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Title: The Water Maser in II Zw 96: Scientific Justification

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Science Justification

Scientific Aims

1. **Assess the relationship between hydroxyl and water megamasers**
   It has broadly been believed that OH and H_2O megamasers must exclude each other due to their respectively narrow range of physical conditions each species demands for masing (see e.g. Lonsdale 2002, Lo 2005). Our recent confirmation of a water megamaser in a known OH megamaser host (II Zw 96; Wiggins et al. in review) is the second known galaxy after Arp 299 to challenge this norm. A reassessment of this paradigm is warranted, calling for VBLI followup on II Zw 96. A spatial correlation between OH and H_2O emission as has been found in Arp 299 (Tarch et al. 2010) would point to a largely unanticipated brotherhood between the two megamaser species (Tarchi 2012).

2. **Identify the cause of dual megamaser emission in II Zw 96**
   The apparent lack of simultaneous water and hydroxyl megamasers and their recently discovered ability to coexist has important implications for interpreting or possibly predicting megamasers. To determine whether conditions in II Zw 96 and Arp 299 are simply unique or whether these galaxies are undergoing a brief but common stage of evolution along the merger sequence can only be determined by locating and imaging the water megamaser. Meaningful connections or contrasts between the II Zw 96 and Arp 299 systems can then be drawn, allowing for a more robust interpretation of simultaneous emission in the context of the current megamaser paradigm.

3. **Determine the pumping mechanism for OH megamaser in II Zw 96**
   II Zw 96 is the host of one of the most powerful, off-nuclear, obscured starbursts known (Inami et al. 2010) and there is evidence for a possible off-nuclear AGN (Migenes et al. 2010), both of which are candidate pumping mechanisms for the water maser (see Wagner 2013). If the water megamaser appears in region C and is image-able, it could be used to discriminate between possible pumping sources or even confirm the presence of a contested obscured AGN in the source.

We propose a VLBI search to image and locate the water emission in II Zw 96. We propose 3 sites within II Zw 96 for VLBI followup (see the proposed target listing below). We request 2.5 hours of on-source integration time with the VLBA per source. The array will achieve $\sim 65\mu$Jy sensitivity in K band in this time which will be sufficient to detect luminous water maser features.

Background

Megamasers are powerful probes of extragalactic phenomena. They have been employed to constrain Hubble's constant (e.g. Humphreys et al. 2013; Reid et al. 2013; Kuo et al. 2013; Braatz et al. 2010; Herrnstein et al. 1999), probe the parsec-scale environments of AGN, obtain highly accurate supermassive black hole mass estimates (e.g. Greene et al. 2013; Kuo et al. 2011; Reid et al. 2009), and estimate the galaxy merger rate (Darling 2002). Megamasers also possess the exciting potential to serve as diagnostics of galaxy evolution at high redshift when the host galaxy itself cannot be resolved (see Pihlström 2007). Understanding the environments in which megamasers arise is critical in searches for megamasers and accurately interpreting maser activity.

Most megamasers are created by either hydroxyl or water molecules. Luminous hydroxyl emission generally accompanies intense star formation ("starbursting") while water megamasers are associated with AGNs (see

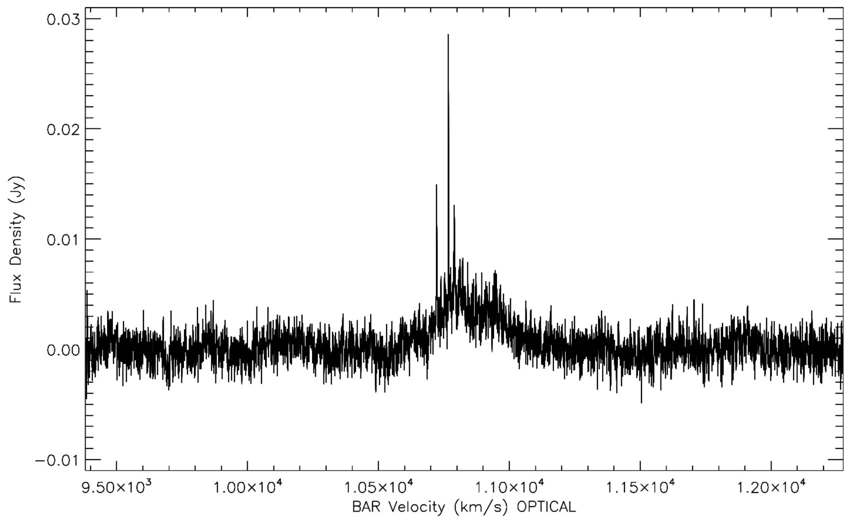

Figure 1: 22 GHz line detection toward IIZw96 after 1 hour of integration, baseline removal and 4 channel boxcar smoothing (see Wiggins et al. in review, arXiv:1504.07194). Our study found multiple luminous narrow features on the blue "hump" of II Zw 96 strongly suggestive that some water maser emission is compact and so could be detectable by VLBI. RMS noise is 1.22 mJy. This figure was generated in GBTIDL.

Lo 2005 for a review). For their remarkable utility, however, megamasers present a series of standing issues. Predicting megamasers or distingushing megamaser galaxies from those without megamasers is an open question in the literature (e.g. Darling & Giovanelli 2006; Zhang 2012; Zhu 2011; but also see Constantin 2012; Darling 2007; Zhang et al. 2006; Kondrakto e al. 2006). Interestingly, though starbursting and AGN activity frequent the same galactic nucleus (e.g. Dixon et al. 2001), hydroxyl and water megamasers until recently had never been observed in the same galaxy. The lack of simultaneous water and hydroxyl detections lead to the hypothesis (Lonsdale 2002) the hydroxyl and water masers exclude each other and that water appears as hydroxyl megamasers are destroyed as a starbursting nucleus transitions to an AGN. This view was supported by the fact that each molecule demands different and respectively narrow conditions to mase[1]. However, new work is now calling this well-accepted paradigm into question.

Open Issues

The relationship between OH and H_2O megamasers and their respective relationship to galactic processes is likely more complicated than previously believed. Simultaneous water and hydroxyl megamasers were discovered in IC 694, a galactic nucleus in the Arp 299 merger system (Tarchi et al. 2010), a discovery which calls the Lonsdale hypothesis mentioned above into question. Studies of this exotic object reveal a buried AGN (Perez-Torres et al. 2010) in addition to vigerous starbursting which could explain the simultaneous emission. However, it is possible that Arp 299 occupies a very narrow phase of galaxy evolution (e.g transition between starburst and AGN nucleus), which could explain the general lack of simultaneous emission of megamasers in both molecular species elsewhere (see Tarchi 2012). Water emission was then tentatively detected toward II Zw 96, an established OH megamaser host (Wagner 2013). In our recent survey for water emission among OH megamaser galaxies (Wiggins, Migenes & Smidt 2015, in review, arXiv:1504.07194), we confirmed to 8σ a bone fide water megamaser toward II Zw 96 (see Figure 1), establishing it as the second galaxy to co-host dual megamasers. This finding opens a range of questions. Other similarities between II Zw 96 and Arp 299 have been celebrated in the literature (e.g. Goldader et al. 1997). Is II Zw 96 simply an Arp 299 "look-alike" or does this finding suggest a brotherhood (Tarchi 2012) between megamaser species for

[1] OH masers are created at $\sim$ 160 K with relatively high gas densities through FIR pumping while water is collisionally pumped (de Jong 1973) at yet higher temperatures ($\sim$ 300 K) and yet higher densities.

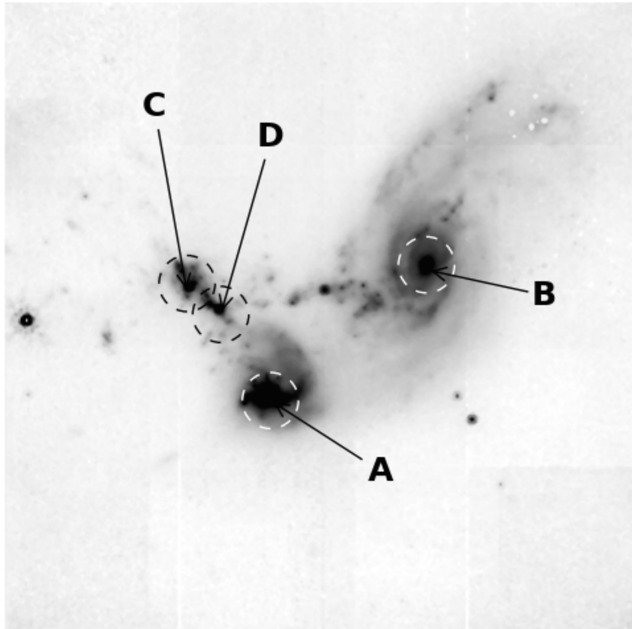

Figure 2: Sites A, C and D are our proposed VLBI targets (see Table 1) within II Zw 96. (e.g. Inami et al. 2010). Approximate fields of view limited by time-smearing for 1s time integration ($\sim$ 2 arcseconds) in K band for the VLBA are superimposed as dashed circles. It is possible that water emission originates from multiple regions within II Zw 96. Credit: HST.

which no previous evidence has been found? Only VLBI folllow-up to pinpoint the location of the megamaser in II Zw 96 will adequately explore this question.

In Figure 1, we note our discovery of narrow features in II Zw 96's water maser emission, strongly suggestive of compact emission which could be located by VLBI. The VLBA is the best suited instrument in the world for this study. This work will be a part of a doctoral thesis in physics and astronomy.

Proposed Targets within II Zw 96

Our proposed sites are indicated by letters B-D in Figure 2. The complex II Zw 96 system offers a wealth of environments in which to search for water megamasers, with various components of the system in different stages of interaction. The location of the water maser would offer insight into not only how but possibly when water emission appears along the merger sequence. In the event the full requested time cannot be granted, we note that not all sites have equal priority. We discuss the proposed sites below.

- **Sites C and D. (20:57:24.47 +17:07:39.9; 20:57:24.34 +17:07:39.1)** ***High priority.***
The reddish globs comprising sites C and D are the home of the OH megamaser (Migenes et al. 2010). They are the strongest sources of IR emission and appear to be an obscured off-nuclear starburst (Inami et al. 2010) though the region is distinguished from A by a very strong, hard (2-7 keV) x-ray flux for its relative size and is the second strongest emitter in Hα. Doppler broadening of the OH emission line to 200 km s^{-1} could indicate the presence of heavily obscured AGN in region C (Migenes et al. 2010). We anticipate that water emission originates from these regions . If water emission is found in region C, the only confirmed galaxies with dual megamasers would host both species of megamasers in the same spatial region. Analysis of the water maser spots in position and velocity space will link the water emission to one of the proposed pumping mechanisms for the maser, the established starburst (Wagner 2013) or a rare, off nuclear obscured AGN (Migenes et al. 2010).

- **Site A. (20:57:24.09 +17:07:35.3)** ***Moderate priority***
Bright blue region which is the dominant source of Hα (Migenes et al. 2010) and soft x-rays (0.5-2 keV) and the principle site of UV emission (Inami et al. 2010): an unobscured star burst. The authors judge this to be the second most likely position for the water maser.

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