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ORIGINAL ARTICLE

Molecular absorptions in high-z objects

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Abstract Molecular absorption lines measured along the line of sight of distant quasars are important probes of the gas evolution in galaxies as a function of redshift. A review is made of the handful of molecular absorbing systems studied so far, with the present sensitivity of mm instruments. They produce information on the chemistry of the ISM at z $\sim$ 1, the physical state of the gas, in terms of clumpiness, density and temperature. The CMB temperature can be derived as a function of z, and also any possible variations of fundamental constants can be constrained. With the sensitivity of ALMA, many more absorbing systems can be studied, for which some predictions and perspectives are described.

Keywords Galaxies: interstellar medium · Quasars: absorption lines · Galaxies: evolution · Galaxies: high-redshift

1 Introduction

Molecular absorptions at intermediate redshift began to be studied more than a decade ago, after the discovery of CO absorption in front of the BL Lac object PKS1413+135 at z = 0.25 (Wiklind and Combes 1994). Although many groups undertook active searches, there are still now only 5 molecular absorbing systems detected at high z: PKS1413+135 and B3 1504+377, which are self-absorbing systems, and 3 gravitational lens systems B0218+357, PKS1830-211, PMN J0134-0931 (with OH only). Table 1 summarises the properties of these systems, together with the few local extra-galactic ones.

With respect to emission, absorption measurements are quite sensitive, even to a small amount of molecular gas along the line of sight. The detection depends mainly on the background source intensity, and the rarity of the detections until now is due to that of strong millimetric radio sources. Due to its sensitivity increase, there could be $\sim$30–100 times more sources detected with ALMA.

1.1 Scientific goals

The study of molecular absorbing systems at intermediate and high redshift allows to reach several goals:

- to detect molecules at high z with much more sensitivity (down to 1 $M_\odot$) than with emission searches and with complementary insight in physical conditions
- to study the evolution with z of chemical abondances: not only CO lines are detectable, but molecular surveys are possible
- to measure the CMB temperature as a function of redshift, to independently estimate the Hubble constant, through the time delay between two gravitational lens images
- to probe the variation of fundamental constants (α, g_p, $\mu = m_e/m_p$). Several theories based on superstrings, Kaluza-Klein theory, or compactified extra-dimensions, predict spatio-temporal variations of the fundamental constants (Uzan 2003; Murphy et al. 2003; Chand et al. 2006).

1.2 New local absorptions

The Centaurus A (NGC 5128) dust lane is well known to absorb in front of the strong internal radio source, and the absorption is diluted in the emission for the CO lines (the same

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Table 1 Brief census of molecular absorbers in radio

Source	z_a[1]	z_e[2]	N_c[3]	$N(H_2)$[4] cm^{-2}	ΔV[5] km/s	Molecules
Cen-A	0.0018	0.0018	17	2.0×10^{20}	80.	CO, HCN, HCO^+, N_2H^+, CS...
3C 293	0.045	0.045	3	1.5×10^{19}	40.	CO, HCN, HCO^+
4C 31.04	0.06	0.06	2	1.0×10^{19}	120.	CO, HCN, HCO^+
PKS1413+135	0.247	0.247	2	4.6×10^{20}	2.	CO, HCN, HCO^+, HNC
B3 1504+377	0.673	0.673	2	1.2×10^{21}	75.	CO, HCN, HCO^+, HNC
B 0218+357	0.685	0.94	1	4.0×10^{23}	20.	CO, HCN, HCO^+, H_2O, NH_3, H_2CO
PMN J0134-0931	0.765	2.22	3	–	100.	OH
PKS1830-211	0.885	2.51	2	4.0×10^{22}	40.	CO, HCN, HCO^+, N_2H^+, CS...

[1]Redshift of absorption lines

[2]Redshift of background continuum source

[3]Number of components in absorption

[4]Maximum H_2 column density over components

[5]Maximum velocity width

phenomenon is occurring also for M82 in a lesser extent). The absorption is however completely detached for the high density tracers, like HCO^+ and HCN (Wiklind and Combes 1997a). The absorption extends over very broad wings, suggesting perturbed kinematics, or outflows.

Recently, very broad absorption extending to the blue wing was observed in the HI line towards 3C 293 by Morganti et al. (2003): the total width of 1400 km/s absorption implies neutral gas entrained in the radio jet towards the observer. This observation is confirming theoretical expectations of AGN feedback on the interstellar medium of the host galaxies. The 3C 293 host galaxy has already been observed in the CO line, and found quite rich in molecular gas (Evans et al. 1999). Garcia-Burillo et al. (2006) have observed this strong radio source at 1 mm and 3 mm with the IRAM interferometer, and found several absorption components, in CO, HCO^+ and HCN. The high resolution helps to disentangle absorption from emission in the nucleus. The shape of the CO emission map suggests an interaction between the jet and the ISM, able to redirect the jet, and produce the HI outflow. The molecular lines are however not as broad as the HI line. The HCO^+ absorption has not only a component in front of the nucleus, but also in front of the radio jet. Strong HCO^+ and CO absorptions are also detected in front of 4C 31.04, clearly on the blue-side of the total spectrum, delineated by emission.

2 Higher redshift absorptions

After the first system PKS 1413+135, another internal absorption was detected with several components in B3 1504+377 (Wiklind and Combes 1996a). Then the absorption was detected in intervening systems, which amplifies the background quasar by lensing effects (B0218 +357, Wiklind and Combes 1995; Menten and Reid 1996; Gerin et al. 1997); in front of PKS1830-211, the redshift of the lens was found by sweeping the band over 14 GHz. This meant observing with 14 tunings, before detecting 2 absorption lines and determining unambiguously the redshift (Wiklind and Combes 1996b). The third gravitationally lensed quasar is PMN J0134-0931, detected only in the OH lines, but not in CO or HCO^+ (Kanekar et al. 2005).

The absorbing redshifts range up to $z \sim 1$ (the background quasar up to $z \sim 2$), and it becomes difficult to find higher redshift radio sources, that are strong enough in the millimeter domain. The synchroton spectrum is frequently steep, and the intensity fades at high frequency. This means that the K-correction plays a very negative role here. In addition, the number of quasars per comoving volume is expected to decrease after $z = 2$. A solution is to follow the high-z quasars and their emission in red-shifting our observations, down to the centimeter domain.

With the present instrumentation at IRAM, a full search was undertaken with selection of candidates as:

1—strong mm source (at least 0.15 Jy at 3 mm), about 150 sources, searching at the host redshift when known,

2—or at a different z, if already an absorption is detected in HI-21 cm, or DLAs, or MgII or CaII (e.g. Carilli et al. 1993),

3—all mm-strong radio-source with a known gravitational lens (VLBI) (Webster et al. 1995; Stickel and Kühr 1993; Jackson and Browne 2007).

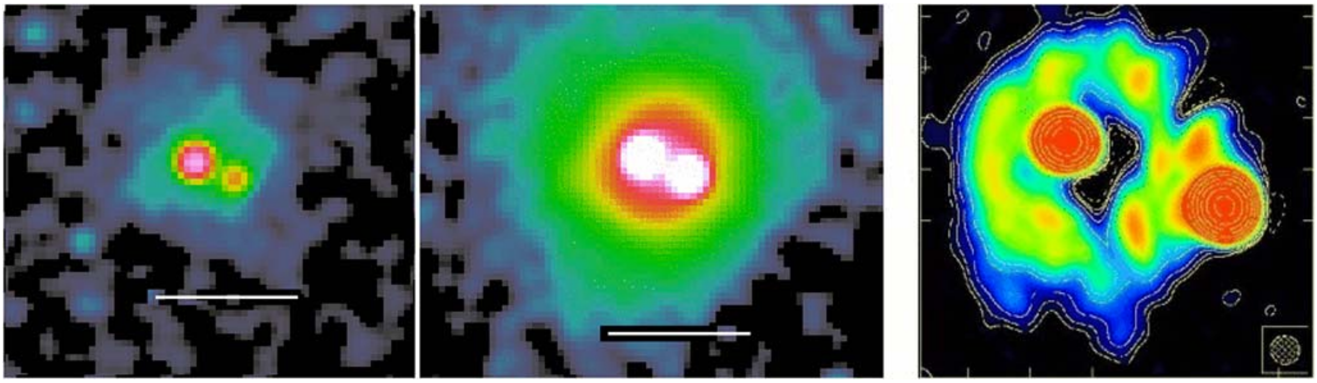

Fig. 1 The B0218+357 gravitational lens imaged by the HST in 2 bands, V (*left*) and H (*middle*, Jackson et al. 2000 and the CASTLES collaboration; in the *left* and *middle panels*, the *white bar* is 1 arcsec), and in radio with JIVE (*right*, Biggs et al. 1999). The distance between the two gravitational images is 0.335 arcsec

This survey led to mostly negative results, meaning that a much larger sample of radio-sources, and much more sensitivity is required to find more molecular absorption systems.

2.1 Absorption in the quasar host

The BL Lac PKS1413+135 at $z = 0.247$ is an edge-on galaxy, and the nucleus is obscured by $Av > 30$ mag (McHardy et al. 1994). On the line of sight, a very narrow absorption <1 km/s has been found: since the continuum source is highly variable, it was possible to probe the small scale structure of the interstellar medium (Wiklind and Combes 1997b).

Towards B3 1504+377 at $z = 0.672$, 7 different molecular absorption lines are detected, with a large separation 330 km/s, which could be explained by a highly non-circular motions in the center, with a more regular spiral arm in the outer parts. The observed HNC/HCN absorption ratio implies thermalization of the gas, with the excitation temperature equal to the kinetic one. As is frequently observed in molecular absorptions, the HCO^+ is enhanced by 10–100, which can only be explained by a combination of a diffuse and a clumpy medium (e.g. Lucas and Liszt 1994, 1998).

2.2 Absorption in the intervening lens galaxy

2.2.1 B0218+357

B0218+357 is amplified by a gravitational lens at $z = 0.685$: the source is split in 2 main images A and B, with an Einstein ring (cf Fig. 1). In VLBI, the A and B components reveal a detailed structure, with two bright cores and extended radio jet components (Biggs et al. 2003). It is the absorber with the largest column density around 10^{24} cm^{-2} at maximum. All three CO isotopic lines up to $C^{18}O$ are optically thick (Combes and Wiklind 1995).

This has allowed the search of many molecules, and in particular important ones undetected in our Galaxy due to atmospheric absorption at $z = 0$. Search for O_2 lines at 56, 119, 368 and 424 GHz in the rest frame have led to upper limits $O_2/CO < 2 \times 10^{-3}$ (Combes and Wiklind 1995; Combes et al. 1997), suggesting that most of the oxygen should be in the form of OI. The H_2O molecule at 557 GHz has been detected, and tentatively LiH at 444 GHz in the rest frame (Combes and Wiklind 1997, 1998), with $H_2O/H_2 = 10^{-5}$ and $LiH/H_2 \sim 3 \times 10^{-12}$. NH_3 has been detected at 2 cm (Henkel et al. 2005).

Recent deep HST imagery reveals the lensing galaxy, almost face-on, with spiral arms complicating the lens analysis (York et al. 2005). Due to extinction, the distance between the two images A and B, is 317 mas in optical, while 335 mas in radio. Monitoring the time-delay, together with a lensing model, taking into account the spiral arms, leads to an estimation of the Hubble constant of $H-0 = 70$ km/s/Mpc (while 61 km/s/Mpc if spiral arms are masked out).

2.2.2 PKS1830-211

Towards PKS1830-211, the lensing galaxy at $z = 0.88582$ splits the background source in two images A and B, each absorbed by a different velocity component (Frye et al. 1997; Wiklind and Combes 1998). The intrinsic temporal variability allows to monitor the time delay between the two components.

Even without resolving spatially the two images, it is possible to follow the intensity ratio between the two, since they are absorbing at two different velocities. The IRAM monitoring during 3 years (1 h per week) led to a time delay of 24 ± 5 days, and estimation of $H_0 = 69 \pm 12$ km/s/Mpc (Wiklind and Combes 1999).

The study of a large variety of molecules allows to tackle the evolution of chemical conditions. There does not seem to

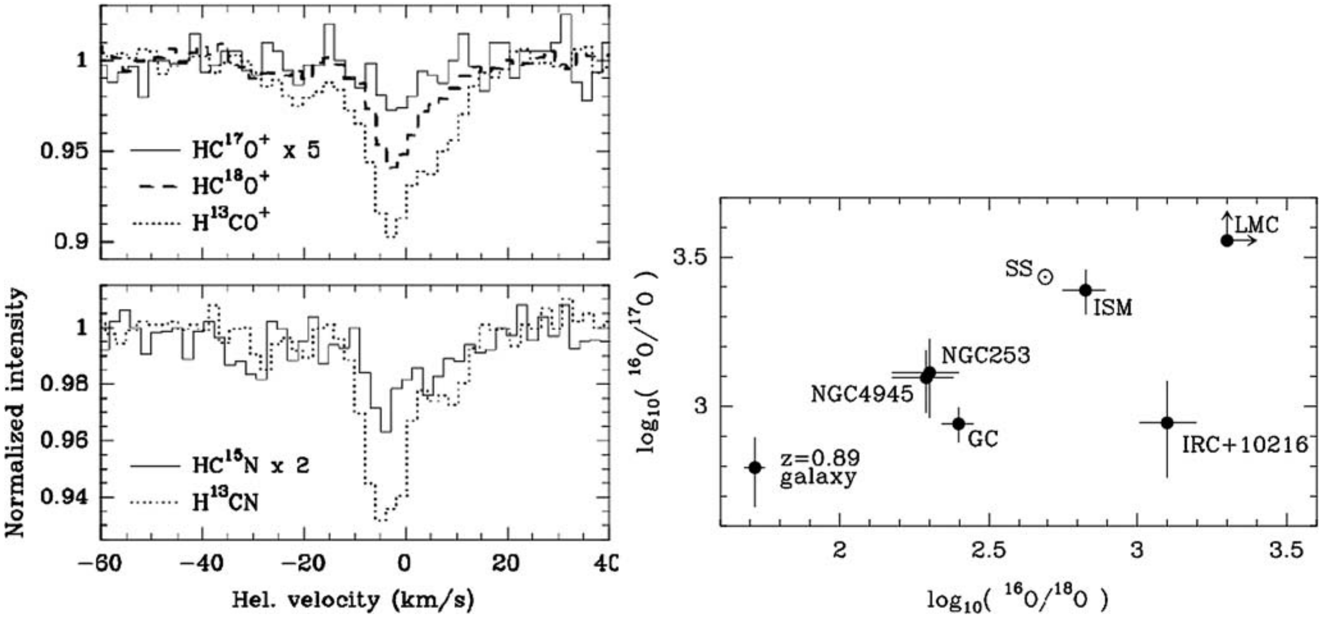

Fig. 2 (*Left*) Molecular absorption lines including isotopes, like ^{15}N, ^{17}O or ^{18}O, in PKS1830-211 by Müller et al. (2006). (*Right*) Oxygen isotopic ratios ^{16}O/^{17}O versus ^{16}O/^{18}O for different sources. The relative abundances of the oxygen isotopes at $z = 0.89$ suggests that enrichment by low mass stars had not yet time to dominate in this young lens galaxy, in front of PKS1830-211

be variations at high z in comparison with $z = 0$ absorptions, but there is a large scatter, even locally (Lucas and Liszt 1994; Liszt et al. 2006).

Upper limits were reported for deuterated molecules (Shah et al. 1999) and for CI (Gerin et al. 1997). A recent survey with the IRAM interferometer of several isotopes (C, N, O or S) begins to find evidence for abundance evolution (Müller et al. 2006, Fig. 2).

Only low excitation diffuse gas is observed on the line of sight of PKS1830-211, the volumic density is so low that $T_{ex} \sim T_{CMB}$. The observation of several lines of the rotational ladder of the same molecule (HCN, HNC, N_2H^+, $H^{13}CO^+$, CS...) can then lead to a measure of T_{CMB}. Millimeter absorptions can then complement the measurement of $T_{CMB}(z)$ obtained from UV H_2 lines (Srianand et al. 2000; Reimers et al. 2003; Cui et al. 2005).

2.2.3 PMN J0134-0931

This recent absorber has been detected in HI and OH lines at GBT (Kanekar et al. 2005), from the $z = 0.7645$ lens in front of the background quasar at $z = 2.22$. The latter is split in 6 apparent images. Surprisingly, only upper limits of HCO^+ or H_2CO lines were obtained on this source, probably due to small-scale structure of the ISM, and very different continuum source extent across the radio spectrum. The absorption system provides a good probe of the fundamental constant variation.

2.3 Variations of constants

Although laboratory measurements and solar system observations (e.g. Olive et al. 2002; Uzan 2003) do not show evidence for time variations of the fundamental constant α, high-z observations have revealed a possible variation over larger time-scales and also with space (Webb et al. 2001; Murphy et al. 2003) with some controversy (Chand et al. 2006; Tzanavaris et al. 2006).

While from Alkali Doublet (CIV, SiII, SiIV, MgII, AlIII, ...) on 22 absorbing systems and the "many-multiplet" method on 143 systems, a positive result $\Delta\alpha/\alpha = (-0.6 \pm 0.1) \times 10^{-5}$ has been claimed (Murphy et al. 2003), this has not been confirmed with the same method, $\Delta\alpha/\alpha = (-0.05 \pm 0.2) \times 10^{-5}$ by Chand et al. (2006), but see Murphy et al. (2006). Independent methods with radio lines are then welcome to better understand the systematics of the various techniques.

The radio domain has the big advantage of heterodyne techniques, with a spectral resolution of 10^6 or more, and dealing with cold gas and narrow lines. Also different constants can be probed, while comparing the optical lines with the HI 21 cm, the OH 18 cm and CO or HCO^+ rotational lines, which depend very differently on α, the electron-proton mass ratio $\mu = m_e/m_p$, or the proton gyromagnetic ratio g_p. Note that Ubachs and Reinhold (2004) and Reinhold et al. (2006) respectively put bounds and report an indication of cosmological variation of μ based on laboratory measurement and reanalysis of H_2 spectra of $\Delta\mu/\mu = (2.0 \pm 0.6) \times 10^{-5}$.

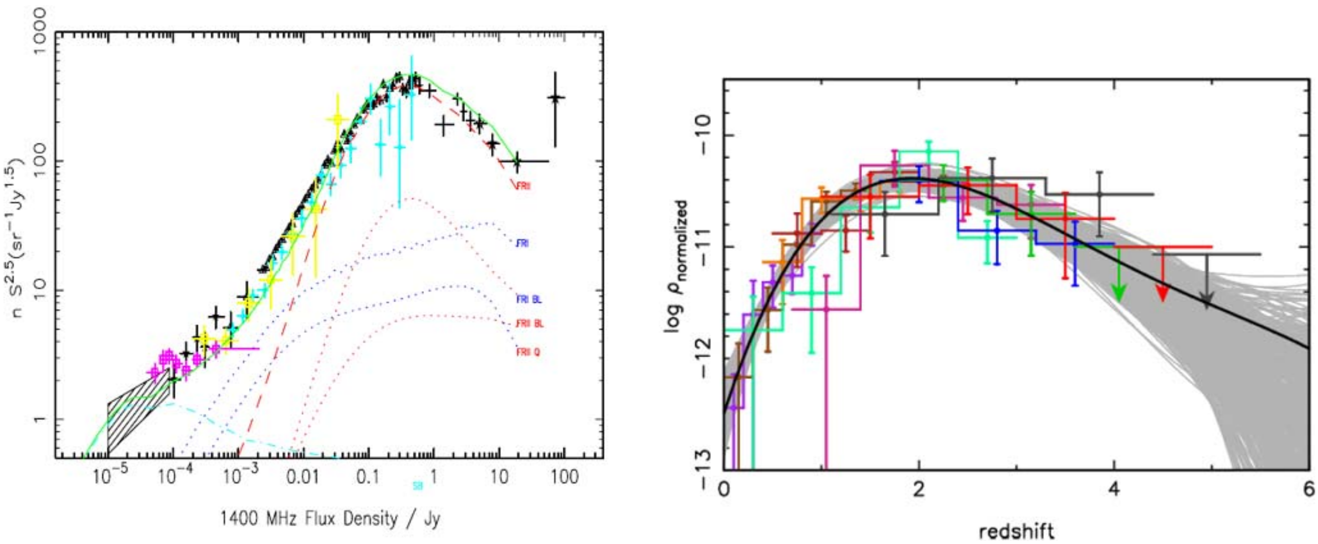

Fig. 3 The distribution of radio continuum sources, from several observed samples (as the Parkes flat-spectrum sample), fitted with models as a function of flux (*Left*, Jackson 2004), and redshift (*Right*, Wall et al. 2005). There is a strong increase in the density of radio-sources until $z = 2$, which translates into a strong increase in density of sources with decreasing flux, above what is expected for the euclidean count (falloff dn/dS as $S^{-5/2}$)

In PKS1413+135, a resolution of 40 m/s is required to resolve the lines, and the obtained upper limits for variations on $y = \alpha^2 g_p \mu$ are $\Delta y/y = (-0.20 \pm 0.20) \times 10^{-5}$ and $\Delta y/y = (-0.16 \pm 0.36) \times 10^{-5}$ for B0218+357 (Murphy et al. 2001). The main systematics is the kinematical bias, i.e. that the different lines do not come exactly from the same material along the line of sight, with the same velocity. Statistics with absorptions of HI and HCO^+ in our own Galaxy in front of remote quasars (Lucas and Liszt 1998) have measured a dispersion of about 1.2 km/s, corresponding to $\Delta y/y = 0.4 \times 10^{-5}$. The results combining lines in PMN J0134-0931 and B0218+357 on $F = g_p[\alpha^2/\mu]^{1.57}$ are $\Delta F/F = (0.44 \pm 0.36^{stat} \pm 1.0^{syst}) \times 10^{-5}$ for $0 < z < 0.7$ (with statistical and systematical errors separated). No variation is detected, while the sensitivity at 2σ on the α variation is $\Delta\alpha/\alpha \sim 6.7 \times 10^{-6}$, and on the mass ratio $\Delta\mu/\mu \sim 1.4 \times 10^{-5}$ over half of the age of the universe (Kanekar et al. 2005). It is then needed to find much more sources with ALMA.

3 Perspectives

The number of molecular absorptions so far (5 at high-z) and also the number of HI-21 cm absorbers (about 50 for $z > 0.1$) is surprisingly low. Why so few radio absorbers? One explanation, at least for the molecular absorptions, is that the high column density expected obscures the background quasars, introducing a strong bias against the optical detection of these remote sources. At least some could be known only in radio, but with no redshift available. Curran et al. (2006) have noticed a strong correlation between the molecular fraction and the red colors of the quasars. Those with molecular absorptions are in general compact flat spectrum sources, where most of the emission is covered. Future searches should concentrate on sub-DLA systems, where the H_2 fraction is higher, as well as metals (Khare et al. 2006; Kulkarni et al. 2006).

Typical first projects with ALMA could be (included in the DRSP):

1— Molecular survey of PKS1413, PKS1830, CenA, in 7 wide priority bands, with spectral resolution of 1–4 km/s;

2—Search for new systems, towards 60 selected radio loud AGNs with mm cont flux >50 mJy, with criteria of obscuration, gravitational lensing and/or suppressed soft X-ray flux. When no redshift is known, the search could be over the entire redshift range using the technique of frequency scanning.

As shown in Fig. 3, it is now well-known that the volumic density of radio quasars peaked around $z = 2$ (Shaver et al. 1996; Wall et al. 2005), and there is a cutoff after $z = 3$. Optical quasars follow the same curve, in a similar way to the star formation history. In parallel, the number of sources as a function of flux N(S) increases well above the euclidean curve in $S^{-1.5}$, and we could expect to detect 1 or 2 orders of magnitude more quasars with ALMA. However at high-z, their millimeter flux is weakened by the non-favorable K-correction (compact and flat-spectrum sources being rare). In this domain, it is interesting to search 3 mm systems at cm wavelengths, with Band 1 and 2 of ALMA in the future.

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