of the nuclear bar is seen to overlap with the outer ILR (oILR; $r = 1.2$ kpc) of the oval (Schinnerer et al. 2000; García-Burillo et al. 2010, 2014). These overlapping resonances favour the decoupling of the nuclear bar. García-Burillo et al. (2014) analysed the velocity field of the gas inside the SB pseudo-ring, finding strong inflow motions, an indication that the gas in the spiral has settled into an independent mode. The strong inflow motions along the spiral arms may explain the accumulation of gas and the increase of cloud-cloud collisions in the region connecting the spiral arms with the ends of the nuclear bar. This is consistent with most of the youngest SSCs found in this paper being formed in this region.

5.3 HC$_3$N* as a discriminator between AGN and star formation activity in galaxies

The amount of HC$_3$N* found in NGC 253 (Rico-Villase et al. 2020) and that found in the NGC 1068 SHC location, contrasts with its absence in the CND of NGC 1068, where HC$_3$N column densities are similar to those found in the SHC. While in NGC 253 UV radiation has been found to be the dominant excitation mechanism of H$_2$ emission (Rosenberg et al. 2013), in the CND of NGC 1068 it is most likely to be heated by X-ray irradiation (Galliano & Alloin 2002), where gas is also being heated by shocks (Kelly et al. 2017; García-Burillo et al. 2014; Viti et al. 2014).

The different excitation mechanism present in the CND, where no recent star formation is taking place (last starburst was 200 – 300 Myr ago Davies et al. 2007), compared to those observed in the young star-forming regions where HC$_3$N* has been observed, suggests that HC$_3$N* could be used as a discriminator between AGN and early obscured star formation activity in galaxies. So far, HC$_3$N* has been detected in two active galaxies, the LIRG NGC 4418, located at 35.8 Mpc with $L_{\text{IR}} = 1.5 \times 10^{11} L_{\odot}$ (Costagliola & Aalto 2010), and the ULIRG Arp 220 (Martín et al. 2011), located at 79.4 Mpc and with $L_{\text{IR}} = 1.5 \times 10^{12} L_{\odot}$. For both galaxies the origin of the high IR luminosity (AGN versus SB) is highly debated due to the extremely large extinctions. For NGC 4418, Sakamoto et al. (2013) favored the heating by a Compton-thick AGN, but Varenius et al. (2014) claimed to be SB dominated. A similar controversy also exists for Arp 220, (e.g. Sakamoto et al. 1999; Wilson et al. 2014; Barcos-Muñoz et al. 2015; Sakamoto et al. 2017).

For NGC 4418, Costagliola et al. (2015) estimated a $T_{\text{Vib}} = 340$ K, with a brightness temperature in the $J = 24 – 23$, $\nu = 1$ line of $9$ K for a source size of 0.4″. Assuming optically thick emission for that line we derive a lower limit to the size of 0.07″ (i.e. 13 pc). For Arp 220, Martín et al. (2011) estimated a $T_{\text{Vib}} \sim 355$ K. Following the same procedure than for NGC 4418, we derive a size lower limit of $\sim 80$ pc from the $J = 25 – 24$, $\nu = 1$ line beam brightness temperature of 263.9 mK in a 8.4″ × 6.1″ beam. Following the results obtained for the heating of the CND by the AGN in NGC 1068 (Eq. 6), one would expect the size of the region emitting the bulk of the hot gas ($\sim 340$ K) observed in HC$_3$N* for NGC 4418 and Arp 220, to be a hot dust (also at 340 K) region of about 8 and 50 pc, respectively, if the heating is dominated by a central source, i.e the AGN. The predicted hot regions by Eq. 6 are already smaller than the measured lower limits to the sizes of the HC$_3$N* emission in both sources. The rather small predicted sizes of the hot dust region heated by the AGN would indicate that the heating is instead distributed over the large region observed in HC$_3$N* due to star formation as observed in the NGC 1068 SB ring.

However, as discussed in Sec. 5.1, Eq. 6 can only be applied to predict the dust temperature profile for the case of an optically thin cloud (open systems) in the IR. González-Alfonso & Sakamoto (2019) have studied in detail the dust temperature profile due to the heating by an AGN and a SB in a spherical cloud considering the back warming effect due to extremely high extinction (i.e. closed systems) as observed in NGC 4418 and Arp 220. They found that for a luminosity surface brightness of $1 – 2 \times 10^8 L_{\odot} \text{pc}^{-2}$ for NGC 4418 and
Figure 5. NGC 1068 map as seen by CO 1−0 (grey scale), Pa α (black contours) and continuum emission at 147 GHz (red contours). The AGN position is marked with a star. Type II SN 2018ivc position is marked with a triangle (Bostroem et al. 2020). The stellar bar is indicated with a straight dashed black line. The ILRs from the outer oval and the stellar bar (Schinnerer et al. 2000; García-Burillo et al. 2010) are indicated by solid blue lines, respectively. The estimated ages ($t_{\text{Age}, \text{Pa}}$) for the different positions are color coded following the color wedge on the right.

Arp 220 and an H$_2$ column density of 10$^{25}$ cm$^{-2}$, the size of the region with $T_d > 300$ K is of about 20 pc and 100 pc for NGC 4418 and Arp 220, basically independent from the nature of the heating source.

Discriminating between AGN and SB heating using HC$_3$N* emission in IR optically thick galaxy nuclei can only be done when the spatial resolution is high enough to measure the $T_{\text{vib}}$ profile close to the central heating source, where the temperature gradient is expected to show the largest difference between the AGN and SB heating.

6 SUMMARY AND CONCLUSIONS

We have used archival ALMA data to study the HC$_3$N emission from its ground and vibrationally excited states, along with the 147 GHz continuum emission, in the SB ring and in the CND of NGC 1068. The main results can be summarised as follows:

- We have detected emission from HC$_3$N (lines $J = 11−10$, 12 − 11, 16 − 15, 24 − 23) in the ground state towards the SB ring and the CND. In spite of the bright HC$_3$N emission observed towards the CND East, we did not detect any vibrationally excited emission. In contrast, vibrationally excited emission from the $v^7 = 1e$ and $1f$ lines ($J = 16 − 15$ and 24 − 23) of HC$_3$N was detected towards one star-forming region on the northern part of the SB ring.

- For the star-forming region in the SB ring with HC$_3$N* emission, the LTE analysis yields a vibrational temperature ($T_{\text{vib}}$) between the $v = 0$ and $v^7 = 1$ levels of 236 ± 18 K and a rotational temperature, $T_{\text{rot}}$, between the rotational levels in the ground state of 98 ± 7 K. The difference in excitation temperatures suggests that the vibrational levels are excited by IR pumping at the dust temperature while the rotational levels are collisionally excited. This is consistent with the derived $T_{\text{dust}}$ and H$_2$ densities from our non-LTE analysis of 248 ± 28 K and (5.9 ± 0.2) × 10$^5$ cm$^{-3}$, respectively. The latter indicates that we are observing a Super Hot Core (SHC) similar to those observed in NGC 253 (Rico-Villas et al. 2020).

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From the dust temperature and the lower limit to the size of the SHC in the SB ring we estimated an IR luminosity of $\sim 5.8 \times 10^8 L_\odot$, typical of the proto-Stellar Star Clusters (proto-SSC) observed in NGC 253, which are believed to be tracing the earliest phase of the SSC formation.

In addition to the SHC, we have also identified from our continuum map at 147 GHz another 14 young star-forming regions undergoing the H$\alpha$ region phase in the SB ring. Assuming that the continuum is dominated by free-free emission, we have obtained the stellar mass of ZAMS massive stars for the regions in the SB ring. These embedded star-forming regions contain stellar masses $\sim 10^5 M_\odot$, typical of SSCs and proto-SSC. Unfortunately, our sensitivity on the $HC_3N^*$ emission is not high enough to discard the presence of the proto-SSC phase.

We have also used the Pa$\alpha$ emission to trace a more evolved star formation phase in the SB ring. We combined the tracers of the different evolutionary phases to estimate the ages of the SSCs, which range from few $10^4$ yr for the proto-SSCs to $10^7$ yr for the most evolved SSCs with little extinction as derived from the ratio of the Pa$\alpha$ to 147 GHz another young star-forming region phase in the SB ring. As-

The most recent and still embedded star formation episodes would be taking place in this region.

For the CND East and West positions, our LTE and non-LTE analysis of $HC_3N^*$ emission yield an upper limit to $T_{\text{vib}}$ of $\lesssim 98$ K and a $T_{\text{rot}}$ of $41 \pm 1$ K and $29 \pm 3$ K, respectively. The derived H$_2$ densities are of $(5.9 \pm 0.3) \times 10^5$ and $(3.5 \pm 0.5) \times 10^5$ cm$^{-3}$.

The low dust temperature $< 100$ K derived towards the CND, is consistent with the expected heating by the AGN in NGC 1068 for a luminosity of $1.1 \times 10^{11} L_\odot$ considering the IR optically thin case and that the dust in the CND is being externally heated (open system). The opposite happens in the SHC, which is being internally irradiated by the forming proto-stars and is optically thick in the IR (closed system).

We discussed if, as observed in NGC 1068, the $HC_3N^*$ emission observed in NGC 4148 and Arp 220 can be used to discriminate between AGN and SB activity. We concluded that just the detection of $HC_3N^*$ emission cannot be used as a discriminator because of the greenhouse effect in heavily obscured galactic nuclei (closed systems) makes the AGN and SB dust profiles to be similar at large distances. Only the combination of spatially resolved images of several $HC_3N^*$ lines might provide the insight for the discrimination.

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