Chemical Properties of a High-*z* Dusty Star-forming Galaxy from ALMA Cycle 0 Observations

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The chemical properties of galaxies provide strong constraints on galaxy evolutionary scenarios, but diagnosing the chemical properties of high-*z* dusty galaxies by means of optical and near-infrared spectroscopy has been challenging. We have therefore focussed on far-infrared fine-structure emission lines in high-*z* dusty galaxies, whose detection is feasible with ALMA. From ALMA Cycle 0 observations, we have detected [N II] 205 μm emission in a submillimetre galaxy at $z = 4.76$ whose [C II] 158 μm emission has been already detected in our previous APEX observations. The measured flux ratio of [N II] 205 μm/[C II] 158 μm implies solar metallicity in this galaxy, suggesting a significant chemical evolution even at $z = 4.76$ when the cosmic age was only ~1.3 billion years.

One of the main goals of modern astronomy is to understand the whole picture of galaxy evolution. However, the early phases of galaxy evolution in the early Universe are still poorly understood, partly because detailed observations of faint high-*z* galaxies are very difficult even with largest aperture telescopes available, such as the Very Large Telescope (VLT). Particularly at $z > 3.5$, the most important restframe optical emission lines are redshifted beyond the near-infrared atmospheric windows and therefore diagnosing the physical and chemical properties of galaxies is difficult (see, e.g., Maiolino et al., 2008). In addition, galaxies in their growth phase are often enshrouded by a huge amount of dust, which makes the restframe optical diagnostics unusable for such interesting populations of galaxies.

Therefore we have focused on the millimetre wavelength band, where we can examine spectra of galaxies without suffering from serious dust extinction effects. More specifically, some far-infrared emission lines, which can be used for diagnosing the physical and chemical properties of galaxies (e.g., Nagao et al., 2011), are redshifted into the submillimetre and millimetre bands at high-*z*. Therefore millimetre spectroscopy is, in principle, a promising tool to diagnose rapidly growing high-*z* dusty galaxies. However, such observations are very challenging because the diagnostic fine-structure emission lines are expected to be very faint. Recently we observed LESS J033229.4-275619 (a submillimetre galaxy [SMG] at $z = 4.76$, hereafter LESS J0332) with APEX and detected its strong [C II] 158 μm emission (De Breuck et al., 2011). This SMG hosts a heavily obscured active galactic nucleus (AGN) according to Gilli et al. (2011), but its effects on the emission line spectrum are expected to be small. This object is an interesting target because its star formation rate is very high, reaching ~1000 $M_\odot$ yr^{-1} (Coppin et al., 2009). However, until recently it has been impossible to detect any other fine-structure lines in this SMG due to the lack of sensitivity of previous facilities, thus preventing us from investigating in detail the properties of LESS J0332.

ALMA observations of LESS J0332

Within this context ALMA allowed us to make a major step forward. In order to assess the chemical properties of LESS J0332, we proposed to observe its [N II] 205 μm emission whose expected flux is only a few percent of the [C II] 158 μm emission. The observations were intermittently carried out from October 2011 to January 2012 with the band 6 receivers and 18 antennas. The redshifted [N II] 205 μm emission was successfully detected with a high significance (signal-to-noise of ~ 8) at the expected frequency, 253.9 GHz (Figure 1). In Figure 2 the resulting ALMA [N II] 205 μm spectrum is compared with the APEX [C II] 158 μm spectrum, showing that the measured [N II] 205 μm flux is only ~ 4 % of the [C II] 158 μm flux. It is surprising that such a faint [N II] 205 μm emission was detected with only 3.6 hours of integration with ALMA, while the [C II] 158 μm observation required 14.5 hours of integration with APEX. This demonstrates the amazing sensitivity of ALMA, even in Cycle 0.

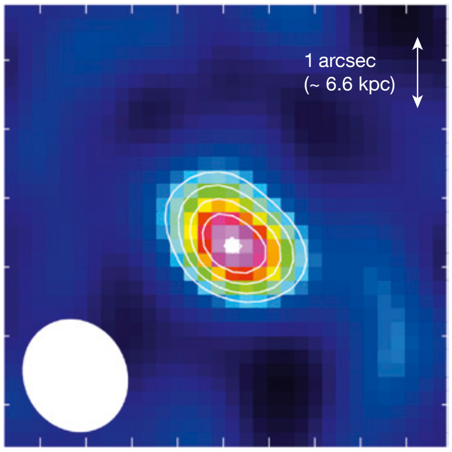

Figure 1. The ALMA image of the [N II] 205 μm emission from LESS J0332 (from Nagao et al., 2012). The size of the white arrow is equal to one arcsecond, equivalent to approximately 6.6 kpc at the distance of LESS J0322. The white ellipse at the left bottom shows the ALMA spatial resolution for the observation.

In order to assess the chemical properties of LESS J0332, we compared the observed flux ratio of [N II] 205 μm/[C II] 158 μm with predictions from photoionisation models. The comparison shows that the chemical composition of the gas clouds in LESS J0332 is close to the Solar value, i.e., $\log(Z_{gas}/Z_{sun}) = 0.0 \pm 0.4$. This is a surprising result, given the fact that we are observing a rapidly evolving SMG at $z = 4.76$, where the cosmic age was only ~1.3 billion years. Since SMGs are thought to be progenitors of local massive galaxies, our observational result suggests that massive galaxies had completed their chemical evolution much earlier than less massive galaxies. This is consistent with the "downsizing" evolutionary picture recently suggested for galaxies, i.e., mas-

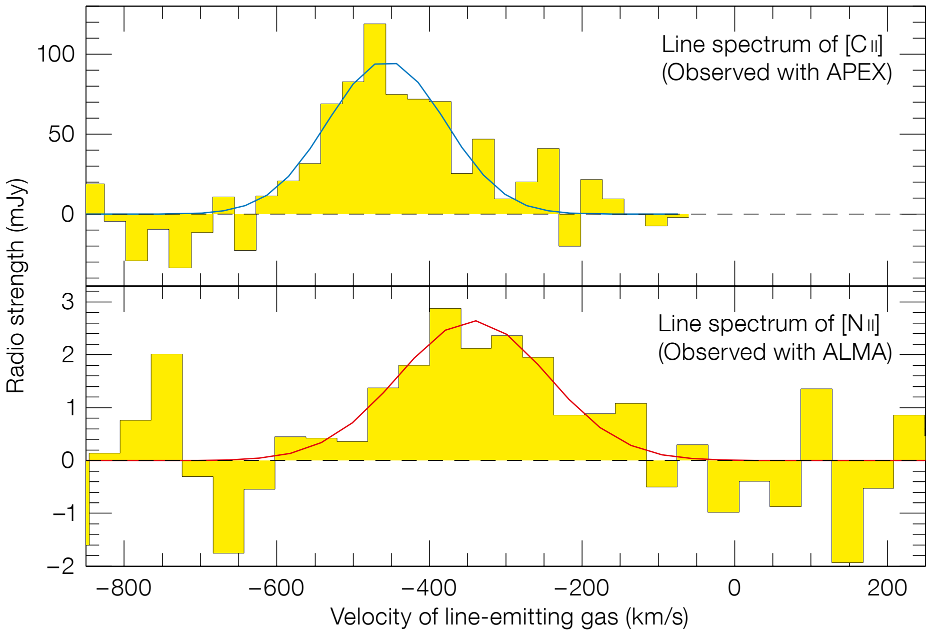

Figure 2. The APEX spectrum of the [C II] 158 µm emission (from De Breuck et al., 2011) is compared to the ALMA spectrum of the [N II] 205 µm emission (from Nagao et al., 2012) from LESS J0332.

sive galaxies underwent more evolution in earlier epochs than less massive galaxies. Note that the early metal enrichment in massive systems has also been inferred through observations of high-*z* active galactic nuclei such as quasars and radio galaxies (e.g., Nagao et al., 2006a, 2006b; Matsuoka et al., 2011).

The obvious next step is to obtain tighter constraints on the chemical properties of LESS J0332 to discriminate between different galaxy evolutionary scenarios. The current large uncertainty in the inferred metallicity is due to the fact that we have measured only two fine-structure lines, [C II] 158 µm and [N II] 205 µm. Additional observations of other lines such as [O I] 145 µm would give further constraints on the physical properties of the gas clouds in LESS J0332 and, accordingly, reduce the metallicity uncertainty.

The internal structure of the chemical properties in this SMG is also an interesting issue, because different evolutionary models of galaxies predict different redshift evolutionary scenarios of the spatial metallicity distribution (see, e.g., Cresci et al., 2010). When completed, ALMA will achieve a sensitivity and a spatial resolution significantly better than the current (already amazing) capabilities. Future ALMA observations of high-*z* SMGs, including LESS J0332, will shed additional light on the early evolutionary phase of massive galaxies.

References

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One of the ALMA 12-metre-diameter European antennas is shown being moved on the antenna transporter during testing at the ALMA Operations Support Facility. See Picture of the Week 16 July 2012 for more information.