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EVN Observations of the Active Galaxy NGC 6240

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The luminous infrared galaxy NGC 6240 (d = 103 Mpc; H_0 = 73 kms^{-1}Mpc) hosts two active nuclei in the nuclear region. Two epoch multi-frequency VLBI observations using the European VLBI Network (EVN) were conducted at 1.6, 2.2, 5.0, and 8.4 GHz for clarifying the radio properties of the nuclear components of the galaxy. The new observations detected four radio components, which are the northern nucleus, the southern nucleus, and two new compact radio components located southwest and northeast of the southern nucleus. The new radio components at the southern nucleus are interpreted as luminous radio supernovae associated with the starburst activity. The spectra of the two nuclei suggest the presence of both AGN and starburst activity.

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1. Background

NGC 6240 is a galaxy-galaxy merging system that hosts two galactic nuclei in the central region with a 1".5−1".8 (0.71−0.85 kpc) separation from radio wavelengths to X-ray [3, 2, 8, 4, 9]. According to the Very Large Array (VLA) observations at centimeter wavelengths [3, 1], the central 2" region of the galaxy largely comprises three major components (N1, N2, N3) and surrounding diffuse radio emission. However only two of these radio major components, N1 (southern nucleus) and N2 (northern nucleus) remain unresolved by earlier VLBA observations [4]. Reconstruction of the orbital mechanics suggests that the nuclei have an actual separation of 3.4 kpc and that the southern nucleus N1 lies lies behind the northern nucleus and would this have the higher absorbing column density [1]. Goals of the European VLBI Network (EVN) observations are twofold: 1) to study the nature of the two nuclei by obtaining spectral indices across radio frequencies, and 2) to image the detailed appearance of the nuclei at higher angular resolution. The 1.6 and 2.3 GHz VLBA observations by Gallimore & Beswick (2004) showed the resolved structures of the milliarcsec-scale radio nuclei in the nuclear 2" region. According to their interpretation, the radio nuclei indicate some hints of nuclear starburst obscured by a foreground optically thick medium, which could be caused by free-free absorption (FFA) or synchrotron self-absorption (SSA). Our new observations aim to detect these two nuclei at higher frequencies up to 8.4 GHz with the better sensitivity of the EVN. The overall spectra enable us to further investigate the nature of the nuclei.

2. EVN observations

The nuclear region of NGC 6240 was observed using the EVN in phase-referencing mode. On 30 October and 10 November 2003 (epoch 1), 1.6 and 5.0 GHz observations were made, using seven elements of the EVN. In the second epoch (epoch 2), 2.2, 5.0, and 8.4 GHz observations were conducted on 16 and 17 June 2009 by employing the nine EVN elements. The four or eight 8 MHz IF bands with dual polarization were recorded at a recording rate of 256 Mbps (epoch 1) or 512 Mbps (epoch 2). The rms noise of the EVN images ranges from $\sim$0.055 to 0.13 mJy beam^{-1}.

3. Results and Discussion

The EVN observations resulted in the detection of four compact sources: the two nuclei, N1 and N2, at higher frequencies of 5.0 and 8.4 GHz, and two new compact sources near N1, RS1 and RS2 (Fig. 1). RS1 is resolved and located southwest of N1 at both 5.0 and 8.4 GHz, while RS2 is detected northeast of N1 at 1.6 and 5.0 GHz. Fig. 1 displays the EVN images of N1 plus RS1 and N2 at 5.0 and 8.4 GHz. RS1 has remained visible at 5.0 GHz for nearly 6 years since the first detection in epoch 1. The brightness temperatures of the two nuclei at 5.0 GHz are 2-6 $\times$ 10^6 K. High brightness temperatures exceeding 10^6 K argue for an AGN nature for these nuclei. The east-west continuum structure of N2 (extending about 10 pc) may suggest a core-jet structure that is typically seen towards AGN. However, this extended structure may not be real because of insufficient phase and amplitude calibration: self-calibration was not possible because of low signal-to-noise ratios of the images.

Fig. 2 indicates that the spectra of N1 and N2 show a frequency turnover at lower frequency, without significant flux variation of the continuum between epochs. The inverted spectrum of N1,

PoS(10th EVN Symposium)083

including the upper limits, would indicate free-free absorption. Alternatively, this may be due to SSA or a combination of FFA and SSA. Fig. 2 shows a fitted curve of the N2 spectrum using a pure FFA or an SSA model, assuming the same foreground opacity to all parts of N2. Both models do not result in a good fit for the N2 spectral data, suggesting that it cannot be explained by these pure models. Any SSA at N2 is not likely as there is no compact source with a brightness temperature exceeding $\sim 10^{11}$ (K). However, the spectrum at N2 is clearly turning over at lower frequencies, which is suggestive of absorption occurring through an ionized gas in the foreground of the nuclei.

VLA/MERLIN observations at lower angular resolutions [3, 2] do not show a frequency turnover, indicating that the absorbing clouds structures are very compact ($<$ 10pc). N1 looks more compact and would be considered the most dominant AGN in the galaxy based on the detections of the 6.4 keV Fe line [8] and the H_2O maser at the nucleus [5]. Considering these aspects, we conclude that the southern nucleus N1 hosts both an AGN and a starburst region. The presence of an AGN in N1 remains an open question. The new compact radio source (RS1) identified in the 5.0/8.4 GHz images (Fig.1) is $\sim$ 10 pc southwest of N1 and the new radio source (RS2) $\sim$100 pc northeast of N1. The radio power of these sources (1.7–3 $\times$ 10^{21} W Hz^{-1}) is comparable with those of the brightest RSN in Arp220 [10]. The possibility that RS1 could be ejecta, i.e. jet component, from the AGN may be ruled out because it shows relatively flat ($\alpha \simeq 0.3$) and it has remained in the same location (within limits) over about 6 years. It is thus most likely that both RS1 and RS2 are Type-II young radio supernovae and are part of a circum-nuclear starburst at N1, which is consistent with the earlier VLBI detections of other radio compact sources near the nuclei [4].

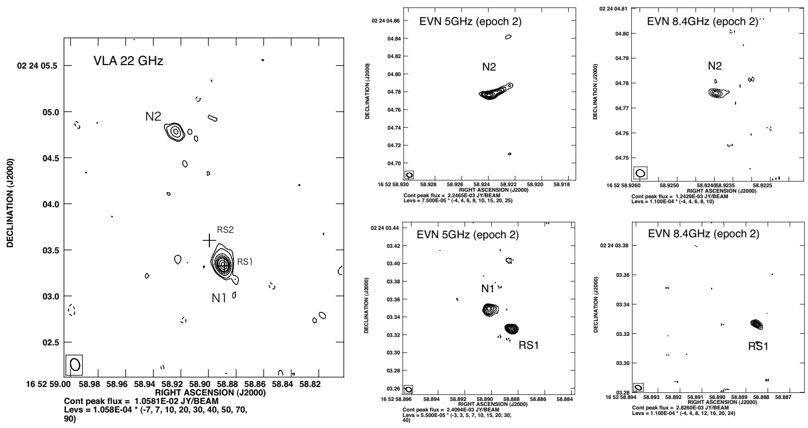

Figure 1: Radio continuum images of the nuclear region made with the VLA and the EVN at the epoch 2. The 22 GHz radio continuum map of the nuclear region, obtained with the VLA in A-configuration in 2008 and 2009, indicates two radio nuclei labeled as N1 and N2 [7]. The positions of the new radio components, RS1 and RS2, are denoted by a cross in this image. Four radio continuum images of the nuclear region made with the EVN at 5.0 GHz and 8.4 GHz at epoch 2 have been displayed. The 1.6 GHz and 5.0 GHz images obtained at epoch 1 in late 2003 were presented in [6]. The synthesized beams at 5.0 GHz and 8.4 GHz are about 6.1 $\times$ 4.9 mas and a3.4 $\times$ 2.8 mas, respectively. The synthesized beams have been displayed in the bottom left corner of each image.

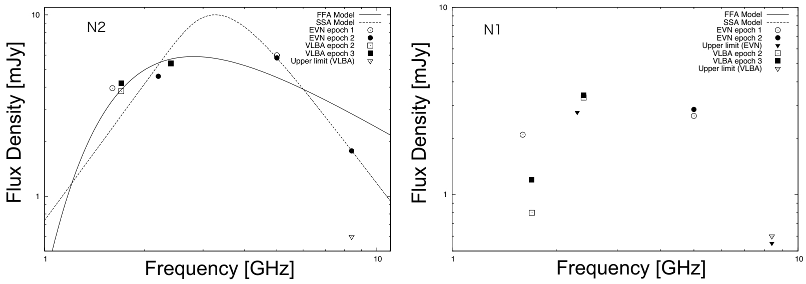

Figure 2: Radio continuum spectra of the two nuclear components N1 and N2 at frequencies of 1.6, 2.2, 5.0, and 8.4 GHz. Open and filled circles show data from the EVN epoch 1 and the EVN epoch 2, respectively. Open and filled squares display data from the earlier VLBA observations. All upper limit values at 2.2 and 8.4 GHz are for 5 σ. *Left*: The spectrum of the northern nucleus, N2. The solid line represents the free-free absorption (FFA) model fitted to the EVN epoch 1 and 2 data, assuming no significant flux density variation between the two observing epochs. The dotted line represents the synchrotron self-absorption (SSA) model fitted to the same data in the case of FFA. *Right*: The spectrum of the southern nucleus, N1.

4. Conclusion

The two epochs of VLBI observations using the EVN allowed us to resolve the nuclear radio components at higher frequencies of 5.0 and 8.4 GHz. The detected two nuclei in NGC6240 seem to have both an AGN and a circum-nuclear starburst with SNe. We have detected at least two variable compact radio sources with a relatively flat spectrum near the southern nucleus whose structures are unresolved on scales of a few parsecs. Both of these components could be interpreted as long-lived Type-II radio supernovae resulting from an ongoing circum-nuclear starburst in the southern nucleus.

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