Giant Lyα nebulae in the high redshift (z ≥2) Universe

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Abstract

High redshift radio galaxies (z ≥2) are believed to be progenitors of the giant ellipticals of today. They are often associated with giant Lyα nebulae (sometimes >100 kpc), which have been for more than two decades valuable sources of information about the evolutionary status of the host galaxy and its chemical enrichment and star formation histories.

I present in this paper a summary of the most relevant results about the giant nebulae obtained in the last ∼10 years and the implications on our understanding of the early phases of evolution of massive elliptical galaxies. An interesting earlier review can be found in McCarthy (1993).

Key words: cosmology: observations, early Universe, galaxies: active, galaxies: evolution

1. Introduction

Our current belief is that the hosts of powerful radio sources in the distant Universe are destined to become the giant ellipticals of today: the most massive galactic systems we know (McLure et al. 1999). High redshift radio galaxies (HzRG, z >2) are, therefore, unique tools to investigate the early phases of massive elliptical galaxies in the high redshift Universe.

HzRG are often surrounded by giant Lyα nebulae which sometimes extend for more than 100 kpc (e.g. Reuland et al. 2003, Villar-Martín et al. 2003, McCarthy et al. 1990) and sometimes beyond the radio structures (e.g. Maxfield et al. 2002, Pentericci et al. 2000, Eales et al. 1993). Their morphologies are clumpy, irregular (with features such as filaments, plumes, ionization cones, e.g. Reuland et al. 2003) and often aligned with the radio axis (McCarthy, Spinrad & van Breugel 1995). They are characterized by extreme kinematics, with measured FWHM ≥1000 km s⁻¹ (e.g. Villar-Martín et al. 2003, McCarthy, Baum & Spinrad 1996), compared with values of a few hundred km s⁻¹ in low-redshift radio galaxies (e.g. Baum, Heckman & van Breugel 1990, Tadhunter, Fosbury & Quinn 1989).

They have typical values of ionized gas mass ~10⁹–¹⁰ M⊙, Lyα luminosities ~several×10⁴³–⁴⁴ erg s⁻¹ and densities n_e ~ few to several hundred cm⁻³ (e.g. McCarthy 1993, Villar-Martín et al. 2003).

They emit a rich emission line spectrum (Fig.1) which reveals high levels of metal enrichment and excitation mechanisms mostly related to the nuclear activity (rather than stars), at least in the direction along the radio structures (e.g. Vernet et al. 2001).

Such nebulae have been for more than two decades valuable sources of information about the evolutionary status of the host galaxy, its chemical enrichment history and the early phases of evolution of massive ellipticals.

In this review I present a summary of the most relevant results obtained in the last ~10 years about the giant nebulae associated with HzRG. An interesting earlier review can be found in McCarthy (1993).
2. Jet gas interactions

The Lyα nebula that surround HzRG are in general aligned with the radio source axis (McCarthy, Spinrad & van Breugel 1995). Their morphological and kinematic properties (see §1) are known to be strongly distorted by interactions between the radio structures and the ambient gas (e.g. Bicknell et al. 2000, van Ojik et al. 1997).

Detailed studies of low redshift powerful radio galaxies (z < 0.5) have been very useful to understand the impact of such interactions on the gaseous environment (Tadhunter 2002, Villar-Martín, et al. 1999, Clark et al. 1998, van Breugel et al. 1985). At low redshift we have the advantage of a much more detailed spatial information and the possibility to use optical rest frame emission lines (the [OII]λ3727 doublet, [OIII]λ4959,5007, Hα, etc) which are less affected by reddening and, unlike some strong UV rest frame lines such as Lyα and CIVλ1548,1551, are not sensitive to resonance scattering effects.

These studies have shown how jet-gas interactions perturb the kinematics, distort the morphology of the nebula and change (decrease) the ionization level of the gas. We have identified these effects in a sample of 10 radio galaxies at z ∼ 2–3. A good example is MRC 0943-242 at z = 2.9 (see Fig. 2; Humphrey et al. 2006a, Villar-Martín et al. 2003). This radio galaxy is associated with a giant nebula which extends for ∼ 70 kpc. The gas within the radio structures has higher surface brightness, very perturbed kinematics (FWHM > 1000 km s⁻¹) and lower ionization level. The low surface brightness emission extending beyond the radio structures shows quieter kinematics (FWHM ∼ 400–600 km s⁻¹) and higher ionization level. These marked differences are a consequence of jet-gas interactions.

Although evidence for jet-gas interactions has been found in many HzRG, the impact relative to other phenomena (such as pure illumination by the active nucleus (AGN) varies strongly from object to object. We have recently shown (Humphrey et al. 2006a) that the variation between objects on the ionization, kinematic and morphological properties of the giant nebulae associated with HzRG can be explained by the different impact of such interactions. In general, small radio sources present more evidence for jet-gas interactions than large radio sources (see also Best et al. 2000). Small radio sources are more likely to interact with the richer gaseous environment which is likely to exist near the central AGN.

Humphrey et al. (2006a) have found evidence that the perturbed gas is part of a jet-induced outflow whose effects can extend for tens of kpc from the nuclear region. This can have profound implications, since such mechanism may be more efficient than starburst driven superwinds for massive galaxies to lose gas, eject metals and suppress star formation (Nesvabda et al. 2006; see also Rawlings 2003). It could be an effective mechanism for regulating galaxy growth and polluting the intergalactic medium with metals. This issue deserves and will surely be subject of further investigation.

3. Metal enrichment

The emission line spectrum of ionized nebulae contains valuable information about the chemical abundances of the gas and, ultimately, the history of formation of the stars responsible for producing the metals. Numerous studies of low z objects have proven the power of such technique, based on optical rest frame emission lines such as [OIII]λ4959,5007, Hα, [NII]λ6548,6583, [SII]λ6716,6731, etc.

For HzRG, this issue is complicated for two main reasons: until recently, the chemical abundances of the gas were investigated using the UV rest-frame lines, redshifted into the optical window. The behaviour of some of these lines (e.g. Lyα, NVλ1238,1242, CIVλ1548,1551) is very complex due to resonance scattering effects and the much higher sensitivity to dust.

On the other hand, there is an important complication derived from the uncertainty on what the dominant ionizing mechanism of the gas is: is it jet-driven shocks or photoionization by the active nucleus? (see Tadhunter 2002 for a review). The degeneracy between shock and AGN photoionization model predictions is the main reason why this issue has not been disentangled after many years of discussion.

There are a few clear cut cases, such as the radio galaxy MRC 0943-242 at z = 2.9, discussed in §2 (Villar-Martín et al. 2003). The uncertainty of what ionizes the gas dissapears in this case: the quiescent gas (i.e. not perturbed by jet-gas interactions) which extends beyond the radio structures (Fig. 2) must be clearly photoionized. The strength of the NV emission relative to the other lines such as CIV and HeII (Fig. 3) implies at least half solar abundances (Humphrey 2005, Humphrey et al. 2007, in prep.).
UV-optical spectra have a coverage of \( \sim \) powerful HzRG are close to their solar values and the metallicity is unprecedented for radio galaxies at any redshift. We reject, on the other hand, the interpretation of a metallicity gradient between objects.

At low \( z \), this type of studies (e.g. Robinson et al. 1987) have shown that the EELRs of powerful radio galaxies are characterized by abundances of at least 1/10 solar, and they are probably within a factor of 2 of solar. We have plotted (Fig. 4) our high \( z \) radio galaxy sample in three diagnostic diagrams together with the low \( z \) sample of Robinson et al. (1987). The diagrams show that there is no significant difference between the two samples, suggesting that they are also similar in metal abundances and physical conditions of the ionized nebulae.

The high chemical abundances in the giant nebulae associated with HzRG suggest that such objects have already undergone intense star formation activity. It is consistent with chemical evolution models for giant ellipticals and supports the idea that distant powerful radio galaxies are progenitors of the most massive galaxies we know (Vernet et al. 2001).

4. Star formation in HzRG and the giant Ly\( \alpha \) nebulae

Investigating the existence of young stars in HzRG (rather than in companion objects, e.g. Pentericci et al. 2000, Venemans et al. 2005) using optical data has proven to be a difficult task. Because of the powerful active nucleus, the optical (UV rest frame) continuum is likely to be contaminated, sometimes dominated, by components related to the nuclear activity, i.e., nebular continuum and/or scattered light. Polarization and emission line measurements are essential to determine whether a young stellar population also contributes (e.g. Vernet et al. 2001, Cimatti et al. 1998, Dey et al. 1997). Submm studies have been more efficient on the search for young stars in HzRG (e.g. Stevens et al. 2003, Archibald et al. 2001). Provided that the dust responsible for the submm emission is heated by young stars (e.g. Tadhunter et al. 2005) enormous star formation rates of thousands M\(_{\odot}\) yr\(^{-1}\) are implied.

In spite of the difficulties inherent to optical studies, the existence of young stars in HzRG has been inferred indirectly from polarization studies (e.g. Vernet et al. 2001, Cimatti et al. 1998, Dey et al. 1997). Although scattered light contaminates the UV rest frame continuum in numerous radio galaxies, the level of polarization changes noticeably between objects. This is more naturally explained if a young stellar population dilutes the polarization.

So, the presence of young stars in a fraction of HzRG is relatively well established. What has not been clear so far is whether they contribute to the excitation of the giant Ly\( \alpha \) nebulae. Using their emission line spectra to investigate this issue (as in non active star forming galaxies) might seem impossible, since the excitation of the gas is predominantly a consequence of AGN related processes. However, recent results suggest that young stars do contribute to the excitation of the Ly\( \alpha \) nebula in some HzRG.
Fig. 4. Comparison between our sample of HzRG (light blue symbols) and the low z radio galaxy sample (black symbols) of Robinson et al. (1987). Both samples overlap in the diagrams. This suggests that the ionized gas in both samples is characterized by similar abundances (within a factor of two solar) and physical properties. The colour lines are predictions of different models. We will highlight here the dark purple sequence, which best reproduces the data. Notice that the data set seems to follow this one parameter sequence characterized by a standard power law ionizing continuum with index $\alpha = -1.5$, solar abundances and such that the ionization parameter $U$ varies along the sequence. Taken from Humphrey (2005).

We have recently found (Villar-Martín et al. 2006a) that $\sim 54\%$ of HzRG at $z \geq 3$ and $\sim 8\%$ of radio galaxies at $2 \leq z < 3$ emit Ly$\alpha$ unusually strong compared with the general population of HzRG. The Ly$\alpha$/HeII and Ly$\alpha$/CIV ratios and the Ly$\alpha$ luminosities in these objects (that we have called Ly$\alpha$ excess objects or LAEs) are $\sim 2-3.5$ times higher than in the vast majority of HzRG (see also De Breuck et al. 2000). Star formation is the most successful explanation to supply the extra continuum photons needed to explain the Ly$\alpha$ excess. Star forming rates of $\sim$several hundred $M_\odot$ yr$^{-1}$ are implied by our models (ignoring Ly$\alpha$ absorption and dust reddening). This interpretation is strongly supported by the clear trend for objects with lower optical continuum polarization level to show larger Ly$\alpha$/HeII ratios (see Fig. 5). It is possible that LAEs have recently undergone a merger event which triggered the formation of young stars and the AGN and radio activities.

Our interpretation is further supported by the tentative trend found by other authors for $z \geq 3$ radio galaxies to show lower UV-rest frame polarization levels (De Breuck et al. 2007, in prep.) or the dramatic increase on the detection rate at submm wavelengths of $z > 2.5$ radio galaxies (Archibald et al. 2001).

We argue that, although the fraction of LAEs may be incompletely determined, both at $2 \leq z < 3$ and at $z \geq 3$, the much larger fraction of LAEs found at $z \geq 3$ is a genuine redshift evolution and not due to selection effects (Villar-Martín et al. 2006a). Therefore, our study suggests that the radio galaxy phenomenon was more often associated with a massive starburst at $z > 3$ than at $z < 3$. In other words, powerful radio galaxies (and, according to the unification model, powerful radio quasars), appear in more actively star forming galaxies at $z > 3$ than at $z < 3$.

Fig. 5. log(Ly$\alpha$/HeII) vs. percentage of polarization of the optical continuum (UV rest frame) for all radio galaxies at $z \geq 2$ for which both have been measured. Black solid symbols correspond to LAEs, while hollow symbols are objects with no Ly$\alpha$ excess. Errorbars are shown when available. Notice the clear trend for objects with the highest Ly$\alpha$/HeII ratios to show lower polarization, as expected if the Ly$\alpha$ enhancement is due to stellar photoionization. The trend is broken by 1243+036, which shows too high $P(\%)$ for its large Ly$\alpha$/HeII ratio (but see Villar-Martín et al. 2006a).

5. The origin

Different scenarios have been proposed to explain the origin of the giant nebulae associated with HzRG. It has been suggested that they could be cooling flow nebulae or gas ejected by jet-, AGN- or starburst-driven superwinds or giant rotating structures (e.g. Villar-Martín et al. 2003, 2006b; van Ojik et al. 1996).

The kinematic pattern of the nebulae could provide im-
important information on this regard. However, the nuclear activity complicates our work again. As explained in §2, the jet-induced shocks distort the gas kinematics, which does not reflect the intrinsic original pattern.

Around the year 2000, most spectroscopic studies of HzRG had been based on long slit data with the slit aligned along the radio structures, where the impact of jet-gas interactions is likely to be strongest. Van Ojik et al. published an interesting paper in 1996 on the radio galaxy MRC 1243+036 (z = 3.6). In addition to the typical kinematically perturbed gas (≥1000 km s⁻¹) often found in HzRG, the authors detected a low surface brightness giant nebula (∼140 kpc) which extends well beyond the radio structures and with very quiescent kinematics (FWHM and velocity shift ∼few hundred km s⁻¹). It is clear that this gas is not affected by the interactions with the radio structures.

In spite of the profound impact that the jet-induced shocks have on the nebular properties, we expect naturally, that there are large regions of the giant nebulae which do not notice the passage of the radio structures. The results of van Ojik et al. (1996) suggested to us that it should be possible to detect the non-perturbed gas. If we could isolate the emission from this ionized gas in other objects, we would be in an excellent position to study the ionization, morphological and kinematic properties of the nebulae, previous to any jet-induced distortion. Ultimately, this information could be critical to understand the origin of the nebulae and its possible link with the formation process of the galaxy.

So, we looked for the quiescent nebulae in a sample of 10 HzRG (∼2-3), based on long slit spectroscopic data obtained with the LRISp spectrograph on Keck II (see Verne et al. 2001 for a description of the observations and the data). We found that, in addition to the highly perturbed gas, all objects are embedded in giant (often ≥100 kpc), low surface brightness nebulae of metal rich, ionized gas with quiescent kinematics, with FWHM and velocity shifts of ∼several hundred km s⁻¹ (Villar-Martín et al. 2002, 2003).

With the goal of investigating the kinematic, ionization and morphological properties of the nebulae in two spatial dimensions, we started an observational program of 3D integral field spectroscopy with the fiber-fed integral field spectrographs Vimos on VLT and PMAS/PPAK on the 3.5m telescope in Calar Alto.

I show in Fig. 6 some results on one of the 6 radio galaxies we have observed. It is the velocity and dispersion fields of the quiescent giant Lyα nebula (∼120 kpc) associated with the radio galaxy MRC 2104-242 (z = 2.49) based on VIMOS data (Villar-Martín et al. 2006b). Such an ordered and symmetric kinematic pattern is quite striking for a HzRG. Our first thought was that we were looking at a giant rotating structure, whose motions imply a dynamical mass of ≥3×10¹¹ M⊙. However, we found that, due to the lack of knowledge on the intrinsic gas distribution (the nebula is anisotropically illuminated by the central active nucleus), we could not discriminate between rotation and radial motions. In the latter case, at least we could reject outflows, based on the radio properties of the source.

Based on the thesis work of Andy Humphrey (2005), we have advanced substantially on our understanding of the intrinsic kinematic pattern of the giant quiescent nebulae (Humphrey et al. 2006b). Making use of the LRISp long-slit spectra of the Keck sample discussed above, and the valuable information provided by the radio maps (Carilli et al. 1997), we have identified several correlated asymmetries: on the side of the brightest radio jet and hot spot (i) the quiescent nebulae have the highest redshift, (ii) Lyα is brighter relative to the other lines and continuum, (iii) the radio spectrum is flattest and (iv) the radio structure has its highest polarization. Interestingly, the correlation (i) also appears to be present in powerful radio galaxies with 0 < z ≤ 1.

Collectively, these asymmetries are most naturally explained as an effect of orientation, with the quiescent nebulae in infall (Fig. 6). This is the first study to distinguish between the rotation, infall, outflow and chaotic motion scenarios for the kinematically quiescent emission line nebulae around powerful AGN.

The infalling gas of HzRG is highly enriched with metals (see §3) and these objects are likely to have undergone already an intense period of star formation activity (e.g. Villar-Martín et al. 2006b). Therefore, it is not certain that the infall process is related to the early phases of formation of the central galaxy. Since we find that infall seems to be taking place in powerful radio galaxies at low z as well, where the elliptical galaxy is already highly evolved, it is clear that infall does not necessarily imply an early phase in the formation process.
6. Summary and conclusions

High $z$ radio galaxies ($z > 2$) are associated with ionized nebulae which often extend for more than 100 kpc. The kinematic, ionization and morphological properties of the nebulae are strongly influenced by the nuclear activity.

The giant nebulae consist of two main gaseous components: perturbed and quiescent gas. The first component is usually spatially located within the radio structures while the quiescent gas often extends beyond. The perturbed gas has lower ionization level and extreme kinematics (FWHM of the lines $>1000 \text{ km}^{-1}$ vs. several hundred $\text{ km}^{-1}$ for the quiescent gas). Such marked differences between both gaseous components are naturally explained by the impact of jet-gas interactions.

While the perturbed gas is part of a jet-induced outflow, the quiescent component, which has not been affected by the passage of the radio structures, is infalling towards the center. The giant nebulae are characterized by high metal abundances (at least half solar). Although AGN related processes dominate the ionization mechanism of the gas, evidence for stellar photoionization has been found in some radio galaxies (most of them at $z > 3$).

At $z < 3$, powerful radio galaxies have already undergone an intense period of star formation activity and chemical enrichment, which explains the high metal abundances. Different studies suggest that powerful radio galaxies at $z > 3$ were more often associated with a massive starburst.

A plausible scenario to describe HzRG is this: these massive galaxies formed the bulk of their stars at $z > 3$ (e.g. Seymour et al. 2006, Villar-Martín et al. 2006b), embedded in the giant infalling nebulae.

Since then, the nebulae have undergone a rapid chemical
evolution process. At some point, the nuclear activity starts and the central quasar acts like a flash bulb that illuminates the gaseous environment rendering the nebulae visible at tens of kpc from the nuclear region.

When the radio activity is triggered and the radio structures advance through the nebula, the shocked gas reverses its kinematic pattern and a powerful outflow is generated. In some cases, its kinematic pattern and a powerful outflow is generated. The rest of the nebula keeps falling towards the center.

Since infall is found in radio galaxies at all, the available gas mass could be consumed in less that $10^8$ yr, an interesting possibility is that the radio activity is fed by the infalling gas so that it is only detected when the infall is happening and feeding efficiently the active nucleus.

A similar variety of Lyα morphologies, sizes, line luminosities and FWHM values characteristic of high z radio galaxies has been observed in high redshift radio quiet Lyα nebulae (e.g. Lyα blobs, Steidel et al. 2000, van Breugel et al. 2006). Although in these objects the radio structures are not present, what has been learned for more than 20 years about giant nebulae associated with high z radio galaxies, can be very valuable to understand the nature and origin of the recently discovered radio quiet Lyα nebulae.

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