Sub-arcsecond resolution CO(J=3−2) imaging of a strongly-lensed wet-merger at z∼0.65

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Star formation modes and molecular gas dynamics beyond the local universe

Tremendous progress has been made towards our understanding of the high-z universe over the past two decades (see recent reviews by Carilli & Walter 2013; Madau & Dickinson 2014; Casey et al. 2014). These studies suggest that the elevated star formation rates (SFRs) and specific SFRs observed in galaxies at the peak epoch of star formation ($1 \lesssim z \lesssim 3$) are primarily driven by their increased in molecular gas mass fractions and star formation efficiencies (SFE) compared to local galaxies, and that star formation at this epoch/in these early systems can be grossly categorised into two dominant modes – quiescent mode in disc-like galaxies versus starburst mode in submillimetre galaxies (SMGs) and quasar host galaxies (e.g. Sargent et al. 2012). The systematically enhanced molecular gas fractions observed in high-z galaxy populations implies that their star-forming clumps are expected to be larger in size, and in more turbulent conditions compared to nearby galaxies. Indeed, recent studies have found gas clumps on the order of kpc scales at z=1–2 (e.g. Swinbank et al. 2012a,b), providing direct evidence that the interstellar medium (ISM) dynamics of galaxies evolve as a function of cosmic time. This highlights the importance of resolving the gas dynamics of galaxies on these scales and at various epochs in order to investigate the mechanisms and physical processes responsible for leading to the two star-formation modes and for causing the steep decline in the cosmic SFR density since $z \sim 1.5$ (e.g. Lagos et al. 2011; Popping et al. 2012).

While studies using spatially resolved CO observations in local ultra-luminous IR galaxies (ULIRGs) and their high-z analogues ($z \gtrsim 1$ starburst systems) have enabled a better understanding of the gas properties of mergers at these epochs (e.g. Engel et al. 2010; Bothwell et al. 2010), the gas properties such as excitation, distribution, and dynamics of mergers at intermediate redshift ($0.6 \lesssim z \lesssim 1$) remain largely unknown due to the lack of spatially resolved CO observations at these redshifts. Thus, to understand of the role of mergers throughout the cosmic history and to obtain a coherent picture connecting high-z galaxy populations to present-day galaxies, it is vital to carry out detailed studies of the gas kinematics and dynamics at intermediate-z.

We here propose to observe the CO(J=3−2) line emission in a strongly-lensed quasar host galaxy of a merger system at $z \sim 0.65$ using the **A+C array configuration**. By combining the magnification provided by gravitational lensing with the improved spatial resolution and sensitivity of NOEMA, the proposed observations at an angular resolution (∼0.6") corresponding to a physical scale of ∼1.8 kpc at the target redshift will allow us to study the internal gas dynamics and distribution down to the physical scales of high-z star-forming clumps in a total of **3.2 hours including overheads**. We have already detected the CO(J=2−1) and CO(J=3−2) lines at high significance with the PdBI/NOEMA and the CARMA, respectively (Leung, Riechers & Pavesi, submitted; hereafter Leung et al. 2016), and thus this is a low risk project. Since our target is currently the only source with spatially resolved CO imaging at intermediate redshift with existing multi-wavelength analysis spanning rest-frame UV-to-radio, obtaining the proposed observations will enable, for the first time, a kpc-scale characterization of the gas, dust, and stellar populations of different ages in a quasar host galaxy and merger at intermediate redshift.

Unique Nature of our target RXJ 1131−1231

Our target RXJ 1131−1231 (hereafter RX1131) is a quadruply-imaged optical quasar with its host galaxy being lensed into a partial Einstein ring (Fig. 1; Sluse et al. 2003). HST observations (rest-frame UV) have revealed distinct emission from recent star-formation (lensing arcs) and from the AGN (bright knots) in the background galaxy, demonstrating the great potential for probing its ISM conditions in detail. Lens modelling of an optical image has identified seven distinct structures in the source plane and a companion galaxy of size ∼700 pc across, at ∼2.4 kpc away from the AGN host galaxy (Brewer & Lewis 2008). We have recently confirmed that both galaxies are at the same rmedshift by detecting their CO(J=2→1) emission and decomposing their gas distribution via our uv-plane lens modeling in the velocity-space (Leung et al. 2016; see Fig. 3f). The lensing-corrected IR luminosity of $1.5 \times 10^{12}\, L_\odot$ implies that RXJ1131 can also be classified as a ULIRG.

Proposed Observations and Science Goals

The intrinsically symmetric double-horned line profile (Fig. 3g) of RXJ1131 and its source-plane velocity gradient (Fig. 2) extending $\gtrsim$6 kpc in radius reconstructed from dynamical lens modeling of our CO(J=2−1) data suggest that it is a disc galaxy. At the resolution of our CO(J=2−1) data, the disc-like kinematics and galaxy-scale star formation properties resembling those of high-z massive disc galaxies (Daddi et al. 2010) suggest that the star formation modes of intermediate-z mergers are already different than the local ones. Since recent studies also find that high-z discs are more clumpy and dynamically unstable compared to local discs, studying the molecular gas in RXJ1131 on the scales of its star-forming clumps would enable us to gain insights into how star formation in massive disc galaxies differ since the peak epoch of star formation.

At the resolution of our CO(J=2−1) data, we find disturbed gas morphologies with an unusually high velocity dispersion ($\gtrsim$400km s^{-1} near the central region of RXJ1131; Fig. 3e). Higher resolution imaging, as proposed here, is necessary to infer its true velocity structure and dynamical state to distinguish between a rotationally-dominated versus dispersion-dominated system. We will achieve this by reconstructing the source-plane spatial distribution of the gas and its velocity field, and deriving the v/σ ratio (as a proxy to the Toomre Q parameter). This will allow us to contrast the dynamical properties between mergers and discs galaxies at low and high-z. We will also measure spatially resolved line ratios between the CO(J=3−2) and CO(J=2−1) emission within RX1131 to gain insight into its gas excitation conditions. The cold gas distribution, kinematics and line ratio variations will provide clues on the main driver of star formation in RXJ1131 (e.g. if the warmer gas is concentrated toward the central region of RX1131 like nearby ULIRGs), how its interaction with the companion may influence the molecular gas in fueling its ongoing star formation and the central quasar, and how its gas excitation differs from other galaxy populations at different cosmic epochs. In addition, at the proposed resolution, we will be able to obtain a more accurate lens model, enabling us to resolve the intrinsic velocity gradient at finer details, and thus to obtain a better-constrained rotation curve and dynamical mass estimate.

Given the unique lensing configuration and nature of our target, the proposed observations present an excellent opportunity to investigate the molecular gas excitation and the kinematical and dynamical state of a distant quasar host galaxy of a merging system. The addition of spatially resolved CO(J=3−2) data will allow us to investigate how physical parameters, e.g. stellar mass, dust temperature, SFR, morphology, clumpiness, internal gas dynamics, which have been investigated at both nearby and $z\gtrsim1$ galaxies vary at intermediate redshift depending on the molecular gas conditions, providing important constraints for current models of galaxy evolution.

Technical justification

We estimate the source size of CO(J=3−2) emitting gas in RXJ1131 based on the most extended kinematic component in our dynamical lens model of our PdBI/NOEMA CO(J=2−1) emission, which takes into account the asymmetric line emission and spatial extent across different velocity bins (arising due to differential lensing). We therefore expect the source to be resolved over ∼10 beams at the proposed angular resolution of ∼0.66". We compute the expected CO(J=3−2) line strength based on our CARMA CO(J=3−2) line flux of $I = 35.7$ Jy km s^{-1} and line FWHM of ∼700 km s^{-1}. To secure enough S/N for lens modelling, we require of 10σ detection of $\sigma = 1.35$ mJy beam^{-1} per 100km s^{-1} channel. We note that the requested sensitivity will correspond to S/N>10 for channels with spatially less extended emission, which are also found to have lower magnification factors (and thus lower apparent flux density). We thus note that the requested sensitivity is conservative but reasonable given that our scientific goals rely heavily on having enough S/N per channel over the entire line profile (especially in the red wing which is spatially more extended).

1 Supporting material

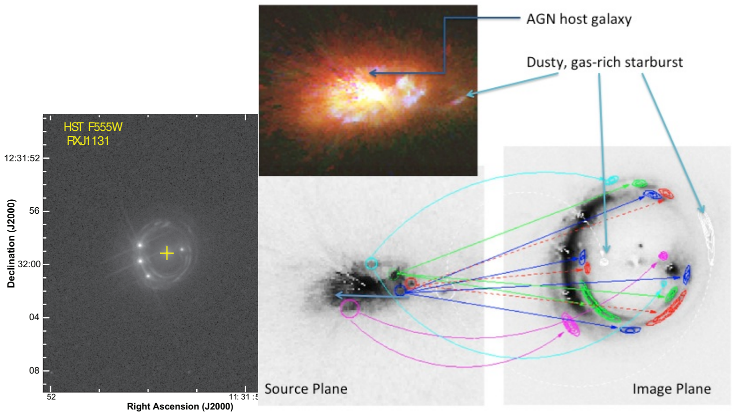

Figure 1: **Stellar light distribution in the AGN host galaxy RXJ 1131-1231 and its reconstructed source plane morphology.** *Left:* Rest-frame UV emission (tracing recent star formation) is lensed into an almost complete Einstein ring with diameter ∼3.8". *Right:* Lens modeling of the optical emission identifies complex structures in the host galaxy and an optically faint companion (white component as indicated by the blue arrows; Claeskens et al. 2006), which we have recently confirmed by lens-modeling our CO(J=2−1) data (Fig. 3; Leung et al., submitted). Here, we propose to map the CO(J=3−2) emission in this intermediate-z disc-like quasar host galaxy of a merger system.

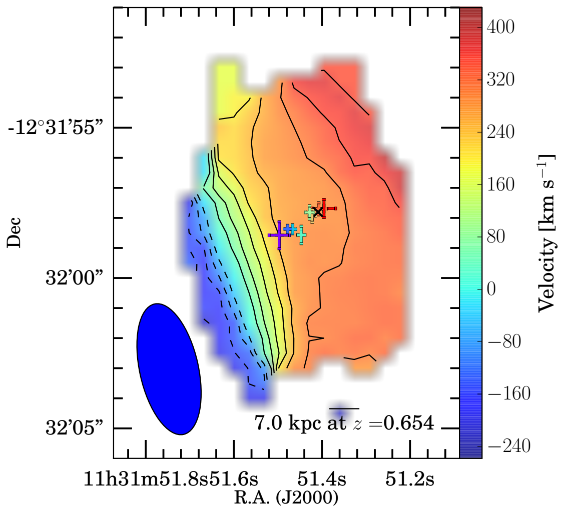

Figure 2: **Image- and source-plane velocity gradient of the CO(J=2−1) line emission in the AGN host galaxy RXJ1131.** Source-plane positions reconstructed from the best-fit uv-plane lens modeling of our PdBI/NOEMA CO(J=2−1) data in the velocity-space are indicated as color markers atop the observed first moment map. At the proposed resolution, we will be able to obtain a more accurate lens model, enabling us to resolve the intrinsic velocity gradient at finer details, and obtain a better-constrained rotation curve and dynamical mass estimate for this intermediate-z quasar host galaxy.

References • Bothwell et al. 2010, MNRAS, 405, 219 • Brewer et al. 2008, MNRAS, 390, 39 • Carilli et al. 2013, ARA&A, 51, 105 • Casey et al. 2014, Phys. Rep., 541, 45 • Claeskens et al. 2006, A&A, 451, 865 • Daddi et al. 2010, ApJ, 713, 686 • Engel et al. 2010, ApJ, 724, 233 • Lagos et al. 2011, MNRAS, 418, 1649 • Madau et al. 2014, ARA&A, 52, 415 • Popping et al. 2012, MNRAS, 425, 2386 • Sargent et al. 2012, ApJ, 747, L31 • Sluse et al. 2003, A&A, 406, L43 • Swinbank et al. 2012a, ApJ, 760, 130 • Swinbank et al. 2012b, MNRAS, 426, 935

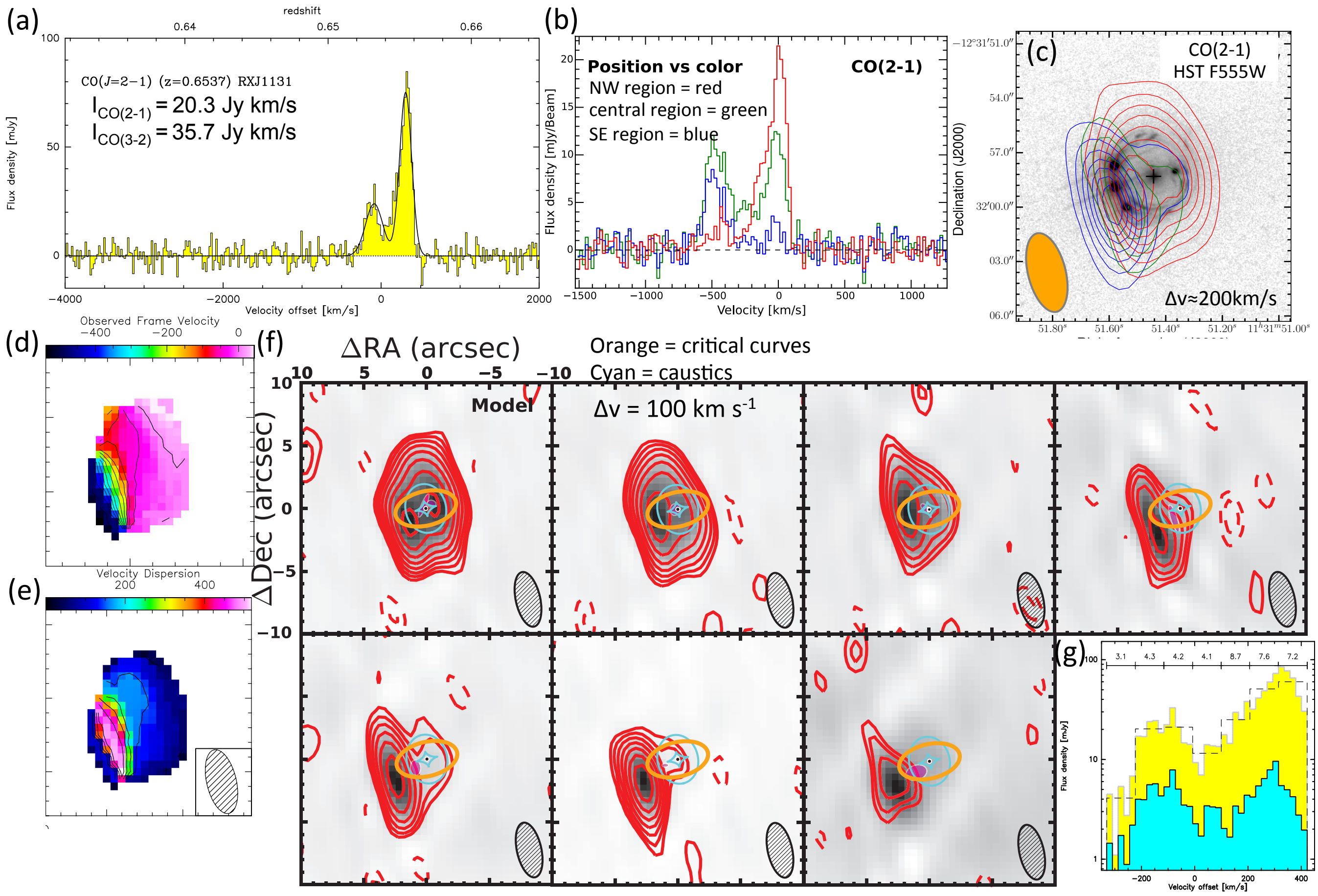

Figure 3: **Recent CO(J=2−1) data from NOEMA (Leung et al., submitted).** *(a):* Asymmetric double-horned line profile observed towards our target. *(b):* Spectra taken at three locations along the strongest velocity gradient, demonstrating differential lensing of the kinematic components of a gas-rich "disc" and the wealth of dynamical information that is already available at this resolution. *(c):* Observed spatial variations across different velocity components due to differential lensing, as shown by the red (redshifted), green (line center), and blue (blueshifted) contours. *(d):* The observed velocity gradient is suggestive of a disc morphology at the current resolution limit. The spectrally resolved lensed emission allows us to probe dynamical structures on smaller spatial scales than otherwise possible. *(e):* An unusually high velocity gradient ($\gtrsim$400 km s^{-1}) near the center of RXJ1131 may be a result of perturbations from the AGN, or internal turbulence due to interactions with the companion, or instability due to the huge gas reservoir. *(f):* Channel maps of the CO emission (red) overlaid on our best-fit lens models (grayscale). The foreground lensing galaxy is represented by a black dot. The reconstructed source morphology (magenta ellipses) is also suggestive of a "disc". *(g):* Full resolution spectrum (yellow; same as panel *a* but shown in log-scale) and the seven channels (dashed) used for lens modeling. Using the magnification factors shown above the model channels, we recover an intrinsically symmetric profile (blue). We here propose to observe CO(J=3−2) line in RXJ1131 at the spatial scales of high-z gas clumps in order to investigate its molecular gas excitation, kinematical and dynamical state and examine how physical properties, e.g. stellar mass, dust temperature, SFR, morphology, clumpiness, internal gas dynamics, vary at intermediate redshift depending on the molecular gas conditions.