VLBA PROPOSAL COVERSHEET

BW 89

rcvd: 5-26-07

DEADLINES: 1st of Feb., June, Oct.
EMAIL TO: proposevn@HP.mpifr-bonn.mpg.de
OR MAIL TO: EVN Scheduler, MPIfR, Auf dem Hugel 69, D-53121 Bonn, Germany
EMAIL TO: propsoc@nrao.edu
OR MAIL TO: Director NRAO, Edgemont Rd. Charlottesville, VA 22903-2475, USA

(1) Date Prepared: May 26, 2007

(2) Title of Proposal: **Radio Emission from the Intermediate-Mass Black Hole in NGC 4395**

(3) AUTHORS (Add * for new location)	INSTITUTION	E-mail	G/U	Students Only: For Thesis?	Students Only: Ph.D. Year
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L. C. Ho	Carnegie Observatory	lho@ociw.edu			

(4) Related previous or current VLBI proposal(s): BW046, BW080, BM251, BW087 ○ Resubmission

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(7) Scientific Category: ○ astrometry & geodesy ○ galactic ⊗ extragalactic ○ other:
Rapid Response Science: ○ Known Transient ○ Exploratory ○ Target of Opportunity

(8) Wavelength(s) requested (those not available on the global network are indicated with a small circle):
○ 90cm ○ 50cm ∘ 30cm ⊗ 21cm ○ 18cm ○ 13cm ○ 6cm ∘ 5cm ○ 3.6cm ○ 3.6/13cm
∘ 2cm ○ 1.3cm ○ 7mm ∘ 3mm
○ Global Network standard bands ⊗ Special frequencies: Where VLBA gains are measured at 1.4 GHz.

(9) Recording format: ○ Default continuum setup (VLBA only), ⊗ VLBA/MkIV, ○ MkIII: Mode
Bandwidth per BaseBand channel: 8
Aggregate bit rate: 512 (16 BB channels at 16 MSamples/sec of ○ 1 bit, ⊗ 2 bit)

(10) ○ Multi-epoch observation: ____ epochs of ____ hours each, separated by ____

(11) Network	Requested antennas	Total time requested
EVN & MERLIN		
VLBA	HSA = VLBA+Y27+GBT+AR+EB	8 hours (AR 2 hours; EB 6 hours)
other NRAO		
Non-VLBI Intruments		

(12) ABSTRACT (Do not write outside this space. Please type)

The Seyfert 1 nucleus of NGC 4395 is energized by a black hole of mass $3.6 \times 10^5 M_\odot$, making it one of only three nuclear black holes of intermediate mass, $\sim 10^3 - 10^6 M_\odot$, detected in the radio regime. Building upon UV and X-ray evidence for outflows from this Seyfert nucleus, we used the HSA at 1.4 GHz to search for extended structure on scales greater than 5 mas (0.1 pc). Elongated emission was discovered, extending over 15 mas (0.3 pc) and suggesting an outflow on subparsec scales from this intermediate-mass black hole (Wrobel & Ho 2006, ApJ, 646, L95). We propose follow-up HSA imaging of this suspected outflow, with improved resolution and sensitivity, to strengthen the case for an outflow and to characterize its substructure, sidedness and length scale. The follow-up HSA imaging will also confirm or refute hints of extranuclear emission in the vicinity of a blue *HST* arc and improve the search for emitters in the nuclear star cluster hosting the intermediate-mass black hole.

Scheduler use only

(13) Observation type: ⊗ Interferometry, ○ Spectroscopy, ○ Pulsar, ⊗ Phase referencing

(14) Proposal is ○ Suitable ⊗ Unsuitable for dynamic scheduling.

(15) Polarization: ○ Single Polarization ⊗ Dual Circular Polarization
Global network standard for single polarization is LCP for all λs except 13cm (RCP) and 3.6cm (RCP).

(16) Tape usage (Show <recording time>/<total time>): ______

(17) Assistance required:
Observation Setup: ○ Consultation, ○ Extensive help, ○ Observe file preparation
Postprocessing: ○ Consultation, ○ Extensive help, ○ Calibration service

(18) Processor: ⊗ Socorro, ○ JIVE, ○ Haystack, ○ Bonn, ○ Washington, ○ Other ______
Special processing: ⊗ XPol, ○ Pulsar gate, ○ Multiple Fields: ______
Averaging time: ______ Spectral channels per baseband channel: ______
○ Other special processing: ______

(19) Postprocessing Location: NRAO-SOC

(20) Source list: ⊗ J2000 ○ B1950
If more than 4 sources, please attach list. If more than 30, give only selection criteria and GST range(s)

	Source 1	Source 2	Source 3	Source 4
Name(s)	NGC 4395			
RA (hh mm)	12 25 48.8774			
Dec (dd.d)	+33 32 48.715			
GST range (Europe)	14-20 h EB			
GST range (US)	14-22 h			
GST range (Other)	16-18 h AR			
Band(s)	L			
Flux density (Total, Jy)	0.0017			
Flux density (correlated, mJy)	$\sim$ 0.2			
RMS needed (mJy/beam)	$\sim$ 0.005			
Peak/RMS needed	$\sim$ 40			

(21) Preferred VLBI session or range of dates for scheduling, and why:
2007 April when NGC 4395 is a nighttime target, to reduce ionospheric effects.

(22) Dates which are NOT acceptable, and why:

(23) Attach a self-contained scientific justification, not in excess of 1000 words.
Preprints or reprints will not be forwarded to the referees.

Information about the capabilities of the VLBA may be found on the World Wide Web by starting at the NRAO home page, http://www.nrao.edu, and selecting the VLBA from "Sites and Telescopes."

A brief summary of the capabilities of the EVN antennas is given in the EVN STATUS TABLE in the EVN USER GUIDE, which may be found at http://www.evlbi.org/user_guide/user_guide.html.

Please include the full postal addresses for first-time users or for those that have moved (if not contact author).

Scientific Justificaton

Dynamical studies have established that supermassive black holes, with masses $10^6 - 10^9 M_\odot$, occur in the nuclei of most nearby galaxies with stellar bulges. The focus has now turned to searches for intermediate-mass black holes (IMBHs), with masses about $10^3 - 10^6 M_\odot$, in nearby galactic nuclei. Finding IMBHs will help to define the nature of the seed black holes that figure in models for the growth of black holes over cosmic time and to predict the gravitational radiation background expected for *LISA* due to mergers of IMBHs. In this mass regime, dynamical searches currently fail beyond the Local Group and are being replaced by surveys for signatures of active galactic nuclei (AGNs) [5]. Such AGN searches are strongly guided by the discovery of a candidate IMBH in NGC 4395 [3], for which a recent reverberation study [16] finds a mass of $3.6 \times 10^5 M_\odot$ with a factor of three error. NGC 4395 is a bulgeless Sdm galaxy at a Cepheid distance of 4.3±0.3 Mpc with a scale 0.021 pc mas^{-1} [18]. Its nucleus has the emission properties of a Seyfert 1, with broad permitted emission lines [3,4,16] and a hard X-ray source that is highly time-variable [12,17,19].

Building upon UV and X-ray hints of outflows [2,12,17] as well as a VLBA detection [20], we used the HSA to search for extended structure at 1.4 GHz on scales greater than 5 mas (0.1 pc). As shown in Figs. 1-2, elongated emission was discovered, extending over 15 mas (0.3 pc) and suggesting an outflow on subparsec scales [21]. For NGC 4395, the energizing IMBH has an Eddington ratio of only $\sim 1.2 \times 10^{-3}$ [16]. Two other candidate nuclear IMBHs have VLA detections [6,10]. But those candidates are much more distant and, with Eddington ratios near unity, may well have radio structures quite different from NGC 4395. Given the uniqueness and proximity of NGC 4395, its suspected subparsec outflow deserves HSA follow-up, as argued below. Two parsec-scale topics also require HSA follow-up and are described below.

1. Substructure in the Outflow: The bolometric luminosity of the nuclear IMBH in NGC 4395 in highly sub-Eddington [16]. By analogy with supermassive black holes and stellar-mass black holes, such an Eddington ratio suggests that this IMBH is in a low/hard or quiescent state and, thus, is expected to launch a steady polar outflow [7,14]. The elongated structure in Fig. 2 is indeed suggestive of a radio outflow on subparsec scales [21]. But the resolution and sensitivity of the HSA images only provide approximate structural information. By repeating the HSA observation with EB added, we will improve the (uniform) angular resolution by a factor of about 0.8. This will allow us to strengthen the case for an outflow from this IMBH, as well as to seek evidence for a core or other features in the outflow. We will also be able to investigate the sidedness of the outflow in terms of free-free absorption and/or relativistic boosting, concepts not yet applied to the environs of a nuclear IMBH.

2. Length Scale of the Outflow: Twenty of the 44 low-luminosity AGN (LLAGN) surveyed at mas resolution by [13] show structure on subparsec scales. Six of those 20 have subparsec scale structures with weak or no known larger scale jets, perhaps because the jet does not propagate beyond the inner few parsecs. For NGC 4395 at 1.4 GHz, its steep-spectrum VLA source lacks adjacent emission and has the same integrated flux densities for deconvolved sizes of 10-40 pc, whereas the HSA imaging traces a suspected outflow on subparsec scales [8,21]. Given these VLA and HSA properties, NGC 4395 was added to the subset of LLAGN whose known emission does not extend beyond the inner few parsecs. Still, a subparsec scale for the suspected HSA outflow corresponds to 10^7 Schwarszchild radii for the nuclear IMBH, very different from the upper limits of 10^3 to 10^4 Schwarszchild radii inferred for several LLAGN with flat radio spectra [1].

The potential importance of outflows in mediating black-hole growth has been highlighted by [15], motivating an estimate of the kinetic luminosity of the suspected outflow from NGC 4395. The requisite ancillary data are, as yet, unavailalble. But by analogy with the similar LLAGN in M51, a kinetic luminosity on the order of the bolometric luminosity, $\sim 5.4 \times 10^{40}$ ergs s^{-1} [16], could be available in NGC 4395. Approximating the radio luminosity of NGC 4395 as the product of the frequency times power, the luminosity of the emission recovered in Fig. 1 is 2.4×10^{34} ergs s^{-1}. Although this radio luminosity is about six orders of magnitude below the bolometric luminosity of the Seyfert nucleus, the HSA imaging helps set a characteristic length scale for the available kinetic luminosity [21]. Fig. 1 recovers 0.74 mJy but Fig. 2 recovers only 0.63 mJy. We need to image the missing 0.11 mJy. We also need to try to trace the outflow beyond 15 mas (0.3 pc). We will do this by repeating the HSA track with EB and AR added, thus improving the (uniform) angular resolution by a factor of about 0.8 and the (natural) sensitivity by a factor of about 0.5.

3. The Faint Five-Parsec Feature: In WFPC2 B-band and I-band images, there are two features to the west, a small blue arc offset by 250 mas (5.2 pc) and an extended blue plume offset by about 1 arcsec (21 pc). These two features probably trace [OIII] emission from gas within a nuclear ionization cone [11]. We retrieved the WFPC2 data from the *HST* archives and analyzed those data, but we were unable to improve upon the results presented in [11]. As reported in [21], there are HSA hints of 5 σ = 0.05 mJy beam^{-1} emission about 250 mas (5.2 pc) to the west of the Seyfert nucleus, thus in the vicinity of the small blue arc [11]. Fig. 3 shows a naturally-weighted image which is slightly improved over that discussed in [21]. The 5 σ = 0.048 mJy beam^{-1} feature is labelled. While the reality of this feature is still uncertain, it could be a clue about the location of some of the $\sim$ 1 mJy missing between VLA [8] and HSA [21] scales. HSA imaging with improved sensitivity could confirm or refute this faint extranuclear emission. If we are able to confirm the reality of this faint feature, it could have profound implications for the length scale of the outflow from the Seyfert nucleus. Moreover, might the structure of the faint radio feature, near the blue *HST* arc, hint at a termination shock? Given the demise of the ACS on board the *HST*, HSA imaging might be the only way to investigate - admittedly indirectly - an [OIII] shock origin for the blue arc [11].

4. The Eight-Parsec Star Cluster: In a WFPC2 I-band image, the Seyfert nucleus is located at the center of a nuclear star cluster with a half-light diameter of 380 mas (8.0 pc) [4]. Little is known about the cluster's stellar populations. There is no UV evidence for the P Cygni profiles expected from winds from massive OB stars [3]. The calcium infrared triplets are detected, indicating that red supergiants are present [4]. To further constrain the stellar populations, the naturally-weighted HSA image was searched for cluster emitters [21]. None were found above 5 σ = 0.05 mJy beam^{-1}. This remains the case from Fig. 3, where the large circle shows the half-light diameter (380 mas = 8.0 pc) of the nuclear star cluster. The associated radio luminosity is $< 2 \times 10^{33}$ ergs s^{-1}. For perspective, [9] finds that ultraluminous X-ray sources typically have radio luminosities $< 2 \times 10^{34}$ ergs s^{-1}. HSA imaging with better sensitivity (and at another epoch) would improve the search for radio emitters in the nuclear star cluster.

Technical Justification

We will follow our successful HSA=VLBA+Y27+GBT strategies for BW080 [21], using phase referencing with a switching angle of 1.5d, a switching time of 5 minutes, including some astrometric/coherence check sources, and integrating on-source for about 4 hours during a total time of 8 hours (for u-v coverage). We now add EB for a total of 6 hours to improve the (uniform) angular resolution by a factor of about 0.8; this is essential for item 1 above. We also double the bit rate from 256 to 512 Mbps and add AR for a total of 2 hours, thereby improving the (natural) sensitivity by a factor of about 0.5; this is essential for items 2, 3 and 4 above.

Three VLBA antennas are especially key. The MK antenna is needed to provide the long baseline to EB, essential for item 1 above; and the SC and PT antennas are needed to provide the short baselines to AR and Y27, respectively, that are essential for items 2 and 3 above. We request nighttime observations in 2007 April, to reduce ionospheric effects. The phased VLA, recording at only 256 Mbps, will probably be in its C configuration with a synthesized beam of about 19 arcsec at FWHM. The HSA field of view, for a 10-percent peak reduction, will be limited by bandwidth smearing to about 8 arcsec.

References

[1] Anderson et al. 2004, apj, 603, 42
[2] Crenshaw et al. 2004, apj, 612, 152
[3] Filippenko et al. 1993, apj, 410, L75
[4] Filippenko & Ho 2003, apj, 588, L13
[5] Greene & Ho 2004, apj, 610, 722
[6] Greene, Ho & Ulvestad 2006, apj, 636, 56
[7] Ho 2005, apss, 300, 219
[8] Ho & Ulvestad 2001, apjs, 133, 77
[9] Koerding et al. 2005, aa, 436, 427
[10] Miller et al. 2007, in preparation
[11] Matthews et al. 1999, aj, 118, 208
[12] Moran et al. 2005, aj, 129, 2108
[13] Nagar et al. 2005, aa, 435, 521
[14] Narayan 2005, apss, 300, 177
[15] Pellegrini 2005, apj, 624, 155
[16] Peterson et al. 2005, apj, 632, 799
[17] Shih et al. 2003, mnras, 341, 973
[18] Thim et al. 2004, aj, 127, 2322
[19] Vaughan et al. 2005, mnras, 356, 524
[20] Wrobel et al. 2001, apj, 553, L23
[21] Wrobel & Ho, 2006, apj, 646, L95

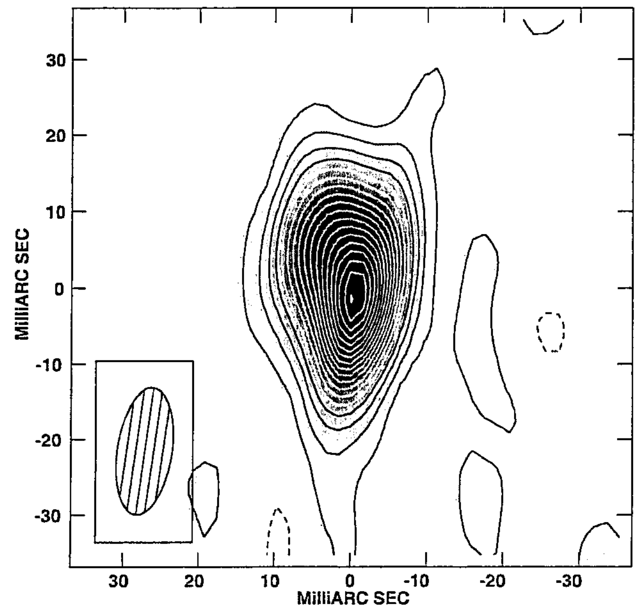

Figure 1: *HSA image of Stokes I emission from the Seyfert nucleus of NGC4395 at a frequency of 1.4 GHz and spanning 70 mas (1.5 pc) per coordinate [21]. Epoch is 2005 May 1. Natural weighting was used, giving an rms noise of 0.010 mJy beam*$^{-1}$ *(1* σ*) and beam dimensions at FWHM of 17 mas (0.4 pc) by 7.2 mas (0.2 pc) with elongation PA -8d (boxed ellipse). The grey scale spans* -0.04 *mJy beam*$^{-1}$ *to the peak of 0.36 mJy beam*$^{-1}$*. The contours are at -6, -4, -2, 2, 4, 6, 8, 10, 12, 14, ... 36 times* σ*. Negative contours are dashed and positive ones are solid.*

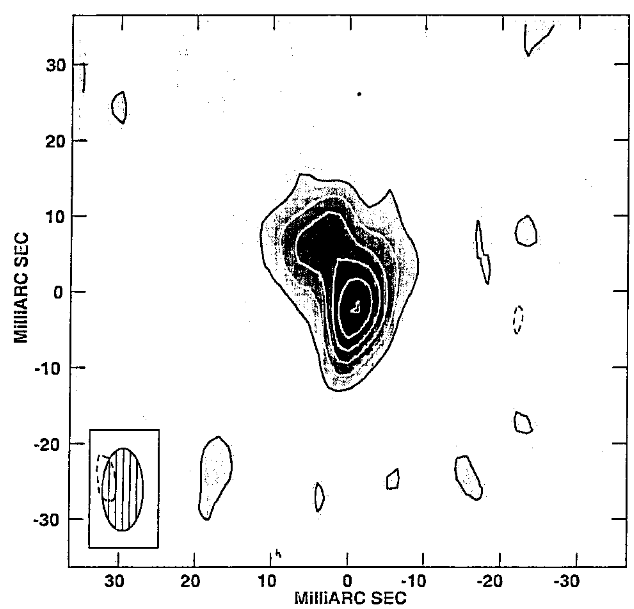

Figure 2: *As for Fig. 1 but robustness parameter of -0.3, giving an rms noise of 0.019 mJy beam*$^{-1}$ *(1* σ*) and beam dimensions at FWHM of 11 mas (0.2 pc) by 5.4 mas (0.1 pc) with elongation PA 0d (boxed ellipse). The grey scale spans* -0.04 *mJy beam*$^{-1}$ *to the peak of 0.23 mJy beam*$^{-1}$*. The contours are at -6, -4, -2, 2, 4, 6, 8, 10, and 12 times* σ*.*

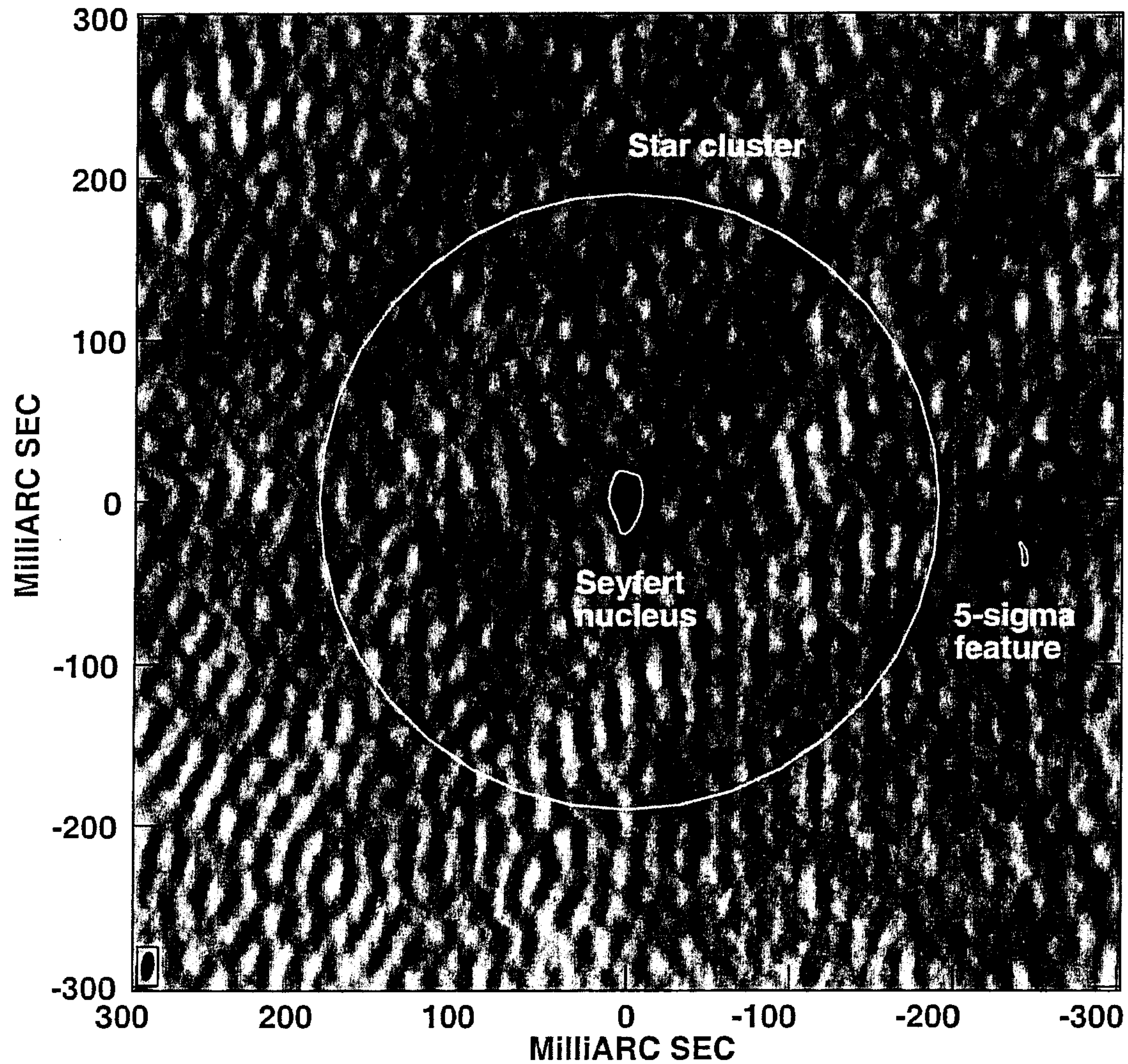

Figure 3: *As for Fig. 1 but spanning 600 mas (13 pc) per coordinate. This naturally-weighted image is slightly improved over that discussed in [21] and has an rms noise of 0.0097 mJy beam*$^{-1}$ *(1* σ*). The grey scale spans* ± 0.0048 *mJy beam*$^{-1}$*. The contours are at -5 and 5 times* σ*. The Seyfert nucleus is labelled. The 5* σ *feature about 250 mas (5.2 pc) to the west of the nucleus is labelled; this feature is near the blue HST arc [11]. The large circle indicates the half-light diameter (380 mas = 8.0 pc) of the nuclear star cluster [4].*