Observing NGC 4151 with the Keck Interferometer

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ABSTRACT

Observations of the nucleus of NGC 4151 at 2.2 μm using the two 10-meter Keck telescopes as an interferometer show a marginally resolved source less than or equal to 0.1 pc in diameter. These observations are the first measurement of an extragalactic source with an optical/IR interferometer. These observations represent a ten-fold improvement in angular resolution when compared to previous near-infrared measurements of AGN and make it possible to test the subparsec-scale, near-infrared emission models of NGC 4151.

Keywords: interferometer, AGN.

1. Introduction

Active Galactic Nuclei (AGN) have the unique ability to generate more power than an entire galaxy in a region a light year or less in diameter. The mechanism for this energy release is thought to require accretion of matter onto a black hole millions of times more massive than our sun. The extent to which the light we see in these galaxies comes directly from the accretion disk or from clouds of gas or dust that *reprocess* energy from the accretion disk is key to so-called unification schemes that attempt to unify various classes of apparently different AGN. One of the nearest and most easily studied AGN lies in the Seyfert galaxy NGC 4151; however, the source of the near-infrared emission has not been clear. This paper discuss novel high-angular resolution measurements[1] that imply the near-infrared emission in this source is unexpectedly compact, < 73 light days in diameter. The most plausible interpretation of this and other results is that the compact infrared source is mainly thermal emission from a central accretion disk. This would imply that an AGN accretion disk can generate substantial near-infrared emission and that AGN unification models invoking hot, optically thick dust may not be universally applicable to Seyfert galaxies.

NGC 4151 is the nearest and brightest Seyfert (a class of relatively low-powered active galactic nuclei) and has been identified as the "archetype"' of Seyfert 1 galaxies[2]. Because the origins of the nuclear infrared emission, which dominates galactic near-infrared emission, have been unclear, NGC4151 has also been identified as "one of the most enigmatic" of galaxies[3]. Over the past 30 years, arguments for both thermal and nonthermal emission mechanisms (primarily synchrotron) have been proposed[2]. Evidence of K band variability on 1—2 month timescales[4,5,6] and low (0.1—0.5%) degrees of H and K band linear polarization[7,8] can be explained by both thermal and nonthermal models. Recently, the prevailing view has been that the near-infrared emission is thermal and arises from the inner edge of a dust torus[9] that is heated primarily by UV and soft X-ray emission from the corona of the accretion disk surrounding a massive black hole. In this picture, the source of the near-infrared emission would appear spatially unresolved by the largest single aperture infrared telescopes and would have low polarization. Observations[2] at 11 μm strongly imply the presence of a 10 pc diameter source where dust grains are heated to around 200 K and are responsible for the mid-infrared emission. Estimates for the inner radius of the dust, which could correspond to the inner edge of a torus, have ranged from as small[5] as about 0.03 pc, to as large as values in the 0.2—1 pc range favored more recently[9—11]. In some AGN unification schemes, the torus is supposed to be optically and physically thick[9]. The radius of the broad line region[12] (BLR) is about 0.01 pc, putting the smallest estimates of the dust torus' inner radius very close to the black hole and accretion disk.

The parent galaxy for the NGC 4151 Seyfert nucleus is nearly face-on (i=21° to the line of sight) and has a weak radio jet[13] at P.A.= 77° E. of N. While the radio feature corresponding to the UV/optical nucleus has been uncertain, the candidate features contain emission knots that are unresolved[13,14] on angular scales of a few milliarcseconds and have a surface brightnesses of a few mJy/beam. The 2MASS K band flux for NGC 4151 is 8.519 +/- 0.018 magnitudes, and at

least 90% of the flux is contained[7] in the central 1 arcsecond. The bolometric luminosity of the AGN is about 10^{44} erg/s, and a 10^7 solar mass black hole is thought to lie at the center of the broad line region[15]. The distance[13] to NGC 4151 is taken as 13.3 Mpc (for H_0=75 km/s), where 1 milliarcsecond corresponds to 0.065 pc (75.3 light days) in projection.

The nucleus of NGC 4151 was observed at 2.2 μm using the two 10-meter Keck telescopes as an interferometer. Interferometric combination of the twin Keck telescopes[16] provides sensitivity to 2.2 μm emission on angular scales of ~1 milliarcsecond. The angular resolution of these observations is sufficient to test the subparsec-scale, near-infrared emission models of NGC 4151 and represents an order of magnitude improvement with respect to previous observations. Optical/IR interferometry has traditionally been limited to relatively bright stellar objects. These observations represent the first measurement of an extragalactic source with an optical/IR interferometer.

2. Observations

The Keck Interferometer optics transport and combine the light from the two 10 m Keck telescopes. These telescopes are separated by 85 m with the baseline position angle oriented 38° (E of N). Both telescopes are equipped with adaptive optics systems[17], which are required for K band interferometer observations. The interferometer field of view on the sky is approximately one diffraction-limited resolution element of the Keck telescopes, ~50 milliarcseconds in the K band, and is set by a single-mode fiber ahead of the detector; the interferometer is not sensitive to emission outside of this field of view. The fringe tracker uses a 4-bin synchronous fringe demodulation[18] algorithm, similar to that used at the Palomar Testbed Interferometer[19]. For the data presented here, the system operated at a 200 Hz frame rate (corresponding to 0.05 seconds for the 4-bin acquisition time).

No development mentioned

NGC 4151 was observed with the Keck Interferometer on 2003 May 20 and 21. The data shown in Fig. 2 are from the white-light channel (λ_{center}=2.16~μm and $\lambda/\Delta\lambda$ ~0.3 μm). The observations consist of a series of interleaved integrations on the source and several calibrators. Each integration includes 120 seconds of fringe data followed by a background measurement. Accompanying the fringe data are periodic measurements of the single-telescope fluxes. The data are shown as the visibility amplitude squared, normalized such that an unresolved object has V^2=1.0. On May 20, only limited data were collected on NGC 4151 and calibrators due to weather; however, the source was detected and resolved on both nights, with internally consistent visibility. The results discussed here use data from 21 May.

The system visibility, the instrument response to a point source, was measured with respect to the calibrator stars HIP58918, HD 105925, and HIP60286. The calibrator angular sizes were derived by fitting photometry from SIMBAD and 2MASS. All of the calibrators have estimated angular diameters of less than 0.2 milliarcseconds and are unresolved by the interferometer. The calibrator angular size uncertainty was set to 0.1 milliarcseconds. Source and calibrator data were corrected for bias using sky calibrations[20] and averaged into blocks of 5 seconds each. The calibration procedure includes a per-scan correction for the bias due to mismatched fluxes between the two telescopes (which includes Strehl mismatch) using the single-telescope flux measurements.

The data were then calibrated for the system visibility[21]. The calibrated data points for the target source are the average of the 5 second blocks in each integration, with an uncertainty given by the quadrature of the internal scatter and the uncertainty in the calibrator size. In addition to the measurement error, any systematic error[22] in the calibrated visibility was estimated to be less than 0.05. This systematic error was summed quadratically with the measurement and calibration errors. The resulting average visibility is 0.84 +/- 0.06 at an average projected baseline of 82.7 m at a P.A. = 37° E of N. The calibrated visibilities and the system visibility estimates are shown in Fig. 2.

NGC 4151 is a difficult source to observe with the Keck Interferometer for several reasons. First, the adaptive optics system must be run at a fairly low loop because the nuclear available optical emission in NGC 4151 is reduced by the current interferometer infrared extraction dichroic. The effect of running the adaptive optics system at a low loop rate is to reduce the average value of the Strehl and possibly to increase Strehl fluctuations. Second, the H band nuclear emission from NGC 4151 is sufficiently faint that the interferometer angle tracker must be run at a slower loop rate. Third, the K band nuclear emission in NGC 4151 is near the current limit of the interferometer fringe tracker performance. Reduced Strehl values further reduce the light available to the fringe tracker. In addition, interferometer angle tracking errors create intensity fluctuations due to the spatial filter used in the fringe tracker optics. The result of

the combination of these effects is that NGC 4151 can only be observed with the Keck Interferometer during nights with relatively good seeing. During the past year, attempts at follow-up observations on this object have not been successful due to weather.

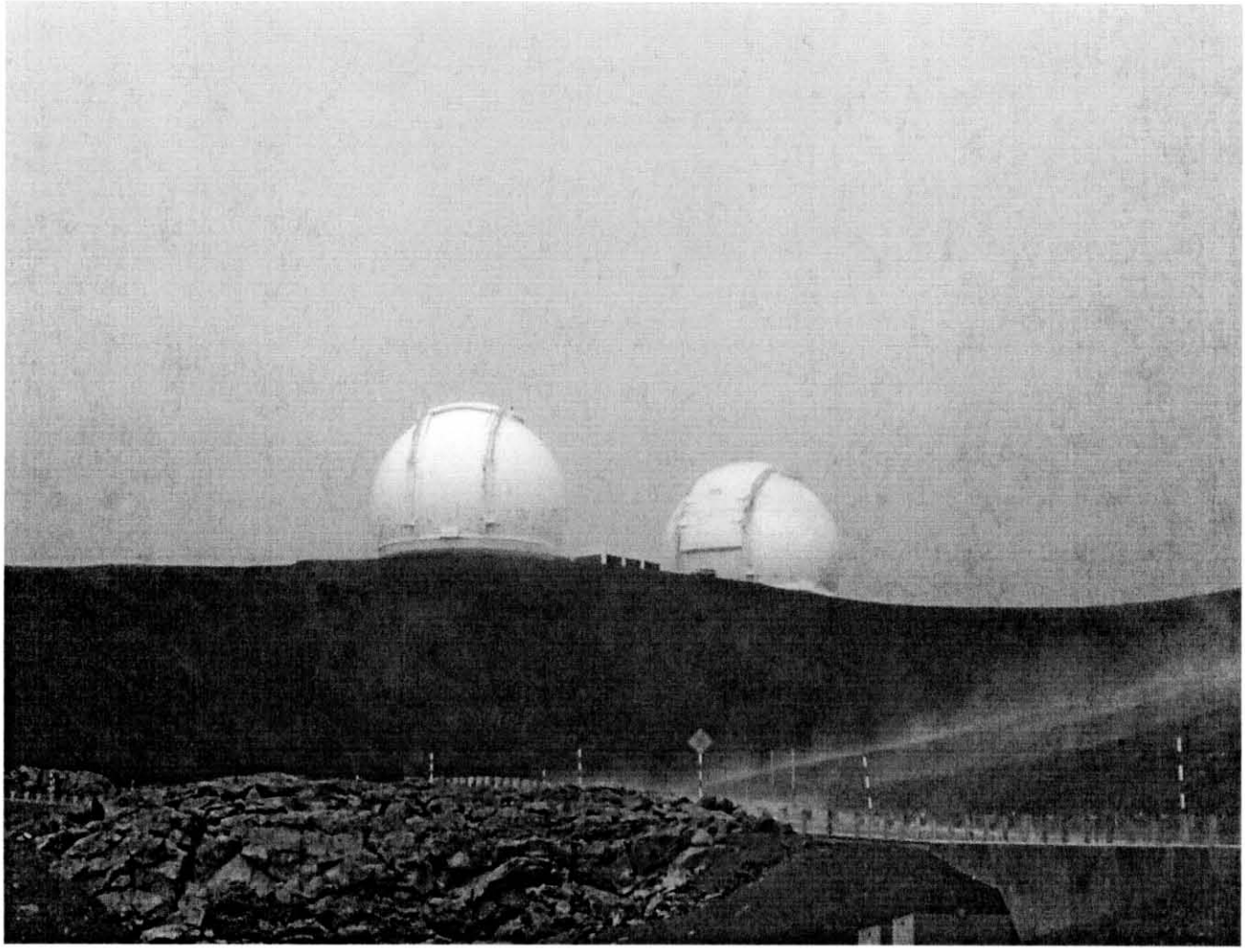

Fig. 1. The twin 10 meter Keck telescopes are located on the summit of Mauna Kea. The interferometer beam transport and combination optics are housed in the basement of the building connecting the two telescopes.

3. Discussion

3.1 Compact Emission

The calibrated V^2 would be unity if all the light in the interferometer field of view (approximately the diffraction limit of the single telescope) came from an unresolved point source. The calibrated V^2 for NGC 4151 is relatively high, implying the source of this emission is small; at the three sigma level, the measured V^2 is consistent with a point source.

The current data set cannot distinguish between a variety of flux distributions that could result in the measured visibility. However, limits to the contribution from resolved and unresolved emission components can be estimated in the context of a model. Also, any emission overresolved at the interferometer fringe spacing yet within the 50 milliarcsecond field of view decreases the measured V^2. The following simple models have been used to estimate the angular size of the

emission; the models are "face-on" and are constrained to fit the measured V^2. In the case of the ring model, the width is set to match the total K band flux for an optically thick medium with a temperature of 1500 K.

- Gaussian: FWHM = 0.98 +/- 0.18 milliarcseconds
- Ring: inner diameter = 0.96 +/- 0.26 milliarcseconds; width = 0.06 milliarcseconds
- Point Source + Extended: Point-source flux = 0.92 +/- 0.04 of the total flux

The models imply that whatever the details of the emission distribution or mechanism, the bulk of the emission comes from a compact (less than or equal to 1.52 milliarcseconds) region. The measurements rule out any scenario with a majority of the K band nuclear emission coming from a region with a radius larger than 0.05 pc at the 3 sigma level.

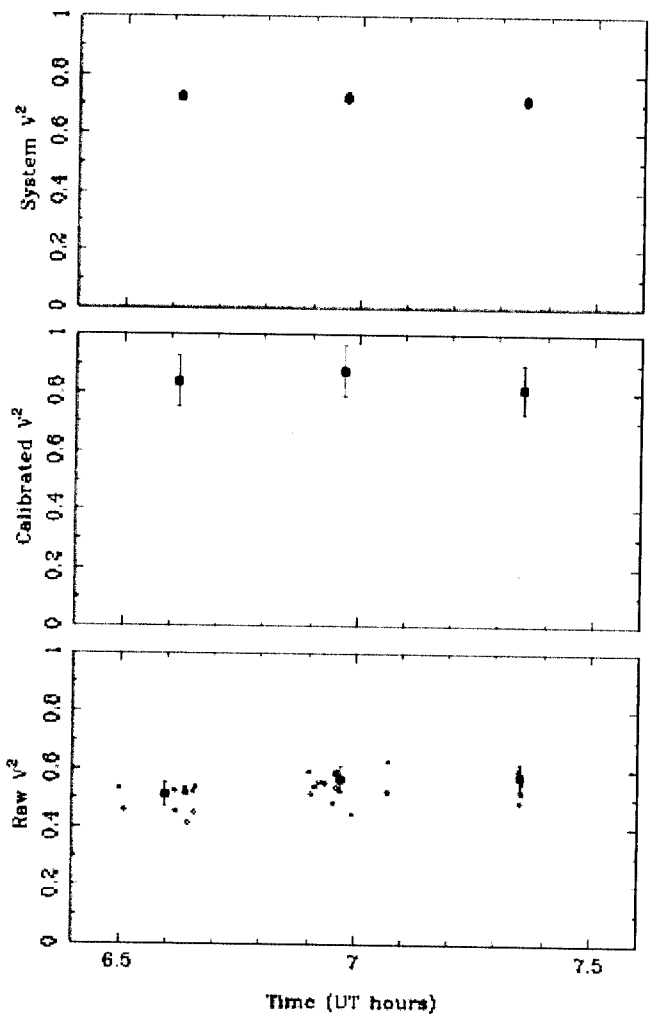

Fig. 2. Raw (bottom), calibrated (middle), and system visibility (top) for NGC 4151. In the plot of the raw data, the 5-second averages are shown with open circles and the scan averages (130 seconds) are shown with filled squares. The calibrated visibility is 0.84+/- 0.064; the error bars in the calibrated data contain a 5% systematic component. The hour angles for the averaged points are 0.03, 0.33, and 0.71 hr, respectively. The projected baseline length ranges from 81.8 to 83.6 m, and the position angle ranges from 39.3° to 33.9° (East of North). The errors in the V^2 estimator are dominated by the systematic error component. The source of the systematic error in these data is understood. Future Keck Interferometer observations of NGC 4151 at K band should have errors more consistent with the raw V^2 errors. In the current configuration of the Keck Interferometer, the raw V^2 errors are due in part to NGC 4151 being very near the limit of the instrument performance, both in terms of fringe and angle tracking. Errors in both fringe and angle tracking lead to intensity fluctuations, which contribute to the V^2 errors in these data.

3.2 Possible Emission Mechanisms

Four possible mechanisms for the K band emission are considered. Because of the combined constraints implied by these measurements and other observations, two of the cases are judged to be unlikely.

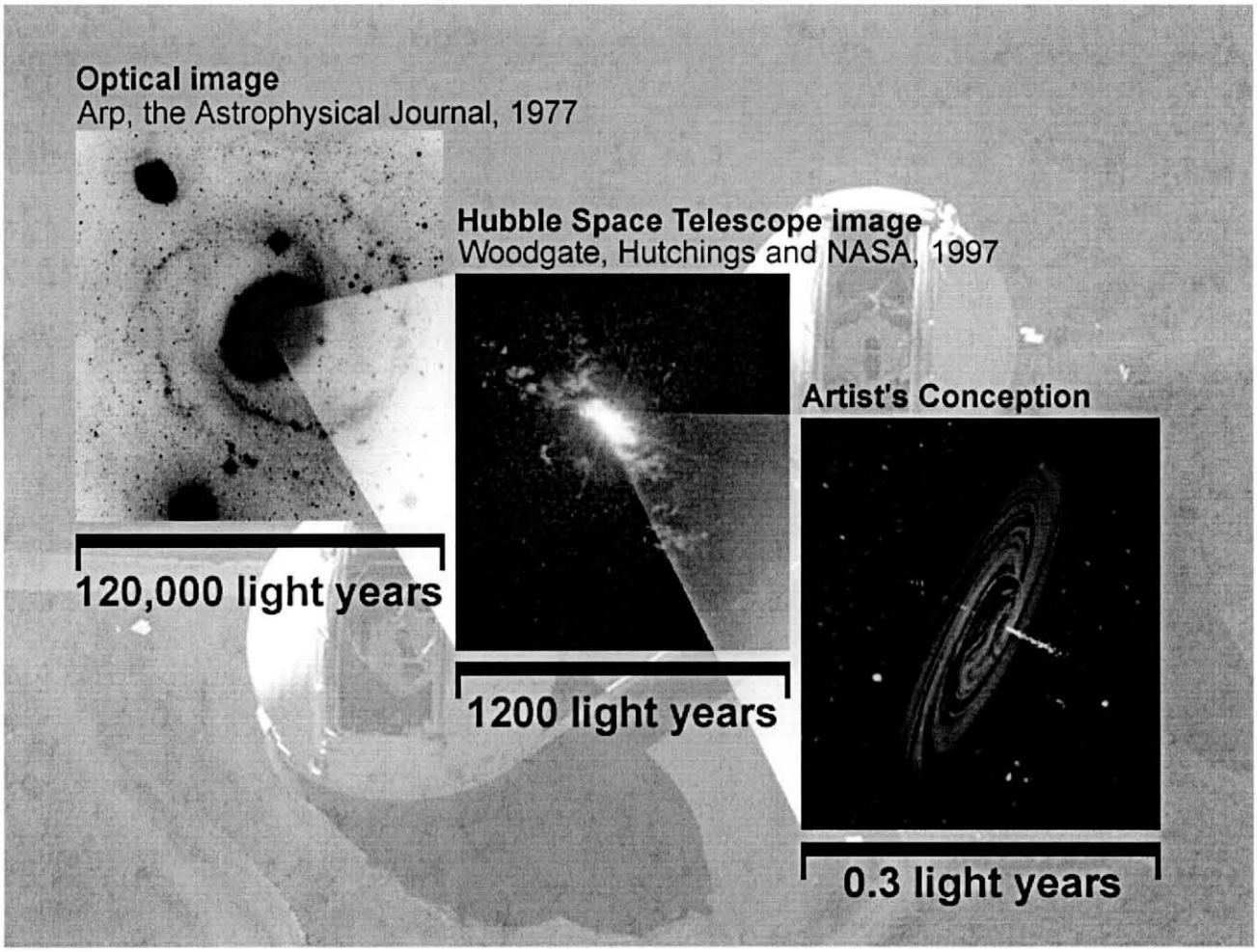

Fig. 3. An illustration showing how advances in astronomical instrumentation have increased our knowledge of the nucleus of NGC 4151. The image (left) taken using the Palomar 200 inch telescope, shows the nuclear region and spiral arms. The Hubble Space Telescope image (center), shows the narrow line region where gas has been ionized by UV radiation from the active galactic nucleus. The cone shape of the emission in the middle image is thought to arise from an obscuring dust torus. The Keck Interferometer observations allowed measurements on a scale an order of magnitude smaller than previously possible. The artists conception (right) represents an accretion disk orbiting the black hole located at the center of NGC 4151.

Synchrotron Emission: VLBA imaging of NGC 4151 at a few milliarcsecond scales[14] reveals that its parsec-scale radio jet is subluminous in that it is several orders of magnitude fainter than the parsec-scale radio jets imaged in nearby classical radio galaxies. Measurements at 18 cm and 6 cm of the nuclear region show a relatively flat spectrum $\alpha \sim -0.3$ source with a peak flux density of about 1 mJy midliarcseconds^{-2}. In contrast, the large near-infrared flux density of $\sim 10^2$ mJy milliarcseconds^{-2} is inconsistent with the radio fluxes and implies that the nuclear near-infrared source is unrelated to the radio source and, by inference, unrelated to a subparsec-scale synchrotron jet.

Star Cluster: Explaining the compact K band emission as stellar would require ~ 3×10^6 O stars in a volume of ~0.003 pc^3. This explanation is unlikely, as it would imply an implausible density for young stars ~100,000 times higher than in our own galactic center[23]. A stellar component is also incompatible with the measured infrared intensity fluctuations[5, 24].

Thermal Dust: If the dust is distributed as a physically thick torus, the inner radius is much smaller than typically estimated. The smallest possible scale for thermal dust emission is set by the dust sublimation radius (the radius at which direct heating from the AGN nucleus causes the dust to sublimate). Interpreting the interferometer measurement using a standard model[5] results in an estimated dust temperature of 1900 K, corresponding to a sublimation radius of 0.05 pc. Thus, if the infrared emission is from centrally heated dust, it is consistent with the observations only if the dust is very hot and the K band emission is localized near the dust sublimation radius.

Thermal Gas: If the thermal material is distributed as a disk, it is consistent with at least one accretion disk model. A simple, face-on, geometrically thin disk model[26], with $T\sim r^{-3/4}$ and with an inner temperature of ~ 3.5×10^5 K (consistent with the soft X-ray emission[15], predicts a K band magnitude of 8.4, 95% of which is inside a radius of ~ 0.01 pc. This accretion disk model predicts an unresolved point source at about the right magnitude and is plausibly consistent with the interferometer measurement. In this case the thermal material could be gas or dust. As the central engine is unobscured, it is plausible there could be an accretion disk component that is contributing to the measured visibility.

Both the thermal dust and thermal gas models are consistent with the observations. However, centrally heated dust, which is thought to reprocess UV/optical radiation from the central engine, produces a specific signature[25,27] known as the "infrared bump". There is no evidence for a comparable feature[5,28,29] in NGC 4151. Also, an optically thick dust torus with a well-defined, but small, inner radius (corresponding to the sublimation radius) would give similar time delays between fluctuations in the UV/optical flux and fluctuations in the H and K band flux; this is inconsistent with the UV/optical to infrared time delay observations[6]. Thus, because of the absence of the "infrared bump" and the H/K time delay difference, the interpretation that a substantial component of the flux measured with the interferometer arises from an unresolved accretion disk seems the most likely. This compact source could be accompanied by some extended emission that is consistent with dust heated by a central source.

6. Summary and Conclusions

The Keck Interferometer has measured the angular diameter of the K band emission in the nucleus of NGC 4151. These observations rule out any emission mechanism that requires a large fraction of the nuclear K band emission to be produced at a radius of greater than 0.05 pc from the black hole. Taken in the context of other observations, this measurement implies that a majority of the K band emission could arise from a central accretion disk.

Long baseline infrared interferometry is poised to make a major contribution to the understanding of the physics of AGN. For the first time, an observational technique is available with sufficient angular resolution to distinguish between proposed models for the nuclear infrared emission. Over the next few years, measurements of the angular diameter as a function of baseline position angle and wavelength will provide powerful constraints on models of AGN. In low luminosity AGN, it is possible that changes in the angular diameter might be observed on time scales of a few months. Thus, infrared interferometry may have role in helping to understand some of the dynamical processes in AGN.

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