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Letter to the Editor

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, abundances - Galaxies: Individual: APM 08279+5255 - Techniques: interferometric

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 10^{10} $M_\odot$ 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 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, Weiß 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 $L_{bol} = 7\ 10^{15} L_\odot$), 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.

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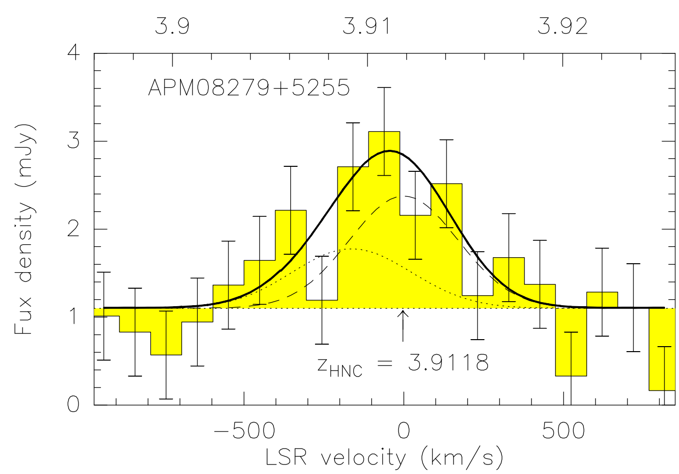

Fig. 1. Spectrum of the HNC(5–4) and CN (4–3) emissions from APM 08279+5255, The velocity scale is relative to the HNC frequency redshifted by z = 3.9118. The velocity resolution is 97 km s^{-1}, the r.m.s. noise 0.5 mJy. The thick line represents the best fit synthetic spectrum and the dotted and dashed lines the contributions from CN and HNC to this spectrum. The CN contribution is the blend of 2 fine-structure components.

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 92307 MHz and 92350 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 FWHP 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 hours.

The resulting spectrum, smoothed to a resolution of 97 kms^{-1}, is shown in Fig. 1. The total emission map, integrated over the 1820 kms^{-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 Fig. 2 (b-d). A line is clearly detected on Fig. 1 and Fig. 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 line width is 500 ± 110 km s^{-1} and its center frequency, relative to the LSR, is 92294 ± 12 MHz. The latter is 12 MHz higher than the HNC line frequency and 38 MHz lower than that of the barycenter of the CN line components. The fitted width and center frequency, which are somewhat larger than those observed for HCN, suggest that we have detected a blend of HNC and CN.

We have fitted the unsmoothed line profile with a synthetic profile representing a blend of the HNC and CN lines. The relative position of the line components (2 components for CN, one for HNC) were fixed according to the redshifted transition frequencies and the component widths were set equal to Δv = 400 kms^{-1}, the FWHP of the HCN (5-4) line(We06). The intensities derived for z = 3.9118, the redshift derived from CO, are shown in Table 1. They correspond to a HNC/CN integrated line intensity ratio of r = 1.7. Obviously, CN is only a minor constituent of the observed line. The observed profile can be marginally fit by HNC alone (1 σ), but not by CN alone: fitting this profile with only the CN components yields a much too high redshift, z = 3.9139 ± 0.0008. We conclude that the detection of HNC in APM 08279+5255 is certain, whereas that of CN is only tentative. A fit of the component width, while keeping the intensities fixed, yields $\Delta v = 480 \pm 100$ kms^{-1} a value similar, within the errors, to the HCN and HCO$^+$ line widths. This is consistent with HNC, HCN and HCO$^+$ being co-spatial.

The derived velocity-integrated HNC and CN line intensities (and the corresponding line luminosities) are compared in Table 1 to those of HCN, HCO$^+$ (5–4) and CO (4–3). The relatively large error bars reflect the difficulty of resolving CN from HNC. The HNC line intensity is surprisingly large: ≃ 2/3 of those of HCN and HCO$^+$ and ≃ 1/7 of that of CO. The CN line intensity is certainly smaller and remains very uncertain.

3. Discussion

The detection of HNC and the tentative detection of CN in APM 08279+5255, after those of CO, HCN and HCO$^+$, brings to 5 the number of molecules observed in high redshift quasars. More than just supplying new tracers of dense gas, it gives us an opportunity to measure the [HNC]/[HCN] abundance ratio, a ratio very sensitive to the physical and chemical state of the gas.

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 ≥ 1 in dense dark clouds (Hirota et al. 1998), ≃ 1/5 in diffuse clouds (Liszt & Lucas 2001) and only few ×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 ≥ 1 at $n < 10^5$ cm^{-3}, $T_K < 30$ K (the conditions prevailing in dense dark clouds) to [HNC]/[HCN] ∼ 3 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), Wa05 and We06 have analyzed, using a LVG 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 ≥ 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. 40K < T_K < 200 K, 10^{-5} < [CO]/[H_2] < 10^{-4} and 10^{-4} < [HCN]/[CO] < 10^{-2}). The gas density n should be comprised between a few ×10^{4}cm^{-3} and a few ×10^{5}cm^{-3}. The solution favored by We06, who assumed [CO]/[H_2]= 5 10^{-5} and [HCN]/[CO]=10^{-3}, is $n = 10^5$cm^{-3}, $T_K = 45$ K; Wa05, who adopted N(CO)/Δv= 4 10^{17} cm^{-2}km^{-1}s and [HCN]/[CO]= 10^{-2}, find n = 4 10^{4}cm^{-3} and $T_K = 80$ K. The HCN(5–4) line opacities (τ) derived in these studies are 50–150.

With such values of n and τ, the HCN(5–4) line, which has a critical density of 2×10^7 cm^{-3}, 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) shows that dividing N(HCN) by 3, decreases the HCN(5–

Table 1. Properties of the HNC, HCN and HCO^+ (5–4) lines compared to the CO(4–3) line towards APM 08279+5255

Line	ν_{obs} [GHz]	I_{line} [Jy km s^{-1}]	L′ [10^{10}K km s^{-1} pc^2]	F_{cont} [mJy]	Ref
HNC(5–4)	92.282	0.54^d±0.25	2.3±1.1	1.1^e±0.15	Present work
CN(4–3)	92.332	0.31^d±0.25	1.3 ±1.1	1.1^e±0.15	Present work
HCN(5–4)	90.229	0.85±0.12	3.6±0.5	1.3±0.2	(a)
HCO^+(5–4)	90.797	0.87±0.13	3.5±0.6	1.2±0.1	(b)
CO(4–3)	93.870	3.70±0.50	14.7±1.5	1.2±0.3	(c)

NOTES. – (a) We06; (b) GB06; (c) Downes et al. (1999); (d) blended line HNC and CN fitted together with FWHP fixed to 400 km s^{-1}; (e) fitted to the line-free channels. The luminosities are calculated from equation [1] of Downes et al. (1999) using the standard concordance cosmology parameters with H_0 = 71 $kms^{-1}Mpc^{-1}$, Ω_m = 0.27 and Ω_Δ = 0.73 (Spergel et al. 2003). They are not corrected for the lens amplification.

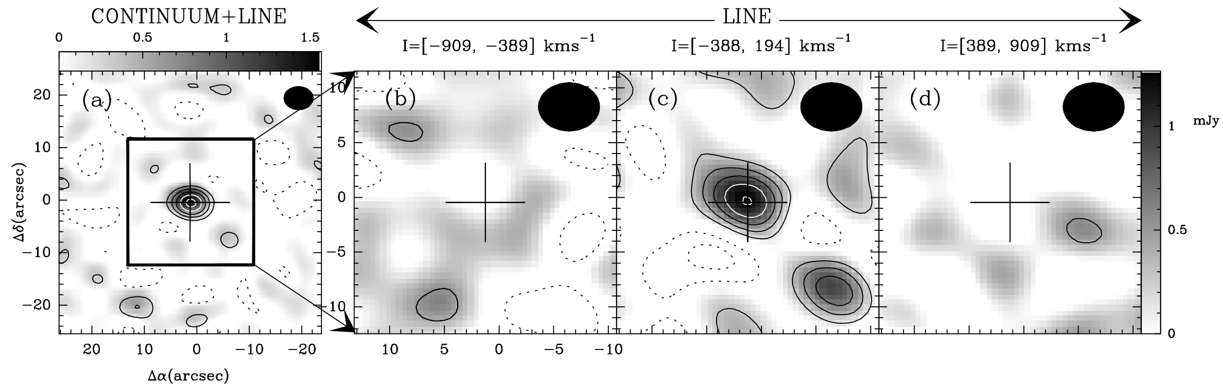

Fig. 2. a: Total (continuum+line) emission map of APM 08279+5255 integrated from −909 to 909 kms^{-1} and centered on 92.29 GHz. Levels are -2σ (dashed) and 2σ to 10 σ in steps of 2 σ (σ = 0.15 mJy/beam). **b-d**: Velocity-channel maps obtained after subtraction of a point-like 1.1 mJy continuum source, located at the position of maximum emission. The data have been averaged over the three velocity intervals delineated in Fig. 1. **b:** I = [−909, −389], **c:** I = [−388, +194] and **d:** I = [389, 909] kms^{-1}. The emission from the HCN(5–4) and CN (4–3) lines appears in the central channel (**c**). Contours are -2σ, -1σ (dashed) and 1σ to 5σ in steps of σ for (c) and -2σ and 2σ for (b) and (d) (with 1σ = 0.25 mJy/beam). The synthetized beam is shown as a grey ellipse on the top right corner. The offsets (in arcseconds) are relative to the peak of the continuum+line emission at ($08^h31^m41^s69, 52^o45'17''12$) (J2000), shown by the crosses.

4) line intensity by a factor of 2.5, despite the large value of τ. The same considerations apply to HNC, which has almost exactly the same electric dipole moment as HCN (3.0 debye) and similar rotational level spacings. Recent calculations by Wernli et al. (2006) for the collisional excitation of HCCCN with He and with H_2 and on-going calculations for HCN, based upon recent potential energy surfaces (M. Wernli & P. Valiron, *private communication*), indicate that for such heavy molecular rods, the dynamics of the collision is mainly driven by the hard core interaction with the rod and is weakly sensitive to the details of the potential surface, in fair agreement with the pioneering calculations for HCN-He by Green & Chapman (1978). We can thus safely assume that HNC and HCN present similar collisional rates and critical densities for temperatures well below the isomerisation barrier of 1440 K. Thanks to this and provided HCN and HNC co-exist in the same clouds, the HNC/HCN intensity ratio in APM 08279+5255 should reflect these species' abundance ratio. In that case, [HNC]/[HCN]≃ 0.6 within a factor of 2, close to the ratio predicted by Schilke et al. (1992) in O-rich environments for $T_K \leq 80$ K, $n \leq 10^5$ cm^{-3}, but higher than those predicted for hotter and denser regions, such as the Orion hot core.

The [CN]/[HCN] abundance ratio is more difficult to derive for 3 reasons. First, the CN line intensity is fairly uncertain. Second, the J = 4–3 CN line is much easier to excite than HCN (5–4), due to its lower energy and smaller dipole moment, so that the line intensity ratio depends critically on the gas density. Third, the collisional cross sections of CN with H_2, or even He, are not known. Following Black & van Dishoeck (1991), we assume that they are similar to those of CS (Green & Chapman 1978) and adopting once more T_K = 45 K, $n = 10^5$ cm^{-3}, we estimate [CN]/[HCN]≤ 1/10.

3.2. Fluorescent excitation

We have assumed above that there is no radiative coupling between the different clouds in the J =5-4 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 20μm, 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).

The transitions ν_2=1–0 connecting the lowest excited bending states of HCO^+, HCN and HNC to the ground vibrational state have wavelengths of 12.1, 14.0 and 21.7μm, respectively. Their Einstein A coefficients are fairly large ($A \simeq 1-7\,\mathrm{s}^{-1}$, Nezu et al. 1999), so that the ν_2 =1–0 lines are expected to be optically thick in APM 08279+5255. As argued by GB06 (see also Barvainis et al. 1997), the mid-infrared radiation from the hot 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 (ν_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 Ω subtended by the hot dust at the molecules should not be too small (say $f = \Omega/4\pi \geq 0.1$). A value of $f > 0.1$ 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 ν_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 μm is twice that at 14μm. 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 μm. This emission will be particularly effective, since the cold dust is better mixed with the HNC molecules than the hot dust, so that $f \simeq 1$.

In contrast to triatomic molecules that have low energy bending states, the lowest vibrational transition of CN lies at 4.9 μm, where the flux of APM 08279+5255 is 5 times weaker than at 20μm. The comparison of HCN, HNC and CN may then offer a way to weigh 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 $\simeq$ 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 $\simeq$ 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 10^5 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 $\simeq$ 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, $\simeq 2\,10^7$ 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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