Co-Evolution of Central Black Holes and Galaxies
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OSIRIS View of Submillimeter Galaxies: A 2–D Spectroscopic Insight to Starburst Galaxies in the High-Redshift Universe

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Abstract. Ultra-luminous infrared galaxies ($L_{\rm IR} > 10^{12}\,L_\odot$) are locally rare, but appear to dominate the co-moving energy density at higher redshifts ($z > 2$). Many of these are optically faint, dust-obscured galaxies that have been identified by the detection of their thermal dust emission in the sub-mm. Multi-wavelength spectroscopic follow-up observations of these sub-mm galaxies (SMGs) have shown that they are massive ($M_{\rm stellar} \sim 10^{11}\,M_\odot$) objects undergoing intense star-formation (SFRs $\sim 10^2$–$10^3\,M_\odot\,{\rm yr}^{-1}$) with a mean redshift of $z \sim 2$, coinciding with the epoch of peak quasar activity. Furthermore, the presence of AGNs in $\sim$ 28–50% of SMGs has been unveiled in the X-ray and near-IR. When both AGN and star-formation activity are present, long-slit spectroscopic techniques face difficulties in disentangling their independent contributions from integrated spectra. We have observed Hα emission from a sample of three SMGs in the redshift range $z \sim$ 1.4–2.4 with the integral field spectrograph OSIRIS on Keck, in conjunction with Laser Guide Star Adaptive Optics. The spatially resolved, two-dimensional spectroscopic insight that these observations provide is the only viable probe of the spatial distribution and line-of-sight motion of ionized gas within these galaxies. We detect multiple galactic-scale sub-components, distinguishing the compact, broad Hα emission arising from an AGN from the more extended narrow-line emission of star-forming regions spreading over $\sim$ 8–17 kpc. We explore the dynamics of gas in the inner galaxy halo to improve our understanding of the internal dynamics of this enigmatic galaxy population. We find no evidence of ordered orbital motion such as would be found in a gaseous disk, but rather large velocity offsets of a few hundred kilometers per second between distinct galactic-scale sub-components. Considering the disturbed morphology of SMGs, these sub-components are likely remnants of originally independent gas-rich galaxies that are in the process of merging, hence triggering the ultraluminous SMG phase.

Keywords. galaxies: high-redshift, galaxies: starburst, galaxies: active, galaxies: kinematics, dynamics, techniques: spectroscopic

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1. Submillimeter Galaxies: Ultra-Luminous Infrared Galaxies at High Redshift and Sites of Rapid SMBH Growth

In the past two decades, hundreds of galaxies have been identified by submillimeter (submm) and millimeter (mm) surveys at $\lambda \sim 850 - 125\,\mu$m (Smail *et al.* 1997; Barger, Cowie & Sanders 1999; Eales *et al.* 1999; Bertoldi *et al.* 2000; Cowie *et al.* 2002; Scott *et al.* 2002; Borys *et al.* 2003; Webb *et al.* 2003; Coppin *et al.* 2005; Younger *et al.* 2007). These submm observations preferentially pick out extremely luminous objects with cold dust temperatures, sufficient to boost the far-IR region of the thermal dust SED bump (e.g., Blain *et al.* 1999). The abundant dust that makes these submillimeter galaxies (SMGs) such prodigious submillimeter emitters inevitably hampers the detection of rest-frame ultraviolet (UV) and optical emission from these objects. Photometric techniques that have been very successful at picking out large numbers of high-redshift galaxies (e.g., Lyman break galaxies or LBGs; Steidel *et al.* 2003) have thus proved ineffectual for SMGs. Furthermore, the large 13-arcsec beam of the discovery mm and submm images does not offer sufficient angular resolution to pinpoint the precise location of SMGs for follow-up observations at other wavelengths. Their subsequent study has been facilitated by their detection as μJy radio sources. Ultra-deep 1.4 GHz radio surveys with the Very Large Array (VLA) – with a $\sim 1\farcs5$ beam – have provided the adequate angular resolution to identify μJy radio counterparts to a substantial fraction of SMGs (e.g., Ivison *et al.* 1998; Ivison *et al.* 2002). In this manner, it has been possible to determine spectroscopic redshifts for $\sim 65\%$ of SMGs with $S(850\,\mu\mathrm{m}) > 5\,\mathrm{mJy}$ (see Chapman *et al.* 2005, hereafter C05, and references therein).

Detailed follow-up observations of these radio-identified SMGs have revealed total IR luminosities of $L_{8-1000\mu\mathrm{m}} \gtrsim 10^{12}$–$10^{13}\,L_\odot$ (C05), placing them under the ULIRG luminosity class (Sanders & Mirabel 1996). With large stellar masses $M_{\mathrm{stellar}} \sim 10^{11}\,M_\odot$ derived from photometry (Borys *et al.* 2005) and high SFRs, in excess of 100–1000 $M_\odot\,\mathrm{yr}^{-1}$ from optical (C05), near-IR (Swinbank *et al.* 2004) and X-ray work (Alexander *et al.* 2005), SMGs are the likely progenitors of today's most massive galaxies ($L \gg L^*$; Lilly *et al.* 1999; Smail *et al.* 2004).

Deep optical and near-IR imaging has shown that SMGs typically display disturbed morphologies suggestive of merging or interacting systems (Smail *et al.* 1998; Smail *et al.* 2004), similar to what is observed in local ULIRGs. These results have prompted the idea that SMGs may be the high-z analogs of these extreme local objects, likely hosting similar astrophysical processes (e.g., C05). Local ULIRGs have been shown to be powered by intense and compact nuclear activity, either starburst in nature or arising from an embedded AGN, though in most instances being a composite of both. In the case of SMGs, ultra deep X-ray studies using the unique 2-Ms *Chandra* Deep Field-North (CDF-N) Survey suggest that $\sim 28 - 50\%$ host an obscured AGN (Alexander *et al.* 2005), albeit under large columns of obscuring material ($N_{\mathrm{H}} \gtrsim 10^{23}$–$10^{24}\,\mathrm{cm}^{-2}$). These results all indicate that star formation and AGN activity coexist within many SMGs. The large fraction of AGNs in SMGs and the derived supermassive black hole (SMBH) masses in these galaxies suggest that the submm phase may play an important role in the rapid growth of SMBHs that leads to the establishment of the local Magorrian relation (Alexander *et al.* 2008).

With a mean redshift of $\langle z \rangle \sim 2.2$, the redshift distribution of radio-identified SMGs coincides with the global peak epoch of quasar activity (C05). The observational evidence connecting individual SMGs and AGNs, plus the coincidence of their redshift distributions, strongly suggests that an evolutionary connection exists between these two populations. Such a connection is reminiscent of the merger–ULIRG–quasar evolution scenario first proposed by Sanders *et al.* (1988). Within this scenario, a merger between two gas-rich galaxies ignites intense star formation, which is initially obscured and likely corresponds to a dust-obscured ULIRG/submm-bright phase. As the central SMBH grows, feedback outflows carve channels through the dust-obscuring material until the system becomes visible, entering the optically bright quasar phase.

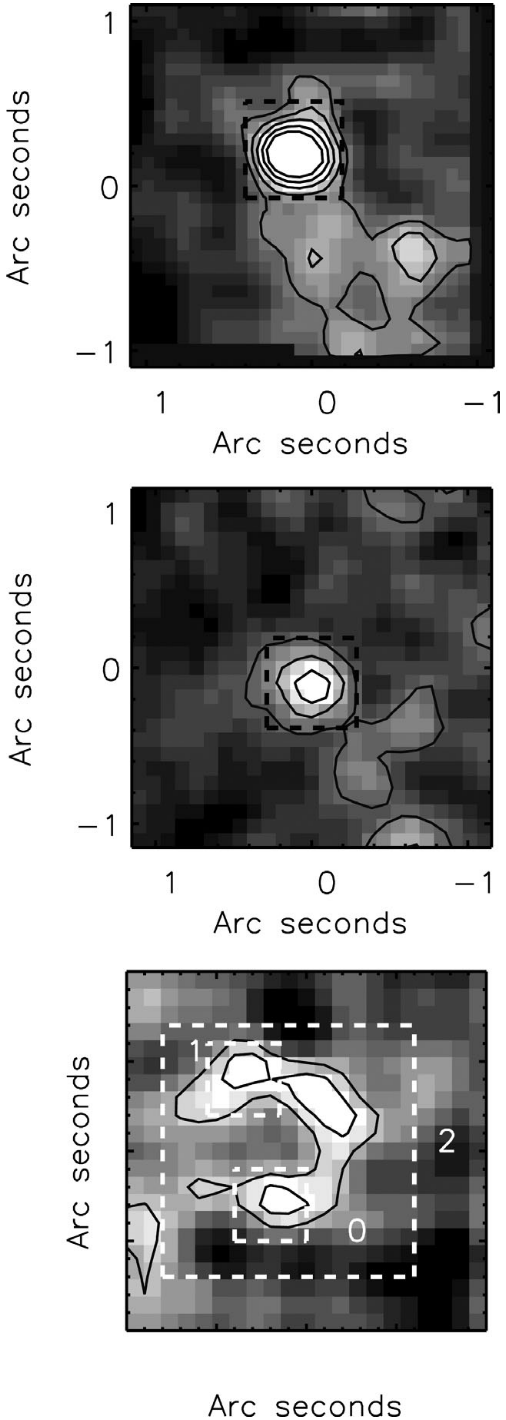

Figure 1. OSIRIS narrow-band Hα images for the three SMGs in our sample with overlaid intensity contours. Hα contours show a combination of compact emission and more extended, diffuse regions. These images, resulting from $\sim$ 3hr/object observations, are produced by collapsing the science cube along the dispersion direction over a range $\Delta v \sim$ 1000–2000 km s^{-1} centered at the redshifted Hα line for each of our targets. The top two images are a $2'' \times 2''$ view of observations taken with the 0.″1 OSIRIS plate scale, while the bottom is a $1'' \times 1''$ image taken with the finer 0.″05 scale. *Top:* SMM J030227.73 is dominated by a bright, compact knot (box), while the faint and diffuse emission appears at a lower S/N. From the spatial distribution of Hα line-widths we find that the compact knot displays a somewhat broad Hα component ($\sigma_{\rm rest} \sim 1000$ km s^{-1}) while the more diffuse emitting region shows a much narrower component ($\sigma_{\rm rest} \lesssim 200$ km s^{-1}; Menéndez-Delmestre *et al.*, in preparation). Optical and near-IR spectra by C05 and S04 place this galaxy at $z \sim 1.408$, with a high [N II]/Hα ratio (1.38 ± 0.07; S04) suggesting the presence of AGN activity. *Center:* SMM J123549.44 displays a prominent point source. Displaying a broad Hα line (FWHM$_{\rm rest}$ $\gtrsim$ 1000 km s^{-1}), we take this emission knot to be associated with AGN activity. Long-slit near-IR observations of this source (S04) and ultra-deep *Chandra* images (Alexander *et al.* 2005) have revealed clear AGN signatures. *Bottom:* SMM J163650.43 shows diffuse emission extending in the shape of an arc, within which Hα line characteristics differ: the north-east clump (box 1) displays a broad Hα line, while other regions of the diffuse emission display a narrow Hα line (box 0). Long-slit spectroscopic observations by S04 detected narrow Hα emission with an underlying broad Hα component (FWHM$_{\rm rest}$ $\sim$ 306 ± 47 and 1753 ± 238 km s^{-1}, respectively). We emphasize that the long-slit spectroscopic view provides insight solely to the integrated emission from the region enclosed within the slit (roughly represented by the large box).

2. Limits of Long-Slit Near-IR Spectroscopy and the Power of Integral Field Spectrographs

Deep long-slit spectroscopic observations of Hα emission in SMGs with the Near-Infrared Spectrograph (NIRSPEC) on Keck have provided constraints on star formation

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rates (SFRs) and dynamical masses of SMGs: Swinbank *et al.* (2004) (hereafter, S04) find $\langle \mathrm{SFR} \rangle \sim 1000\, M_\odot\, \mathrm{yr}^{-1}$ and $\langle M_{\mathrm{dyn}} \rangle \sim (1.5 \pm 0.9) \times 10^{11}\, M_\odot$ for a sample of 30 SMGs. However, the presence of an AGN in these systems may enhance observed line kinematics, modify line ratios, and boost absolute line emission fluxes. Such mixing is indeed reported by S04, with broad Hα emission (FWHM(Hα) $\gtrsim 1000\, \mathrm{km\, s^{-1}}$) present in $\gtrsim$ 40% of their SMG sample. In a parallel study, Takata *et al.* (2006) used a combination of long-slit spectrographs from the Subaru, VLT and Keck telescopes and found that roughly 40% of the 22 SMGs in their sample display broad Balmer lines. Although the line widths found for SMGs in these studies are narrower than those typically found for classical quasars (FWHM(Hα) $\gtrsim$ 2–8 $\times 10^3\, \mathrm{km\, s^{-1}}$; e.g., Puchnarewicz *et al.* 1997), they are markedly larger than those found for other populations of starburst-dominated galaxies (e.g., FWHM$_{rest} \lesssim$ 500 km s^{-1} in LBGs; Erb *et al.* 2003). These large velocity dispersions suggest that we are seeing the broad-line region close to a central AGN. Having access only to the integrated flux over the portion of the galaxy that falls within the slit, long-slit spectra face difficulties in disentangling the independent contributions from the AGN component and the star-forming regions. Dynamical information has also proved difficult to extract from long-slit data (S04), even for the less extreme and likely more ordered cases of optically selected LBGs at similar redshifts (Erb *et al.* 2003).

Integral field spectroscopy opens the possibility of investigating the properties of nebular emission at different scales within a galaxy. The 2D velocity fields can cast new light on the nature of these galaxies, whether consisting of gas forming stars in a disk or a merger between galaxies. Results from the SPectrometer for Infrared Faint Field Imaging (SPIFFI) on the ESO Very Large Telescope (VLT) first showed how 2D spectroscopy could reveal structure in line emission across a dusty galaxy at $z \sim 2.5$ (Tecza *et al.* 2004). Since then, a number of authors have investigated the details of near-IR emission from a handful of SMGs using integral-field units (IFUs; Swinbank *et al.* 2006; Nesvadba *et al.* 2007; Bouché *et al.* 2007). Their marginally resolved (seeing-limited) spectra reveal sub-structure in nebular and continuum emission, including multiple components and extended emission.

3. A Kiloparsec-Scale View of SMGs with OSIRIS Using Laser Guide Star Adaptive Optics

We have undertaken an observing program with the OH-Suppressing Infrared Imaging Spectrograph (OSIRIS) on Keck to study the 2D distribution of Hα emission in three SMGs. In addition to the larger photon collecting area provided by Keck, OSIRIS is a lenslet array that benefits from superior spectral resolution ($R \sim 3000-3800$). Moreover, OSIRIS is designed to be used with the Keck Laser-Guide Star Adaptive Optics (LGS-AO) system, allowing for diffraction-limited resolution to be reached with ground-based observations to probe for kpc-scale structures in galaxies at $z \sim 2$. With a field of view of $\sim 5'' \times 6''$, our adopted lenslet scale of $0\farcs05$–$0\farcs1$ allows us to probe down to a resolution of roughly ten times that of previous seeing-limited observations. These are the *first* integral-field spectroscopic LGS-AO observations of SMGs (Menéndez-Delmestre *et al.*, in preparation).

Taking advantage of existing near-IR long-slit Hα spectroscopy (S04, Takata *et al.* 2006), we selected SMGs with the brightest Hα lines, $S(\mathrm{H}\alpha) \gtrsim 10^{-15}\, \mathrm{erg\, s^{-1}\, cm^{-2}}$ to optimize detection with OSIRIS. Our SMG targets are SMM J030227.73+000653.5 ($z = 1.408$), SMM J123549.44+621536.8 ($z = 2.203$) and SMM J163650.43+405734.5 ($z = 2.385$), from the spectroscopically confirmed radio-identified sample of C05.

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4. Main Results

The OSIRIS Hα narrow-band images in Figure 1 show the spatial extent of nebular emission within our targets. The overall distribution of the line emission allows us to distinguish between compact and more diffuse regions of emission, where the former is likely associated with an AGN or a compact starburst, while the latter is likely dominated by extended star formation. However, one of the major appeals of integral field spectroscopy is that it allows for a 2D spatial insight to the *spectral* properties of an object. We extract spectral information at each spatial pixel to compare line properties in different regions within the target SMGs. An Hα velocity map reflecting the relative spectral position of the line centroids at each spatial pixel allows us to probe for velocity offsets between distinct components in each system, while an Hα FWHM map characterizing the velocity dispersions of the Hα gas allows us to probe for the presence of AGNs, as revealed by large line widths ($\mathrm{FWHM}_{rest} \gtrsim 1000$ km s^{-1}).

Within the SMGs in our sample we distinguish regions with broad Hα emission, likely dominated by AGN activity, from those with narrow Hα emission where star formation is taking place (see Figure 1). Diffuse, narrow Hα emission – where star-formation activity likely dominates the Hα energetics – extends over spatial scales of $\sim 0.''7$–$2''$. At the redshifts covered by our targets, these angular sizes correspond to 8–17 kpc. These sizes compare reasonably well to those presented by S06 and Tecza *et al.* (2004), who report resolved nebular emission on scales from 4–11 kpc for a total of seven SMGs.

Two of the SMGs in our sample have also been studied in detail using high-resolution CO observations taken with the IRAM Plateau de Bure Interferometer (Tacconi *et al.* 2008): SMM J163650.43 reveals a two-peaked CO profile emission spread over an elliptical region with an intrinsic FWHM size of $0.8 \pm 0.2 \times 0.4 \pm 0.3$, while in SMM J123549.44 the CO emission is dominated by a compact source ($\lesssim 0.''5$) with a prominent double-peaked CO profile, which Tacconi *et al.* associate with the orbital motions of gas within a disk close to the central AGN.

From the global dynamics revealed by the OSIRIS Hα velocity maps of our SMG targets, we find no continuous velocity structure across these galaxies that would suggest rotationally supported ordered gas kinematics, as would be present in a large gaseous disk (Menéndez-Delmestre *et al.*, in preparation). This is in contrast to relatively recent reports on massive high-redshift LBGs (e.g., Law *et al.* 2009; Förster Schreiber *et al.*(2009)), where continuous, gradual velocity gradients have been identified in individual cases as evidence for ordered rotation. SMGs do not appear to host such ordered kinematics.

We find velocity offsets between distinct galactic-scale sub-components in the SMGs of our sample. This result strengthens the conclusion derived from deep rest-frame optical *HST*-imaging that SMGs are disturbed systems, likely corresponding to mergers (Smail *et al.* 1998; Smail *et al.* 2004). Within this context, the distinct components that comprise the SMGs could potentially be associated with the remnants of the pre-merger galaxies. This is also in agreement with Greve *et al.* (2005), where they discuss the likelihood that the observed double-peaked CO profile in a sample of 18 SMGs corresponds to either a disk or a merger. Taking into account estimates of gas masses and source sizes, they conclude that such high mass surface density would imply high dynamical instabilities for a disk to survive. They thus conclude that the double-peaked nature of the CO lines traces distinct gas-rich components undergoing a merger or arise from a disk collapsing under gravitational instability. Within this scenario, the merging of these galactic-scale sub-components are likely triggering the ultraluminous SMG phase.

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