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A survey of HC₃N in extragalactic sources

Is HC₃N a tracer of activity in ULIRGs?★

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ABSTRACT

Context. HC₃N is a molecule that is mainly associated with Galactic star-forming regions, but it has also been detected in extragalactic environments.

Aims. To present the first extragalactic survey of HC₃N, when combining earlier data from the literature with six new single-dish detections, and to compare HC₃N with other molecular tracers (HCN, HNC), as well as other properties (silicate absorption strength, IR flux density ratios, C II flux, and megamaser activity).

Methods. We present mm IRAM 30 m, OSO 20 m, and SEST observations of HC₃N rotational lines (mainly the $J = 10-9$ transition) and of the $J = 1-0$ transitions of HCN and HNC. Our combined HC₃N data account for 13 galaxies (excluding the upper limits reported for the non-detections), while we have HCN and HNC data for more than 20 galaxies.

Results. A preliminary definition “HC₃N-luminous galaxy” is made based upon the HC₃N/HCN ratio. Most (~80%) HC₃N-luminous galaxies seem to be deeply obscured galaxies and (U)LIRGs. A majority (~60% or more) of the HC₃N-luminous galaxies in the sample present OH mega- or strong kilomaser activity. A possible explanation is that both HC₃N and OH megamasers need warm dust for their excitation. Alternatively, the dust that excites the OH megamaser offers protection against UV destruction of HC₃N. A high silicate absorption strength is also found in several of the HC₃N-luminous objects, which may help the HC₃N to survive. Finally, we find that a high HC₃N/HCN ratio is related to a high dust temperature and a low C II flux.

Key words. galaxies: ISM – galaxies: starburst – galaxies: active – radio lines: galaxies – radio lines: ISM – ISM: molecules

1. Introduction

Finding useful tracers of the interaction between the activity in galaxy nuclei and surrounding interstellar medium (ISM) is an important and growing aspect of current extragalactic molecular astronomy. In this context, single dish surveys of polar molecules such as HCN, HNC, HCO⁺, and CS have been used to investigate possible correlations between molecular line ratios and type/intensity of activity (e.g. Kohno et al. 2001; Aalto et al. 2002; Imanishi et al. 2004; Graciá-Carpio et al. 2006; Krips et al. 2008; Baan et al. 2008). For example, it has been suggested that an elevated HCN/HCO⁺ 1–0 line intensity ratio indicates the presence of an AGN (Graciá-Carpio et al. 2006). Around an active galactic nucleus (AGN) the chemistry is supposedly dominated by hard X-rays in an X-ray dominated region (XDR),

and some chemical models predict an abundance enhancement of HCN paired with selective destruction of HCO⁺ (Maloney et al. 1996) – which could lead to an elevated HCN/HCO⁺ line ratio (under the circumstances that the line ratio directly reflects the abundance ratio). However, more recent chemical models instead suggest that HCO⁺ is enhanced in XDRs (Meijerink & Spaans 2005; Meijerink et al. 2007), and HCO⁺ is also expected to be under-abundant in regions of very young star formation (Aalto 2008), so the line ratio is ambiguous.

Other molecular tracers could help resolve the dichotomy of the HCN/HCO⁺ line ratio. The serendipitous discovery of the $J = 10-9$ line of HC₃N near the HNC $J = 1-0$ line in a survey by Aalto et al. (2002) led us to look more closely at this molecule. HC₃N is the simplest of the cyanopolyynes (carbon chains with an attached CN group) and is a grain chemistry product, in contrast to molecules such as HCN and HCO⁺. HC₃N thrives in warm, dense shielded regions such as hot cores where abundances can reach 10⁻⁸ or even higher, since it is easily destroyed by photo-dissociation (Rodríguez-Franco et al. 1998) and C⁺ ions (Prasad & Huntress 1980). Therefore, HC₃N line emission could be used to identify galaxies where star formation is in the early, embedded stage of its evolution. Recently, HC₃N

* Appendix is only available in electronic form at

<http://www.aanda.org>

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was found in high abundance in the highly obscured galaxy NGC 4418 (Aalto et al. 2007), as well as the ULIRG Arp 220 (Aalto et al. 2002).

We have searched for HC₃N line emission in a sample of galaxies in various stages and types of activity: AGNs, starbursts, and ultraluminous galaxies (ULIRGs). In some of the galaxies the nature of the activity is elusive since it is embedded in huge columns of dust absorbing emission at optical and infrared wavelengths. In some cases, the extinction is so strong that no emission emerges at optical or IR wavelengths requiring us to probe the nature of the activity at radio and mm wavelengths. HC₃N has a rich mm and sub-mm wavelength spectrum consisting of a multitude of rotational and vibrational lines often appearing close to each other in the same band. Through its vibrational transitions, HC₃N responds strongly to the IR field from dusty nuclei (Costagliola & Aalto 2010). Therefore, combining the rotational and vibrational line information of HC₃N allows us to study the abundance of HC₃N (comparing with chemical models of XDRs and starbursts) as well as the intensity and temperature structure of the buried IR source.

Rotational lines of vibrationally excited HC₃N have recently been discovered in a few galaxies (NGC 4418 (Costagliola & Aalto 2010), Arp 220 (Martín et al. 2011), and IC 860 (Costagliola et al. 2011)), therefore showing that it is important to take both radiative and collisional excitation into consideration when interpreting HC₃N line emission from IR luminous galaxies.

It can also be noted that absorption lines of HC₃N has been found in a $z \sim 0.89$ galaxy located in front of the quasar PKS 1830-211 (Henkel et al. 2009).

1.1. Outline

Here, the first survey of extragalactic HC₃N data is presented. We report new HC₃N observations in 19 galaxies (detections in six of them), mainly (U)LIRGs and starburst galaxies, and complete this sample with data from all earlier extragalactic HC₃N emission line single-dish detections found in the literature. The aim of the study is to compare the HC₃N luminosity with other molecular tracers as well as galaxy properties to see if the presence of HC₃N can be used to predict other galaxy properties, e.g. the source of activity in the galaxy.

In Sect. 2, the general properties of HC₃N in space are discussed. In Sect. 3 we present the new observations and discuss the collection of data from the literature. In Sect. 4 we present the results in terms of line intensities and line ratios. In Sect. 5 we discuss the interpretation of the HC₃N results and compare them with silicate absorption strength (Sect. 5.2), OH megamaser activity (Sect. 5.3), IR flux density ratios (Sect. 5.4), C II flux (Sect. 5.5), and the HNC/HCN 1-0 line ratio (Sect. 5.6). In Sect. 5.7 future studies resulting from this project are discussed.

2. HC₃N in space

2.1. Generation of HC₃N

Acetylene, C₂H₂, exists on grains in the ISM (Chapman et al. 2009). After evaporating from the grains there are at least two different paths the C₂H₂ may follow. If a high UV field is present (the region being a PDR), it will photo-dissociate into the ethynyl radical, C₂H (Meier & Turner 2005; Cherchneff et al. 1993; Heikkilä et al. 1999):



If no strong UV field is present (no PDR), but CN (the cyano radical) is available for reactions, the C₂H₂ will instead react with the CN to form HC₃N (Meier & Turner 2005; Chapman et al. 2009; Fukuzawa & Osamura 1997):



This hypothesis is strengthened by interferometric maps of HC₃N and C₂H in IC 342 found in Meier & Turner (2005). The maps show a clear anti-correlation between the distributions of the molecules. Using the abundances of HC₃N, C₂H, and CN in a region where it is expected that grains with C₂H₂ first were present, it should therefore be possible to tell whether a strong UV field is present or not.

Irvine et al. (1987) find that C₂H, contrarily to HC₃N, is two orders of magnitude more abundant in the Orion ridge than in its hot core. Possibly, the hot core shields the HC₃N and C₂H₂ from photo-dissociating into C₂H. Some of the C₂H₂ instead reacts with the CN (although not very abundant) and forms even more HC₃N. The highest HC₃N abundances are found in Sgr B2 hot cores, being in the order of 10⁻⁷ of the H₂ abundance (de Vicente et al. 2000).

We have not included all possible HC₃N formation mechanisms here, and investigations of other processes are ongoing, as for example the notion of ice formation of HC₃N (Szczepanski et al. 2005).

2.2. Destruction of HC₃N

In the Galaxy, HC₃N is associated with warm, dense, shielded gas around young stars or star-forming regions, and is easily destroyed by UV radiation and reactions with C⁺ ions (Rodríguez-Franco et al. 1998; Meier & Turner 2005). It will form either C₂H or C₃N when being photo-dissociated (Cherchneff et al. 1993), and C₃H⁺ or C₄N⁺ when reacting with C⁺ (Bohme & Raksit 1985). Among the possible reactions destroying HC₃N are:



Reaction rates of these reactions, as well as those in Sect. 2.1, can be found in e.g. Cherchneff et al. (1993).

2.3. Abundances of HC₃N

Irvine et al. (1987) give the relative abundances of several molecules in the core and ridge of the Orion molecular cloud. The detections of these molecules in the Galaxy are indicative of their abundances in high and low density molecular regions. The relative HC₃N abundance lies around 10⁻⁹ of the H₂ abundance in the core (dense region), and 10⁻¹⁰ in the ridge (low density region). This is a relatively small difference between high and low density regions, as compared to e.g. HCN, with about 10⁻⁷ of the H₂ abundance in the core, and 10⁻⁹ in the ridge.

The intense radiation from starburst regions and/or AGNs in the centre of many galaxies will turn surrounding gas clouds into regions where the chemical structure depends highly on the radiation field, either photon-dominated regions (PDRs) or X-ray dominated regions (XDRs). In XDRs the abundance of several molecules (e.g. CN and CH₂) are expected to be enhanced with respect to the abundance commonly found in PDRs. Due to the

Table 1. Data for the observations reported in this work.

Galaxy	Molecule	Line	Telescope	Date
Arp 220	HC ₃ N	10-9	OSO	2001-11-11
Arp 220	HC ₃ N	12-11	OSO	2001-11-09
Circinus	HNC	1-0	SEST	2001-01-14
IC 694	HC ₃ N	12-11	OSO	2001-11-10
IC 860	HC ₃ N	28-27	IRAM	2007-12-16
IC 860	HNC	1-0	IRAM	2007-12-16
I17208	HC ₃ N	10-9	IRAM	2007-12-16
I17208	HNC	1-0	IRAM	2006-06-28
Maffei 2	HC ₃ N	12-11	IRAM	2007-08-25
NGC 34	HNC	1-0	SEST	2001-01-14
NGC 613	HCN	1-0	SEST	2001-02-11
NGC 613	HNC	1-0	SEST	2001-02-13
NGC 1056	HC ₃ N	16-15	IRAM	2006-06-30
NGC 1056	HNC	1-0	IRAM	2006-06-30
NGC 1377	HC ₃ N	16-15	IRAM	2007-12-13
NGC 1377	HC ₃ N	25-24	IRAM	2007-12-13
NGC 1377	HCN	1-0	IRAM	2007-12-13
NGC 1377	HNC	1-0	IRAM	2007-12-13
NGC 1614	HNC	1-0	SEST	2001-02-13
NGC 2146	HC ₃ N	10-9	OSO	2001-11-08
NGC 2146	HC ₃ N	12-11	OSO	2001-11-08
NGC 2623	HC ₃ N	12-11	OSO	2001-11-12
NGC 3079	HC ₃ N	10-9	IRAM	2006-05-14
NGC 3079	HC ₃ N	16-15	IRAM	2006-05-14
NGC 3079	HC ₃ N	25-24	IRAM	2006-05-14
NGC 3690	HC ₃ N	12-11	OSO	2001-11-09
NGC 4418	HCN	1-0	IRAM	2008-07-19
NGC 4945	HNC	1-0	SEST	2001-01-15
NGC 5135	HNC	1-0	SEST	2001-01-13
NGC 6946	HC ₃ N	12-11	IRAM	2007-08-25
UGC 5101	HC ₃ N	10-9	IRAM	2007-12-13
UGC 5101	HNC	1-0	IRAM	2007-12-13

Notes. For the observations cited from the literature, see the respective articles referred to in Tables 4–6. We would like to point out that some of the HC₃N 10–9 data reported by us come from SEST HNC 1–0 spectra.

high C⁺ abundance in XDRs, a low HC₃N abundance is expected (Aalto 2008). The HC₃N/CN abundance ratio found in PDRs is also very low compared to the same ratio measured in hot, dense cores (Rodriguez-Franco et al. 1998). For further discussion about PDR and XDR chemistry, see e.g. Tielens & Hollenbach (1985); Lepp & Dalgarno (1996); Meijerink & Spaans (2005); Maloney et al. (1996).

3. Observations

The new observations reported in this work were carried out with the IRAM 30 m¹, OSO 20 m, and SEST 15 m telescopes between 2001 and 2008. Detailed lists with system temperatures and dates for the observations reported in this work are found in Table 1). The pointing accuracy was better than 2'' for all the observations, and typical system temperatures were 150 K (IRAM 90–110 GHz), 250 K (IRAM 125 GHz), 400 K (IRAM 225–250 GHz), and 300 K (OSO and SEST). In this survey we also include data from the literature using the already mentioned telescopes, as well as the NRO 45 m, NRAO 12 m, and FCRAO 14 m telescopes. Whenever using data from the literature, the beam sizes and efficiencies given in the respective

¹ Based on observations carried out with the IRAM 30m Telescope. IRAM is supported by INSU/CNRS (France), MPG (Germany), and IGN (Spain).

Table 2. Observational parameters.

Transition	ν [GHz] ^a	HPBW ['] ^b	η_{mb} ^b
<i>IRAM:</i>			
HC ₃ N 10–9	90.979	28	0.80
HC ₃ N 12–11	109.174	24	0.73
HC ₃ N 16–15	145.561	17	0.67
HC ₃ N 25–24	227.419	10.5	0.63
HC ₃ N 28–27	254.699	9	0.59
HCN 1–0	88.632	28	0.80
HNC 1–0	90.664	28	0.80
<i>OSO:</i>			
HC ₃ N 12–11	109.174	36	0.52
HC ₃ N 10–9	90.979	42	0.59
<i>SEST:</i>			
HC ₃ N 10–9	90.979	55	0.75
HCN 1–0	88.632	57	0.75
HNC 1–0	90.664	55	0.75

Notes. ^(a) From the NIST database *Recommended Rest Frequencies for Observed Interstellar Molecular Microwave Transitions* (<http://physics.nist.gov/cgi-bin/micro/table5/start.pl>).

^(b) The half-power beamwidths and main beam efficiencies are collected from the respective telescope web pages.

articles have been used for calculations of line ratios. The parameters used for all new observations reported in this work are given in Table 2.

One could argue that the many different instruments used to obtain the data in this article might introduce a bias difficult to compensate for. However, when comparing the HNC/HCN 1–0 line ratios obtained with IRAM and SEST respectively, no systematic bias is detected. The average line ratio was calculated to 0.51 ± 0.11 for SEST data and 0.51 ± 0.08 for IRAM data.

All objects investigated (observed by us or with data from the literature) are listed in Table 3, along with some important characteristics.

The relative HC₃N abundances calculated in this work will be expressed as line ratios between an HC₃N line (mostly the $J = 10–9$ transition) and the $J = 1–0$ transitions of HCN and HNC. These two molecules are chosen as they are good tracers of high density regions (see e.g. Papadopoulos 2007; Aalto et al. 2002), where we expect to find the HC₃N (Meier & Turner 2005). Also, HCN and HNC data are available for most of the objects in the sample. We note that the line ratios are not linearly proportional to ratios between the abundances of the species, since they will also depend on excitation conditions and optical depths in the galaxies. A high HC₃N/HCN ratio might thus sometimes be a tracer of discrepancies in temperatures, densities, or IR pumping in the galaxies.

A discussion of the method used when calculating the line ratios can be found in Appendix A. A few of the most nearby galaxies in the survey have such a large angular distribution that the measured values might not represent a global value for molecular gas in the galaxy, but rather a value for a certain (central) region of the galaxy. This effect is discussed in Appendix A.1.

The sample of galaxies observed by us has been chosen to have a high probability of finding HC₃N – it is by no means intended to be an unbiased sample of some random galaxies, and thus the relatively high detection ratio should definitely not reflect the amount of HC₃N-luminous galaxies in the universe. The same is most likely true for the galaxies found in the literature. Another important selection effect for the objects from the

Table 3. List of investigated objects and some of their properties. For the galaxies with new observations reported, the given positions are those used for our observations. For objects not observed by us the position in NED (2009) is given.

Galaxy	RA (J2000.0)	Dec (J2000.0)	Type ^a	cz^b [km s ⁻¹]	D^c [Mpc]	$\log L_{\text{FIR}}^d$ [L_{\odot}]	θ_{HCN}^e ["]
Arp 220	15 34 57.1	+23 30 11.3	ULIRG, Obsc., SB?	5450	78.1	12.15	2 ¹
Circinus	14 10 34.3	-64 52 12.5	AGN, cp?	434 ^f	3.13	...	21 (CO 3-2) ²
IC 342	03 46 48.5	+68 05 46	SB	31	4.00	10.01	20 ³
IC 694 ^g	11 28 33.6	+58 33 46.0	SB	3159	58.2	11.74 ^h	5 ⁴
IC 860	13 15 03.5	+24 37 08.0	Obsc.	3887	59.1 ⁱ	11.14	*
I17208 ^j	17 23 21.9	-00 17 00.9	ULIRG, Obsc., SB?	12852	178	12.35	0.67 ⁵
M82	09 55 52.7	+69 40 46	SB	187	5.68	10.61	>30 ¹
Maffei 2	02 41 55.1	+59 36 15.0	SB	-17 ^f	3.34	...	20 × 7 ⁶
NGC 34	00 11 06.5	-12 06 26.6	SB	5931	79.8	11.34	*
NGC 253	00 47 33.1	-25 17 18	SB	261	3.22	10.29	18 × 8 ⁷
NGC 613	01 36 36.7	-29 09 50.4	cp	1475	18.6	10.22	40 (CO 1-0) ⁸
NGC 1056	02 42 48.3	+28 34 27.1	AGN	1545	22.7	9.79	-
NGC 1068	02 42 40.7	-00 00 47.0	cp	1005	15.3	10.89	4.5 ¹
NGC 1365	03 33 36.4	-36 08 26.1	cp	1636	19.9	10.86	34 (CO 2-1) ⁹
NGC 1377	03 36 39.1	-20 54 08.0	Obsc., AGN?	1792	22.5	9.95	-
NGC 1614	04 36 24.2	-08 28 40.3	SB	4746	63.4	11.43	12 (CO 2-1) ¹⁰
NGC 1808	05 07 42.3	-37 30 47	SB, cp?	1000	11.2	10.55	18 (CO 2-1) ¹⁰
NGC 2146	06 18 37.8	+78 21 22.9	SB	885	16.9	10.93	20 ¹
NGC 2623	08 38 24.1	+25 45 17.2	SB	5538	76.9	11.48	1.8 ¹¹
NGC 3079	10 01 57.81	+55 40 47.1	SB? AGN?	1142	19.7	10.65	13 × 5 (CO 1-0) ¹²
NGC 3256	10 27 51.3	-43 54 14	SB	2781	36.5	11.43	9 (CO 2-1) ¹⁰
NGC 3690 ^g	11 28 31.0	+58 33 40.0	SB	3159	46.9	11.74 ^h	1.56 ⁵
NGC 4418	12 26 54.8 ^k	-00 52 42.0 ^k	Obsc., AGN?	2104	32.6	11.00	5 (CO 1-0) ¹³
NGC 4945	13 05 27.0	-49 28 04.5	SB, cp?	560	4.85	10.41	15 (CO 3-2) ²
NGC 5135	13 25 44.0	-29 50 02.2	cp	4114	56.0	11.06	15 × 5 (CO 1-0) ¹⁴
NGC 6946	20 34 52.3	+60 09 14.0	SB	53	5.64	10.01	10 ¹
NGC 7130	21 48 19.5	-34 57 05	cp	4824	65.4	11.23	10 (CO 1-0) ¹⁰
UGC 5101	09 35 51.6	+61 21 11.7	LIRG, cp	11785	165	11.87	3.50 (CO 1-0) ⁵

References. (1) Table in Krips et al. (2008); (2) Table in Curran et al. (2001a); (3) HCN map in Meier & Turner (2005); (4) HCN map in Aalto et al. (1997); (5) Table in Graciá-Carpio et al. (2008); (6) HCN map in Nguyen-Rieu et al. (1994); (7) HCN map in Knudsen et al. (2007); (8) CO 1-0 map in Bajaja et al. (1995); (9) CO 2-1 source size in Curran et al. (2001b); (10) Table in Aalto et al. (1995); (11) Table in Bryant & Scoville (1999); (12) CO 1-0 map in Koda et al. (2002); (13) CO 1-0 map in Dale et al. (2005); (14) CO 1-0 map in Regan et al. (1999).

Notes. ^(a) The classifications have been obtained by careful investigation of the notes in NED (2009). SB = starburst, AGN = active galactic nucleus, cp = composite of SB and AGN, Obsc. = obscured, ULIRG = Ultra-luminous Infrared galaxy, LIRG = Luminous Infrared galaxy. ^(b) Heliocentric radial velocity of source, from Sanders et al. (2003). ^(c) Distance to source, corrected for Virgo infall only, from NED (2009). ^(d) Far Infrared Luminosity, from Sanders et al. (2003). ^(e) Source sizes, given for HCN 1-0 line if not specified otherwise. For galaxies with an asterisk (*), no value has been found, but $D \geq 45$ Mpc, allowing the point-like approximation ($\theta_{\text{HCN}} = 0$) with an error $\leq 5\%$ if the dense molecular gas in this galaxy is not unusually widely distributed. For galaxies marked with a dash (-), no value has been found, and $D < 45$ Mpc. ^(f) From NED (2009). ^(g) IC 694 and NGC 3690 are together also known as the merger Arp 299. ^(h) This is the FIR luminosity of IC 694 and NGC 3690 together. ⁽ⁱ⁾ From Sanders et al. (2003). ^(j) Short for IRAS 17208-0014. ^(k) For the HCN 1-0 data the following coordinates have been used: RA 12 26 54.63, Dec -00 52 39.6 (J2000.0).

literature is that detections are much more likely to be reported than non-detections, which also leads to a biased sample.

To increase the chance of detecting HC₃N, almost all of the galaxies that were chosen to be part of the sample have earlier detections of HCN, which means that they should have large amounts of dense gas, increasing the possibility of finding HC₃N. As the goal of the study is to investigate if HC₃N can trace the source of the activity in active galaxies, the sample consists only of active galaxies – starburst galaxies and AGN galaxies (the source of the activity is although disputed or unknown in many of the galaxies in the sample).

Throughout the article, the T_{A}^* scale will be used for all our data. For the data from the literature, the temperature scale used in each article will be used in our tables, clearly noted whenever the T_{A}^* scale is not used. This will make it easier to detect any errors that might have occurred in the survey work. When the line ratios are calculated, the efficiencies will be taken into account properly.

Data analysis was performed with the X-Spec² software package. A first order baseline was subtracted from all spectra.

4. Results

All new HC₃N, HCN, and HNC spectra reported in this work are displayed in Figs. 1–7. The observed values of the spectral line intensities can be found in Tables 4–6. Data from the literature are also included in these tables.

Some observations of HC₃N 10-9 and HNC 1-0 performed with SEST include both these lines in the same spectrum, due to the large bandwidth. The spectra are in these cases labelled according to the central peak. The frequency difference between the two peaks is 315 MHz, as can be seen in Table 2. This gives a velocity difference of approximately 1000 km s⁻¹.

² <http://www.chalmers.se/rss/oso-en/observations/data-reduction-software>

Table 4. Data from HC₃N observations.

Galaxy	Line	$I(\text{HC}_3\text{N})^a$ [K km s ⁻¹]	$S_{\nu}\Delta\nu$ [Jy km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	Telescope	η_{mb}	θ_{mb} [$''$]	T scale ^a	References
Arp 220	10-9	2.02 ± 0.15	45 ± 3	340	OSO 20 m	0.59	44	T_{A}^*	(1)
Arp 220	10-9 ^b	0.4 ± 0.15	11 ± 4	350	SEST 15 m	0.75	55	T_{A}^*	(2)
Arp 220	12-11	0.96 ± 0.1	23 ± 2	170	OSO 20 m	0.52	36	T_{A}^*	(1)
Circinus	10-9 ^b	1.01 ± 0.1	27.6 ± 2.7	290	SEST 15 m	0.75	55	T_{A}^*	(1)
IC 342	10-9	2.6 ± 0.7	14 ± 4	52	IRAM 30 m	0.8	25	T_{R}^*	(3)
IC 694	12-11	<0.30	<7.4	...	OSO 20 m	0.52	36	T_{A}^*	(1)
IC 860	28-27	0.54 ± 0.07	3.9 ± 0.5	175	IRAM 30 m	0.59	9	T_{A}^*	(1)
I17208	10-9	0.33 ± 0.03	2.2 ± 0.2	330	IRAM 30 m	0.80	28	T_{A}^*	(1)
M82	12-11	5.6 ± 0.6	30 ± 3	155	IRAM 30 m	0.80	25	T_{R}^*	(3)
Maffei 2	12-11	1.42 ± 0.05	10.9 ± 0.4	200	IRAM 30 m	0.73	24	T_{A}^*	(1)
NGC 34	10-9 ^b	<0.45	<12	...	SEST 15 m	0.75	55	T_{A}^*	(1)
NGC 253	9-8	5.8 ± 0.6	27 ± 3	63 ^c	IRAM 30 m	...	29	T_{mb}	(4)
NGC 253	10-9	5.8 ± 0.6	27 ± 3	63 ^c	IRAM 30 m	...	26	T_{mb}	(4)
NGC 253	12-11	4.4 ± 0.7	19 ± 3	63 ^c	IRAM 30 m	...	21	T_{mb}	(4)
NGC 253	15-14	4.4 ± 0.3	24 ± 2	77, 85	IRAM 30 m	...	19	T_{mb}	(5)
NGC 253	15-14	3.6 ± 0.6	16 ± 3	63 ^c	IRAM 30 m	...	17	T_{mb}	(4)
NGC 253	16-15	3.8	19	77 ^c , 85 ^c	IRAM 30 m	...	17	T_{mb}	(5)
NGC 253	17-16	3.0 ± 0.2	15 ± 1	72 ^c	IRAM 30 m	...	16	T_{mb}	(5)
NGC 253	17-16	3.4 ± 0.4	15 ± 2	63 ^c	IRAM 30 m	...	15	T_{mb}	(4)
NGC 253	18-17	2.2 ± 0.5	11 ± 2	73	IRAM 30 m	...	15	T_{mb}	(5)
NGC 253	19-18	4.6 ± 0.6	22 ± 3	74	IRAM 30 m	...	14	T_{mb}	(5)
NGC 253	26-25	3.2 ± 0.7	21 ± 5	63 ^c	IRAM 30 m	...	12	T_{mb}	(4)
NGC 613	10-9 ^b	<0.26	<7.0	...	SEST 15 m	0.75	55	T_{A}^*	(1)
NGC 1056	16-15	<0.17	<1.3	...	IRAM 30 m	0.67	17	T_{A}^*	(1)
NGC 1068	10-9 ^b	0.39 ± 0.05	11 ± 1	100	SEST 15 m	0.75	55	T_{A}^*	(1) ^d
NGC 1365	10-9 ^b	<0.61	<417	...	SEST 15 m	0.75	55	T_{A}^*	(1) ^d
NGC 1377	16-15	<0.28	<2.1	...	IRAM 30 m	0.67	17	T_{A}^*	(1)
NGC 1377	25-24	<0.26	<1.9	...	IRAM 30 m	0.63	10.5	T_{A}^*	(1)
NGC 1614	10-9 ^b	<0.39	<11	...	SEST 15 m	0.75	55	T_{A}^*	(1)
NGC 1808	10-9 ^b	0.2 ± 0.1	6 ± 3	250	SEST 15 m	0.75	57	T_{A}^*	(2)
NGC 2146	10-9	<0.38	<7.7	...	OSO 20 m	0.59	42	T_{A}^*	(1)
NGC 2146	12-11	<0.38	<9.2	...	OSO 20 m	0.52	36	T_{A}^*	(1)
NGC 2623	12-11	<0.50	<12	...	OSO 20 m	0.52	36	T_{A}^*	(1)
NGC 3079	10-9	0.60 ± 0.05	4.0 ± 0.3	500	IRAM 30 m	0.80	28	T_{A}^*	(1)
NGC 3079	16-15	<0.54	<4	...	IRAM 30 m	0.80	17	T_{A}^*	(1)
NGC 3079	25-24	<0.40	<3	...	IRAM 30 m	0.80	10.5	T_{A}^*	(1)
NGC 3256	10-9 ^b	<0.12	<3.3	...	SEST 15 m	0.75	55	T_{A}^*	(2)
NGC 3690	12-11	<0.31	<7.5	...	OSO 20 m	0.52	36	T_{A}^*	(1)
NGC 4418 ^e	10-9	0.8 ± 0.08	5 ± 0.5	122	IRAM 30 m	0.77	27	T_{A}^*	(6)
NGC 4418 ^e	16-15 ^f	1.7 ± 0.08	12 ± 0.6	130	IRAM 30 m	0.70	17	T_{A}^*	(6)
NGC 4418 ^e	25-24	1.6 ± 0.2	15 ± 2	140	IRAM 30 m	0.53	11	T_{A}^*	(6)
NGC 4945	9-8	2.16 ± 0.50	47 ± 11	230	SEST 15 m	0.78	63	T_{mb}	(7)
NGC 4945	10-9	1.99 ± 0.21	41 ± 4	290	SEST 15 m	0.75	55	T_{mb}	(7)
NGC 4945	11-10	2.92 ± 0.35	65 ± 8	340	SEST 15 m	0.73	52	T_{mb}	(7)
NGC 4945	12-11	4.18 ± 0.38	98 ± 9	340	SEST 15 m	0.71	49	T_{mb}	(7)
NGC 4945	15-14	2.13 ± 0.29	52 ± 7	250	SEST 15 m	0.65	40	T_{mb}	(7)
NGC 4945	16-15 ^g	5.02 ± 0.19	120 ± 5	330	SEST 15 m	0.63	37	T_{mb}	(7)
NGC 4945	17-16	2.26 ± 0.55	48 ± 12	280	SEST 15 m	0.61	33	T_{mb}	(7)
NGC 4945	24-23	<0.60	<12	...	SEST 15 m	0.48	23	T_{mb}	(7)
NGC 4945	25-24	<0.60	<12	...	SEST 15 m	0.46	22	T_{mb}	(7)
NGC 5135	10-9 ^b	<0.13	<3.7	...	SEST 15 m	0.75	55	T_{A}^*	(1)
NGC 6946	12-11	<0.32	<2.5	...	IRAM 30 m	0.73	24	T_{A}^*	(1)
NGC 7130	10-9 ^b	<0.10	<2.7	...	SEST 15 m	0.75	55	T_{A}^*	(2)
UGC 5101	10-9	<0.12	<0.76	...	IRAM 30 m	0.80	28	T_{A}^*	(1)

References. (1) This work; (2) Aalto et al. (2002); (3) Henkel et al. (1988); (4) Mauersberger et al. (1990); (5) Martín et al. (2006); (6) Aalto et al. (2007); (7) Wang et al. (2004).

Notes. ^(a) The temperature scale of the integrated intensities are given in the T scale column. Upper limits are 2σ calculated from the rms of the noise surrounding the line for our data. For our data, errors are given in 1σ and calculated from the rms. Since many articles lack information about sizes of errors and methods used when calculating the errors, most errors are given as printed in the respective article. However, if the size of the error is clearly written, it has been recalculated to 1σ . ^(b) Measured in HNC 1-0 spectrum. ^(c) Fixed when fitting Gaussian. ^(d) These values are calculated from HNC 1-0 spectra already published in Pérez-Beaupuits et al. (2007). ^(e) See Costagliola & Aalto (2010) for an extensive survey of HC₃N in this galaxy, with data not included in this table. ^(f) Contaminated by para-H₂CO, estimated to 20%. The given value is only for the HC₃N component. ^(g) Contaminated by para-H₂CO.

Table 5. Data from HCN 1-0 observations.

Galaxy	$I(\text{HCN})\ 1-0^a$ [K km s ⁻¹]	$S_\nu \Delta\nu$ [Jy km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	Telescope	η_{mb}	θ_{mb} [$''$]	T scale ^a	References
Arp 220	9.7 ± 0.4	57 ± 2	530	IRAM 30 m	0.82	29.5	T_{mb}	(1)
Circinus	5.2 ± 0.8	110 ± 20	300	SEST 15 m	0.75	57	T_{mb}	(2)
IC 342	15.5 ± 0.9	36 ± 2	...	NRO 45 m	0.54	19	T_{mb}	(3)
IC 694	1.29 ± 0.09	8.4 ± 0.6	...	IRAM 30 m	0.82	28	T_{A}^*	(4)
IC 860	...	...	...	...	...	...	N/A ^b	
I17208	2.19 ± 0.16	14 ± 1	...	IRAM 30 m	0.82	28	T_{A}^*	(4)
I17208	0.91 ± 0.19	34 ± 7	...	NRAO 12 m	0.89	72	T_{R}^*	(5)
M82	29 ± 0.2	170 ± 1	130	IRAM 30 m	0.82	29.5	T_{mb}	(1)
Maffei 2	13.8 ± 0.9	32 ± 2	...	NRO 45 m	0.54	19	T_{mb}	(3)
NGC 34	1.6 ± 0.2	33 ± 4	600-700	SEST 15 m	0.75	57	T_{mb}	(6)
NGC 253	40.8	175	150	NRO 45 m	0.45	23	T_{A}^*	(7)
NGC 613	0.53 ± 0.08	15 ± 2	130	SEST 15 m	0.75	57	T_{A}^*	(8)
NGC 1056	...	...	...	...	...	...	N/A ^b	
NGC 1068	24.5 ± 0.9	145 ± 5	220	IRAM 30 m	0.82	29.5	T_{mb}	(1)
NGC 1365	6.0 ± 0.1	125 ± 2	300-400	SEST 15 m	0.75	57	T_{mb}	(6)
NGC 1377	0.47 ± 0.1	3.0 ± 0.6	140	IRAM 30 m	0.80	28	T_{A}^*	(8)
NGC 1614	1.5 ± 0.22	40 ± 6	300	FCRAO 14 m	0.60	50	T_{A}^*	(5)
NGC 1808	4	110	...	SEST 15 m	0.74	56	T_{A}^*	(9)
NGC 2146	5 ± 0.1	30 ± 1	290	IRAM 30 m	0.82	29.5	T_{mb}	(1)
NGC 2623	...	...	...	...	...	...	N/A ^b	
NGC 3079	5.7 ± 0.8	29 ± 4	420	IRAM 30 m	0.80	28	T_{mb}	(10)
NGC 3079	2.6 ± 0.42	97 ± 16	365	NRAO 12 m	0.89	72	T_{R}^*	(5)
NGC 3256	2.3 ± 0.2	48 ± 4	165	SEST 15 m	0.77	57	T_{mb}	(11)
NGC 3690	2.04 ± 0.11	13.2 ± 0.7	300	IRAM 30 m	0.82	28	T_{A}^*	(4)
NGC 4418	1.96 ± 0.04	12.4 ± 0.3	170	IRAM 30 m	0.80	28	T_{A}^*	(8)
NGC 4945	22.4 ± 0.4	436 ± 8	305	SEST 15 m	0.75	55	T_{mb}	(12)
NGC 5135	0.65 ± 0.07	14 ± 1.5	50-60	SEST 15 m	0.75	57	T_{mb}	(6)
NGC 6946	8.7 ± 0.9	20 ± 2	...	NRO 45 m	0.54	19	T_{mb}	(3)
NGC 7130	0.7 ± 0.1	15 ± 2	100	SEST 15 m	0.75	57	T_{mb}	(6)
UGC 5101	1.40 ± 0.14	9.1 ± 0.9	500	IRAM 30 m	0.82	28	T_{A}^*	(4)

References. (1) Krips et al. (2008); (2) Curran et al. (2001a); (3) Sorai et al. (2002); (4) Graciá-Carpio et al. (2008); (5) Gao & Solomon (2004); (6) Curran et al. (2000); (7) Nguyen-Q-Rieu et al. (1989); (8) This work; (9) Aalto et al. (1994); (10) Pérez-Beaupuits et al. (2007); (11) Casoli et al. (1992); (12) Wang et al. (2004).

Notes. ^(a) The temperature scale of the integrated intensities are given in the T scale column. Upper limits are 2σ calculated from the rms of the noise surrounding the line for our data. For our data, errors are given in 1σ and calculated from the rms. Since many articles lack information about sizes of errors and methods used when calculating the errors, most errors are given as printed in the respective article. However, if the size of the error is clearly written, it has been recalculated to 1σ . ^(b) No single-dish HCN data were found in the literature for these objects.

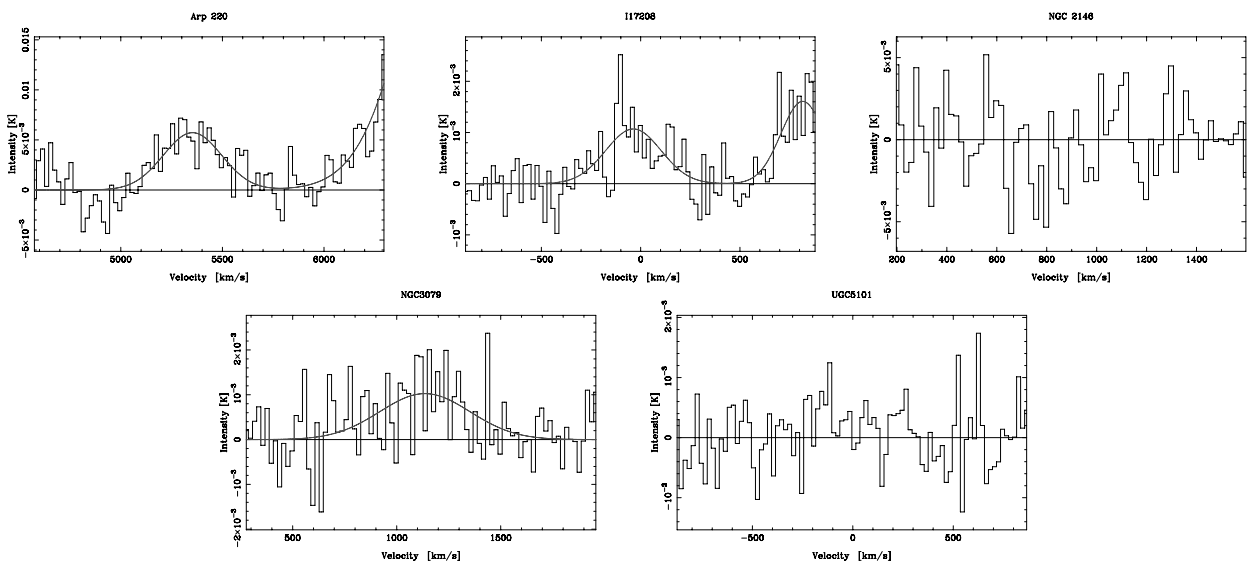


Fig. 1. HC₃N 10-9 spectra for Arp 220, IRAS 17208-0014 (detections), NGC 2146 (non-detection), NGC 3079 (detection), and UGC 5101 (non-detection). For Arp 220 and IRAS 17208-0014, part of the HNC 1-0 line is also visible. Some of the reported HC₃N 10-9-detections are found in the HNC 1-0 spectra, see Fig. 7.

Table 6. Data from HNC 1-0 observations.

Galaxy	$I(\text{HNC})$ 1-0 ^a [K km s ⁻¹]	$S_\nu \Delta\nu$ [Jy km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	Telescope	η_{mb}	θ_{mb} [$''$]	T scale ^a	References
Arp 220	0.95 ± 0.2	26 ± 6	...	SEST 15 m	0.75	55	T_A^*	(1)
Circinus	1.99 ± 0.1	55 ± 3	280	SEST 15 m	0.75	55	T_A^*	(2)
IC 342	9.2 ± 0.7	48 ± 4	47	IRAM 30 m	0.8	25	T_R^*	(3)
IC 694	0.75 ± 0.2	15 ± 4	300-400	OSO 20 m	0.59	42	T_A^*	(1)
IC 860	0.70 ± 0.04	4.6 ± 0.3	230	IRAM 30 m	0.80	28	T_A^*	(2)
I17208	1.12 ± 0.06	7.4 ± 0.4	350	IRAM 30 m	0.80	28	T_A^*	(2)
M82	7.3 ± 0.6	31 ± 3	129	IRAM 30 m	0.64	25	T_{mb}	(4)
Maffei 2	7.3 ± 0.8	31 ± 3	91, 50	IRAM 30 m	0.64	25	T_{mb}	(4)
NGC 34	<0.44	<12	...	SEST 15 m	0.75	55	T_A^*	(2)
NGC 253	50.0 ± 2.8	210 ± 12	72, 136	IRAM 30 m	0.64	25	T_{mb}	(4)
NGC 613	<0.24	<6.5	...	SEST 15 m	0.75	55	T_A^*	(2)
NGC 1056	<0.17	<1.1	...	IRAM 30 m	0.80	28	T_A^*	(2)
NGC 1068	3.2 ± 0.5	65 ± 10	260	SEST 15 m	0.75	55	T_{mb}	(5)
NGC 1068	11.4 ± 0.7	48 ± 3	232	IRAM 30 m	0.64	25	T_{mb}	(4)
NGC 1365	4.7 ± 0.6	96 ± 12	150	SEST 15 m	0.75	55	T_{mb}	(5)
NGC 1377	<0.15	<0.99	...	IRAM 30 m	0.80	28	T_A^*	(2)
NGC 1614	<0.38	<10	...	SEST 15 m	0.75	55	T_A^*	(2)
NGC 1808	1.2 ± 0.1	33 ± 3	300	SEST 15 m	0.75	55	T_A^*	(1)
NGC 2146	1.6 ± 0.3	6.7 ± 1.3	237	IRAM 30 m	0.64	25	T_{mb}	(4)
NGC 2623	0.6 ± 0.15	12 ± 3	500-600	OSO 20 m	0.59	42	T_A^*	(1)
NGC 3079	2.9 ± 0.5	15 ± 3	380	IRAM 30 m	0.80	28	T_{mb}	(5)
NGC 3079	6.9 ± 1.0	29 ± 4	545	IRAM 30 m	0.64	25	T_{mb}	(4)
NGC 3256	0.6 ± 0.05	16 ± 1	250	SEST 15 m	0.75	55	T_A^*	(1)
NGC 3690	...	...	...	...	...	...	...	N/A ^b
NGC 4418	1.24 ± 0.12	7.9 ± 0.8	156	IRAM 30 m	0.77	27	T_A^*	(6)
NGC 4945	8.6 ± 0.2	230 ± 5	290	SEST 15 m	0.75	55	T_A^*	(2)
NGC 5135	<0.13	<3.5	...	SEST 15 m	0.75	55	T_A^*	(2)
NGC 6946	4.0 ± 0.3	17 ± 1	138	IRAM 30 m	0.64	25	T_{mb}	(4)
NGC 7130	0.4 ± 0.05	11 ± 1	...	SEST 15 m	0.75	55	T_A^*	(1)
UGC 5101	1.24 ± 0.1	8.2 ± 0.7	500	IRAM 30 m	0.80	28	T_A^*	(2)

References. (1) Aalto et al. (2002); (2) This work; (3) Henkel et al. (1988); (4) Hüttemeister et al. (1995); (5) Pérez-Beaupuits et al. (2007); (6) Aalto et al. (2007).

Notes. ^(a) The temperature scale of the integrated intensities are given in the T scale column. Upper limits are 2σ calculated from the rms of the noise surrounding the line for our data. For our data, errors are given in 1σ and calculated from the rms. Since many articles lack information about sizes of errors and methods used when calculating the errors, most errors are given as printed in the respective article. However, if the size of the error is clearly written, it has been recalculated to 1σ . ^(b) No HNC data were found in the literature for this object.

4.1. New detections

This is not only the first text to put together a survey of all extragalactic HC₃N emission line data, but it also reports the first HC₃N detections in six galaxies: Circinus, IC 860, IRAS 17208-0014, Maffei 2, NGC 1068, and NGC 3079. The number of extragalactic sources where HC₃N has been detected is thus almost doubled. Three of the HNC detections are also made in sources without earlier HNC detections: Circinus, IC 860, and IRAS 17208-0014. Finally, the first detection of HCN in NGC 613 is also reported.

4.2. Line ratios

The line ratios have been calculated using the method described in Appendix A, and are shown in Table 7. As already mentioned, the HC₃N/HCN and HC₃N/HNC line ratios of some of the most nearby galaxies will be somewhat overestimated due to their source size being larger than the beam size of the telescope. See Appendix A.1 for a discussion on this subject. The galaxies in our survey that do not fulfil the criterion $\theta_s \lesssim \theta_{\text{mb}}$ are IC 342, M82, Maffei 2, and NGC 253, and we therefore expect the real HC₃N/HCN and HC₃N/HNC ratios to be somewhat lower for these galaxies.

In Table 7, preference has been given to HC₃N 10-9 lines before other HC₃N lines. Only if no 10-9 line is available, another HC₃N line (specified in the footnotes) has been used for the ratios.

A few of the galaxies appear twice in Table 7. For these, several observations have been found for the same transition. As can be seen, the values of these observations do not always agree. If the HC₃N and HNC data are found in the same spectrum in one of the observations, preference has been given to this observation, as it will increase the accuracy on the HC₃N/HNC ratio. In all other cases, the spectrum of each observation has been investigated (when available), and the values from the spectra with the lowest noise levels have been given priority and are put first in Table 7.

4.2.1. HC₃N-luminous galaxies

A definition of an HC₃N-luminous galaxy is now desirable. As HCN is the most common dense gas tracer, and also should be a more stable component of the dense gas than HNC, the HC₃N/HCN ratios were decided to be used for this definition. It seems like most galaxies have HC₃N/HCN ratios below 0.15, with the exception for a few interesting galaxies. Thus, we consider in the rest of the paper that galaxies with $\frac{I(\text{HC}_3\text{N})}{I(\text{HCN})} > 0.15$

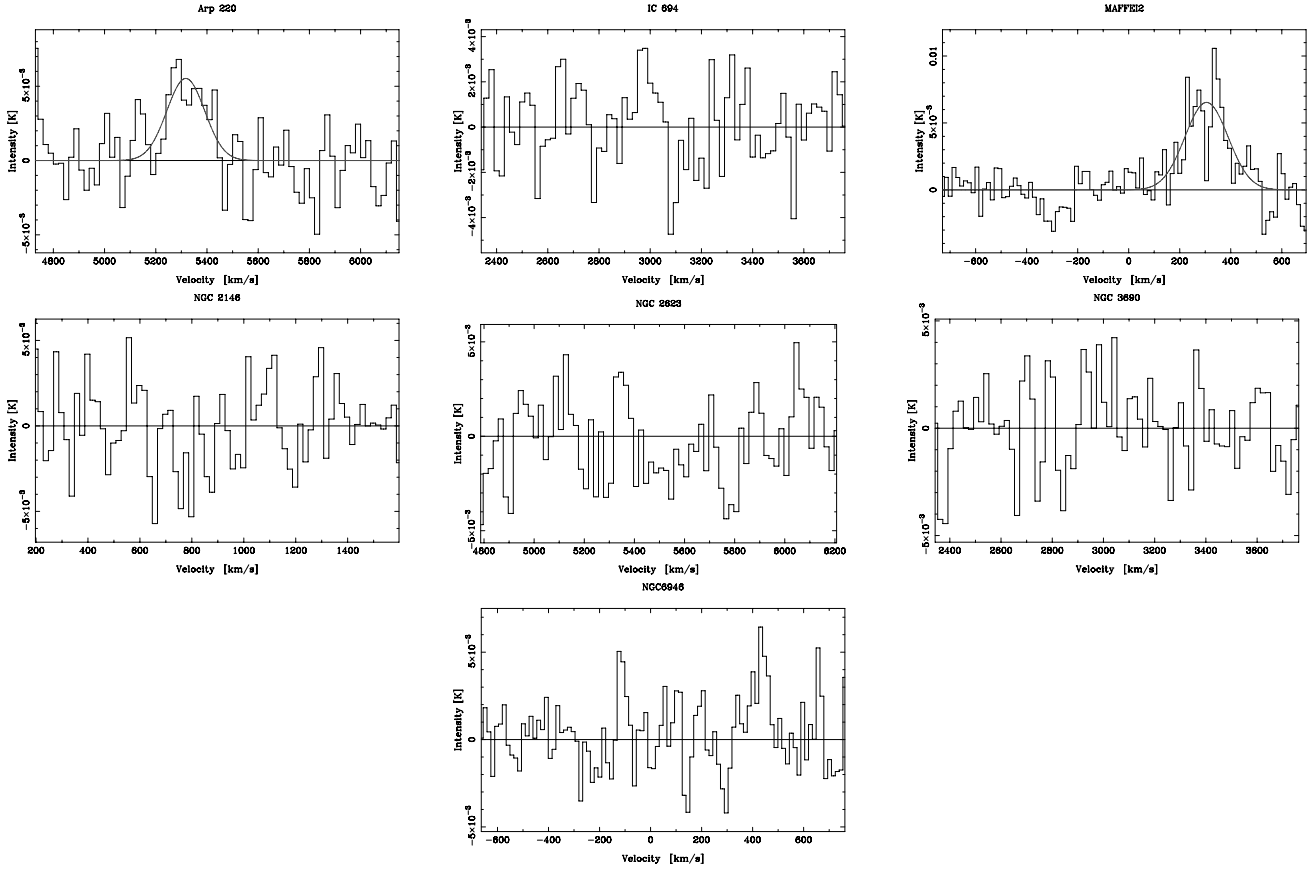


Fig. 2. HC_3N 12-11 spectra for Arp 220 (detection), IC 694 (non-detection), Maffei 2 (detection), NGC 2146, NGC 2623, NGC 3690, and NGC 6946 (non-detections).

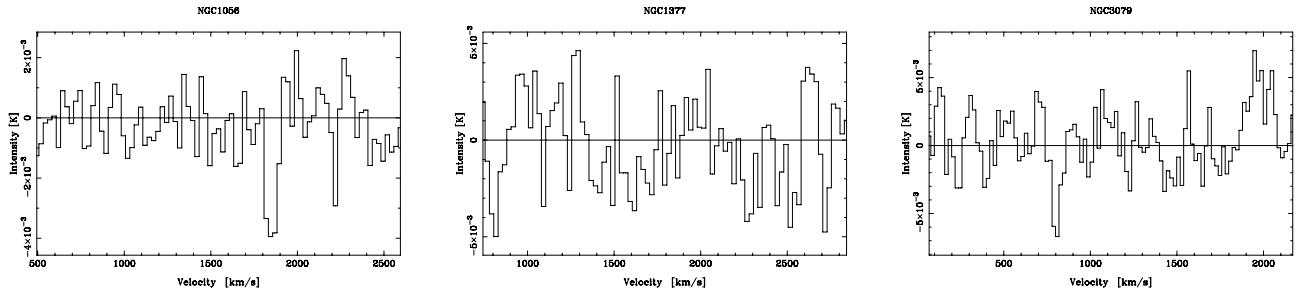


Fig. 3. HC_3N 16-15 spectra for NGC 1056, NGC 1377, and NGC 3079 (non-detections). The absorption-like features in the NGC 1056 spectrum are most likely due to a problem with the backend of the receiver.

are HC_3N -luminous galaxies. If a corresponding limit should be set on the $\text{HC}_3\text{N}/\text{HNC}$ ratio, it would be around 0.25 to include the same galaxies.

The galaxies thus seen as HC_3N -luminous or HC_3N -rich are NGC 4418, IC 342, Circinus, M82, Maffei 2, Arp 220, and IRAS 17208-0014. We also choose to include IC 860, considering that its moderate $\text{HC}_3\text{N}/\text{HNC}$ ratio is for the HC_3N 28-27 transition, as the higher transitions seem to be weaker than the $J = 10-9$ line in most galaxies where more than one line has been observed (when beam effects are compensated for). A few of these galaxies are quite nearby, and as discussed above, the $\text{HC}_3\text{N}/\text{HCN}$ ratio of galaxies with source sizes larger than the telescope beam size will probably be overestimated. This is particularly the case for M82, IC 342, and Maffei 2.

Some galaxies can definitely be seen as HC_3N -poor, since they have $\text{HC}_3\text{N}/\text{HCN}$ ratios (or upper limits for this ratio) less than or equal to 0.10: NGC 253, NGC 1068, NGC 1808,

NGC 3256, NGC 4945, NGC 6946, and UGC 5101. Since NGC 253 also belongs to the nearby galaxies, this value should probably be even lower.

5. Discussion

It is not surprising to find that most galaxies in our sample from published articles show HC_3N detections – otherwise they would not be submitted for publication. However, if only counting the galaxies first investigated by us, there are only 6 HC_3N detections in the 19 galaxies. This sample of galaxies was nevertheless made to find a high number of HC_3N -luminous galaxies. This could mean one of three things:

- Our search-criteria for HC_3N -luminous galaxies are not appropriate.
- The limit for HC_3N -luminous galaxies is set too high to include all “interesting” objects.

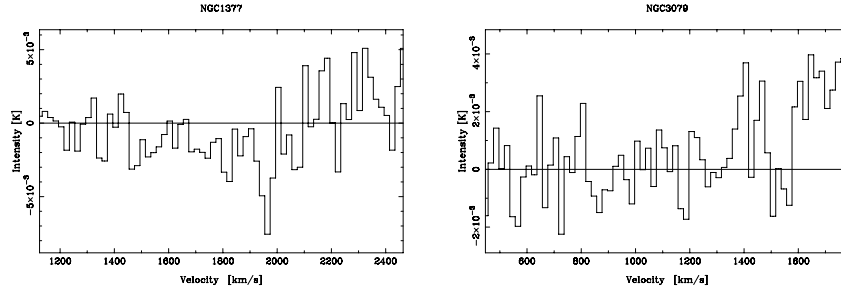


Fig. 4. HC₃N 25-24 spectra for NGC 1377 and NGC 3079 (non-detections).

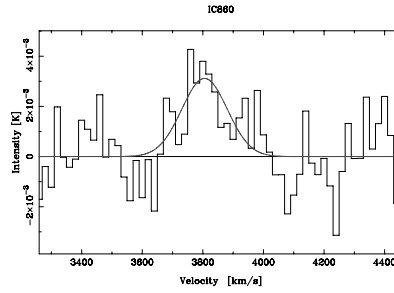


Fig. 5. HC₃N 28-27 spectrum for IC 860 (detection).

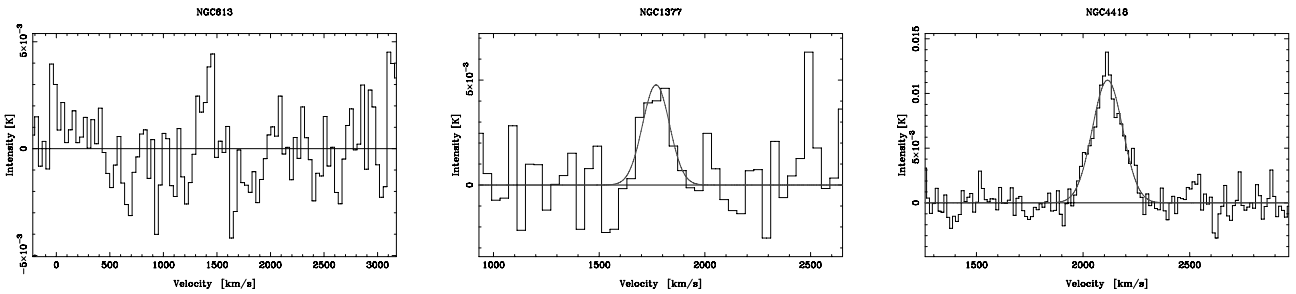


Fig. 6. HCN 1-0 spectra for NGC 613 (non-detection), NGC 1377, and NGC 4418 (detections).

- HC₃N-luminous galaxies are very rare, even among active galaxies.

Several possible correlations between a high HC₃N intensity and other properties of the galaxies have been examined. This will be discussed below.

5.1. In which types of galaxies do we find HC₃N?

If the HC₃N-rich and -poor galaxies are compared with the galaxy classifications of Table 3, the most obvious trend is that most of the HC₃N-poor galaxies are starbursts, with the exception for the LIRG UGC 5101. It is difficult to see any trend for the AGNs due to the low number of such objects in the sample.

When removing the nearby galaxies from the HC₃N-rich category due to their overestimated HC₃N/HCN-ratios mentioned earlier, the common denominator of the remaining galaxies seems to be that their source of activity is unknown or disputed – they are labelled as “obscured” or ULIRGs. Thus, HC₃N might thrive in deeply obscured, shielded regions, where it cannot be destroyed by radiation. In starbursts, it might be destroyed by the strong UV field – or not even created, as C₂H₂ on the grains will photo-dissociate into C₂H (see Sect. 2.1).

5.2. Silicate absorption strength

In Spoon et al. (2002), several absorption features from ice and silicates as well as emission from PAHs in active galaxies are discussed. In Spoon et al. (2007), an evolutionary plot for active galaxies is produced, showing two distinct regions in a plot over the equivalent width of the PAH 6.2 μm emission line versus the strength of the silicate 9.7 μm absorption band. Starburst galaxies tend to have a high PAH equivalent width, Seyfert galaxies have low PAH equivalent width and low silicate absorption strength, while ULIRGs have high silicate absorption strength and often also low PAH equivalent width.

By private communication with H. W. W. Spoon, the numerical values for silicate absorption strength in all the galaxies in his sample were obtained. Most galaxies in our sample are also included in his sample. When comparing these values to our HC₃N/HCN ratios, a tentative pattern seems to appear.

In Fig. 8, the relation between the HC₃N/HCN ratio and the silicate absorption strength is plotted. We note that two of the three nearby galaxies in the sample, M82 and IC 342, are showing too high HC₃N/HCN ratios to fit into the pattern of the figure, which was expected (see Appendix A.1). A correlation seems possible when excluding the nearby M82, NGC 253, and IC 342 (correlation coefficient $r = -0.49$). One explanation to the correlation might be that HC₃N is formed in regions with silicates, where the silicates protect the HC₃N from radiation.

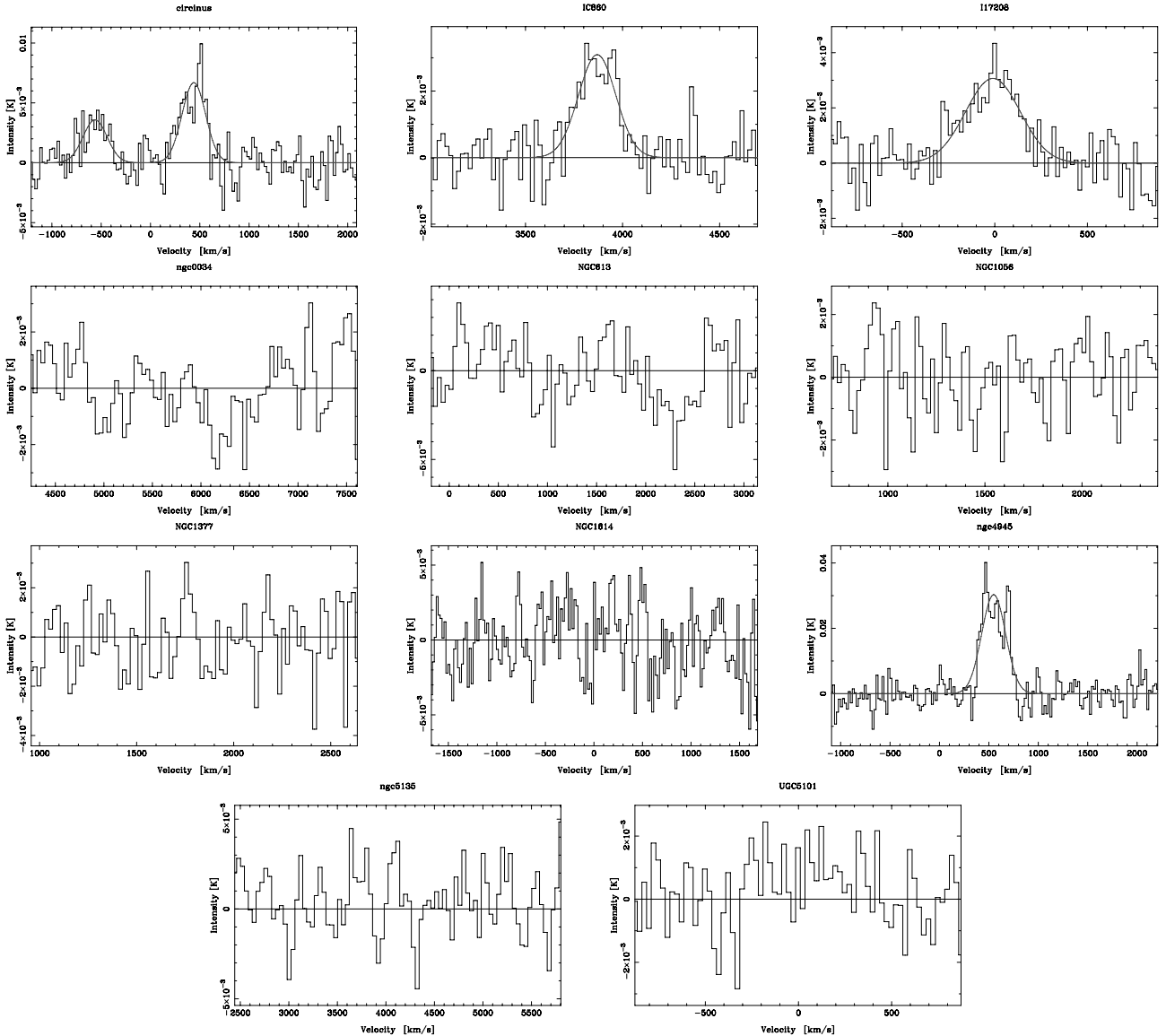


Fig. 7. HNC 1-0 spectra for Circinus, IC 860, IRAS 17208-0014 (detections), NGC 34, NGC 613, NGC 1056, NGC 1377, NGC 1614 (non-detections), NGC 4945 (detection), NGC 5135, and UGC 5101 (non-detections). For Circinus, the HC₃N 10-9 line is also visible. Bandwidths for the spectra of NGC 34, NGC 613, NGC 1614, and NGC 5135 are broad enough to include non-detections of the HC₃N 10-9 line, thus giving upper limits for these lines.

Thus, HC₃N survives better in regions heavily obscured by silicates.

5.3. Megamasers

Neglecting the most nearby galaxies, where the HC₃N/HCN ratios probably are somewhat overestimated, all HC₃N-luminous galaxies have OH mega- or kilomasers (Darling & Giovanelli 2006). A few of the HC₃N-poor galaxies also have OH mega- or kilomaser activity (NGC 253, NGC 1068, and UGC 5101). The concept of defining megamaser strength only from its luminosity is however somewhat misleading. Firstly, a galaxy with much molecular gas is more likely to harbour a strong megamaser than one with little molecular gas – the data in Darling (2007) show a strong correlation between OH megamaser strength and CO and HCN luminosity. Thus, it is more reasonable to normalise the OH megamaser luminosity with some kind of luminosity for

the molecular gas in the galaxy. The CO 1-0 luminosity has been chosen for this, since CO is the primary tracer of molecular gas.

For IC 860, no CO 1-0 luminosity value has been found in the literature, but from an observation performed with the IRAM 30 m telescope by F. Costagliola the luminosity could be calculated from the intensity with the method described in Solomon et al. (1997). The used equation is:

$$L_{\text{CO}} = 23.5 \Omega_{s*b} D_L^2 I_{\text{CO}} (1+z)^{-3} \quad (7)$$

where L_{CO} is the line luminosity in K km s⁻¹ pc², Ω_{s*b} is the solid angle of the source convolved with the telescope beam in arcsec², D_L is the luminosity distance in Mpc, I_{CO} is the main beam intensity of the line in K km s⁻¹, and z is the redshift of the source. The intensity 9.83 K km s⁻¹, the beam width 22'', and the distance 59.1 Mpc gives a luminosity of 3.07×10^8 K km s⁻¹ pc², assuming that the source size is much smaller than the beam size, which is valid for IC 860.

Table 7. Calculated line ratios.

Galaxy	$\frac{I(\text{HC}_3\text{N})}{I(\text{HCN } 1-0)}$	$\frac{I(\text{HC}_3\text{N})}{I(\text{HNC } 1-0)}$	$\frac{I(\text{HNC } 1-0)}{I(\text{HCN } 1-0)}$
Arp 220	0.19 ± 0.07 ^a	0.42 ± 0.2 ^a	0.45 ± 0.1
Arp 220	0.78 ± 0.06 ^b	1.73 ± 0.4 ^b	0.45 ± 0.1
Circinus	0.24 ± 0.04	0.51 ± 0.06	0.48 ± 0.08
IC 342	0.28 ± 0.08	0.28 ± 0.08	1.00 ± 0.1
IC 694	<0.61 ^c	<0.34 ^c	1.79 ± 0.5
IC 860	...	0.11 ± 0.02 ^d	...
I17208	0.16 ± 0.02 ^e	0.30 ± 0.03	0.53 ± 0.05 ^e
I17208	0.062 ± 0.01 ^f	0.30 ± 0.03	0.21 ± 0.05 ^f
M82	0.21 ± 0.02 ^c	0.96 ± 0.1 ^c	0.22 ± 0.02
Maffei 2	0.20 ± 0.02 ^c	0.25 ± 0.03 ^c	0.81 ± 0.1
NGC 34	<0.35	...	<0.34
NGC 253	0.094 ± 0.01	0.15 ± 0.02	0.63 ± 0.04
NGC 613	<0.46	...	<0.44
NGC 1056	...	...	...
NGC 1068	0.072 ± 0.06	0.15 ± 0.15 ^g	0.45 ± 0.19 ^g
NGC 1365	<0.13	<0.17	0.74 ± 0.20
NGC 1377	<0.26 ^b	...	<0.32
NGC 1614	<0.25	...	<0.24
NGC 1808	0.05 ± 0.025	0.18 ± 0.09	0.29 ± 0.02
NGC 2146	<0.20	<0.85	0.26 ± 0.06
NGC 2623	...	<0.70 ^c	...
NGC 3079	0.13 ± 0.02 ⁱ	0.26 ± 0.05 ⁱ	0.51 ± 0.11 ⁱ
NGC 3256	<0.065	<0.20	0.32 ± 0.04
NGC 3690	<0.39 ^c	...	...
NGC 4418	0.40 ± 0.04	0.65 ± 0.09	0.61 ± 0.06
NGC 4945	0.09 ± 0.01	0.17 ± 0.02	0.51 ± 0.02
NGC 5135	<0.26	...	<0.25
NGC 6946	<0.073 ^c	<0.10 ^c	0.71 ± 0.1
NGC 7130	<0.18	<0.25	0.71 ± 0.1
UGC 5101	<0.084	<0.09	0.91 ± 0.1

Notes. The HC₃N line used is the 10–9 line, whenever it is available. If another line is used, this is stated below. The errors are 1σ and have been calculated by error propagation from the errors given in Tables 4–6. ^(a) HC₃N value from Aalto et al. (2002) used. ^(b) HC₃N value from this work used. ^(c) HC₃N 12–11 line. ^(d) HC₃N 28–27 line. ^(e) HCN value from Graciá-Carpio et al. (2008) used. ^(f) HCN value from Gao & Solomon (2004) used. ^(g) HNC value from Pérez-Beaupuits et al. (2007) used. ^(h) HC₃N 16–15 line. ⁽ⁱ⁾ HCN and HNC values from Pérez-Beaupuits et al. (2007) used.

In Table 8, the OH megamaser luminosity is compared with the CO luminosity. The data in this table is also shown in the form of a histogram in Fig. 9. The non-detections of OH megamasers and OH absorbers reported in Darling (2007) are also listed, most of them being either HC₃N-poor or without any HC₃N detection (the exceptions are IC 342 and M82, whose HC₃N/HCN ratios probably are overestimated, see Appendix A.1).

It can be seen that the OH megamaser luminosities normalised with the galactic CO luminosities are much higher in the HC₃N-luminous galaxies than in the HC₃N-poor galaxies with an OH megamaser, especially when ignoring the nearby galaxies M82 and IC 342. The average of the OH/CO luminosity ratios is more than 10 times higher in the HC₃N-luminous galaxies than in the HC₃N-poor galaxies. The non-detections (where HC₃N-poor galaxies are overrepresented) are not included in these averages. UGC 5101 is the only HC₃N-poor galaxy with an OH megamaser that is strong compared to the amount of molecular gas in the galaxy. Also without the CO normalisation the trend can be seen clearly.

A possible explanation of the HC₃N correlating with OH megamasers is that the HC₃N is protected against destructive

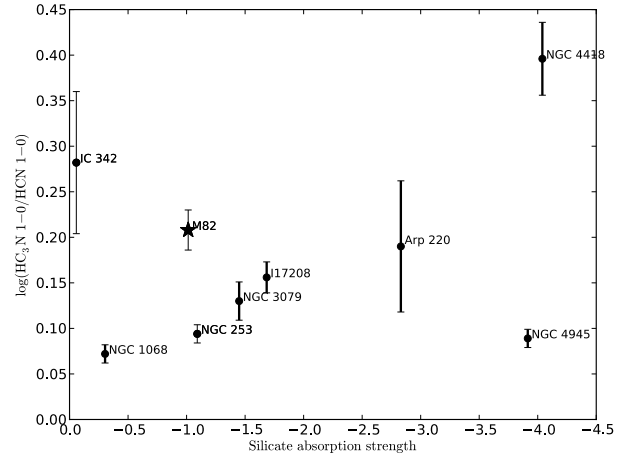


Fig. 8. Tentative correlation between HC₃N/HCN ratio and silicate absorption strength. The HC₃N/HCN values for IC 342, NGC 253, and M82 are probably overestimated (indicated by thinner error bars, see Appendix A.1). The objects for which the HC₃N 12–11 line has been used instead of the HC₃N 10–9 line when calculating the HC₃N/HCN ratio are indicated by a star. The silicate absorption strength is in a magnitude scale: A higher negative number means stronger silicate absorption.

Table 8. OH maser luminosities and CO luminosities for some of the sources in the sample.

Galaxy	log L_{OH} [L_{\odot}]	$L_{\text{CO}1-0}$ [$10^8 \text{ K km s}^{-1} \text{ pc}^2$]	$\frac{L_{\text{OH}}}{L_{\text{CO}1-0}}$ [$\frac{L_{\odot}}{10^8 \text{ K km s}^{-1} \text{ pc}^2}$]
Arp 220	2.58	78.5	4.8
IC 342	None	...	...
IC 694/NGC 3690	1.38	29	0.83
IC 860	0.27 ^a	3.07 ^b	0.61
I17208	3.04	146.9	7.5
M82	-1.7	5.7	0.0035
NGC 253	-1.3	4.6	0.011
NGC 1068	-0.3	20.7	0.024
NGC 1365	None	...	...
NGC 1614	None	...	...
NGC 2146	None	...	...
NGC 3079	Abs.	...	...
NGC 4418	0.04 ^a	1.03 ^c	1.1
NGC 4945	Abs.	...	...
NGC 5135	None	...	...
NGC 7130	None	...	...
UGC 5101	1.61	50.8	0.80

Notes. Data are from Darling (2007) unless stated otherwise below. The note "None" in the L_{OH} column indicates that Darling (2007) has not detected any OH megamaser emission, and "Abs." that an OH absorber is detected. The names of the HC₃N-luminous galaxies are written in bold-face. The HC₃N/HCN values for IC 342 and M82 are probably overestimated (see Appendix A.1). ^(a) From Darling & Giovanelli (2002). ^(b) From observations by F. Costagliola. ^(c) From Albrecht et al. (2007).

UV radiation by the warm dust which is needed to power the megamaser (Darling & Giovanelli 2006). Another possibility is that the HC₃N is pumped by the IR field caused by the warm dust, which also pumps the OH megamaser.

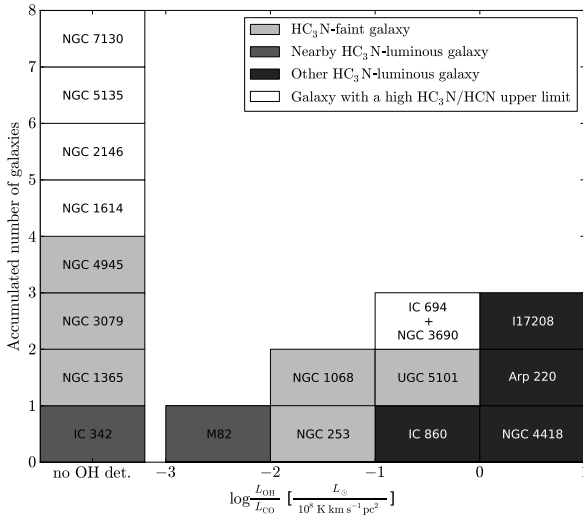


Fig. 9. Histogram over number of galaxies in normalised OH megamaser luminosity. Light-grey corresponds to galaxies considered HC₃N-poor, medium-gray corresponds to nearby HC₃N-luminous galaxies whose HC₃N/HCN ratios probably are overestimated (see Appendix A.1), dark-grey corresponds to all other HC₃N-luminous galaxies, and white corresponds to galaxies where the upper limit on the HC₃N/HCN ratio is too high to tell whether it is HC₃N-luminous or not. The galaxies for which OH maser emission is non-detected in Darling & Giovanelli (2002) and/or Darling (2007) are stacked in the leftmost column of the histogram.

5.4. IR flux density ratios

In several of the HC₃N rich galaxies, rotational-vibrational HC₃N lines have been detected (Costagliola & Aalto 2010; Martín et al. 2011; Costagliola et al. 2011). This suggests that IR pumping of the emission is present in these galaxies, which in turn indicates a warmer spectral energy distribution (SED) in these sources. We have thus compared the HC₃N/HCN ratios with the IRAS 60 μ m/100 μ m flux density ratios, but no linear correlation could be found. However, when plotting the data as a histogram (Fig. 10), we see a trend towards HC₃N-luminous galaxies having higher IRAS 60 μ m/100 μ m ratios, corresponding to warmer SEDs. NGC 4418, the object with the highest HC₃N/HCN ratio in the sample is also the galaxy with the highest IRAS 60 μ m/100 μ m ratio.

It should however be mentioned that the global 60 μ m/100 μ m flux density ratios might not be completely relevant, since they may tell more about the temperature on the extended dust distribution (and/or foreground dust) than the dust temperature in the nucleus, where the pumping likely occurs.

5.5. C II flux

Many of the objects with high HC₃N/HCN ratios also have low C II/FIR flux ratios. This can be explained by that the C⁺ ions are able to destroy HC₃N through reactions 5 and 6 in Sect. 2.2. We have searched in the literature for available C II fluxes of the objects, which were found for more than half of the objects in our sample. With the limited amount of data, no linear correlation could be established. Instead, we display the data in the form of a histogram in Fig. 11, where we clearly see that a majority of the HC₃N-rich galaxies are very poor in C II flux. We also see that the nearby galaxies for which the high HC₃N/HCN ratio

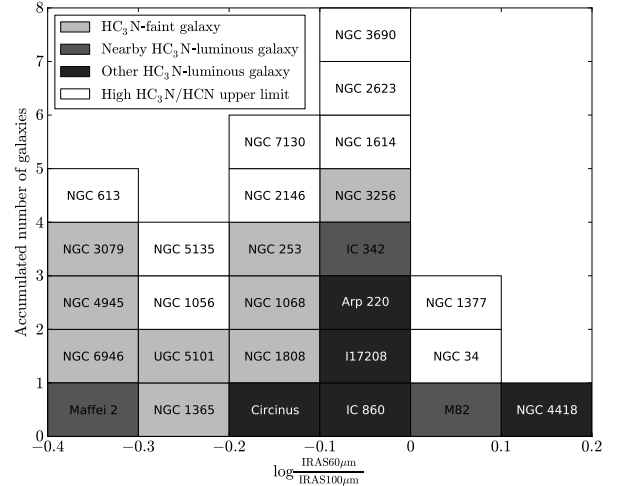


Fig. 10. Histogram over number of galaxies in IRAS 60 μ m/100 μ m flux density ratio. Light-grey corresponds to galaxies considered HC₃N-poor, medium-gray corresponds to nearby HC₃N-luminous galaxies whose HC₃N/HCN ratios probably are overestimated (see Appendix A.1), dark-grey corresponds to all other HC₃N-luminous galaxies, and white corresponds to galaxies where the upper limit on the HC₃N/HCN ratio is too high to tell whether it is HC₃N-luminous or not. IRAS 60 μ m/100 μ m flux density values are all from Sanders et al. (2003), except for Circinus and Maffei 2, which are from Beichman et al. (1988).

we expected to be an over-estimation due to beam effects (see Appendix A.1) all belong to the C II rich part of the histogram. Also in this case, NGC 4418 is the most extreme galaxy, with the lowest upper limit on the C II/FIR flux ratio.

5.6. HNC/HCN

The HNC/HCN 1-0 ratio is an indicator of the physical and chemical conditions in the dense molecular gas. Overluminous HNC is a sign of XDR chemistry (Aalto 2008), while a low HNC/HCN ratio indicates shocks (Schilke et al. 1992). As is seen in Fig. 12, we find a correlation between the HC₃N/HCN and HNC/HCN 1-0 line ratios. The HC₃N/HCN ratios of M82, Maffei 2, IC 342, and NGC 253 are probably overestimated (see Appendix A.1), and the correlation coefficient is $r = 0.65$ when these four objects are excluded. This correlation will be further discussed in Costagliola et al. (2011).

Attempts were also made trying to find a correlation between the HC₃N ratios and ratios of higher HNC and HCN transitions, e.g. the HNC/HCN 3-2 ratio. However, too few HNC 3-2 and HCN 3-2 spectra for the galaxies in the sample are available in the literature – with only five data points no conclusions can be drawn. It was although noticed that the HCN 3-2 and HNC 3-2 intensities seem to be very uncertain, at least for Arp 220 and NGC 4418. Shortly, it seems like the different instruments used for the observations affect the measured value to a non-negligible extent. This is further discussed in Lindberg (2009).

We were not able to reproduce the weak correlation between the HNC/HCN 1-0 ratio and the FIR luminosity described in Aalto et al. (2002).

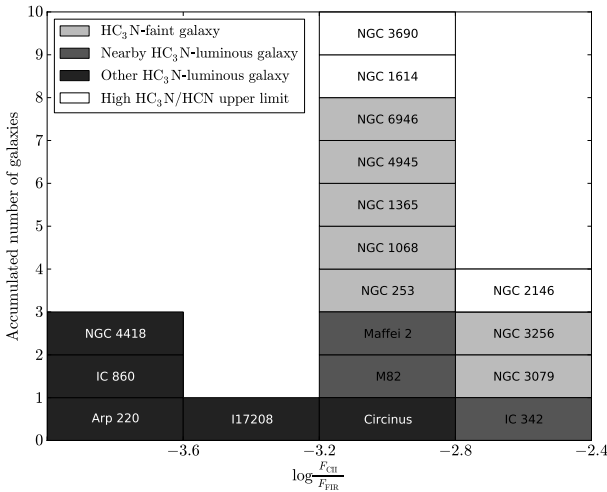


Fig. 11. Histogram over number of galaxies in C II flux normalised by FIR flux. Light-grey corresponds to galaxies considered HC₃N-poor, medium-gray corresponds to nearby HC₃N-luminous galaxies whose HC₃N/HCN ratios probably are overestimated (see Appendix A.1), dark-grey corresponds to all other HC₃N-luminous galaxies, and white corresponds to galaxies where the upper limit on the HC₃N/HCN ratio is too high to tell whether it is HC₃N-luminous or not. FIR fluxes were calculated from IRAS 60 μ m and 100 μ m fluxes with the method described in Bizyaev (2001). The references for the used IRAS fluxes are given in the caption of Fig. 10. C II flux values are from Negishi et al. (2001), except for IC 342 and NGC 3079 (Stacey et al. 1991); IC 860 and NGC 4418 (Malhotra et al. 2001); Arp 220 (Luhman et al. 2003); and NGC 1614 (Brauer et al. 2009).

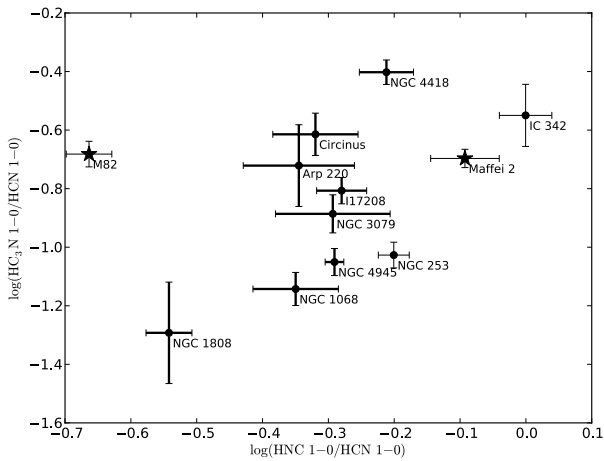


Fig. 12. log-log plot of the HC₃N/HCN line ratio versus the HNC/HCN line ratio. The HC₃N/HCN values for IC 342, Maffei 2, M82, and NGC 253 are probably overestimated (indicated by thin error bars, see Appendix A.1). The objects for which the HC₃N 12-11 line has been used instead of the HC₃N 10-9 line when calculating the HC₃N/HCN ratio are indicated by a star.

5.7. Future observational tests

We have found a strong trend between the HC₃N/HCN ratio and OH megamaser activity (see Sect. 5.3). By studying different excitation levels of HC₃N in these and other OH megamaser galaxies, the cause of this correlation can be investigated. If HC₃N is pumped, higher transitions, including vibrational transitions,

should be found. This has already been detected in NGC 4418 (Costagliola & Aalto 2010).

To better establish the importance of HC₃N as an indicator of activity in certain galaxies, it is important to do further line surveys of HC₃N, HCN, and HNC, as well as other molecules who trace the properties of the molecular gas, such as HCO⁺ and C₂H. Such a line survey could also test our weak correlation between the HC₃N/HCN and HNC/HCN line ratios, and perhaps finding other correlations which would enable a better understanding of the chemistry in obscured and active galaxies. A new line survey was made with the new EMIR receiver at the IRAM 30 m telescope in June 2009, and the results from this survey will be published in Costagliola et al. (2011). The sample in this survey has been chosen to get more HC₃N data on sources in Spoon’s sample to test the possible correlations between the HC₃N/HCN ratio and PAH equivalent width and/or silicate absorption strength. The bandwidth of the EMIR receiver allows for several spectral lines being observed in the same spectrum, and thus many different molecular species can be observed at the same time.

It might also be interesting to search for other long-carbon-chain molecules in the HC₃N-luminous galaxies, e.g. HC₅N, C₂H, C₄H, C₃H₂, and C₄H₂, which have all been found in star-forming regions in the Galaxy (Sakai et al. 2008, 2009).

Finally, we suggest mapping of HC₃N, C₂H, HCN, and HNC in a larger number of galaxies, especially in the HC₃N-luminous galaxies, to compare the results with the maps of IC 342 in Meier & Turner (2005). The HC₃N absorption lines detected in a $z \sim 0.89$ galaxy in front of PKS 1830-211 (Henkel et al. 2009) indicate that HC₃N is not only present in the core of a galaxy, but may also be present in the disc.

6. Conclusions

We have presented the first survey of HC₃N observations in extragalactic objects. The main conclusions from this survey are as follows:

1. Bright HC₃N emission is rather uncommon in galaxies. It was only detected in 6 of the 19 galaxies which had not been investigated before, even though that sample was selected to find many HC₃N-luminous galaxies.
2. Most HC₃N-luminous galaxies are obscured galaxies. Starburst galaxies seem to be poor in HC₃N. There are too few AGN galaxies in the sample to tell if these normally are rich or poor in HC₃N.
3. A weak correlation can be seen between the HC₃N/HCN ratio and silicate 9.7 μ m absorption strength.
4. There is a strong correlation between OH megamaser activity and HC₃N luminosity. Most HC₃N-luminous galaxies have an OH megamaser. This could be related to a high dust obscuration in the HC₃N-luminous galaxies.
5. There is a connection between the HC₃N/HCN ratio and the IRAS 60 μ m/100 μ m flux density ratios, indicating a higher dust temperature in these galaxies, which could cause vibrational excitation of the HC₃N molecule.
6. There is a strong connection between a high HC₃N/HCN ratio and a low C II/FIR flux ratio in the studied objects. This could be explained by C⁺ ions being required to destroy the HC₃N molecule.
7. There is a correlation between the HC₃N/HCN and HNC/HCN line ratios.

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References

- Aalto, S. 2008, *Ap&SS*, 313, 273
- Aalto, S., Booth, R. S., Black, J. H., Koribalski, B., & Wielebinski, R. 1994, *A&A*, 286, 365
- Aalto, S., Booth, R. S., Black, J. H., & Johansson, L. E. B. 1995, *A&A*, 300, 369
- Aalto, S., Radford, S. J. E., Scoville, N. Z., & Sargent, A. I. 1997, *ApJ*, 475, L107
- Aalto, S., Polatidis, A. G., Hüttemeister, S., & Curran, S. J. 2002, *A&A*, 381, 783
- Aalto, S., Monje, R., & Martín, S. 2007, *A&A*, 475, 479
- Albrecht, M., Krügel, E., & Chini, R. 2007, *A&A*, 462, 575
- Baan, W. A., Henkel, C., Loenen, A. F., Baudry, A., & Wiklund, T. 2008, *A&A*, 477, 747
- Bajaja, E., Wielebinski, R., Reuter, H.-P., Harnett, J. I., & Hummel, E. 1995, *A&AS*, 114, 147
- Beichman, C. A., Neugebauer, G., Habing, H. J., Clegg, P. E., & Chester, T. J., 1988, *Infrared astronomical satellite (IRAS) catalogs and atlases*, Explanatory supplement, 1
- Bizyaev, D. 2001, *Ap&SS*, 276, 775
- Bohme, D. K., & Raksit, A. B. 1985, *MNRAS*, 213, 717
- Brauhar, J. R., Dale, D. A., & Helou, G. 2009, *VizieR Online Data Catalog*, 217, 80280
- Bryant, P. M., & Scoville, N. Z. 1999, *AJ*, 117, 2632
- Casoli, F., Dupraz, C., & Combes, F. 1992, *A&A*, 264, 49
- Chapman, J. F., Millar, T. J., Wardle, M., Burton, M. G., & Walsh, A. J. 2009, *MNRAS*, 394, 221
- Cherchneff, I., Glassgold, A. E., & Mamon, G. A. 1993, *ApJ*, 410, 188
- Costagliola, F., & Aalto, S. 2010, *A&A*, 515, A71
- Costagliola, F., Aalto, S., Rodriguez, M. I., et al. 2011, *A&A*, in press
- Curran, S. J., Aalto, S., & Booth, R. S. 2000, *A&AS*, 141, 193
- Curran, S. J., Johansson, L. E. B., Bergman, P., Heikkilä, A., & Aalto, S. 2001a, *A&A*, 367, 457
- Curran, S. J., Polatidis, A. G., Aalto, S., & Booth, R. S. 2001b, *A&A*, 373, 459
- Dale, D. A., Sheth, K., Helou, G., Regan, M. W., & Hüttemeister, S. 2005, *AJ*, 129, 2197
- Darling, J. 2007, *ApJ*, 669, L9
- Darling, J., & Giovanelli, R. 2002, *AJ*, 124, 100
- Darling, J., & Giovanelli, R. 2006, *AJ*, 132, 2596
- de Vicente, P., Martín-Pintado, J., Neri, R., & Colom, P. 2000, *A&A*, 361, 1058
- Fukuzawa, K., & Osamura, Y. 1997, *ApJ*, 489, 113
- Gao, Y., & Solomon, P. M. 2004, *ApJS*, 152, 63
- Graciá-Carpio, J., García-Burillo, S., Planesas, P., & Colina, L. 2006, *ApJ*, 640, L135
- Graciá-Carpio, J., García-Burillo, S., Planesas, P., Fuente, A., & Usero, A. 2008, *A&A*, 479, 703
- Heikkilä, A., Johansson, L. E. B., & Olofsson, H. 1999, *A&A*, 344, 817
- Henkel, C., Schilke, P., & Mauersberger, R. 1988, *A&A*, 201, L23
- Henkel, C., Menten, K. M., Murphy, M. T., et al. 2009, *A&A*, 500, 725
- Hüttemeister, S., Henkel, C., Mauersberger, R., et al. 1995, *A&A*, 295, 571
- Imanishi, M., Nakanishi, K., Kuno, N., & Kohno, K. 2004, *AJ*, 128, 2037
- Irvine, W. M., Goldsmith, P. F., & Hjalmarsen, Å. 1987, in *Interstellar Processes*, ed. D. J. Hollenbach & H. A. Thronson, Jr., *Astrophys. Space Sci. Libr.*, 134, 561
- Knudsen, K. K., Walter, F., Weiss, A., et al. 2007, *ApJ*, 666, 156
- Koda, J., Sofue, Y., Kohno, K., et al. 2002, *ApJ*, 573, 105
- Kohno, K., Matsushita, S., Vila-Vilaró, B., et al. 2001, in *The Central Kiloparsec of Starbursts and AGN: The La Palma Connection*, ed. J. H. Knapen, J. E. Beckman, I. Shlosman, & T. J. Mahoney, *ASP Conf. Ser.*, 249, 672
- Krips, M., Neri, R., García-Burillo, S., et al. 2008, *ApJ*, 677, 262
- Lepp, S., & Dalgarno, A. 1996, *A&A*, 306, L21
- Lindberg, J. 2009, Master's thesis, Chalmers Univ. Technol., Göteborg
- Luhman, M. L., Satyapal, S., Fischer, J., et al. 2003, *ApJ*, 594, 758
- Malhotra, S., Kaufman, M. J., Hollenbach, D., et al. 2001, *ApJ*, 561, 766
- Maloney, P. R., Hollenbach, D. J., & Tielens, A. G. G. M. 1996, *ApJ*, 466, 561
- Martín, S., Krips, M., Martín-Pintado, J., et al. 2011, *A&A*, 527, A36
- Martín, S., Mauersberger, R., Martín-Pintado, J., Henkel, C., & García-Burillo, S. 2006, *ApJS*, 164, 450
- Mauersberger, R., Henkel, C., & Sage, L. J. 1990, *A&A*, 236, 63
- Meier, D. S., & Turner, J. L. 2005, *ApJ*, 618, 259
- Meijerink, R., & Spaans, M. 2005, *A&A*, 436, 397
- Meijerink, R., Spaans, M., & Israel, F. P. 2007, *A&A*, 461, 793
- NED. 2009, *NASA Extragalactic Database*
- Negishi, T., Onaka, T., Chan, K., & Roellig, T. L. 2001, *A&A*, 375, 566
- Nguyen-Q-Rieu, Nakai, N., & Jackson, J. M. 1989, *A&A*, 220, 57
- Nguyen-Rieu, Viallefond, F., Combes, F., et al. 1994, in *Astronomy with Millimeter and Submillimeter Wave Interferometry*, ed. M. Ishiguro & J. Welch, *ASP Conf. Ser.*, 59, IAU Colloq. 140, 336
- Papadopoulos, P. P. 2007, *ApJ*, 656, 792
- Pérez-Beaupuits, J. P., Aalto, S., & Gerebro, H. 2007, *A&A*, 476, 177
- Prasad, S. S., & Huntress, Jr., W. T. 1980, *ApJ*, 239, 151
- Regan, M. W., Sheth, K., & Vogel, S. N. 1999, *ApJ*, 526, 97
- Rodriguez-Franco, A., Martín-Pintado, J., & Fuente, A. 1998, *A&A*, 329, 1097
- Sakai, N., Sakai, T., Hirota, T., & Yamamoto, S. 2008, *ApJ*, 672, 371
- Sakai, N., Sakai, T., Hirota, T., Burton, M., & Yamamoto, S. 2009, *ApJ*, 697, 769
- Sanders, D. B., Mazzarella, J. M., Kim, D.-C., Surace, J. A., & Soifer, B. T. 2003, *AJ*, 126, 1607
- Schilke, P., Walmsley, C. M., Pineau Des Forets, G., et al. 1992, *A&A*, 256, 595
- Solomon, P. M., Downes, D., Radford, S. J. E., & Barrett, J. W. 1997, *ApJ*, 478, 144
- Sorai, K., Nakai, N., Kuno, N., & Nishiyama, K. 2002, *PASJ*, 54, 179
- Spoon, H. W. W., Keane, J. V., Tielens, A. G. G. M., et al. 2002, *A&A*, 385, 1022
- Spoon, H. W. W., Marshall, J. A., Houck, J. R., et al. 2007, *ApJ*, 654, L49
- Stacey, G. J., Geis, N., Genzel, R., et al. 1991, *ApJ*, 373, 423
- Szczepanski, J., Wang, H., Doughty, B., Cole, J., & Vala, M. 2005, *ApJ*, 626, L69
- Tielens, A. G. G. M., & Hollenbach, D. 1985, *ApJ*, 291, 722
- Wang, M., Henkel, C., Chin, Y.-N., et al. 2004, *A&A*, 422, 883

Appendix A: Line ratios and source sizes

We have calculated the line ratios between the observed HC₃N, HCN, and HNC lines, and the used method will be demonstrated in this appendix. The method accounts for beam size/source size effects, using the following formula for a line ratio between the spectral lines A and B:

$$\frac{I(A)}{I(B)} = \frac{\theta_{\text{mbA}}^2 + \theta_s^2}{\theta_{\text{mbB}}^2 + \theta_s^2} \frac{\eta_{\text{mbB}}}{\eta_{\text{mbA}}} \frac{\int T_{AA}^* dv}{\int T_{AB}^* dv}, \quad (\text{A.1})$$

where θ_{mb} is the main beam half-power beam width (or main beam size) of the telescope, η_{mb} is the main beam efficiency of the telescope, θ_s is the source size of the observed object, and $\int T_A^* dv$ is the integrated intensity of the signal. The temperature can also be given in T_{mb} scale – in this case, the main beam efficiency corresponding to that observation should be omitted since $T_{\text{mb}} = \frac{T_A^*}{\eta_{\text{mb}}}$.

Some of the galaxies have very large angular distributions. The measured intensities might in these few cases not represent a global value for molecular gas in the galaxy, but rather a value for a certain (central) region of the galaxy. This will be discussed in Sect. A.1. If the different observations for the same galaxy are made in different parts of the galaxies the line ratios might be misleading. The exact positions of observation are given in most of the references, and these have been compared. The largest difference in position between two observations in the same galaxy is for IC 342, which has a 3'' difference between the HCN observation in Sorai et al. (2002) and the HNC and HC₃N observations in Henkel et al. (1988). Compared to the sizes of HNC and HC₃N distribution (Meier & Turner 2005) as well as the used beam sizes (19'' and 25''), this offset is although rather small. For all other galaxies, the position difference is at most 1''.

Another issue is that two molecules compared in a line ratio might not have the same spatial distributions, and too narrow a beam might exclude more flux from one molecule than from the other. The problem gets even greater if the two molecular lines are observed with two different beam sizes. The problem mainly affect the most nearby galaxies in the sample, whose source sizes are comparable with the used beam sizes.

The size of the dense molecular region is also important when converting from measured temperature to brightness temperature, and as a consequence of this also when computing the line ratios between two transitions in a galaxy when different telescopes have been used. When available, the source size has been estimated from tables or maps showing the HCN source size, thus assuming that the HCN source size is similar to the source sizes of the other molecules used in the line ratio calculations (HNC and HC₃N) as all these lines are expected to be present only in the dense molecular regions (Meier & Turner 2005). When an HCN source size has not been found, the source size of the CO emission has been used instead. Preference has then been given to the higher CO transitions, as these are better tracers of dense gas than CO 1-0, which traces much thinner molecular gas, giving too high a value on the source size. The source sizes used in this work are shown in Table 3, and unless no transition is stated, HCN 1-0 should be assumed.

For some of the galaxies no reliable value on the source size (neither HCN nor CO) has been found. This might still not be a problem when calculating the line ratios. In Sect. A.2 it will be shown that the error when assuming a point source is less than 5% for objects more distant than 45 Mpc, and less than 10% for objects more distant than 30 Mpc. These errors are calculated for a line ratio made with the most different beam sizes used in this

work. When the beam sizes of the telescopes used for the observations are (almost) the same, the source sizes will just cancel. In any case, this error should be smaller than errors introduced by the use of so many different telescopes and instruments.

A.1. Nearby galaxies

As mentioned above, some of the most nearby galaxies have source sizes larger than the beam size of the telescope used for the observation. When calculating molecular line ratios, this might pose a problem. Only if we expect the distributions of the two molecules to have the same shape and size, and the observations are made with the same beam sizes, we will achieve the same ratio as for a global measurement on the galaxy. In particular, we expect the HC₃N to be concentrated in a smaller region of the galaxy than HCN and HNC (Meier & Turner 2005), which makes the calculations of these ratios depend on the beam size to be large enough to cover the whole dense molecular region of the galaxy (e.g. the whole HCN region).

If the beam size is smaller than the HCN (or HNC) emitting region, but larger than the HC₃N region, the HC₃N/HCN (or HC₃N/HNC) ratio will be overestimated, as all HC₃N will be seen, but not all HCN (or HNC). However, if the opposite would be true, the HC₃N/HCN and HC₃N/HNC instead would be underestimated. But since HCN and HNC are more abundant than HC₃N in all studied sources, this seems very unlikely.

Not knowing the HC₃N source size will also affect the line ratios from the more distant galaxies to some extent, since the source size used for the line ratio calculations is an HCN source size (in a few cases even a CO source size) also for the HC₃N intensities. However, assuming the proportion between the HCN and HC₃N source sizes to be similar for all galaxies, this will affect all line ratios in the same way, thus making all line ratios a little bit too high.

Another problem for the line ratios of the nearby galaxies is that the two different observations used to calculate a line ratio sometimes are made with different beam sizes. When comparing HCN 1-0, HNC 1-0, and HC₃N 10-9 observations made with the same telescopes the difference in source size is negligible, but if a line ratio is calculated from observations from two different telescopes the two molecular intensities are observed towards regions with different sizes. For distant galaxies this is not a problem, since the whole molecular region of the galaxy is unresolved in any beam. For the more nearby galaxies, one of the molecules might be observed more or less globally in the galaxy, while the other is observed very locally in the galactic centre, giving an erroneous line ratio. The galaxies affected by this issue should be the same as those affected by the previously mentioned beam size issue.

A.2. Unknown source sizes

The source sizes used in this study are found in Table 3. However, for some sources no reliable value for the source size has been found. We will here discuss why this is not always a problem, and estimate sizes of the errors inflicted from not knowing the source size.

As can be seen above, the line ratios depend on the source and beam sizes with the factor $\frac{\theta_{\text{mbA}}^2 + \theta_s^2}{\theta_{\text{mbB}}^2 + \theta_s^2}$. The source size θ_s can be ignored if both beam sizes $\theta_{\text{mbA}}, \theta_{\text{mbB}} \gg \theta_s$. If the beam sizes $\theta_{\text{mbA}} \approx \theta_{\text{mbB}}$, the source size will also cancel. However, if θ_s is comparable to the beam sizes, and θ_{mbA} and θ_{mbB} are non-similar, the source size becomes an important factor.

The error when assuming the source to be point-like, e.g. setting $\theta_s = 0$, will be

$$\frac{\theta_{\text{mbA}}^2 / \theta_{\text{mbB}}^2}{\frac{\theta_{\text{mbA}}^2 + \theta_s^2}{\theta_{\text{mbB}}^2 + \theta_s^2}}. \quad (\text{A.2})$$

For the sources where an HCN source size has been used, the corresponding source diameter has never exceeded 1.6 kpc (NGC 2146). For the CO source sizes, the largest is found in NGC 5135, with a source diameter of 4.1 kpc in CO 1-0, but the HCN source sizes should be smaller than this.

Assuming no larger HCN source diameter than 1.6 kpc, and the largest and smallest beam sizes at 90 GHz (SEST with 57'' and IRAM with 28''), the error will be less than 5 % for distances greater than 45 Mpc, and less than 10 % for distances greater than 30 Mpc. Thus, even for objects closer than 30 Mpc, the error caused by the point-like approximation ($\theta_s = 0$) is notable only if the θ_{mb} of the two observations used to calculate the ratio have notably different sizes (at least a 30% difference in beam sizes is needed to produce an error of 10 %).