Extended baselines for the IRAM Plateau de Bure interferometer: First results

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ABSTRACT

The line of sight to the quasar B0218+357, one of the most studied lensed systems, intercepts a \( z = 0.68 \) spiral galaxy, which splits its image into two main components A and B, separated by ca. 0.3″, and gives rise to molecular absorption. Although the main absorption component has been shown to arise in front of image A, it is not established whether some absorption from other velocity components is also occurring in front of image B. To tackle this question, we have observed the HCO\(^+(2–1)\) absorption line during the commissioning phase of the new very extended configuration of the Plateau de Bure Interferometer, in order to trace the position of the absorption as a function of frequency. Visibility fitting of the self-calibrated data allowed us to achieve position accuracy between \( \sim 12 \) and 80 mas per velocity component. Our results clearly demonstrate that all the different velocity components of the HCO\(^+(2–1)\) absorption arise in front of the south–west image A of the quasar. We estimate a flux ratio \( f_A/f_B = 4.2^{+0.4}_{-0.2} \) at 106 GHz.

KEY words. galaxies: quasars: individual: B0218+357 – galaxies: quasars: absorption lines – techniques: interferometric

1. Introduction

Molecular absorption at intermediate redshifts has been detected only in a few objects (e.g. Wiklind & Combes 1995, 1996a, 1997, 1998; Kanekar et al. 2005). Among these, three absorption systems are caused by a galaxy lying on the line-of-sight of a quasar and acting as a gravitational lens. Two systems, one in front of PKS1830–211 (at \( z = 0.89 \)), the other in front of B0218+357 (at \( z = 0.68 \)) are detected at millimeter wavelengths in the lines of several molecules, including HCO\(^+\), HCN and H\(_2\)CO.

The light rays associated with the quasar PKS1830–211 form two bright images that probe different regions of the intervening galaxy. This provides information on the latter’s kinematics, its mass, as well as on the physical and chemical conditions in its interstellar medium (Wiklind & Combes 1998; Muller et al. 2006). These two papers showed that the two \( z \sim 0.89 \) absorption components of PKS1830–211 are associated each with one of the two gravitational images.

The second mm-absorption system occurs in the line of sight to B0218+357 and is caused by a galaxy at a redshift of \( z = 0.68466 \) (Browne et al. 1993; Carilli et al. 1993; Wiklind & Combes 1995). Two bright images of the quasar, hereafter referred to as A (to the SW) and B (to the NE), have been resolved at radio cm wavelengths (O’Dea et al. 1992; Patnaik et al. 1993). The distance AB between the two images is \( \sim 0.3″ \), the smallest angular separation among the known galaxy-mass lenses. The flux ratio is \( f_A/f_B \sim 3 \) between 5 GHz and 22 GHz. Image B lies in the center of an Einstein ring whose diameter is similar to the distance AB. Each image reveals intricate substructures at very high angular resolution (Patnaik et al. 1995; Biggs et al. 2003). The constraints provided by the complex image pattern and by the time variability of the background source flux, make of B0218+357 one of the best objects to measure \( H_0 \) at intermediate redshifts (Biggs et al. 2003; Wucknitz et al. 2004; York et al. 2005). Deep ACS/HST observations of B0218+357 by York et al. (2005) reveal that the lensing object is a spiral galaxy seen nearly face-on and whose center lies close to image B, the center of the Einstein ring. According to the lensing model proposed by Wucknitz et al. (2004), image A is located at about 2 kpc from the center of the lensing mass distribution, and image B at 0.4 kpc. HI absorption is detected over a velocity width of about 100 km s\(^{-1}\) (Carilli et al. 1993; Kanekar et al. 2003), in front of image A (Carilli et al. 2000), although some absorption may also occurs in front of the Einstein ring (Kanekar et al. 2003). H\(_2\)CO (212–211) absorption has been observed by Menten & Reid (1996) towards image A, with a total width of \( \sim 12 \) km s\(^{-1}\), much narrower than the HI profile. Because of limited signal-to-noise ratio, they could however not exclude the possibility of absorption in front of B.

Figure 1 shows the HCO\(^+(1–2)\) absorption profile towards B0218+357 observed with a high sensitivity and velocity resolution (Muller et al., in prep.). Like the HCN (1–2) profile, it shows at least four velocity components over a width of 25 km s\(^{-1}\), much broader than that of H\(_2\)CO (212–211). The component with the deepest absorption matches in width and velocity the H\(_2\)CO.
and its bandwidth restricted to 440 MHz in order to avoid contamination by the HCO\(^+\)\((1−2)\) line.

The method used to self-calibrate on the half-resolved continuum source was similar to the one used by Muller et al. (2006), for localizing the absorption components in front of PKS1830−211. The data from November 8th and 9th were calibrated separately, using the GILDAS/CLIC software, with the following procedure: in a first step, the radio frequency (RF) bandpass of L03 and L04 was calibrated directly on the B0218+357 continuum signal. The main purpose of using these absorption-free bands was to correct for short term phase and intensity variations linked to atmosphere fluctuations by self-calibrating on the continuum. L01 was calibrated in RF separately, using low order polynomials (first degree in amplitude and third degree in phase). The narrowness of the absorption line (<10 MHz) with respect to the L01 bandwidth (80 MHz) ensured that the calibration was not badly affected by the absorption features. Note that we choose a baseline-based RF calibration, rather than an antenna-based, as the signal intensities for the longest baselines were severely affected by atmospheric phase decorrelation.

Next, the continuum sub-bands were self-calibrated in amplitude and phase by calculating the complex gains corresponding to a system of two point-like sources separated by \(\Delta RA = 309\) mas, \(\Delta Dec = 128\) mas, and with a flux ratio of 4.2 (a justification of these values will be given in Sect. 3, and/or can be found in the reviews by Wucknitz et al. 2004; Mittal et al. 2006a,b). The total continuum intensity (~0.4 Jy) was normalized to unity. The gains calculated for the continuum sub-bands were then applied to the visibilities of the L01 sub-band channels. Finally, the continuum visibilities, as derived from the double-source model, were subtracted from the calibrated L01 visibilities.

The calibrated L01 datasets from November 8th and 9th were then combined. The visibilities corresponding to uv radii larger than 200 m were fitted, channel by channel, with a single point-like source representing the position and strength of the absorption signal. Visibilities with shorter uv radii were discarded, as they bring little information on the signal position. The fitted source intensities showed a small offset (~10% of the total continuum) with respect to zero (the continuum level as defined from the continuum sub-bands) — probably the result of residual IF and/or RF bandpass calibration errors. This was taken care of by averaging the visibilities of the L01 channels that are free of any absorption and by subtracting the so-computed residual continuum visibility from all L01 channels. The fit of the point-like absorption sources was then repeated.

Figure 2 shows the result of the final fits. The upper plot (i) shows the absorption profile as a function of velocity, while the two middle plots (ii and iii) show the position of the absorption (or, more exactly, the position of the centroid of the absorption) as a function of velocity. The removal of the continuum insures that zero intensity (0) and zero offset (0.0) effectively correspond to the intensity and position of the centroid of the continuum sources. The source position accuracy in the individual velocity channels was calculated by the GILDAS fitting routine UVFIT. It can be crudely expressed as \(-\theta_{\text{beam}} / 2 \times \text{SNR}\), where \(\theta_{\text{beam}}\) is the FWHP of the synthesized beam (~1.2 \times 0.7\"), PA 176") and SNR, the signal-to-noise ratio on the source intensity. The noise level, per 0.9 km s\(^{-1}\) velocity channel, is 3.4% of the continuum intensity. For all channels with absorption signal (~10 < \(v_{\text{HEL}} < +12\) km s\(^{-1}\)), the fitted phases indicates that, within the uncertainties, the absorption arises from a small size region that coincides in position with image A. We further
has a steeper spectrum than the core and its emission, which is already weak in the radio domain should be negligibly at millimeter wavelengths. The relevant size of the background continuum, regarding millimeter absorption, should be <4 mas$^2$.

Assuming a flat universe, with standard cosmological parameters ($H_0 = 70$ km $s^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$), the angular size scale is 7.1 kpc/$z$ at a redshift $z = 0.68$. The mm continuum emission of image A should therefore have an extent lower than $\sim 30$ pc$^2$. This value, corrected from the filling factor, gives an estimate of the size of the molecular absorbing clouds.

It is difficult to determine a direct value of the flux ratio $f_A/f_B$ from our current data. Nevertheless, we have repeated the self-calibration procedure described in Sect. 2, by varying the flux ratio in the source model. The fitted positions of the absorption, averaged over $V_{HEL} = -10$ to $+12$ km $s^{-1}$, were then compared to the position of image A set by the source model (see Fig. 3). Given the size of the continuum source, the average position of the absorption is consistent with the position of image A for $f_A/f_B = 4.2^{+1.0}_{-1.2}$. We emphasize at this point that the average position derived in this way changes by less than $\pm 20$ mas when $f_A/f_B$ varies from 3 to 6, i.e. by the range of possible $f_A/f_B$ ratios, so that our conclusion that all the absorption arises in front of A is robust. Similarly, the self-calibration method that we have used depends little on the continuum source model, in particular on the distance between A and B, so that the uncertainties on this distance do not affect our results.

Although indirect, our measurement of the flux ratio $f_A/f_B$ is the first at frequencies higher than 22 GHz. The value of 4.2 is slightly higher than those measured at 15 and 22 GHz with the VLA (O’Dea et al. 1992; Patnaik et al. 1993; Biggs et al. 1999), and almost twice higher than those observed around 2 GHz (Mittal et al. 2006a). This is consistent with the model developed by Mittal et al. (2006b), where image A is obscured at radio frequencies by a HII region associated with the molecular cloud. We note that the $f_A/f_B$ ratio might be affected by the time variability of the quasar, due to the time difference $\Delta t$ between the transit times of the light in A and B. The time delay, however, is relatively short ($\Delta t \sim 10$ days, Biggs et al. 1999), making the chance of a factor of 1.5–2 variation of the quasar intensity in less than $\Delta t$ rather unlikely.

Adopting $f_A/f_B = 4.2$ and assuming a filling factor $f_c = 1$, we derive a maximum optical depth $\tau_{\text{max}} = 1.5$ for component c, i.e. the peak opacity is large. Conversely, a lower limit to the filling factor $f_c$ can be derived by assuming $\tau_{\text{max}} \rightarrow \infty$; this yields $f_c \geq 0.77$. The H$_2$CO (Menten & Reid 1996), NH$_3$ (Henkel et al. 2005) and H$_2$O (Combes & Wiklind 1997) absorptions are probably caused by the same cloud as component c. For the other velocity components, the filling factors and/or the peak opacities must be lower. A filling factor $f_c \approx 0.9$ is consistent with the fact that image A, despite a high column density of absorbing gas, is strongly attenuated on optical V-band images, with respect to $H$-band images, but still visible. It might also naturally explain why the optical distance AB ($\sim 317$ mas, York et al. 2005) appears lower than in radio ($\sim 334$ mas). The optical barycenter of image A should indeed be shifted closer to image B, if the absorption occurs mostly on the opposite border.

By co-adding all our observations in the compact configuration of the PdBI at the frequency of the HCO$^+$(1–2) line, we do not detect any new absorption feature, outside the $V_{HEL} = -10$ to $+12$ km $s^{-1}$ components just described, over the range $V_{HEL} = -200$ to $+1300$ km $s^{-1}$, and this down to a level of $3\sigma = 3.7\%$ of the continuum at a velocity resolution of 7.1 km $s^{-1}$. As the intervening galaxy is seen face-on, it is unlikely that the difference in velocity between positions A and B, located at either sides of the

![Fig. 2. Relative intensity and position of the centroid of the HCO$^+$(1–2) absorption as derived from the fit of a point like-source to the self-calibrated visibilities, for each velocity channel. i) The intensity scale is zero at the continuum level and at $-1$ for full absorption. The profile of the absorption, as fitted in Fig. 1, is overlaid as a dashed line. ii, iii) Position offsets relative to the centroid of the continuum. iv) Position of the four Gaussian velocity components, compared with the locations of the two lensed images of the quasar (grey disks, not to scale).](image-url)
center of the galaxy, is more than 200 km s$^{-1}$. HCO$^+$ is known to be easily detectable in absorption in the Galaxy, even in diffuse molecular clouds (Lucas & Liszt 1996). Therefore, either the region intercepted by the light path associated with image B and located at $\sim$400 pc from the center of the galaxy, is free or almost free of molecular gas ($\tau_{\text{HCO}^+} < 0.2$), or the filling factor is low ($f_f < 0.2$).

### 4. Conclusion

Sensitive observations of the quasar B0218+357 in the HCO$^+$(1–2) line, redshifted by $z = 0.68$, show at least four velocity components in absorption with velocities between $V_{\text{HEL}} = -6$ to $+10$ km s$^{-1}$ and widths $\Delta V = 5$ km s$^{-1}$. By fitting the visibility obtained from new observations with the very extended configuration of the Plateau de Bure Interferometer, we show unequivocally that all these components arise in front of the SW gravitational image (A) of the quasar. We see no other HCO$^+$ absorption components over a range $V_{\text{HEL}} = -200$ to $+1300$ km s$^{-1}$, that could arise from image A, from the NE image B, or from the weak Einstein ring visible at radio frequencies. This implies either a low average column density of HCO$^+$ ($\tau < 0.2$) in front of B and, presumably, a low average molecular hydrogen column density, or a low filling factor ($f_f < 0.2$). We derive a flux ratio $f_A/f_B = 4.2^{+1.0}_{-0.8}$ for the two main components, A and B, at 106 GHz, which is slightly higher than those derived between 15 and 22 GHz and almost twice larger than observed at frequencies around 2 GHz. This measurement, strictly speaking, applies only to Nov. 8 and 9, 2005, the dates of our extended configuration observations.

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### References

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**Table 1.** Average positions of the different absorption components. For comparison, the positions of images A and B, as fixed in our continuum source model, are indicated. Offsets are given relatively to the barycenter of the continuum emission.

<table>
<thead>
<tr>
<th>Velocity component</th>
<th>$V_{\text{HEL}}$ (km s$^{-1}$)</th>
<th>Absorption depth</th>
<th>$\Delta V$ (km s$^{-1}$)</th>
<th>RA offset (mas)</th>
<th>Dec offset (mas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>$-6.3$</td>
<td>0.31</td>
<td>4.7</td>
<td>$-84 \pm 36$</td>
<td>$+28 \pm 75$</td>
</tr>
<tr>
<td>b</td>
<td>$-0.3$</td>
<td>0.32</td>
<td>4.5</td>
<td>$-73 \pm 24$</td>
<td>$-28 \pm 51$</td>
</tr>
<tr>
<td>c</td>
<td>$+5.9$</td>
<td>0.63</td>
<td>4.5</td>
<td>$-60 \pm 12$</td>
<td>$-11 \pm 26$</td>
</tr>
<tr>
<td>d</td>
<td>$+10.3$</td>
<td>0.30</td>
<td>4.4</td>
<td>$-57 \pm 38$</td>
<td>$-27 \pm 79$</td>
</tr>
<tr>
<td>a+b+c+d</td>
<td>$-10$ to $+12$</td>
<td></td>
<td></td>
<td>$-61 \pm 15$</td>
<td>$-15 \pm 32$</td>
</tr>
<tr>
<td>Image A</td>
<td>$-59$</td>
<td>$-25$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Image B</td>
<td>$+250$</td>
<td>$+103$</td>
<td></td>
<td></td>
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</tr>
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</table>

† From the fit of the spectrum obtained in the compact configuration (cf. Fig. 1).
‡ With respect to the total continuum intensity.