Observing Application

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Legacy ID :	BC195
PI :	Kenneth Cavagnolo
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IMAGING THE MISDIRECTED QSO OF IRAS 09104+4109

Abstract:

We propose 20 cm and 6 cm observations of the uncommon, low-redshift, ultraluminous infrared (ULIRG), brightest cluster galaxy (BCG) IRAS 09104+4109 (I09), which is known to harbor an obscured quasar (QSO) that is beaming radiation in a direction nearly orthogonal to a pair of symmetric large-scale jets. Our proposed observations will resolve the nuclear radio structure and help us constrain, or definitively determine, the origin of the misalignment. For example, a single supermassive black hole (SMBH) may have undergone a dramatic realignment of its spin axis in the last million years, there may be multiple active SMBHs in the nucleus, or a single active SMBH may have a binary partner. Investigation of these scenarios will yield insight to the relationship between BCG assembly, SMBH formation, and evolution of the AGN/QSO feedback paradigm. The milliarcsecond resolution and sub-mJy sensitivity of VLBA are required for such a study.

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Related proposals:

Joint:

Not a Joint Proposal

Observing type(s):

Continuum

VLBA Resources

Name	Wavelength	Processor	Stations	Observing Parameters	Correlation Parameters

Name	Wavelength	Processor	Stations	Observing Parameters	Correlation Parameters
VLBA 6 cm	6 cm	Socorro-DiFX	VLBA ✓ Br ✓ Fd ✓ Hn ✓ Kp ✓ La ✓ Mk ✓ Kp ✓ Ov ✓ Pt ✓ Sc ✓ HSA Ar Ef GBT VLA-Y27 VLA-Y1 Geodetic	Bandwidth: 8 MHz Baseband Channels 4 Sample Rate (Msample/s) 16 Bits/Sample 2 Polarization RCP & Agg. Bit Rate (Mbits/sec) 128	Full Polarization ✓ Pulsar Gate Correlator Passes 1 Integration Period (sec) 4 Spectral Points /BBC 16 No of Fields 1
VLBA 21 cm	21 cm	Socorro-DiFX	VLBA ✓ Br ✓ Fd ✓ Hn ✓ Kp ✓ La ✓ Mk ✓ Kp ✓ Ov ✓ Pt ✓ Sc ✓ HSA Ar Ef GBT VLA-Y27 VLA-Y1 Geodetic	Bandwidth: 8 MHz Baseband Channels 4 Sample Rate (Msample/s) 16 Bits/Sample 2 Polarization RCP & Agg. Bit Rate (Mbits/sec) 128	Full Polarization ✓ Pulsar Gate Correlator Passes 1 Integration Period (sec) 4 Spectral Points /BBC 16 No of Fields 1

Sources:

Name	Position		Velocity		Group
IRAS09104+4109	**Coordinate System**	Equatorial	**Convention**	Redshift	VLBA
	Equinox	J2000			
	Right Ascension	09:13:45.494 00:00:00.0	**Ref. Frame**	LSRK	
	Declination	+40:56:28 00:00:00	**Redshift**	0.4418	

Sessions:

Name	Session Time (hours)	Repeat	Separation	GST minimum	GST maximum	Elevation Minimum
IRAS09	12.00	1	0 day	00:00:00	24:00:00	0

Session Constraints:

Name	Constraints	Comments

Session Source/Resource Pairs:

Session Name	Source	Resource	Time	Figure of Merit
IRAS09	IRAS09104+4109	VLBA 21 cm	6.0 hour	0.038 mJy/bm
IRAS09	IRAS09104+4109	VLBA 6 cm	6.0 hour	0.039 mJy/bm

Staff support: Consultation Plan of Dissertation: no

SCIENTIFIC JUSTIFICATION

Unlike most ULIRGs, I09 is a BCG, but unlike most BCGs, I09 hosts a heavily-obscured QSO which gives rise to the enormous IR luminosity [7, 10, 12]. Hines et al. [11] convincingly demonstrate that beamed QSO radiation is emerging from the nucleus in a direction coincident with a photoionized, [O III]-dominated nebula (see Fig. 1), and Cavagnolo et al. [1] further show that the X-ray emission associated with this region is well-modeled as QSO irradiation of the nebula and surrounding intracluster medium (ICM). Additionally, there is a spur of radio emission protruding from the nucleus which is coincident with the nucleus beaming direction. The observational evidence strongly indicates the presence of an active nucleus with a beaming axis directed to the NE of I09. However, the beamed emission is significantly misaligned with the large-scale radio jets which run NW & SE from the nucleus [10, 11]. Further, the radio source is a peculiar borderline FR-I/II with a core spectrum which is significantly flatter than the jets, so much so that it appears the jets are no longer being fed by the nucleus [10]. The beamed nuclear radiation and jets clearly constitute two distinct physical systems, but are their origins one in the same? Is there a single SMBH in the nucleus which created the jets and is now beaming in a dramatically new direction? Or could it be that the nucleus hosts multiple SMBHs with anisotropic spin axes? Assuming SMBH spin, beaming, and jet axes are co-aligned, the central engine of I09 was re-oriented no less than 70 kyr ago [11], but no more than ~ 10 Myr [1] adding a further constraint on the processes which caused the misalignment. But while understanding the nature of the I09 nucleus is interesting in its own right, I09 is also an important low-redshift analog of higher-redshift systems where the majority of SMBH formation and massive galaxy/BCG assembly occurs.

Most galaxies harbor a central SMBH which likely co-evolved with the host galaxy, giving rise to well-known correlations between bulge luminosity, stellar velocity dispersion, and black hole mass [13, 14]. It is believed that a key element of the co-evolution, in addition to mergers, is energetic feedback from accreting SMBHs, either in a radiatively-dominated quasar-mode [*e.g.* 18] or a kinetically-dominated radio-mode [*e.g.* 3]. The quasar-mode is expected to be brief, expelling large quantities of cold gas from the host galaxy, whereas the radio-mode is prolonged & intermittent, heating the extended hot halo (*e.g.* the ICM) such that future cooling is regulated. As evidenced by AGN excavated cavities in X-ray halos, there are numerous examples of systems dominated by mechanical feedback [*e.g.* 8], and there are indications that many high-redshift galaxies are dominated by QSO feedback [22]. But, in a unified feedback model, there are expected to be "transition" systems which bridge the dominance of one mode over another. I09 is curious because it has cavities in the X-ray halo ($L \sim 10^{44}$ erg s^{-1}) and a powerful QSO ($L \sim 10^{47}$ erg s^{-1}), prompting Cavagnolo et al. [1] to suggest, among other reasons, that I09 is a "transition" system and that the beam-jet misalignment is signaling the evolution of the feedback mode from radiation dominance to mechanical dominance. The implication being that we are getting a glimpse of a very short-lived epoch of the AGN/QSO feedback cycle, and thus I09 provides us the opportunity to study how SMBH evolution relates with the host environment. But a key to advancing this understanding is further resolving the nucleus.

Simply put, a multitude of models and explanations are possible for the misalignment, and evaluating these models in the context of the feedback paradigm first requires resolving the nuclear structure. For example, rapid spin axis realignment is predicted in some black hole merger scenarios, *e.g.* the "spin flip" model of [15]. But, rapid jet reorientation can also occur as a result of accretion disk instabilities [5]. There is the remote possibility that the beaming direction has not been altered at all, but what we are witnessing is the jet outflow being diverted by external pressure gradients causing a back-flow [*e.g.* 21]. Or, there may simply be two or more SMBHs. Another tantalizing model is that of retrograde spin evolution [9]. In this model SMBHs are expected to pass through a low spin state where a massive accretion flow would be capable of rapidly changing the spin axis. But in this model, the kinetic power output of the AGN (which we have directly estimated with the X-ray cavities) is tied to the handedness of the SMBH spin relative to the accreting material. The difference between these scenarios being that, the number of nuclear sources, the synchrotron power of the accretion disk, and the sub-kpc scale jet structures are fundamentally different: pairs of continuous, deformed jets versus sparse, distinctly separate jet pairs; one point source versus more than one point source; the connection of the small-scale jets to the large-scale jets. If we find the family of models which involve mergers are consistent with the I09 nucleus, then it suggests I09 is a reasonable template for similar massive galaxies. But if the more rare processes like spin-slip or retrograde spin evolution seem to be more appropriate, then I09 would seem to be an oddity in the massive galaxy formation model.

It is also worth noting that the radio spur NE of the core does not have a SW counter-spur. The proposed observations will reveal whether there is a counter-jet or if the system is one-sided. This determination will yield insight regarding the inclination of the beaming axis. This information will be used to further constrain the orientation and structure of obscuring nuclear material, which has been the focus of extensive study, but with some ambiguity [*e.g.* 19, 20].

Additional radio observations are needed to directly image the synchrotron emission of relativistic particles which are markers of on-going process which are below the sensitivity and resolution limits in other wave-bands, *i.e.* X-ray, optical, and UV. While I09 has been observed at the highest resolution attainable with the VLA, the sub-arcsecond capabilities of the VLBA are needed to further probe the nuclear structure and minimize confusion between multiple radio sources. Technical details of our requests are discussed in the next section.

TECHNICAL JUSTIFICATION

To determine the observational parameters needed to achieve our scientific goals, the highest-resolution VLA images were used as a guide and subsequent exposure times calculated using the EVN Calculator[1]. The I09 radio core has a flux of 1.6 mJy at 6 cm (4.9 GHz) and 5.9 mJy at 20 cm (1.5 GHz). The VLA A-configuration observations at 6 cm ($\approx 0.4'' \times 0.3''$ beam) and 20 cm ($\approx 1.3'' \times 1.2''$ beam) have respective peak flux densities of 1.0 mJy beam^{-1} and 4.6 mJy beam^{-1}, and both have off-axis $\sigma_{\rm rms}$ of ≈ 35 μJy beam^{-1}. We find that for a VLBA setup with 2 polarizations, 4 sub-bands per polarization, and 8 MHz of bandwidth, an integration time of 360 min will result in image thermal noise (1σ; natural weighting) of ≈ 38 μJy beam^{-1} for L-band (21 cm) and ≈ 40 μJy beam^{-1} for C-band (6 cm) with an aggregate bit rate of 256 Mbps (2 bit sampling). This is comparable to the VLA noise levels which resulted in high-quality imaging. The maximum half-power beam-widths will be ≈ 5.0 mas at 21 cm and ≈ 1.4 mas at 6 cm, with respective time-smearing limited field-of-views (FOVs) of $10.8''$ and $3.1''$ (shown in Fig. 1). For a ΛCDM cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1} , $\Omega_{\rm M} = 0.27$, and $\Omega_\Lambda = 0.73$, these resolutions equate to 30 pc at 21 cm and 8 pc at 6 cm. The requested observations are sufficient to yield 3σ detections of sources with fluxes $\gtrsim 1$ mJy and obviously resolve structures separated by $\gtrsim 10$ pc. Observing I09 during two 6 hr sessions will ensure excellent *uv* coverage and sufficiently deep observations to yield reliable imaging of the rich GHz intensity structure.

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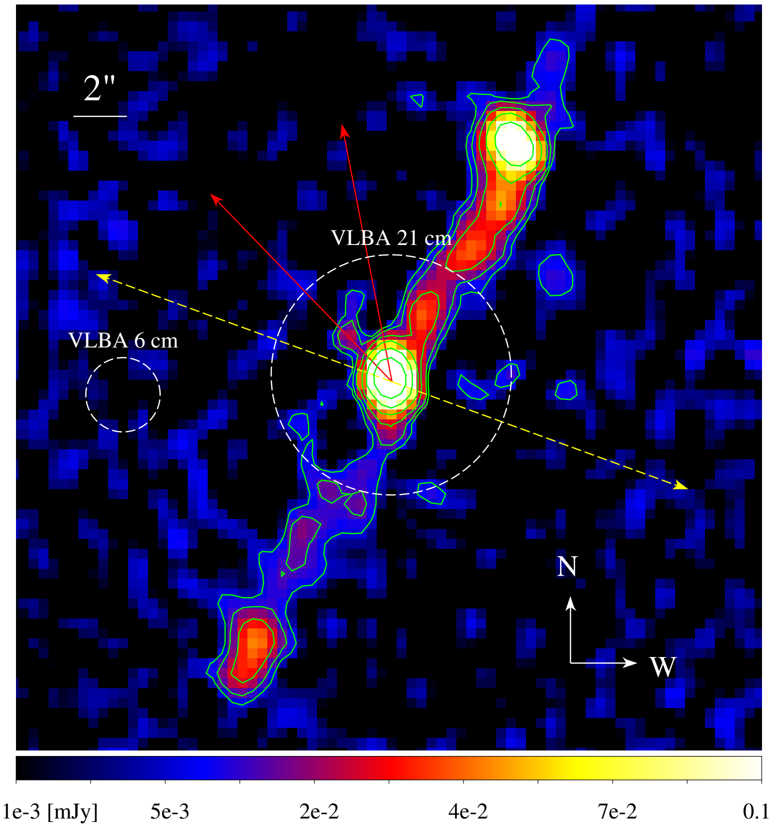

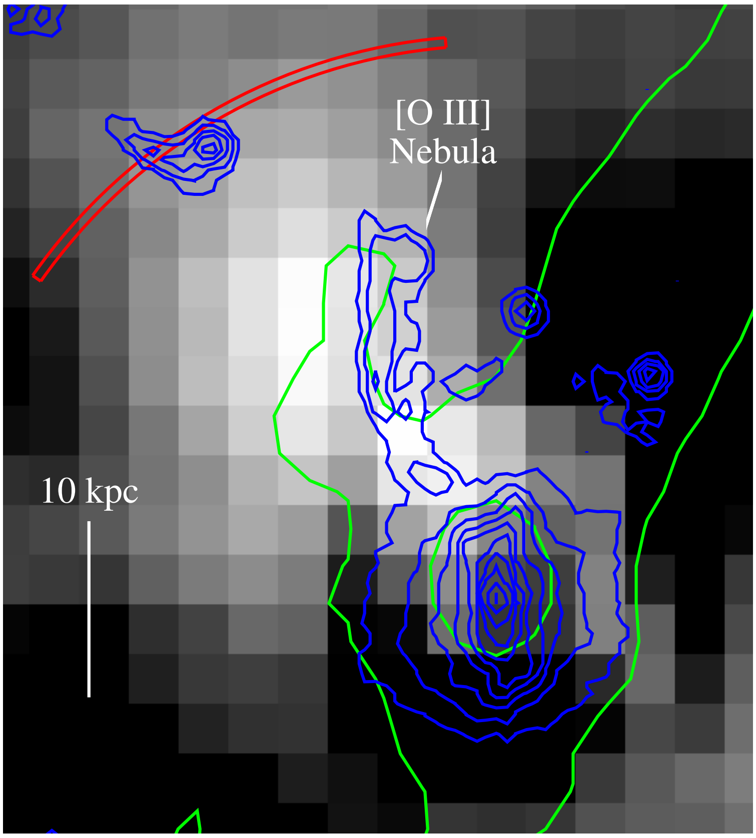

Figure 1: *Left*: 20 cm VLA A-configuration image in mJy. Green contours trace 20 cm emission, dashed white circles denote VLBA FOVs, dashed yellow vector is semi-major axis of RX J0913.7+4056, and red vectors bound QSO beaming direction. *Right:* X-ray image of RX J0913.7+4056 core after subtracting off ICM emission. Green contours are lowest and highest significance 20 cm emission, blue contours are optical emission, and red wedge marks the extent of scattered UV emission.