Massive Young Star Clusters Near and Far: From the Milky Way to Reionization
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Bright Submillimeter Galaxies: Evidence for Maximal Starbursts

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Abstract AzTEC is a sensitive bolometer camera that, coupled with 10–15m-class sub-mm telescopes, has mapped more than 3 sq. deg of the extragalactic sky to depths between 0.7 and 1.1 mJy at 1.1mm, prior to its current installation and operation on the 32m Large Millimeter Telescope (LMT). These extragalactic surveys targeted towards blank-fields and biased high-z environments alike have allowed us to identify a few thousands of submillimeter galaxies, powerful obscured starbursts at high-redshifts ($z > 1$), some of which have intrinsic Star Formation Rates SFR$\gtrsim 1000\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ and furthermore are extremely compact ($\sim 1\,$kpc). Our results imply that these extraordinary systems are forming stars in a *gravitationally bound* regime in which gravity prohibits the formation of superwinds, leading to matter accumulation within the galaxy and further generations of star formation.

1 Introduction

A key contribution to the star formation history of the Universe comes from the far-IR to millimeter wavelength regime, which has been shown to uncover ultraluminous violently star-forming galaxies at high redshifts ($z \gtrsim 2$) that would have gone undetected at traditional optical-near IR wavelength surveys due to their intrinsic high obscuration (Smail, Ivison & Blain 1997; Barger et al. 1998; Hughes et al. 1998). Named the (Sub-)Millimeter Galaxy population (SMG for short), this population has been linked to the formation of massive elliptical galaxies, with large luminosities $L > 10^{12}\mathrm{L}_\odot$, large star formation rates $> 100\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, large reservoirs of gas $\gtrsim 10^{10}\mathrm{M}_\odot$, and large dynamical $\gtrsim 10^{11}\mathrm{M}_\odot$ and stellar masses $\gtrsim 10^{11}\mathrm{M}_\odot$ (e.g. Greve et al. 2005; Tacconi et al. 2008; Dye et al. 2008; Targett, Dunlop & McLure 2012).

Due to the steep rise with frequency of the Spectral Energy Distribution (SED) of SMGs on the Rayleigh-Jeans tail ($S_\nu \propto \nu^{3-4}$), the FIR peak is redshifted into the sub-mm/mm observing bands with increasing distance, resulting in a strong negative k-correction that roughly cancels the effects of cosmological dimming with redshift for observations at $\lambda \gtrsim 500\mu$m and between $1 < z < 10$ (Blain, & Longair 1993). This effect represents a unique opportunity for an unbiased view of star formation over a wide redshift range back to the earliest epochs of galaxy formation. However, identifying and understanding the nature of these discrete sources has proven to be challenging because of the low angular resolution of single-dish telescopes ($\theta_{\mathrm{FWHM}} \sim 14-35''$), the faintness of counterparts in the rest-frame optical and ultraviolet (UV) bands, and the limited statistics of poor samples (Blain et al. 2002; Casey, Narayanan, & Cooray 2014, and references therein). Significant effort, using multi-wavelength observations to identify counterparts, has been made to calculate the redshift distribution of submillimeter galaxies, their intrinsic luminosities, masses, morphologies, etc. A common method

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to find counterparts is to use surrogate wavelengths indicative of star-formation, such as high resolution radio continuum and *Spitzer*/Multiband Imaging Photometer for *Spitzer* (MIPS) 24 μm observations, however these wavelengths suffer from a well-known systematic bias against high redshift ($z \gtrsim 3$) sources. Indeed, a large fraction of the counterparts identified using direct interferometric imaging in the mm/submm wavelengths are shown to be extremely faint in nearly all other wavelength bands ($r > 26$, $K > 24$) with little or no radio or *Spitzer*/MIPS 24 μm emission (Iono et al. 2006; Wang et al. 2007; Younger et al. 2007, 2009), and a fraction of high redshift SMGs may have been missed or mis-identified with a foreground source in earlier studies due to surrogate-wavelength counterpart identification before sub-millimeter interferometry of large samples has become available (e.g. Hodge et al. 2013).

Nevertheless, given the flatness of the k-correction between $1 < z < 10$ at 1.1mm and the fact that most of the population is at $z > 1$, the FIR luminosities of SMGs have been firmly placed at $L_{\rm FIR} \sim 10^{12} - 10^{13} L_{\odot}$, corresponding to SFR$\sim 100 - 1000 M_{\odot}\,{\rm yr}^{-1}$ setting these galaxies as one of the most violently star forming systems known to date.

2 AzTEC surveys

AzTEC is a bolometric camera utilizing 144 silicon nitride micromesh detectors that operate at 1.1mm (Wilson et al. 2008). The first scientific campaign with AzTEC was conducted at the 15m-James Clerk Maxwell Telescope (JCMT, angular resolution $\theta \approx 18''$) in the winter of 2005-2006. The second and third campaign were conducted on the Japanese 10m Atacama Submillimeter Telescope Experiment (ASTE), during June to November in 2007 and 2008 ($\theta \approx 30''$). Since 2013 AzTEC is being operated at the Large Millimeter Telescope (LMT) where a new generation of millimeter surveys at higher angular resolution ($\theta \approx 8''$ for the 32m configuration) are being completed, with a mapping speed a factor of ~ 30 that of AzTEC on ASTE (equivalent to that of the SCUBA-2 camera on the JCMT).

Collectively, in the 2005-2007 campaign AzTEC mapped about 1.6 sq. deg. of the blank-field extragalactic sky to an rms of 0.7 to 1.7 mJy at 1.1mm (Scott et al. 2012, and references within) with high uniformity in the noise properties across the fields and fidelity in the extraction of sources. In this set of surveys under 1000 SMGs were detected.

A large part of the blank-field surveying effort was devoted to map the 0.72 sq. deg. central part (Scott et al. 2008; Aretxaga et al. 2011) of the Cosmological Evolution Survey (COSMOS) 2 sq. deg. field, that has been extensively targeted by a wide array of observations in order to probe the cosmic evolution of galaxies and the large-scale structure in which they are immersed (Scoville et al. 2007). With a wealth of multi-wavelength data spanning from X-rays to radio-wavelengths, and a core deep UV-optical-IR survey with the highest resolution and sensitivity offered by space facilities (HST, Spitzer, GALEX), it provides a unique opportunity to study the relationships and interactions among galaxy populations selected at different wavelengths and across a wide array of environments in cosmic time.

The AzTEC data showed an overdensity of sources with respect to the population of SMGs found in previous large blank-field surveys (Austermann et al. 2010). We identified departures to occur more significantly in the $S_{1.1{\rm mm}} \gtrsim 5$ mJy regime, and demonstrated that these differences are related to the areas where galaxies at redshifts $z \lesssim 1.1$ are more densely clustered (Aretxaga et al. 2011). The positions of optical-IR galaxies in the redshift interval

$0.6 \lesssim z \lesssim 0.75$ are the most strongly correlated with the positions of the 1.1mm bright population ($S_{1.1\text{mm}} \geq 6$ mJy), a result which does not depend exclusively on the presence of rich clusters within the survey sampled area. The most likely explanation for these departures in number counts at 1.1mm is galaxy-galaxy and galaxy-groups of galaxies lensing at moderate amplification levels ($\sim 30\%$), that increases in amplitude as one samples larger and larger flux densities. Our results and the comparison with the previously published number counts illustrated the fact that even ~ 0.70 sq. deg. surveys are still subject to variance due to the small volume sampled by the mapped areas in conjunction to the chance amplification by foreground structures.

3 Bright SMGs, maximal starbursts

About 15% of SMGs, initially detected at 0.85 to 1.3mm in low-resolution ($\sim 15'' - 30''$) wide-field surveys, break-up into multiple counterparts in $\sim 2''$ resolution (sub-)mm interferometric images (Younger et al. 2009; Smolcic et al. 2012; Hodge et al. 2013), sometimes at unrelated redshifts (Wang et al. 2011), while most still show compact unresolved structures at those resolutions. Higher-resolution (FWHM $\sim 0.5 - 0.8''$) continuum and line imaging of over a dozen SMGs has been performed with IRAM PdBI and SMA at ~ 350 GHz, establishing sizes in the range of $\lesssim 1.5$ to $7 - 8$ kpc (e.g. Engel et al. 2010). About 40% of the moderately bright ($5 \lesssim S_{850\mu m} \lesssim 8$ mJy) SMGs break into close binary systems, which gives support to a major merger scenario, stimulating the further growth of the stellar mass of the final object.

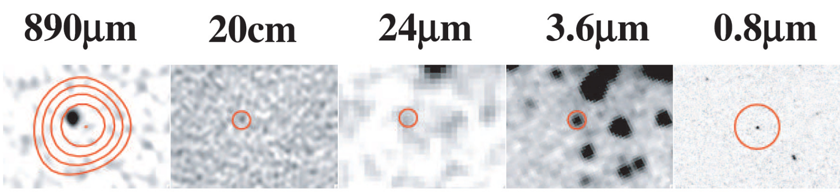

Fig. 1: $37'' \times 27''$ ($15'' \times 11''$ for ACS 0.8μm) postage stamps of radio-IR-optical counterparts of AzTEC1 in COSMOS (Younger et al. 2007). The left panel shows the high-resolution ($\theta \approx 2''$) Submillimeter Array (SMA) interferometric image of AzTEC 1 and superimposed is the poorer resolution AzTEC contours ($\theta \approx 18''$). To the right images at different wavelengths, where the circle marks the beam-size of the SMA identification. AzTEC1 appears isolated, with no big intervening galaxies nearby, and thus it is thought not to be a lensed system, despite its large brightness.

Among the SMGs followed-up at high resolution ($\theta < 1''$), AzTEC 1 in COSMOS (Fig.1) stands out as being an extremely compact ($\lesssim 1.3 \times 2.0$ kpc^2), bright ($S_{1.1mm} = 10.9 \pm^{1.7}_{1.4}$ mJy) and massive galaxy ($M_* \sim 2 \times 10^{11}M_\odot$) at $z \approx 4.6$, with a star formation rate ~ 1300 M$_\odot$yr^{-1} (Younger et al. 2008; Smolcic et al. 2011). The star formation density $\gtrsim 500$ M$_\odot$yr^{-1} kpc^{-2} is thus at least a factor of ~ 6 larger than $z \sim 2$ SMGs studied at resolutions of $0.4 - 0.6''$ (Engel et al. 2010).

An even more extreme system is the rare high-redshift bright source found in the large-area sub-mm survey HerMeS conducted at 250–500μm with the Herschel satellite, HFLS3 (Riechers et al. 2013): $M_{\rm gas} \approx 1 \times 10^{11}M_\odot$, $M_* \approx 4 \times 10^{10}M_\odot$, $L_{\rm IR} \approx 3 \times 10^{13}L_\odot$, SFR $\sim 2900\,$M$_\odot$ yr^{-1} with a surface density $\Sigma \approx 600\,$M$_\odot$ yr^{-1} kpc^{-2} at $z \approx 6.337$, the highest redshift SMG known to date.

Other SMGs measured at high resolution have sizes ranging less than 1 to 5 kpc, and SFRs between 100 and 1000 M$_\odot$ yr^{-1}.

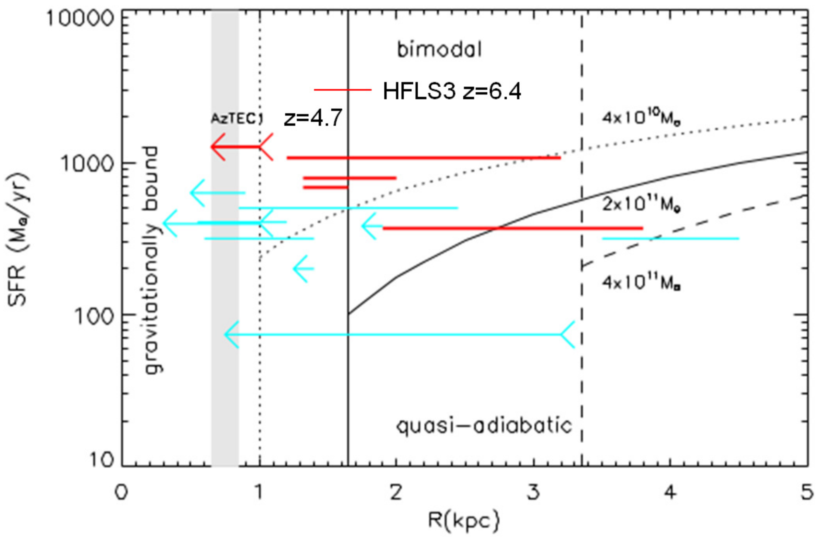

Fig. 2: SFR versus size for star formation systems. For each galaxy mass, defined by the solid, dotted and dashed lines, the plot is divided into three areas corresponding to 3 feedback regimes: galactic wind (quasi-adiabatic regime), bimodal or gravitationally bound regime (adapted from Silich et al. 2010). The 2D sizes of SMGs derived from published high-resolution continuum data are represented as thick red horizontal bars, and the CO-based sizes are shown in blue. The bars represent the galaxy size (in any orientation) measured within the 68% confidence intervals. Arrow heads denote 3σ upper limits. Double-upper limits (at the end of each bar) denote upper limits derived in 2 orthogonal orientations.

The luminosity versus size plane defines the fate of the gas relased by stars and the type of feedback these systems might be experiencing (Fig. 2, Silich et al. 2010). Feedback is recognized to be one of the key ingredients in galaxy formation modelling (e.g. Dekel & Silk 1986). The large photon output from massive stars and their violently injected mechanical energy make them major players in the dynamics of the Interstellar Medium (ISM) and key negative agents able to stop star formation, defining the efficiency of the process. This has driven a large body of studies where it is assumed that massive bursts of star-formation are the source of galactic superwinds that quench the further turning of gas into stars in the initial stages of formation of the galaxy (e.g. Granato et al. 2000). However, as shown by recent studies (Silich et al. 2010) in the case of powerful compact star forming regions, where gravity wins over thermal pressure, feedback turns positive, inducing further star formation into the very center.

AzTEC 1 and HFLD3 could be explained in these terms if the ultracompact size of the starbursts have forced the recycled gas of stars into a gravitationally bound regime, rapidly forming further generations of stars. Alternatively, if the systems break into smaller subcomponents, they could be interpreted as a late phase of a merger scenario, with multiple distributed regions forming at less extreme (sub-maximal) rates. Even within the small sample of SMGs imaged at high resolution at sub-mm wavelengths a tentative trend for the brightest SMGs to be more compact is seen, and taking into the stellar masses measured in most of the SMGs ($M \gtrsim 10^{11}\mathrm{M}_\odot$), the luminosity-size ratio falls within a regime that predicts they will develop either a gravity-bound wind or at bimodal flow, that induces both positive and negative feedback.

Observations at resolutions $\theta \lesssim 0.3''$ of these extreme objects with the Atacama Large Millimeter Array (ALMA) are necessary to measure the size of the dust enshrouded star-formation regions of a large sample of intrinsically very bright submillimeter galaxies (SMGs) at high-redshift ($z > 1$), discriminate between single compact bursts of star-formation and coalescence of clumps indicative of a late phase of a merger. At the same time, large-area millimeter-wavelength surveys spanning tens to hundreds of square degrees with the new-generation continuum cameras planned for the LMT will allow us to identify the most extreme systems, analogs to AzTEC 1 in COSMOS and HFLS3, to statistically characterize the properties of galaxies forming stars at rates in excess of $1000\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ and relate the fate of the gas expelled by the stars into enriching the intergalactic medium or creating a run-away process of star-formation that could build large spheroids rapidly in the first Gyr of life of these galaxies.

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