On the fate of gas in ultraluminous infrared galaxies at low and high redshift

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ABSTRACT

It is often suggested that the distant galaxies recently identified in 850-µm surveys with the SCUBA bolometer array on the JCMT Telescope are high-redshift analogues to local ultraluminous infrared galaxies, based on their similar spectral energy distributions and luminosities. We show that these two populations of objects must differ in at least one fundamental way from each other. This assertion is based on a consideration of the possible fates of gas in the high redshift SCUBA galaxies, given the requirement that they most evolve into some subset of the low-redshift galaxy population with a comoving density of about $10^{-4}$ Mpc$^{-3}$. One possibility is that the SCUBA galaxies have similar gas density profiles to local ultraluminous galaxies. If this is the case, then they must derive almost all their power from AGNs, which appears not to be the case for local ultraluminous galaxies, which are predominantly star-formation powered. Another possibility is that the SCUBA galaxies have more extended gas density profiles than local ultraluminous galaxies. In this case they must be almost all star-formation powered, and much of the star formation in the Universe can happen in these objects. Either way there is a significant difference between the low- and high-redshift populations.

Key words: galaxies: formation – infrared: galaxies – quasars: general – cosmology: observations

1 ULTRALUMINOUS GALAXIES AT LOW REDSHIFT

Ultraluminous infrared galaxies (ULIGs) are peculiar galaxies with infrared luminosities in excess of $10^{12}$ L$_{\odot}$ (Sanders & Mirabel 1996). These galaxies have very dense gas cores, as indicated by molecular line measurements, both of CO (Sanders, Scoville & Soifer 1991), and also of high-density traces like HCN (Solomon, Downes & Radford 1992) and CS (Solomon, Radford & Downes 1990). A number of measurements at infrared, radial, and optical wavelengths (Condon et al. 1991, Surace et al. 1998, Surace & Sanders 1999, Soifer et al. 1999) suggest that most of the very substantial bolometric luminosities of these galaxies comes from these dense molecular cores.

The existence of these extreme objects leads to the question: what do they evolve into? One approach to answering this question is to look for stellar systems at redshift $z = 0$ with central densities (see Fig. 1 of Binggeli 1994 for measurements of stellar densities in local galaxies) of about $100$ M$_{\odot}$ pc$^{-3}$ or greater, the gas densities of the ULIG cores. Kormendy & Sanders (1992) made this comparison and showed that the only realistic candidates on these grounds at $z = 0$ are giant elliptical (gE) cores. Galaxy disks (which have lower surface-brightnesses than gE cores; Freeman 1970) do not have high enough stellar densities. These gE cores are dense but have profiles that are flatter than an extrapolation of a de-Vaucouleurs $r^{1/4}$ law to small radii; they are rarely isothermal (Lauer 1985). Recent Hubble Space Telescope imaging (Faber et al. 1997) has confirmed the existence of such cores in the most luminous ellipticals (they are, however, less common in lower-luminosity ellipticals). Often the cores are kinematically decoupled from the rest of the galaxy (e.g. Forbes et al. 1996), suggesting that their formation happens in a different way to that of the rest of the galaxy. These cores also tend to have supermassive black holes (BHs) in their centers, as inferred from stellar-kinematical measurements. The bigger the galaxy, the bigger this BH (Magorrian et al. 1998, van der Marel 1999, Ferrarese & Merritt 2000, Gerhardt et al. 2000). Additionally, the bigger the galaxy, the bigger the core (Lauer 1985).

An additional connection between the dense molecular cores of the ULIGs and the gE stellar cores + BHs is that their masses and sizes are similar, in addition to their densities. Typical masses for both are several times $10^9$ M$_{\odot}$ and typical radii are several hundred parsecs (see Sakomoto et al. 1999 for details of Arp 220, the nearest ULIG, and Lauer...
et al. 1985 for the core properties of gE cores). The BH contribution to the gE core masses can be added in from the correlations of Magorrian et al. 1998 or van der Marel 1999 which relate the BH mass to the galaxy mass, in combination with Tables 2 and 3 of Lauer 1985, which relate the core size to the size of the whole galaxy. Masses of the stellar cores can be computed directly from the core sizes, along with the mass-to-light ratio of Fukugita, Hogan & Peebles (1998).

But locally, gE galaxies are much more common than ULIGs. The number density of ULIGs with far-infrared luminosities in excess of $10^{12} L_\odot$ is about $1.1 \times 10^{-7} \text{ Mpc}^{-3}$ (Saunders et al. 1990). Typical ULIGs have total $K$-band (2.2 $\mu$m) absolute magnitudes of $M_K = -25.4$ (Carico et al. 1988, 1990; here, as throughout this paper we assume an Einstein-de Sitter cosmology with $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$), most of which comes from pre-existing stars in the progenitor galaxies (the dense cores are optically thick at $K$-band; Goldader et al. 1995). The number density of normal galaxies with $M_K < -25.4$ is $1.6 \times 10^{-4}$ Mpc$^{-3}$ (Szokoly et al. 1998), a factor of about 1500 larger than the density of ULIGs. Most of these $K$-band-luminous normal galaxies are early-type galaxies, which have the cores + BHs discussed in the previous two paragraphs; the contribution of luminous disks, which tend to be blue, to the $K$-band luminosity function at the very bright end is small (e.g. Binggeli, Sandage & Tammann 1988 for the optical luminosity function of the different Hubble types, and Huang et al. 1997 for the optical-near-infrared colors).

Therefore if gE cores were made by ULIGs, the comoving density of ULIGs must have been a factor 1500 higher in the past than it is today, approximately $10^{-4}$ Mpc$^{-3}$. But this is very similar to the comoving density (e.g. Trentham, Blain & Goldader 1999) of the SCUBA (> 1 mJy at 850 $\mu$m in the observer frame) sources (Smail, Ivison & Blain 1997, Barger et al. 1998, Hughes et al. 1998, Eales et al. 1999), which are presumably high-redshift objects, and which Barger et al. (1998) argue are ULIGs based on their similar bolometric luminosities and spectral energy distribution (SEDs). Therefore a picture in which SCUBA sources make gE cores and their associated black holes seems very likely not just based on similarities of their SEDs and luminosities to those of local ULIGs but also due to the comoving number density of local gE cores + BHs being similar to that of the high-redshift SCUBA galaxies. It is this possibility that we investigate in the rest of this paper.

2 ULTRALUMINOUS GALAXIES AT HIGH REDSHIFT

In the previous section we argued that the SCUBA sources are probably the high-redshift analogues of low-redshift ULIGs, both in terms of their SED and luminosity concordance, and also in terms of the comoving number density concordance between the SCUBA galaxies and the likeliest remnants of the local ULIGs (the gE cores + BHs).

This SED (Ivison et al. 1998) and luminosity (Barger et al. 1999) concordance is observed for individual sources, and is also implied on statistical grounds. By this it is meant that: if the SCUBA sources were significantly hotter than local ULIGs, then they would overproduce the far-infrared background shortward of about 500 $\mu$m measured by Fixsen et al. (1998) using COBE. If they were significantly colder than local ULIGs, they would severely underpredict the background at 450 $\mu$m: the SCUBA sources are observed to generate at least one-third of the background measured by Fixsen et al. at 450 $\mu$m (Blain et al. 1999a). These two statements assume a median source redshift of approximately 3 (see the radio measurements of Smail et al. 2000) and then follow directly from the result that almost the entire background at 850 $\mu$m is generated by the SCUBA sources (Blain et al. 1999b, Barger, Cowie & Sanders 1999). Both statements are independent of any specific model of SCUBA source luminosity and density evolution.

Now let us make the following additional assumption, which we will call A1:

The density structure of the gas in the SCUBA sources is the same as in local ULIGs.

This is an assumption, not an observation, since we have no direct probes of the gas densities in the SCUBA sources. We only know about CO in two of the SCUBA sources (Frayer et al. 1998, 1999), and have no measurements at all of high-density tracers like HCN or CS in these objects. There are two indirect pieces of evidence supporting A1. Firstly, HCN has been detected in the Cloverleaf quasar (Barvainis et al. 1997), a strongly-lensed infrared quasar which has an SED at far-infrared wavelengths similar to those of the SCUBA sources. Secondly, if the burst producing the high far-infrared luminosity is shortlived (see e.g. Blain et al. 1999a), then it is unlikely that it can be maintained in a coherent way over a galactic scale (in this case, the large scale over which the luminosity emerges from requires that the ultimate power source is star formation). Therefore the gas fuelling the burst is unlikely to be distributed over the whole galaxy. Scenarios do exist in which positive feedback can happen where explosions in one part of a galaxy can trigger those in another part (e.g. Taniguchi, Trentham & Shioya 1998), but these mechanisms are not powerful enough to generate the kinds of luminosity required here over a whole galaxy.

The important point is that if A1 is correct, then the above suspicion of the connection between local ULIGs and the SCUBA sources based on the (remnant) number density and SED concordance now becomes a very strong assertion. This is because the only things that the SCUBA sources can evolve into are elliptical galaxy cores and their associated black holes.

We do not consider the possibility that stars are made in the nucleus of the galaxies (as would be required by A1) and then redistributed throughout the galaxy in stellar-kinematical mergers because (1) the dense stellar cores so produced will not be disrupted by mergers (or secular evolution), (2) we would require about 100 mergers per L* elliptical and the observed merger rate (e.g. Carlberg et al. 2000) is not that high, and (3) the number density concordance described above is then lost due to the large number of mergers.

Van der Marel 1999 finds the black hole mass (in solar units) $\log_{10} M_{BH} \approx -1.83 + \log_{10} L_V$. Therefore for a Schechter (1976) $L^*$ elliptical galaxy ($M_V = -21.5$) at redshift $z = 0$, the central black hole has mass $5.1 \times 10^7 M_\odot$. For the same elliptical galaxy, the stellar core mass is

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$M_{\text{ac}} = 1.6 \times 10^3 M_\odot$, assuming that the core is approximately isothermal at small radii ($r < r_c$ where $r_c$ is the core radius), that the galaxy has a de Vaucouleurs $r^{1/4}$ profile at large radii, that the ratio of $r_c$ to the de Vaucouleurs effective radius $r_e$ is 0.033 (derived from the sample of Lauer 1985), and a value of $(M/L_\odot) = 3.86$ for elliptical galaxies (see the discussion in Section 2.1.3 of Fukugita et al. 1998 – this assumes the stellar initial mass function (IMF) of Gould, Bahcall & Flynn 1996, which turns over at about 0.5 $M_\odot$, similar to the IMF of Kroupa, Tout & Gilmore (1993) that we adopt below). Therefore, for typical luminous elliptical galaxies

\[
\frac{M_{\text{BH}}}{M_{\text{ac}}} \approx \frac{1}{3}
\]  

(1)

Given the scatter in the correlations presented by van der Marel and Lauer, and the fact that many cores deviate significantly from isothermality, the most extreme galaxies may deviate from this ratio by as much an order of magnitude.

For accretion onto a black hole,

\[
L_{\text{acc}} = \eta M \dot{c}^2
\]  

(2)

where $\eta$ is the efficiency of accretion and $\dot{M}$ is the mass accretion rate.

For dust-enshrouded star formation where almost all the flux is absorbed and reradiated at far-infrared wavelengths, the star formation rate (in $M_\odot$ yr$^{-1}$) is (Rowan-Robinson et al. 1997)

\[
\dot{M}_* = 1.2 \times 10^{-10} L_*
\]  

(3)

where $L_*$ (in $L_\odot$) is the total luminosity generated by the young stars. This relation adopts a value of $\phi = 0.45$ appropriate to the stellar IMF of Kroupa et al. (1993), and a value of $\kappa = 1$ (see Section 3 of Rowan-Robinson et al. 1997 for a definition of those parameters and a discussion of the derivation of this equation and other approaches). The IMF chosen here has been shown to be consistent with most current observations of both star-forming regions and the solar neighbourhood (Gilmore & Howell 1998).

Combining the two previous equations yields

\[
\frac{L_{\text{acc}}}{L_*} \sim 1700 \eta.
\]  

(4)

Accretion is a lot more efficient than star-formation at generating luminosity per unit mass: a $10^{12} L_\odot$ galaxy has a star formation rate of about 80 $M_\odot$ yr$^{-1}$ but a $2 \times 10^{12} L_\odot$ quasar has an accretion rate of about 1 $M_\odot$ yr$^{-1}$ for $\eta = 0.1$ (e.g. Chokshi & Turner 1992). Therefore averaged over time in the SCUBA sources:

\[
< \frac{L_{\text{acc}}}{L_*} > \sim 560 \eta
\]  

(5)

This ratio is very big, meaning that the total power generated in the SCUBA sources comes almost entirely from accretion if A1 is correct. Note that throughout this calculation, we have been working backwards, deriving the properties of the progenitor from the properties of the remnants under the assumption that we can match particular progenitors to particular remnants; this is quite a different calculation from one in which we start out with a cloud of gas and attempt to track its progress.

The fact that the power sources are so heavily accretion-dominated means that most SCUBA sources must be dust-enshrouded active galactic nuclei (AGNs) if A1 is correct.

This is not surprising, since the SCUBA sources contribute at least 10 per cent of the bolometric luminosity density of the Universe, and this could not be generated from the stars in the SU cores alone, which comprise less than 1 per cent by mass of the stars in the Universe, and these are the only stars that the SCUBA sources are allowed to make if A1 is correct.

3 ADDITIONAL EVIDENCE FOR THE SCUBA SOURCE - AGN CONNECTION

There exist other reasons for suggesting a connection between the SCUBA sources and dust-enshrouded AGNs.

1. The local supermassive BH density (Magorrian et al. 1998, van der Marel 1999) is high and its production generates a bolometric background of

\[
5.1 \left( \frac{\rho_{\text{AGN, dusty}}}{2 \times 10^5 M_\odot \text{Mpc}^{-3}} \right) \text{nWm}^{-2} \text{sr}^{-1}
\]

(Trentham & Blain, 2000) if they radiate at one-tenth of the Eddington luminosity and if the luminosity density of obscured AGNs follows that measured by Boyle & Terlevich (1998) for optical quasars. This equation follows from a consideration of the energy released by accretion processes per comoving volume element given a final MDO density some part $\rho_{\text{AGN, dusty}}$ of which was generated by dust-enshrouded accretion. The fiducial $\rho_{\text{AGN, dusty}}$ is the estimate of Salucci et al. (1999) for obscured quasars. The SCUBA sources in Fig. 1 generate about 7 nWm$^{-2}$sr$^{-1}$, which is close to this value.

2. There is growing evidence that the hard (30 keV) X-ray background originates from absorbed quasars which radiate energy absorbed at optical, ultraviolet, and soft X-ray at far-infrared and submillimetre wavelengths. Were this the case, Fabian & Iwasawa (1999) find a total re-radiated density of about 3 nWm$^{-2}$sr$^{-1}$. This is close to the numbers in the previous paragraph, and it is therefore plausible that these same AGNs that we are hypothesizing are the SCUBA sources are also the objects which contribute to the hard X-ray background (see also Maiolino et al. 1999 and Bautz et al. 2000). Note that if Compton-thick sources are very common (see Maiolino et al. 1998), the re-radiated energy will be somewhat higher than 3 nWm$^{-2}$sr$^{-1}$.

3. The Madau plot – that is, the cosmic star-formation rate of the Universe as a function of redshift – when determined by ultraviolet and optical measurements alone (e.g. Steidel et al. 1999) and integrated over time, produces a total stellar density in critical units of $\Omega_\star \sim 0.044$ (Pettini 1999), equal to the observed local value (Fukugita et al. 1998). Therefore an additional population of objects which are star-forming would lead to $\Omega_\star$ being overproduced. Since $> 10$ per cent of the bolometric luminosity of the Universe is generated in the SCUBA sources, were they to be star-forming, they would be producing a substantial fraction of $\Omega_\star$. We therefore require an alternative power source, such as accretion onto a black hole. The Madau plot described above includes a correction for star-formation obscured by dust in normal galaxies, which are not the same as the ULIGs or SCUBA sources described in the previous sections: their predicted
4 PROBLEMS WITH THE SCUBA SOURCE - AGN CONNECTION

The previous two sections have provided some evidence in support of a picture where A1 is true. But there are problems with such a scenario:

1. The ratio of the number of ULIGs powered by accretion onto a BH to the number of ULIGs powered by star formation must change from about 1/3 at $z = 0$ (Genzel et al. 1998) to about 80 at the redshift of the SCUBA sources (for $\eta = 0.1$) if A1 is correct. This is very large effect, and there exists no clear physical mechanism to account for such a big difference, particularly since the low-redshift ULIGs and high-redshift SCUBA galaxies are similar in every other respect if A1 is true.

2. The $q$ value (relating the far-infrared flux to the 4.85 GHz radio flux; Condon, Frayer & Broderick 1991) of SMM J02399−0136 is high, suggesting that about half of its power (at most 3/4) comes from star formation (Frayer et al. 1998). Recent X-ray measurements of this galaxy with Chandra (Bautz et al. 2000) also suggest that the fraction of the bolometric luminosity contributed by star-formation is at least 20 %, probably more. This is much higher than the value of $1/(560\eta + 1)$ predicted in Section 2. For this not to be a concern, SMM J02399−0136 must be a very unrepresentative example of a SCUBA galaxy (which is not the case given the optical spectroscopy of Ivison et al. 1998 and Barger et al. 1999) or its AGN must emit an amount of radio luminosity given its bolometric luminosity that somehow mimics starbursts.

3. If the SCUBA sources are powered by AGNs, the infalling gas must lose at least 99 % of its initial angular momentum before reaching the BH event horizon. This is not achievable by any known mechanism. Suggested mechanisms include global gravitational or magnetic processes (Begelman 1994), but the details are unclear. Note that the radius of the orbit of the two nuclear gas disks in Arp 220 is about 250 pc (Sakamoto et al. 1999), which is approaching the size scale on which the central black hole dominates the gravitational potential. Although this has been a long-standing problem, the increased angular resolution of the gas achieved by current interferometry gives it an additional importance if A1 is to be regarded as a plausible hypothesis.

One possible solution that simultaneously addresses all three problems above could be that: the ULIGs undergo an intense star formation phase in the center that generates a bolometric luminosity of $10^{12} L_\odot$ followed immediately by an AGN phase that lasts for a shorter time, but generates a higher bolometric luminosity, say about $10^{14} L_\odot$. If one selects objects instantaneously with bolometric luminosities above $10^{12} L_\odot$, one would end up with a sample dominated by starbursts, perhaps in a ratio similar to what Genzel et al. (1998) found locally if the relative timescales and luminosities between the starburst and AGN phase are extremely large and small, respectively. This could remain true even if the time-averaged luminosity was generated predominantly by AGNs, as required by eq. (5). Such a scenario could help the angular momentum problem since the black hole could accrete the stars themselves (Begelman 1994); given eq. (1) about one-fourth by mass of the total stars produced would have to be accreted. It is also consistent with a picture in which the most luminous things that exist at any redshift are AGN-powered (see e.g. Sanders & Mirabel 1996).

Another possible solution is that the fraction of ULIGs at $z = 0$ that are AGNs has been underestimated because the AGNs are so heavily obscured that they are invisible even at mid-infrared wavelengths. The detection of hard X-ray emission from NGC 6240 (Vignati et al. 1999) suggests that the bolometric luminosity of this infrared-luminous galaxy, previously thought to be starburst-powered, originates from an AGN. If this object is at all typical of ULIGs, then the possibility of a much higher ratio of local ULIGs that are AGN-powered than one-third seems possible (see however the discussion in the final section of Lutz et al. 1999).

5 DISCUSSION AND SUMMARY

We have shown that if the SCUBA sources, which appear on SED and luminosity grounds to be ULIGs at high $z$ have the same gas density structure as local ULIGs, then they must generate most of their power from embedded AGNs. Such a scenario is attractive for many reasons: it generates the correct local number density of elliptical galaxy cores of the correct mass, the correct local mass density of their associated black holes, and gives a formation mechanism for kinematically decoupled cores (which probably form in some other way from the rest of the galaxy). These SCUBA sources would then be very different from local ULIGs, which derive most of their power from star formation.

But there are problems (see Section 4). If these cannot be resolved, then A1 must be abandoned. In this event, the gas in the SCUBA sources must be far more diffuse than in local ULIGs because in order to generate such huge luminosities, a substantial fraction of the stars in the galaxies must be made; in $z = 0$ galaxies, large fractions of the stars in galaxies do not reside at extremely high densities of $100 M_\odot$ pc$^{-2}$ or greater so it is improbable that they were made out of gas at these densities. In local ULIGs all the bolometric luminosity seems to come out of regions associated with gas at this high density.

Either way, there is a big difference between local ULIGs
On the fate of gas in ultraluminous infrared galaxies at low and high redshift

and high-redshift SCUBA sources. This is the main result of this letter.

Testing the validity of A1 will be an important exercise in the future. HCN measurements (like for the Cloverleaf quasar) would be best, but until these and other millimetre wave spectral diagnostics (other than CO) are available, the best hope is to rely on indirect methods like those outlined in the letter.

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