ALMACAL: Exploiting ALMA Calibrator Scans to Carry Out a Deep and Wide (Sub)millimetre Survey, Free of Cosmic Variance

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We present the latest results from ALMACAL, a novel, wide and deep (sub-)millimetre survey that exploits ALMA calibration data that comes for free during science observations. Combining compatible data acquired during multiple visits to many ALMA calibrators, sufficiently low noise levels can be reached to detect faint dusty star-forming galaxies (DSFGs). As of April 2016, we have analysed data for more than 240 calibrators, reaching noise levels as low as ~ 10 μJy beam^{-1}, at sub-arcsecond spatial resolution. We have found 15 DSFGs, some less luminous than the sources detected by the deepest far-infrared surveys. Future analyses will deliver larger samples, free of cosmic variance, with redshifts determined via detection of multiple (sub-)millimetre lines, and dust emission imaged at milliarcsecond spatial resolution. The combination of area and depth reached by ALMACAL is unlikely to be surpassed by any other ALMA (sub-)millimetre survey.

A fraction of the restframe ultra-violet light emitted by star-forming galaxies (SFGs) is internally absorbed by dust and re-emitted at far-infrared wavelengths (Lutz et al., 2014). Detecting dust emission using far-infrared surveys is then essential to determine accurate star formation rates (SFR) and levels of dust attenuation for SFGs and, therefore, to understand the star formation history of the Universe. Indeed, this has been one of the main goals of many surveys carried out with past and current far-infrared/submillimetre facilities (for example, Spitzer, Herschel, James Clark Maxwell Telescope or the Atacama Pathfinder EXplorer). However, due to their limited sensitivity, the detection of dust emission has been restricted to the most extreme sources at each redshift, hindering broader studies of galaxy formation and evolution.

Currently, the Atacama Large Millimeter/submillimeter Array (ALMA) is the only facility able to surpass these limits and select galaxies more than ten times fainter, which are responsible for much of the SFR density at redshift $z > 1$ and the main contributors to the extragalactic background light — the integrated unresolved emission from extragalactic sources. Furthermore, this faint far-infrared population might be the link between the far-infrared-bright galaxies extensively studied in the past — submillimetre galaxies or SMGs — and the less extreme SFGs selected in optical/near-infrared surveys (and typically represented by Lyα emitters or Lyman-break galaxies) for which far-infrared detections are found for only ~ 5 % of the total population (Oteo et al., 2013).

ALMACAL: A wide and deep (sub-)millimetre survey

Using ALMA calibration observations, we are carrying out a novel, wide and deep (sub-)millimetre survey: ALMACAL (Oteo et al., 2016). Every ALMA science project includes calibration observations of very bright, compact sources to set the flux density scale, to measure the bandpass response, and to calibrate the amplitude and phase of the visibilities of the science targets (Fomalont et al., 2014). Observations of such calibrators are essential and represent a significant fraction of each observing block (OB). Each calibrator will typically be observed several times, often many times, on different dates, in several different ALMA bands, as part of one or several OBs corresponding to one or several ALMA science projects. Therefore, by combining compatible data for a high number of calibrators, it is possible to reach sensitivities and areas that allow the detection of dusty star-forming galaxies.

There are several, key advantages of using ALMA calibrators to search for and analyse high-redshift DSFGs. First, the sensitivities that can be reached after combining compatible data for different calibrators allow us to detect DSFGs fainter than those detected previously with the ESA Herschel satellite or other submillimetre, ground-based single dish observations. This opens a window to study dust emission in normal SFGs, with the data coming for free. Perhaps more importantly, a number of calibrators will be observed at extremely high spatial resolution, if this is amongst the requirements of the science project within which they are observed. The simultaneous presence in the map of one or more DSFGs and a bright ALMA calibrator lends itself perfectly to self-calibration (for example, Pearson & Readhead, 1984), which permits near-perfect imaging, even with the longest available interferometric baselines and highest frequencies. This advantage enables us to analyse the morphological properties in exquisite detail for any DSFG that is fortuitously located in a calibrator field.

The fact that each calibrator is often observed in several different ALMA frequency bands allows us to ensure that the faint detections are genuine with high confidence. Furthermore, such multi-band data allows the study of the spectral indices of DSFGs at matched spatial resolution, and determination of their redshifts via detections of (sub-)millimetre spectral lines (for example, Weiss et al., 2009). Furthermore, the number counts obtained for the selected galaxies, and the properties derived for those galaxies, come from sparse sampling of the astronomical sky and are thus relatively free of cosmic variance. ALMACAL is not however restricted to the detection of continuum sources. Several additional science goals include: blind searches for emission-line galaxies in the ALMACAL cubes to constrain the CO and [C II] luminosity functions (Decarli et al., 2014; Popping et al., 2016) and the cosmic H_2 mass density, to compare with models (for example, Lagos et al., 2011); studies of the physical mechanisms involved in the emission of powerful jets from quasars; and searches for common interstellar species in the lines of sight towards bright quasars (for example, Muller et al., 2014).

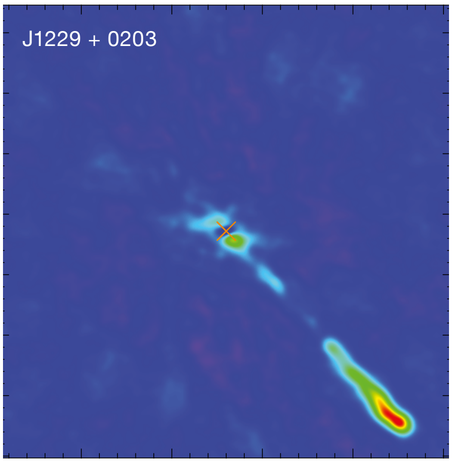

Figure 1. ALMA Band 6 (1.2 mm) image of the spectacular jet emanating from the calibrator J1229+0203. The multi-frequency observations provided by ALMACAL enable the nature of these jets to be studied in exquisite detail.

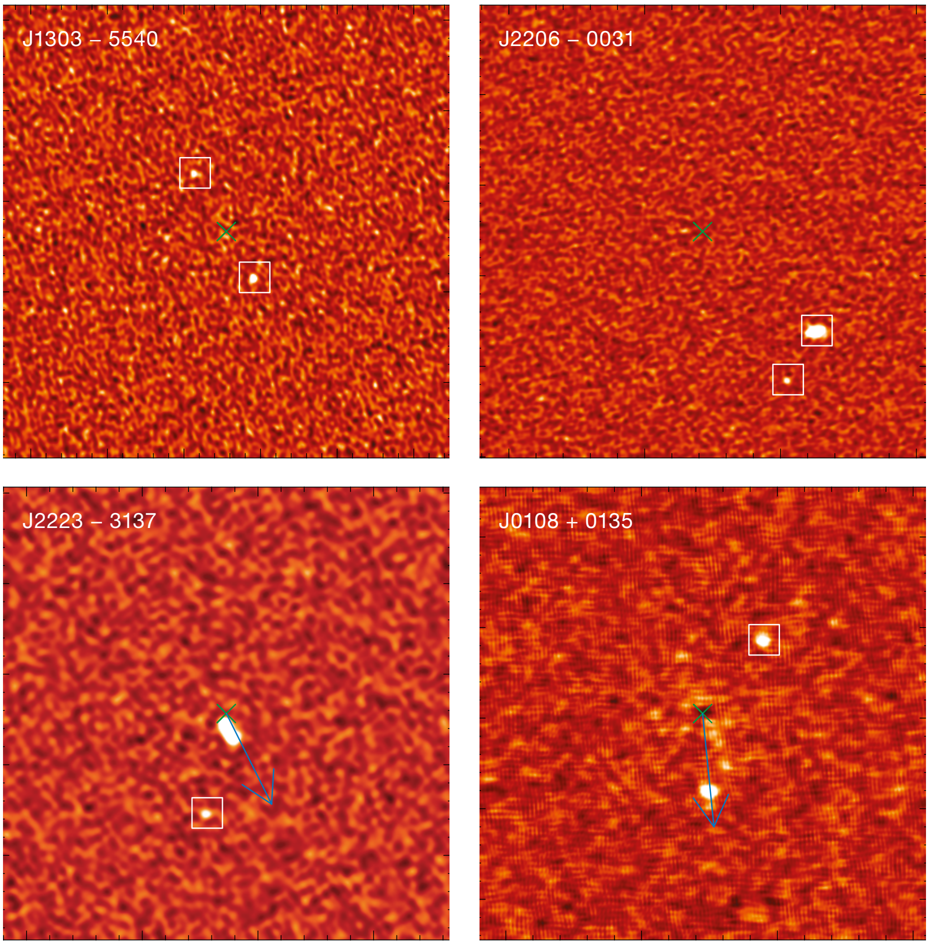

Figure 2. ALMA images (Band 6, 1.2 mm) of four calibrator fields in each of which at least one DSFG has been detected. Jets emanating from calibrators (identified via 3 mm imaging) are represented by the blue arrows, while DSFGs are indicated by white open squares. The calibrators, which have been subtracted in the *uv* plane using point-source models, are located in the centre of the images (green crosses).

Source selection

We have extracted from the ALMA archive all calibration data between the beginning of ALMA Cycle 2 and April 2016. No restriction on ALMA bands was applied, since different bands are useful for different science cases. First, the data for each calibrator in each OB are calibrated, following standard procedures. Then, for each observation, the calibrator is subtracted from the data in the Fourier *uv* plane using a point-source model, and the visibilities and clean maps are visually inspected, discarding all those datasets which show evidence of poor calibration. Next, all data for each calibrator in each band are combined after rescaling the visibility weights. In order to detect DSFGs via their dust emission, we focus the source extraction on ALMA Band 6 (B6, 1.2 mm) and Band 7 (B7, 870 μm). Imaging in Bands 3 and 4 are used to identify jets emanating from the calibrators, which are quasars. Some jets are very obvious once the central bright calibrator is subtracted from the maps (one of the most spectacular cases found so far is shown in Figure 1). However, others may appear as unresolved "blobs" and are easily confused with DSFGs. Whenever possible, we compute the B3 or B4 to B6 or B7 flux density ratios for the B6-/B7-detected sources. Ratios higher than unity indicate jets, while lower ratios, or a lack of detection in B3 and/or B4, are compatible with the far-infrared spectral energy distribution of a high-redshift DSFG. At the present phase of the survey, where data for more than 240 calibrators have been analysed, we have found 15 robust ALMACAL DSFGs (see Figure 2 for a small selection). Their far-infrared spectral indices (B7 to B6 flux density ratios) are compatible with them being at $z \sim 2$–3.

The importance of ALMACAL DSFGs

The discovery of a population of DSFGs with flux densities 5–10 times fainter than the faintest SMGs from the SCUBA2 survey (Koprowski et al., 2015) allows us to study the sub-mJy population that might overlap with normal SFGs, such as Lyα emitters, star-forming galaxies selected by their *BzK* colours (s*BzK*), or Lyman-break galaxies, which all lack dust emission detections in 95 % of cases. Uniquely detecting dust emission and measuring the total SFR of normal SFGs, without the uncertainties of ultraviolet-based dust correction factors, is feasible without having to rely on analysis via stacking (Béthermin et al., 2012). Additionally, faint ALMACAL DSFGs are among the very few high-redshift populations, alongside bright and extreme SMGs and gravitationally amplified systems (where interpretation is complicated by lens modelling), for which superb high-resolution imaging will be available from self-calibration by the bright calibrator in the centre of the map.

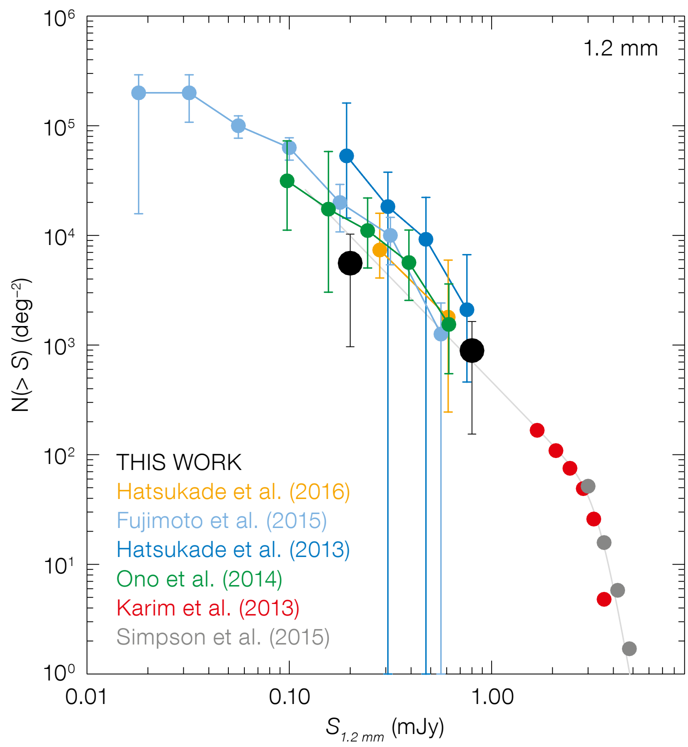

Figure 3. Cumulative number counts of DSFGs derived from ALMACAL at 1.2 mm, along with previous results (Hatsukade et al. 2013; Karim et al. 2013; Ono et al. 2014; Fujimoto et al. 2015; Simpson et al. 2015). Number counts derived in previous works have been converted to 1.2 mm by using the average far-infrared spectral energy distribution of SMGs at $z \sim 2.3$ (Swinbank et al., 2014). The grey curve is the fit obtained in Simpson et al. (2015), extrapolated toward the flux densities covered in the present ALMACAL phase.

The (sub-)millimetre number counts

The cumulative number counts (i.e., the number of galaxies above a given flux density) is an observable that any credible model of galaxy formation and evolution must match. Most recent models can reproduce the bright end of the number counts ($S_{1.2\,mm} > 1$ mJy), but there are disagreements at fainter flux density levels. For example, model predictions based on the redshift evolution of the mass function of SFGs (Béthermin et al., 2011) give a number density of sources about five times lower than those based on the spectral energy distribution of the galaxies (da Cunha et al., 2013) and about 2.5 times smaller than predictions based on epoch-dependent luminosity functions (Cai et al., 2013). Therefore, firmer constraints on the faint end of the (sub-)millimetre number counts are needed to discriminate between the plausible models. At present, ALMACAL has derived number counts down to $S_{1.2\,mm} \sim 0.2$ mJy, resolving about 50 % of the extragalactic background light, and those counts are found to be lower than previously reported (Figure 3).

One of the main differences between ALMACAL and previous work is the source extraction technique. Whilst in ALMACAL only sources detected at $> 5\sigma$ are included in the sample, other works employ significantly lower thresholds to compensate for the lower area and/or sensitivity and boost the number of sources. This leads to contamination by spurious detections. Although statistical corrections are normally applied, these are not always accurate. Recently, Hatsukade et al. (2016) also obtained slightly lower number counts, considering only $> 5\sigma$ detections. One of the unique aspects of ALMACAL is that most of the galaxies are observed in multiple bands, so we can be confident that all ALMACAL DSFGs are real. Furthermore, and very importantly, since ALMA calibrators are distributed over the whole southern and equatorial sky, the ALMACAL (sub-)millimetre number counts are relatively free from cosmic variance. The apparent flattening we observe in the (sub-)millimetre number counts towards low flux densities has strong implications for our understanding of the dust emission from (and attenuation in) SFGs. ALMACAL will be the key to a fuller understanding.

The future

ALMACAL is continuously in progress, adding more and more calibration data on a daily basis. We will keep gathering and combining observations while ALMA keeps observing. This will likely result in the largest ALMA (sub-)millimetre map down to a depth of several μJy, a unique dataset to study the nature of the faint submillimetre population. Apart from compiling more and more calibrator data, future work includes the characterisation of the ALMACAL detected sources via multi-wavelength observations to determine their redshift (for the sources without multiple millimetre line detections), stellar mass or obscuration. This step is needed to explore the relation between ALMACAL DSFGs and the normal SFG population typically represented by Lyα emitters, Lyman-break galaxies or *sBzK* galaxies selected in ultra-violet/optical/near-infrared-based surveys.

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