CN and HNC Line Emission in IR Luminous Galaxies

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Abstract

We have observed HNC 1-0, CN 1-0 & 2-1 line emission in a sample of 13 IR luminous (LIRGs, $L_{\rm IR} > 10^{11}$ L$_\odot$) starburst and Seyfert galaxies. HNC 1-0 is detected in 9, CN 1-0 is detected in 10 and CN 2-1 in 7 of the galaxies and all are new detections. We also report the first detection of HC_3N (10-9) emission in Arp 220.

1 Introduction

In order to understand the activities in the centers of luminous galaxies it is essential to also understand the prevailing conditions of the dense gas. The polar molecule HCN is commonly used as a racer of dense molecular gas ($n(H_2) \geq 10^4\,{\rm cm}^{-3}$). In particular in distant luminous ($L_{\rm IR} > 10^{11}$ L$_\odot$, LIRGs) and ultraluminous ($L_{\rm IR} > 10^{12}$ L$_\odot$, ULIRGs) systems the HCN 1–0 line is the prototypical tracer of dense gas content (e.g., Solomon *et al* 1992; Helfer & Blitz 1993; Curran *et al* 2000 (CAB)).

Solomon *et al* (1992) find a tighter correlation between FIR and HCN luminosity than the one found between FIR and CO. They suggest that, in general, the IR luminosities originate from star formation rather than AGN activity in FIR luminous galaxies. The HCN to CO intensity ratio, however, varies substantially ($\frac{1}{3}$ - $\frac{1}{40}$) among luminous galaxies, and it is unclear whether this difference can simply be interpreted as variations in the dense gas content or is also due to abundance and/or excitation effects.

Hence, apart from observing higher transitions of HCN it is important also to study the emission from other high density tracers. One such tracer is the HNC molecule, the isomer of (and chemically linked to) HCN. For example, at high temperatures HNC can be transferred into HCN via the reaction HNC + H $\rightarrow$ HCN + H.

The radical CN is another tracer of dense gas, with a somewhat lower (by a factor of 5) critical density than HCN and is also an excellent tracer of regions affected by UV radiation (Rodriguez-Franco *et al* 1998), thus it can serve as a measure of the relative importance of gas in Photon Dominated Regions (PDRs).

We have searched for HNC and CN emission in a sample of LIRG and ULIRG galaxies with warm ($\frac{f(60\,\mu{\rm m})}{f(100\,\mu{\rm m})} \geq 0.75$) FIR colors. We were interested to see whether the HNC emission would be relatively fainter compared to the cooler, nearby objects studied by Hüttermeister et al (1995). Would HNC be a reliable cold gas tracer, or would we find evidence for the contrary? We furthermore wanted to assess the relative importance of dense PDRs in these objects through comparing the CN line brightness with that of HCN. If indeed the HNC emission is a tracer of the amount of cold, dense gas, then perhaps an anti-correlation between the CN and HNC emission is to be expected. Many of the galaxies in the survey are powered by prodigious rates of star formation and thus a bright CN line relative to that HCN is to be expected. Some of the galaxies are dominated by an AGN where the expected CN brightness may also be high (e.g., Krolik & Kallman 1983).

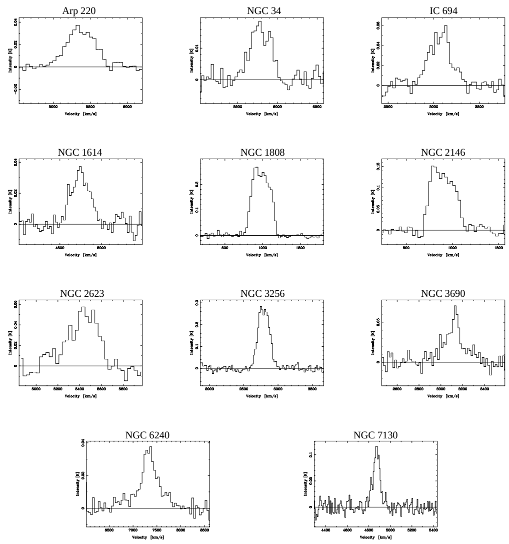

Figure 1a. The HCN spectra

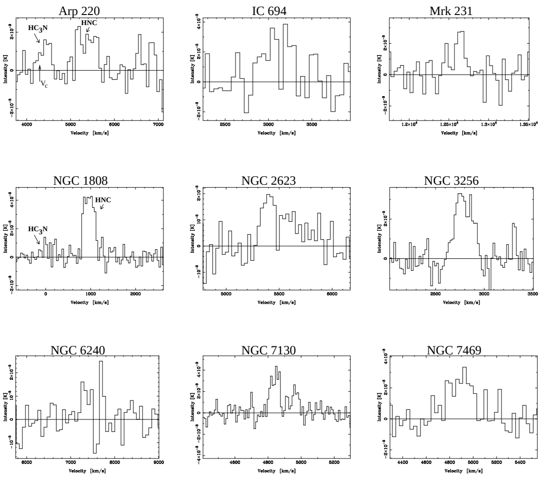

Figure 1b. The HNC spectra

2 Observations

We have used the SEST and OSO 20m to measure the HNC 1-0 (90.663 GHz) and the CN 1-0 113.491 GHz (1-0, J=3/2-1/2, F=5/2-3/2) line intensity in a selection of 13 LIRGs and ULIRGs and in the lower IR luminosity NGC 1808. The selected galaxies all have global $\frac{I(\mathrm{CO})}{I(\mathrm{HCN})}$ 1-0 intensity ratios $\leq$ 15 (apart from NGC 3256 and NGC 1808). For the southern galaxies observed with SEST, we were also able to measure the CN 2-1 line (226.874 GHz (2-1, J=5/2-3/2, F=7/2-5/2), 226.659 GHz (2-1 J=3/2-1/2 F=5/2-3/2)). Furthermore, the CN 1-0 113.191 GHz line (1-0 J=1/2-1/2 F=3/2-3/2) is shifted +806 km s^{-1} from the main line and we have obtained limits to its intensity in several cases. For Arp 220 the two CN 1-0 spingroups are blended because the line is so broad. For four galaxies the bandwidth was wide enough to also include the 90.983 GHz 10-9 line of HC_3N.

Observations were made in 1999 October (HNC, OSO), December (HNC, SEST) and 2000 June (CN, OSO), August (CN, SEST). For OSO, the system temperatures were typically 300 K for HNC. For SEST, typical system temperatures were 230 K for the HNC measurements and 400 K for both the 113 GHz and the 226 GHz CN observations. In Figure 1 we show the spectra of the HNC and the CN(1-0) lines.

3 Results

This survey is the first in its kind for IR luminous galaxies. The main conclusions we draw from this survey are as follows:

1. We have detected HNC 1-0 in 9 of the galaxies, while CN 1-0 is detected in 10 galaxies. The CN 2-1 lines (J=5/2-3/2, F=7/2-5/2; J=3/2-1/2 F=5/2-3/2) (which could only be measured at SEST) are detected in 7 galaxies — in one (NGC 34) the CN 1-0 line was not detected, while the 2-1 line was.

2. The line intensities vary significantly from galaxy to galaxy and the line ratios relative to the "standard" high density tracer, HCN, are far from constant. The $\frac{\mathrm{HCN}}{\mathrm{HNC}}$ ratios vary from 1 to $\geq$ 6 and the $\frac{\mathrm{HCN}}{\mathrm{CN}}$ ratios range from 0.5 to

≥ 6. From this we can learn that the actual properties of the dense gas vary significantly from galaxy to galaxy, even if their HCN luminosities are similar.

3. We report the detection of HC_3N 10-9 emission in Arp 220 at 40% of the HNC 1-0 intensity. In NGC 1808 the line is tentatively detected at 16% of the HNC 1-0 intensity and in NGC 7130 and NGC 3256 we have upper limits to the line (see Figure 1a).

4. We find that the IR luminous galaxies are at least as HNC luminous as more nearby (IR-fainter) galaxies. This is contrast with our expectation that HNC would be relatively fainter in our sample of warm luminous galaxies, compared with the nearby starburst galaxy sample of Hüttermeister et al (1995), given the temperature dependence of the $\frac{HCN}{HNC}$ (see Section 1).

   We conclude that the HNC emission is not a reliable tracer of cold (10 K) gas in the center of luminous IR galaxies, the way it may be in clouds in the disk of the Milky Way. Instead, we examined several alternative (and testable) explanations. Provided that the situation in the centers of starburst galaxies can be approximated with a steady state chemistry, the observed $\frac{\mathrm{HCN}}{\mathrm{HNC}}$ line ratios can be explained by the emission originating in gas of densities $n \leq 10^5 cm^{-3}$ where the chemistry is dominated by ion-neutral (where the temperature dependence of the HNC production is strongly suspended), instead of neutral-neutral, reactions. The temperature dependence of the HNC production in the ion-neutral reactions is strongly suppressed.

5. In general CN is bright in starburst galaxies hinting that the dense gas is affected by photo-dissociation. On the contrary in AGNs, CN 1-0 is difficult to detect. High resolution studies of systems where both an AGN and a starburst region exist (e.g. NGC1068), may reveal whether the CN abundance is associated with one or the other kind of activity.

6. The CN $\frac{2-1}{1-0}$ line intensity ratio suggests that the CN emission is sub-thermally excited apart from in NGC 6240 (and NGC 34 with an upper limit to the CN 1-0 emission). In general the ratio is lower than 0.4 indicating gas densities $\leq 5 \times 10^4 cm^{-3}$ (Fuente *et al* 1995) which are about one order of magnitude below the critical density.

   The CN 2-1 spingroup ratio (>2 in all cases, except for NGC6240 where the lines are blended) is above the LTE case hinting that the lines are of low optical depth.

7. We were surprised to find that the CN emission of the more luminous galaxies (like Mrk273, NGC2623, NGC6240, IC694 and NGC34) is often faint. This can be consistent with the relative faintness of other PDR tracers such as the 158 μm [C II] line. Both these phenomena can be understood in terms of a two-component molecular ISM consisting of low density molecular gas surrounding dense clouds. However, the relative brightness of CN in Arp 220 may be difficult to reconcile with its relative [C II] faintness.

8. Within Arp 299 (the merging pair IC 694 and NGC3690) there is a line ratio difference between the two nuclei. NGC 3690 has a CN luminosity twice that of HCN and its ISM is thus strongly affected by UV radiation while CN is not detected towards IC 694. This reflects an evolutionary gradient in the burst — or that the star formation activity takes place in very different environments in the two galaxies. For Arp 220 there may also be an evolutionary gradient between the two nuclei because of differences in emission velocities for CN and HC_3N, showing that CN peaks at the western nucleus while the HC_3N peaks at the eastern nucleus. As Rodriguez-Franco et al (1998) show, the emission from HC_3N is bright toward hot, dense cores, while the HC_3N/CN abundance

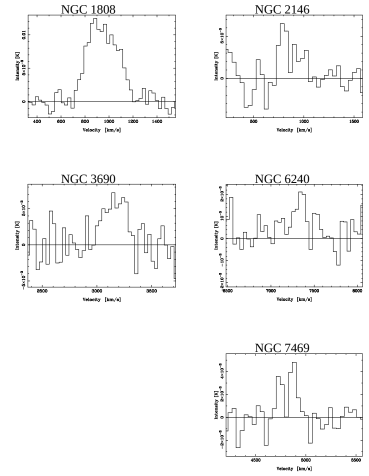

Figure 2a. The CN(1-0) spectra

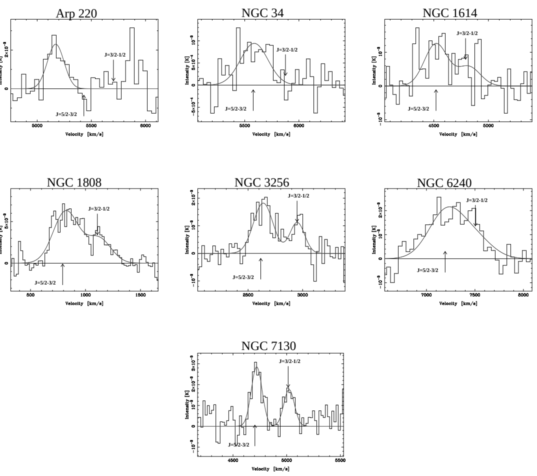

Figure 2b. The CN(2-1) spectra

ratio is only 10^{-3} in PDRs. Thus the eastern nucleus seems to be in an earlier evolutionary phase where star formation has just begun. It is tempting to suggest that in both cases we are observing an *evolution of the starburst* with the CN bright nucleus being the site of the older starburst where dense PDR regions exist.

9. The measured line ratios can in general be used to identify stages in the starburst evolution, We examine simple senarios, dividing the observed galaxies in rough categories according to their line rations. For example the HCN bright but HNC and CN weak galaxies may be dominated by ward dense gas early in the starburst development. For those galaxies where I(CN) is $\geq I$(HCN) a significant part of the ISM should be in PDRs. These CN luminous galaxies are very clearly in the phase where the ISM is being strongly affected by an intense UV field.

   However, we conclude that the dichotomy between scenarios is a complication. For example, faint HNC emission is expected both in a shock dominated ISM (i.e. an evolved stage of the starburst where supernovae, or even an AGN dominate) as well as for a cloud ensemble dominated by dense warm gas in the very early stages of a starburst. Similarly the absence of PDR traces such as CN emission (or the 158/mum [CII] line does not necessarily mean that the starburst is young, as in high pressure dusty ULRIGs it is possible that the formation of PDRs is suppressed.

The reader can find detailed information on the observations and the results presented in this paper in Aalto et al (2001).

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