EXTENDED X-RAY EMISSION IN RADIO GALAXIES: THE PECULIAR CASE OF 3C 305

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ABSTRACT

Extended X-ray structures are common in active galactic nuclei. Here, we present the first case of a compact steep spectrum radio galaxy, 3C 305, in which the X-ray radiation appears to be associated with the optical emission line region, dominated by the [O iii]5007. On the basis of a morphological study performed using a comparison between the X-rays, the optical, and the radio bands, we argue that the high-energy emission has a thermal nature and it is not directly linked to the radio jet and hotspots of this source. Finally, we discuss the origin of the extended X-ray structure connected with the optical emission line region following two different interpretations: as due to the interaction between matter outflows and shock-heated environment gas, or as due to gas photoionized by nuclear emission.

Key words: galaxies: active – galaxies: individual (3C 305) – radiation mechanisms: thermal – radio continuum: galaxies – X-rays: general

1. INTRODUCTION

The origin of the extended X-ray emission from compact steep spectrum (CSS) radio galaxies is still unclear. It may be expected as a result of the radio source evolution and its expansion in the surrounding interstellar medium (ISM) and intergalactic medium (IGM) (Heinz et al. 1998). It can be generally described as due to (1) a relic of past activity, (2) a confining medium, (3) signatures of interactions between the jet and the ISM or, if present, (4) to an X-ray cluster (Siemiginowska et al. 2008). The information in the X-ray band is limited by the number of available observations.

On the other hand, several analyses have been performed on the optical emission line region in CSS sources (e.g., Labiano et al. 2005; Prinov et al. 2008) and there is still a considerable debate on its origin, despite the larger amount of data available in the optical band than in the X-rays. Narrowband Hubble Space Telescope (HST) imaging in [O i] and [O iii] emission lines has shown that in these sources the optical line emission is cospatial and strongly aligned with the radio source at all redshifts (e.g., de Vries et al. 1999; Axon et al. 2000; Prinov et al. 2008). This radiation can be interpreted as due either to the photoionization from the nucleus or from the jet–environment interactions, or a combination of the two. In the case of the jet–environment interaction scenario the origin could be in the form of collisional ionization or an “autoionizing” shock, as suggested by Dopita & Sutherland (1995, 1996).

The connection between the extended soft X-ray structure and the optical emission line region has been recently investigated in the case of radio-quiet active galactic nuclei (AGNs). The detailed X-ray spectral analyses of the three brightest Seyfert galaxies, NGC 1068 (Kinkhabwala et al. 2002; Brinkman et al. 2002; Ogle et al. 2003), Circinus (Sambruna et al. 2001; Massaro et al. 2006), and Mrk 3 (Sako et al. 2000; Bianchi et al. 2005; Bianchi Pounds & Page 2005) have shown that their soft X-ray spectrum looks to be a blend of emission lines from He- and H-like light metals and L transitions of Fe. These emission lines are produced by photoionized gas rather than hot gas in collisional equilibrium (Bianchi et al. 2006). Chandra observations have shown that the soft X-ray emission of these three sources is extended (Sambruna et al. 2001; Sako et al. 2000).

Combining the high spatial resolution capabilities of Chandra with those of HST, Young et al. (2001) compared the extended optical emission with that in the X-ray band in the Seyfert galaxy NGC 1068. They found that the size and the morphology of the soft X-ray region is associated with the narrow-line region (NLR), mapped by the [O iii]5007 emission line, interpreting this emission as due to the photoionization and fluorescence of gas by radiation from the Seyfert nucleus located several kpc from it.

Bianchi et al. (2006) performed a deeper investigation on a sample of eight Seyfert galaxies observed by Chandra, XMM-Newton, and HST selected on the basis of an extended [O iii]5007 emitting region. They showed unambiguously that there is a spatial correlation between the soft X-ray emission and their [O iii]5007 emitting region. The XMM-Newton RGS spectral analysis and the comparison with numerical simulations also suggested that the soft X-ray component is mainly produced by photoionized gas, and described in terms of a blending of emission lines. They also showed that the X-ray and the [O iii]5007 emitting gas had the same ionization source. The role of radio jets in this scenario is still under debate and they seem to be related to the NLR/soft X-ray emission.

The hot 0.5–1 keV normal ISM of the host elliptical is also detected in radio galaxies (O’Dea et al. 2006; Evans et al. 2006; Worrall et al. 2003). In these sources, the association between the optical emission line region and the X-ray diffuse emission has been recently found only in a few cases (e.g., 3C 321, Evans et al. 2008; 3C 33, Kraft et al. 2007), where the X-ray emission has been interpreted as due to collisionally ionized
gas. However, there are also a few examples of radio galaxies or quasars in which the soft X-ray spectrum has been described in terms of emission lines due to photoionization, similar to the Seyferts, such as 3C 234 (Piconcelli et al. 2008).

The radio galaxy 3C 305, observed as part of the Chandra snapshot survey of 3C sources at redshift lower than 0.3 (see Massaro et al. 2008b and Macchetto et al. 2008, for preliminary results), has revealed a very intriguing morphology, characterized by an extended soft X-ray emission (0.2–2 keV), not coincident with its radio structure.

3C 305 is relatively low radio power radio galaxy located at redshift \( z \sim 0.0416 \). It has been classified as a peculiar FR I on the basis of the radio power and morphology ( Heckman et al. 1982) and it presents a prominent extended emission line region of roughly the same dimension as the radio structure.

The first multiwavelength investigation of 3C 305 was carried out by Heckman et al. (1982), who presented radio maps, and optical images and spectroscopy of the central region. They found that the emission line region is approximately dumbbell shaped and oriented NE–SW. The radio emission follows this pattern, with the exception of a plume extending southward of the NE lobe and a lack of coincidence between the radio and the optical structures in the lobe. It is also highly depolarized where the emission lines are brighter.

Jackson et al. (1995) presented the first HST image of this radio galaxy. They found that the major concentration of the line emission lies beyond the end of the radio jet, suggesting that it can be excited by a shock propagating outward from an interaction between the radio jet itself and the external medium. This extended optical emission line region is also associated with an outflow of neutral hydrogen (Morganti et al. 2005), and the [O\textsc{iii}]5007 emission line region is aligned with the jets and hotspots (Privon et al. 2008).

A study of the neutral hydrogen absorption (H\textsc{i}) has been conducted on the basis of MERLIN observations by Jackson et al. (2003), in comparison with HST optical and infrared images. They argue that profiles of the [Fe\textsc{ii}] line at 1.644 \textmu m and [O\textsc{iii}]5007 are different: in the northern region, where the jet terminates, there is the peak of the [Fe\textsc{ii}] line while the [O\textsc{iii}]5007 is more evenly distributed throughout the emission line region. The interpretation suggested by Jackson et al. (2003) on the basis of the [Fe\textsc{ii}] analysis was in favor of an emitting gas collisionally ionized by shocks around an interaction region.

In this Letter, we present the comparison between the radio, optical, and X-ray images of 3C 305 to investigate the morphology and the nature of the emitting gas. For the first time in a CSS source we found that the soft X-ray emission is associated with the optical emission line region, dominated by the [O\textsc{iii}], arguing that its nature is thermal.

We assumed a flat cosmology with \( H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.27 \), and \( \Omega_A = 0.73 \) (Spergel et al. 2007). This means that for 3C 305, 1' corresponds to 0.811 kpc, and its luminosity distance is 181.6 Mpc.

2. THE PECULIAR RADIO MORPHOLOGY

We investigated the radio structure of 3C 305, on the basis of archival VLA and MERLIN data, to derive a better classification of the source and to compare the emission of its radio jet and hotspots with that in the X-rays.

The radio emission of 3C 305 at 1.7 GHz\(^{10}\) is peculiar (Heckman et al. 1982; Jackson et al. 2003). It is characterized by an extremely faint radio core with two-sided jets, which terminates in a high-brightness region (similar to but fainter than hotspots which characterize the powerful radio sources), from where the radio emission extends with a plumed structure with a very symmetric H\textsc{ii} shape. The NE lobe is more extended to the SE with a low-brightness region in between the core and the bright spot. The SW lobe is more symmetric with the bright spot located at the center of the low-brightness region.

We reduced VLA archival data at 8.4 GHz with the AIPS standard reduction procedure (amplitude calibrator: 1331+305, phase calibrator: 1637+574). The final image is in good agreement with the 1.7 GHz radio map. To derive a spectral index distribution we obtained images at 1.7 GHz and 8.4 GHz with the same cell size and resolution, matching the \( uv \) coverage as much as possible. The jets, lobes, and also the two bright spots have a moderately steep spectrum \((\alpha_{1.7} \sim 0.8)\) with no clear trends. The only steeper regions are in the external part of the NE lobe and unexpected in the inner part of the SW lobe.

This source is small in size: the distance between the two bright spots is only \( \sim 3.5 \) kpc. The total radio spectrum is straight and steep (we found \( \alpha_{14000} = 0.9 \) from the archive data\(^{11}\)) suggesting that 3C 305 is an aged confined source. Its steep radio spectrum together with the small size extension is in agreement with the identification of 3C 305 as a CSS source.

The core is very faint in the radio band (<2 mJy at 1.7 GHz), in agreement with Jackson et al. (2003). From this result and the jet to counter-jet brightness ratio we estimated that this source is oriented near to the plane of the sky \((\sim 65^\circ - 70^\circ)\) and that the jets are highly relativistic in the inner region \((\sim 0.9c)\) and slow down reaching a velocity of \( \sim 0.5c \) at \( \sim 2'' \) \((1.5\) kpc) from the core. This picture is confirmed by the marginal core detection in VLBI data (Giovannini et al. 2005).

3. THE EXTENDED X-RAY EMISSION

3C 305 was observed by Chandra (Obs ID 9330) on 2008 April 7, with the ACIS-S camera, operating in VERY FAINT mode, with an exposure of about 8 ks. The data reduction was performed following the standard procedures described in the Chandra Interactive Analysis of Observations (CIAO) threads (http://cxc.harvard.edu/ciao/guides/index.html), and using the CIAO software package version 3.4 (see Massaro et al. 2008a for details). The Chandra Calibration Database (CALDB) version 3.4.2 was used to process all files. Level 2 event files were generated using the \texttt{acis\_process\_events} task, after removing the hot pixels with \texttt{acis\_run\_hotpix}. Events were filtered for grades 0, 2, 3, 4, 6 and we removed pixel randomization. Astrometric registration was done by changing the appropriate keywords in the fits header so as to align the nuclear X-ray position with that of the radio. We also registered the HST images in the same way.

We created three different flux maps (soft, medium, and hard, in the ranges 0.5–1, 1–2, and 2–7 keV, respectively) by dividing the data with the exposure maps. When constructing the flux maps, we normalized each count by multiplying by \( hv \) where \( v \) corresponds to the energy used for the corresponding exposure map. Thus, we could measure the flux in any aperture in cgs units with only a small correction for the ratio of the mean

\(^{10}\) Radio map available on the Web site: http://www.jb.man.ac.uk/ "An Atlas of DRAGNs."

\(^{11}\) We assume flux density \( S(v) \propto v^{-\alpha} \).
energy of the counts within the aperture to the nominal energy for the band.

The total counts detected in the X-ray band between 0.5 and 7.0 keV is 148, for an extraction region of 6" centered at the position of the radio nucleus (R.A.: 14 49 21.661, decl.: +63 16 14.12). Only 8% (13 counts) of these counts are in the hard X-ray band (2.0–7.0 keV), while the majority of the X-ray emission lies in the soft X-ray energy range between 0.5 and 2.0 keV. Its low flux together with the absence of broad emission lines in the optical spectrum suggests that it is absorbed as observed in other type II CSS sources (Siemiginowska et al. 2008). The radio map at 1.7 GHz with the soft X-ray contours overlaid is shown in Figure 1 (left panel).

The soft X-ray emission extends beyond the radio one and the X-ray flux peaks are not coincident with those in the radio. Comparing the Chandra image with the optical one (see Figure 1, right panel), we found that the X-ray emission is associated with the optical emission line region dominated by the \([\text{O}^\text{iii}]\)5007. The coincidence between the soft X-ray and the \([\text{O}^\text{iii}]\)5007 is notable, both in extension and in the overall morphology. It has also been shown in Figure 1 (right panel) that the majority of the soft X-ray emission lies in the northern region; this fact is probably due to the presence of the dust lane in the southern region. The number of counts in the southern region is about 2/3 of that in the northern one.

The striking resemblance of \([\text{O}^\text{iii}]\)5007 structures to the soft X-ray structures favors a common origin for both components. On the basis of this association, assuming that the soft X-ray radiation is dominated by emission lines, we selected an extraction region for the soft X-ray emission which covers the \([\text{O}^\text{iii}]\)5007 pattern.

We measured the soft X-ray flux in the 0.5–2.0 keV energy range (observer frame) and its ratio with the \([\text{O}^\text{iii}]\)5007. We found a soft X-ray flux \(F_{0.5-2\text{keV}} \sim 3.49 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}\) that corresponds to an observed soft X-ray luminosity \(L_{0.5-2\text{keV}} \sim 1.38 \times 10^{41} \text{ erg s}^{-1}\) corrected for the Galactic H1 absorption \(N_{\text{H}} \geq 3.30 \times 10^{20} \text{ cm}^{-2}\); Kalberla et al. 2005, assuming a photon index of 2). The observed \([\text{O}^\text{iii}]\)5007 flux is \(F_{\text{[O}^\text{iii}] \sim 3.68 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}\) corrected for the Galactic extinction \((A_{\lambda}5007 \sim 0.097); Cardelli et al. 1989). Their ratio \(F_{\text{[O}^\text{iii}]} / F_{0.5-2\text{keV}}\) is of order unity.

The XMM-Newton spectrum available in the public archive does not allow to discriminate between collisional and photoionized gas. Evans et al. (2008) investigated the XMM-Newton spectrum of 3C 305 and they argued that it cannot be described by a simple unabsorbed power-law model. They found an acceptable fit combining a single unabsorbed power-law with a thermal emission due to collisional ionized gas (APEC model in xspec; Arnaud 1996). However, we argue that the statistics of the XMM-Newton observation cannot exclude a photoionized model to interpret the X-ray emission of 3C 305.

4. DISCUSSION AND CONCLUSIONS

The interpretation of the X-ray extended emission in CSS sources is still unclear and several scenarios have been proposed to understand its nature.

3C 305 represents the first clear case of a CSS source where the extended X-ray emission is not connected with radio structure. Investigating the radio structure of 3C 305 we found that the radio emission at 8.4 GHz is in agreement with that at 1.7 GHz, showing that the jets, lobes, and also the two bright spots have a moderately steep spectrum. This fact together with the small size extension suggests that 3C 305 belongs to the class of CSS radio galaxies.

On the basis of our morphological study, we showed that the extended soft X-ray emission lies beyond the radio one. The X-ray flux peaks are not coincident with those in the radio, mostly corresponding to the hotspots. This fact led us to conclude that the X-rays are not produced by the same mechanism responsible for the radio jet emission.

The pattern of the X-ray radiation compared with the radio jet emission seems to support the scenario of a collisionally ionized gas driven by shocks, in which the bow shock is produced beyond the radio emission. On the other hand, by comparing the Chandra image with the optical one, we found that the X-ray emission is cospatial with the optical emission line region dominated by the \([\text{O}^\text{iii}]\)5007. This favors the idea that the origin of the X-ray emission has a thermal nature, and that it could be interpreted as due to the interaction between the radio jet and the ISM. It is worth noting that the majority of the X-ray flux is below 2 keV, where the majority of emission lines of collisional ionized gas are present.
However, the association between the X-ray and the [O\textsc{iii}]5007 region and the X-ray emission itself can also be described as due to photoionized gas, following the same interpretation as for Seyfert galaxies. Thus, the soft X-ray energy range could be dominated by emission lines due to photoionized gas.

Considerable debate has developed on the interpretation of these extended structures in Seyfert galaxies, where it has been associated with the optical emission line region, dominated by the [O\textsc{iii}]5007. Two different scenarios have been proposed for this emission: as produced by the radio jet interactions with the circumnuclear environment, (collisional ionization or a radiative autoionizing shock as argued by Dopita & Sutherland, 1995, 1996) or by emission from photoionized gas, in the form of blend of emission lines (as claimed by Bianchi et al., 2006).

Recently, the latter scenario appears to be favored on the basis of the comparison between the Chandra X-ray observations and the HST images (Bianchi et al., 2006). Our recent Chandra observations of 3C 305, presented in this work, show that this debate can be extended to the CSS radio galaxies.

We evaluated the ratio between the [O\textsc{iii}]5007 and the soft X-ray flux and found that it is of order unity, the same order of magnitude as for Seyfert galaxies by Bianchi et al., 2006.

Furthermore, we note that Simpson et al. (1996) have presented a diagnostic diagram involving the ratio [O\textsc{iii}]5007/\text{H}\alpha to study the emission line region, and 3C 305 lies approximately in the region of Seyfert galaxies in this diagram (Jackson et al., 2003). Such behavior is in agreement with our results for the [(O\textsc{iii}]5007/F0.5–2keV) ratio. These analogies with the case of Seyfert galaxies suggest that the nature of the extended X-ray emission could have the same origin.

Even if there are some similarities with the Seyfert galaxies scenario, the previous preferred interpretation of the extended emission line region in 3C 305 is in favor of the interaction between the radio jet and the ISM (Heckman et al., 1982; Jackson et al., 1995, 2003). 3C 305 represents a unique case to investigate this process because with respect to the case of Seyfert galaxies it is a powerful radio source.

The discovery of the association between the soft X-ray emission and the [O\textsc{iii}]5007 emission line region in 3C 305 constitutes the first step in understanding the nature of the extended emission line region in CSS sources. Our results strongly suggest that in this case the extended X-ray emission has a thermal origin. However, the short Chandra observation does not allow us to solve the dichotomy between a jet-driven scenario and a photoionization scenario. An investigation based on a deeper XMM-Newton spectral analysis and a deeper Chandra observation is crucial to achieve the final interpretation.

We thank D. E. Harris for his suggestions and for several comments and G. Privon for the HST images. F.M. is grateful to S. Bianchi for his suggestions, to M. Mur gia for discussions on radio reduction, and to A. Siemiginowska for comments on X-ray data analysis. F.M., A.B., and E.L. thank E. Brentzel for his help in presenting the image of 3C 305 at the “NRAO image contest 2008” (2nd prize). Finally, we thank our referee for several comments which were helpful toward improving our presentation. This research has made use of NASA’s Astrophysics Data System and SAOImage DS9, developed by the Smithsonian Astrophysical Observatory and the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation. The work at SAO is supported by NASA grant GO1-9114A.

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