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Complex organic molecules in the circumnuclear disc of a young radio galaxy

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Abstract

Detailed studies of the composition, kinematics and physical conditions of cold gas in extreme environments, such as close to an active galactic nucleus (AGN) provide new insights into the chemical pathways which are not observed in other environments. We present the discovery of an unusually strong absorption feature at 92.36 GHz – detected owing to the broad frequency coverage of NOrthern Extended Millimeter Array (NOEMA) – in a radio-loud AGN 4C 31.04 at $z = 0.0598$. We identify this line to arise either from Ethyl Cyanide (CH_3CH_2CN) or Methyl Mercaptan (CH_3SH). We also find other absorption and emission lines from CH_3CH_2CN at $\sim$116.5 GHz and $\sim$98.5 GHz respectively, suggesting that the line at 92.36 GHz is most likely due to CH_3CH_2CN. Intriguingly, the generally expected transitions of other molecules such as CH_3OH, SO_2 and CS are absent, suggesting a very different chemistry in this case than that observed in the central molecular zone or the hot cores in the Galaxy. Based on pc-scale atomic gas observations, we conclude that the molecular absorption arises from a highly turbulent circumnuclear gas with which the radio jets of 4C 31.04 are interacting strongly, driving an outflow. Irrespective of the identification of the line, we find a significant abundance enhancement of many orders of magnitude for the complex organic molecule giving rise to this absorption ($> 10^{-3}$). This is the first time that such complex organic molecules are detected in the circumnuclear disc of an AGN and we suggest that the unexpectedly high gas-phase abundance so close to the active SMBH is likely due to the extreme shocks driven by the radio jets where the chemistry is not yet well explored. These findings potentially present a new challenge to the existing chemical models regarding the production and sustenance of such complex molecules in extreme environments.

1 Introduction

The physical conditions of the interstellar medium (ISM) can be effectively probed via the study of molecules. For example, observations of transitions of various species of molecules combined with the chemical models have provided new insights into processes such as star formation both within the Galaxy and in extragalactic sources [1]. Over the last many years, observations have shown that molecular gas exists in more extreme conditions as well. Molecular gas is found to be a main component of the multi-phase ISM in the active galactic nuclei (AGN). Cold gas has also been observed to be the most massive component of AGN-driven outflows which impact the evolution of their host galaxies [2]. The chemistry governing the formation and survival of cold gas in such extreme environments is still being explored. Thus, a study of the physical condition, kinematics and morphology of different tracers of cold gas in extreme environments is of great importance.

Just as the extreme conditions in radiatively efficient AGN provide a good laboratory for such studies, radio-loud AGN also are interesting in this context. Young radio jets expanding into the ISM are predicted to give rise to widespread shocks with shock velocities even reaching 1000 km s^{-1} [3]. Thus the nuclear regions of young radio galaxies too provide extreme environments where the chemistry of molecules is yet to be well understood and as such are of great interest in understanding the impact of shocks on cold gas [3].

We present results from the cold molecular gas study of a young, 140 pc size radio galaxy, 4C 31.04, estimated to be only 500 - 5000 years old [6]. It embedded in a galaxy, at $z = 0.0598$, rich in both atomic and molecular gas, especially in the nuclear region. Studies have already detected cold atomic hydrogen (H I), HCO^+, CO and CN in this galaxy [4, 5, 6]. Furthermore, observations of warm molecular gas find that gas even at kpc scale is shock excited due to the widespread shocks generated by the interaction of the radio jets with the ISM at parsec scales [7]. All these make 4C 31.04 a particularly interesting target to study the cold gas chemistry under extreme conditions.

2 Strong molecular absorption at 92.36 GHz

We used NOrthern Extended Millimeter Array (NOEMA) to observe molecular gas in 4C 31.04 at a spatial resolution of $\sim$2.7 kpc and we detect a host of molecular lines – thanks to the broad frequency coverage of the instrument. The spectra of the detections, both emission and absorption, are shown in Fig. 1.

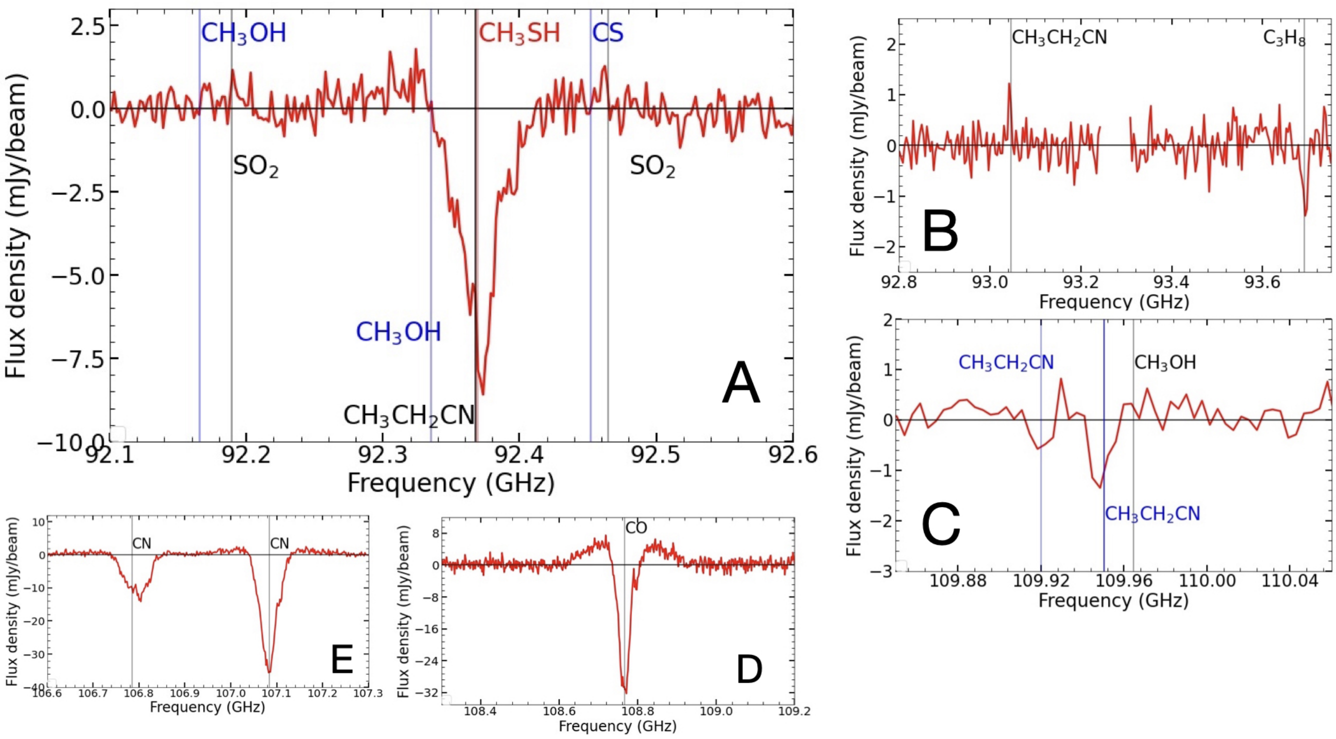

Figure 1. The spectra of the lines covered in our NOEMA observations. Transitions of various commonly detected molecules are marked on the spectra. **1A:** The deep absorption at 92.36 GHz which may correspond to either CH_3CH_2CN(6-7) or CH_3SH(30-31) transitions. **1B:** The CH_3CH_2CN(11-10) emission and C_3H_8 absorption. **1C:** The CH_3CH_2CN(12-13) and CH_3CH_2CN(8-9) transitions. **1D:** CO(1-0) emission and absorption. **1E:** CN(1-0) emission and absorption lines.

The most intriguing finding is the strong absorption at 92.36 GHz against the unresolved radio continuum (Fig. 1A). At $z = 0.0598$ for 4C 31.04, this may correspond either to CH_3CH_2CN(6-7) (Ethyl Cyanide) at a rest frequency of 97.891 GHz or CH_3SH(31-30) (Methyl Mercaptan) at a rest frequency of 97.892 GHz.

If the absorption arose from CH_3SH, we would expect to also detect the lighter homologue, CH_3OH. However, as can be seen in Fig. 1A, we do not detect CH_3OH. Furthermore, we also do not detect the CH_3SH(4-3) transitions at $\sim$101 GHz rest frequency. On the other hand, we detect CH_3CH_2CN(11-10) at 98.61 in emission (Fig. 1B) and also tentatively, CH_3CH_2CN(13-12) and CH_3CH_2CN(8-9) transitions at $\sim$116.5 GHz rest frequency in absorption (Fig. 1C). Thus it is more likely that the absorption at 92.36 GHz corresponds to the CH_3CH_2CN(6-7) transition at 97.89123480 GHz rest frequency.

However, except for one emission line, we do not detect other strong suite of CH_3CH_2CN(11-10) lines, also expected at $\sim$98.5 GHz rest frequency. Also, we note that if it were indeed the CH_3CH_2CN(6-7) transition giving rise to the absorption, the peak of the absorption is redshifted with respect to the systemic velocity, compared to if the line were to arise from CH_3SH(30-31) transition. Thus, although we speculate that the line likely arises from CH_3CH_2CN, with the current data it is not possible to definitively confirm the same. In any case, irrespective of whether the absorption arises from CH_3CH_2CN or CH_3SH, we note that the line is unusually strong even compared to the other extra galactic detections of emission or absorption from the same molecules [1, 8].

In addition to these lines, we also detect wide, deep, CO(1-0) and CN(1-0) absorption (Figs. 1D, 1E) and also absorption from Propane (C_3H_8) at 99.295 GHz rest frequency (Fig. 1B).

As can be seen in Fig 1, the CO(1-0), CN(1-0) and the possible CH_3CH_2CN(6-7) absorption are very wide, with full width at zero intensity (FWZI) > 200 km s^{-1}, highly suggestive of extreme gas kinematics. The other lines are relatively narrow (FWZI < 30 km s^{-1}), similar to that observed in the Galactic ISM [11] likely because they arise from gas clouds spatially separated from those producing the wide lines.

3 Complex organic molecules in a turbulent circumnuclear disc

The molecular gas absorption is unresolved in our NOEMA observations since the radio source providing the background for the absorption is only $\sim$140 pc in size. Hence it is not possible to directly infer the morphology and kinematics of the absorbing gas. However, by combining these

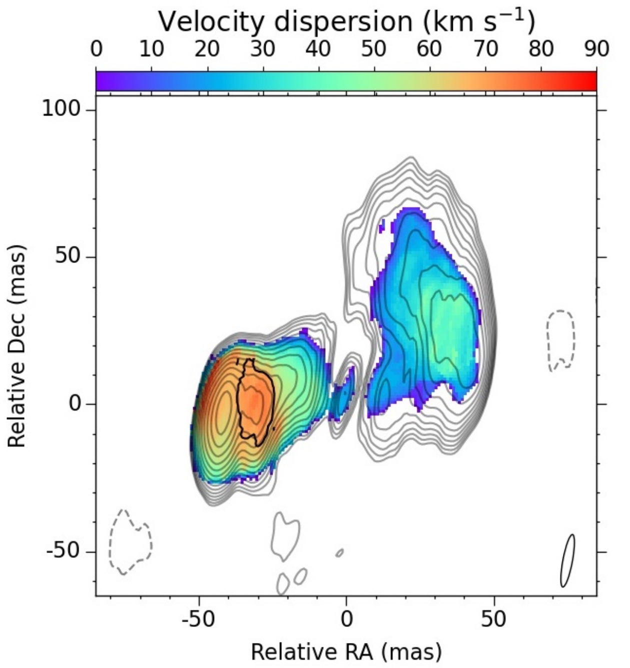

Figure 2. The distribution of H I (in colour) with respect to the radio source (grey contours) at parsec scales. We find that the H I envelops the radio source and is also highly turbulent on account of strong jet – ISM interaction.

results with pc-scale study of cold neutral atomic gas (H I), it is possible to further understand the kinematics of the absorbing molecular gas [9, 10]. We have carried out pc-scale mapping of H I in absorption in this source using the Very Long Baseline Interferometry (VLBI) techniques. Figure 2 shows distribution of H I with respect to the radio source and the velocity dispersion of the gas. The H I absorption arises entirely from gas that is enveloping the radio source and strongly interacting with it, as seen by the overall high velocity dispersion (> 40 km s^{-1}), with especially enhanced velocity dispersion along the eastern lobe (up to 90 km s^{-1}). Our H I study has also found that the gas is in a circumnuclear disc being disrupted by the radio jets that are making the gas highly turbulent and also driving an outflow.

Figure 3, shows the integrated H I absorption profile compared with the broad molecular absorption from possibly CH_3CH_2CN(7-6) transition. We find that the absorption profiles are in excellent agreement with each other. Thus we argue that molecular gas giving rise to this broad absorption feature is co-spatial with the atomic gas, and hence is a part of the same pc-scale turbulent circumnuclear disc being disrupted by the radio jets.

4 Jet-driven shocks into irradiated molecular gas: pushing chemical models into new territory

In order to further understand the physical conditions of the gas, we estimate the column densities and abundance ratios

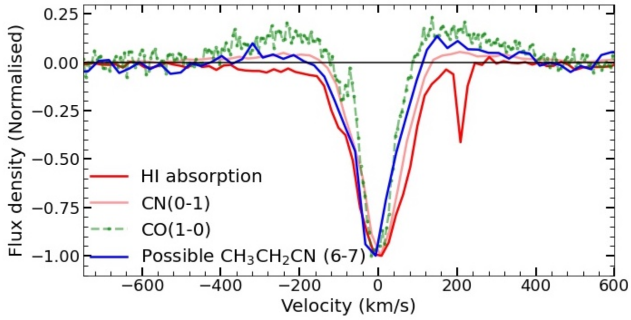

Figure 3. The molecular absorption profiles compared with the H I absorption profile. The profiles are in excellent agreement with each other, strongly suggesting that the gas giving rise to the molecular absorption is co-spatial with H I and shares similar extreme morphology and kinematics.

for the absorption lines. These are shown in Table. 1. These abundance ratios are several orders of magnitudes enhanced compared to that found in other galaxies, and also the hot cores and the central molecular zone of the Galaxy [1, 8].

It is especially so with the complex organic molecule (COM) giving rise to the absorption at 92.36 GHz. Although the current data suggest that the line is very likely from CH_3CH_2CN(7-6) transition, we still cannot definitively rule out the possible CH_3SH(31-30) transition. However, if the absorption were to arise from either of the molecules, the corresponding abundance is unusually high ($\geq 10^{-3}$; see Table. 1).

Such abundance enhancements are possible in the presence of strong shocks. Because COMs are formed via chemical reactions on dust-grain surfaces and in ice mantles, and then released into gas phase by desorption [12], shocks are thought to greatly enhance the abundance of some COMs in the molecular gas, owing to mantle evaporation. In fact, in 4C 31.04, there is evidence for widespread shocks exciting warm molecular gas even at distances much larger than the physical extent of the radio source [7]. Therefore we speculate that the on-going strong jet – ISM interaction in 4C 31.04 has given rise to strong shocks resulting in the observed unusual molecular gas composition and abundances.

Overall, our results suggest that extreme conditions such as strong jet – ISM interaction can give rise to unique chemical pathways not observed in other environments. By expanding such studies to a large number of sources, it may be possible to use such chemical imprints to identify the presence of shocks driven by radio jets and also understand the mechanisms resulting in the survival of cold gas in such extreme conditions.

5 Acknowledgements

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Table 1. Properties of the molecular gas species detected in absorption. The columns are: (1) The transition (2) Rest frame frequency of the transition for $z = 0.0598$. (3) Integrated optical depth of the absorption line, (4) Column density of the gas. For CH_3CH_2CN(8-9) and CH_3CH_2CN(12-13) transitions, we used $T_{ex} = 22$ K. For the rest of the lines, $T_{ex} = 200$ K since the lines are very broad and arise from the circumnuclear disc. (6) The abundance ratio for all the species. This is calculated assuming $N_{CO}/N_{H_2} = 10^{-4}$, there by $N_{H_2} = 3.3 \times 10^{24}$ cm^{-2}.

Transition	$\nu_{\rm rest}$ (GHz)	$\int \tau dv$ (km s^{-1})	N ($\times 10^{20}$ cm^{-2})	Abundance ($N/N_{H_2} \times 10^{-4}$)
(1)	(2)	(3)	(4)	(5)
CO(0-1)	115.27120180	20.49	0.33	1
CH_3CH_2CN(8-9)	116.49326440	0.21	0.017	0.06
CH_3CH_2CN(12-13)	116.52546900	0.35	0.017	0.06
CN(0-1)	113.48812020	31.9	0.027	0.1
	113.17050200	15.95	0.06	0.2
CH_3CH_2CN(6-7)	97.89123480	4.89	7.38	27.9
CH_3SH(30-31)	97.89291380	4.89	800	300

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