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Recurrent radio emission and gas supply: the radio galaxy B2 0258+35

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ABSTRACT

Outlined is the discovery of a very faint, diffuse, low surface-brightness (0.5 mJy beam^{-1}, 1.4 mJy arcmin^{-2} on average) structure around the radio source B2 0258+35 hosted by an HI-rich early-type galaxy (NGC 1167). Because B2 0258+35 is a young compact steep spectrum (CSS) source, the newly discovered structure could represent a remnant from an earlier stage of activity of an active galactic nucleus (AGN). We explain in detail all possibilities for triggering the radio activity in B2 0258+35 regarding gas accretion in a recurrent AGN activity framework. NGC 1167 hosts a very regular, extended and massive H I disk that has been studied in great detail. It has regular kinematics on large scales, which, together with stellar population studies of NGC 1167, exclude the possibility of a recent merger as the trigger for the current AGN activity that is responsible for the CSS source. Previous studies of the H I closer to the core seem to preclude the assumption of a circum-nuclear disk of H I as the source of the accreting gas. We consider the cooling of gas from the hot X-ray halo as a possible alternative option for the fueling of the AGN, as suggested for other sources of similar radio power as B2 0258+35. This would provide a more likely explanation for the recurrent activity. Furthermore, if the previously made suggestion in the literature that the inner CSS may not be able to grow to large scales is correct, this implies that different cycles of activity may have different characteristics (e.g. radio power of the emission). Estimates are given for the age of the faint diffuse emission as well as for the current accretion rate, which agree well with literature values. If our assumptions about the accretion mechanism are correct, similar large-scale, relic-like structures should be more commonly found around early-type galaxies, which will hopefully be confirmed by the next generation of sensitive, low-frequency radio surveys.

Key words. galaxies: active – radio continuum: galaxies – galaxies: individual: B2 0258+35

1. Introduction

Active galactic nuclei (AGN) have been recognized in recent years to have a profound influence on their surrounding interstellar medium (ISM) and, in consequence, also on the evolution of the host galaxy (see Kauffmann & Haehnelt 2000; Di Matteo et al. 2005; Bower et al. 2006). Radio-loud AGN can exert this influence not only through their collimated radio jets but also through the cocoon of shocked medium around them (Wagner & Bicknell 2011; Wagner 2012). Therefore, they can influence a large volume in (and outside) the host galaxy. Although this type of AGN is relatively rare and shortlived, the radio phase can be recurrent during the life of the galaxy (see Saikia & Jamrozy 2009; Randall et al. 2011; Best et al. 2005, for some examples). This may substantially increase the impact that radio-loud AGN have on the ISM and their role in galaxy evolution. However, the life-cycle of a radio source still poses many open questions (e.g. if radio activity is occurring in every galaxy and what are the details of the "duty cycle" of the recurrent activity), which limit our understanding of the impact of this type of nuclear activity.

What do we know about the life-cycle of a radio source? The first phase of a radio source has been identified with compact sources with a steep or peaked spectrum (so called compact steep spectrum (CSS) and gigahertz peaked spectrum (GPS) sources), see Fanti et al. (1990), O'Dea (1998) and Fanti (2009) for a recent overview. These sources already have the morphology of grown-up sources but their size is comparable to galactic scales, i.e. the inner few kpc of the host galaxy. Most of them are expected to grow to large radio galaxies (Fanti 2009) although some may actually never reach this phase, either because the fueling of the AGN "engine" stops or because of a hostile ISM (Kunert-Bajraszewska et al. 2006). See also de Vries et al. (2009a) and de Vries (2009b), Chap. 6.

The typical lifetime of a radio source ranges between 10^7 and 10^8 yr (Parma et al. 1999, 2007) and after that the nucleus switches off. This may result in the formation of a relic source that will slowly fade away. The relic structures (with no nuclear activity present) are very rare, with only a handful known (Cordey 1987; Parma et al. 2007). The situation seems to be more common where the radio source is intermittently active; in that case one may find fossil radio plasma left over from an earlier phase of activity, while newly restarted core and radio jets are visible as well. Evidence for a re-start in the activity of radio sources after a period of shut-down of the central engine, or of rejuvenated sources has been found in several cases (Schoenmakers et al. 1999; Murgia et al. 2011; Stanghellini et al. 2005; Saikia & Jamrozy 2009) although proper statistics of the occurrence and characteristics are not available.

The off-phase in most cases appears to be shorter than or at most comparable with the active phase (Parma et al. 2007).

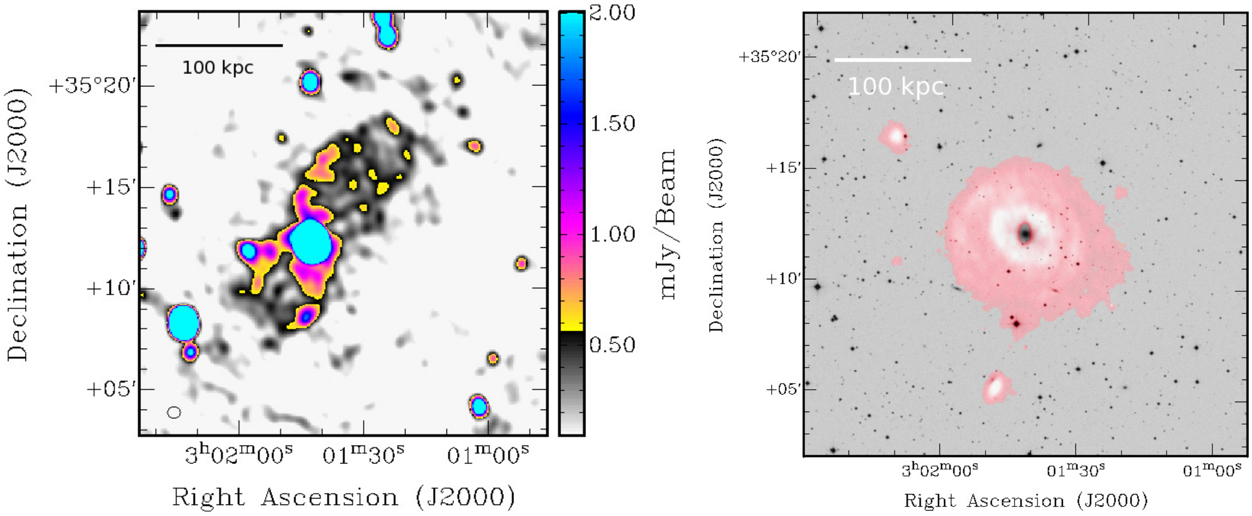

Fig. 1. *Left*: continuum image of the diffuse emission around B2 0258+35. The synthesized beam is indicated with the ellipse at bottom left. The intensity ranges from 100 μJy (1σ) to 2 mJy (20σ). *Right*: 21-cm H I total intensity image taken from Struve (2010) superposed onto a DSS2 optical image. Scale as indicated.

However, statistical studies using luminosity functions (Shabala et al. 2008; Best et al. 2005) have shown that the life-cycle of radio-loud AGN depends on the radio power, with powerful (i.e. Fanaroff-Riley type 2 or FRII, Fanaroff & Riley 1974) radio sources becoming active only every one-to-few Gyr, while low-power radio sources (Fanaroff-Riley type 1, FRI) would need to spend more than a quarter of their life in an active phase (Best et al. 2005). This would suggest that signs of past radio-loud activity could be more common in the latter sources. Unfortunately, no systematic search for such signatures has been possible so far and studies of single objects are relatively sparse and limited (Stanghellini et al. 2005; Tremblay et al. 2010). Whether radio emission from a previous phase of activity is still observable also depends on the external conditions, with the hot X-ray environment particularly suitable for keeping the relic confined and limiting the adiabatic losses (Murgia et al. 2011).

For understanding the origin of the recurrent nuclear activity, it is also important to have comprehensive information about the assembly and evolution of the host galaxy. The commonly considered way to (re-)trigger an AGN is to provide a fresh supply of gas. The presence of gas is often observed in early-type galaxies, typical hosts of radio-loud AGN. Although the presence of this gas does not appear to have a clear connection with the presence of an active nucleus (see Oosterloo et al. 2010), it is interesting to note that the occurence of H I in restarted sources seems to be higher than in other radio sources (Chandola et al. 2010; Saikia & Jamrozy 2009). This could suggest a possible link between the presence or injection of gas and the activity.

Thus, identifying cases of recurrent radio activity and understanding their time scale (as well as the gas content and kinematics close to the AGN) is challenging, but extremely important to fully probe the impact of radio-loud AGN on the host galaxy and their importance for feedback effects. The study of objects for which information at different wavebands is available allows a better understanding of the origin of the activity and to connect the history of the host galaxy with the history of the nuclear activity. This combination has triggered our interest in the object that is the subject of this paper.

We present the discovery of diffuse, low-brightness extended radio emission around the young CSS radio source B2 0258+35. A first hint of this structure was detected in a preliminary continuum image obtained by Struve (2010). This has inspired a more detailed look at the data that we present now in this paper.

B2 0258+35 is hosted by the field early-type galaxy NGC 1167 (z = 0.0165[1]). The central radio source has been studied by Giroletti et al. (2005) and was classified as a CSS source (see Fig. 2, inset). These authors derived an age for this structure of 9×10^5 yr. The CSS source has a radio luminosity of $L_{408\ \mathrm{MHz}} = 10^{24.37}$ W Hz^{-1}. The radio structure of the CSS source has no hot spots (although the structure appears to be the result of a strong interaction with the ISM), so if this is indeed a young radio galaxy, it might evolve into an FR I. This is consistent with the measured radio power. However, Giroletti et al. (2005) have argued that this source might represent an example of a CSS source that will not grow to become a kilo-parsec-scale radio galaxy.

What makes B2 0258+35 notable is the *large, massive disk of H I* that has been studied in detail and can provide additional insight into the formation history of the host galaxy. The disk (with $M_{\mathrm{H\,I}} = 1.5 \times 10^{10}\ M_\odot$ and diameter of 160 kpc, see Fig. 1 right, Noordermeer et al. 2005; Struve et al. 2010) shows *extremely regular kinematics* within the inner $r < 65$ kpc and signs of interaction with several satellite galaxies in the outer regions where the gas appears to be slightly disturbed. The detailed work of Struve et al. (2010) shows that the disk has grown by accretion of cold gas from satellite galaxies. Furthermore, its regularity implies that the host galaxy has not suffered a major merger in the center in at least the past 1 Gyr. H I has been detected also in absorption – with much higher resolution observations – against the central CSS source. The kinematics of this gas have been studied in Struve (2010), Chap. 7, and appear to be quite regular, consistent with the velocities of the large-scale disc. However, a blueshifted, possibly outflowing component has being detected both in H I and in CO. Thus, thanks to the H I, we have a clear view of the recent assembly history of the host galaxy. In this paper we explore how this relates (or not) to the radio-loud phase(s) of activity.

[1] The adopted cosmology in this work is: H_0 = 73 km s^{-1} Mpc^{-1}, Ω_{matter} = 0.27, Ω_{vacuum} = 0.73. At the redshift of B2 0258+35, 1″ = 0.34 kpc.

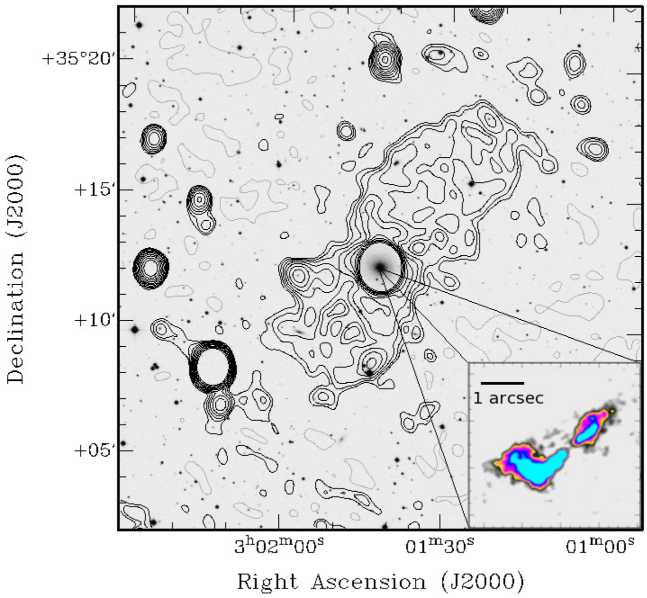

Fig. 2. Contours of the diffuse radio emission around B2 0258+35 overlaid on a DSS2 image. The contour levels range from 0.2 mJy beam^{-1} to 20 mJy beam^{-1} (2σ to 20σ) increasing by a factor of 1.5 and are marked in black. Negative countours at −0.2 mJy beam^{-1} are gray. The inset at bottom right shows the VLA image of the central CSS source (Giroletti et al. 2005). Note the similarity in the orientation between the CSS source and the diffuse emission.

The paper is structured in the following way. In Sect. 2 we describe the observations and the data reduction procedure. Section 3 presents the results and discusses the origin of the newly found extended radio structure as a possible signature of recurrent activity in this galaxy. In Sect. 4 we combine this with information about the gas supply by using results from (recent) H I studies. Section 5 presents some additional implications and discusses future work prospects.

2. Observations and data reduction

B2 0258+35 was observed with the Westerbork Synthesis Radio Telescope (WSRT) for 12 × 12 h. The data were originally taken for line (H I) observations (analysis and discussion of the results are presented in Struve et al. 2010, see that paper for more details). Because of this, the observations were centered around the frequency of 1.39 GHz (H I in the rest frame of the source) and used a bandwidth of 20 MHz. The data reduction was performed using the Miriad package (Sault et al. 1995) as described in Struve et al. (2010). 3C 48 and 3C 147 were used as flux and band-pass calibrators, respectively.

We have extracted from these data the continuum with the line-free channels in the band. The continuum subtraction was performed on the visibilities using the task *uvlin* with a second-order polynomial. Data from eleven of these observing runs were used to produce continuum maps. One dataset was not included in the final map because of low quality of the data owing to technical problems in that observation.

Each observation was separately imaged and several self-calibration runs were performed (solving, at the beginning, for phase only and for amplitude and phase at the end of the procedure) before obtaining the final image. The images were obtained using uniform weighting, but were subsequently convolved with a Gaussian of 30″ *FWHM* to enhance the extended emission. These images were then combined to produce a final image where an extended low surface brightness emission appears very clearly (see Fig. 1, left panel). The r.m.s. noise of the final image is 100 μJy beam^{-1}, with a beam size of 39″ × 33″ at a position angle of 2°.

3. Low surface-brightness, extended structure: a radio relic?

The final radio continuum image is shown in Fig. 1 in the left panel. In addition to the central (unresolved at our spatial resolution) CSS source, we detect an extended, low surface brightness structure. The average surface brightness is 0.5 mJy beam^{-1} (measured in a region encompassing the northern lobe). This translates into about 1.4 mJy arcmin^{-2} which is on the faint end compared to the source sample published by Saripalli et al. (2012). Accordingly, even after the spatial smoothing, the structure remains very faint, only a few sigma above the noise. The high contrast in the flux levels between the central CSS source and the extended structure additionally complicates imaging this structure (Fig. 2). The extended radio emission has a total projected linear size of 240 kpc and a distinctive double-lobed appearance, with relatively bright edges in some locations. The central CSS source has a total flux of 1.8 Jy ($L_{1.4\ \mathrm{GHz}}$ = 2.1 × 10^{23} W Hz^{-1}), while the peak of the extended structure is ~2.4 mJy. It has a total flux of 119 mJy (integrated over a region determined by visual inspection of the image encompassing the entire diffuse emission region). This gives a radio luminosity of $L_{1.4\ \mathrm{GHz}}$ = 5.5 × 10^{22} W Hz^{-1} for the diffuse emission.

Because of the extremely low surface brightness and the lack of collimated and/or compact features (such as jets and hot spots), the newly found, extended radio structure can be explained as lobes left over from a previous cycle of nuclear activity. The spatial resolution of our image does not allow us to verify whether a connection exists between the inner CSS source and the extended, low surface brightness lobes. Neither can we derive any value for the spectral index: if some injection of "fresh" electrons is still ongoing, we would not expect these extended structures to have an extremely steep spectral index. Therefore, the question of whether the extended, low surface brightness structure in B2 0258+35 is a relic structure or if the lobes still receive some feeble injection of fresh electrons cannot be answered with the present observations. This will be possible with planned follow-up low-frequency observations.

However, we note that the extended structure shows relatively bright edges, in particular in the northern lobe. This could be the result of the interaction of the radio plasma with the ISM/IGM and may suggest in-situ acceleration of the electrons. Alternatively, the structure is not a relic but radio plasma is still flowing through from the active nucleus, albeit likely at a low rate. The morphology of the extended structure bears some similarities with radio-bubble structures found in low-luminosity radio sources (see Hota & Saikia 2006, for a compilation) and in some radio galaxies, such as Centaurus A (Morganti et al. 1999) and M 87 (Churazov et al. 2001). In both cases, spectral index studies (Hardcastle et al. 2009, for Centaurus A and the recent study at low frequencies using LOFAR for M 87, de Gasperin et al., in prep.) have found no steepening in the spectral index of the diffuse lobes. This suggests that, indeed, some injection of fresh electrons is still ongoing.

In the absence of spectral index data, we attempted to obtain an estimate of the age of the extended radio emission in B2 0258+35 by treating it as buoyant bubbles rising through the IGM away from the host galaxy. The forces considered to act on the bubble are the buoyancy and IGM ram pressure forces. Under these assumptions, we can use an expression for the velocity with which the bubble rises (Ogrean et al. 2011; Churazov et al. 2001):

$$v \sim \sqrt{\frac{r}{R}\frac{8}{3C}} \cdot v_{\rm k},$$

where r is the radius of the bubble, R the distance of the bubble center from the host galaxy, $v_{\rm k} = \sqrt{gR}$ is the Keplerian velocity at the distance of the bubble, g the gravitational acceleration, and C is the drag coefficient. We restricted our attention to the northern lobe and approximated its radius (assuming spherical geometry) by half of its width (as observed in Fig. 1) for our purposes. This is motivated by the fact that the width would reflect its real size most closely; the height is influenced by the expanding motion, which would yield a poorer size estimate. Consequently, we have $r = 50$ kpc, $R = 50$ kpc and $C = 0.75$. The value for the drag coefficient was adopted following Churazov et al. (2001), who derived it based on hydrodynamical simulations of buoyant bubbles traveling through a stratified and compressible medium. In contrast, Ogrean et al. (2011) adopted a value of 0.5, which is a value for a solid sphere moving through an incompressible fluid. We assumed the value for the Keplerian velocity from Struve et al. (2010), who measured the rotational velocity of the H I disk at a distance of $R = 50$ kpc from the host galaxy to be $v_{\rm k} = 325$ km s^{-1}. Using these values for the variables, we obtain for the bubble rising speed a value of ~613 km s^{-1}. Treating this bubble as originating from the last burst of AGN emission before shutdown, and assuming a uniform motion, we derive the time elapsed since the activity ceased to be as $\sim 8 \times 10^7$ yr. This is a lower limit because of projection effects, and it broadly agrees with estimates from previously cited publications in this paper for relics around CSS sources.

It is interesting to note that the estimated age of the CSS source is very young (the ratio of the timescales is about 0.01) when compared to the estimated time elapsed since cessation of the AGN activity in the previous cycle. Therefore, if we assume that the CSS source marks the beginning of the current newest phase of AGN activity, the time between subsequent phases of activity is about 10^8 yrs, in agreement with current estimates (Parma et al. 2007). All of this holds, of course, if we assume that the observed extended structure is indeed a radio relic.

4. Recurrent activity and supply of gas

As was mentioned in the introduction, radio structures that represent signatures of past activity in the host galaxy have been found in several objects. The question for all these objects – including B2 0258+35 – is what causes the activity to stop and restart. Gas and dust are considered the source of fuel for the triggering (or re-triggering) of AGN. Although radio-loud AGN are typically hosted by early-type galaxies, it has been shown that gas is observed in many of them at least on the kpc scale (Oosterloo et al. 2010; Serra et al. 2012; Alatalo et al. 2011; Young et al. 2011). Therefore, the availability of gas, at least on these large scales, is not a problem. However, this gas does not appear to have a clear connection with an active nucleus (Oosterloo et al. 2010).

Perturbations produced by mergers or accretions could provide a mechanism for the gas to loose angular momentum and fall into the super massive black hole (SMBH). B2 0258+35 is a rare case for which the recent merger history of the host galaxy can be reconstructed from the kinematics of the gas. H I has been detected in this object not only in absorption against the radio core, but also in a large-scale (~160 kpc diameter) disk structure (see Fig. 1, right panel). Owing to sensitivity limitations of current radio telescopes, H I emission is quite rarely detected at the typical distance of radio galaxies. Even more rare are cases of large H I disks for which a detailed analysis of the gas kinematics can be performed. The kinematics of the H I over the inner 65 kpc radius are extremely regular (see Fig. 5 in Struve et al. 2010). Outside this radius, signs of recent or ongoing interaction are seen, although the H I disk remains kinematically regular. This has suggested that, even if part of the gas was brought in by a major merger, this must have been *more than a Gyr ago*. After that, the continuous supply from gas-rich satellite galaxies has been the main mechanism bringing new cold gas. However, this has happened at the outskirts of the disk and without significantly disturbing the kinematics of the gas. No small halo clouds were found in this object.

Therefore, considering this detailed analysis and comparing the time scale with those of the radio structures derived for the "relic" (Sect. 3) and for the inner CSS (Giroletti et al. 2005), we conclude that despite the huge reservoir of H I in this object, we do not find a link between merger or accretion activity and the cycle of radio emission. The data rule out a major merger as trigger of the radio emission. Signatures of minor accretions are observed in the outer regions of the disk and they do not appear to have left any signature that could indicate a clear link between the formation history of the host galaxy and the life-cycle of the radio activity. Even invoking an extreme time-delay between these events (longer than in other studied cases, see Emonts et al. 2006), the fact that more than one stage of activity is seen cannot be unambiguously linked to clear events in the process of building of the gas disk. This is reminiscent of what was already found in the case of Centaurus A (Struve et al. 2010b). Therefore, despite the large reservoir of H I in the disk, the actual fuel of the AGN may have a different origin.

Mass loss from stars formed during a star-burst phase (e.g. triggered by a merger) has been suggested as a reservoir for the growth of the black hole and the trigger of its activity (Wild et al. 2010). This way of fueling could also explain a delay (of a few ×100 Myr) between the star-burst phase and the onset of the radio phase observed in several radio sources (Emonts et al. 2006). However, in B2 0258+35, the optical spectrum does not show signatures of young stars (Emonts 2006, Chap. 4). This would imply a far too long delay (on the order of Gyr) between the stellar evolution and the onset of the radio emission, making this scenario very unlikely (see however Ciotti et al. 2010, for further details).

The possibility that warm halo clouds (10^4–10^6 $M_\odot$) fuel the AGN has been recently proposed by McKernan et al. (2010). The main problem in this scenario is the assumption that the orbits of these warm halo clouds are random. However, there is clear evidence that the halo clouds are likely rotating, and are not in random orbits. Any amount of rotation would cause these clouds never to fall to the center (only the non-rotating clouds on radial orbits will fall to the center) but, instead, to strongly interact with the halo (Marasco et al. 2012). The current theory is also that most of these clouds would evaporate before hitting the disk or the center (Heitsch & Putman 2009).

Finally, the possibility that gas cooling from the hot galactic halo supplies fuel to the SMBH via e.g. Bondi accretion, and that it is the dominant mode of accretion in low-power radio galaxies has been suggested by several studies (Croton et al. 2006; Allen et al. 2006; Hardcastle et al. 2007; Balmaverde et al. 2008). This is also supported by the analysis of the optical emission lines in radio galaxies carried out by Buttiglione et al. (2010). In radio galaxies with low-excitation spectra (a group that includes all low-power radio galaxies, i.e. FR I type) the characteristics of the optical lines and the powering of the jets can be explained as proceeding directly from the hot X-ray emitting phase of the ISM/IGM in a manner analogous to Bondi accretion. In addition to this, Binney et al. (2009) have suggested a possible formation mechanism for high-velocity clouds; they can in turn supply the fuel to the SMBH.

Using the information from the radio data, we can infer the accretion rate necessary for fueling the radio AGN following the method presented by Allen et al. (2006), Balmaverde et al. (2008; see also Morganti et al. 2009). The radio core flux density of B2 0258+35 at 1.6 GHz was measured by Giroletti et al. (2005) – using the VLBA – to be 7.4 mJy.

This gives a core luminosity of $L_{\rm core} \approx 3.5 \times 10^{21}$ W Hz^{-1}, which can be converted into jet power – $P_{\rm j} \approx 1.2 \times 10^{36}$ W. Balmaverde et al. (2008) found a relation between the Bondi accretion power and the jet power that, if applied to B2 0258+35, gives $P_{\rm B} \approx 6.5 \times 10^{37}$ W, corresponding (using $P_{\rm B} = 0.1\,\dot{M}c^2$) to a mass accretion rate of at most 0.1 $M_\odot$ yr^{-1}.

Unfortunately, although X-ray observations at 2–10 keV (Akylas & Georgantopoulos 2009) show an X-ray halo that extends beyond $D_{25} \sim 49$ kpc (Rasmussen, priv. comm.), the modeling of the density and temperature profile for estimating the Bondi accretion rate is not available. Thus, we limit ourselves to comparing the values obtained with what is found for other radio galaxies. For example, using the same reasoning as outlined above, $\dot{M} \sim 0.1\,M_\odot$ yr^{-1} was found for NGC 315 (Morganti et al. 2009), quite high when compared to e.g. the sample in Allen et al. (2006), but inside the range (although toward the high end) of the distribution for radio galaxies found by Balmaverde et al. (2008). This seems to support the argument that cooling of hot gas, resulting in a Bondi type of accretion, can be responsible for feeding the AGN.

If the cooling of the hot gas is at the origin of the activity fueling, one may wonder whether, in the process of cooling, the gas would spend enough time in the H I phase, and be observable in H I absorption against the nuclear regions of radio continuum. The advantage of observations of H I in absorption is that the gas can be traced to very small scales (unlike for hot gas observed in X-ray) and can provide the kinematics and the distribution of at least the cold component. In this respect, it is intriguing that the occurrence of H I in the central regions of restarted radio sources appears to be higher than in other radio sources (Chandola et al. 2010; Saikia & Jamrozy 2009; Gereb et al., in prep.). If confirmed for more objects, this suggests that the presence/availability of (cold) gas may be connected with the duty-cycle of radio sources. B2 0258+35 confirms this trend with H I absorption detected against the central component (Struve 2010). However, is this H I able to reach the SMBH and fuel the AGN?

For the FR I radio galaxy NGC 315, an in-falling cloud of H I has been observed at a few pc distance from the core (Morganti et al. 2009), corresponding to accretion rates in the range 10^{-4}–10^{-3} $M_\odot$ yr^{-1} (inferred from H I absorption studies using the radio continuum of the core). Although the presence of the H I in-fall is intriguing, the accretion rate is lower than what is required to fuel the AGN. However, it has to be mentioned that this is probably a lower limit, since the H I absorption probes only the gas detected against the continuum. For B2 0258+35, the highest resolution available so far for H I absorption studies does not reach these small linear scales. The H I absorption study (Struve 2010) shows that, down to a linear scale of ~300 pc, most of the gas has relatively regular kinematics, in good agreement with the kinematics of the large scale disc. At this resolution, the only deviation from circular motion appears to be the gas associated with a blueshifted, possibly outflowing component that has been detected both in H I and in CO. If the lack of additional deviation from circular motion, and in particular infalling cloud(s), is confirmed by high-resolution VLBI observations, this would imply that the hot gas dominates the accretion and e.g. the cooling gas would spend only a very short time in the H I phase.

If the activity is related to cooling of the X-ray gas, one can imagine, as already described by other authors, a cycle that would explain not only the triggering but also the interruption of the activity.

The radio emission would be responsible for heating the ISM/IGM, thus stopping the accretion, and, as a consequence of this, the radio emission would be interrupted. This would allow the ISM/IGM to cool again, and after a while the radio emission would restart – thus the cycle can go on (McNamara & Nulsen 2007; Randall et al. 2011; Gaspari et al. 2012).

5. Conclusion and future studies

We have presented the discovery of an extended and low surface brightness radio emission around the young (CSS) radio source B2 0258+35 hosted in an H I-rich early-type galaxy. The newly found radio emission has a distinct double-lobed appearance and is likely a left-over from a previous cycle of activity of the galaxy. The faint lobes may indeed not be completely dead relics, but may still be weakly refueled with "fresh" electrons from the nucleus in a similar way as e.g. the middle lobe of Centaurus A (Morganti et al. 1999). This may explain why the large and faint structure is still visible (although the source is not in a cluster environment). Only a study of the spectral index may help in verifying this hypothesis.

It is intriguing to note the speculation from Giroletti et al. (2005) that the inner CSS (with an estimated age of 9×10^5 yr) might not grow to become a large-scale radio galaxy. No final hot spots are observed although the structure appears to be the result of a strong interaction with the ISM. Considering that the previous cycle of activity did manage to expand to hundreds of kpc in size, this would suggest that every cycle of activity can have different characteristics or that the ISM is now particularly rich and can affect the new radio source more drastically.

The huge H I disk found in B2 0258+35 has a very regular kinematics that do not show any obvious connection with the triggering of the radio source. According to the conclusion of Struve et al. (2010), no major merger has recently occurred in this galaxy and, therefore, a major merger as a trigger of the radio emission is ruled out. Minor accretions are also excluded, because they appear to have perturbed the H I only mildly at large radii. We see no indication in the high-resolution data (Struve 2010) that (some of the) gas in a circum-nuclear disk is indeed fueling the AGN. However, we cannot completely exclude the presence of such a gas until even higher resolution data are available. Future VLBI studies may be able to shed more light on this. The possibility that despite the large reservoir of H I in the disk, the actual fuel of the AGN may originate from the cooling of gas in the hot halo is an interesting alternative and would also help to explain the recurrent activity.

In the future, sensitive low-frequency surveys that cover a large area of the sky will allow finding out how common leftover radio emission from a previous cycle of activity is and tell us about the duty cycle of the radio emission. Sensitive, low-frequency observations are a reliable way to identify these sources, see Dwarakanath & Kale (2009), van Weeren et al. (2009). Increasing the known number of these structures (which is now limited) will allow us (combined with multi-waveband information) to understand under which conditions the radio phase (re-)starts, what the time-scales of this phenomenon are and, as a result, we will learn more about the impact of the radio plasma on the host galaxy and the surrounding IGM. In particular, if the cooling of the hot halo is, indeed, a reservoir for the triggering of the AGN, then we would expect relatively regular cycles of activity and we would expect to observe structures similar to B2 0258+35 in many more objects.

All these requirements are currently being met by LOFAR (and will be met by the SKA in the future). The deep surveys planned with LOFAR (Röttgering 2010) which will cover large areas of the sky, will allow us to find, how common structures like the one detected in B2 0258+35 are. LOFAR 60 MHz observations of B2 0258+35 have been already performed to detect or set a limit to the brightness of the extended structure at lower frequency and learn more about its origin. These data will be presented in a future paper.

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