Near-Infrared Imaging of QSO Host Galaxies

J.P.E. GERRITSEN and P.D. BARTHEL, Kapteyn Astronomical Institute, Groningen, The Netherlands

Introduction

Three decades after the discovery of the first QSOs, the triggering of QSO activity is still an intriguing issue[1]. Which conditions lead to fuelling the "monster", responsible for the non-thermal continuum emission? The environment may be important, but then: is it the immediately surrounding parsec-scale region, the large-scale intergalactic medium or is it the intermediate galaxy-scale environment (the intergalactic medium) that makes the difference between quiet and active galaxies? Related crucial questions concern the radio-loudness and the nature of the monster: what is the physical reason behind the fact that 5–10% of (UV-excess selected) QSOs develop large extended radio sources, and what is the evidence for black hole mass accretion?

In our project we concentrate on the intergalactic environment for QSOs, but one remark on the cluster environment of QSOs should be made: studies by, e.g., Smith & Heckman (1990) and Ellingson, Yee & Green (1991) indicate that there is a remarkable difference in the cluster environment for radio-loud and radio-quiet QSOs. The former tend to lie in rich clusters while the latter do not. This implies that radio-loudness is a not a phase in the lifetime of an otherwise radio-quiet QSO host galaxy.

As for the host galaxies themselves, they have up till now mostly been studied at the optical wavelengths (e.g., Hutchings, Janson & Neff, 1989, Hutchings & Neff, 1992, Véron-Cetty & Woltjer, 1990). The accepted scenario from these studies is that radio-loud QSOs seem to reside in elliptical galaxies, while most radio-quiet QSOs reside in spiral galaxies. However, some radio-quiet QSO hosts show signs of interaction or signatures of elliptical galaxies. It is clearly an oversimplification to describe these host galaxies as luminous spiral or elliptical galaxies. This is for instance demonstrated by recent HST images (Bahcall, Kirhakos & Schneider, 1994, 1995) and ties in with the idea that QSO activity preferentially occurs in interacting systems (e.g., Stockton 1990).

In the local universe only one type of galaxy can compete with QSOs in total bolometric luminosity: the Ultraluminous IRAS Galaxies. Optical imaging showed that these systems are all in interacting systems (e.g. Sanders et al. 1989). The note that quasar activity may also be related to interactions with companion galaxies has led Sanders et al. to propose an evolutionary connection between Ultraluminous IRAS Galaxies and quasars. In this evolution scenario, merging of gas-rich systems will lead to QSO activity preceded by an ultraluminous far-infrared/starburst phase. Additional motivation for this connection is the comparable local space density for the ultraluminous far-infrared galaxies and QSOs. This scenario suggests that star formation is, or has been, an important ingredient in QSOs.

In several nearby Seyfert galaxies, which can be considered as low-luminosity QSOs, there appears to be a symbiosis of violent star formation and nuclear activity (e.g., NGC 1068, Neff et al., 1994). On intergalactic scales, therefore, one likes to know if there is a relationship between galaxy type and QSO activity and what the connection is between star formation and this activity.

Near-Infrared Observations of Quasar Host Galaxies

The intergalactic environment of quasars can probably best be studied in the Near-Infrared. There the contribution of the active nucleus to the total emission is much lower than in the optical, and so the quasar host galaxies are better seen in the NIR. Moreover, the seeing in the NIR is generally better than in the optical, allowing to detect more structure in the host galaxies. Finally, the optical emission is dominated by emission from massive stars (thus traces recent star formation), whereas the NIR emission is more generated by the old stellar population, i.e. it traces much better the mass of the galaxy.

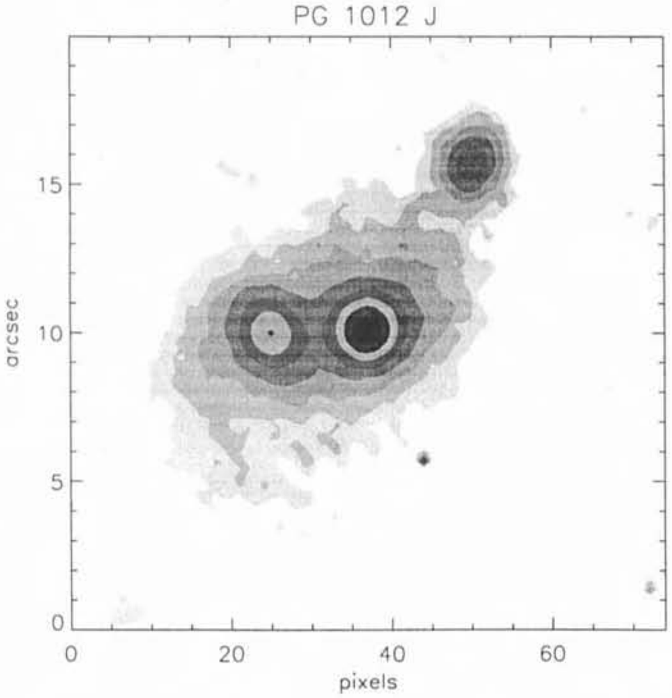
Recently, imaging in the Near-Infrared has been carried out by two groups: Dunlop et al. (1994) presented K-band observations and McLeod & Rieke (1994) published H-band images. Dunlop et al. conclude from their observations that the host galaxies for quasars are large galaxies (minor-axis > 40 kpc), while McLeod & Rieke conclude that the host galaxies can be normal L_* spiral galaxies, but not the result of a merger of two L_* spiral galaxies. The galaxies are bluer than normal early-type galaxies (0.5 mag in V–H), indicating there is ongoing star formation in the galaxies or the galaxies have recently undergone a starburst.

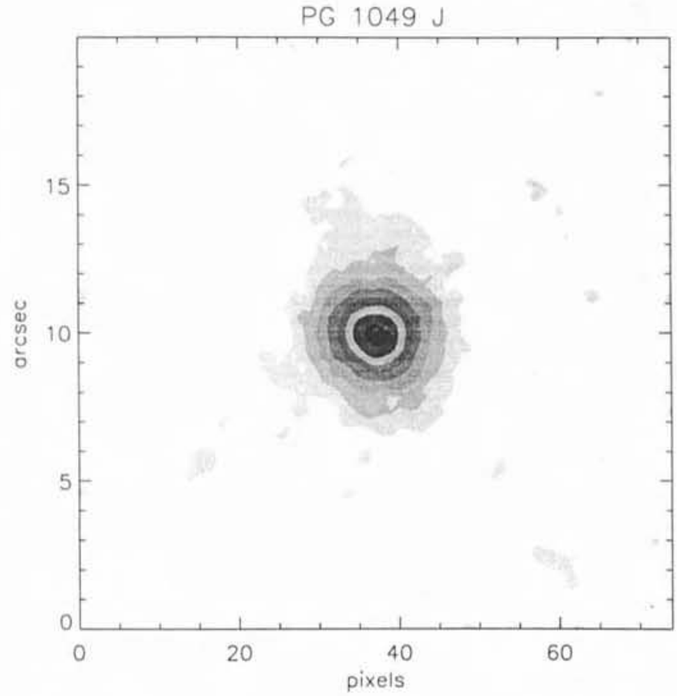
A Near-IR, Radio, and Optical QSO Imaging Survey

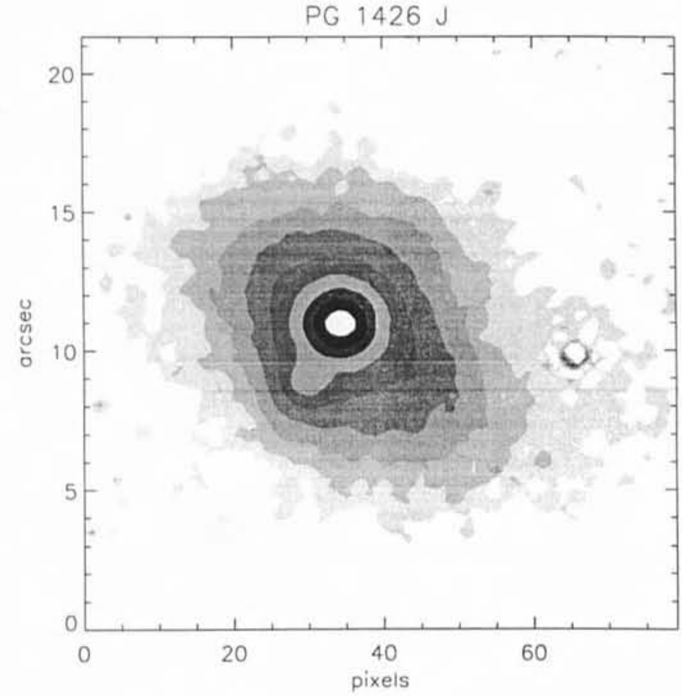
In order to investigate the intergalactic structure of QSO host galaxies we are conducting a Near-IR, radio, and optical imaging survey of nearby radio-quiet QSOs. Sample objects were drawn from the Bright Quasar Survey (Schmidt & Green 1983), a UV-excess selected QSO sample. In order to be able to combine the La Silla with the Socorro (NRAO VLA) sky coverage, we selected an equatorial sample, restricting ourselves to $z < 0.36$ objects. Low redshift will enhance chances of observing the host galaxy, enable extracting structure information at sub-kpc resolution, and furthermore allow comparison with ($z < 0.1$) ultraluminous IRAS galaxies. Since the latter are radio-quiet and since radio-quiet QSOs form the majority of the population, we restrict ourselves to radio-quiet QSOs.

The aim of the near-IR images is to get a better knowledge of the QSO host galaxies. Analysis of the J and K colour images will yield information on the structure of the mass component of the hosts. Combined with optical data, the colours of the host galaxies may teach us about recent or ongoing star formation, possibly connected to nuclear activity. To address the question of the importance of star formation in these QSOs further, we will use deep, high-resolution radio data with the sensitive 8 GHz system of the NRAO Very Large Array, at 0.25 arcsec resolution (recall that radio-quiet is NOT radio-silent; typical flux density values for the sample QSOs are 1 mJy). Together with accurate astrometric position measurements of the QSOs (with the aid of the Carlsberg Meridian Circle at La Palma), these data having spatial resolution of order 100 pc will allow us to separate the nuclear and diffuse contribution to the

[1]We use QSOs for the combined population of radio-loud and radio-quiet quasi-stellar objects.







J band images of PG 1012+00, PG1049-00, PG 1426+01. Levels increasing in factors of 2, lowest level at 1.5 σ; north to the top, east to the left.

radio emission and thus the importance of the monster and of circumnuclear star formation to the emission from the quasar. As such, these data will be useful to test predictions of the Warmer model (e.g., Terlevich et al., 1992).

Near-IR Observations and Reduction

The observations were carried out on 2 and 3 March 1995, with the ESO 2.2-metre telescope and the IRAC2B camera. The weather was photometric during one and a half night. Since the objects are small and we are interested in small-scale structure, we used lens B (with a resolution of 0.27 arcsec/pixel) for our observations. The seeing was typically 1 arcsec or slightly better.

Since all the sample objects are approximately point sources, we could move the objects along the array, thus obtaining object and sky at the same time, without losing observing time by moving to an empty field. In general, we did four integrations of five minutes. In the J window we integrated 20×15 seconds, while we integrated 5×60 seconds with the K filter.

The four images were then median filtered to obtain a local sky frame. From this local sky frame we subtracted a dark frame of the same integration time and normalised it to get a local flat field. We then subtracted the sky frame from individual observations and flat-fielded these to obtain sky-subtracted, flat-fielded images. The four individual frames were added, again using median filtering, to obtain the final image.

During the nights we regularly observed standard stars for calibration. Since we took only two shifted observations in each filter, we used the science frames for the sky subtraction and dome flat fields for the flat fielding. The photometric accuracy obtained is about 0.1 mag.

First Results

Since we had not yet completed our observing programme while writing this report, the detailed analysis of the data is still in progress. However we can make some general remarks about the host galaxies from the reduced images:

– some quasars are really point-sources,

– other quasars have just faint stuff surrounding the nucleus,

– a few quasars contain multiple nuclei,

– several beautiful galaxies are seen; the largest galaxy (PG1426+01) has a diameter of at least 40 kpc.

It seems that quasar activity may occur in all kinds of galaxies. A next step will be the separation of the nuclear contribution to the images in order to estimate the magnitude of the host galaxies. A comparison of ground-based and HST data shows that the former tend to overestimate the magnitude of the host galaxies, so this task will have to be done very carefully. Interesting will be

HST images in cycle 7 with the NICMOS array.

Some Individual Galaxies

PG 1012+00 ($z = 0.185, M_B = -24.33$). This quasar has two secondary nuclei. There is a spiral (or tidal) arm SE of the system. 25% of the radio emission at 5 GHz is diffuse emission, the remainder is slightly resolved at 0.5 arcsec resolution, and has a steep spectral radio index, so may not be nuclear.

PG 1049–00 ($z = 0.357, M_B = -25.70$). There is some fuzz extending to the north of the nucleus. The extension is also seen in a R-filter image. At most half of the radio emission at 5 GHz is nuclear, with a flat radio spectrum.

PG 1426+01 ($z=0.086, M_B = -23.51$). There is a large asymmetric galaxy under the nucleus and a small secondary nucleus to the SE at 2.5 arcsec (4 kpc) distance. One quarter of the 5 GHz radio emission is diffuse, and the remainder has a steep radio spectrum. As in other sample objects, precise astrometry will tell where exactly the radio emission is located.

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For further information please contact the authors:
gerritse@astro.rug.nl, pdb@astro.rug.nl

Have We Detected the Primeval Galaxies?

D. MACCHETTO[1] and M. GIAVALISCO[2], Space Telescope Science Institute

The identification of the population of primeval galaxies, namely the first galaxies to form stars in the Universe, is essential to provide the much needed observational underpinning to modern theories of galaxy formation and evolution, without which these theories are destined to remain in the realm of speculation. Until recently, and despite decades of intensive search, primeval galaxies had not been identified and thus the epoch (or the epochs!) and the early physics of galaxy formation are still substantially unknown. The combination of ground-based photometry and spectroscopy with the Hubble Space Telescope high angular resolution, is changing this situation and we are now obtaining empirical evidence that a population of galaxies of relatively normal luminosity was already in place at redshifts z > 3 and in an evolutionary state characterised by active star formation.

Thanks to telescopes of large apertures and superior image-quality, and to high-efficiency spectrographs, modern deep-galaxy surveys can now obtain redshift identifications for galaxies at about half the age of the Universe, or redshift of about $z \lesssim 1.5$. Combined with the morphological information provided by the exceptional angular resolving power of the Hubble Space Telescope, this is providing a reasonably detailed picture of the evolutionary state of the galaxy population over the latter half of the history of the Universe. A consistent result from the work by several groups (Lilly, 1993; Songaila et al., 1994; Glazebrook et al., 1995a and 1995b; Driver et al., 1995a and 1995b; Steidel, Dickinson & Persson, 1994 and 1995) is that galaxy evolution appears to be strongly dependent on luminosity and morphological type. While the population of bright spirals and ellipticals ($L \sim L^*$, with $L^* = 10^{10}\ L_\odot$) have evolved rather passively from redshifts $z \sim 1$ to the present epoch, the fainter galaxies with luminosity $L \ll L^*$ have undergone a spectacular evolution in morphology, luminosity and number density over the same time span.

The relative lack of evolution in the bright galaxy population suggests that their formation took place at redshifts considerably higher than those probed by the current surveys. Can we observe and track the evolving population of bright galaxies at very high redshifts?

Unfortunately, optical and near-IR spectroscopy of galaxies at redshifts $z > 1.5$ is much harder to obtain due to the limited sensitivity of the current instrumentation and the relative lack of information in the spectral energy distribution which can be probed from the ground. The early primeval galaxy surveys attempted to detect them via their supposedly intense Lyα emission (Partridge and Peebles, 1967; Charlot and Fall, 1993) with optical narrow-band imaging covering the redshift interval $1.8 \lesssim z \lesssim 6$. With few exceptions. Noticeably dominated by discoveries made with the ESO 3.6-m and NTT telescopes, including the most distant radio-quiet Lyα galaxy at $z = 3.428$ by Macchetto et al. (1993), no systematic detections of primeval galaxies have been reported with this technique (see Giavalisco, Macchetto & Sparks, 1994 for a review). More recently, these surveys have been extended to near-infrared wavelengths to extend the redshift range up to $z \sim 20$ (Thompson et al., 1994 and 1995; Pahre and Djorgovski, 1995) and/or to include emission lines such as [OII]λ3727, Hβ, [OIII]$\lambda\lambda$4969 5007, and Hα, which do not suffer from the severe attenuation by resonant scattering that affects the Lyα line. With a handful of exceptions, no systematic detections have been reported even in this case. We must conclude that either the redshift ranges searched do not correspond to the epoch during which the presumably violent bursts of star formation took place, or that the theoretical expectations of what a primeval galaxy should look like are not realistic (cf. Baron and White, 1987; Charlot and Fall, 1993).

Recently, a more successful technique to detect primeval galaxy candidates at high redshifts has been pioneered by Steidel and Hamilton (1992). This consists of a redshift-tuned colour photometry derived from broad-band imaging

[1]Affiliated with the Space Science Department, ESA.
[2]Hubble Fellow.