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

How to cite:

For guidance on citations see FAQs.

© 2010 ESO

Version: Version of Record

Link(s) to article on publisher’s website:
http://dx.doi.org/doi:10.1051/0004-6361/201014565

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online’s data policy on reuse of materials please consult the policies page.
Herschel: the first science highlights

**Herschel ATLAS: The cosmic star formation history of quasar host galaxies**


(Affiliations are available in the online edition)

Received 30 March 2010 / Accepted 7 May 2010

**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 $-22 > I_{AB} > -26$. 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 $z$ ~ 3. The volume-averaged star formation rate of ~22 > $I_{AB}$ > ~24 quasars evolves as $(1+z)^{2.1\pm0.7}$ at $z < 2$, but the evolution at higher luminosities is much faster reaching $(1+z)^{3.4\pm0.9}$ 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 hyper-luminous starbursts also bears a striking similarity to the K – z relation of radio galaxies (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 close 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 semianalytic 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 100μm luminosities of QSOs typically scal-
ing 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 re-
results were obtained with an Arp 220 SED. This SED insensitivity
can be readily understood: at a fixed bolometric luminos-

ity, 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 forma-
sion, 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 Hα magni-

tude, 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 luminos-

ity. We assume density parameters Ω_M = 0.3 and Ω_Λ = 0.7 and

a Hubble constant of H_0 = 70 km s^{-1} Mpc^{-1}. I-band QSO magni-

tudes are quoted in the AB system with K-corrections assuming

$d \ln S_\nu/d \ln v = -0.5$ 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 us-

ing stacking analyses of Sloan Digital Sky Survey (SDSS) galax-

ies. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a factor of 2 in optical luminos-

ity. Neptune was used for flux calibration, requiring multipli-

cation calibrations of changes by a
Measurements taken off these maps report the point source flux plus a background flux contribution from other sources. To set the latter to zero we convolve our maps with a further kernel $K$ with a zero total, i.e. $\int_0^\infty K(r)2\pi rdr = 0$. $K$ was set to a constant negative value at radii $r$ of 2.5 to 6 times the point spread function FWHM, with a unit $\delta$ function in its central pixel, and zero everywhere else. After convolution with $K$, every galaxy makes an exactly zero net contribution to the map. If there is a non-zero angular cross-correlation function from galaxies with a physical association with the QSO, then they may still contribute to the far-infrared and submm fluxes. One approach is to use constraints on the angular correlation function of these galaxies to place a bound on this contribution (e.g. Serjeant et al. 2008). However, in this case we are studying the assembly of the stellar mass and the companion galaxies may in time be accreted by the QSO host galaxy. We have therefore chosen to associate all the star formation inferred from the flux in the far-infrared beam with the QSO host galaxy.

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-Smirnov 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 $\mu$m respectively, equivalent to 12.0$\sigma$, 9.1$\sigma$ and 5.7$\sigma$. This is not due simply to the presence of bright sources, since removing QSOs with fluxes $>100 \text{mJy}$ and comparing with regions of the map with flux measurements $<100\text{mJy}$ still yields significance levels of 11.9$\sigma$, 9.0$\sigma$ and 5.6$\sigma$. The average fluxes of the QSOs in the H-ATLAS science demonstration field are $S_{250\mu m} = 9.41 \pm 0.88 \text{mJy}$ (11$\sigma$ detection), $S_{350\mu m} = 7.68 \pm 0.87 \text{mJy}$ (8.9$\sigma$ detection) and $S_{500\mu m} = 5.14 \pm 0.92 \text{mJy}$ (5.6$\sigma$ detection).

When calculating 100 $\mu$m rest-frame luminosities for H-ATLAS QSOs, we use the closest SPIRE filter to 100(1 + $z$)$\mu$m. Table 1 lists our estimates of the mean 100 $\mu$m 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 ($\chi^2 = 0.93$) by the expression

$$\log L_{\nu}(100\mu m) / 10^{42} \text{L}_{\odot} = \alpha(z)L_{\nu}(AB) + \beta(z),$$

where $\alpha(z)$ = (0.0371 $\pm$ 0.0048) $\times$ min$(z, 4) - 0.235 \pm 0.016$, $\beta(z)$ = (−1.19 ± 0.30) $\times$ min$(z, 4) + 27.42 \pm 0.37$, 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 & Hatzipanagoulou (2009; see also Mullaney et al. 2010).

QSO number densities $\Phi(L_{\nu}, z)$ at these absolute magnitudes and redshifts are already well-determined. We adopted the luminosity functions of Croom et al. (2004) at $z < 2.1$ and the pure density evolution model of Meiksin (2005) at $z > 3$, with an optical spectral index of −0.5 to transform to $I$-magnitudes. Between $z = 2.1$ and $z = 3$ we interpolate in log $\Phi$ between these models at fixed optical luminosities. We assume the far-infrared is dominated by giant molecular clouds so $\nu L_{\nu}(100\mu m) / 10^{42} \text{L}_{\odot} = 265 \text{M}_{\odot}\text{year}^{-1}$ as appropriate for our assumed SED and a Salpeter initial mass function from 0.1 to 100 $M_{\odot}$ (Kennicutt 1998). Table 1 also lists the comoving star formation densities inferred from $\nu L_{\nu}(100\mu m) \times \Phi(L_{\nu}, z)$.

Figure 2 plots the data in Table 1, interpolating between the upper and lower bounds of the comoving star formation densities at the mid-points of each redshift bin. The evolution in the comoving star formation density of $-22 > L_{\nu} > -24$ QSOs from the 0.05 $< z < 0.5$ bin to the $1 < z < 2$ bin scales as $(1 + z)^{2.3 \pm 0.7}$, but the evolution at higher luminosities is much faster: at $-26 > L_{\nu} > -26$ the variation is $(1 + z)^{4.6 \pm 6}$, while at $-26 > L_{\nu} > -28$ it reaches an astonishing $(1 + z)^{10.8 \pm 2}$ over this redshift range (mostly but not entirely due to the luminosity function). There are no QSOs at $L_{\nu} < -28$ at $z < 0.5$ but

---

### Table 1. Average stacked QSO 100 $\mu$m rest-frame luminosities for bins in redshift and $I$-band absolute magnitude.

<table>
<thead>
<tr>
<th>$L_{\nu}$ (100$\mu$m)</th>
<th>SFD</th>
<th>$10^{42} \text{L}_{\odot}$</th>
<th>$M_{\odot}\text{year}^{-1}\text{Mpc}^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\nu}$ (100$\mu$m)</td>
<td>$\text{SFD}$</td>
<td>$10^{42} \text{L}_{\odot}$</td>
<td>$M_{\odot}\text{year}^{-1}\text{Mpc}^{-3}$</td>
</tr>
<tr>
<td>$L_{\nu}$ (100$\mu$m)</td>
<td>$\text{SFD}$</td>
<td>$10^{42} \text{L}_{\odot}$</td>
<td>$M_{\odot}\text{year}^{-1}\text{Mpc}^{-3}$</td>
</tr>
<tr>
<td>$L_{\nu}$ (100$\mu$m)</td>
<td>$\text{SFD}$</td>
<td>$10^{42} \text{L}_{\odot}$</td>
<td>$M_{\odot}\text{year}^{-1}\text{Mpc}^{-3}$</td>
</tr>
<tr>
<td>$L_{\nu}$ (100$\mu$m)</td>
<td>$\text{SFD}$</td>
<td>$10^{42} \text{L}_{\odot}$</td>
<td>$M_{\odot}\text{year}^{-1}\text{Mpc}^{-3}$</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$\mu$m rest-frame luminosities, for QSOs with $-22 > L_{\nu} > -24$ (red), $-24 > L_{\nu} > -26$ (orange), $-26 > L_{\nu} > -28$ (green) and $L_{\nu} < -28$ (blue). The 2 $< z < 4$, $-22 > L_{\nu} > -24$ 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 $(2.9 \pm 0.7) \times 10^{5} \text{M}_{\odot}\text{year}^{-1}\text{Mpc}^{-3}$ (e.g. Serjeant et al. 2002).
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)^{−3.4}. 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 z < 2 is simultaneously driven by major galaxy-galaxy mergers (e.g. di Matteo, Springel, & Hernquist, 2005). Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the NSF, the U.S. Department of Energy, NASA, the Japanese Monbukagakusho, the Max Planck Society, and HEFCE.

References


Acknowledgements. We thank the anonymous referee for useful comments. This work was funded in part by STFC (grants PP/D002400/1 and ST/G002533/1).