A multi-wavelength approach of AGN feedback in LINERs: The case of NGC 4438 as a pilot study for a large survey

Puig-Subirà, M., Márquez, I., Masegosa, J., Moldón, J., Hermosa-Muñoz, L., Cazzoli, S.

Instituto de Astrofísica de Andalucía - CSIC, Glorieta de la Astronomía s/n, 18008 Granada, Spain

Abstract

We present the first results of the pilot study focused on NGC 4438 that validates the feasibility of our methodology to explore the connections between the ionised gas and the radio jets in LINER galaxies with evidence of outflows. It provides the precursor for a larger sample: the Hα imaging atlas of 70 nearby LINERs published in Hermosa-Muñoz et al. 2022. Radio-flux images and spectral index maps are obtained through comprehensive radio coverage from 1.4 to 9 GHz, combining VLA and e-MERLIN data. We characterise radio emission, with a particular focus on non-thermal processes. This allows us to compute the energetics of radio jets, thereby revealing how jets may modify the structure of ionised gas and determining whether LINER outflows are driven by jets. We compare the morphology and energetics of jets and outflows, and complement the study with X-ray data for improving the AGN and outflow tracing. The results of the pilot study demonstrate the feasibility of our approach, confirming the co-spaciality of the outflow and the jet and indicating a preliminary connection and compatibility between their energetics.

1 Introduction

Low Ionization Nuclear Emission-line Regions (LINER) represent the most numerous Active Galactic Nuclei (AGN) population in the local Universe; the frequency of multi-phase outflows in LINERs has been confirmed. Their lack of strong star formation makes them a promising opportunity to study AGN's feedback effects, in particular in innermost regions. Since LINERs exhibit both low Eddington ratios and radiative inefficiency, commonly observed radio jets appear as potential power sources for their ionised gas outflows.

In order to explore the connections between the morphology of ionised gas and the radio continuum structures, a multifrequency radio study is conducted. We present the first results of the pilot study focused on NGC 4438 that validates the feasibility of our methodology.

NGC 4438 is a highly inclined spiral galaxy located near the center of the Virgo cluster (d = 17 Mpc; [16]). Among Virgo galaxies, NGC 4438 stands out as the most perturbed, showing a complex morphology. The location and nature of its core was somewhat ambiguous, partly due to a dust band that obscures the central region [12]. Optical spectroscopic studies classified NGC 4438 as a LINER ([15]; [9]; [3]). Based on radio observations, the location of the nucleus is proposed within its main radio structure [8] (current coordinates in NED, J2000: RA 12:27:45.5, Dec 13:00:31.3). The AGN nature was suggested for the broad-line component in the nucleus [6] and confirmed via X-ray [2]. The asymmetric morphology of this galaxy, extending westward on both large scales and nuclear regions, makes it an appealing target for multi-wavelength and multi-scale studies. Properties of the interstellar medium (ISM) in NGC 4438 suggest several possible and potentially compatible scenarios [9]. On large scales, these include high-velocity ISM–ISM collision between NGC 4438 and NGC 4435 (also postulated in [11]) and interaction with the dense intracluster medium at the Virgo core. In nuclear regions, radio ([6], [7]) and X-ray studies ([13]) also suggested nuclear activity, possibly resulting from energy input from the AGN or a cocooned starburst.

Our current study is focused on the nuclear region NGC 4438, the central kpc. It aims to understand and potentially link the central features observed around the AGN, thus getting insights of how feedback works, in particular for the eventual connection between the ionised gas outflows and radio jets. We propose a multiwavelength approach considering optical imaging and spectroscopy and radio data, supported by X-ray observations. The clear Hα bubble emerging from the nucleus has been suggested as an outflow [14]. Indeed, Integral Field Spectroscopy (IFS) was needed to properly confirm it [5]. The ionised gas outflow detected is co-spatial with the radio continuum emission [8]. Shell-like radio structures are detected in the VLA data at 4.8 and 8.5 GHz [7], which have also been identified in Hubble Space Telescope (HST) Hα and *Chandra* X-rays. They are interpreted as a result of the synchrotron-emitting particles interacting with the ISM.

There is still no clear understanding of the mechanism that launches and drives outflows in radiatively inefficient systems, such as LINERs. To address this, an in-depth radio analysis is essential, since radio jets are the best candidates for driving outflows in low luminosity AGNs ("kinetic or jet mode", [1]). High-sensitivity and high-resolution data allow us to study the radio morphology and determine the energetics of the jets. By comparing the energetics of the outflow [5] with the final results of our study we can determine if the NGC 4438 jet is powerful enough to play this role.

2 Data and methodology

To characterise the radio structures in NGC 4438 we propose a multi-frequency study. By combining e-MERLIN and VLA data, we can obtain a comprehensive radio coverage from 1.25 to 9 GHz. We study the radio emission by obtaining the radio flux in each band and spectral index maps. This approach allows the separation of thermal and non-thermal emission components based on their origin. The characterisation of the non-thermal radio jets and their energetics reveals how jets can modify the ionised gas structure, caracterised by high-resolution IFS data, and determines whether LINER outflows are driven by jets.

Telescope (1)	Project (2)	Observation date (3)	Frequency (Band)(GHz) (4)	Time (s) (5)
VLA-A	AH230	1986 May 24	1.44 - 1.54 (L)	2640
VLA-A	AH230	1986 May 24	4.84 - 4.94 (C)	2640
VLA-A	AI73	1998 May 13	8.44 - 8.94 (X)	1410
VLA-B	AH551	1995 Oct 12	8.44 - 8.94 (X)	1290
VLA-A	22A-180	2022 Jun 17	3.97 - 8.00 (C)	3960 (1.1h)
e-MERLIN	CY16021	2023 Aug 19-20	1.25 - 1.75 (L)	97200 (27h)

Table 1: Observing log of the data analysed in this study. (1) Telescope and configuration, (2) project code, (3) observation date, (4) range of frequency of the observation in GHz, (5) observation time on source in seconds.

For this purpose, we first examined the VLA data archive and selected data sets with sufficient signal-to-noise ratios (see Table 1). In addition, we submitted a proposal to e-MERLIN to obtain high-resolution L-band data, which has since been approved and the resulting data are included in this work (see Table 1 for details). We have also proposed new VLA observations in the C- and X-bands within the current cycle (semester 2024B); this proposal has been accepted and observations are now scheduled. These additional data sets will allow further analysis in the coming months.

3 First results and discussion

3.1 Radio images

Our study presents high-resolution continuum images of NGC 4438 across L, C, and X-bands, revealing detailed insights into its complex radio morphology. The combined use of e-MERLIN and VLA data allowed us to capture both compact and diffuse emissions. In Figure 1, we show the C-band image, the one we use as a reference.

The **C-band image (4-8 GHz)**, produced from archival VLA data, achieves a resolution of 0.33" x 0.29". It clearly shows the location of the AGN, the main northwestern (NW) bubble with structural details, and a secondary bubble to the southeast (SE). The diffuse emission highlights the connections between the main emitting structures.

The **L-band image (1.25-1.75 GHz)**, acquired by combining e-MERLIN proprietary data with archival VLA data, has a resolution of 0.167" x 0.167". The combination of data sets from both arrays provides us with a good uv-coverage and sensitivity at different scales. While the lower frequency image provides less structural details, it does reveal two primary emission features within the NW bubble. Some emission is observed in the southeastern region, coinciding spatially with the SE bubble. The AGN is not distinguishable at this band.

The **X-band image (8-12 GHz)** is obtained by merging two VLA data sets from A and

B configurations. The aim of this combination is to optimise the sensitivity to both compact and diffuse emission. With a resolution of 0.33" x 0.20", this image highlights the AGN and compact features within the primary bubble. The combined data sets enhance sensitivity to diffuse components, revealing intricate details within the main jet structure of the NW bubble. The southern bubble appears faint at these frequencies.

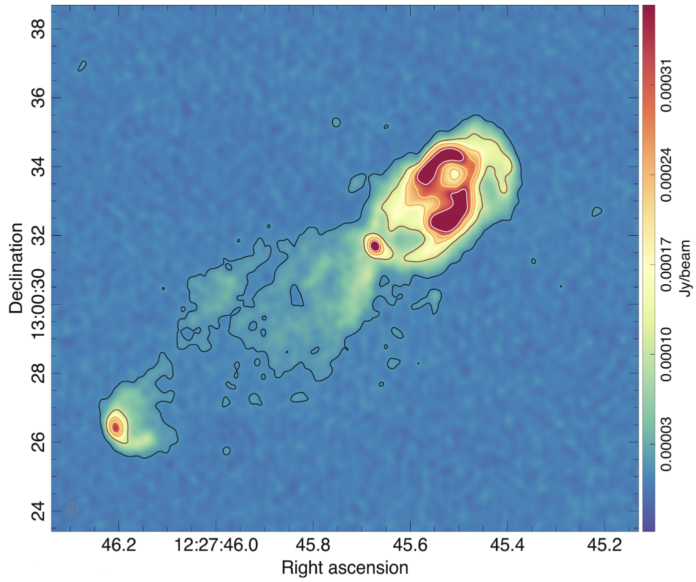

Figure 1: C-band image of NGC 4438. The AGN is located in the central region of the image, with the main bubble visible to the NW. A faint bubble appears, and the outer contour highlights the diffuse emission.

3.2 Spectral Index Mapping and modeling

With the three images we provide essential coverage (1.25-9 GHz) for constructing spectral index maps, which allow us to separate thermal and non-thermal emissions. The C-band spectral index map shows 1) a flat spectral index in the core region, consistent with the presence of an AGN, 2) a negative spectral index in the main bubble, consistent with non-thermal synchrotron emission, 3) a stepper index in the region between the AGN and the southern bubble, indicating the presence of older electrons, and 4) additional synchrotron emission in the south-eastern region. The spectral index analysis enables preliminary modeling of the jet [7] by assessing its energy, age, and diffusion length, though further quantitative analysis is forthcoming (Puig-Subirà in prep.).

3.3 Multiwavelength discussion

Our multi-frequency radio observations of NGC 4438 show structural alignment and spatial consistency with optical data and X-ray evidence, supporting the link between the radio

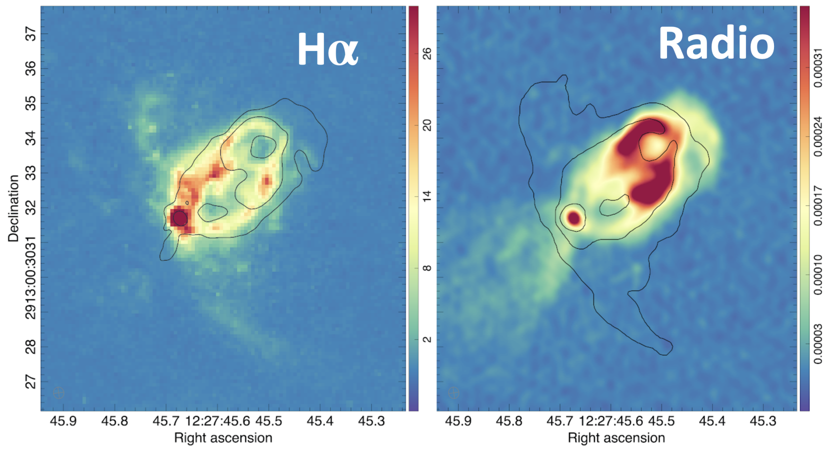

Figure 2: Left: HST image with C-band contours. Right: C-band image with Hα HST contours.

jet, AGN activity and outflow dynamics. Comparison with the Hα image from HST shows that the NW shell-like radio structure and the ionised gas bubble are co-spatial. The two structures, setting into each other, suggest a dynamic AGN-driven structures (Figure 2).

Regarding to kinematic studies [5], the bubble is confirmed as an outflow using IFS data from MEGARA/GTC. The multi-Gaussian fit of the Hα emission line revealed two non-rotational components, spatially aligned with the structures seen in our radio images. The inferred kinetic energy of the outflow ($3.9 \pm 3.2 \times 10^{53}$ ergs [5]) is consistent with our preliminary estimates of the jet, suggesting compatibility between their energetics. The hard X-ray emission, which traces the AGN, is spatially consistent with the radio emission in our study. The soft X-ray emission follows the same direction as the detected outflow.

4 Conclusions

This study aims to investigate the relationship between ionised gas morphology and radio continuum structures in LINERs, establishing a robust parametrization of feedback mechanisms. NGC 4438 was selected as a target case due to its particular nuclear morphology, both in Hα images and radio frequencies. The recent high-resolution IFS study [5] makes it particularly suited to our analysis. Although our final results are not yet available, we presented preliminary L, C and X-band images in our talk. The forthcoming final images and quantitative analysis will be detailed in Puig-Subirà et al. (in preparation).

Our conclusions to date indicate that:

1. The pilot study presented has validated the feasibility of our methodology and serves as a precursor for a larger sample, enabling a systematic study.

2. Multi-wavelength analysis are essential to provide a physical interpretation of the complete feedback scenario.

3. High-resolution data across all wavelengths are crucial for these studies. Thus, radio interferometers such as VLA or e-MERLIN and IFU data from MUSE/VLT or MEGARA/GTC are necessary for this study.

4. NGC 4438 initial results reveal connections between emissions at different wavelengths, highlighting a co-spatial relationship between the ionised gas outflow and the jet and a preliminary correlation and compatibility between their energetics.

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