Observation of H$_2$O in a strongly lensed Herschel-ATLAS source at $z = 2.3^*$

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1. Introduction

Gravitationally lensed sources have played an important role in infrared and submillimeter studies of high-$z$ galaxies since the discovery of IRAS FSC10214+4724 (hereafter IRAS F10214; Rowan-Robinson et al. 1991). The studies of this and two other bright strongly-lensed QSOs, APM 08279+5255 (Downes et al. 1999) and the Cloverleaf (H1413+117; Barvainis et al. 1994), demonstrate the utility of using high gravitational magnification to investigate the detailed properties of distant galaxies. These sources allowed pioneering detections of the infrared and submillimeter continuum and lines of CO, HCN, HNC, and H$_2$O (see e.g., Solomon & Vanden Bout 2005; Guélin et al. 2007; Riechers et al. 2010, 2011a). These three lensed sources also provided the first few spatially resolved measurements on scales of hundreds of parsecs. Before Herschel these sources were without peer, except for SMMJ2135–0102, MM 18423+5938 and SXP1100.001 (Swinbank et al. 2010; Lestrade et al. 2010; Ikarashi et al. 2010).

Now the wide area surveys from space – especially H-ATLAS and HerMES with Herschel, which will observe 570deg$^2$ and 70deg$^2$, respectively (Eales et al. 2010; Oliver et al. 2010) – and from the ground, for example, with the South Pole Telescope (Vieira et al. 2010), are increasing the area of submillimeter surveys by factors of hundreds over previous surveys. Correspondingly, we expect that the number of strongly lensed submillimeter sources will also increase by a very large factor. From the analysis and intensive follow-up of the five strongest lenses found in the H-ATLAS science demonstration (SDP) field of 14.5 deg$^2$ (Negrello et al. 2010, hereafter Ne10), the H-ATLAS team has shown that these lenses are relatively easy to identify. With $S_{240,\mu m} > 100\, mJy$ and $S_{1.2mm} > 10\, mJy$, their number exceeds that of the unlensed high-$z$ submillimeter sources (Negrello et al. 2007). The number of similar high-$z$ strongly lensed galaxies in the full H-ATLAS survey will be larger than 100.

CO lines are almost the only molecular lines currently detected with the very broad band spectrometers such as Z-Spec (Lupu et al. 2010, hereafter Lu10; Scott et al. 2011) and Zpectrometer (Frazier et al. 2011) and with interferometers (Cox et al. 2011; Riechers et al. 2011b; Leeuw et al., in prep.). Apart from ~20 CO-line detections in high-$z$ Herschel galaxies, the only other molecule detection reported in these sources is the tentative detection with Z-Spec of the emission line of para-H$_2$O $2_0$–$1_1$ (rest LST frequency 987.93 GHz) in the $z = 2.305$ source H-ATLAS J090302.9-014127B – hereafter SDP.17b (Lu10). However, the noise is high in this part of the Z-Spec spectrum and, in addition, the line is partially blended with another strong feature that was identified as CO(5–4) emission from the intervening massive lensing galaxy at $z = 0.942$ H-ATLAS J090302.9-014127A – hereafter SDP.17a – as
discussed in Lu10 and Ne10. Here we report new measurements of the $H_2O\ 2\alpha - 1\alpha$ line in SDP.17b using the IRAM Plateau de Bure interferometer (PdBI), which confirm the line and enable a more detailed study of its properties.

We adopt a cosmology with $H_0 = 71\ \text{km s}^{-1}\ \text{Mpc}^{-1}$, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$ (Spergel et al. 2003).

### 2. Water lines in high-z galaxies

Conducting studies of $H_2O$ in high-$z$ galaxies is important. If is not locked in grains, $H_2O$ may be one of the most abundant molecules in the gas. It is known to be a tracer of the dense, warm gas and possibly of strong infrared radiation because its large dipole and high energy levels make its excitation difficult and sensitive to the interstellar conditions (González-Alfonso et al. 2010, hereafter G-A10).

Spectra from the Infrared Space Observatory (ISO) have shown that the far-infrared $H_2O$ lines are a factor $\geq 50$ stronger than the $H_2O$ lines. Similarly, in the starburst galaxy SDP.17b, where the velocity scale is centred on its observed frequency at 298.93 GHz (corresponding to $z = 2.3049$). The rms noise is $\sim 4.7\ \text{mJy/beam}$ in 31.6 MHz channels. A Gaussian fit to the $H_2O$ spectrum is shown as a solid line while the dotted line shows the underlying dust continuum emission. The $H_2O$ line is clearly asymmetric and not well fit by a Gaussian profile.

![Fig.1. Spectrum of the para $H_2O\ 2\alpha - 1\alpha$ emission line towards SDP.17b, where the velocity scale is centred on its observed frequency at 298.93 GHz (corresponding to $z = 2.3049$). The rms noise is $\sim 4.7\ \text{mJy/beam}$ in 31.6 MHz channels. A Gaussian fit to the $H_2O$ spectrum is shown as a solid line while the dotted line shows the underlying dust continuum emission. The $H_2O$ line is clearly asymmetric and not well fit by a Gaussian profile.](image)

In order to confirm the detection towards SDP.17b of the redshifted $H_2O\ 2\alpha - 1\alpha$ emission line, we used the PdBI with six antennae and the new “Band 4” receiver, which covers the frequency range 277–371 GHz. Because the wide-band correlator, WideX, provides a contiguous frequency coverage of 3.6 GHz in dual polarization, it allowed us to include the frequency of 297 GHz at the edge of the bandpass where Lu10 reported a second strong, but partially blended line, which they identified as the CO($5$–$4$) emission of the lensing galaxy SDP.17a at $z = 0.942 \pm 0.004$.

First observations were made in the compact D-configuration on 2011 January 3 in conditions with good atmospheric phase stability (seeing of $0.7\,\prime\prime$) and reasonable transparency (PWV $\leq 0.5\,\text{mm}$). They were complemented by observations in extended A- and B-configurations in February and March 2011. With a total of $\sim 6.2\,\text{h}$ on-source integration, a strong signal was detected both in the continuum and in the purported $H_2O$ line (Fig. 1). The dust continuum flux density at 1.0 mm is $32.3 \pm 2\,\text{mJy}$, which agrees well with the value derived from Z-Spec by Lu10, and used in the SED fits of Ne10 and Lu10. However, the respective contributions of $\text{SdP.17b and SDP.17a to this value remain uncertain.}$ The maximum flux density and integrated intensity of the $H_2O$ line are $29\,\text{mJy}$ and $7.8 \pm 0.5\,\text{Jy km s}^{-1}$, respectively, with a $FWHM$ of $250 \pm 60\,\text{km s}^{-1}$. The line central frequency of 298.93 GHz corresponds to $z = 2.3049 \pm 0.0006$, which is consistent with the value reported by Lu10, 2.308 $\pm 0.011$.

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Table 1. Observed parameters of the H$_2$O $2_{02}$–$1_{11}$ emission line in SPD.17b

| Source | $v_{\text{rest}}$ [GHz] | $v_{\text{obs}}$ [GHz] | $z$ | $S_a$ [mJy] | $\Delta V_{\text{FWHM}}$ [km s$^{-1}$] | $I$ [Jy km s$^{-1}$] | $L^a$ [10$^{17}$ L$_{\odot}$] | $L^a/10^{10}$ |
|--------|-----------------|-----------------|----|----------|-----------------|----------------|-----------------|-----------------|
| SPD.17b | 987.93 | 298.93 | 2.3049 ± 0.0006 | 29 | 250 ± 60 | 7.8 ± 0.5 | 85 ± 0.6 | 2.5 ± 0.2 |

Notes. Quoted errors are the statistical errors derived from a Gaussian fit to the line profile. (a) Equations (1) and (3) of Solomon et al. (1997). The line luminosities are not corrected for the magnification. Typical amplifications of ~10 (or more) are derived for the lensed sources detected by Herschel (Ne10).

Table 2. Properties of the para H$_2$O $2_{02}$–$1_{11}$ emission line in active galaxies

| Source | $z$ | $I$(H$_2$O)$^a$ [Jy km s$^{-1}$] | $L$(H$_2$O)$^a$ [10$^{17}$ L$_{\odot}$] | $L_{H_2}$/$L_{CO}$ |
|--------|----|-----------------|-----------------|-----------------|
| SPD.17b | 2.305 | 7.8 ± 0.5 | 85/µL$_{\odot}$ | 0.5 ± 0.2 |
| Mrk 231$^b$ | 0.042 | 718 | 2.4 | 0.75 ± 0.23 |
| Cloverleaf$^a$ | 2.565 | 20.3 ± 6.1 | 21(1/µL$_{\odot}$) | 0.4 ± 0.2 |

Notes. (a) H$_2$O $2_{02}$–$1_{11}$ line. (b) $I$(H$_2$O $2_{02}$–$1_{11}$)/$I$(CO(8–7)) from Lu10. (1) G-A10; (2) Bradford et al. (2009).

Compared to the value previously reported by Lu10 of 19 ± 7 Jy km s$^{-1}$, the intensity is lower by a factor 2.4 and marginally consistent within 1.6σ. The relatively low angular resolution (∼1$''$) did not allow us to study the spatial properties of the signal. The source does not seem to be resolved and it is unlikely that significant flux is missed, either from the H$_2$O line or the continuum flux, as shown by the consistency of the latter with the Z-Spec value.

Clearly, there is no other strong line in this spectral range with an intensity approaching that of H$_2$O. In particular, this precludes the presence of a CO(5–4) line of SPD.17a stronger than about 3 Jy km s$^{-1}$, i.e. 1/10 of the tentative detection reported by Lu10 (29 ± 9 Jy km s$^{-1}$), in the redshift range 0.922 < $z$ < 0.944. However, emission from SPD.17a in the CO(5–4) line is not ruled out and could be present at a redshift $z > 0.944$, outside of the bandpass of the current observations.

4. Discussion: high-excitation gas

4.1. Properties of SPD.17b

In order to assess the implication of the detection of H$_2$O emission in SPD.17b, it is important to summarize the current information on the properties of SPD.17b and to consider this source in relation to other submillimeter lensed sources. SPD.17b is one of the five prominent high-$z$ lensed SMGs found by Ne10 in the H-ATLAS SDP field, with an apparent infrared luminosity $L_{IR} = 4 \times 10^{13} L_{\odot}$ (8–1000 µm, Lu10). The information on the lensing system remains limited because no high-resolution sub/millimeter image is available yet. However, Ne10 suggested that the deflector SPD.17a could consist of two foreground lensing masses at similar high redshifts ($z \sim 0.8$–0.9). The amplification factor of SPD.17b is still unknown and could reach values of ≈10 or more (Ne10). The infrared luminosity of SPD.17b is thus comparable to typical ULIRGs, including Mrk 231 ($L_{IR} = 4 \times 10^{12} L_{\odot}$). The mid-infrared photometry of SPD.17b is unknown, but, because it is detected at 100 µm (Ne10), there might be an AGN contribution.

The most remarkable property of SPD.17b is the richness of its 200–300 GHz Z-Spec spectrum (Lu10). Besides the H$_2$O line, it displays three CO lines ($J = 6–5$, 7–6(+CI) and 8–7) at $z = 2.3$. Despite the relatively low individual $S/N$ ratios (∼1.5–3) of these line intensities, their distribution has no clear sign of a turnover up to $J = 8–7$, pointing to a similarity with both Mrk 231 and the Cloverleaf (Lu10). In fact, the CO spectral line energy distribution of Mrk 231 also has a peak between the CO(5–4) and CO(6–5) transitions, but it has in addition a strong high-excitation component as seen in vdW10. However, there is as yet no information about CO lines above $J = 8–7$ in SPD.17b. Note that SPD.17b is one of the rare examples among the strongly lensed galaxies detected by Herschel (together with HERMESJ 105751.5+573027 (HLSW-01), Scott et al. 2011) that display strong high-$J$ CO lines. While the information about high-$J$ CO lines is still lacking in many of them, several other well studied high-$z$ lensed sources either from H-ATLAS (J091304.9-005344 (SPD.130), Lu10; J142413.9+022304 (SPD.15.141), Cox et al. 2011) or from elsewhere (Weiß et al. 2005; Danielson et al. 2011; Lestrade et al. 2010) have a clear turnover at lower $J$ values.

Nothing is published yet about the results of observations of lower-$J$ CO millimeter lines of SPD.17b. However, several studies are in progress at CARMA, the GBT (with Zpectrometer) and PdBI, including observations of the $J = 1–0$, 3–2 and 4–3 lines (Leeuw et al., in prep.; Frayer et al., in prep.; Cox et al., in prep.). These results will provide information on both the molecular gas of SPD.17b and the lensing system. It will be interesting to compare the profiles and the spatial distributions of the H$_2$O and CO emission lines and to study the connection between the warm gas (emitting in H$_2$O lines) and the colder gas (traced in CO), in particular the cold gas traced by the CO(1–0) line.

The FIRST radio survey (Becker et al. 1995) yields S$_{1.4\text{GHz}} = 464 \pm 145\mu$Jy for SPD.17 from the $L_{IR}$ value and using the definition of Sajina et al. (2008), we find for the IR/radio parameter $q = 2.53$. This value is well within the range of $q$ values for $z \sim 2$ starburst sources (e.g. Sajina et al. 2008; Fiolet et al. 2009; Ivison et al. 2010). This suggests that SPD.17b is not a radio-loud source and that star formation is responsible for most of its far-infrared luminosity (similar conclusions could apply to SPD.17a). However, it would be important to check whether the actual radio spectral index could suggest that some fraction of the radio emission is powered by an AGN, as in the case of SPD.81 (H-ATLAS J090311.6+003907; Valtchanov et al. 2011).

4.2. Implication of H$_2$O emission in SPD.17b

As discussed in Sect. 2, the detection of H$_2$O in SPD.17b implies special excitation conditions in an intense infrared radiation field and a warm dense gas, similar to Mrk 231 (e.g. with $n(H_2) \sim 10^4$ cm$^{-3}$ and $T_{\text{gas}} \sim 100$ K). Note, however,
that the density is far below the critical densities of H$_2$O (n(H$_2$O)$_{cr}$ > 10$^5$ cm$^{-3}$). It is thus impossible to determine the density because the excitation is dominated by the radiation field. Indeed there is currently no information for SDP.17b about other strong emission in H$_2$O lines with higher excitation, as in the case of Mrk 231, and it remains difficult to infer the detailed conditions of the gas from the detection of a single line. However, despite the uncertainty in the amplification factor, clearly the intrinsic H$_2$O line luminosity is at least comparable to that of Mrk 231 (Table 2). Similarly, the ratio I(H$_2$O(2$_{02}$−1$_{01}$))/I(ICO(8−7)) found for SDP.17b (~0.5) is consistent with that found for Mrk 231 (~0.75), but is completely different from standard PDRs (Sec. 2). In addition, the ratio L(H$_2$O)/L$_\text{IR}$ is three times higher in SDP.17b than in Mrk 231 (2.1 $\times$ 10$^5$ vs. 0.6 $\times$ 10$^5$). All the evidence suggests that SDP.17b and Mrk 231 have similar properties. SDP.17b may thus display excitation conditions as special as and a chemistry as rich as those of Mrk 231 (see Sect. 2), suggesting the influence of a luminous AGN.

However, strictly speaking, without observations of other PDRs, the excitation of H$_2$O in SDP.17b could be lower than in Mrk 231 and mostly limited to levels with energy $\sim$100 K, as the 2$_{02}$ level. As discussed by G-A10, the 2$_{02}$−1$_{11}$ line does not provide unique constraints on the overall excitation conditions, because it also can have a large contribution from gas excited by cooler dust ($T_{\text{dust}}$ $\sim$ 40 K). This excitation might be achieved in less extreme conditions found in warm dense gas over a more extended region, through dense hot cores, and/or via shocks, and is not necessarily associated with excitation by a powerful AGN. But it remains unclear if the above conditions could boost the H$_2$O/CO line intensity ratio to the values that are observed.

We conclude that SDP.17b is likely to be an analogue of Mrk 231. Most of the water lines detected by vdW10 in Mrk 231 could already be detected in SDP.17b or in other less dense sources detected by Herschel (including SDP.81 and HLSW-01) using the PdBI today or during ALMA’s early science phase.

The results reported in this paper are an example of the studies that can be initiated when many bright, lensed high-z submillimeter galaxies become available (through Herschel or other facilities). Follow-up observations of these sources, especially with the increased sensitivities afforded by ALMA or NOEMA, will allow the undertaking of comprehensive studies of molecular lines in sources similar to SDP.17b and provide new insights into the physical conditions of the dense warm molecular gas of high-z SMGs and their AGN.

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