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Jets Arcs and Shocks: NGC 5195 at radio wavelengths

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ABSTRACT

We studied the nearby, interacting galaxy NGC 5195 (M 51b) in the radio, optical and X-ray bands. We mapped the extended, low-surface-brightness features of its radio-continuum emission; determined the energy content of its complex structure of shock-ionized gas; constrained the current activity level of its supermassive nuclear black hole. In particular, we combined data from the European Very Long Baseline Interferometry Network ($\sim$1-pc scale), from our new e-MERLIN observations ($\sim$10-pc scale), and from the Very Large Array ($\sim$100–1000-pc scale), to obtain a global picture of energy injection in this galaxy. We put an upper limit to the luminosity of the (undetected) flat-spectrum radio core. We find steep-spectrum, extended emission within 10 pc of the nuclear position, consistent with optically-thin synchrotron emission from nuclear star formation or from an outflow powered by an active galactic nucleus (AGN). A linear spur of radio emission juts out of the nuclear source towards the kpc-scale arcs (detected in radio, H and X-ray bands). From the size, shock velocity, and Balmer line luminosity of the kpc-scale bubble, we estimate that it was inflated by a long-term-average mechanical power $\sim$3–6 10^{4} erg s over the last 3–6 Myr. This is an order of magnitude more power than can be provided by the current level of star formation, and by the current accretion power of the supermassive black hole. We argue that a jet-inflated bubble scenario associated with previous episodes of AGN activity is the most likely explanation for the kpc-scale structures.

Key words galaxies: active - galaxies: individual (NGC 5195) - radio continuum: galaxies - X-rays: galaxies - techniques: radio astronomy - interferometric

1 INTRODUCTION

The early-type galaxy NGC 5195 (M51b) is the junior partner in the interacting system Messier 51, dominated by the grand-design spiral NGC 5194 (M 51a). The peculiar appearance of NGC 5195 (tidally disturbed in the interaction) has led to discrepant classifications such as $SB0_1$-pec (Sandage & Tammann 1981), SBa (Hyperleda[1]) and I0-pec (de Vaucouleurs et al. 1991).

The nature of the nuclear activity of NGC 5195 has been an outstanding problem. The *Spitzer* detection of mid-infrared high excitation lines, such as [Ne V]λ14.32μm, in the inner $\approx (200 \times 400)$ pc, was interpreted (Goulding & Alexander 2009) as evidence of AGN activity. Optical line

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[1] `http://leda.univ lyon1.fr/`

ratios also place the nucleus in the LINER class (Moustakas et al. 2010; Ho et al. 1997), despite the relatively low X-ray luminosity of its nuclear black hole (BH) (Terashima & Wilson 2004).

A recent *Chandra* study by Schlegel et al. (2016) revealed an X-ray emitting region with a double arc-like structure, located on the south side of the galaxy, between about 15″ and 30″ from the nucleus. Schlegel et al. (2016) attributed the X-ray-bright arcs to outgoing shocks, which sweep gas as they radially expand. In addition, they found that the morphology of the H emission closely matches that of the X-ray emission (Figure 1), with an H arc located just outside the outer X-ray arc. Schlegel et al. (2016) suggested that the arcs are the result of episodic outflows driven by mechanical feedback from the nuclear BH; this may have been caused by infalling matter driven by the interaction between NGC 5195 and NGC 5194 (interaction timescale of 50–500 Myr: Salo & Laurikainen 2000; Dobbs et al. 2010; Mentuch Cooper et al. 2012).

Hydrodynamical simulations show (Saxton et al. 2005; Massaglia et al. 2016; Mukherjee et al. 2017) that the lack of obvious jet signatures such as hot spots is expected for a system with low jet power ($P_{\rm jet} \lesssim 10^{42}$ erg s ^{1}) and/or a jet propagating in an inhomogeneous medium. In those cases, the jet entrains ambient gas and gradually dissipates its kinetic energy along the way, losing collimation and forming a bubble or cocoon, with an arc-like front. Weak jets are also subject to the magnetic kink instability (Tchekhovskoy & Bromberg 2016), which favours the dissipation of the jet power in a bubble. (See also the review of jets and bubbles by Soker 2016.) On the other hand, starburst-driven superwinds can also produce large galactic bubbles and bipolar outflows (*e.g.*, Baum et al. 1993; Jogee et al. 1998; Hota & Saikia 2006).

In this paper, we want to determine whether the arc structures in NGC 5195 are more likely to have a starburst or a jet origin. To do so, we follow up on the findings of Schlegel et al. (2016), by investigating the connection between the current nuclear activity and the kinetic energy required to create the arcs/bubble structure. We present the results of our new observations with the enhanced Multi-Element Remote-Linked Interferometer Network (e-MERLIN) at 18cm and 6cm, as part of the Legacy e-MERLIN Multi-Band Imaging of Nearby Galaxies Survey (LeMMINGS) project (Baldi et al. 2018; Beswick et al. 2014). We combine those observations with our data from the European VLBI (very long baseline interferometry) Network (EVN), and with archival Very Large Array (VLA) observations, in order to map the radio properties from the nuclear region (pc scale) to the arc region (kpc scale), and determine how energy was injected from the former to the latter region. We support our analysis with a *Chandra* study of the X-ray emission from the nuclear region, and with *Hubble Space Telescope* (*HST*) narrow-band imaging of the Balmer line emission in the arc region.

Throughout this paper we define spectral index, , as $S_\nu \propto \nu$, where S_ν is the measured flux density at frequency, ν. For consistency with Schlegel et al. (2016), we adopt a distance to NGC 5195 of 8.0 Mpc (thus, 1′ ≈ 40 pc).

2 OBSERVATIONS AND DATA ANALYSIS

2.1 European VLBI Network data

We observed NGC 5195 (RA = $13^{\rm h}29^{\rm m}59.537^{\rm s}$; Dec = $+47°15′58″.38$ [J2000.0]) with the EVN on 2011 November 7, for 8 hr (UTC: 01:30–09:30) at a wavelength of 18cm, with a single target pointing centred on NGC 5194. Details of the observing set-up are given in Rampadarath et al. (2015).

The observation was phase referenced to J1332+4722 (RA = $13^{\rm h}$ $32^{\rm m}$ $45.246424^{\rm s}$; Dec = $+47°$ $22′$ $22″.667700$ [J2000.0]) located 31′ from NGC 5194, and used a phase-referencing cycle of 5 minutes on target and 1 minute on the calibrator. Using the multiple-phase-correlation technique (Deller et al. 2011; Morgan et al. 2011), a field of ≈ 8′ was surveyed using 192 sub-fields, including one centred on NGC 5194. Each sub-field covered 41″ × 41″, at a maximum resolution of 5 mas. The phase centres, including NGC 5194 were calibrated and primary beam corrected using the Astronomical Image Processing System (IPS)[2] as described by Rampadarath et al. (2015). Images of the NGC 5194 centred field were made with different combinations of UV-ranges (10% to 100%) and image weights, which did not reveal any detections. Using the most sensitive image, we place a 5-σ upper limit on the flux density of $F_\nu < 132\mu$Jy beam ^{1}.

2.2 e MERLIN data

NGC 5195 was observed with e-MERLIN as part of the LeMMINGS project, at both L and C bands[3]. The observations are summarised in Table 1. The L-band observation was phase referenced to J1335+4542 (RA = $13^{\rm h}35^{\rm m}21^{\rm s}.9623$; Dec = $+45°42′38″.231$ [J2000.0]), located 1°.81 from our target. The C-band observation was phase-referenced to the nearby calibration source J1332+4722 (RA = $13^{\rm h}32^{\rm m}45^{\rm s}.246$; Dec = $+47°22′22″.667$ [J2000.0]) located 0°.48 from NGC 5195. All observations used a phase-referencing cycle of 7 minutes on target and 1 minute on the calibrator. We observed the standard flux calibrator 3C 286 to calibrate the flux density scale to an accuracy of 5%, and used J1407+2827 (OQ 208) to calibrate the bandpass.

Both e-MERLIN datasets were obtained with 512 channels per intermediate frequency (four in the C-band, eight in the L-band), and were averaged to 128 channels per intermediate frequency in post-processing. Following extensive flagging of bad data due to radio frequency interference and telescope dropouts, we calibrated the datasets with IPS, using the e-MERLIN calibration pipeline[4] (Argo 2014), with the procedure described in the e-MERLIN Cookbook[5].

To make full use of the wide-bandwidth e-MERLIN data, we imaged the calibrated datasets with the multi-scale, multi-frequency synthesis algorithm (Rau & Cornwell 2011) in the Common Astronomical Software Appli-

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[2] The Astronomical Imaging Processing System is owned and maintained by the National Radio Astronomical Observatory (NRAO)

[3] The L-band covers 1–2 GHz; the C-band 4–8 GHz; the X-band 8–12 GHz.

[4] `http://www.e merlin.ac.uk/observe/pipeline/`

[5] `http://www.e merlin.ac.uk/data_red/tools/`
`e merlin cookbook_V3.0_Feb2015.pdf`