Herschel ATLAS: the cosmic star formation history of quasar host galaxies

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ABSTRACT

We present a derivation of the star formation rate per comoving volume of quasar host galaxies, derived from stacking analyses of far-infrared to mm-wave photometry of quasars with redshifts 0 < z < 6 and absolute $I$-band magnitudes $-22 > I_{AB} > -32$. We use the science demonstration observations of the first ~16 deg$^2$ from the Herschel Astrophysical Terahertz Large Area Survey (H-ATLAS) in which there are 240 quasars from the Sloan Digital Sky Survey (SDSS) and a further 171 from the 2dF-SDSS LRG and QSO (2SLAQ) survey. We supplement this data with a compilation of data from IRAS, ISO, Spitzer, SCUBA and MAMBO. H-ATLAS alone statistically detects the quasars in its survey area at > 5σ at 250, 350, and 500 μm. From the compilation as a whole we find striking evidence of downsizing in quasar host galaxy formation: low-luminosity quasars with absolute magnitudes in the range $-22 > I_{AB} > -24$ have a comoving star formation rate (derived from 100 μm rest-frame luminosities) peaking between redshifts of 1 and 2, while high-luminosity quasars with $I_{AB} < -26$ have a maximum contribution to the star formation density at $z \sim 3$. The volume-averaged star formation rate of $-22 > I_{AB} > -24$ quasars evolves as $(1 + z)^{2.6\pm0.3}$ at $z < 2$, but the evolution at higher luminosities is much faster reaching $(1 + z)^{10.9\pm0.1}$ at $-26 > I_{AB} > -28$. We tentatively interpret this as a combination of a declining major merger rate with time and gas consumption reducing fuel for both black hole accretion and star formation.

Key words. galaxies: active – infrared: galaxies – quasars: general – galaxies: formation – submillimeter: galaxies – galaxies: starburst

1. Introduction

The cosmic star formation history (e.g. Madau et al. 1996 and others) was quickly realised to bear a striking apparent similarity to the evolving luminosity density of quasars (QSOs) at most redshifts (e.g. Boyle & Terlevich 1998; Franceschini et al. 1999), suggesting a link between the physical drivers of black hole growth and stellar mass assembly. Other data also indirectly suggested links. Mid-infrared spectra (e.g. Genzel et al. 1998; Spoon et al. 2007) and radiative transfer modelling (e.g. Farrah et al. 2002) imply higher luminosity starbursts have increasingly large bolometric fractions from active galactic nuclei (AGN). The tight $K$-band Hubble diagram of far-infrared-selected hyperluminous starbursts also bears a striking similarity to the $K-z$ relation of radiogalaxies (e.g. Serjeant et al. 2003; though see Smail et al. 2004 for their submm-selected counterparts).

A close relationship between black hole growth and stellar mass assembly is also demanded by the observed cross correlations between supermassive black hole masses and spheroid properties (e.g. Magorrian et al. 1998; Merritt & Ferrarese 2001), which exist despite the enormous disparities of spatial scales and masses. Such correlations are predicted by models with radiative and/or kinetic energy outputs from the AGN regulating the star formation in their host galaxies (e.g. Granato et al. 2006), but these feedback models have many adjustable parameters. Feedback is arguably the principal uncertainty in semi-analytic models of galaxy evolution. One of the few observational approaches available to constrain feedback models is to measure the star formation rates in QSO host galaxies, but so far very few QSOs have direct far-infrared, submm or mm-wave detections from which star formation rates could be inferred.

The Herschel Astrophysical Terahertz Large Area Survey (H-ATLAS, Eales et al. 2010) is the largest open time key program on the Herschel Space Observatory (Pilbratt et al. 2010). The survey aims to map 550 deg$^2$ at five wavelengths from 110–500 μm to 5σ depths in the range 32–50 mJy at ≥250 μm. Among the key science goals is a constraint on the star formation rates of many thousands of QSOs through far-infrared and submm photometry. In preparation, Serjeant & Hatziminaoglou (2009) used a compilation of available far-infrared to mm-wave photometry of QSOs from IRAS, ISO, Spitzer, SCUBA and MAMBO, to predict the numbers of QSOs directly detectable by H-ATLAS. Several hundred QSO direct detections are expected.
in H-ATLAS and the first H-ATLAS detections are described in e.g. Gonzalez-Nuevo et al. (2010). Serjeant & Hatziminaoglou (2009) also assumed an M 82 spectral energy distribution (SED), used observations close to 100(1 + z)μm where possible, and found the stacked 100 μm luminosities of QSOs typically scaling roughly as the square root of the optical luminosities with a redshift-dependent normalisation, supporting the idea of coupled black hole mass and stellar mass assemblies. Almost identical results were obtained with an Arp 220 SED. This SED insensitivity can be readily understood: at a fixed bolometric luminosity, the SWIRE template SEDs (Polletta et al. 2007) for the starbursts M 82, Arp 220, NGC 6090, IRAS 20551−4250 and IRAS 22491−1808 have 100 μm monochromatic luminosities all within a factor of two (note that we are only concerned with the starburst bolometric contribution).

In this paper we extend this analysis to the first data from H-ATLAS. We interpret the 100 μm luminosities as star formation, since AGN dust tori SEDs are expected to peak in the mid-infrared, (e.g. Efstathiou & Rowan-Robinson 1995; though see the discussion in Netzer et al. 2007). We estimate the mean star formation rate in bins of redshift and absolute $I_{AB}$ magnitude, then use the QSO luminosity function to make the first constraints on the star formation rate per comoving volume of QSOs from 0 < z < 6 and a factor of 10$^4$ in optical luminosity. We assume density parameters $\Omega_M = 0.3$ and $\Omega\Lambda = 0.7$ and a Hubble constant of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. I-band QSO magnitudes are quoted in the AB system with K-corrections assuming d ln $S_\nu$/d ln $\nu = -0.5$ and no internal dust extinction correction.

2. Data acquisition and analysis

2.1. Herschel ATLAS

We use only data from the SPIRE instrument (Griffin et al. 2010) in this paper. For more details of the data analysis see Pascale et al. (in prep.); we summarise the main points here. The SPIRE images were registered to a common reference frame using stacking analyses of Sloan Digital Sky Survey (SDSS) galaxies. Neptune was used for flux calibration, requiring multiplicative calibration changes of 1.02, 1.05 and 0.94 at 250, 350 and 500 μm respectively relative to the previous Ceres flux calibration (Griffin et al. 2010; Swinyard et al. 2010). Jumps in thermometer timelines were identified and corrected using the mean levels on either side of each jump. Thermal drift modelling was achieved through low-pass filtering. Bolometer timelines were filtered using high-pass 4 mHz filtering to remove correlated 1/f noise. Maps were made using the naive map maker in HIPE and filtered optimally for point sources.

2.2. Quasar compilations

The survey areas of H-ATLAS were chosen for their supplementary multi-wavelength coverage. The H-ATLAS science demonstration field is covered by the SDSS with 240 QSOs in its spectroscopic QSO catalogue in the field. There are also 171 QSOs from the 2dF-SDSS LRG and QSO (2SLAQ) survey.

We supplement our H-ATLAS QSOs with the compilation from Serjeant & Hatziminaoglou (2009), including the authors’ IRAS ADDSCAN photometry of Palomar-Green QSOs and Spitzer photometry of QSOs from the Spitzer SWIRE legacy survey (Lonsdale et al. 2003; 2004), together with QSOs observed at 850 μm or 1200 μm (Omont et al. 1996; 2001; Carilli et al. 2001; Isaak et al. 2002; Omont et al. 2003; Priddey et al. 2003a,b; Robson et al. 2004; Wang et al. 2007). Figure 1 shows the distribution of our QSO compilation in the optical luminosity–redshift plane. Red crosses mark QSOs in the Herschel ATLAS survey. Open circles are SDSS QSOs with SWIRE coverage, while filled circles are Palomar-Green QSOs with IRAS and B-band data. Diamonds represent QSOs observed at 850 μm while open squares represent QSOs observed at 1200 μm. Adding H-ATLAS QSOs extends the range of absolute magnitudes at redshifts $z < 3$.

3. Methods

We adopt the methodology of Serjeant et al. (2004, 2008, 2009) for comparing QSO fluxes with the flux distributions of the H-ATLAS maps as a whole. We use unweighted means to estimate H-ATLAS QSO fluxes and use the Kolmogorov-Smirnov statistic to compare flux distributions. The advantage of this statistic is that it contains its own control test, i.e. there is no need for performing stacks on randomised QSO positions.

While most QSOs can only be detected in the far-infrared and submm through stacking analyses, there are a few QSOs with direct detections. How should one combine these? For example, if one has a single non-detection of 0 ± 4 mJy and single detection of 100 ± 4 mJy, what can one say about the average flux $\mu$ of this population? Clearly the answer is not $\mu = 50±2$ mJy. We have adopted the methodology of Serjeant & Hatziminaoglou (2009) and treated flux measurements of individual QSOs as attempts to determine the population mean. The dispersion in the population is an error term on this measurement, which one would add in quadrature to the noise on any individual measurement. We determine the population dispersion from our data and made a simultaneous maximum-likelihood fit to the mean $\mu$ and dispersion $\sigma$. There is no covariance between these parameters because of the independence of signal and noise. Where there are fewer than 3 objects being considered we set $\sigma = 0.84 \mu$. More details can be found in Serjeant & Hatziminaoglou (2009).

We used this method to combine direct detections with nondetections. We also combine the Serjeant & Hatziminaoglou (2009) sample with our H-ATLAS data. We use the point-source-convolved H-ATLAS maps (Pascale et al. 2010).
4. Results

4.1. Stacking analysis results

We compared the flux measurements at the positions of our H-ATLAS QSOs with the distribution of flux measurements throughout the H-ATLAS maps. The Kolmogorov-Smirnoff statistic rejects the null hypothesis that these are drawn from the same distribution at significance levels of \(3 \times 10^{-33}, 7 \times 10^{-20}\) and \(7 \times 10^{-19}\) at 250, 350 and 500 µm respectively, equivalent to 12.0σ, 9.1σ and 5.7σ. This is not due simply to the presence of bright sources, since removing QSOs with fluxes >100 mJy and comparing with regions of the map with flux measurements <100 mJy still yields significance levels of 11.9σ, 9.0σ and 5.6σ. The average fluxes of the QSOs in the H-ATLAS science demonstration field are \(S_{250\mu m} = 9.41 \pm 0.88\) mJy (11σ detection), \(S_{350\mu m} = 7.68 \pm 0.87\) mJy (8.9σ detection) and \(S_{500\mu m} = 5.14 \pm 0.92\) mJy (5.6σ detection).

When calculating 100 µm rest-frame luminosities for H-ATLAS QSOs, we use the closest SPIRE filter to 100(1+z) µm. Table 1 lists our estimates of the mean 100 µm rest-frame luminosities of the whole QSO compilation in redshift and optical luminosity bins, using the methodology of Sect. 3. The results are well-fit by the expression

\[
\log L_{\nu}(100\mu m) = \alpha(z) I_{AB} + \beta(z),
\]

where \(\alpha(z) = (0.0371 \pm 0.0048) \times \log(z) - 0.235 \pm 0.018\), \(\beta(z) = -1.19 \pm 0.30\), \(\log(z) = \min(3, 4) - 27.42 \pm 0.37\), and \(\min(z, 4) = z\) at \(z < 4\) and 4 otherwise. The slope of the luminosity-luminosity correlation is shallower at high redshift, as found by Serjeant & Hatzipanaglou (2009; see also Mullaney et al. 2010).

<table>
<thead>
<tr>
<th>(N)</th>
<th>(z_{\min})</th>
<th>(z_{\max})</th>
<th>(I_{min})</th>
<th>(I_{max})</th>
<th>(L_m(100\mu m))</th>
<th>SFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.05</td>
<td>0.5</td>
<td>22</td>
<td>19</td>
<td>0.126 \pm 0.69</td>
<td>(2.0 \pm 1.1) \times 10^{-4}</td>
</tr>
<tr>
<td>72</td>
<td>0.05</td>
<td>0.5</td>
<td>24</td>
<td>22</td>
<td>0.115 \pm 0.019</td>
<td>(4.94 \pm 0.79) \times 10^{-5}</td>
</tr>
<tr>
<td>29</td>
<td>0.05</td>
<td>0.5</td>
<td>26</td>
<td>24</td>
<td>0.31 \pm 0.13</td>
<td>(3.6 \pm 1.5) \times 10^{-6}</td>
</tr>
<tr>
<td>9</td>
<td>0.05</td>
<td>0.5</td>
<td>28</td>
<td>26</td>
<td>0.52 \pm 0.38</td>
<td>(8.8 \pm 6.4) \times 10^{-10}</td>
</tr>
<tr>
<td>9</td>
<td>0.5</td>
<td>1</td>
<td>22</td>
<td>19</td>
<td>0.028 \pm 0.065</td>
<td>(5.0 \pm 1.2) \times 10^{-10}</td>
</tr>
<tr>
<td>73</td>
<td>0.5</td>
<td>1</td>
<td>24</td>
<td>22</td>
<td>0.173 \pm 0.034</td>
<td>(1.58 \pm 0.31) \times 10^{-10}</td>
</tr>
<tr>
<td>38</td>
<td>0.5</td>
<td>1</td>
<td>26</td>
<td>24</td>
<td>0.40 \pm 0.084</td>
<td>(6.1 \pm 1.3) \times 10^{-10}</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>1</td>
<td>28</td>
<td>26</td>
<td>1.54 \pm 0.24</td>
<td>(4.06 \pm 0.63) \times 10^{-6}</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>1</td>
<td>32</td>
<td>28</td>
<td>5.5 \pm 4.5</td>
<td>(4.9 \pm 4.0) \times 10^{-6}</td>
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<tr>
<td>46</td>
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<td>2</td>
<td>24</td>
<td>22</td>
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</tr>
<tr>
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<td>26</td>
<td>24</td>
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<td>(5.38 \pm 6.9) \times 10^{-4}</td>
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<tr>
<td>75</td>
<td>1</td>
<td>2</td>
<td>28</td>
<td>26</td>
<td>1.81 \pm 0.26</td>
<td>(8.6 \pm 1.2) \times 10^{-5}</td>
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<tr>
<td>32</td>
<td>1</td>
<td>2</td>
<td>32</td>
<td>28</td>
<td>5.1 \pm 1.9</td>
<td>(8.6 \pm 3.2) \times 10^{-7}</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>2</td>
<td>24</td>
<td>22</td>
<td>1.1 \pm 0.7</td>
<td>(0.4 \pm 8) \times 10^{-3}</td>
</tr>
<tr>
<td>52</td>
<td>2</td>
<td>2</td>
<td>26</td>
<td>24</td>
<td>1.05 \pm 0.54</td>
<td>(3.9 \pm 2.0) \times 10^{-4}</td>
</tr>
<tr>
<td>108</td>
<td>2</td>
<td>4</td>
<td>28</td>
<td>26</td>
<td>3.47 \pm 0.68</td>
<td>(3.30 \pm 0.63) \times 10^{-4}</td>
</tr>
<tr>
<td>66</td>
<td>4</td>
<td>4</td>
<td>32</td>
<td>28</td>
<td>5.42 \pm 0.76</td>
<td>(9.9 \pm 1.4) \times 10^{-4}</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>7</td>
<td>24</td>
<td>22</td>
<td>1.7 \pm 1.9</td>
<td>(2.1 \pm 2.4) \times 10^{-4}</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>7</td>
<td>26</td>
<td>24</td>
<td>2.0 \pm 2.2</td>
<td>(1.9 \pm 2.1) \times 10^{-4}</td>
</tr>
<tr>
<td>58</td>
<td>4</td>
<td>7</td>
<td>28</td>
<td>26</td>
<td>2.32 \pm 0.46</td>
<td>(5.6 \pm 1.1) \times 10^{-4}</td>
</tr>
<tr>
<td>64</td>
<td>4</td>
<td>7</td>
<td>32</td>
<td>28</td>
<td>4.25 \pm 0.69</td>
<td>(1.95 \pm 0.32) \times 10^{-7}</td>
</tr>
</tbody>
</table>

Notes. An M82 SED has been assumed, though the results are only very weakly dependent on the assumed SED. The first column gives the number of QSOs in the bin in question. The final column gives the comoving volume-averaged star formation densities of QSO host galaxies in each bin.

![Fig. 2. Cosmic star formation history of QSO host galaxies inferred from 100 µm rest-frame luminosities, for QSOs with \(z < 22\) (red), \(22 > z > 24\) (orange), \(z > 26\) (green) and \(z < 28\) (blue). The 2 \(< z < 4\), \(22 > z > 24\) data point has too high a noise level to be usefully constraining and has been omitted for clarity. For comparison, the \(z = 0\) total galaxy star formation rate is \((2.9 \pm 0.7) \times 10^{-2} M_{\odot} \mathrm{yr}^{-1} \mathrm{Mpc}^{-3}\) (e.g. Serjeant et al. 2002).](image-url)
between the 0.5 < z < 1 and 1 < z < 2 bins, the evolution of the volume-averaged star formation in $I_{AB} < -28$ QSOs scales as $(1+z)^{+0.6}$. An important caveat is that we are only addressing the optically-defined QSO population, so we are necessarily missing the type-2 QSOs and Compton-thick objects (see e.g. the discussion in Almaini et al. 1999). A similar downsizing effect is seen in the QSO soft X-ray luminosity function (e.g. Hasinger et al. 2005). The type-2 QSO fraction increases with redshift (e.g. Hasinger 2008) which would increase our inferred evolution rates.

5. Discussion and conclusions

Could the co-evolution of the total cosmic star formation history and total black hole accretion be explained by both being simultaneously driven by major galaxy-galaxy mergers (e.g. di Matteo et al. 2005)? Most star formation at high redshifts is seen in the QSO soft X-ray luminosity function (e.g. Hasinger et al. 1999). A similar downsizing effect is seen in type-2 QSOs and Compton-thick objects (see e.g. the discussion in Almaini et al. 1999). An important caveat is that we are only addressing the optically-defined QSO population, so we are necessarily missing the type-2 QSOs and Compton-thick objects (see e.g. the discussion in Almaini et al. 1999). A similar downsizing effect is seen in the QSO soft X-ray luminosity function (e.g. Hasinger et al. 1999). A similar downsizing effect is seen in type-2 QSOs and Compton-thick objects (see e.g. the discussion in Almaini et al. 1999).

References


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