

Observation of H₂O in a strongly lensed *Herschel*-ATLAS * source at z=2.3 **

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ABSTRACT

The *Herschel* survey, H-ATLAS, with its large areal coverage, has recently discovered a number of bright, strongly lensed high-*z* submillimeter galaxies. The strong magnification makes it possible to study molecular species other than CO, which are otherwise difficult to observe in high-*z* galaxies. Among the lensed galaxies already identified by H-ATLAS, the source J090302.9-014127B (SDP.17b) at $z = 2.305$ is remarkable due to its excitation conditions and a tentative detection of the H₂O 2₀₂-1₁₁ emission line (Lupu et al. 2010). We report observations of this line in SDP.17b using the IRAM interferometer equipped with its new 277–371 GHz receivers. The H₂O line is detected at a redshift of $z = 2.3049 \pm 0.0006$, with a flux of 7.8 ± 0.5 Jy km s⁻¹ and a FWHM of 250 ± 60 km s⁻¹. The new flux is 2.4 times weaker than the previous tentative detection, although both remain marginally consistent within 1.6σ . The intrinsic line luminosity and ratio of H₂O(2₀₂ – 1₁₁)/CO_{8–7} seem comparable with those of the nearby starburst/enshrouded-AGN Mrk 231, suggesting that SDP.17b could also host a luminous AGN. The detection of a strong H₂O 2₀₂ – 1₁₁ line in SDP.17b implies an efficient excitation mechanism of the water levels that must occur in very dense and warm interstellar gas.

Key words. Galaxies: high-redshift – Galaxies: starburst – Galaxies: active – Infrared: galaxies – Submillimeter: galaxies – Radio lines: galaxies

1. Introduction

Gravitational 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, HCO⁺, HCN, HNC, CN, CS & H₂O (see e.g., Solomon & Vanden Bout 2005, Riechers et al. 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 SXDF1100.001 (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 570 deg² and 70 deg², 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. 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 deg² (Negrello et al. 2010, hereafter Ne10), the H-ATLAS team has shown that such lenses are relatively easy to identify. With $S_{500\mu m} > 100$ mJy and $S_{1.2mm} > \sim 10$ 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 (Frayer et al. 2011) and with interferometers (Cox et al. 2011, Riechers et al. 2011b, Leeuw et al. in prep.). Besides ~ 20 CO-line detections in these sources, the only other molecule detection currently reported in high-*z* *Herschel* galaxies is the tentative detection with Z-Spec of

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** Colour figure only available in the electronic form via <http://www.edpsciences.org>

the emission line of para-H₂O 2₀₂ – 1₁₁ (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 H₂O 2₀₂ – 1₁₁ line in SDP.17b using the IRAM Plateau de Bure interferometer (PdBI) confirming the line and enabling 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 H₂O in high- z galaxies is important. If not locked in grains H₂O 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).

Since ISO, far-infrared H₂O lines are known to be prominent in local ULIRGs and composite AGN/starburst galaxies, such as Mrk 231 and Arp 220, which show a series of H₂O lines in absorption (González-Alfonso et al. 2008, 2004). The recent *Herschel* SPIRE FTS submillimeter spectrum of Mrk 231 provides a wealth of molecular emission lines including high-J CO lines up to J=13, seven rotational lines of H₂O almost comparable in strength to the CO emission lines, as well as many other species (OH⁺, H₂O⁺, CH⁺ and HF) which were never observed before in external galaxies (van der Werf et al. 2010 [hereafter vdW10]; G-A10); Fischer et al. 2010). A high intensity of the H₂O lines implies a high H₂O column density in a compact nuclear component, and thus a H₂O abundance approaching 10⁻⁶ (G-A10). This is most probably the consequence of shocks, cosmic rays, dense hot cores, possibly an XDR (X-ray dominated) moderated chemistry, and/or an ‘undepleted chemistry’ where grain mantles have evaporated. Therefore a composite model might be necessary to explain the water emission – shocks excited by the mechanical energy of the starburst or perhaps an AGN may enhance the gas phase abundance of water, while a strong infrared radiation field from a intense starburst or AGN (similar to Mrk 231) may be responsible for the high excitation. As stressed by G-A10, the high H₂O/CO ratio makes it unlikely that the H₂O emission originates in classical Photo-Dissociation Regions (PDR), since in the Orion Bar, the proto-typical Galactic PDR, CO lines are a factor ≥ 50 stronger than the H₂O lines. Similarly, in M82, this ratio is ≈ 40 (Weiß et al. 2010). The favored model for explaining these extraordinary features implies a high H₂O abundance and the presence of a small star forming disk, composed of clumps of dense gas exposed to strong ultraviolet radiation, dominating the emission of CO lines up to J = 8 (vdW10, G-A10). X-rays from the accreting supermassive black hole in Mrk 231 are likely to contribute significantly to the excitation and chemistry of the inner disk, as shown by the presence of OH⁺ and H₂O⁺ lines.

The number density of galaxies similar to Mrk 231 is expected to be at least two orders of magnitude larger at

high than at low redshift (Fabian et al. 2000; Alexander et al. 2005). They should represent a significant fraction of all submillimeter galaxies (SMGs), and thus of *Herschel* lensed SMGs. At high- z , the far-infrared lines of molecular species such as H₂O are redshifted into the atmospheric sub/millimeter windows. For strongly lensed sources, these molecular lines are within the detection reach of present sub/millimeter interferometers such as Plateau de Bure Interferometer (PdBI) and future facilities such as ALMA and NOEMA. Tentative detections of H₂O were reported in the Cloverleaf for the 2₂₀ – 1₁₁ transition (Bradford et al. 2009, Table 2) and IRAS F10214 for the 2₁₁ – 2₀₂ transition (Casoli et al. 1994). In addition, a luminous water maser ($\nu_{\text{rest}} = 22.2 \text{ GHz}$) was detected in a lensed quasar at $z = 2.64$ (Impellizzeri et al. 2008) and tentatively reported in F10214 (McKean et al. 2011). The H₂O 1₁₀ – 1₀₁ line was also detected in absorption at $z = 0.685$ towards B0218+357 by Combes & Wiklind (1997). It is likely that in the near future, the whole set of molecular lines (including the water lines) seen in Mrk 231 and other local sources (vdW10) will be detectable with ALMA in high- z lensed galaxies, provided they are comparable to Mrk 231.

3. Observations and Results

In order to confirm the detection towards SDP.17b of the redshifted H₂O 2₀₂ – 1₁₁ emission line, we used the PdBI with six antennas and the new ‘Band 4’ receiver, which covers the frequency range 277-371 GHz. Since 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'') and reasonable transparency (PWV $\leq 0.5 \text{ mm}$). They were completed by observations in extended A- and B-configurations in February and March 2011. With a total of ~ 6.2 hour on-source integration, a strong signal was detected both in the continuum and in the purported H₂O line (Fig. 1). The dust continuum flux density at 1.0 mm is $32.3 \pm 2 \text{ mJy}$ in good agreement with the value derived from Z-Spec by Lu10, and used in the SED fits of Ne10 and Lu10. However, the respective contributions of SDP.17b and SDP.17a to this value remain uncertain. The maximum flux density and integrated intensity of the H₂O line are 29 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 $z = 2.3049 \pm 0.0006$. Compared to the value previously reported by Lu10 of $19 \pm 7 \text{ Jy km s}^{-1}$, the intensity is lower by a factor 2.4 and marginally consistent within 1.6σ . The relatively low angular resolution ($\approx 1''$) 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 a significant flux is missed, either from the H₂O 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 H₂O. In particular, this precludes the presence of a CO(5–4) line of SDP.17a stronger than about 3 Jy km s^{-1} , i.e. 1/10 of the tentative detection reported by Lu10 ($29 \pm 9 \text{ Jy km s}^{-1}$), in

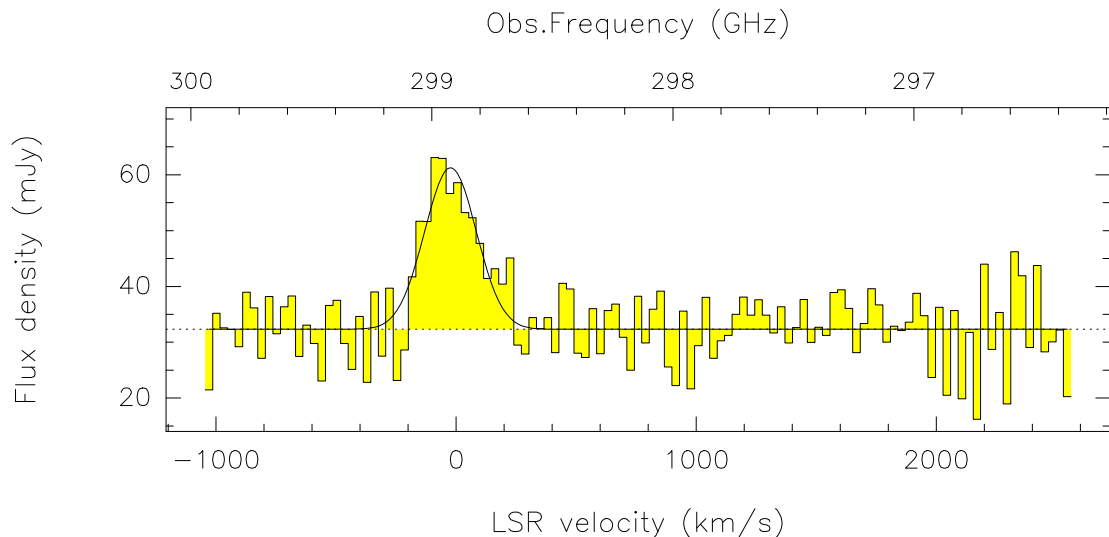


Fig. 1. Spectrum of the para H₂O 2₀₂ – 1₁₁ emission line towards SDP.17b, where the velocity scale is centered on its observed frequency at 298.93 GHz (corresponding to $z = 2.3049$). The r.m.s. noise is ~ 4.7 mJy/beam in 31.6 MHz channels. A Gaussian fit to the H₂O spectrum is shown as a full line while the dotted line shows the underlying dust continuum emission. The H₂O line is clearly asymmetric and not well fit by a Gaussian profile.

Table 1. Observed parameters of the H₂O 2₀₂ – 1₁₁ emission line in SPD.17b

Source	ν_{rest} [GHz]	ν_{obs} [GHz]	z	S_{ν} [mJy]	ΔV_{FWHM} [km/s]	I [Jy km s ⁻¹]	L^a [10 ⁷ L _⊙]	$L'^a/10^{10}$ [K km/s pc ²]
SDP.17b	987.93	298.93	2.3049 ± 0.0006	29	250 ± 60	7.8 ± 0.5	85 ± 0.6	2.5 ± 0.2

Quoted errors are the statistical errors derived from a Gaussian fit to the line profile.

^aEqs. 1 & 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 *Herschel* detected lensed sources (Ne10).

the redshift range $0.922 < z < 0.944$. However, emission of SDP.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 SDP.17b

In order to assess the implication of the detection of H₂O emission in SDP.17b, it is important to summarize the current information on the properties of SDP.17b and to replace this source in relation with other submillimeter lensed sources. SDP.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 $L_{\text{IR}} = 4 \cdot 10^{13}$ L_⊙ (8–1000 μm , Lu10). The information on the lensing system remains limited since no high-resolution sub/millimeter image is yet available. However, Ne10 identified that the deflector SDP.17a could consist of two foreground lensing masses at similar high redshifts ($z \sim 0.8 - 0.9$). The amplification factor of SDP.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 Mkr 231. The mid-infrared photometry of SPD.17b is unknown, but, as it is detected at 100 μm (Ne10), there might be an AGN contribution.

Table 2. Properties of the para H₂O 2₂₀ – 1₁₁ emission line in active galaxies

Source	z	$I(\text{H}_2\text{O})^a$ [Jy km s ⁻¹]	$L(\text{H}_2\text{O})^a$ [10 ⁷ L _⊙]	$I_{\text{H}_2\text{O}}^a/I_{\text{CO}}^b$
SDP.17b	2.305	7.8 ± 0.5	$85/\mu_L$	0.5 ± 0.2
Mrk 231 ¹	0.042	718	2.4	~ 0.5
Cloverleaf ²	2.565	20.3 ± 6.1	$21(11/\mu_L)$	0.4 ± 0.2

^aH₂O 2₀₂-1₁₁ line

^b $I(\text{H}_2\text{O } 2_{02}-1_{11})/I(\text{CO}[8-7])$ from Lu10

[1] G-A10; [2] Brafford et al. (2009)

The most remarkable property of SDP.17 is the richness of its 200-300 GHz Z-Spec spectrum (Lu10). Besides the H₂O 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 ($\sim 1.5 - 3$) of these line intensities, their distribution has no clear sign of a turnover up to J = 8–7 pointing to the similarity with both Mrk 231 and the Cloverleaf (Lu10). In fact, the CO spectral energy distribution of Mrk 231 also peaks in 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 yet no information about CO lines above J = 8–7 in SDP.17b. Note that SDP.17b is one of the rare examples among the *Herschel* strongly

lensed galaxies (together with HERMESJ 105751.1+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 (SDP.130), Lu10; J142413.9+022304 (SDP.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 yet published about the results of observations of lower-J CO millimeter lines of SDP.17b. However, several works are in progress at CARMA, GBT/Zpectrometer and IRAM/PdBI, including observations of lines J=1-0, 3-2 and 4-3 (Leeuw et al. in prep.; Frayer et al. in prep.; Cox et al. in prep.). Their results will provide various information about the molecular gas and the lensing system. In particular, it will be interesting to compare the H₂O and CO line profiles and eventually their spatial images, and to study the connection between the warm gas emitting H₂O lines and the colder gas emitting CO lines, and especially the cold gas traced by the CO J=1-0 line (Frayer et al. in prep.).

The FIRST radio survey (Becker et al. 1995) yields $S_{1.4\text{GHz}} = 464 \pm 145 \mu\text{Jy}$ for SDP.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 SDP.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 SDP.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 SDP.81 (H-ATLAS J090311.6+003907; Valtchanov et al. 2011).

4.2. Implication of H₂O Emission in SDP.17b

As discussed in §2, the detection of H₂O in SDP.17b proves special excitation conditions in a warm dense gas and an intense infrared radiation field, similar to Mrk 231. Indeed there is currently no information in SDP.17b about other strong emission in H₂O 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, it is clear that the intrinsic H₂O line luminosity is at least comparable to that of Mrk 231 (Table 2). Similarly, the ratio $I(\text{H}_2\text{O}(2_{02} - 1_{11}))/I(\text{CO}(8 - 7))$ seems comparable for both sources and completely different from standard PDRs (§2). All the evidence points to the fact 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 Mrk 231, suggesting the influence of a luminous AGN.

However, strictly speaking, in the absence of observation of other transitions, the excitation of H₂O in SDP.17b could be lower than in Mrk 231 and mostly limited to levels with energy $\sim 100\text{K}$, as the 2_{02} level. As discussed by G-A10, such an excitation might be achieved in less extreme conditions found in warm dense gas of a more extended region, through dense hot cores, and/or shocks, and is not necessarily associated with excitation by a powerful AGN. But it remains unclear if the above conditions could boost

the H₂O/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 wdW10 in Mrk 231 could already be detected in SDP.17b or in other *Herschel* lensed sources (including SDP.81 and HLSW-01) using the PdBI today or during the Early Science of ALMA.

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 to undertake 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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