ALMA Resolves Turbulent, Rotating [C II] Emission in a Young Starburst Galaxy at z = 4.8

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Over the last decade, the [C II] 158 μm line has emerged as one of the most powerful probes of the interstellar medium at high redshift. It is one of the brightest far-infrared lines, opening up the possibility to spatially and spectrally resolve the emission in high-redshift galaxies. ALMA has already demonstrated this during Cycle 0. Our ALMA [C II] kinematical study of the galaxy ALESS73.1 at z = 4.8, observed 1.2 Gyr after the Big Bang, shows evidence for turbulent, rotating emission in a galaxy that is still forming most of its stars.

In the local Universe, studies of the [C II] fine structure line (rest wavelength 158 μm) can only be performed from space, since the Earth's atmosphere is opaque at wavelengths around 160 μm. Since far-infrared space telescopes only have relatively small apertures, it remains difficult to spatially resolve [C II] emission in compact sources. Recent Herschel observations have begun to resolve [C II] at 0.1–1 kpc scales in nearby galaxies (Beirao et al., 2012; Parkin et al., 2013), but full dynamical studies are not yet possible. Ironically, observing [C II] becomes easier with redshift as the line shifts into increasingly better transmission windows of the Earth's atmosphere. However, to observe a line at such a short wavelength requires good atmospheric transparency and hence a dry site, like Chajnantor.

The Atacama Large Millimeter/submillimeter Array (ALMA) has already demonstrated its potential to study high-redshift galaxies in [C II] from Cycle 0 observations (e.g., Swinbank et al., 2012). We have now deepened such studies by observations of the dusty star-forming galaxy ALESS73.1 at z = 4.8 with ALMA Band 7. This source was first detected in the submillimetre (submm) with the Atacama Pathfinder EXperiment (APEX) telescope in the course of the Large APEX BOlometer CAmera (LABOCA) Extended Chandra Deep Field South (ECDFS) Sky Survey (LESS; Weiß et al., 2009). ALESS73.1 had been identified as an active galactic nucleus (AGN) from spectroscopy with VLT FORS (Faint Object Red Spectrograph) of this field (Vanzella et al., 2006). At the time of discovery, ALESS73.1 was the most distant submm-selected galaxy, and, as such, subject to an intensive follow-up campaign which includes: a CO(2-1) detection with the Australia Telescope Compact Array (Coppin et al., 2010); an initial [C II] detection with APEX (De Breuck et al., 2011); an ALMA [N II] detection (Nagao et al., 2013); and deep X-ray spectroscopy suggesting that the source hosts a Compton-thick AGN (Gilli et al., 2011; 2014).

ALMA observations of ALESS73.1

Our ALMA observations of ALESS73.1 (De Breuck et al., 2014) were performed in the extended Cycle 0 configuration, providing a spatial resolution of 0.5 arcseconds, or 3 kpc at this redshift. This ALMA spatial resolution approaches that of the Hubble Space Telescope (HST) in the optical/near-infrared. HST has also obtained deep observations of this galaxy as part of the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS). HST's identification is spatially unresolved because it is dominated by the AGN, whose nature is revealed by the power-law emission from the restframe ultraviolet to near-infrared. In contrast, the far-infrared emission is dominated by strong star formation with rates of 1000 $M_\odot$ yr^{-1} (for comparison, the Galaxy forms stars at a rate of only a few $M_\odot$ yr^{-1}).

In an independent ALMA Band 6 observation, Gilli et al. (2014) showed that the dust continuum emission is marginally spatially resolved at 0.3-arcsecond scales. This implies a compact host galaxy with a very high star formation density. The gas and dust associated with this vigorous starburst may even explain some of the high column density absorption seen in the X-ray spectrum (Gilli et al., 2014).

The high signal-to-noise provided by the ALMA observations allows the [C II] data-cube to be binned into 18 channels of 25 km s^{-1} width each (Figure 1), enabling the first detailed dynamical study of the [C II] line in such a high-redshift object. Interestingly, the [C II] emission is extended over 0.6 arcseconds and shows a pronounced velocity gradient, as is evident from Figure 2. This velocity field is consistent with a rotating disc with a radius of ~ 2 kpc, i.e., about twice as large as the dust continuum extension.

Our disc models (see Figure 2) constrain the dynamical mass to 3 ± 2 × 10^{10} $M_\odot$. Combined with the observed H_2 mass of 1.6 × 10^{10} $M_\odot$ and the atomic gas of 5 × 10^9 $M_\odot$ derived from the [C II] luminosity, the stellar mass is constrained to < 3 × 10^{10} $M_\odot$. ALESS73.1 therefore has a very high specific star formation rate of > 80 Gyr^{-1}. This galaxy will thus double its stellar mass in ~ 12 Myr, and we are likely observing it during one of its first major star-forming episodes.

The spatially resolved kinematical study also allows us to check whether this rotating emission is stable against gravitational collapse. Figure 3 shows the intrinsic velocity dispersion (σ), which is only three times lower than the rotational velocity (V), i.e. V/σ ~ 3, suggesting that this is a dispersion-dominated disc. We confirmed this by deriving the Toomre Q

parameter, and find it to be < 1 throughout the disc, indicating that the disc is unstable. This suggests that the [C II] line may be tracing the star-forming gas of this young galaxy.

Prospects

These [C II] observations show that ALMA can perform a dynamical analysis at an epoch when galaxies were undergoing their first major burst of star formation. Our Cycle 0 observations are still limited by spatial resolution (but not by signal-to-noise). The spatial resolution of the final ALMA array will improve on this by more than an order of magnitude. This improvement should open up new opportunities for kinematical studies of galaxies at wavelengths which can probe deep into the dust-obscured regions and at a resolution of ~ 100 pc, i.e., the size of their individual star-forming clouds.

References

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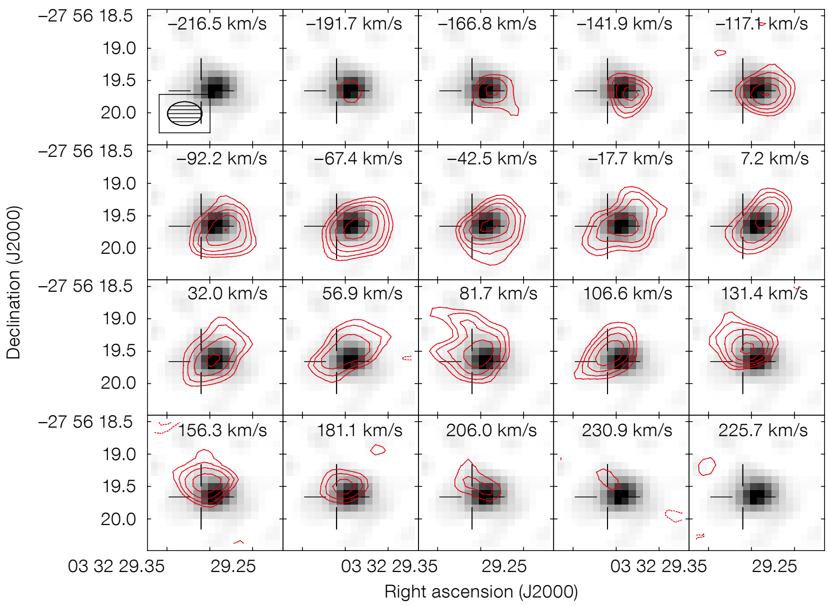
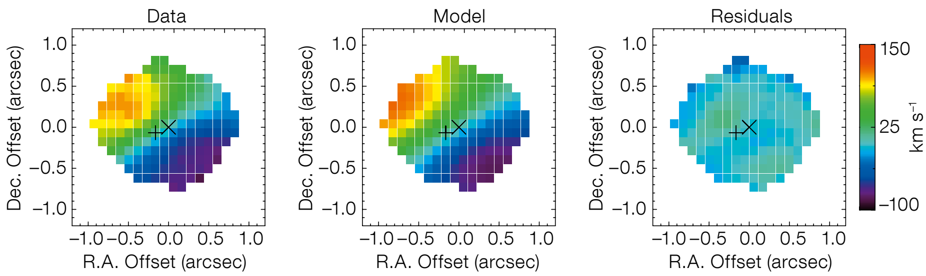


Figure 1. (Upper) ALMA channel maps (red contours) of [C II] overlaid on the line-free 326 GHz dust continuum image. The open cross marks the position of the AGN in the HST image of this source. Note that the dynamical centre coincides with the compact dust continuum source.

Figure 2. (Lower) The [C II] velocity field of ALESS73.1 is shown. The left panel presents the observed data, the central panel the best-fit rotating disc model and the right panel the residuals on this fit. The plus and cross mark the locations of the AGN and the [C II] peak, respectively (c.f., Figure 1). The observed motions of the [C II] emission are consistent with a rotating disc model.



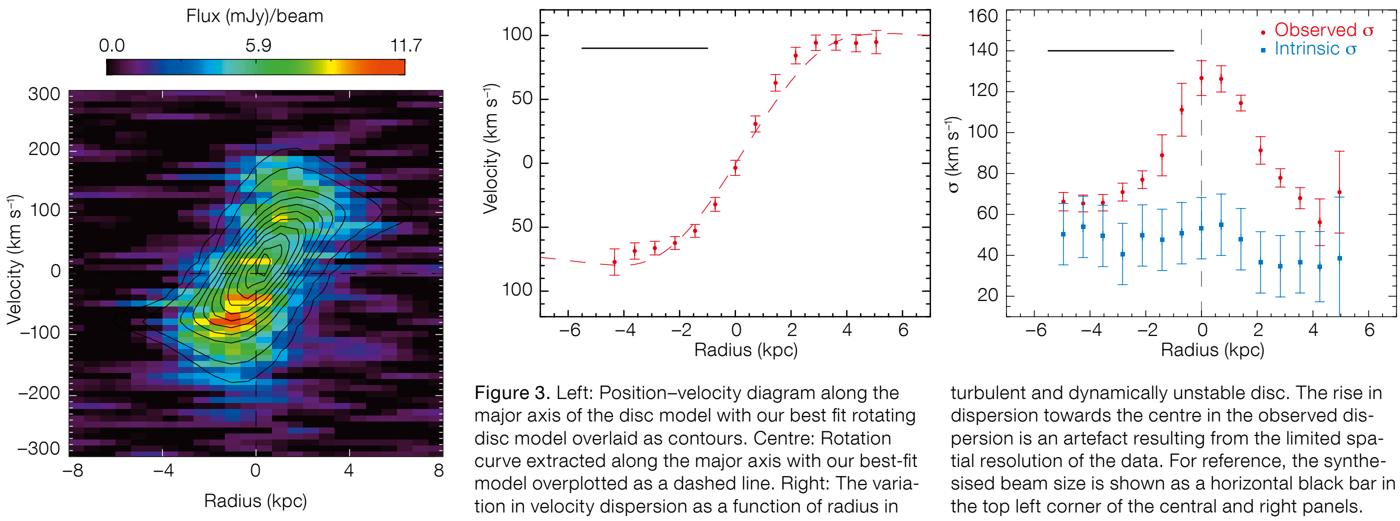


Figure 3. Left: Position–velocity diagram along the major axis of the disc model with our best fit rotating disc model overlaid as contours. Centre: Rotation curve extracted along the major axis with our best-fit model overplotted as a dashed line. Right: The variation in velocity dispersion as a function of radius in the disc. The low $V/\sigma \sim 3$ value shows this is a turbulent and dynamically unstable disc. The rise in dispersion towards the centre in the observed dispersion is an artefact resulting from the limited spatial resolution of the data. For reference, the synthesised beam size is shown as a horizontal black bar in the top left corner of the central and right panels.