Lyα emitting gas in distant radio galaxies: an evolutionary probe?

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Abstract

One of the most remarkable features of distant radio galaxies is that they often possess giant luminous Lyα halos of ionized gas. In this contribution we will first discuss properties of the halos, including the HI absorption that often disfigures the Lyα emission profiles and the relations that exist between the properties of the halo and the radio source. Subsequently, we will advocate an evolutionary scenario in which the properties of the Lyα halo change while the radio jet is advancing through the halo. Finally, several aspects of this scenario are further illustrated using new data on the halos of two high redshift radio galaxies (0406−244, $z = 2.44$ and 2104−242, $z = 2.49$).

1 Introduction

An important reason for high-redshift radio galaxies (HzRGs) playing an important role in cosmology is that they contain a number of observable components, including stars, gas at various temperature ranges, dust and relativistic plasma (e.g. McCarthy 1993; Röttgering and Miley 1996). Since emission from these components can be very luminous, especially when compared to "normal galaxies" at similarly high redshifts, it often can be studied in great detail enabling important constraints to be placed on physical models of these components.

One of the most remarkable features of distant radio galaxies is that they often possess giant luminous halos of ionized gas (for a review see McCarthy 1993). Since these halos can be very extended (> 150 kpc) and extremely luminous ($> 10^{44}$ erg s^{-1}) in the Lyα emission line, they can be studied in great detail. In general the velocity dispersion of the Lyα line can be very high ($\sim$ 1000 km/s). The UV-emission line ratios can be explained assuming that the gas is ionised by a central quasar that is hidden from our direct view (e.g. McCarthy et al. 1990). Model parameters that are then often used are a filling factor for the emission line gas of order 10^{-5}, and a density of 1 cm^{-3}. The spatial scale then dictates that the mass in the emission line gas can be of order a few times 10^9 $M_\odot$. Alternatively, it has been argued that shocks are the dominant physical mechanism that ionises the emission line clouds (Clark et al. 1998, Villar-Martín et al. 1997). The most reasonable view seems that both ionising mechanisms are at work, but that their relative contribution not only varies from source to source, but also depends on the location within the emission line region.

Possibly the most interesting question regarding these halos is what is their origin? Is the gas expelled by the galaxy during a massive gaseous wind driven out by an enormous starburst? Or is this the gas that is cooling out from a primordial halo surrounding the radio source and providing the material from which the galaxy is being made. A clear answer on this will be important for our understanding of how massive galaxies form.

In this contribution we will first review some of the work that our group has been carrying out on this topic over that last few years. This group includes George Miley, Rob van Ojik, Dick Hunstead and Chris Carilli. Subsequently, we will advocate an evolutionary scenario in which the properties of the Lyα halo change while the radio jet is advancing through the halo. Finally, several aspects of this scenario are further illustrated using new data on the halos of two HzRGs (0406−244, $z = 2.44$ and 2104−242, $z = 2.49$).

2 The two component structure in the Lyα halo

At the end of the eighties the first prime examples of distant radio galaxies with extended halos were discovered. The most noteworthy studies are those on the halos in 3C326.1 (McCarthy et al. 1987) and 3C295 (McCarthy et al. 1990), with one of the most interesting outcomes being that the size of such halos can extend to up to 170 kpc.

Our group has extensively studied the Lyα halo around 1243+036 at $z = 3.6$ (van Ojik et al. 1996). The narrow band image (Figure 1) shows that the Lyα emission has a complicated morphology with the two most distinct features being: (i) the inner region that has a cone shaped morphology extending for about $2''$. Such a morphology is expected in the case of the gas being ionised by an obscured quasar nucleus and (ii) a spherical shaped region on scales of $8''$ containing a significant amount of clumpy or filamentary structure.

A high resolution spectrum of 1243+036 (Figure 2) shows that the Lyα gas

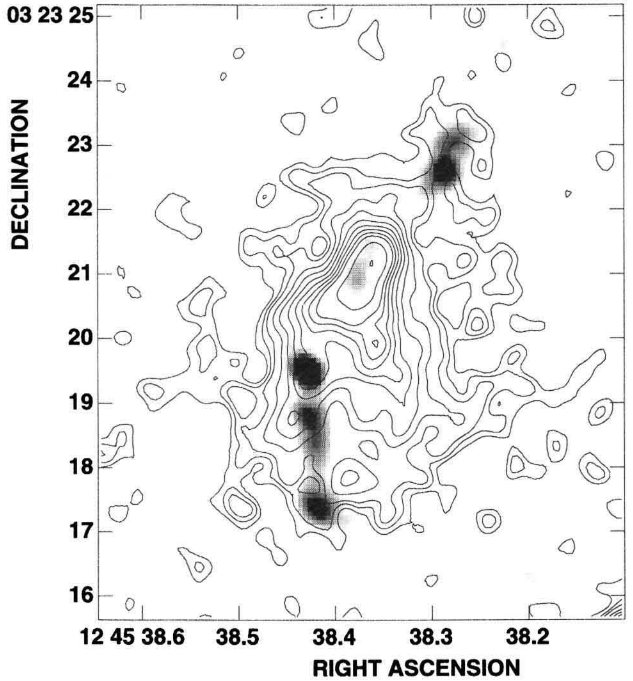

Figure 1. A contour plot of the Lyα halo of the radio galaxy 1243+036 at $z = 3.6$, with a greyscale plot of the 8.3-GHz VLA map superimposed (from van Ojik et al. 1996).

has a complicated kinematic structure. The gas contained within the radio structure has a relatively high velocity width ($\sim$ 1500 km s^{-1} FWHM). The component of the Lyα emission that coincides with the bend in the radio structure is blue-shifted with respect to the peak of the emission by 1100 km s^{-1}. At this location the jet seems to be vigorously interacting with the emission line gas. This is direct evidence that high velocity dispersion in the emission line gas is mainly due to this kind of interaction. There is low surface brightness

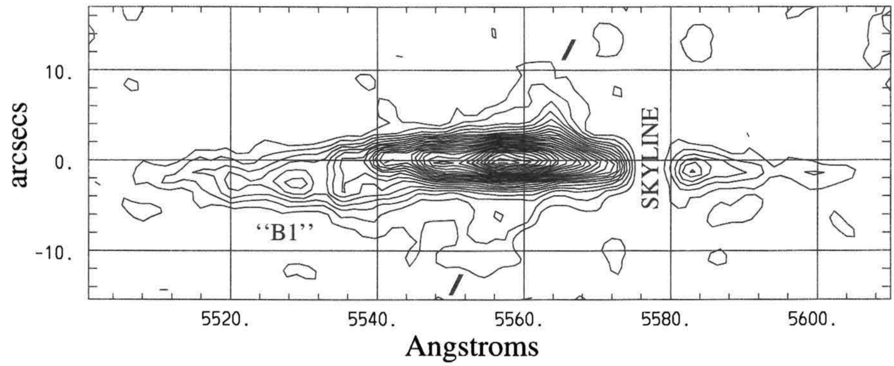

Figure 2. A two-dimensional representation of the 2.8 Å resolution NTT spectrum of Lyα of 1243+036 ($z = 3.6$) taken through a slit oriented along the main axis of the radio emission (from van Ojik et al. 1996).

Lyα emission aligned with, but extending 40 kpc beyond both sides of the radio source. This halo has a narrow velocity width ($\sim$ 250 km s^{-1} FWHM) and a velocity gradient of 450 km s^{-1} over the extent of the emission.

The data on the Lyα emission gas clearly indicates that there are two distinct components to the halo. There is an *inner halo* that is contained within the radio source which has a high velocity dispersion. The *outer halo* is located beyond the extremities of the radio source and has much lower velocity dispersion. In the high resolution spectrum taken perpendicular to the radio axis this outer halo is not seen, and therefore it seems that the structure might be two dimensional. Since over the full scale of the outer halo there is a gradient apparent of order 450 km s^{-1}, this "pancake" might be rotating around the radio galaxy, which then would have a mass of $\sim 10^{12}$ M$_{\odot}$. Although disk formation seems to be a natural consequence of hierarchical clustering models (e.g. Evrard et al. 1994), the large size of this "disk" would be difficult to explain in standard scenarios (e.g. Mo et al. 1998).

3 Strong HI absorption and the case of 0943-242

The Lyα emission from distant radio galaxies can be very bright ($> 10^{-15}$ erg s^{-1}), and therefore it is possible to measure absorption against this Lyα emission. The source with one of the deepest and best defined HI absorption

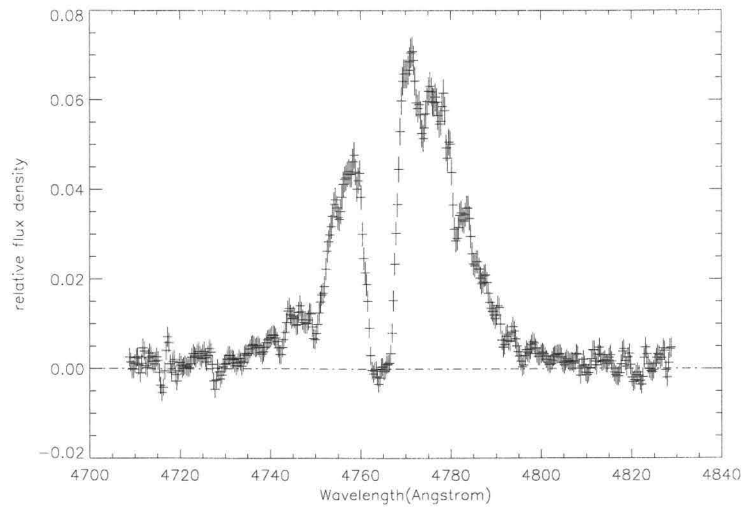

Figure 3. Part of the high resolution spectrum spectra (1.5 Å) of the Lyα region of the $z = 2.9$ radio galaxy 0943−242. (see also Röttgering et al. 1995).

systems is 0943−242 at $z = 2.9$. The high resolution AAT spectrum (1.5 Å) of the Lyα region of the $z = 2.9$ radio galaxy 0943−242 reveals a complex emission line profile which is dominated by a black absorption trough centered 250 km s^{-1} blueward of the emission peak (Röttgering et al.1995). The main absorption covers the entire Lyα emission region. Since the Lyα emission region has a projected linear size of at least 13 kpc, the spatial scale of the absorber should be at least 13 kpc. Also the C IV line shows absorption, the column density for the absorber being $10^{14.4}$ cm^{-2} (Röttgering and Miley 1996). Combined with the measured column density for the HI absorber (10^{19} cm^{-2}), this indicates that the spatially extended absorber is metal enriched.

We have analysed deep high resolution spectra for a sample of 18 distant radio galaxies (van Ojik 1995; van Ojik et al. 1997) and HI absorption features appear widespread in Lyα profiles. Eleven radio galaxies out of the sample of 18 have strong ($> 10^{18}$ cm^{-2}) HI absorption. Since, in most cases, the Lyα emission is absorbed over the entire spatial extent (up to 50 kpc), the absorbers must have a covering fraction close to unity. Given the column densities and spatial scales of the absorbing clouds, the typical HI mass of these clouds is $\sim 10^8$ $M_\odot$.

4 Statistics and relations

For the sample of 18 HzRGs with deep high resolution spectra, we found abundant evidence that the properties of the emission line gas, the radio source and the optical light are closely related:

i. The HzRGs larger than about 50 kpc do not show strong absorption; almost all the smaller ones do.
ii. Higher velocity dispersions in the Lyα gas are found in the smaller radio sources.
iii. Larger radio sources tend to have larger regions of Lyα emission
iv. The amount of the distortion in the Lyα gas strongly correlates with the amount of distortion in the radio sources.
v. It seems that – at least in some sources – there are 2 components in the Lyα halo; an inner halo located within the boundaries of the radio source, that has a high velocity dispersion ($700 - 1600$ km s^{-1}) and an outer halo located outside the radio source that has a low velocity dispersion (~ 300 km s^{-1}).

Further important evidence that the radio jets have an important impact on its surroundings includes:

vi. In a careful study of the correlated radio and optical asymmetries in 3CR radio galaxies, McCarthy et al. (1991) find that the extended emission line region is almost always brightest on the side of the radio lobe that is closer to the nucleus. This provided the first direct evidence that environmental effects are at least partly responsible for the structural asymmetries in powerful radio sources.
vii. The optical morphologies as observed by HST of a complete sample of 3CR radio galaxies with redshifts $1 \lesssim z \lesssim 1.3$ are highly dependent upon their radio properties (Best et al. 1996; see Plate 9). There is a clear evolution of the optical structures as the size of the radio source increases: small radio sources consist of many bright knots, tightly aligned along the radio axis, whilst more extended sources contain fewer (generally no more than two) bright components and display more diffuse emission.

5 Scenarios

Three different scenarios can be invoked to explain the observed correlations between the radio and gas properties. They are based on differences in (i) orientation of the system with respect to the line of sight, (ii) properties of the environment, with the smaller radio sources being situated in denser environments than the larger radio sources and (iii) evolutionary stage.

It seems difficult to understand these trends as reflecting differences in orientation. For example, in such a scenario it is not clear why smaller radio sources show such a pronounced absorption. It is possible to explain a number of the trends through a scenario in which the smallest radio sources are in the densest environments. In such a dense environment there is a lot of neutral gas around the small radio sources to absorb the Lyα emission. The radio source heavily interacts with the dense gas leading to disturbed radio morphologies and relatively small radio source sizes.

However, there is rather compelling evidence that the large differences in radio source size with $z \sim 1$ powerful radio sources are more naturally explained due to differences in ages of the radio sources rather than due to differences in the density (Best et al. 1996). We therefore like to advocate an evolutionary scenario in which the radio jet has a dramatic impact on its environment while advancing through the halo.

During its trip through the halo, the radio jet interacts violently with the emission line gas, and a number of the relations can be directly explained through this interaction. Since the most vigourous interaction is taking place near the end of the jet, the larger Lyα halos are found among the larger radio sources. The most vigourous interaction will take place when the radio source is at a relatively dense part of the halo, e.g. near the host galaxy. This explains why the smallest radio sources have the highest velocity dispersion. As the radio source grows it will inflate a spherically shaped cocoon, whose boundaries are traced by shocks with a modest Mach number (Begelman and Cioffi 1989). These shocks will overtake the region containing the HI gas responsible for the Lyα absorption. A large fraction of the HI gas then gets ionised and consequently, the larger radio sources do not show strong HI absorption.

The interaction of the jet with its gaseous surroundings could induce a massive starburst (e.g. Rees 1989), leading to the radio-optical alignments seen in the powerful radio galaxies. As the radio source grows and hence gets older the newly formed stellar populations dims dramatically and the strong alignment effects observed for the smaller sources will disappear (Best et al. 1996). In addition, the newly formed stars will disperse from the place where they were born. Since the time scale within which this takes place will be of order the age of the larger radio sources ($\sim 10^7$ yrs), this effect will also contribute to the disappearance of the alignment effect for the larger radio sources.

6 New observations of Lyα halos: probing an evolutionary sequence?

We are carrying out a programme of high resolution spectroscopy on the Lyα halos of a sample of radio galaxies that have HST images (Pentericci et al., this volume). Recently we obtained high resolution spectroscopy on two radio galaxies, 0406−244 ($z = 2.44$) and 2104−242 ($z = 2.49$) using the EMMI spectrograph mounted on the NTT. With a 2.5 arcsec slit, aligned the along the radio axis, and ESO grating # 3, a resolution of 2.8 Å was obtained.

The optical, radio and emission line properties of 0406−242 have been discussed by Rush et al. (1997) and McCarthy et al. (1996). In their narrow band images the Lyα halo has an extent of $3'' \times 5''$. On the HST scale the Lyα emission appears to have two dominant components surrounded by filamentary emission. Our two-dimensional NTT spectrum of the Lyα emission line (Figure 4), shows that these two dominant emission components are offset in velocity by 1100 km/s and spatially by 2 arcsec. Rush et al. (1997) suggest that the these two components can be associated with two galaxies colliding during the early collapse phase of a cluster. Although this is certainly a plausible interpretation, it is tempting to speculate whether part of the gap between the two components is due to HI absorption. Especially the red edge of the blue component seems relatively steep, indicative of HI absorption.

The Lyα halo of 2104−242 extends for more than 12 arcsec along the radio axis and has a high velocity dispersion (McCarthy et al. 1996; Koekemoer et al 1996). Our high resolution spectrum shows confirms the large size of the emission region and shows that the velocity distribution has multiple velocity peaks. The spectrum does not show any sign of HI absorption.

In this contribution we have argued that that many of the differences between the characteristics of the halo can be explained in a scenario in which the radio jet has a dramatic impact on the halo as it advances through the halo. It is interesting to consider how the data on the 4 sources that has been discussed in this contribution fit this scenario. These four sources are, in order of radio size: 0943−242 (29 kpc), 1243+036 (50 kpc), 0406−244 (78 kpc) and 2104−242 (177 kpc). The smallest radio galaxy, 0943−242 would then be the youngest

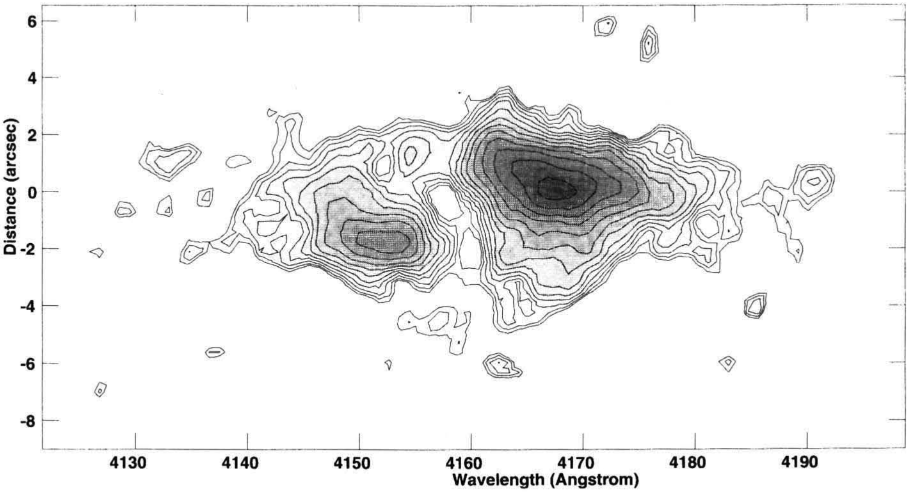

Figure 4. A two-dimensional representation of the 2.8 Å resolution NTT spectrum of Lyα of 0406-244 ($z = 2.44$) taken through a slit oriented along the main axis of the radio emission

radio galaxy. Its cocoon is still too small to have ionised the surrounding clouds of neutral gas and therefore emission from the small Lyα region is strongly absorbed. The two intermediate sized sources 1243+036 and 0406−244 would form transition objects between smaller and larger objects. 1243+036 does not show obvious HI absorption; in 0406−244 there might be still some HI left. The gas that is observed beyond the lobes of 1243+036 and which has a low velocity dispersion has not yet been overtaken by the radio source. As soon as this radio source has doubled its size, it will have done this and as a consequence the halo will be significantly larger. In the largest source, 2104−242, the lobes have broken out of the halo, leaving behind a large Lyα halo without any sign of neutral gas absorption.

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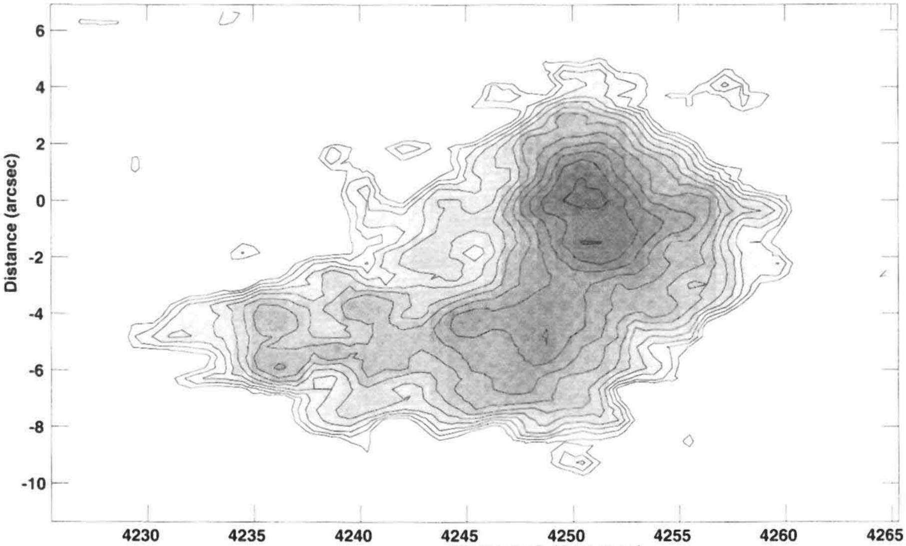

Figure 5. A two-dimensional representation of the 2.8 Å resolution NTT spectrum of Lyα of 2104−242 (z = 2.49) taken through a slit oriented along the main axis of the radio emission

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