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# ALMA unveils an outflow and a stellar bulge in an isolated $z \sim 6$ QSO

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**Abstract.** We present the results of a detailed study of the continuum, [CII] and $H_2O$ emission lines of the $z \sim 6$ QSO SDSS J2310+1855, using a new ALMA observation with 900 pc resolution. We were able to detect a [CII] outflow approximately located in the central kpc, with a mass outflow rate in the range $\dot{M}_{\rm out} = 1800 - 4500$ $M_\odot yr^{-1}$. Moreover, our dynamical analysis of the [CII] disc suggests the presence of a central compact mass component in J2310, which is composed by a super massive black hole (SMBH) and a stellar bulge having similar masses of the order of $\sim 10^{10}$ $M_\odot$. For the first time, we also mapped a spatially resolved water vapour disk through the $H_2O$ v=0 $3_{(2,2)} - 3_{(1,3)}$ emission line. Studying the evolutionary path of the QSO and its host galaxy, we found that the SMBH accretion is slowing down in this QSO while stellar mass assembly is still vigorously taking place in the host galaxy.

**Key words.** quasars: individual: SDSS J231038.88+185519.7 - galaxies: high-redshift galaxies: active - galaxies:ISM - techniques: interferometric

## 1. Introduction

In the last few decades the Atacama Large millimeter/sub-millemeter Array (ALMA), together with *Herschel*, the Northern Extended Millimeter Array (NOEMA) and the Very Large Array (VLA), has been able to shed light on the nature of luminous quasi-stellar objects (QSOs) and their host galaxies at the epoch of reionisation, when the Universe was only 0.5-1 Gyr old. Among the most crucial questions regarding these powerful objects, we aim at investigating some of them using a new high-resolution ALMA observation of the QSO SDSS J2310+1855 (hereafter J2310) at $z \sim 6$: (1) What are the properties of the dust and the cold gas in these early objects? (2) What is the

**Table 1.** Properties of J2310's host galaxy

| | | |
|---|---|---|
| $T_{dust}$ | [K] | $71 \pm 4$ |
| $M_{dust}$ | $[10^{10}\ M_\odot]$ | $0.044 \pm 0.007$ |
| $M_{gas}^{(a)}$ | $[10^{10}\ M_\odot]$ | $4.4 \pm 0.2$ |
| $M_{dyn}$ | $[10^{10}\ M_\odot]$ | $5.2^{+2.3}_{-3.2}$ |
| $M_{bulge}$ | $[10^{10}\ M_\odot]$ | $1.7^{+1.04}_{-1.17}$ |
| $M_{BH}^{(b)}$ | $[10^{10}\ M_\odot]$ | $0.5 \pm 0.3$ |
| GDR | ... | $101 \pm 20$ |
| $L_{TIR}$ | $[10^{13}\ L_\odot]$ | $2.48^{+0.62}_{-0.52}$ |
| $L_{H_2O}$ | $[10^{8}\ L_\odot]$ | $3.6 \pm 0.1$ |
| SFR | $[M_\odot\ yr^{-1}]$ | $1240^{+310}_{-260}$ |
| $\dot{M}_{out}$ | $[M_\odot\ yr^{-1}]$ | 1800-4500 |

Notes. $^{(a)}$ $M_{gas}$ is derived from CO(2-1) and CO(6-5) (Li et al. 2020; Feruglio et al. 2018). $^{(b)}$ The BH mass is derived from the MgII emission line profile (Mazzucchelli in prep., Tripodi et al. 2022).

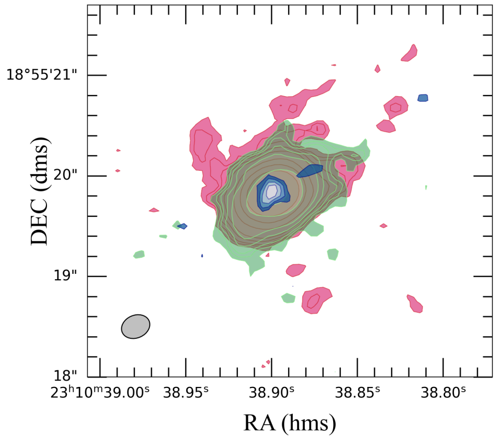


**Fig. 1.** Comparison among the 260 GHz dust continuum map (red), the [CII] map (green) and $H_2O$ map (blue). Levels are $3, 4, 5, 7, 10, 25, 50, 100\sigma$ with $\sigma = 8.8\mu$Jy for the continuum map, $3, 4, 5, 7, 10, 25, 50\sigma$ with $\sigma = 25\mu$Jy for the [CII] map, and $3, 4, 5, 6, 7\sigma$ with $\sigma = 26\mu$Jy for the water vapour map. The clean beam ($0.26 \times 0.21$ arcsec$^2$) is showed in the bottom left corner of the image.

evolutionary scenario that characterizes at high redshift the supermassive black hole (SMBH) residing at the center of a QSO and its host galaxy (BH dominance, galaxy dominance or symbiotic growth, Volonteri 2012)? (3) What are the characteristics and the role of the active galactic nucleus (AGN) feedback in the first QSOs?

J2310, first discovered in SDSS (Jiang et al. 2006; Wang et al. 2013), is one of the most far infrared (FIR)-luminous QSOs and one of the brightest optical QSOs known at $z = 6.00 \pm 0.03$(Wang et al. 2013), with $L_{bol} = 9.3 \times 10^{13}\ L_\odot$. A molecular gas mass of $M(H_2) = (4.4 \pm 0.2) \times 10^{10} M_\odot$ was derived for J2310, using CO(6-5) and CO(2-1) emission lines (Li et al. 2020; Feruglio et al. 2018). The most recent estimate of the black hole mass, based on high signal-to-noise X-SHOOTER spectroscopy of the MgII and CIV lines, is $M_{BH} = (5.0 \pm 3.4) \times 10^9 M_\odot$ (Mazzucchelli et al. in prep.; Bischetti et al. 2022). Bischetti et al. (2022) also reported evidence for an AGN-driven ionised gas wind traced by UV broad absorption lines (BAL). Recently, Shao et al. (2019) presented a detailed analysis of the FIR and sub-mm spectral energy distribution (SED) and derived a dust temperature of $T \sim 40$ K, a dust mass of $M_{dust} = 1.6 \times 10^9 M_\odot$, and a star formation rate (SFR) of 2400 – 2700 $M_\odot yr^{-1}$.

In (Tripodi et al. 2022), we presented a detailed analysis of the deep ALMA observation of the sub-mm continuum, [CII], and $H_2O$ emission lines with 900 pc resolution, complemented by multiple ALMA archival datasets probing the infrared continuum emission of the $z \sim 6$ QSO J2310+1855. These allowed us to perform a detailed study of dust properties and cold gas kinematics and dynamics. Here we report the most important outcomes of that work and new results from an improved dynamical modelling of J2310's rotation curve (Tripodi in prep.). In Table 1 we summarize the most important physical properties derived for J2310's host galaxy.

We adopt a $\Lambda$CDM cosmology from Planck Collaboration et al. (2016): $H_0 = 67.7$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.308$ and $\Omega_\Lambda = 0.692$. Thus, the angular scale is 5.84 kpc/arcsec at $z = 6$.

## 2. Results

Thanks to the accurate sampling of the QSO's SED, we were able to constrain with high accuracy the dust temperature, dust mass, and

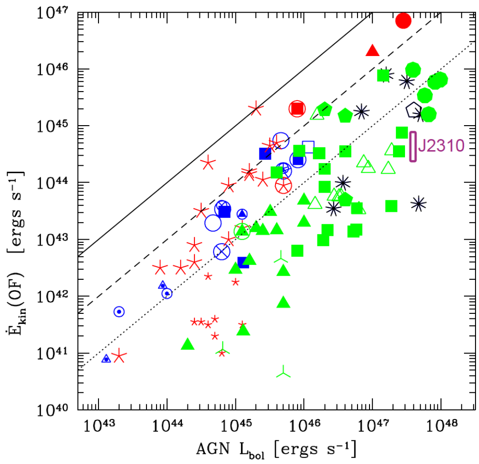


**Fig. 2.** Wind kinetic power as a function of the AGN bolometric luminosity. Solid, dashed and dotted lines represent the correlations $\dot{E}_{\rm kin} = 1, 0.1, 0.01\ L_{\rm bol}$. Our result for J2310 is shown as a purple rectangle, whose length represents the uncertainty on the $\dot{E}_{\rm kin}$. Adapted from Fiore et al. (2017).

emissivity index (see Table 1), modelling the large-scale dust in the inter stellar medium (ISM) and dusty torus emission with a modified black body (MBB) and dusty torus templates (Carniani et al. 2019; Stalevski et al. 2016). Both the value of dust temperature and dust mass are $\sim 2\times$ higher and $\sim 4\times$ smaller, respectively, than those derived by Shao et al. (2019), that uses another prescription for modelling the dusty AGN torus. In our analysis, we showed that our prescription for the torus does not influence our results for the MBB, but this may not be the case for the modelling presented in Shao et al. (2019). Different modelling of the AGN torus can in principle affect the determination of the parameters related to the large-scale dust emission that is modelled with an MBB. We derived an SFR= $1240^{+310}_{-260}$ $\rm M_\odot yr^{-1}$, accounting for the QSO contribution to dust heating and adopting a Chabrier IMF.

In (Tripodi et al. 2022), we performed an extensive analysis of the 260 GHz continuum emission and the [CII] emission line. Moreover we serendipitously detected and analysed the $H_2O$ emission line and we were able to spatially resolve it for the first time at this high-z. The luminosity ratio $L_{\rm H_2O}/L_{\rm TIR} = 1.4 \times 10^{-5}$ was consistent with line excitation by dust-reprocessed star formation in the ISM of the host galaxy; however, the faintness of this emission line made it unsuitable for more detailed dynamical studies. In Figure 1 we compare the spatial distributions of the continuum flux, the [CII] and $H_2O$ fluxes. The continuum is more extended and more peaked of both the line emissions, and in particular the water vapour is extremely concentrated at the center of the galaxy, having a size of $\sim$ 2 kpc. Studying the surface brightness profiles of the continuum and the [CII] line, we found that they reach a maximum size of 6.7 kpc and 5 kpc, respectively. A similar behaviour with a steeper dust continuum distribution with respect to the gas is seen in other high-z QSOs (e.g. Walter et al. 2022) and has been attributed to the contribution of the QSO to the dust heating.

Although individual detections of cold gas outflows in very high redshift QSOs are still relatively rare (Maiolino et al. 2012; Izumi et al. 2021a,b; Bischetti et al. 2019), J2310 shows evidence of a [CII] outflow approximately located in the central kpc, with an outflow mass $M_{\rm out} = 3.5 \times 10^8$ $\rm M_\odot$. This is about 5% of the neutral gas mass in the disc, consistent with expectations of recent zoom-in hydrodynamical simulations presented by Valentini et al. (2021). We estimated the mass outflow rate in the range $\dot{M}_{\rm out} = 1800 - 4500$ $\rm M_\odot yr^{-1}$, which also agrees well with the results of zoom-in cosmological hydrodynamical simulations of the $z \sim 6$ luminous QSO analysed in Barai et al. (2018), who found $\sim 2000 - 3000$ $\rm M_\odot yr^{-1}$ within 1 kpc. We also estimated $\dot{E}_{\rm out} \sim 0.0005 - 0.001\ L_{\rm bol}$ and in Figure 2 we compare our result with the ones presented by Fiore et al. (2017). We note that $\dot{E}_{\rm out}/L_{\rm bol}$ is consistent with the scaling for ionised winds.

Our analysis of the [CII] dynamics, based on the $^{\rm 3D}$Barolo dynamical model (Di Teodoro & Fraternali 2015), indicated a disc that is inclined at $i \sim 25$ deg, is rotationally supported, and marginally unstable with a Toomre parameter of $Q \sim 1-5$ out to r=1.7 kpc. The high resolution and high S/N of the [CII] observation

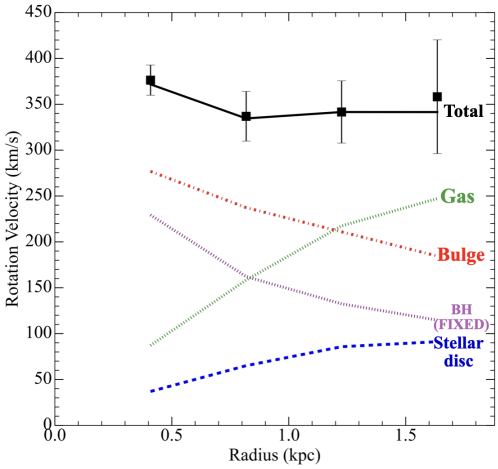


**Fig. 3.** Dynamical modelling of J2310's rotation curve. Black squares with errorbars are derived from $^{3D}$Barolo modelling of the [CII] emission. The best-fitting model (black solid line) is the sum of the contributions from: stellar disc (dashed blue line), cold gas disc (green dotted line), stellar bulge (dot-dashed red line) and BH (purple dotted line). If a fixed parameter is used, it is specified under the label of the component as (FIXED).

allowed us to retrieve the best estimate for the dynamical mass $M_{\rm dyn} = 5.2 \times 10^{10}$ $M_{\odot}$ within $r = 1.7$ kpc, giving us a rough estimate of the stellar mass, $M_{*} \sim 3 \times 10^{9} M_{\odot}$ . The latter, together with the AGN-corrected SFR, place the QSO host galaxy well above the main sequence for star-forming galaxies at $z \sim 6$ (see e.g. Mancuso et al. 2016; Pearson et al. 2018), indicating a strongly star-bursting host galaxy.

We improved over the $^{3D}$Barolo modelling presented in (Tripodi et al. 2022), changing the value of the position angle, reducing the number of rings in order to have nearly independent measures, and cropping the [CII] data cube in order to minimize the impact of the outflowing material on our results (Tripodi in prep.). We performed a dynamical decomposition of the new rotation curve (that is in agreement with the previous one in Tripodi et al. 2022), considering four mass distributions within the galaxy: a thick gaseous disc, a thick stellar disc, a SMBH and a stellar bulge. Our free parameters were the inclination of the gas disc and the gas, stellar and bulge mass: we fixed the BH mass to the observed value $5 \times 10^{9} M_{\odot}$ in order to break the degeneracy between the bulge and the BH mass. This occurs because the spatial resolution of the rotation curve cannot discern a central point source from a more extended central mass concentration. We present our results in Figure 3. We found that a central component such as a stellar bulge of $\sim 10^{1}0 M_{\odot}$ is required to properly describe the rotation curve of J2310. This represents the highest-$z$ candidate bulge known to date. Several mechanisms have been proposed for the formation of galaxy bulges: disc instabilities (Combes & Sanders 1981; Bournaud et al. 2007), major mergers (Toomre 1977; Hernquist & Barnes 1991), minor mergers (especially when frequent in number, e.g. Kannan et al. 2015), SF in AGN driven outflows (Ishibashi & Fabian 2014), and direct dissipative collapse (Eggen et al. 1962; Sandage 1990). For J2310, disc instabilities can be likely ruled out because such secular processes occur on long timescales (~3-5 Gyr) while the age of the Universe at $z \simeq 6$ is only ~900 Myr in the adopted cosmology. All the other mechanisms, instead, appear viable. The host galaxy of J2310 does not show any evidences of ongoing mergers based on the high resolution ALMA data available to date, but the orbital time at the last measured point of the rotation curve is only 26 Myr, so the [CII] disc may relax in just ~100 Myr (~4 revolutions) after a violent event. This implies that a potential merger between (proto-) galaxies with masses of a few times $10^{9}$ $M_{\odot}$ must have occurred at $z > 6.5$. Other potential mechanisms which could favour the formation of a spheroidal component are related to AGN feedback, in the form of large-scale outflows driven by the radiation pressure on dust or by shock propagation that triggers the formation of new stars at outer radii, leading to the development of extended stellar envelopes (Ishibashi & Fabian 2014). This scenario is observationally supported by Maiolino et al. (2017), who found that SF can occur within galactic outflows where the newly formed stars follow ballistic trajectories that can fall back in the potential so forming a spheroidal component. In the case of J2310, the evidences of AGN-driven outflows in multiple gas phases

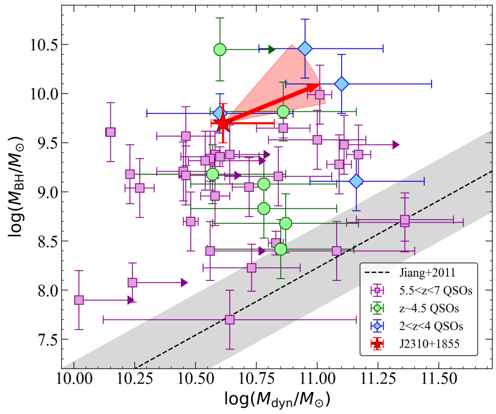


**Fig. 4.** BH mass as a function of the dynamical mass for J2310+1855 (red star), compared with QSOs at different redshifts. For J2310, the slope of the red arrow, with its uncertainty (shadowed red region), indicates how much the growth efficiency of the SMBH is slowing down with respect to the growth of the host galaxy. A complete description of this plot can be found in (Tripodi et al. 2022).

might be linked to the early formation of a stellar bulge in the host-galaxy.

Regarding the BH-galaxy co-evolution for J2310, we found $\dot{M}_{\rm BH}/M_{\rm BH} < {\rm SFR}/M_{\rm dyn}$, suggesting that AGN feedback is effectively slowing down the accretion onto the SMBH, while the host galaxy is growing fast (Volonteri 2012). In particular, the BH growth efficiency is ∼50% lower than that of the QSO host galaxy, as represented by the the slope of the red arrow in Fig. 4 (a slope of 45 deg corresponds to the case of ${\rm SFR}/M_{\rm dyn} = \dot{M}_{\rm BH}/M_{\rm BH}$). The shadowed red region arises from the uncertainties on $M_{\rm BH}$ and $M_{\rm dyn}$. One of the likely causes of the slow-down of the SMBH accretion are radiatively driven AGN winds that impact on the accreting matter, providing enough momentum to stop further accretion, and which can further propagate outwards on the scale of the host galaxy. In SDSS J2310+1855, the SMBH accretion may be limited by the ionised wind traced by a CIV BAL system with velocity $V_{\rm BAL} = 26900$ km s$^{-1}$ and balnicity index $BI = 600$ (Bischetti et al. 2022).

Finally, we studied the environment of J2310, scanning the data cube for line emitters. No line emitter was detected down to a $3\sigma$ upper limit of $L_{\rm [CII]} < 2.7 \times 10^7$ L$_{\odot}$, assuming a typical line width of 200 km s$^{-1}$. We tested all the regions obtained masking the cube with $3\sigma$-threshold. This led us to conclude that the QSO J2310 does not show any evidence of companions, interaction, or merger at least on scales of ∼ 50 kpc. Zana et al. (2022) have investigated the effects of QSO outflows on the visibility of companion galaxies by comparing two cosmological zoom-in simulations of a $z \sim 6$ QSO, in which AGN feedback is either included or turned-off. They found that within the virial radius of the central galaxy, the number of satellites increases in a similar way, while at larger distances the number of satellites in the AGN-on simulation is smaller than in the AGN-off simulation. In particular, we would expect to detect three companions with $L_{\rm [CII]} \sim 10^8$ L$_{\odot}$ within 250 kpc from the QSO, and seven companions with $L_{\rm [CII]} = 2.7 \times 10^7$ L$_{\odot}$ in approximately the same region. The isolated nature of J2310 may be explained by the effect of very powerful AGN-driven outflows that, by dispersing stars and gas in the surrounding region, boost the dynamical friction and, consequently, increase the galaxy merger rate.

## 3. Conclusions

The picture that finally arises is that of an isolated QSO, without evidence of ongoing mergers, that is characterised by a rotationally supported disc. The gas kinematics shows evidence of a gaseous outflow within the central kpc, and to better constrain the nuclear gas kinematics and spatially resolve the outflow, observations with a resolution of ∼ 0.03 arcsec are required. Moreover, the fact that ${\rm SFR}/M_{\rm dyn} > \dot{M}_{\rm BH}/M_{\rm BH}$ suggests that the SMBH accretion is slowing down in this QSO, probably owing to the BAL wind seen in CIV, while the stellar mass assembly takes place vigorously in the host galaxy. Our study may suggest that this $z \sim 6$ QSO is witnessing the fall of the black-hole dominance phase. In order to test whether this conclusion can be generalised to the entire population of $z \gtrsim 6$ QSOs, we aim to complement this study through the analysis of other QSOs at high-z in order to confirm or rule out a particular evolutionary scenario. The observed rotation curve indicates the presence of a spheroidal component (i.e. a stellar bulge), with a mass of $\sim 10^{10} M_\odot$, in this QSO at $z \sim 6$, when the Universe was only 1 Gyr old. We plan to further investigate the mechanisms of bulge formation at high-z in forthcoming work.

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