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The Evolution of Quasar Host Galaxies

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Abstract

Establishing how the mass of quasar host galaxies changes as a function of redshift can provide a key measurement for constraining the formation and growth of galaxy spheroids and their central black holes. From observations using NICMOS on HST we have derived the best estimate to date of the luminosity evolution of the hosts of both radio-quiet and radio-loud quasars from the local universe out to z=2. However, in order to accurately convert these host luminosities into galaxy masses we require additional information on the stellar composition of the hosts. New observations of these quasar hosts with HST/WFPC2 are now allowing us to derive the first reliable rest-frame U-V colours for high-z quasar hosts and the results of these studies are summarized here.

1.1 Introduction: Low-Redshift Quasar Hosts

Several comprehensive studies of low-redshift ($z < 0.3$) quasar hosts have now been carried out using HST and ground-based instruments (eg Hutchings & Morris 1995, Bahcall et al. 1997, Hooper et al. 1997, McLeod et al. 1999, Hamilton et al. 2002). These studies indicate that powerful nuclear activity in the local universe is usually associated with massive, bulge-dominated hosts - exactly the type of galaxies in which one would expect to find the most massive black holes.

In our own HST study of radio galaxies and quasars at $z \simeq 2$ we found that the hosts of all quasars more luminous than $M_R \simeq -24$ were consistent with massive, luminous elliptical galaxies - regardless of the radio luminosity of the quasar (McLure et al. 1999, Dunlop et al. 2003).

1.2 Quasar Hosts at High Redshift

In order to explore the evolution of quasar host galaxies over a large interval of cosmic history we defined two new quasar samples at $z \simeq 1$ and 2. By observing with NICMOS on HST through $J-$ and $H-$band filters respectively we imaged the objects in their restframe $V-$band, thus avoiding strong emission lines associated with the quasar activity as well as ensuring that the data is directly comparable with our images of quasar hosts at low redshift. The new samples contain both radio loud and radio quiet quasars and are limited to objects with $-24 > M_V > -25$. The results of this study are described in detail in Kukula et al. (2001), and can be summarised as follows:

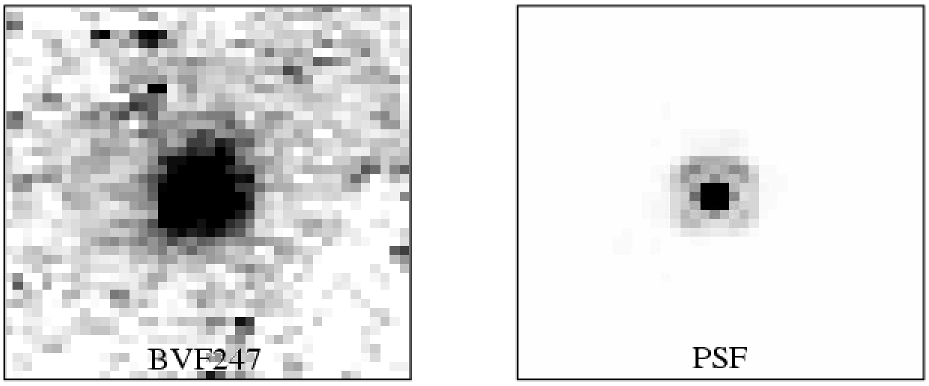

Fig. 1.1. Left: NICMOS *J*-band image of the RQQ BVF247 after removal of the central point source to reveal the underlying host galaxy. Right: *J*-band point-spread function of NICMOS with the same greyscale cut.

1.2.1 Detection of quasar hosts at $z \simeq 1$

Figure 1.1 shows an example of one of the quasars in our $z \simeq 1$ sample, imaged in J−band with NICMOS. The left-hand panel shows the NICMOS image after removal of the nuclear point source, revealing the underlying extended starlight from the host galaxy. The right-hand panel shows the J−band PSF with the same greyscale cut, demonstrating the presence of a resolved host galaxy in the quasar image.

Just as at low redshift, we find that the host galaxies of quasars at $z \simeq 1$ are large, luminous systems. In three objects we also find strong evidence that the hosts follow a de Vaucouleurs surface brightness profile, but for the remaining 6 hosts we are unable to obtain an unambiguous fit to the radial light profile.

However, evidence that these quasar hosts are indeed massive elliptical galaxies comes from a comparison with radio galaxies at similar redshifts from the 3C sample, also imaged with HST (Best & Longair 1997, 1998). When the two types of active galaxy are plotted on the surface-brightness/half-light-radius projection of the fundamental plane, we find that they occupy exactly the same region of the diagram and have the same slope and normalisation. The implication is that just like the radio galaxies, and the hosts of quasars at low redshift, the hosts of powerful quasars at $z \simeq 1$ are predominantly large, luminous elliptical galaxies.

1.2.2 Detection of quasar hosts at $z \simeq 2$

It proved much more difficult to detect and characterise the host galaxies of the quasars in our $z \simeq 2$ sample. The signal-to-noise in the H−band NICMOS images was too low in most cases to allow galaxy morphologies and scalelengths to be accurately determined. However, extended starlight was detected in every object (Figure 1.2) and we were able to place tight constraints on the luminosity of the hosts.

From this we can conclude that the host galaxies of quasars at $z \simeq 2$ are already luminous systems, but there are indications that the galaxies may be somewhat smaller than their low-luminosity counterparts, perhaps indicating that they are still in the process of formation. In

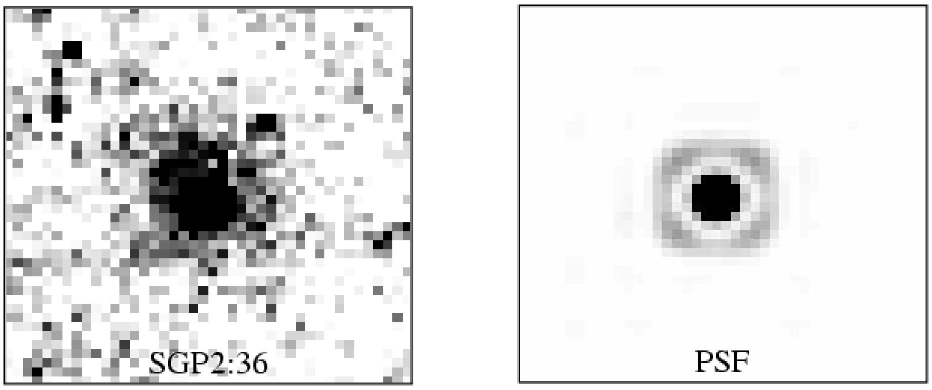

Fig. 1.2. Left: NICMOS H-band image of the RQQ SGP2:36 after removal of the central point source to reveal the underlying host galaxy. Right: H-band point-spread function of NICMOS with the same greyscale cut.

a separate HST study of quasar hosts at similar redshifts, using higher resolution than the our observations, Hutchings et al. (2002) find that the host morphologies are mostly irregular, indicating that the galaxies are interacting or merging.

1.3 Host Galaxy Evolution from $z \simeq 2$ to $z \simeq 0.2$

By combining the data from our quasar samples at $z \simeq 0.2$, 1 & 2 we can track the luminosity evolution of the host galaxies. Figure 1.3 shows galaxy absolute magnitude as a function of redshift and illustrates the tendency for the hosts to brighten towards higher z. To see whether this increase in luminosity is consistent with passive evolution of a fixed mass of stars we also plot the luminosity curves for three present-day luminous galaxies (dotted lines), assuming that they formed all their stars in a single burst at high redshift ($z \sim 5$) and evolved passively thereafter.

At first glance the host galaxies do seem to behave according to the passive evolutionary scenario, but a more detailed look at the data shows that this is probably not the case.

1.3.1 Separating Radio-loud and Radio-quiet Objects

When we split our galaxy samples according to whether the quasar is radio loud or radio quiet, we see the first signs of a change in behaviour. Whilst the RLQ hosts continue to brighten with increasing redshift in agreement with passive stellar evolution, the RQQ hosts show little change in luminosity, implying that the galaxies are somewhat less massive at high redshift by a factor of 2-3. Since RQQs are roughly 10 times more common than RLQs it is likely that the RQQ hosts provide a more representative picture of the behaviour of massive galaxies in general (at a redshift of ~ 2 the comoving number density of RQQs is comparable to that of the massive elliptical population in the local universe, to within an order of magnitude).

However our results do imply that a selection effect may be at work in our RLQ sample, to the extent that, at any redshift, choosing powerful radio sources seems to bias us towards

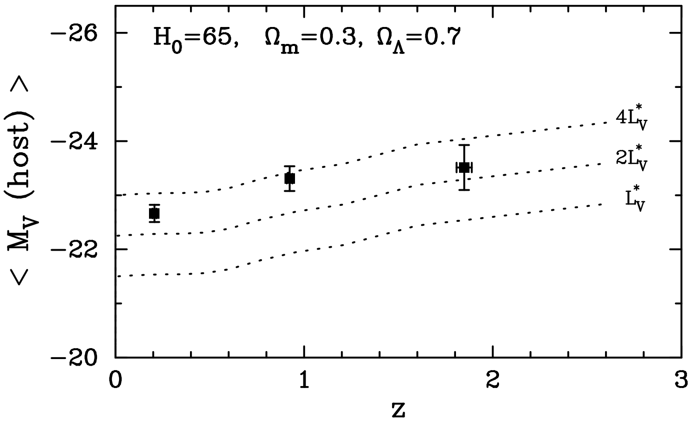

Fig. 1.3. Mean absolute magnitude versus redshift for the quasar host galaxies from our HST imaging programmes (McLure et al. 1999, Kukula et al. 2001, Dunlop et al. 2003). The dotted lines show the passive evolutionary curves for present day $L^\star$, $2L^\star$ & $4L^\star$ galaxies assumining they formed in a single starburst event at $z \sim 5$.

the most massive galaxies which have had time to form at that particular epoch. This may be telling us something interesting about the origins of 'radio loudness' in AGN.

1.3.2 From galaxy luminosities to masses

J and $H-$band images of the quasar hosts at $z \simeq 1$ & 2 give us galaxy luminosities at restframe $V-$band. The hosts are clearly luminous systems, but without spectral or colour information we cannot convert these luminosities into galaxy masses. Thus, at high redshifts we cannot properly distinguish between fully-formed massive galaxies with mature stellar populations and smaller, still-growing galaxies with many luminous young stars.

By reobserving our quasar samples at $z \simeq 1$ & 2 with WFPC2 through V and $I-$band filters respectively, we sample the near-ultraviolet region of their restframe spectrum. After modelling and analysis these images can be compared to our existing NICMOS (restframe $V-$band) images to yield UV-V colours for the hosts. Soince the two wavebands straddle the 4000Å break feature in the host galaxy's restframe spectrum, these colours are particularly sensitive to the age of the dominant stellar population in the host.

Analysis of the data was still underway at the time of writing, but initial results from the objects at $z \simeq 1$ indicate that the hosts are quite red, typical of early-type galaxies at the same redshift.

1.4 Conclusions

We have detected luminous host galaxies around quasars out to redshifts of ~ 2. At low redshifts the hosts of luminous quasars are typically bulge-dominated systems, and these galaxies appear to be almost fully formed, with mature stellar populations, by a redshift of ~ 1. At redshifts of ~ 2 the situation is less clear. There is evidence, amongst the RQQs at least, of a modest drop in host galaxy mass, and other studies indicate that that the galaxies are irregular and relatively blue. Forthcoming results from our $I-$band study of $z \sim 2$ hosts will provide further constraints on the nature of the stellar populations in these objects and thus enable us to make accurate measurements of the galaxy masses.

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