Baltic Astronomy, vol. 14, 420–424, 2005.

SUBPARSEC-SCALE IMAGING OF EXTRAGALACTIC H_2O MASER EMISSION

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Received: 2004 December 1

Abstract. The results of the VLA observations at sub-arcsec angular resolutions of 22 GHz H_2O masers in the starburst galaxy M 82 and active galaxies NGC 4051 and NGC 6240 are presented. The VLA measurements enable one to explore the connection of these masers with active galactic nucleus (AGN)-activity. The masers in these galaxies have relatively low luminosity, which suggests that the origin of these H_2O masers is due not to the nuclear activity of host galaxies but to the exotic extragalactic star formation.

Key words: galaxies: ISM, active, starburst – masers

Since the discovery of extragalactic H_2O masers 25 years ago, there has been much progress in studies of H_2O masers in active galactic nuclei (AGNs). H_2O masers with high-luminosity ($L_{\mathrm{H_2O}} > 10\ L_\odot$) have been predominantly detected in narrow-line AGNs like LINERs and Type 2 Seyferts, which confirms a connection of the masers with AGN-activity, while low-luminosity ($L_{\mathrm{H_2O}} < 1$–$10\ L_\odot$) H_2O masers appear to arise in star-forming sites rather than in AGNs. The latter populations are not always intense enough for interferometric observations, but it is of great interest to image unfamiliar extragalactic star-forming phenomena on the subparsec scales.

NGC 6240 ($D = 97$ Mpc) has two compact radio nuclei with an angular separation of about 1.5″. H_2O maser emission ($L_{\mathrm{H_2O}} \sim 40\ L_\odot$) was convincingly detected for the first time at Effelsberg in 2001, and the emission is highly red-shifted by some 400 km s^{-1} with respect to the systemic velocity of $V_{\mathrm{LSR}}= 7131$ km s^{-1} (Figure 1) (Hagiwara et al. 2002). Follow-up VLA observations were carried out from 2001 to mid-2002, one of which results is the solid detection of the maser peaked on $V_{\mathrm{LSR}}= 7610$ km s^{-1} only towards the southern nucleus (S in Figure 1); however, the emission remains spatially unresolved (Hagiwara et al. 2003a). There was, however, no evidence for maser emission in the northern nucleus (N in Figure 1). The maser coincides with the continuum peak in S within an uncertainty of ~0.007″ or 3 pc. The detected maser may well probe the position of one of the double-nuclei, and the AGN-activity of the galaxy is more dominant at S than N. The X-ray detection of Fe lines at 6.4 keV towards S suggests that a scattering source, i.e., AGN lies at least in S (Komossa et al. 2003). If the maser arises from a tangential point in the receding side of a rotating disc, the presence of blue-shifted counterparts of the red-shifted features, showing a symmetrical velocity distribution, would be expected. However, until now no such counterpart has

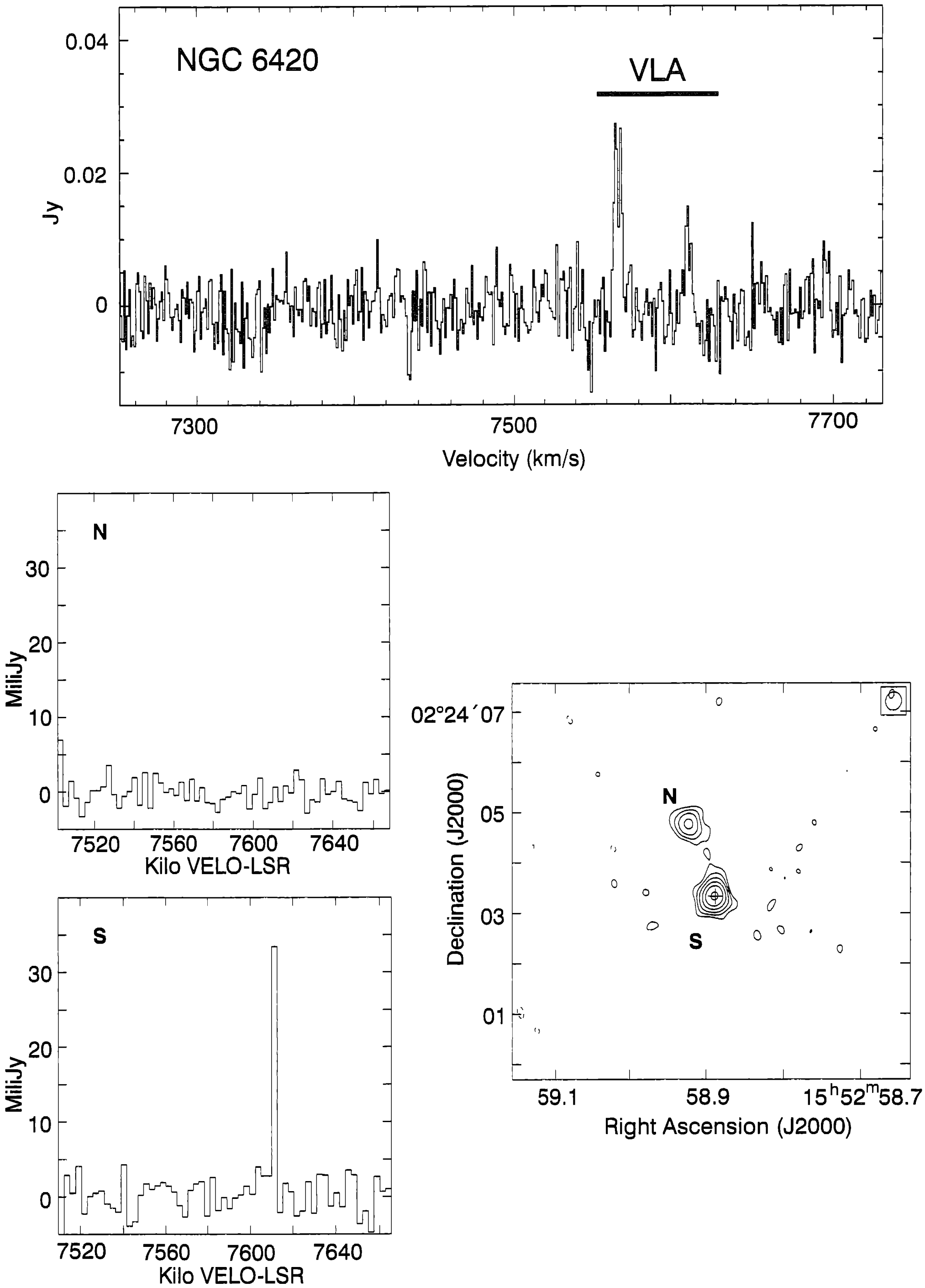

Fig. 1. Top panel: single-dish spectrum of the water maser emission in NGC 6240 obtained at Effelsberg, including the velocity coverage of VLA observations. The spectrum displays two distinct maser features, red-shifted more than 400 km s^{-1} with respect to the systemic velocity of the galaxy ($V_{\rm LSR}$ = 7131 km s^{-1}). Bottom panel: VLA spectra of the maser towards the double nuclei N and S (Hagiwara et al. 2003a).

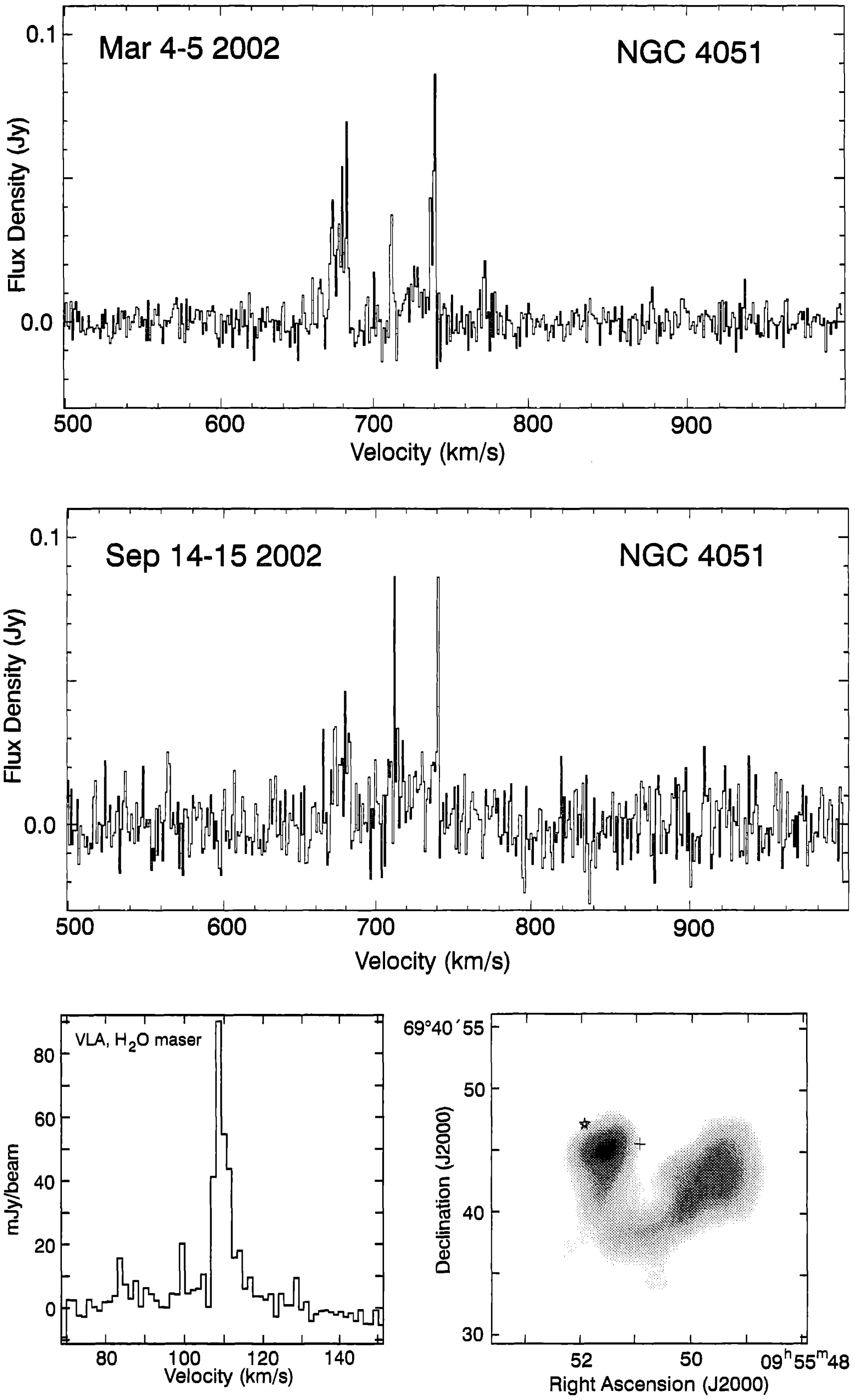

Fig. 2. Top and middle panels: single-dish maser spectra of NGC 4051 taken at Effelsberg (Hagiwara et al. 2003b). The systemic velocity is $V_{\rm LSR} = 730\pm5$ km s^{-1}. Bottom-left panel: blue-shifted H_2O maser spectrum of M 82, observed with VLA in A-Configuration. Bottom-right panel: the location of the H_2O maser (indicated by a cross) in M 82, superposed with a CO (J = 1–0) integrated-intensity map. CO intensity integrated over $V_{\rm LSR}$ = 118–212 km s^{-1} (Matsushita et al. 2000). An infrared nucleus is marked by a star.

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been found within 800 $\mathrm{km\,s^{-1}}$ of the systemic velocity. It is possible that the red-shifted maser emission is associated with the jet-activity of AGN. Alternatively, the large red-shift of the maser could trace infall of molecular gas into an active nuclei under the influence of galaxy-galaxy merger.

NGC 4051 ($D = 9.7$ Mpc) is a Type 1 Seyfert galaxy with a narrow-line emission region. Hagiwara et al. (2003b) discovered H_2O maser emission ($L_{H_2O} \sim 2\ L_\odot$) for the first time in a Type 1 Seyfert nucleus. A VLA snapshot was carried out several weeks after the detection in 2002. Several narrow Doppler-shifted features of the maser were tentatively detected at $\sim 3\,\sigma$ noise level. The positions of most of the maser features were identified within a $\sim 0.04''$ region. The features peaked at $V_{\mathrm{LSR}}=$ 712 $\mathrm{km\,s^{-1}}$ and 740 $\mathrm{km\,s^{-1}}$ are coincident with the 8.4 GHz nuclear radio continuum to $\sim 0.1''$, or 5 pc. These masers could be associated with AGN-activity. The low-luminosity (2 $L_\odot$) of the maser and the smaller Doppler-shifts of any maser features can be explained by a lower inclination angle of a disk-like intervening medium to the line of sight (LOS) of a disk. The proposed low disk-inclination model is consistent with the observed smaller LOS velocities ($v_{\mathrm{los}} = v_{\mathrm{rad}} \sin i$, i is the disk inclination angle) of the high-velocity components in a disk. The low disk inclination (30–40°) in NGC 4051 would reduce the apparent LOS velocities by about 40–50 per cent as compared to those in a more edge-on disk ($i > 70°$). However, one cannot rule out that the low-luminosity maser in NGC 4051 is associated with star-forming activity.

M 82 (D = 3.5 Mpc) is a nearby star-forming galaxy observed with a number of molecular lines. Although the luminosity of H_2O maser emission in the galaxy is low $\sim 0.1\ L_\odot$, it represents a unique opportunity to study a less extreme form of maser emission in a region of high star formation. The VLA observations were conducted in 2002 to constrain the positions of the blue-shifted maser to sub-arcsec. The main velocity coverage of the observation was from $V_{\mathrm{LSR}} \simeq$ 70 $\mathrm{km\,s^{-1}}$ to 150 $\mathrm{km\,s^{-1}}$, blue-shifted with respect to the systemic velocity of M 82 ($V_{\mathrm{LSR}}=$ 203 $\mathrm{km\,s^{-1}}$). All the detected maser features (Figure 2) were coincident within the VLA synthesized beam of $0.1''$. The H_2O maser tentatively detected with the MERLIN is split into two separate clusters with the separation of 0.02 arcsec, 0.35 pc. The positions of the maser and the nucleus of M 82 are plotted in a CO(1–0) intensity image (Figure 2). The maser seems to lie at the inner edge of the super-bubble structure probed by CO(1–0) emission (Matsushita et al. 2000); however, the velocity range of the maser ($V_{\mathrm{LSR}}=$ 84–115 $\mathrm{km\,s^{-1}}$) does not overlap that of the CO bubble ($V_{\mathrm{LSR}}=$ 118–212 $\mathrm{km\,s^{-1}}$). In contrast, the maser is located in molecular clouds traced by the CO(2–1), and the velocities of the maser are similar to those of the clouds (Weiss et al. 2001). The blue-shifted ($V_{\mathrm{LSR}} \simeq$ 84–115 $\mathrm{km\,s^{-1}}$) and red-shifted ($V_{\mathrm{LSR}} \simeq$ 320–370 $\mathrm{km\,s^{-1}}$) velocities of the maser straddle the systemic velocity of $V_{\mathrm{LSR}}=$ 203 $\mathrm{km\,s^{-1}}$. Note that low-luminosity water masers generally indicate the site of star formation. With this in mind, the spatial coincidence of the maser with OH maser (A. Pedlar, private communication) and CO clouds may indicate that the maser is associated with a molecular outflow. The angular sizes of the Galactic molecular outflows observed in H_2O maser are typically 0.01–0.1 pc, similar to the maser in M 82. VLBI observations are necessary to resolve the distribution of the maser.

ACKNOWLEDGMENTS. I acknowledge the contributions of W. Baan, P. J. Diamond, M. Miyoshi and E. Rovilos.

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