Detection of HNC and tentative detection of CN at z = 3.9

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ABSTRACT

Aims. Molecular line emission from high-redshift galaxies holds great promise for the study of galaxy formation and evolution.

Methods. The weak signals can only be detected with the largest mm-wave telescopes, such as the IRAM interferometer.

Results. We report the detection of the J = 5–4 line of HNC and the tentative detection of the N = 4–3 line of CN in the quasar APM 08279+5255 at z = 3.9. These are the 4th and 5th molecular species detected at such a high redshift. The derived HNC and CN line intensities are 0.6 and 0.4 times that of HCN J = 5–4. If HNC and HCN are co-spatial and if their J = 5–4 lines are collisionally excited, the [HNC]/[HCN] abundance ratio must be equal to 0.6 within a factor of 2, similar to its value in the cold Galactic clouds and much larger than in the hot molecular gas associated with Galactic HII regions. It is possible, however, that fluorescent infrared radiation plays an important role in the excitation of HNC and HCN.

Key words. galaxies: high-redshift – galaxies: abundances – galaxies: individual: APM 08279+5255 – techniques: interferometric – cosmology: observations

1. Introduction

The presence of large reservoirs of molecular gas in the early Universe has been demonstrated through the detection of rotational transitions of CO in high redshift ultraluminous galaxies and quasars (see Solomon & Vanden Bout 2005, for a review). The derived masses are in excess of 10¹⁰ M⊙ and the gas is found to be warm and dense. Obviously, a prodigious star formation activity is taking place in some of those objects, as attested by the huge far-infrared luminosities. These considerations have triggered searches for molecular species having higher dipole moments than CO and that are better probes of the very dense gas that the gas is found to be warm and dense. Obviously, a prodigious star formation activity is taking place in some of those objects, as attested by the huge far-infrared luminosities. These considerations have triggered searches for molecular species having higher dipole moments than CO and that are better probes of the very dense gas associated with star formation. Two such molecules were detected so far in high-z sources: HCN and HCO⁺.

The gravitationally lensed quasar APM 08279+5255 (z = 3.9118, Weiβ et al. 2006 [We06]) is a prime target for such studies. Its huge intrinsic luminosity, boosted by a large magnifying factor (m = 60–100), makes it not only the most luminous object in the Universe (apparent luminosity Lbol = 7 × 10¹⁵ L⊙), but also one of the most powerful sources of CO emission. The presence of strong CO lines with rotational quantum numbers as high as J = 11–10 indicates that its gas is very dense and warm (Downes et al. 1999, We06). Both HCN and HCO⁺ have been detected in this source (Wagg et al. 2005 [Wa05]; García-Burillo et al. 2006 [GB06]).

To further constrain the physical conditions of the gas in APM 08279+5255 and to probe its chemical composition, we have searched for new high density tracers. In this Letter, we report the first detection of hydrogen isocyanide (HNC) at high-z and the tentative detection of CN.

2. Observations and results

The IRAM Plateau de Bure interferometer (PdBI) was used to observe the HNC J = 5–4 and CN N = 4–3 lines which, redshifted by z = 3.9118 to the 3-mm band, have rest frequencies differing by less than 70 MHz. More specifically, HNC J = 5–4 is a single component line with a redshifted frequency of 92.282 GHz, while CN N = 4–3, due to spin-coupling and spin-spin interactions, shows a complex line pattern, whose strongest components lie close to 92 307 MHz and 92 350 MHz and have intensities in the ratio 1:1.3.

The observations were made in September 2006 with five antennas in a compact configuration. The receivers were tuned to 92.297 GHz. The SSB system temperature was typically 150–200 K. The 560 MHz-wide IF-bandwidth, covering a velocity range of 1820 km s⁻¹, was observed with a channel spacing of 2.5 MHz. The FHWM of the synthesized beam is 5.6″ × 4.4″. Data reduction and analysis were done with the GILDAS software. The flux calibration is based on the PdBI primary calibrator MWC 349 and on reference quasars. The total time on source amounts to 25 h.

The resulting spectrum, smoothed to a resolution of 97 km s⁻¹, is shown in Fig. 1. The total emission map, integrated over the 1820 km s⁻¹-wide bandwidth, is shown in Fig. 2a, while 3 continuum-free velocity-channel maps, obtained after subtraction of a 1.1 mJy continuum source, are shown in Figs. 2b–d. A line is clearly detected in Figs. 1 and 2c. Like the continuum emission, it arises from an unresolved source whose position is identical to those of the CO, HCO⁺ and HCN sources and of the quasar. The line peak flux, derived from the fit of a single Gaussian profile, is 1.76 ± 0.3 mJy (6σ detection). The...
The strength of HNC, HCN and HCO$^+$ in APM 08279+5255 may reflect a high abundance of these species relative to CO. It may also come from an unusually high gas density. Finally, it may result from fluorescent pumping through excited bending states, or from a combination of those three causes (see GB06).

Whereas the abundance of HCN, relative to CO, is stable in Galactic clouds for a wide range physical conditions (Lucas & Liszt 1996), that of HNC is known to vary by orders of magnitude. The [HNC]/[HCN] ratio is found to be $\geq 1$ in dense dark clouds (Hirota et al. 1998), $\approx 1/5$ in diffuse clouds (Liszt & Lucas 2001) and only few $\times 10^{-2}$ in hot and dense star-forming regions, such as the Orion hot core (Schilke et al. 1992).

In dense clouds, both HCN and HNC are thought to mainly result from the dissociative recombination of HCNH$^+$ and to be destroyed by reactions with ions and radicals. HNC is preferentially destroyed by reactions with H, O and OH that proceed only in oxygen-rich hot and/or dense environments. Schilke et al. (1992) have modeled the [HNC]/[HCN] abundance ratio to explain the Orion results. They predict a rapid decrease of this ratio with increasing gas density and temperature, in agreement with observations: in their model, [HNC]/[HCN] decreases from a value of $\geq 1$ at $n < 10^4$ cm$^{-3}$, $T_K < 30$ K (the conditions prevailing in dense dark clouds) to [HNC]/[HCN] $\sim 3 \times 10^{-2}$ at $n = 10^6$ cm$^{-3}$ and $T_K = 100$ K (the conditions in the Orion hot, oxygen-rich core).

In the following, we examine the physical conditions prevailing in the circumnuclear disk of APM 08279+5255 and address the question of HNC excitation, in order to discuss the [HNC]/[HCN] abundance ratio.

3.1 Collisional excitation

The physical conditions in APM 08279+5255 can be derived, in principle, from the observed CO and HCN line intensities. CO and HCN have different dipole moments and their rotational transitions have critical densities in the ratio 1:1000, making the HCN/CO intensity ratio a sensitive indicator of the gas density. Downes et al. (1999), Wat05 and We06 have analyzed, using a LYG code, the CO $J = 1$–0 through 11–10 and HCN($5$–$4$) line intensities in APM 08279+5255. They assume that the observed emission arises from a single uniform component, or from two radiatively decoupled components, and that fluorescent excitation is negligible. With these assumptions, the range of densities for the bulk of the gas is constrained by the fact that the gas density $n$ must be high enough to populate the $J = 5$ level of HCN and low enough to prevent the thermalization of the CO $J \geq 9$ levels. This range depends mildly on the gas temperature ($T_K$) or the molecular abundances and can be derived for reasonable values of those parameters, i.e. $40 K < T_K < 200 K$, $10^{-5} < [\text{CO}] / [\text{H}_2] < 10^{-4}$ and $10^{-4} < [\text{HCN}] / [\text{CO}] < 10^{-2}$. The gas density $n$ should be comprised between a few $\times 10^4$ cm$^{-3}$ and a few $\times 10^5$ cm$^{-3}$. The solution favored by Wat06, who assumed $[\text{CO}] / [\text{H}_2] = 5 \times 10^{-5}$ and $[\text{HCN}] / [\text{CO}] = 10^{-3}$, is $n = 10^5$ cm$^{-3}$, $T_K = 45$ K; Wat05, who adopted N(CO)/$\Delta v = 4 \times 10^{17}$ cm$^{-2}$ km$^{-1}$ s and [HCN]/[CO] = $10^{-2}$, find $n = 4 \times 10^4$ cm$^{-3}$ and $T_K = 80$ K. The HCN($5$–$4$) line opacities ($\tau$) derived in these studies are 50–150.

With such values of $n$ and $\tau$, the HCN($5$–$4$) line, which has a critical density of $2 \times 10^5$ cm$^{-2}$, is only weakly excited. Low excitation implies that the intensity emerging from a uniform cloud is nearly proportional to the molecule column density $N$(HCN). As an illustration of this, let us consider the solution with $n = 10^5$ cm$^{-3}$, $T_K = 45$ K and a line opacity $\tau = 100$. A statistical equilibrium calculation with RADEX (Schröier et al. 2005)

![Fig. 1. Spectrum of the HNC(5–4) and CN (4–3) emissions from APM 08279+5255. The velocity scale is relative to the HNC frequency redshifted by $z = 3.9118$. The velocity resolution is 97 km s$^{-1}$, the rms noise 0.5 mJy. The thick line represents the best fit synthetic spectrum and the dotted and dashed lines the contributions from CN and HNC to this spectrum. The CN contribution is the blend of 2 fine-structure components.](image-url)
shows that dividing \(N(\text{HCN})\) by 3, decreases the HCN(5–4) line intensity by a factor of 2.5, despite the large value of \(r\).

The transitions \(v_2 = 1 \pm 0\) connecting the lowest excited bending states of \(\text{HCO}^+\), HCN and HNC to the ground vibrational state have wavelengths of 12.1, 14.0 and 21.7 \(\mu\)m, respectively. Their Einstein A coefficients are fairly large \((A \approx 1 \pm 7 \text{ s}^{-1}\)).

### 3.2. Fluorescent excitation

We have assumed above that there is no radiative coupling between the different clouds in the \(J = 5 \rightarrow 4\) line and that the excitation is mainly collisional. The first hypothesis seems reasonable in view of the limited inclination (the quasar is bright at visible wavelengths) and large velocity gradient of the rotating disk. The fact that we are dealing with \(J\) levels as large as 4 and 5 makes it also unlikely that cold foreground gas screens efficiently the core emission. The second hypothesis is weaker.

With a spectral energy distribution peaking around 20 \(\mu\)m, APM 08279+5255 is exceptionally bright in the mid-infrared. A fit to the dust emission yields a hot (200 K) plus a cold (70 K) component (Beelen et al. 2006). The latter, whose mass represents more than 9/10 of the total, is probably associated with the dense gas detected in the HCN and HNC lines. The hot dust component could be concentrated close to the central AGN (We06), or distributed in hot flakes scattered throughout the cold disk (Nenkova et al. 2002).
dust can well excite the first bending modes and, by fluorescence, populate the \( J = 4 \) and 5 levels of the ground state. Since the \( J = 3 \) levels are already populated by the cosmic background radiation (their fractional population is 0.17 at 13.4 K), one single pumping cycle – from the \((\nu_2, J) = (0, 3)\) level up to the \((1, 4)\) level and down to the \((0, 5)\) level – is required to populate the \( J = 5 \) level. Besides an optical depth \( \geq 1 \), the only requirement for fluorescent pumping to be efficient is that the solid angle \( \Omega \) subtended by the hot dust at the molecules should not be too small (say \( \Omega/4\pi \geq 0.1 \)). A value of \( \Omega > 0.1 \) could be easily achieved if the gas is clumpy, so that the radiation from the AGN can penetrate deeply into the disk (Nenkova et al. 2002).

If those conditions are fulfilled, fluorescent excitation may well take over collisional excitation for the HCN, HNC and HCO\(^+\) \( J = 5–4 \) lines. The line intensities may then reflect the number of pumping photons, rather than the molecular column densities. The near equality of the HCN and HCO\(^+\) \( J = 5–4 \) line intensities would be naturally explained, as the infrared transition wavelengths of these two species are similar. Also, the constraint on the gas density would be much relaxed, since the CO data alone can be explained by warmer, but less dense gas (We06).

Infrared pumping may introduce interesting differences between HCN and HNC. The wavelength of the \( \nu_2 = 1–0 \) transition of HNC is 1.5 times larger than that of HCN and the flux of APM 08279+5255 at 21.7 \( \mu m \) is twice that at 14 \( \mu m \). Thus, the number of photons able to excite the HNC molecules is at least 3 times larger than that of photons which can excite HCN (or HCO\(^+\)). Moreover, the emission of the colder dust component starts to be significant at 21.7 \( \mu m \). This emission will be particularly effective, since the cold dust is better mixed with the HNC molecules than the hot dust, so that \( f \approx 1 \).

In contrast to triatomic molecules that have low energy bending states, the lowest vibrational transition of CN lies at 4.9 \( \mu m \), where the flux of APM 08279+5255 is 5 times weaker than at 20 \( \mu m \). The comparison of HCN, HNC and CN may then offer a way to weight the relative importance of collisional and fluorescent excitations, assuming these molecules are co-spatial. More transitions would be needed, however, to do so.

### 3.3. Comparison with other galaxies

In nearby starbursts galaxies such as M 82, NGC 253, NGC 1068 and NGC 3079, the HNC and HCN \( J = 1–0 \) lines have intensity ratios \( \approx 0.5 \) (Hüttemeister et al. 1995; Wang et al. 2004). Exceptions are some ULIRGs such as Mrk 231 (Aalto et al. 2002) and Arp 220 (Cernicharo et al. 2006), where this ratio is \( \approx 1 \). However, the fundamental rotational lines are not necessarily good indicators of the HCN and HNC abundances, due to self-absorption. First, these lines have critical densities of \( 2 \times 10^5 \text{ cm}^{-3} \), 100 times lower than the \( J = 5–4 \) lines; they are much easier to excite in dense cores, so that their intensities saturate for lower molecular column densities. Second, in the local Universe the cosmic background temperature is only 2.7 K, so that most of the HNC and HCN molecules in low density gas are in the ground \( J = 0 \) level, making envelopes optically thick to the \( J = 1–0 \) line radiation that emerges from the cores.

A comparison between local ULIRGs and APM 08279+5255 must involve higher \( J \) lines. The \( J = 3–2 \) HNC and HCN lines have recently been observed in Arp 220 (Cernicharo et al. 2006) with an intensity ratio of 2.3, twice the value of the \( J = 1–0 \) line intensity ratio. The \( J = 3–2 \) line intensity ratio is more likely to reflect the [HNC]/[HCN] abundance ratio than the \( J = 1–0 \) intensity ratio, so that HNC should be more abundant than HCN in this source. The relatively high HNC abundance observed in APM 08279+5255 is thus not exceptional.

A survey of CN (\( N = 1–0 \)) emission in luminous IR galaxies has been made by Aalto et al. (2002), who found that the CN/HCN intensity ratio, which is \( \sim 1 \) in many LIRGs can be lower in ULIRGs. The relative weakness of CN in APM 08279+5255 is therefore also not exceptional.

### 4. Summary

We have detected HNC (5–4) and tentatively CN (4–3) emission from the quasar APM 08279+5255 at \( z = 3.9 \), adding to HCN and HCO\(^+\) two new tracers of the very dense gas in high-\( z \) sources. The data are consistent with HNC and HCN being co-spatial.

The \( J = 5–4 \) lines of HCN and HNC are remarkable by their very high, almost equal critical densities, \( 2 \times 10^5 \text{ cm}^{-3} \), which are far larger than the gas density in the central circumnuclear disk. In the absence of mid-infrared pumping, the high critical densities maintain low populations in the \( J = 5 \) and 4 levels. The HCN/HNC (5–4) line intensity ratio is then a good measure of the [HNC]/[HCN] abundance ratio. The latter, which is a sensitive probe of the chemical and physical conditions, is found to be close to 1, much larger than the corresponding ratio observed in the hot and dense Galactic molecular clouds. We stress that the \( J = 1–0 \) lines of the main isotopologues of HNC and HCN are much more easily excited and do not trace properly these species’ abundances when they are optically thick.

HNC is the first metastable isomer detected in high-\( z \) sources. CN, if confirmed, would be the first radical. Their observation in APM 08279+5255 illustrates that the chemistry can be quite evolved in environments as extreme as the vicinity of the most powerful high-\( z \) quasars. Other molecules, including more complex species, might be detectable with present day instrumentation.

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