The Interplay among Black Holes, Stars and ISM in Galactic Nuclei
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Radio observations of $z \approx 2$ luminous QSOs

Andreea O. Petric[1] and Christopher L. Carilli[2]

[1]Department of Astronomy, Columbia University, New York, NY, 10025, USA
email:andreea@astro.columbia.edu

[2]National Radio Astronomy Observatory, P.O.Box 0, Socorro, NM, 87801, USA
email: ccarilli@nrao.edu

Abstract. We present Very Large Array observations at 1.4 and 5 GHz of a sample of 16 quasi-stellar objects (QSOs) at $z = 1.78$ to 2.71. These sources were chosen to have similar optical properties (M_B, spectra) as samples of ($z \geqslant$ 3.7 QSOs) for which we have comparable (sub)millimeter (250 GHz or 350 GHz) and centimeter observations. Half of the chosen quasars are bright at 250 or 350 GHz while the other half have not been detected at (sub)mm wavelengths. All eight submm-loud sources in our study were detected at 1.4 GHz, the majority of these at high significance ($\geqslant 0.2 \pm 0.02$ mJy). Only three of the submm-quiet QSO's were detected at radio frequencies, and these at lower significance ($\leqslant 0.17$ mJy). These results argue for a real physical difference between the submm-luminous and submm-quiet sources, and against a continuum of submm luminosities. Four of these sources have radio spectral indices and radio-to-FIR ratios consistent with star forming galaxies.

1. Introduction and Observations

Studies of the dynamics of stars and gas in the nuclear regions of nearby galaxies suggest that the overwhelming majority of spheroidal galaxies in the nearby universe contain massive black holes and that the mass of the central black holes correlates with the velocity dispersion in the spheroid (e.g.Ferrarese & Merritt 2000, Gebhardt et al. 2000). These two observations suggest a fundamental relationship between the formation of massive black holes and the stellar content of galaxies. To further investigate this hypothesis, we have embarked on millimeter-continuum studies of ($z > 2$) QSO's. Omont et al. (2003), Carilli et al. (2001), find that about 30% of the sources are detected in surveys with flux density limits of 1 to 2 mJy at 250 GHz and mm-to-cm spectral indices of these sources imply that the mm emission is thermal emission from warm dust which may be heated by star formation.

Here we present radio observations of 16 optically luminous, radio quiet, QSOs previously observed at 250GHZ. Eight of these QSO had been detected in FIR and for the remaining 8 we only have 1 σ flux density limits ranging between 0.6 and 1.3 mJy (Omont et al. 2003). The VLA observations at 1.4 GHz were made in the A configuration for about one hour. Standard phase and amplitude calibration was applied, and all sources were self-calibrated using field sources. The the theoretical rms noise ($1\sigma = 23\ \mu$Jy) was roughly achieved in most maps. The Gaussian restoring CLEAN beam Full Width at Half Maximum (FWHM) was typically 1.5". The 8 FIR-bright sources were observed at 5 GHz in C configuration for $\sim$ 20 minutes, achieving an rms sensitivity of order 45 μJy.

2. Results and Discussion

In the local universe star-forming galaxies from optically, IR or radio selected samples follow a very tight linear relation between their radio continuum and FIR luminosities,

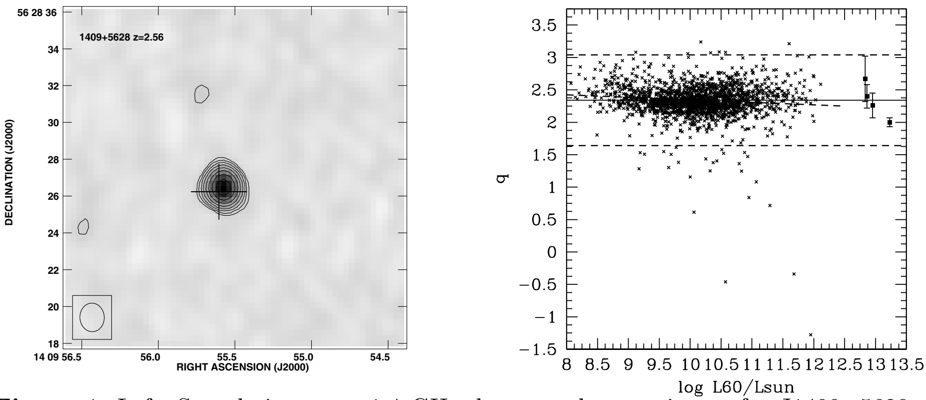

Figure 1. Left: Sample image at 1.4 GHz, here we show an image for J1409+5628. Contour levels (solid lines) are a geometric progression in the square root of two starting at 2σ, with $\sigma = 23\mu Jy$. Three negative contours (dashed) are included. The central cross marks the optical QSO location. Right: The radio to FIR correlation has been quantified through the q parameter, defined as: $q = \log\left(\mathrm{FIR}/3.75 \times 10^{12}\right) - \log\left(\mathrm{S}_{1.4}/\mathrm{Wm}^{-2}\mathrm{Hz}^{-1}\right)$ where FIR corresponds to the FIR luminosity between 40 and 120 μm. This fig shows the distribution of q values plotted as a function of 60 μm luminosity. The crosses are for the IRAS 2Jy sample of Yun et al. (2001). The points with error bars are for the submm-detected QSOs with steep radio spectral indices, the solid line marks the average value of $q = 2.34$, 98% of these are within $\pm$ log(5) of the mean and are star forming galaxies. Significantly lower q imply a contribution form a radio-loud AGN.

with only a factor of two scatter around linearity over four orders of magnitude in luminosity (e.g. Yun et al.2001). If this correlation holds at high redshift (e.g. Elbaz et al. 2002) then the ratio of radio to FIR fluxes can be used to as a a consistency check for star formation (Fig. 1). We find that four of the mm, and radio detected sources satisfy have radio/FIR properties consistent with those of star forming galaxies (Fig 1). If the dust is indeed heated by star formation, the implied star formation rates are of order 10^3 $\mathrm{M}_\odot$ year^{-1} (Omont et al. 2003). At this rate, a large fraction of the stars in the host spheroidal galaxy could form on a timescale of 10^7 to 10^8 years. For one source, J1409+5628, a massive reservoir of molecular gas ($\sim 10^{11}$ $\mathrm{M}_\odot$), the required fuel for such a starburst, has been detected (Beelen et al. 2004).

All eight submm-loud sources in our study were detected at 1.4 GHz, and all but one of these at high significance ($\geqslant 0.2 \pm 0.02$ mJy). Only three of the submm-quiet QSO's were detected at 1.4 GHz, and these at lower flux densities ($\leqslant 0.17$ mJy). All the QSOs were selected to have similar optical magnitudes, such that the radio and submm differences are unlikely to relate to differences in bolometric luminosity or magnification by gravitational lensing. While the sample is very small this suggests a real physical difference between the submm-luminous and submm-quiet sources. Clearly, the definitive test of this hypothesis requires more sensitive surveys of QSOs at submm wavelengths.

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