# Early ALMA Science Verification Observations of Obscured Galaxy Formation at Redshift 4.7

Jeff Wagg[1, 2]
Tommy Wiklind[3]
Chris Carilli[4]
Daniel Espada[5]
Alison Peck[3, 6]
Dominik Riechers[7, 8]
Fabian Walter[9]
Al Wootten[6]
Manuel Aravena[2]
Denis Barkats[3]
Juan Cortes[3]
Richard Hills[1, 3]
Jacqueline Hodge[9]
Violette Impellizeri[3]
Daisuke Iono[5]
Adam Leroy[6]
Sergio Martin[2]
Mark Rawlings[3, 6]
Roberto Maiolino[1]
Richard G. McMahon[9]
Kim S. Scott[6]
Eric Villard[3]
Catherine Vlahakis[3]

1 Cavendish Laboratory, University of Cambridge, UK
2 ESO
3 Joint ALMA Observatory, Santiago, Chile
4 National Radio Astronomy Observatory, Socorro, USA
5 National Astronomical Observatory of Japan, Tokyo, Japan
6 National Radio Astronomy Observatory, Charlottesville, USA
7 Dept. of Astronomy, California Institute of Technology, Pasadena, USA
8 Cornell University, Ithaca, USA
9 Max Planck Institute for Astronomy, Heidelberg, Germany
10 Institute of Astronomy, University of Cambridge, UK

**Roughly half the star formation in the young Universe is thought to have been heavily obscured by dust and molecular gas. A new suite of facilities and experiments operating at submillimetre through to centimetre wavelengths is providing astronomers with the ability to study galaxies whose star formation and AGN activity would be partially invisible to optical telescopes. The most sensitive of these new instruments is ALMA. Even with only a subset of the final number of 12-metre antennas operational, the first ALMA observations are providing sensitive, unobscured images of the formation of massive galaxies. Observations of BR1202-0725 at $z$ = 4.7 are described as an example.**

Understanding how galaxies acquire their gas and convert that gas into stars at high redshift represents one of the outstanding problems in galaxy formation. Studies of atomic hydrogen emission at long radio wavelengths are limited to the very nearby Universe, while cold molecular gas may be probed at millimetre and centimetre wavelengths through observations of redshifted CO line emission out to the epoch of reionisation (e.g., Wang et al., 2010). Major advances in our understanding of the cold gas content in the most distant galaxies can be attributed to interferometers like the Plateau de Bure Interferometer (PdBI), the Combined Array for Research in Millimeter-wave Astronomy (CARMA) and the Jansky Very Large Array (JVLA). The Atacama Large Millimeter/submillimeter Array (ALMA) complements these facilities by providing an order of magnitude increase in shorter submillimetre wavelength sensitivity to cold gas and dust in galaxies over a broad range in redshift. Interferometric observations at these higher frequencies are necessary to resolve spatial variations in the cold dust properties and characteristics of atomic and molecular gas in young galaxies, which will ultimately shed light on how they formed their stars early on.

The first single-dish, submillimetre wavelength continuum observations of cold dust in high-redshift quasars and massive starburst galaxies demonstrated that the formation of these objects can be accompanied by large quantities of dust that may be heated by star formation and/or active galactic nucleus (AGN) activity, leading to high far-infrared luminosities for the most extreme objects (e.g., Omont et al., 1996). These early studies helped to motivate the need for higher spatial resolution imaging with facilities like ALMA, which will be used to constrain the source of the dust heating. Fuelled by high molecular gas fractions (Daddi et al., 2010; Tacconi et al., 2010), star formation in young galaxies is also accompanied by strong emission in far-infrared lines like the 157.7 μm [C II] line. This emission is believed to trace photon-dominated regions and the cold neutral medium, and has now been studied by the Infrared Space Observatory (ISO) and Herschel in large samples of star-forming galaxies and AGN in the nearby Universe (e.g., Genzel & Cezarsky, 2000; Sargsyan et al., 2012) to provide an unobscured probe of star formation activity. [C II] line emission is being detected in high-redshift galaxies between $z \sim 1$ and 7 (e.g., Venemans et al., 2012), confirming its usefulness as a tool to study star formation and the kinematics of distant galaxies.

## ALMA commissioning observations

Located at an elevation of 5000 metres in the Chilean Atacama Desert, ALMA is the largest submillimetre and millimetre wavelength telescope in the world. Part of the commissioning and science verification phase involves demonstrating the efficacy of various calibration-related properties of the array by repeating observations made with other facilities (Hills et al., in prep.). One of the top-level science goals for ALMA is to detect far-infrared (FIR) line emission from ionised gas in star-forming galaxies redshifted to submillimetre wavelengths, and so in order to demonstrate that this is possible we observed the [C II] line and dust continuum emission in BR1202-0725 at $z$ = 4.7.

BR1202-0725 had previously been observed with the Submillimeter Array (SMA) on Mauna Kea (Iono et al., 2006), and is composed of two intrinsically luminous and (presumably) massive galaxies, both rich in molecular gas and dust (Omont et al., 1996). One of the pair is an optically luminous quasar, while the other shows no signs of AGN activity and is undetected in sensitive optical and infrared images. At $z$ = 4.7, the [C II] line is redshifted into the 340 GHz (Band 7) receiver window where ALMA provides a unique increase in sensitivity over other telescopes, even with only the sixteen 12-metre antennas that were typically available early in 2012. The previous SMA observations of [C II] line emission represented the only resolved observations of weak and broad, high redshift line and dust continuum emission at these frequencies, making this a unique target for ALMA science verification. These and other commissioning data have been made public to the community who are encouraged to use them for training or scientific purposes[1].

## Gas and dust in BR1202-0725

Band 7 ALMA observations toward BR1202-0725 were made in January 2012 using seventeen 12-metre diameter ALMA antennas for 25 minutes of total on-source observing time (Wagg et al., 2012). The 340 GHz continuum image with a synthesised beam size of 1.3 × 0.9 arcseconds is shown in Figure 1, and even with such a short integration time this map is already an order of magnitude more sensitive than the previous SMA observations. The northern and southern components of BR1202-0725 are separated by ~ 4 arcseconds, which roughly corresponds to 25 kpc at this redshift, while the positions of the sources in the ALMA map are consistent with SMA and PdBI observations (Omont et al., 1996; Iono et al., 2006; Salomé et al., 2012). These ALMA data reveal a third faint submillimetre counterpart, whose redshift is uncertain, but which may be associated with a Lyman-α emitter at the same redshift as the BR1202-0725 system (Hu et al., 1996). If all three objects lie at the same redshift and are in the process of a dynamical interaction, then it is likely that they will evolve into a massive galaxy with a stellar mass that could grow to $10^{11}$ $M_{\odot}$.

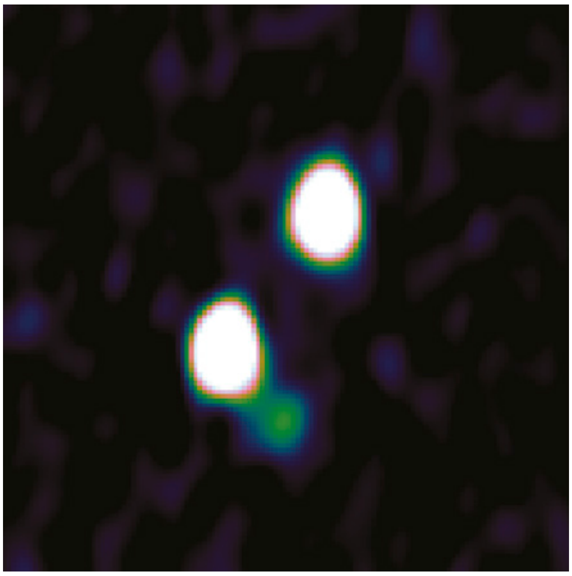
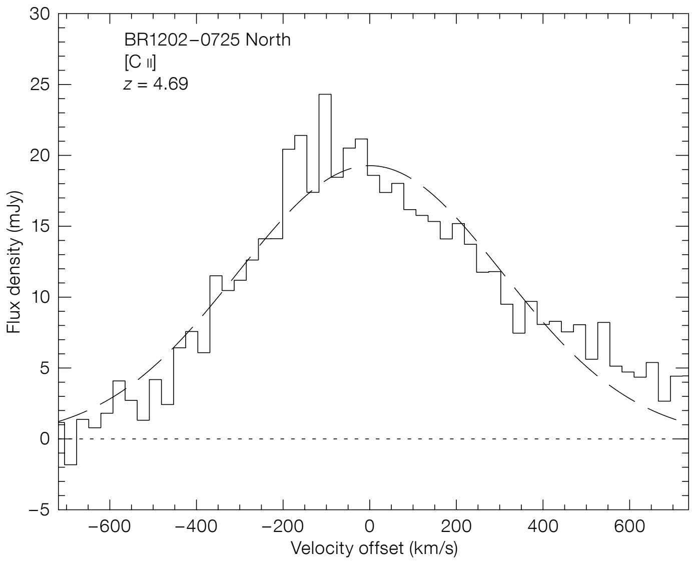


Figure 1. 10 by 10 arcsecond ALMA 340 GHz (Band 7) image of thermal dust continuum emission in BR1202-0725, a system composed of at least two FIR luminous galaxies (a quasar host galaxy and a heavily obscured starburst) that existed 1.3 billion years after the Big Bang. The faint submillimetre source below and to the right of BR1202-0725 South may also be part of the same group of galaxies. The synthesised beam size is 0.9 by 1.3 arcseconds.

We also detect the [C II] line emission with high significance in the two brightest members of the BR1202-0725 system (Figure 2). These are some of the most sensitive spectra of this line obtained in high redshift galaxies, and the line profile for the quasar is even suggestive of the presence of an outflow of ionised carbon. Such outflows of gas from the central AGN can potentially quench star formation in the interstellar medium of galaxies and have been observed in a quasar host galaxy that existed about 850 million years after the Big Bang (Maiolino et al., 2012). The large width of the [C II] line emission in the northern component is similar to what was observed with





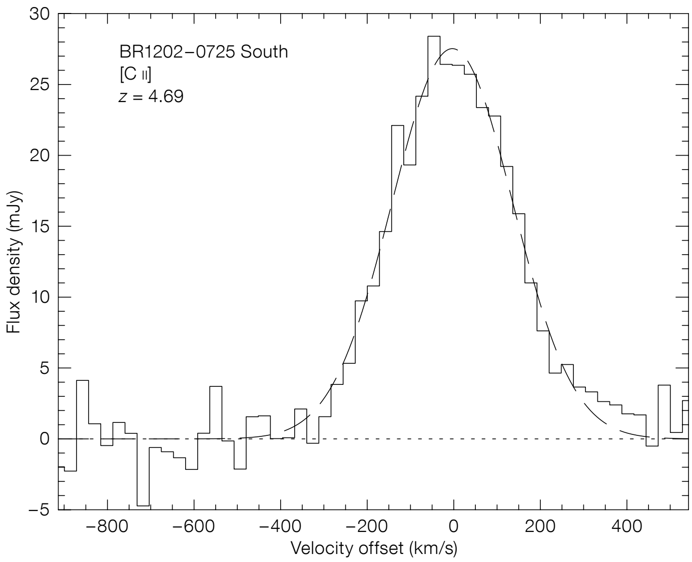




Figure 2. [C II] line emission in BR1202-0725 North and South at $z$ = 4.69 after subtraction of the continuum emission. The spectra have a typical rms of ~ 2 mJy per ~ 28 km/s channel. The high signal-to-noise of these spectra reveal how the starburst galaxy to the north has a larger [C II] line luminosity than the quasar host galaxy, while both have similar FIR luminosities. Figures from Wagg et al. (2012).

the SMA, while the small [C II]-to-FIR luminosity ratio is lower in the quasar than the starburst, which is consistent with what is observed in AGN and starbursts in the nearby Universe and $z \sim 1$ (Stacey et al., 2010; Sargsyan et al., 2012).

Recent observations of high-*J* CO lines and millimetre wavelength dust continuum emission from the PdBI confirm the complex nature of the BR1202-0725 system (Salomé et al., 2012). The CO data agree with the ALMA [C II] observations in that the starburst galaxy exhibits broader linewidths in both species than those observed in the quasar. The CO emission appears to be extended from the quasar, but is not coincident with the faint 340 GHz continuum source detected by ALMA, and all of the data are consistent with this system representing a merger of gas-rich galaxies that existed 1.3 billion years after the Big Bang.

## Prospects

These science verification observations with ALMA demonstrate the ability to detect weak line emission from high redshift galaxies at submillimetre wavelengths. Higher spatial resolution ALMA [C II] line observations will inevitably reveal the dynamical structure of the BR1202-0725 galaxy merger, and determine if the third continuum source is at the same redshift as the two more luminous members. Further observations of redshifted FIR line emission in massive galaxies have now been conducted as part of the early-science operations phase and both [C II] and the weaker [N II] 205 μm line emission have been detected (Nagao et al., 2012; Swinbank et al., 2012; de Breuck et al., in prep.). Taken together, the early results from ALMA provide a preview of how this enormous increase in submillimetre wavelength sensitivity will lead to a transformation in our understanding of the gas content of high-redshift galaxies.

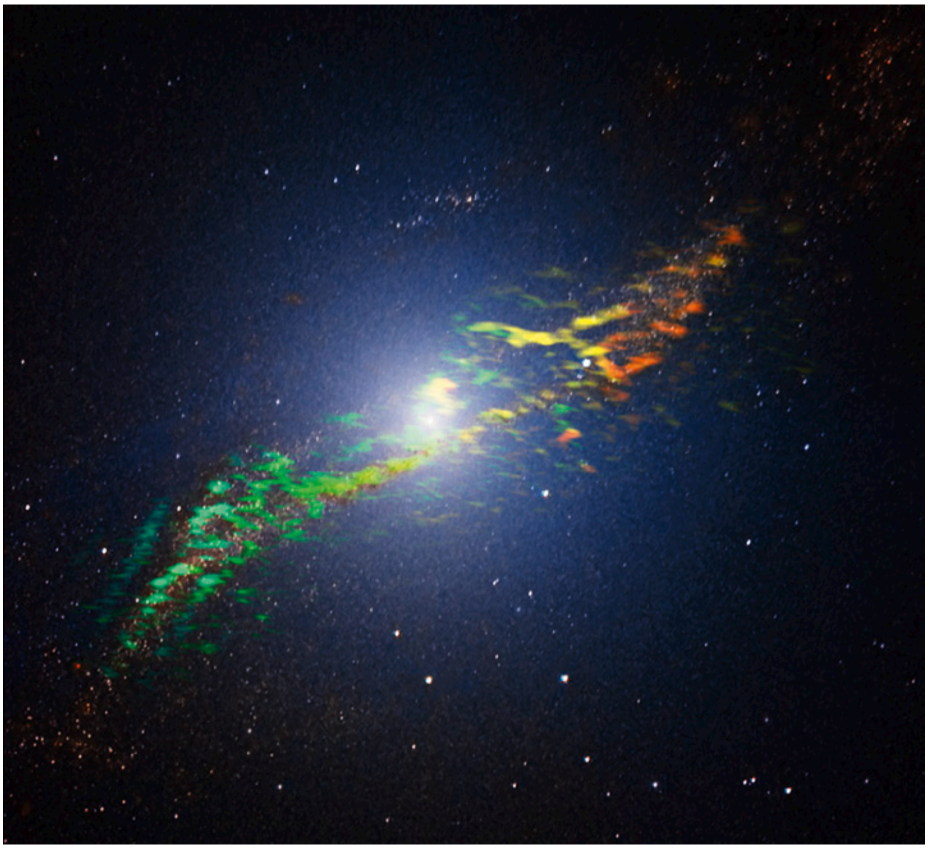
The results presented here are due to the hard work and dedication of many people from around the world, and we are grateful to everyone who has made ALMA a reality.

### References

Daddi, E. et al. 2010, ApJ, 713, 686
Genzel, R. & Cesarsky, C. J. 2000, ARA&A, 38, 761
Hu, E. M., McMahon, R. G. & Egami, E. 1996, ApJL, 459, L53
Iono, D. et al. 2006, ApJL, 645, L97
Maiolino, R. et al. 2012, MNRAS, 425, L66
Nagao, T. et al. 2012, A&A, 542, L34
Omont, A. et al. 1996, Nature, 382, 428
Salomé, P. et al. 2012, A&A, 545, A57
Sargsyan, L. et al. 2012, ApJ, 755, 171
Stacey, G. J. et al. 2010, ApJ, 724, 957
Swinbank, M. et al. 2012, arXiv:1209.1390
Tacconi, L. J. et al. 2010, Nature, 463, 781
Venemans, B. P. et al. 2012, ApJL, 751, L25
Wagg, J. et al. 2012, ApJL, 752, L30
Wang, R. et al. 2010, ApJ, 714, 699

### Links

[1] Access to ALMA Verification data: http://almascience.eso.org/alma-data/science-veification



ALMA (ESO/NAOJ/NRAO); ESO/Y. Beletsky

ALMA Band 3 Science Verification image of the nearby galaxy Centaurus A (NGC 5128) in CO(1-0) emission overlaid on an NTT/SOFI near-infrared image. The CO emission is colour coded by the radial velocity of the molecular gas showing evidence for rotation of the disc around the centre of the galaxy. The galaxy nucleus, visible in the SOFI image, hosts a central massive black hole. See Release eso1222 for more details.