RevMexAA (Serie de Conferencias), **17**, 214–217 (2003)

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

DUSTY GALAXIES AT $Z > 1$

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RESUMEN

Repasamos las propiedades de las galaxias más luminosas en la región submilimétrica identificadas con SCUBA. Como ejemplo, describimos a la fuente SMM J09431+4700, una galaxia infrarroja hiperluminosa con $z = 3.35$, que alberga un AGN oscurecido. Comparamos las propiedades de esta galaxia con la otra galaxia hiperluminosa bien estudiada, identificada en el sondeo SCUBA - la fuente BAL-QSOSMM J02399−0136 con $z = 2.80$. La similaridad de estos sistemas sugiere que la retroalimentación del AGN es importante para regular la evolución de los brotes de formación estelar más luminosos en el Universo temprano.

ABSTRACT

We briefly review the properties of the most luminous submillimeter galaxies identified by SCUBA. We illustrate the main points with a description of the recently discovered submillimeter source, SMM J09431+4700, a $z = 3.35$ hyperluminous infrared galaxy which hosts an obscured AGN. We compare the properties of this galaxy with the only other well-studied hyperluminous galaxy identified by SCUBA surveys – the $z = 2.80$ BAL-QSO SMM J02399−0136. The similarity of the properties of these two systems suggests that feedback from AGN is important in regulating the evolution of the most luminous starbursts in the early Universe.

Key Words: **COSMOLOGY: OBSERVATIONS — GALAXIES: INDIVIDUAL (SMM J09431+4700) — GALAXIES: EVOLUTION — GALAXIES: FORMATION**

1. INTRODUCTION

Over the last five years sensitive surveys in the submillimeter (submm) and millimeter wavebands, in particular those undertaken with the SCUBA instrument on the JCMT, have identified a large population of distant dusty, active galaxies, with a space density far in excess of that seen locally (e.g. Smail, Ivison & Blain 1997; Hughes et al. 1998; Bertoldi et al. 2000; Scott et al. 2002; Smail et al. 2002a; Webb et al. 2002). Galaxies in the flux range probed by these surveys produce the bulk of the far-infrared background at 1 mm, underlining the cosmological importance of these systems (Blain et al. 1999; Cowie et al. 2002). Detailed investigation of a small number of examples shows that they are typically optically faint, have colors which are redder than the general field galaxy population and the handful with spectroscopic redshifts range from $z \sim 1$–3, confirming that these are Ultraluminous Infrared Galaxies, ULIRGs (Smail et al. 2002a). Most importantly, molecular CO mapping of those sources with accurate spectroscopic redshifts shows these gas-rich starbursts have sufficient gas to form an L^*-worth of stars (Frayer et al. 1998, 1999). These submm galaxies can therefore be naturally associated with the earliest, dust-obscured formation phase of the most luminous spheroids, and their resident supermassive black holes, seen in the local Universe. There remain many unanswered questions about the submm population, two of the most pressing are:

1. What is the highest redshift for a submm galaxy identified in a mapping survey? This provides a critical test of galaxy formation models, which already struggle to produce sufficiently large gas masses in galaxies at $z \sim 2$. Identifying similarly luminous gas-rich mergers at $z > 3$ will provide even stronger constraints;
2. What is the role of AGN and starbursts in determining the energetics and evolution of these luminous galaxies?

In this contribution we discuss a newly discovered example of the submm population and the insight this provides on these questions.

2. THE HIGHEST-Z SCUBA GALAXY KNOWN?

The submm galaxy we focus on here was detected by Cowie et al. (2002) in a deep 850μm SCUBA map through the core of the $z = 0.41$ cluster A 851. The source is SMM J09431+4700 with an 850 μm flux of 10.5 mJy. The magnification of this source by the foreground cluster will boost its apparent brightnesses by at most 20–30% (Cowie et al. 2002).

The low resolution of the SCUBA beam, 14″ FWHM, means the position of this source is uncertain at the $\sim 3''$ level. However, we can exploit the

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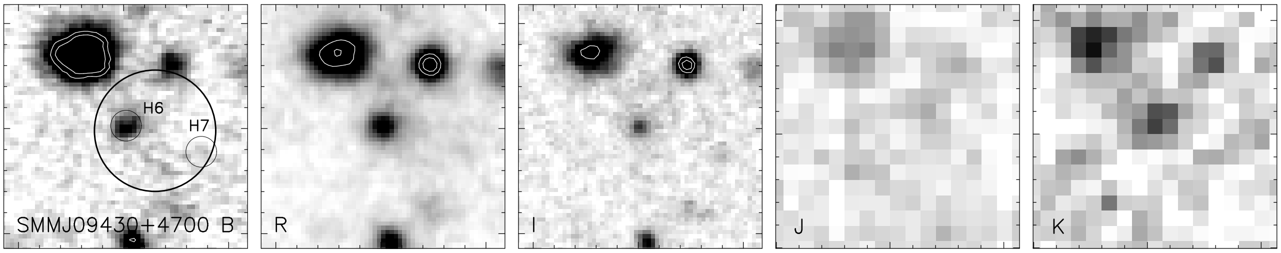

Fig. 1. $BRIJK$ views of the field containing the submm source SMM J09431+4700. The large circle shows the nominal $3''$-radius error circle of the SCUBA source, while the smaller circles identify the two radio counterparts. Each panel is $12'' \times 12''$, details of the optical/near-infrared imaging can be found in Ledlow et al. (2002) and Smail et al. (2002b).

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tight correlation found between far-infrared and radio emission in local star forming galaxies and use a new very deep VLA map of this region with a noise level of $\sigma_{1.4} = 3.5\mu\mathrm{Jy\,beam}^{-1}$ (Owen et al. 2002; Smail et al. 2002b) to search for a radio counterpart to the submm source. We find two radio counterparts within the positional error-box of the submm source (a relatively common occurrence for SCUBA sources, Ivison et al. 2002); the brighter radio source is closer to the nominal position of the submm emission. This is H6 with a 1.4-GHz flux of 72μJy, the fainter radio counterpart is H7 with 55μJy (Ledlow et al. 2002). The $1.5''$ FWHM resolution of the radio map and wide field of view means that these radio sources can be unambiguously associated with optical and near-infrared counterparts in deep Subaru/KPNO imaging of this field (Smail et al. 2002b).

We show the two radio-identified components of SMM J09431+4700, H6 and H7 in Fig. 1. Both radio counterparts are visible in either our optical or near-infrared imaging: H6 has $K = 20.2$ and $(R - K) = 3.6$, while H7 has $R = 25.9$ and $(R - K) \leq 4.6$. These galaxies, while faint, are feasible targets to tackle with an efficient spectrograph on an 8-m class telescope. We therefore observed both galaxies using the GMOS spectrograph (Davies et al. 1997) on Gemini-North during March 2002. These observations clearly identify the redshift for the optically-brightest counterpart, H6, as $z = 3.35$ (Fig. 2). Given the small separation between H6 and H7 – $4''$ or ~ 25 kpc in the source plane at $z = 3.35$ and the low surface density of μJy radio sources, we view it as likely that both radio sources are associated with the submm source.

Our spectroscopic measurements show SMM J09431+4700 to be the most distant submm-selected galaxy known, breaking through the $z = 3$ barrier for the first time. The previous highest-z spectroscopically-confirmed submm-selected galaxy was SMM J02399−0136 at $z = 2.80$ (Ivison et al. 1998). Although this represents only a 20% increase in redshift, it corresponds to a decrease of a factor of two in the abundance of the massive halos, $> 10^{12}\,\mathrm{M}_\odot$, needed to host these luminous galaxies (Jenkins et al. 2001). The exponential decline in the halo masses at higher redshifts underlines the strong constraints which are available from identifying the highest redshift submm galaxies.

At $z = 3.35$ the 850μm flux of SMM J09431+4700 translates into a luminosity of $\mathrm{L}_{FIR} \sim 1.5 \times 10^{13}\,\mathrm{L}_\odot$ (assuming a dust temperature of 38 K) indicating that this system is a Hyperluminous Infrared Galaxy (HyLIRG, Rowan-Robinson 2000). If purely powered by massive star formation, this immense luminosity would require a star formation rate of $\sim 10^4\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$! However, the spectrum of this galaxy shows the signatures of an obscured AGN (Fig. 2). Although the spatially-extended Lyα line has a FWHM of just $200\,\mathrm{km\,s}^{-1}$ in the rest-frame, higher excitation lines such as N Vλ1240 or C IVλ1549 exhibit much broader, structured emission with rest-frame velocity widths of $\sim 500\,\mathrm{km\,s}^{-1}$. A preliminary comparison of structure in the broad lines is illustrated in Fig. 2; there appear to be strong similarities between the morphologies of the N Vλ1240 and C IVλ1549 lines. In particular we highlight the two strong peaks in the C IV line – these are very reminiscent of the structures seen in broad emission lines of some radio galaxies and radio-loud quasars (Perez et al. 1988; Eracleous & Halpern 1994), although these show much larger velocity ranges. These structured emission lines are interpreted as resulting from scattering of radiation from the AGN by out-flowing conical winds (Corbett et al. 1998) and we suggest that the same mechanism is operating in SMM J09431+4700/H6.

The SMM J09431+4700/H6+H7 system has many features in common with other known hyperluminous submillimeter galaxies, such as SMM J02399−0136 (Ivison et al. 1998), as well as the brighter submm sources from the 8 mJy Survey (Scott et al. 2002; Ivison et al. 2002), although

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the latter currently lack published redshifts. These bright submm sources, with 850-μm fluxes of $\gtrsim$ 8 mJy, are frequently detected as radio sources in the deepest VLA maps (e.g. Ivison et al. 2002 detect 60% of their 8 mJy sample down to a 1.4-GHz limit of $\sim 20\mu$Jy). There is a hint that these very luminous submm galaxies have optically brighter counterparts (rest-frame UV) than the fainter submm sources – although there are examples of submm-bright but optically-invisible systems (Frayer et al. 2000). Many of these systems show multi-component morphologies in the optical and near-infrared, suggestive of interactions or tidal debris and indicating that as at lower-z, tidal action on the gaseous components of interacting galaxies is the basic mechanism for provoking a U/HyLIRG-luminosity event.

The spectroscopic identification of a second hyperluminous galaxy from the SCUBA population provides the opportunity of a detailed comparison of the properties of these two galaxies: SMM J02399−0136 and SMM J09431+4700. SMM J02399−0136 was the first submm source detected by SCUBA (Smail, Ivison & Blain 1997), the first source for which a spectroscopic redshift was measured (Ivison et al. 1998) and also the first submm source detected in molecular CO (Frayer et al. 1998). These observations showed that this massive, gas-rich system is identified with an interacting pair of galaxies, L1 and L2, at $z = 2.80$, and has a far-infrared luminosity of $L_{FIR} \sim 1 \times 10^{13}\,L_\odot$. L1 hosts a partially obscured AGN (Ivison et al. 1998), which has recently been identified as a Broad Absorption Line (BAL) QSO (Vernet & Cimatti 2001). The second component L2 is separated from L1 by about 10 kpc in projection. L2 may be tidal debris rather than an independent galaxy, as suggested by the apparent velocity shear across this feature in the spectrum published by Vernet & Cimatti (2001).

Apart from their optical morphologies, the most striking similarity between these two HyLIRGs is that both systems host partially obscured AGN. Actively fueled supermassive black holes (SMBH) are apparently common components of U/HyLIRGs at $z \lesssim 1$, although it should be stressed that these low-z systems are much rarer and much less important for the star formation history of the Universe than the SCUBA-selected population at $z \gg 1$. The structured broad emission lines seen in H6 suggest the presence of vigorous out-flows in this galaxy. Similar out-flows are very obvious in the UV spectrum of SMM J02399−0136 (Ivison et al. 1998). Moreover, the fact that these signatures are visible in the light from the AGN shows that at least one component of

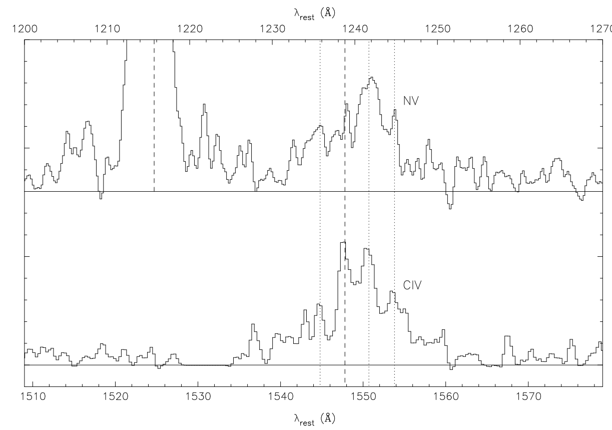

Fig. 2. A preliminary comparison of the morphologies of the NIVλ1240 and CIVλ1549 emission lines in SMM J09431+4700 from our Gemini/GMOS spectroscopy. The spectra have been heavily smoothed to emphasize the structural similarities of the broad emission lines. The dotted vertical lines connect features which may be common between the two lines. Note the breadth of these lines compared to the relatively narrow Lyα emission line which is visible in the top panel.

the winds in these galaxies arises from the nuclear regions close into AGN and is most likely driven by radiation from the AGN. It is likely that more extended winds are also being driven by any starburst within these systems, although these will be much harder to identify (but see Chapman et al. 2002).

Feedback and out-flows were a central theme of this conference – can we learn more about the connection between AGN and out-flows from these extremely luminous galaxies? There is increasing evidence for a relationship between the formation of spheroids, the growth of SMBH and QSOs (e.g. Granato et al. 2001; Archibald et al. 2001). At their most basic, these models begin with a merger-induced starburst within a gas-rich halo at high-z, the gas flow also provides fuel for the growth of the SMBH and hence the creation of an AGN. The feedback on the system from energy injected by the AGN is central to these schemes, and provides one mechanism for creating the observed SMBH to bulge mass correlation seen in local galaxies (Maggorian et al. 1998). It is proposed that such systems will go through a BAL-like phase (e.g. SMM J02399−0136) as a wind powered by the AGN drives out the dust and gas in the nuclear region, eventually transforming the system into an unobscured QSO (Fabian 1999). There is also a growing body of work stressing the role of jets as a mechanism for destroying dust and dissipating gas from around the AGN (Baker et al. 2002). There has been a tentative suggestion of the presence of a small, hence young(?), radio jet in

SMM J02399−0136 (Ivison et al. 1999) which would strengthen this connection – showing both jet and BAL features in a single submm source. The larger separation of the components in SMM J09431+4700, along with the narrower emission line widths and fainter absolute magnitude of the system suggests to us that it is at an earlier stage in its evolution – before the on-set of a strong AGN-driven wind and jet formation. The future evolution of these galaxies will be determined by the ability of the AGN to clear the gas and dust from the nuclear regions – if they can then they will probably evolve into less-obscured QSOs, whose number densities peak a few 100 Myrs later than the era of these SCUBA galaxies.

Feedback from AGN will clearly effect any nuclear starburst in SCUBA galaxies. However, the large sizes inferred for some submm sources (Ivison et al. 2000; 2001) suggest that star formation is occurring over very extended regions in these galaxies, $\gtrsim 10$ kpc. This contrasts with the sub-kpc nuclear starbursts seen in ULIRGs at $z \sim 0$ and suggests that AGN-driven feedback is probably less effective at terminating star formation across the whole galaxy.

3. CONCLUSIONS

We describe the properties of the first submm-selected galaxy spectroscopically confirmed at $z > 3$. This hyperluminous system, SMM J09431+4700, appears to comprise two radio-emitting components separated by ~ 25 kpc at a redshift of $z = 3.35$. One of these components, H6, hosts a partially obscured AGN and exhibits moderately broad high ionization emission lines in the rest-frame far-UV. The second component, H7, is roughly 10× fainter in the optical and infrared than H6, but has a similar radio (and by implication far-infrared) flux. A full description of this galaxy is presented in Ledlow et al. (2002).

The presence of an AGN in this submm galaxy suggests that some fraction of its immense bolometric luminosity may arise from AGN-heated dust. However, based on the detailed study of other submm-selected galaxies with AGN components it is likely that massive star formation still contributes a significant fraction of the total luminosity (Ivison et al. 1998; Frayer et al. 1998). The lack of a detection in the 50-ks XMM/Newton exposure of this field confirms that the AGN does not dominate the bolometric luminosity of SMM J09431+4700.

Both of the well-studied SCUBA-selected HyLIRG show signatures of nuclear winds in their rest-frame UV spectra. These winds are likely to be powered in part by the AGN in these systems and will provide an important source of feedback on any nuclear starburst. However, the spatially extended star formation within these galaxies may be less easily disrupted by this nuclear activity. The impact of starburst- and AGN-driven feedback on the evolution of SCUBA galaxies promises to be an exciting field of research in the next few years.

I gratefully acknowledge financial support from the Conference organisers and the Royal Society which enabled me to attend this conference. I thank Chris Carilli, Scott Chapman, Len Cowie, Tim Heckman, Cedric Lacey, Rowena Malbon, Alice Shapley, Chuck Steidel, Tracy Webb and Min Yun for educational and entertaining conversations.

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