Galaxy Evolution across the Hubble Time
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First Galaxies and AGNs

Fabian Walter

Max Planck Insitut für Astronomie Heidelberg, Germany

Abstract. I will discuss the search for galaxies and QSOs at the highest redshifts, out to the Epoch of Reionization. Observations in the submillimeter play a fundamental role in such searches, in particular once ALMA will become operational. I will focus on the properties of the molecular gas (the phase of the ISM out of which stars form) in the earliest systems as derived through observations in the millimetre and radio regime. These observations allow us to measure the reservoir of molecular gas and to constrain the physical properties and excitation of the gas. Resolved imaging of the host galaxies also allows us to derive first dynamical masses for these objects. Such mass determinations are critical to determine whether there is a possible evolution of the famous M_{BH}–σ_{bulge} relation with redshift or not. Recent measurements in the QSO redshift record holder J1148+5251 (z = 6.42) provide evidence that the black hole in this system assembled before the stellar bulge.

Keywords. early universe, radio lines: general, submillimeter, quasars: general

1. Introduction: QSOs at high z

Over the last few years, the study of high redshift QSOs has been revolutionized in three ways. First, wide field surveys have revealed 100's of high–z QSOs, right back to the epoch of cosmic reionization ($z > 6$; e.g., Fan *et al.* 2006). Second, it has been shown that most (all?) low redshift spheroidal galaxies have central super-massive black holes (SMBH), and that the black hole mass correlates with bulge velocity dispersion. This M_{BH}–σ_v correlation suggests coeval formation of galaxies and SMBH, thereby making SMBHs a fundamental aspect of the galaxy formation process (Gebhardt *et al.* 2000). And third, mm surveys of high redshift QSOs find that 30% of the sources are 'hyper-luminous infrared galaxies' ($L_{FIR} = 10^{13}$ $L_\odot$), corresponding to thermal emission from warm dust, and that this fraction is *independent of redshift out to* $z = 6.4$ (Beelen *et al.* 2004, Omont *et al.* 2004). If the dust is heated by star formation, the implied star formation rates are extreme ($>10^3$ $M_\odot$ year^{-1}), consistent with the formation of a large elliptical galaxy on a dynamical timescale of 10^8 years.

2. Molecular Gas in QSO hosts

Molecular line observations (typically CO) of FIR-luminous high–z QSOs have revealed large gas masses in most cases observed to date (for a review see Solomon & Vanden Bout 2005). Detecting large amounts of warm, extended molecular gas currently provides the strongest evidence that these luminous QSOs are undergoing vigorous star formation. The coeval growth of massive black holes and of massive stellar populations can be examined directly in these unique systems, providing an opportunity to study the cause of the tight correlation between these components that is observed in local spheroidal galaxies. High resolution observations are crucial for this, since the structure of the dense gas which is feeding the starburst and the black hole can reveal the cause of event (e.g. mergers) and the mass of the systems, placing them into the cosmic structure evolution context.

Molecular gas has now been detected in more than a dozen $z > 2$ QSO host galaxies. Most sources have been studied in the higher order transitions ($\geqslant$CO 3–2), although at $z \geqslant 4$ the lower order transitions become accessible to cm telescopes such as the VLA.

The *detection* of CO emission is critical to estimate the reservoir of the molecular gas in these early systems. A second step is then to *spatially resolve the molecular gas distribution*. In particular, given the typical diameters of galaxies of many kpc, a linear resolution of ~1 kpc is needed to *resolve the structure* of the underlying host galaxy. Such measurements are needed 1) to get an estimate for the *size of the host galaxy* (and thus a better estimate for the dynamical mass), 2) to resolve potentially merging systems and 3) to better constrain the *physical properties* of the molecular gas by measuring the brightness temperature of the molecular gas in the hosts. A linear resolution of 1 kpc corresponds to a resolution of $0.15''$ at the redshifts under consideration ($1'' \sim 8.5$ kpc at $z = 2$, $1'' \sim 5.8$ kpc at $z = 6$). Such observations can then in turn be used to constrain the predictions by CDM simulations of early galaxy formation, and, if a large sample was available, put limits on the frequency of mergers at high redshift. In addition, such studies can be used to constrain the possible redshift-evolution of the $\mathrm{M_{BH}}$–σ_v relation (as will be discussed below).

3. Case Study of a QSO at redshift z = 6.42

The QSO J1158+5251 at z = 6.42 is still the redshift record–holder for QSOs. It has been detected in CO(3–2) using the VLA (Walter *et al.* 2003) and in CO(6–5) and CO(7–6) using the Plateau de Bure interferomter (Bertoldi *et al.* 2003). Follow–up VLA B and C array observations clearly resolved the the molecular distribution spatially and also in velocity space (Walter *et al.* 2004, see Fig. 1). The molecular gas distribution in J1148+5251 is extended out to radii of 2.5 kpc. The central region is resolved and shows 2 peaks, separated by 1.7 kpc; they account for about half of the total emission, with the other half present in the more extended molecular gas distribution. Each of these peaks harbors a molecular gas mass of $\sim 5 \times 10^9\,\mathrm{M_\odot}$ within a radius of 0.5 kpc, respectively; this mass is similar to the total mass found in nearby ULIRGS such as Mrk 273 or Arp 220 (Downes & Solomon 1998). The peaks have intrinsic brightnesses of ~35 K (averaged over the 1 kpc-sized beam), similar to what is found in the centres of nearby active galaxies (Downes & Solomon 1998, assuming constant surface brightness down to the CO(1–0) transition), albeit measured over a larger physical area.

Based on the extent of the molecular gas distribution and the line-width measured from the higher CO transitions we derive a dynamical mass of $\sim 4.5 \times 10^{10}\,\mathrm{M_\odot}$ ($\sim 5.5 \times 10^{10}\,\mathrm{M_\odot}$ if we correct for an inclination of $i \sim 65°$). This dynamical mass estimate can account for the detected molecular gas mass within this radius but leaves little room for other matter. In particular, given a black hole mass of mass ~ 1–$5 \times 10^9\,\mathrm{M_\odot}$ (Willot *et al.* 2003), this dynamical mass could not accomodate an order few $\times 10^{12}\,\mathrm{M_\odot}$ stellar bulge which is predicted by the present–day $\mathrm{M_{BH}} - \sigma_\mathrm{bulge}$ relation (Ferrarese & Merritt 2000, Gebhardt 2000), if this relation were to hold at these high redshifts. Even if we assume a scenario in which this bulge was 10 times the scale length of the molecular gas emission, we would still expect a bulge contribution of few $\times 10^{11}\,\mathrm{M_\odot}$ within the central 2.5 kpc (assuming a central density–profile of $\rho \sim r^{-2}$, e.g., Jaffe 1983, Tremaine 1994) which can not be reconciled with our results. Our finding therefore suggests that black holes may assemble before the stellar bulges. Depending on the space density of similar sources at these high redshifts, the smaller dynamical masses may be in better agreement with the masses predicted by CDM simulations in the very early universe as a $10^{12}\,\mathrm{M_\odot}$ bulge would

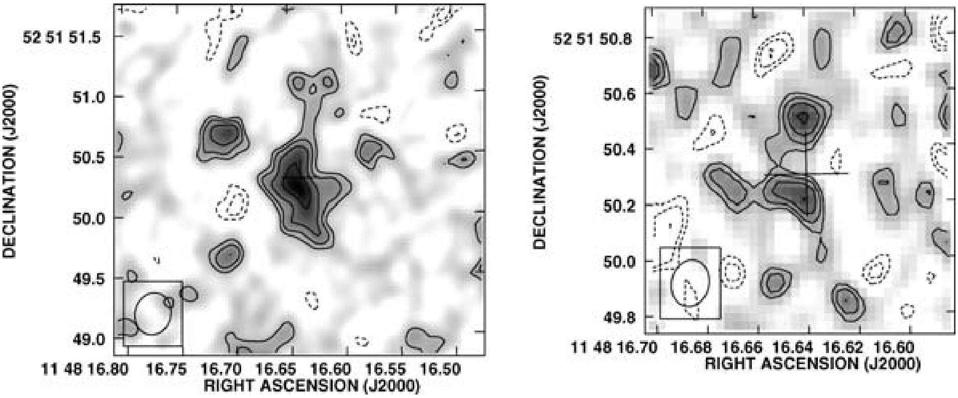

Figure 1. *left*: CO(3–2) map of J1148+5251 of the combined B- and C-array data sets (covering the total bandwidth, 37.5 MHz or 240 km s^{-1}). Contours are shown at -2, -1.4, 1.4, 2, 2.8, and 4 $\times\sigma$ ($1\sigma = 43\ \mu$Jy beam^{-1}). The beam size ($0.35'' \times 0.30''$) is shown in the bottom left corner. *right*: The central region at 1 kpc ($0.17'' \times 0.13''$) resolution ($1\sigma = 45\ \mu$Jy beam^{-1}). 2, 2.8, and 4 $\times\sigma$ ($1\sigma = 45\ \mu$Jy beam^{-1}). This high–resolution map recovers half of the flux seen in the left panel (see Walter *et al.* 2004 for more details). New HST ACS imaging suggests that the AGN seen in the optical is associated with the souther CO clump seen in the right panel (White *et al.* 2005).

imply a rather massive dark matter halo of $>10^{14}$ M$_\odot$. Regardless, these results show the power of high-resolution CO imaging in sources at the end of cosmic reionization.

4. Observations at other wavelengths

Clearly, multi–wavelength observations are critical to constrain the properties of the highest redshift quasars further. Here we will discuss two ongoing projects: Spitzer studies and deep NIR photometry of the highest redshift quasars. E.g., Jiang *et al.* 2006 have presented *Spitzer* observations of thirteen $z \sim 6$ quasars using the Infrared Array Camera (IRAC) and Multiband Imaging Photometer for *Spitzer* (MIPS). They find that most of these quasars have prominent emission from hot dust as evidenced by the observed 24 μm fluxes. Their spectral energy distributions (SEDs) are similar to those of low-redshift quasars at rest-frame $0.15-3.5\ \mu$m, suggesting that accretion disks and hot-dust structures for these sources already have reached maturity (only one of their objects had an unusual SED). This is similar to the results found from the (restframe) FIR imaging of the QSOs, i.e., that their average properties are very similar to what is found in sources at lower redshifts.

We are currently also obtaining deep NIR spectroscopy of the highest redshift quasars accessible from the VLT (see contribution by Kurk at this meeting, Kurk *et al.* 2006). Observations of emission lines of a sample of five $z \sim 6$ quasars, (including fainter objects than observed before) show that the measured FeII / MgII ratios are around solar and consistent with a lack of evolution of the metallicity of the quasar broad line regions (BLR) up to $z \sim 6$, suggesting that stars in their hosts formed at $z \gg 6$. The BH masses, measured from both MgII and CIV line widths are within the range 2–16 $\times 10^8$ M$_\odot$, the smallest found in such distant objects. These results imply that the metallicity of BLRs in quasars does not evolve up to $z \sim 6$, suggesting a period of intense star formation at $z > 10$ in the respective host galaxies (Kurk *et al.* 2006).

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5. Concluding remarks

The recent observations presented here have shown that resolved molecular gas *maps* of objects out to the highest redshifts can already be achieved with today's instrument (i.e. the VLA). Although these observations are time intensive, they have dramatically improved our knowledge of the properties of the molecular gas phase at high redshift. These measurements can then be combined with observations at other wavelengths (e.g., radio, Spitzer, NIR) to constrain the properties of these enigmatic sources further. These results show the enormous potential for future studies of the molecular gas content and dynamical masses in a statistically significant sample of the highest–redshift galaxies using ALMA, where resolutions of $< 0.1''$ will be achieved routinely.

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Discussion

Deborah Dultzin-Hacyan: Just a comment. We have VLT data for 25 quasars with $1 < z < 2.5$ from VLT and find that M_{BH} seems to have a limit of $10^{9.5}$ $M_{\odot}$.

Fabian Walter: Fine

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