HNC0 ABUNDANCES IN GALAXIES: TRACING THE EVOLUTIONARY STATE OF STARBURSTS

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ABSTRACT

The chemistry in the central regions of galaxies is expected to be strongly influenced by their nuclear activity. To find the best tracers of nuclear activity is of key importance to understand the processes taking place in the most obscured regions of galactic nuclei. In this work, we present multiline observations of CS, C³⁴S, HNCO, and C³⁵O in a sample of 11 bright galaxies prototypical for different types of activity. The C³⁴S/C³⁴S isotopic ratio is ~10, supporting the idea of an isotopical C³⁴S enrichment due to massive star formation in the nuclear regions of galaxies. Although C³²S and C³⁴S do not seem to be significantly affected by the activity type, the HNCO abundance appears highly contrasted among starbursts (SBs). We observed HNCO abundance variations of nearly 2 orders of magnitude. The HNCO molecule is shown to be a good tracer of the amount of molecular material fueling the SB and therefore can be used as a diagnostics of the evolutionary state of a nuclear SB.

Key words: galaxies: abundances – galaxies: ISM – galaxies: starburst – galaxies: Seyfert – ISM: molecules – radio lines: galaxies

1. INTRODUCTION

The nuclear regions of active galaxies can harbor different energetic phenomena such as starbursts (SBs) and active galactic nuclei (AGNs) which are responsible for producing the bright emission stemming from their central regions. The heating of the interstellar medium (ISM) in nuclei with different type of activity is expected to be dominated by a variety of mechanisms, such as UV, X-rays, and/or shocks, which will ultimately drive their observed chemical richness (Martín et al. 2006b, and references therein). Disentangling which of these mechanisms is the main source of galactic nuclei is complicated by the high obscuration affecting these objects. This fact becomes critical in the case of ultraluminous infrared galaxies (ULIRGs) and high-z sources. Therefore, the observation of the dense molecular material has become an essential tool to get an insight into the evolution and classification of the nuclear activity in galaxies.

Finding appropriate molecular species to accurately trace each of these heating mechanisms is crucial to establish the nature of the central engine. Molecular species such as HCN and HCO+, and in particular the ratios HCN/CO and HCN/HCO+, have been claimed to be appropriate to differentiate between the SB and the AGN contribution in galactic nuclei (Kohno et al. 2001; Kohno 2005; Krips et al. 2008). Similarly, species such as HNC and CN are thought to show enhanced abundances in extremely irradiated environments (Aalto et al. 2002, 2007). A dichotomy still remains concerning the different evolutionary state of nuclear SB. While at an early stage, the heating of the ISM is thought to be dominated by shocks affecting the molecular clouds fueling the SB, the late stages of SB are vastly dominated by the UV radiation originated in the newly formed massive stars. This scenario has been inferred from the extensive observation of the prototype sources NCG 253 and M 82 in a number of key molecular tracers, such as SO₂, H₂S, OCS (Martín et al. 2003, 2005), HOC+, and CO+ (Fuente et al. 2005, 2006). Unfortunately, these tracers are generally too faint to be detected, but for the brightest prototypical nearby galaxies.

In a recent observational study carried out toward a sample of molecular clouds dominated by different heating mechanisms within the Galactic center region (Martín et al. 2008), we have found that the CS/HNCO abundance ratio is highly contrasted between molecular clouds illuminated by the UV radiation from massive star clusters and the giant molecular cloud complexes shielded from photodissociation and mostly heated by shocks. The origin of the large changes in the CS/HNCO ratio is due to the enhancement of CS in photon-dominated regions (PDRs) through reactions involving S⁺ (Sternberg & Dalgarno 1995) as opposed to the highly photodissociable HNCO, which is destroyed by the UV photons. Both observations of photodissociation regions within our Galaxy and photochemical models show the suitability of CS as a PDR tracer (Goicoechea et al. 2006). In addition, HNCO is enhanced in the presence of shocks due to its injection in the gas phase from the grain mantles (Zinchenko et al. 2000). This paper presents a follow-up study of the CS/HNCO ratio toward a sample of prototype galaxies with different nuclear activity. Although CS has been extensively observed in external galaxies (Baan et al. 2008), HNCO had only been detected in four galaxies prior to this work (Nguyen-Q-Rieu et al. 1991; Wang et al. 2004).

2. OBSERVATIONS AND RESULTS

Observations were carried out with the IRAM 30 m telescope on Pico Veleta, Spain, during three observing periods from summer 2005 through summer 2007. Table 1 shows the sample of galaxies with their coordinates and the rest frequencies of the observed molecular transitions. Observations were performed in symmetrical wobbler switched mode with a frequency of 0.5 Hz and a beam throw of 4′ in azimuth. As spectrometers we used the 512 × 1 MHz filter banks for the 3 mm transitions and the 256 × 4 MHz filter banks for those at 2 and 1.3 mm. Pointing accuracy was estimated to be of ~3″ from frequent continuum cross scans on nearby pointing sources. Data were calibrated using the standard dual load system and main beam temperatures were obtained as $T_{MB} = (F_{eff}/B_{eff}) T^{*}_{A}$, where $B_{eff}$ is tabulated in Table 1 and $F_{eff}$ are 0.95, 0.93, and 0.91 for
NGC 7469 23:03:15.6 08:52:26 66–320 

Arp 220 15:34:57.1 23:30:12 73 

NGC 5194 (M 51) 13:29:52.7 47:11:43 9 

data. 

IC 342 c 03:46:48.6 68:05:46 3 

αJ 

Source 

C34S 

CS 

J 

C18O 

HNCO 50 

Molecule Frequency (GHz) 

Θ 

C34S 

NGC 253 (Martín et al. 2005) we only might expect the emission of CS 

Maffei 2 02:41:55.2 59:36:11 5 

NGC 1068 b 

IC 342 c 

M 82 d 

NGC 4945 

NGC 5194 (M 51) 

Arp 220 

NGC 6946 

NGC 7469 

Table 1 

Observational Parameters 

Source Sample 

NGC 253 

Maffei 2 

NGC 1068 b 

IC 342 c 

M 82 d 

NGC 4945 

NGC 5194 (M 51) 

Table 1. 

M 82 away from our observed position. Similarly, their NGC 5194 (0°, 0′) position is ~4′ away from our observed position. 

The critical densities for CS and HNCO transitions observed in this work are expected to be very similar since the Einstein coefficients and collisional cross sections are estimated to be similar (Schöier et al. 2005). Thus, the HNCO/CS ratio should reflect a reliable abundances ratio. In any case, the possible uncertainties introduced by slightly different critical densities will never account for the large difference in the abundance ratios measured in different galaxies. The differences in the derived molecular abundances might also be affected by molecular excitation differences of each individual source. However, the detailed multitransition study and large velocity gradient (LVG) modeling of dense gas tracers such as HCN and HCO + in a sample of galaxies by Krips et al. (2008) show how for several molecular transitions with similar critical densities, the derived abundances from the line intensities are really determined by real differences in abundances and not by excitation effects. The low-excitation temperatures derived from C18O indicate that a substantial fraction of the column density will be dominated by relatively low-density gas. Since our diagnostic diagrams in Figure 3 are normalized to the total column densities derived from C18O, changes in the H2 total column densities will not change the main conclusions of this paper.

3. SELECTED SOURCES 

The sample of sources observed in this paper has been selected among the brightest prototypes for the different types of nuclear activity. Their distances and corresponding linear scales are shown Table 1. The sources can be grouped as follows.

3.1. Starburst Galaxies (SBGs) 

M 82 and NGC 253 are the strongest and richest extragalactic molecular sources. These are the archetypes of starburst galaxies (SBGs) housing the two brightest extragalactic IRAS sources

Notes. The data for sources in italics were taken from previously published data.

Distances as derived by Baan et al. (2008) and linear scales given in parsecs per arcsecond at those distances.

Central and (0″, −16″) offset (NGC 1068 in the text) positions were observed.

Central and (5″, 15″) offset (IC 342′′ in the text) positions were observed.

Central position was not observed, but the NE molecular lobe at the approximate offset (15″, 7.5″) position, referred to as M 82′′ in the text.

All data are from the IRAM 30 m telescope, but for those of NGC 4945 from SEST (Wang et al. 2004). In this case, the beam is about twice the given size.

Beam efficiency of the IRAM 30 m at the observed frequencies.

This transition is only observed toward Arp 220.

3, 2, and 1.2 mm, respectively. Calibration uncertainties are estimated to be < 15%.

The observed spectra for each source are shown in Figure 1. The HNCO 5−4 and 10−9 lines were observed simultaneously in NGC 253 were observed ~10″ north of the position shown in Table 1. For NGC 4945 we used the observations by Wang et al. (2004). Not all sources in the sample were observed in the CS J = 5−4 transition. The upper limit to the emission to this transition in NGC 6946 (Mauersberger et al. 1989) allows us to constrain the CS column density to <6.2 × 10^13 cm^-2. We have thus used the CS J = 3 − 2 transitions available on NGC 6946 and NGC 5194 (Mauersberger et al. 1989) to estimate the column densities presented in Table 3. Note that for NGC 6946 we used the observed offset (Δα = 10′′, Δδ = −10′′) position in Mauersberger et al. (1989), which is located just ~1″ away from our nominal position. Similarly, their NGC 5194 (0°, 0′) position is ~4″ away from our observed position.

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Figure 1. Observed spectra for each source in the sample. Some of the transitions C$^{18}$O 1–0 and C$^{18}$S 3–2 spectra have been scaled up for the sake of clarity in the profile comparison. Spectra with line intensities below 10 mK have been resampled to a velocity resolution of 20 km s$^{-1}$, otherwise original velocity resolution is shown. C$^{34}$S (3–2) in NGC 1068 and C$^{34}$S (2–1) in Arp 220 are shown with a 30 km s$^{-1}$ velocity resolution. Gaussian fits are shown for all detected transitions. The dotted fits indicate individual velocity components. For Arp 220, where C$^{18}$O and HNCO transitions appear significantly blended, we show both fits in the same spectrum where the overall fit is shown with a continuous line and the individual transition with dotted lines. Temperature scale is $T_{MB}$ (mK).

(Mofer et al. 1989). M 82, as opposed to the young SB in NGC 253, is claimed to be the prototype of evolved SB. This is supported by its observed chemistry characterized by low abundance of complex molecules such as SiO, CH$_3$OH (Mauersberger & Henkel 1993; Martín et al. 2006b), and large abundance of molecular ions such as CO$^+$, HOC$^+$, and H$_3$O$^+$ which are expected to be enhanced in PDRs (Fuente et al. 2005, 2006; van der Tak et al. 2008). In this work we did not observe the central position toward M 82, but a position in the northeast molecular complex (hereafter M 82$^*$) where most of the photodissociation regions are located as observed in the HCO$^+$ emission high-resolution maps (García-Burillo et al. 2002). Maffei 2 is another well-studied starburst spiral galaxy with a high molecular gas concentration in its nuclear region and showing traces of a tidal interaction with a dwarf companion galaxy (Hurt et al. 1996; Mason & Wilson 2004). M 83 is a nearby face on barred galaxy undergoing strong nuclear SB likely due to gas inflow along its bar (Petitpas & Wilson 1998;
This nearly edge-on spiral galaxy harbors a heavily obscured AGN surrounded by an SB ring (Marconi et al. 2000). NGC 5194 (Antonucci & Miller 1985) with more than 95% of its luminosity radiated at 1.1 μm is a prototype of a Seyfert 2 nucleus (Antonucci & Miller 1985). The AGN is enclosed by a circumnuclear SB ring with 14′′ in diameter (Wilson et al. 1991).

Notes. Parameters without error indicate fixed for the Gaussian fitting. Upper limits correspond to 3σ limits.

3.2. Active Galactic Nuclei (AGNs)

NGC 1068 is a nearby luminous infrared galaxy (LIRG) prototype of a Seyfert 2 nucleus (Antonucci & Miller 1985). The AGN is enclosed by a circumnuclear SB ring with 14′′ (~1 kpc) radius (Myers & Scoville 1987; Schinnerer et al. 2000). Thus, we have observed two positions in NGC 1068. One toward the central AGN and an offset position 0′′.16 toward a peak of emission within the circumnuclear ring, hereafter NGC 1068*, mostly tracing the SB. NGC 4945, being one of the three brightest IRAS point sources, has been the target of some; a detailed molecular study by Wang et al. (2004). This nearly edge-on spiral galaxy harbors a heavily obscured Seyfert 2 nucleus (Brant et al. 1997; Maiolino et al. 1999) also surrounded by an SB ring (Marconi et al. 2000). NGC 5194 (M 51) is a nearby grand-design spiral galaxy with a Seyfert 2 nucleus. The proximity of this galaxy as well as its nearly face-on orientation has made it the target of numerous large-scale multiwavelength studies (Scoville & Young 1983; Scoville et al. 2001; Schuster et al. 2007). Its interaction with the companion galaxy NGC 5195 seems to have been the origin of a past period of intense star formation (Thronson et al. 1991; Greenawalt et al. 1998). NGC 7469, the only example of Seyfert 1 nucleus in our sample, also shows a circumnuclear star-forming ring of 3′′ in diameter (Wilson et al. 1991).

3.3. UltraLuminous Infrared Galaxies (ULIRGs)

Arp 220 is one of the best studied nearby ULIRGs (Dopita et al. 2005) with more than 95% of its luminosity radiated at IR/sub-mm wavelengths (Sanders et al. 2003). At a distance of D ~ 77 Mpc (z = 0.018) and star formation rates of 300 M⊙ yr⁻¹, Arp 220 is often referred to as a nearby template of the luminous star-forming galaxies at high-z. Arp 220 is the result of an advanced merger system with two nuclei separated...
by $\sim 1''$ ($\sim 300$ pc) as seen from near-IR and radio images (Baan & Haschick 1995; Scoville et al. 2000) with an enormous concentration of molecular gas within its central region (a few $10^3 M_\odot$; Sakamoto et al. 1999).

### 3.4. “Normal”

We refer to IC 342 as a “normal” galaxy as being the closest spiral galaxies resembling our own Galaxy. It shows a minispiral structure meeting at the inner molecular ring surrounding the central stellar cluster (Ishizuki et al. 1990; Boker et al. 1997; Helfer et al. 2003). Chemical differences have been observed between the gas in the nuclear region, affected by the intense star formation through the radiation from the central cluster, and the molecular material in the spiral structure, mainly affected by shocks (Meier & Turner 2005; Usero et al. 2006). In this work we have observed two positions, one at the central region and the other at the offset position (+5$''$, +15$''$), hereafter IC 342 *, located just in one of the arms of the minispiral.

### 4. DISCUSSION

#### 4.1. C$^{32}$S and C$^{34}$S

We have derived the abundances of CS, C$^{34}$S, and HNCO relative to H$_2$. In order to estimate the H$_2$ column density we have used the observed C$^{18}$O emission, assuming a C$^{18}$O/H$_2$O abundance ratio of 150, as derived in NGC 253 (Harrison et al. 1999) and the standard CO/H$_2$ ratio of $10^{-4}$.

The CS fractional abundance shows a narrow range of values within $1\text{--}3 \times 10^{-10}$. Similarly, the C$^{34}$S abundances are concentrated in the range of $1\text{--}5 \times 10^{-10}$. There are only three exceptions to this trend, namely IC 342*, Arp 220, and NGC 5194. The abundances of CS observed toward IC 342* is a factor of 6 below the average in the sample, while the C$^{34}$S abundance is close to the average value. This is explained by the highly concentrated CS emission toward the nuclear region (Meier & Turner 2005) and the almost twice smaller beam size at the CS 5$\text{--}$4 transition frequency compared to that at the C$^{34}$S 3$\text{--}$2 line (see Table 1). We did not detect neither CS nor C$^{34}$S emission toward NGC 5194. While the C$^{34}$S upper limit is still within the average value obtained for the other galaxies, the limit we derive in the main isotopologue is a factor of 3 below the sample average. On the other hand, the galaxy Arp 220 is observed to have an abundance by a factor of $\sim 5$ over the average in both isotopologues. This points out a real overabundance of CS toward this ULIRG.

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### Table 3

| Source       | C$^{18}$O $(\times 10^{15}$ cm$^{-2}$) | CS $(\times 10^{13}$ cm$^{-2}$) | C$^{34}$S $(\times 10^{12}$ cm$^{-2}$) | HNCO $(\times 10^{13}$ cm$^{-2}$) | (K) |
|--------------|-------------------------------------|----------------------------------|------------------------------------|----------------------------------|-----|
| NGC 253*     | 100 $\pm$ 20                        | 5.6 $\pm$ 0.4                    | 21 $\pm$ 4                         | 19 $\pm$ 4                       | 22 $\pm$ 9 |
| Maffei 2*    | 5.7 $\pm$ 1.5                       | 5.6 $\pm$ 0.6                    | 2.4 $\pm$ 0.7                      | 5.8 $\pm$ 1.1                    | 2.5 $\pm$ 1.2 |
| NGC 1068     | 24 $\pm$ 2                         | 3.3 $\pm$ 0.1                    | 7.0 $\pm$ 1.5                      | 7.3 $\pm$ 1.2                    | 10 $\pm$ 5 |
| NGC 1068*    | 18 $\pm$ 4                         | ...                              | ...                               | $<3.4$                          | 2.9 $\pm$ 1.0 |
| IC 342       | 22 $\pm$ 1                         | 5.7 $\pm$ 0.1                    | 4.6 $\pm$ 0.1                      | 6.9 $\pm$ 1.3                    | 12 $\pm$ 1 |
| IC 342*      | 18 $\pm$ 4                         | ...                              | 0.9 $\pm$ 0.2                      | 4.4 $\pm$ 1.0                    | 19 $\pm$ 1 |
| M 82         | 28 $\pm$ 1                         | 14.5 $\pm$ 0.3                   | 14 $\pm$ 4                         | 8.1 $\pm$ 1.9                    | $<0.7$ |
| NGC 4945c    | 160 $\pm$ 10                       | 6.5 $\pm$ 0.2                    | 58 $\pm$ 12                        | 64 $\pm$ 13                      | 50 $\pm$ 16 |
| NGC 5194     | 8.6 $\pm$ 1.8                      | ...                              | ...                               | $<0.7^d$                        | $<3.0$ |
| M 83         | 11 $\pm$ 2                         | ...                              | 4.9 $\pm$ 1.2                      | 5.6 $\pm$ 1.1                    | 10 $\pm$ 5 |
| Arp 220      | 14 $\pm$ 3                         | 24 $\pm$ 5                       | 26 $\pm$ 5                         | 7 $\pm$ 3                        | ... |
| NGC 6946     | 25 $\pm$ 5                         | ...                              | ...                               | 5.2 $\pm$ 1.0                    | 12 $\pm$ 6 |
| NGC 7469     | 3.2 $\pm$ 0.7                      | ...                              | ...                               | $<1.9$                          | 1.1 $\pm$ 0.4 |

**Notes.** Asterisk (*) indicates offset positions.

* Derived using data from Harrison et al. (1999), Martin05, and Martin06b.

* Abundances derived for each of the two velocity components labeled as Maffei 2a and Maffei 2b in Figure 3.

* Derived using data from Wang et al. (2004).

* Derived using data from Mauersberger et al. (1989).

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![Figure 2](image-url). C$^{34}$S/C$^{32}$S abundance ratio for the detected galaxies as a function of the CS fractional abundance. Sulfur isotopic ratios from the literature for the Galactic disk, and the galaxies NGC 4945 and NGC 253 are represented with continuous, dotted, and dashed lines, respectively, and their corresponding error shown as a gray shade. Labeling of sources is the same as in Figure 3.
4.2. CS Versus HNCO Abundances

In Figure 3, we represent the fractional abundances of CS and C\textsuperscript{34}S versus those of HNCO. We observe that most of the galaxies in the sample are observed with HNCO fractional abundances ranging from $10^{-9}$ to $10^{-8}$, but for two sources, namely NGC 5194 and M 82, showing remarkably low HNCO abundances. For these sources we derived fractional abundance below the average derived from the rest of galaxies in our sample by a factor of $\sim 3$ and $\sim 20$, respectively.

We do not observe major differences in the derived abundances among the AGNs and SBGs in our sample. This homogeneity suggests that the type of nuclear activity does not play a major role at large scales in the production/destruction of these species in the bulk of the molecular gas. This effect is illustrated by the two positions observed in NGC 1068, where the HNCO and C\textsuperscript{34}S abundances decrease by less than a factor of 2 from the nuclear AGN to the SB ring. Of course, we have to bear in mind that the two regions are not fully resolved by the beam of the IRAM 30 m telescope at these frequencies.

If, as suggested by the observations in the Galactic center region (Martín et al. 2008), the abundance of these species is mostly driven by the presence of shocks and strong UV radiation fields in the ISM, then the observed differences are likely linked to star formation activity in these galaxies. Significant differences are observed within the galaxies IC 342 and Maffei 2. In IC 342, the HNCO/C\textsuperscript{18}O ratio increases toward the position in the minispiral and decreases in the central region where ISM is illuminated by the UV radiation from the central clusters. These chemical differences, smoothed to the 10$''$–20$''$ single-dish beam size, are much more contrasted in the high-resolution interferometric maps by Meier & Turner (2005). Although not spatially, we resolve the nuclear region of Maffei 2 by the two velocity components. As seen from the high-resolution maps of $^{13}$CO (Meier et al. 2008) the lower velocity component ($\sim 100$ km s$^{-1}$) is associated with the nuclear and northeastern molecular arm, while the higher velocity component (0 km s$^{-1}$) will be mostly associated with the nuclear and southwest molecular arm. We clearly see a difference in the chemistry of both components with an increase of the HNCO abundance toward the southwest molecular arm of a factor of $\sim 2$ as well as a decrease of the CS abundance of a factor of 3–4. Overall, the HNCO/CS ratio increases by almost an order of magnitude.

We can compare the ratios measured in galaxies with the abundances derived in the central region of the Milky Way (Martín et al. 2008). The vast majority of galaxies show HNCO abundances intermediate between those found in the shock-dominated giant molecular clouds (GMCs) and the Galactic PDR prototypes (see the dashed lines in Figure 3). Two sources in our sample, namely M 83 and IC 342$^*$, clearly fall in the range of abundances found in GMCs. In contrast, M 82 represents the other extreme where HNCO emission is utterly vanished. The upper limit to the detection derived after a deep 5.5 hr integration on the HNCO 5–4 is an order of magnitude lower than the previous limit to the detection in the central position (Nguyen-Q-Rieu et al. 1991), but still HNCO remains undetected. Interferometric maps with the BIMA array show no emission anywhere in the nuclear region of M 82 (Turner & Meier 2008). This nondetection of HNCO supports the idea that M 82 is highly pervaded by a strong UV photodissociating radiation and depleted of dense molecular as also suggested by the low abundance of CH$_3$OH and NH$_3$ (Mauersberger & Henkel 1993; Takano et al. 2002; Martín et al. 2006a). We would expect

Figure 2 shows the C\textsuperscript{32}S/C\textsuperscript{34}S abundance ratio versus the fractional abundance of CS. This ratio is calculated with the 1 mm CS 5–4 and the 2 mm C\textsuperscript{34}S 3–2 transitions which makes it dependent on the assumed rotational temperature to derive the column densities, and to a lesser extent (up to a 30% for the smallest sources) on the considered source size. However, the ratio derived for NGC 4945 and NGC 253 agrees within a factor of 1.5 with the values derived from the complete study of CS by Wang et al. (2004) and Martín et al. (2005), respectively. Although the effects of line opacity have not been taken into account, we can consider the derived C\textsuperscript{32}S/C\textsuperscript{34}S abundance ratio as a rough representation of the $^{32}/^{34}$S isotopic ratio. It appears that almost all the sources in the sample have ratios around $\sim 10$, in agreement with those previously derived for NGC 4945 and NGC 253, and well below the value of $\sim 24$ measured in the Galactic disk (Chin et al. 1996). This result supports the idea of a $^{34}$S overproduction in the nuclei of galaxies by massive stars. Furthermore, we observe this ratio to be independent of the type of nuclear activity, both in AGN and SB dominated galaxies.
to observe a higher abundance of CS in this northeast position where photodissociation is claimed to be dominant (García-Burillo et al. 2002). However, we observe just a slightly higher CS abundance than in the whole sample, and not even that if we consider the isotopologue C\text{\textsuperscript{34}}S. Altogether with M 82, the upper limit to the HNCO abundance derived for NGC5194 is similar to those derived in the Galactic center PDRs. Most of the molecular studies of NGC5194 so far are restricted to the emission of CO and HCN (Kohno et al. 1996, and references therein). The results from this work point out the possible similarities between the chemistries of NGC 5194 and M 82, both with very low abundances of HNCO as compared with the rest of galaxies in this sample. This result agrees with the idea of NGC 5194 being in a post-SB stage after the star formation event triggered by its interaction with NGC 5195 (Greenawalt et al. 1998). Additionally, the HNCO and CS abundances in NGC 253 and NGC 1068\textsuperscript{∗}, a factor of 3 below the average, as well as the significantly high C\text{\textsuperscript{34}}S abundance, could be explained by photodissociation. This would suggest that the UV radiation from the evolved SB plays a significant role in the chemistry of the nuclear ISM in these galaxies. Therefore NGC 253 would contain a significant PDR molecular component, similar to what is observed in M 82. However, the amounts of dense molecular gas shielded from the UV radiation are still 1 order of magnitude larger than that observed in M 82.

Our observations of HNCO confirm that this molecule is one of the best tracers to study the evolutionary state of nuclear SBs in galaxies because of the high contrast shown between the UV-pervaded evolved SBs and the dense and well-shielded molecular material in the early stages of star formation. This molecule shows a higher abundance variation in galaxies than other dense molecular gas tracer such as methanol (Hüttemeister et al. 1997; Martín et al. 2006a). On the other hand, CS does not show a significant variation among the observed sources. This might be due to the fact that CS is not only enhanced in regions with strong UV radiation, but its emission also increases toward the densest molecular cores due to its high critical density. It is interesting to note that the similar FUV field derived by Kramer et al. (2005) toward the nucleus of M 83 and NGC 5194 might explain the different abundances observed in our sample mostly as a consequence of the dense molecular fuel depletion and the molecular cloud structure in their nuclei, and not so much by the differences in the photodissociation fields affecting the nuclear ISM. However, the CS variations in the Galactic center clouds are more moderate (a factor of ~2–3; Martín et al. 2008) than those of HNCO, and therefore it is likely to be averaged out over the central several hundred parsecs covered by the single dish beam.

### 4.3. The Evolution of Nuclear Starbursts

The highly contrasted variation of HNCO abundances over the galaxy sample in this work allows us to trace the dense molecular gas available for fueling the nuclear SB of these galaxies. This is equivalent to defining a chemical timeline in the evolution of the SB event that could be read from right-to-left hand side in Figure 3. It is important to note that the timescales for the chemical processes due to shocks and photodissociation by UV radiation (10\textsuperscript{4}–10\textsuperscript{5} yr, Bergin et al. 1998) are extremely short as compared with the typical timescale of the SB phenomenon (10\textsuperscript{7}–10\textsuperscript{8} yr, Coziol 1996).

In this scenario, at the onset of the SB, large amounts of dense molecular material are driven and compressed into the nuclear region of the galaxy unleashing the star formation. High abundances of HNCO are injected into the gas phase within these clouds due to shocks, likely as a consequence of the cloud–cloud collisions, as observed in the nuclear spiral arms of IC 342 (Meier & Turner 2005). From our galaxy sample, M 83 is shown to have the highest abundances of HNCO, and similar to those observed in the Galactic center GMCs. Subsequently, as soon as the first newly massive star clusters are formed, UV illumination begins to come on stage, photodissociating the material surrounding them. The HNCO abundance in these regions will be quickly dissociated where the CS molecule will be formed. A sort of average equilibrium will be reached between the PDR and the dense gas contribution as long as the infall of molecular fuel keeps feeding the SB. This is the status in which most of the SBGs in our sample are observed. The AGN-dominated galaxies we have observed also show this average CS/HNCO abundances similar to the intermediate state SBs, suggesting the presence of a significant UV radiation field. Once the galaxy gets closer to the end of the short few 10 Myr SB period, the fuel supply is cut off or stopped by superwinds. From our comparative study, this is apparently the point at which NGC 253 stands, where photodissociation becomes more important and the fuel reservoir is being consumed by the last gasp of star formation. Finally, as we observe in M 82 and NGC 5194, most of the molecular gas is pervaded by the UV radiation field with barely no dense UV-shielded molecular material left. The galaxy remains then waiting for a likely next burst of star formation (Coziol 1996). Indeed, chemical enrichment in M 82 points out to recursive SB periods (Origlia et al. 2004).

### 5. Conclusions

From our study of the CS and HNCO abundances in a selected sample of extragalactic sources, we have found differences of nearly 2 orders of magnitude in the HNCO/CS abundance ratios among the SBGs. These differences are in agreement with the results from the observations of Galactic center clouds dominated by various heating mechanisms suggesting that the observed HNCO abundances could be related to the evolutionary stage of their nuclear SB. Shocks affecting the massive dense molecular clouds in the early stages and strong UV fields in the evolved stages dominate the HNCO abundance in galaxies. We do not find significant differences in the molecular abundances of HNCO in galaxies with different type of nuclear activity (i.e., AGN or SB) which implies that these species are not affected differently by these processes at the scales observed by single dish beam telescopes.

As derived from the HNCO abundances, we can point out prototypes of these nuclear SB evolutionary stages. M 83 and the nuclear spiral arms in IC 342 would be representative of the early stage, while M 82 and NGC 5194 nuclei would be in the later stages of evolution. NGC 253, claimed to be a prototype of early SB, shows abundances below the average suggesting an important influence of photodissociation in the heating of its ISM, and therefore chemically closer to M 82 than to M 83.

The 32S/34S isotopic ratio, derived from the C\text{\textsuperscript{32}}S/C\text{\textsuperscript{34}}S abundance ratio, is found to be ~10, and thus similar for all the observed sources. This ratio, found to be well below the value of ~24 in the Galactic disk, supports the idea of the 34S isotope being enriched due to massive star formation events in the nuclear region of galaxies.

The CS emission is suggested to be a good tracer of the molecular gas affected by photodissociation in the Galactic center (Martín et al. 2008). We do not observe a significant
contrast in our sample. Though its abundance is enhanced in UV-radiated regions, its emission is also favored in high-density molecular clouds. Thus, the overall emission over the central few hundred parsecs of galactic nuclei is averaged out, and no significant trends in the CS abundances is found in the observed galaxies.

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**Facility:** IRAM 30m

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