Properties of z > 2 Radio Galaxies

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The morphology of high redshift radio galaxies (HZRGs) cannot be classified in the conventional way as is done at low redshifts. When observing HZRGs at arcsecond resolution the optical continuum is just resolved and observed to be aligned with the orientation of the extended radio emission. The more extended Lyα emission shows a similarly strong alignment effect. The few HZRGs observed with HST so far have their optical continuum clumpy on a subarcsecond scale (i.e. kiloparsec scales) and show no morphological signs of being "nice" proto-ellipticals or proto-spirals. ¿From high resolution optical spectroscopy it has become clear that many of the HZRGs have very strong, spatially extended HI absorption features in their Lyα emission, that must be associated with the radio galaxy or its direct environment. Thus in spite of the presence of a powerful radio source and hard ionizing radiation, considerable amounts of neutral gas are present, which may tell us something about the geometry of these objects or their environment. We have also recently detected CO emission from a radio galaxy at $z = 3.6$ indicating the presence of 10^{11} $M_{\odot}$ of molecular gas of moderate temperature (60–100K). This galaxy may be forming the bulk of its stellar population. More HST observations can tell us more about the continuum morphology of the most distant galaxies and its relation to the radio properties. Future mm–interferometry will allow us to resolve the CO emission region, and therefore enable us to study how widespread starformation is through the galaxy.

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1 Introduction

During the last few years we have found a large number of very distant galaxies ($z > 2$) by selecting ultra steep spectrum radio sources. This has proven to be the most effective way to find distant galaxies. The most distant galaxies have been found at $z \approx 4$. By now our sample contains more than 35 radio galaxies at $z > 2$. In total about 60 galaxies are known at such large distances, almost all of which were found by selecting steep spectrum radio sources. Studying galaxies at such large redshifts may reveal clues to the formation and early evolution of galaxies in general. While at a redshift of 0.5 the relative cosmological lookback time is about 50%, at the highest known redshifts this is 90%. Thus we are looking at the Universe when it had only 10% of its present age, which is likely to have been the epoch of galaxy formation. In that epoch the comoving space density of powerful AGNs was several hundred times larger than at the present time. Active galaxies may therefore have played a fundamental role in the formation and evolution of galaxies in general. A general overview of HZRGs is given by McCarthy (Ann. Rev. Astr. Astrophys., 1993). Here I will describe the morphologies of the high redshift radio galaxies (HZRGs) of our sample observed in several different ways.

2 Continuum and emission line morphology

One of the first important discoveries of HZRGs was the alignment of the optical continuum morphology with the extended radio emission. The most popular explanations involve radio jet induced starformation or scattering of continuum photons from an obscured quasar. HST observations of 2 HZRGs have shown that the alignment effect goes down to kiloparsec and subkiloparsec scales. The optical continuum shows a very clumpy morphology at HST resolution and has no obvious similarities with that of low redshift radio galaxies, which are often ellipticals.

Another prominent feature of HZRGs is their very extended, luminous Lyα emission. With luminosities of 10^{44}–10^{45} erg s^{-1} the halos of ionized hydrogen extend up to 100 kpc. The extended emission line gas is also strongly aligned with the radio axis. Subarcsecond ground-based imaging of the Lyα gas, shows that it has a very clumpy and filamentary structure with similar bending features like the radio structure, suggesting a direct link between the two.

The overall optical properties of radio galaxies in the early Universe show a very diverse and clumpy morphology which is impossible to describe with existing morphological classifications for low redshift galaxies. The HZRGs do not look like ellipticals or bulges with disks.

They may be still in the process of formation, evolving into more regularly shaped galaxies at a later epoch. High spatial resolution imaging is essential to understand this formation process.

3 Associated HI absorption

HZRGs are unique, spatially extended probes of the early universe, allowing studies of the properties of the extended emission line gas. We have carried out high resolution (2.5 Å) spectroscopy of the extended Lyα to obtain information on its kinematics and the extent of possible absorption clouds. We found that strong HI absorption in the Lyα emission line is very common in the radio galaxies in our sample. About 70% of the galaxies that we have investigated show a clear double peaked Lyα profile over the entire spatial extent. The sharpness of the trough in the line profile suggests that it is an absorption feature rather than true velocity structure of the gas. The absorptions infer neutral hydrogen column densities N(HI)= 10^{18}–10^{20} cm^{-2}. ¿From absorption line studies in quasars it is known that the chance of a random intervening HI cloud with such high column density in the small wavelength interval of the Lyα emission line is only $\sim 1\%$. Therefore these HI clouds must be associated with the radio galaxy or its direct environment. If the double peaked Lyα profile were a kinematical signature it might be due to bulk infall or outflow of ionized gas, but as mentioned before the shape of the profile indicates that it is very unlikely to be a true velocity profile and most likely caused by absorption due to neutral hydrogen. With the orientation unification theory of quasars and radio galaxies in mind, the HI absorption might be caused by hydrogen that is outside the cone of ionizing radiation from the obscured quasar, but in our line of sight in front of the ionized hydrogen. As it would also be undisturbed by the radio jet it would have a narrower velocity width and thus cause a strong absorption in the Lyα emission from the ionized gas. Alternatively the HI might be associated with the direct environment of the radio galaxy. At low redshift radio galaxies are observed to reside in clusters. Therefore it is likely that the HZRGs are in (proto)clusters and the cluster galaxies might cause absorptions of the Lyα emission from the radio galaxy. There would need to be a high density of (proto)galaxies in the cluster and the galaxies would need to have large hydrogen halos of large column density to cause a $\sim 70\%$ chance of observing it in front of the radio galaxies extended emission line gas.

4 Molecular gas

In our Galaxy regions of dense molecular gas are observed in sites where starformation is occuring. Large masses of molecular gas are observed in local starburst galaxies like Arp 220. It has so far remained unclear at which rate (radio) galaxies in the early Universe are forming stars. With the discovery of CO emission from the ultraluminous IRAS galaxy F10214+4724 at $z = 2.3$ it appeared that it may be possible to find molecular gas in the most distant galaxies. The study of molecular gas would give indications to the rate of starformation in these galaxies. We have started to search for CO in our sample of HZRGs. From one of the highest redshift galaxies known, at $z = 3.6$, we have detected CO emission in the J=4–3 and J=6–5 transitions (van Ojik *et al.* 1994, submitted). It infers a total mass in molecular gas of 10^{11} $M_{\odot}$ and from the CO line ratio we estimate a density of 10^4–10^5 cm^{-3} and a temperature of 60–100 K. With these CO observations we are probing the quiescent ISM of the underlying galaxy, that does not have violent interaction with the radio plasma. Such a large amount of moderately dense, warm molecular gas, indicates that vigorous starformation must be going on and the galaxy may be forming the bulk of its stellar population. If the presence of a large amount of molecular gas is common in HZRGs it must have played a fundamental role in their evolution. Future mm–interferometry can reveal the morphology of the molecular gas, allowing us to study the extent of starformation in these young galaxies.

5 Conclusions

High redshift radio galaxies are the only class of objects that we know in the early universe that can be relatively easily resolved in many wavelength bands. HST observations of 2 HZRGs have shown that the alignment effect of optical continuum emission and radio emission continues down to kiloparsec scales. On that scale the optical continuum is very clumpy and the galaxies do not look like they are "nice" proto-ellipticals or proto-spirals. More HST data is needed to examine if this is generally the case for HZRGs. The Lyα emission line gas often extends up to 100 kpc and also has an irregular morphology, but is clearly correlated with the radio morphology. In the Lyα emission strong spatially extended HI absorptions are a common feature of HZRGs. These HI absorptions must be related to the underlying galaxy or its direct environment. The recently discovered presence of large amount of molecular gas in one of our HZRGs indicates that these galaxies may be forming the bulk of their stellar population. Observations at high spatial resolution with HST, mm–interferometers and large radio telescopes are needed to disentangle the correlations between the various observed properties.