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The molecular torus in NGC 1052

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The existence of an obscuring torus in the cores of AGN is a key ingredient to the unified scenario, in which a single physical model is used to reproduce radio-quiet type 1 AGN (with broad lines) and type 2 AGN (without broad lines). In the standard picture the torus is an axi-symmetric absorber containing large amounts of molecular gas and dust, and surrounding the accretion disk. Whilst the unified scheme has proven very successful, little is still known about the physical properties of the torus itself. The study of centimetre-wave molecular absorption against strong continuum sources can be used to test these models, but searches for absorption lines of common molecules like CO and OH have mostly yielded non-detections. This has lead to the conclusion that the small-scale molecular tori may not exist. Here, we investigate the effects of radiative excitation due to the proximity of a bright radio nucleus, which can suppress the opacity in the lowest transitions causing excitation into higher states. To explore these effects, we conducted a spectral-line VLBI observation searching for excited OH at 13.4 GHz towards the core of NGC 1052 and obtained a detection. These observations confirm the presence of a molecular torus in this source. The absorption profile suggests an obscuration of the inner jet in a compact region confined within < 0.3 pc from the core, which is likely to be associated with a geometrically thick plasma torus and is located 0.1 pc from the eastern jet and 0.7 pc from the western jet.

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1. Radiative excitation and the molecular torus

1.1 The molecular torus

The unified scheme of AGN aims at unifying two or more classes of objects by suggesting that they are a single type of physical object observed from different angles. In this unified scheme, an absorber consisting of parsec-scale molecular gas as well as hot dust surrounds the central engine (e.g. [1]), thus blocking the broad line region (BLR) from direct view. The geometry of the absorber is thought to be either that of a torus or of a warped disk. Indeed, small-scale (< 1 pc), clumpy tori have been detected through interferometric infrared studies of the hot dust emission in the cores of AGN (e.g. [2],[3]), and water-vapour masers could map the central few parsecs of active nuclei [4], tracing the rotation of nuclear accretion disks. However, the small thickness of these disks cannot account for the frequently observed spatial obscuration and little evidence has emerged for the larger-scale (> 1 pc) molecular components invoked in torus models.

Studies of the molecular absorption and emission can give further clues. The high column densities required for effective obscuration offer us the prospect of finding tori by looking for molecular absorption lines at centimetre wavelengths against a strong nuclear radio synchrotron core. The existence of circumnuclear gas in AGN has been supported by large-scale H I absorption measurements of type 2 radio sources, and observations of CO carried out toward NGC 1068 by e.g. Schinnerer et al. [5] trace rotating molecular clouds with an outer radius of 13 pc from the nucleus. Moreover, from the spectral index distribution, evidence for free-free absorption gives a further indication for obscuration along the line of sight toward the core. Free-free absorption is caused by an ionized region around the central engine, possibly forming an accretion disk or torus.

Despite many efforts to directly detect the expected molecular absorption or emission in a number of surveys, only in very few cases could molecular absorption be confirmed. Single-dish OH surveys at 18 cm wavelength of several hundred galaxies revealed OH absorption towards two Seyferts only and maser emission in five [6], [7], [8]. The lack of absorption in these surveys seems to be in contradiction with the unified scheme, as extragalactic OH has been shown to display the characteristics of the circumnuclear environment of active galaxies. Tracing the low density component of the molecular environment in the inner few hundred parsecs OH should therefore be better tracer for the extended molecular torus.

There are a few possible causes for the absence of detectable molecular absorption: (1) the molecular abundances are low due to harsh conditions, (2) the gas temperature and hence state of excitation due to collisional excitation are high enough that the lowest transitions probe an undetectably small fraction of the molecules and (3) the non-thermal continuum radiation of the central source enforces a high excitation temperature, much higher than the kinetic temperature, that suppresses the opacity in the lowest transitions [9]. Before concluding that tori are not molecular, the last of these points, the radiative coupling to the non-thermal continuum, deserves further attention and influences the selection of the most favourable transitions to observe.

1.2 Radiative excitation in the torus

Assuming that the ionization parameter within the torus is low enough for the gas to be molecular and if the torus is sufficiently compact, the molecules can radiatively couple to the bright radio continuum source increasing the rotation temperature and lowering the fractional population of the low J-levels, increasing the excitation temperature of the lower rotational levels, and thus suppressing the absorption in the lower transitions [9].

Calculations done for radiative coupling of OH at 1.67 GHz were carried out by Black [10], showing that OH suffers similar excitation effects that may make its detection also difficult towards the cores of AGN with strong radio continuum emission. Black [10] calculated that the opacity in the 1.67 GHz transitions of OH located 10 pc from the AGN will be suppressed by a factor of 10^3 due to the proximity of the bright nuclear radio continuum source. In contrast, the opacity of the 6 GHz transitions will be suppressed by a factor of 10^2, and the opacity of the 13.4 GHz transition will increase slightly by a factor of two. Thus, if the molecular gas is concentrated in a 1 pc to 10 pc scale torus, then radiative excitation effects should be strong at 1.67 GHz and the gas would then be best found by looking at higher-order transitions.

2. Observations

To explore these effects we modified the search strategy for molecular absorption, searching for excited OH at 13.4 GHz in NGC 1052 with the VLBA. NGC 1052 is a prime candidate to search for excited OH, as there is observational evidence for obscuration towards the core.

NGC 1052 is a galaxy with a 13.4 GHz continuum flux density of 1 Jy to 2 Jy arising from a central radio source of size ~ 10 mas (see Fig. 1). Free-free absorption was found in the inner few parsecs around the nucleus [11], [12], apparently due to a geometrically-thick, patchy structure oriented roughly orthogonal to the jets. Since the western jet is covered more deeply and extensively, it is thought to be receding. Opacities have been measured implying a dense ($n_{\mathrm{e}} = 10^5\,\mathrm{cm}^{-3}$) plasma associated with the central 0.5 pc [13].

VLBA observations with the aim of looking for the highly excited ${}^2\Pi_{\frac{3}{2}}, J = \frac{7}{2}$ states of OH (290 K above the ground-level) at 13441 MHz (F = 4 – 4) and 13435 MHz (F =3 – 3) were made on December 6 and 8, 2005 for 7 h each day (including observations of the calibrators). Observations were carried out with four IFs to observe two polarizations with 16 MHz bandwidth, corresponding to 357 $\mathrm{km\,s^{-1}}$, per IF. The IFs were centred at the source frame rest frequencies of 13.434 GHz and 13.441 GHz, providing a total bandwindth of 19 MHz and 13 MHz of overlap. With 256 channels per IF, a spectral line velocity resolution of 1.4 $\mathrm{km\,s^{-1}}$ per channel was obtained. The total velocity range was 700 km s^{-1} when two IFs were placed adjacent to each other to form a single spectrum, which allowed one third of the channels to measure the line-free continuum level. The data were calibrated using standard phase and amplitude calibration, using 0423-01 and 3C 84 for bandpass calibration.

3. Results and discussion

The continuum image of NGC 1052 from the VLBA observations is shown in Fig. 1. At 13.4 GHz the source structure is extended, with jets extending east–west up to $\sim$ 1 pc from the core, although some low-level emission was seen further out extending up to $\sim$ 2 pc from the core. The maximum peak flux density of the source is 436 $\mathrm{mJy\,beam^{-1}}$, the noise in the map is 0.7 $\mathrm{mJy\,beam^{-1}}$. Absorption of the rotationally excited OH transition at 13.434 GHz was clearly detected towards the centre of NGC 1052. Absorption was detected predominantly towards the

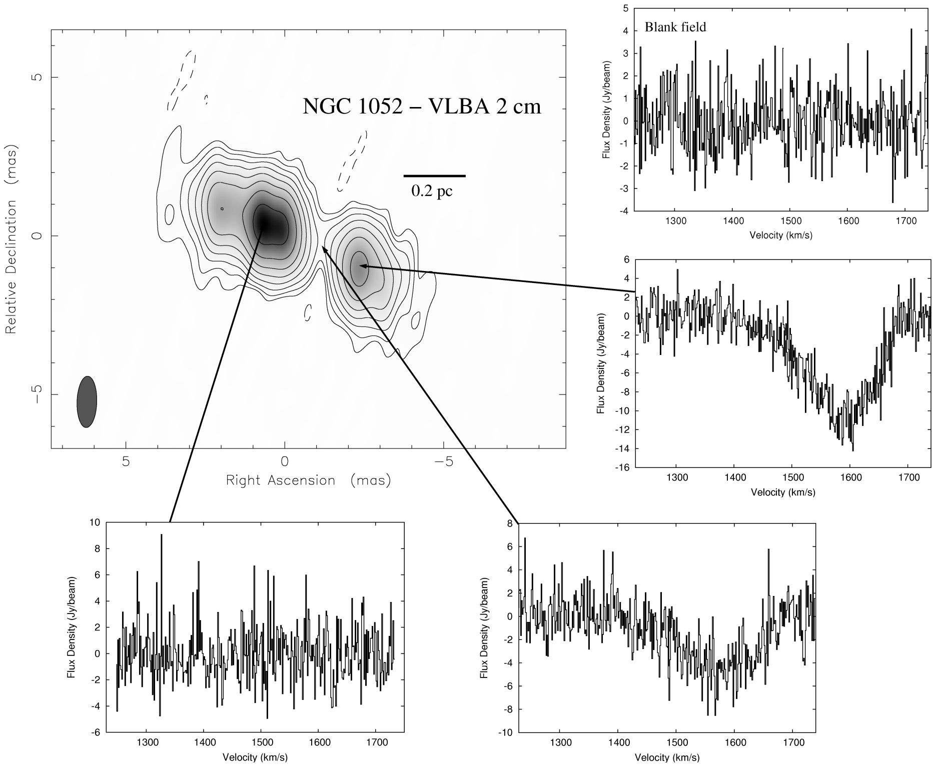

Figure 1: VLBA image of NGC 1052 at 13.4 GHz. The synthesized beam is (1.62×0.62) mas^2. The image is contoured at -3, 3, 6, 12, 24, 48, 96 times the map noise of 0.7 mJy beam^{-1}. The maximum in the map is 0.436 Jy beam^{-1}. The panels show a montage with selected OH absorption spectra. The top right panel shows the absorption spectrum integrated over a blank field off the source.

western jet (the counter-jet), whereas none was found towards the eastern jet. The apparent optical depth of the spectrum taken towards the counter-jet derived from the ratios of intensities of peak absorption and adjacent continuum is $\tau \sim 0.26$ with a line FWHM corresponding to $\sim 200\,\mathrm{km\,s^{-1}}$. Towards the "gap" between the jet and the counter-jet, the apparent optical depth of the line was $\tau \sim 0.23$. Although the absorption line has a line flux density of -4.8 mJy at the gap which is less than the line flux density at the counter jet, -11.2 mJy, the optical depths are comparable in the two regions, due to weaker continuum in the gap.

The absorption profile observed with the VLBA suggests an obscuration of the inner jet region in an extremely compact region confined within a distance < 0.3 pc from the core. The proximity to the core is further supported by the large line width. The line is relatively broad compared to the OH absorption spectrum associated with the nuclear region observed at 1.67 GHz [14], [12]. Also, H I absorption, with different velocity components (a high velocity system and sharper features at low velocity), has been associated with the central few pc region. The 1.67 GHz OH and H I gas are thought to be co-located due to the similarity of their absorption profiles. CO, HCN, and HCO$^+$ have been detected in absorption in this source [15], with line profiles that are broader than the H I and 1.67 GHz OH profiles, and are more similar to our 13.4 GHz spectrum. The broader widths of these lines are due to lower free-free opacity at mm-wavelengths which exposes higher-velocity material nearer to the nucleus. The different velocity peaks at the different transitions trace slightly different components of the nuclear region. However, they share a common overall velocity range. NGC 1052 is also an H_2O megamaser galaxy. The maser originating at 0.1 pc to 0.2 pc to the west of the core in the counterjet is thought to be excited by an interaction of the jet with the surrounding medium [16]. The positions of the H_2O masers are coincident with the position at which the OH absorption presented here is observed, and it seems likely that these molecules, and the gas observed at mm-wavelength coexist.

Free-free absorption in NGC 1052 leads to an asymmetric central gap that opens up towards lower frequencies. The western presumably receding jet is partially obscured by free-free absorption, at least in the inner parsec. The free-free absorption towards the western jet and the gap between eastern and the western jet have been explained with the presence of a geometrically thick plasma torus and a geometry of the jet-torus system in which 0.1 pc of the eastern jet and 0.7 pc of the western jet are obscured [11]. The OH absorption observed here confirms this expectation and appears to be associated with the inferred torus in this source. The H I atomic gas absorption, on the other hand, is distributed in front of the approaching, as well as the receding, jet and has sub-pc scale structure. While the OH gas at 1.67 GHz and the H I gas are likely to be co-located, they do not seem to coincide with the H_2O masers, even though these are at the same velocity [16]. Although the apparent optical depth of the 1.67 GHz line was measured to be $\tau = 0.25$, and is comparable to the optical depth of the 13.4 GHz line, these OH lines probably arise in different regions, that is, we are here tracing gas which is more compact and closer to the nuclear engine. It is remarkable how in the inner parsec around the AGN it appears possible for some molecular and atomic clouds to preserve a relatively quiescent existence.

4. Conclusions

We report here the detection of excited OH at 13.4 GHz towards the core of NGC 1052. Absorption was observed towards the western jet of the source, whereas none was found towards the eastern jet. The optical depth of the absorption line was $\tau \sim 0.26$ with a line FWHM of $\sim 200\,\mathrm{km\,s^{-1}}$. The absorption profile suggests obscuration of the inner jet in a compact region confined within < 0.3 pc from the core. The vicinity to the core is further supported by the large width of the line. The gas is likely to be associated with a geometrically thick plasma torus, which has been inferred from free-free absorption and is located 0.1 pc from the eastern jet and 0.7 pc from the western jet. Also, OH seems to be co-located with the H_2O gas and perhaps with the more compact clouds of CO, HCN, and HCO^+, but not with the H I and OH gas observed at 1.67 GHz, which is more evenly distributed around the nuclear region.

These observations confirm that radiative excitation effects and higher-order transitions should be taken into account when studying the molecular properties in the innermost regions of AGN. The detection of excited OH at 13.4 GHz provides independent evidence for a molecular torus at the centre NGC 1052 on parsec scale.

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