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ABSTRACT

CanariCam is the facility mid-infrared (MIR) instrument for the Gran Telescopio Canarias (GTC), a 10.4m telescope at the Observatorio del Roque de los Muchachos on La Palma. One of the science drivers for CanariCam is the study of active galactic nuclei (AGN). We will exploit the instrument's high sensitivity in imaging, spectroscopy, and polarimetry modes to answer fundamental questions of AGN and their host galaxies. Dust in the nucleus of an active galaxy reprocesses the intrinsic radiation of the central engine to emerge in the MIR. Current work demonstrates that the hot dust immediately associated with the AGN, which blocks direct views of the AGN from some lines of sight, is confined to small (parsec) scales. Thus, high spatial resolution is essential to probe the "torus" of unified AGN models separate from the host galaxy. CanariCam provides a $0.08''$ pixel scale for Nyquist sampling the diffraction-limited point spread function at 8μm, and narrow ($0.2''$) spectroscopy slits (with R=120–1300). New observations with the GTC/CanariCam will provide key constraints on the physical conditions in the clumpy torus, and we will sensitively determine AGN obscuration as a function of nuclear activity. We will therefore address the fueling process and its relationship to the torus, the interaction with the host galaxy, and dust chemistry. These data will be essential preparation for the next generation of telescopes that will observe the distant universe directly to explore galaxy and black hole formation and evolution, and the GTC/CanariCam system uniquely provides multiple modes to probe AGN.

Keywords: Active galaxies, CanariCam, ground-based astronomy, imaging, infrared, instrumentation, polarimetry, spectroscopy

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1. CANARICAM

CanariCam is the facility mid-infrared (MIR) instrument for the 10.4 m Gran Telescopio Canarias (GTC), which received first light in 2007 at Roque de los Muchachos on La Palma. The atmosphere provides two significant windows in the MIR, near 10 and 20 μm, which allow observations from roughly 7.5–13.5 and 16–26 μm. The detector is an arsenic-doped silicon, blocked-impurity-band (BIB or IBD) device from Raytheon, with peak quantum efficiency (QE) across 8–25 μm and a rapid decrease in QE at longer wavelengths. The plate scale of the instrument is matched to the pixel size of 50μm, so the point spread function is Nyquist-sampled at 8μm. The detector array contains 240×320 pixels, which each corresponds to $0.08''$ on the sky, for a field of view of $19'' \times 26''$.

The instrument is optimized for MIR observations, with materials selected to maximize throughput at these wavelengths. The electronics provide rapid readout to avoid saturation in the high thermal background that is characteristic of the MIR, and the light path within the instrument is cooled to < 30K to eliminate instrument background. Two engineering modes, at wavelengths as short as 2μm, are also provided.

CanariCam offers four key science modes: imaging, slit spectroscopy, dual-beam polarimetry, and coronagraphy. The first three of these are most relevant for the study of active galactic nuclei we discuss here. Fundamentally, dust in the immediate nuclear environment reprocesses the hard intrinsic source continuum to emerge in the MIR. The high image quality will contribute to scientific success. Even in the most aberrated part of the image, CanariCam delivers an enclosed energy 95% of the diffraction limit, or a Strehl ratio of 92%. The spectrometer follows a Czerny-Turner layout using one of four classical plane gratings, for low ($R \sim 175$ and 120 at 10 and 20μm respectively) and moderate ($R \sim 1300$ and 900 at 10 and 20μm respectively) resolution, with minimum slit width of $0.17''$. The dual-beam polarimeter is sensitive in the 10μm region. The design permits simultaneous measurement of orthogonally polarized beams, which minimizes seeing effects and changes in atmospheric emission and transparency. In addition, the efficiency of observing compact sources is doubled. For more detailed information about CanariCam, see work by Telesco et al.[1]

2. ACTIVE GALACTIC NUCLEI

The accretion onto the central supermassive black holes in active galactic nuclei (AGN) is fundamental to the evolution of galaxies, ultimately connected to the relationship between central black hole mass and stellar bulge mass that is measured in normal galaxies.[2,3] While the observed characteristics of AGN vary widely, all share common underlying physical processes, as unified theories describe. The presence of a geometrically and optically thick torus of gas and dust that obscures the central engine from some lines of sight is the key component of unified AGN models. Viewed through the equatorial plane of the torus, the fast-moving clouds that produce Doppler-broadened spectral lines are hidden. Only narrow lines due to more distant (slower-moving clouds) appear in the spectra of these type 2 AGN. In contrast, a pole-on orientation provides a direct view of the central engine, with both narrow and broad lines detected in type 1 AGN spectra.

Polarization measurements provide direct evidence for the obscuring torus. NGC 1068 is an archetype of the type 2 Seyfert galaxies, the lower luminosity variety of AGN, exhibiting only narrow optical emission lines. In polarized flux, however, the spectral components that would classify this object as a type 1 are revealed in electron scattered (hence polarized) emission.[4] Further similar examples support the general unification of AGN,[5–7] whereby observational characteristics (and type) depend on viewing geometry, despite the common central engine and anisotropic surroundings.

Accounting for the torus is essential to solve fundamental astrophysical problems that require quantifying black hole growth over cosmic time and obtaining an accurate census of black holes. The torus itself can be observed emitting at MIR wavelengths. The dust reprocesses the intrinsic AGN continuum, and the emergent radiation peaks in the MIR. While the torus is evident in absorption in individual type 2 AGN, the best direct evidence for the presence of a torus in a type 1 AGN is through its MIR emission. Observations with CanariCam and studies of the torus will ultimately address the AGN fueling process and dust chemistry in other galaxies.

High spatial resolution is required to isolate the AGN torus from the surrounding emission of the host galaxy. Current work on 8–10m class telescopes constrains the torus to diameters ≤ 4 pc.[8–11] While space-based observations, such as using *Spitzer*, offer greater sensitivity, their poorer resolution means they suffer from

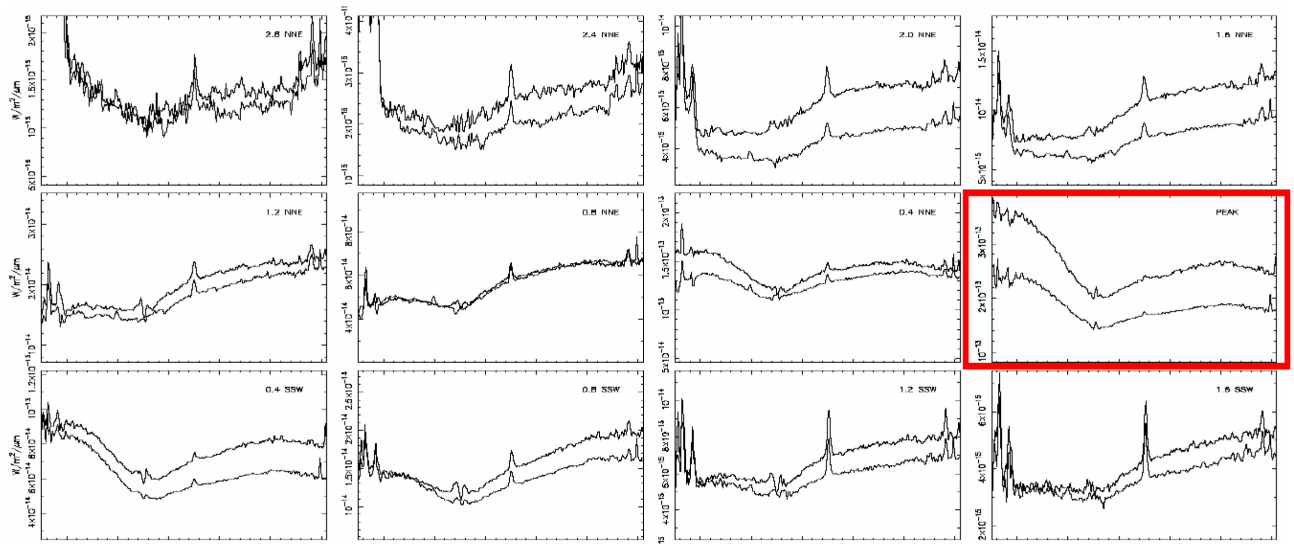

Figure 1. MIR spectra (7.5–13μm) extracted in 0.4$''$ steps over the central region of NGC 1068 reveal differing physical conditions on small scales. Positions are designated north-northeast (NNE) and south-southwest (SSW) of the peak, marked with the heavy box. Black and gray spectra were obtained at different epochs.[15]

much more contamination of the torus measurements from other sources. Ground-based MIR interferometric observations also support a compact torus.[12–14] However, because interferometry requires very bright sources, few if any other AGN may be successfully observed with current instrumentation. Thus, we anticipate great progress through more complete studies of AGN generally on the GTC and other large ground-based telescopes.

Early models of MIR emission assumed a uniform dust density distribution. To contain the cool dust that produces far-IR emission, these models required a large (100 pc scale)[16,17] torus, contrary to current observations. Instead, a “clumpy” distribution of dust in the torus can provide cool dust on small scales, as new models describe.[18] The MIR emission arises on scales of less than about 10 pc. Moreover, the clumpy calculations do not require fine-tuning of the model parameters to reproduce the observed spectral energy distributions. In particular, they replicate the behavior of the silicate features that may appear in emission or absorption near 10 and 18μm in a variety of circumstances.

In the following sections, we present examples of results obtained using current facilities that are comparable to CanariCam on the GTC. We also describe the plans of Los Piratas, the CanariCam Science Team AGN collaboration, to use Guaranteed Time observations to complete a systematic study MIR-bright AGN.

3. SPATIAL RESOLUTION

The GTC will offer diffraction limited resolution $R_{8\mu\mathrm{m}} \sim 0.19''$, which for the nearby and bright AGN NGC 1068 corresponds to about 13 pc. Figure 1 shows comparable observations of NGC 1068 obtained with Michelle on the 8.1 m Gemini North Telescope, illustrating the necessity of high spatial resolution to isolate the torus emission. The hottest dust closest to the AGN produces the concentrated high surface-brightness component, and overall, 80% of the flux comes from within 2” of the core. Significantly, the spectra show variations on sub-arcsecond scales. Differences in continuum slope, silicate feature profile and absorption depth, and fine structure line fluxes reveal differing physical conditions in the dusty region close to the nucleus.[15] We identify only the compact ($0.4''\times 0.4''$) emission as the AGN-obscuring torus. The diffuse component is due to AGN-heated dust in the extended ionization cones, and this would dominate measurements of NGC 1068 in apertures larger than about 1$''$. Other AGN similarly suffer from the same general problem of contamination in large-scale measurements.

The extended MIR sources present in luminous infrared galaxies (LIRGs) further challenge measurement of dust associated with the AGN. On kpc scales, MIR images are extremely similar to those obtained in Paα, which traces stellar activity in HII regions.[19] Spectroscopy obtained over large apertures therefore includes these stellar

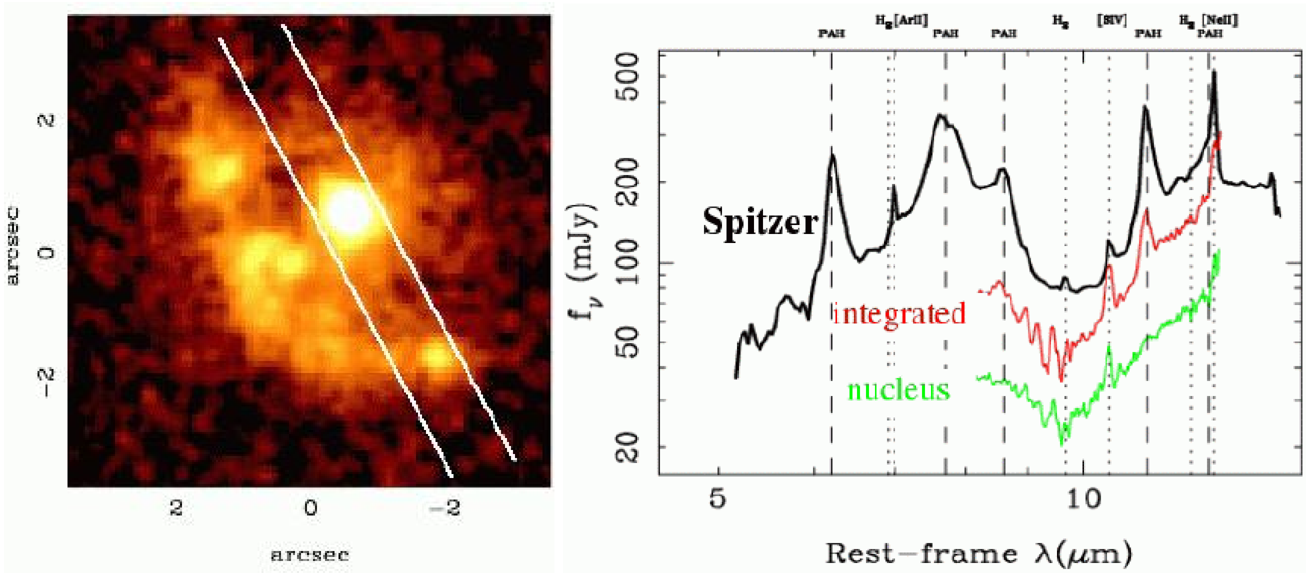

Figure 2. Left: T-ReCs MIR 10μm image of the AGN NGC 5135, which contains significant star formation. The solid lines show the position of the T-ReCS slit. Right: *Spitzer*/IRS spectrum extracted within a 5$''$ ($\sim$ 1300 pc) aperture (thick line; top) compared with two T-ReCS measurements: the nuclear spectrum alone (bottom) and the integrated flux (middle). The image and spectral differences demonstrate that emission on scales larger than 200 pc is not due to the AGN.

contributions and does not allow analysis of the AGN alone. For example, the *Spitzer* spectrum of the Seyfert galaxy NGC 5135 overestimates the nuclear silicate absorption and does not allow for a reliable MIR continuum measurement (Figure 2). In contrast, using T-ReCs on the 8.1m Gemini South Telescope, the AGN and its immediate ($<$ 100 pc-scale) surroundings can be distinguished.[20, 21]

4. CLUMPY AGN MODELS

We use models of clumpy AGN surroundings to interpret these observations. One significant difference compared with any homogeneous torus calculation is that dust temperature does not decline monotonically with increasing distance from the central source. Radiation can propagate freely in the spaces between the clouds. Thus, clouds that are far from the central engine may receive direct heating (and emit significantly), and clouds that are close to the AGN may remain cool if other clouds block their direct view. Another important difference is that the clumpy distribution allows the possibility of observing both the hot cloud surfaces that the AGN illuminates directly and their shadowed sides. A consequence is that the strength of the silicate features is reduced, both in absorption and emission. Specifically, while views through cold dark clouds (or equivalently, through a smooth torus) would characteristically produce deep absorption, the contribution from hot faces within the observing beam fills in the silicate trough.

The net effect of all clouds produces the MIR emission. Thus, while the clouds may be located within a toroidal distribution, the resulting emission is nearly isotropic, in agreement with current observations.[22, 23] In contrast, the MIR emission from a smooth torus exhibits a strong dependence on viewing angle; type 1 objects, having views of the hot inner throat of the torus, appear more luminous than type 2 AGN.[16]

We use the numerical radiative transfer calculations of Nenkova et al.[18] They employ an iterative scheme to account for both direct heating by the central engine and indirect heating of clouds in the ambient bath of other clouds' emission. Individual clouds are optically thick, having optical depth measured at 0.55μm $\tau_{0.55\mu\mathrm{m}} \geq 10$. The clouds are distributed according to Poisson statistics in a toroidal geometry. The innermost ones are located at the distance corresponding to the dust sublimation temperature ($\sim$ 1500K). For an AGN heating spectrum, this distance scales $R_d = 0.4\sqrt{L_{45}}$ pc, where L_{45} is the bolometric luminosity measured in units of 10^{45}erg s^{-1}. The radial distribution of clouds is given by a power law, with the number proportional to R^{-q}. The average

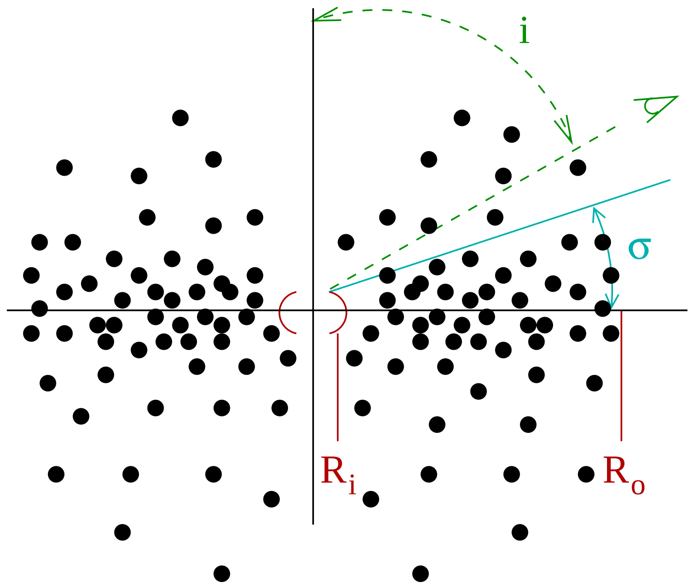

Figure 3. Cartoon of the clumpy torus. Clouds are distributed from an inner radius, R_i, located where dust sublimates, to an outer radius, R_o, according to a power law ($\propto R^{-q}$). The clouds are concentrated in the equatorial plane and distributed with a scale height σ, which has a gradual (Gaussian) edge. An average of N_0 clouds are located along a ray through the equatorial plane. Individual clouds are optically thick, and radiation passes freely among clouds. The resulting emission is calculated as a function of viewing angle, i. Type 1 AGN are more likely viewed along lines of sight near the pole (small i), and large values of i preferentially result in type 2 AGN, although with the stochastic cloud distributions, the type of a particular AGN is not a strict function of viewing angle.

number of clouds along an equatorial ray is N_0. The torus has a smooth edge, with the number along radial rays at angle β from the equator declining as $\exp(-\beta^2/\sigma^2)$. For a given set of these model parameters, the subsequent spectral energy distribution is calculated for all viewing angles, i, from pole-on ($i = 0°$) to equatorial ($i = 90°$).

Figure 4 shows the result of fitting the models to the high resolution 10μm spectrum of NGC 1068.[15] Observations of masers[24] show the inclination angle of the accretion disk to be nearly edge-on. We therefore constrain the torus viewing angle $i \approx 90°$ in the model fitting. The models are degenerate, with many describing the data well, although the acceptable models exhibit some common characteristics. We find that the clouds located close to the AGN dominate the MIR emission, and we prefer compact cloud distributions. With $q = 2$, for example, nearly 90% of the clouds are located within the central 3 pc, independent of the total extent of the distribution. (Flatter radial distributions are also possible, provided the outer boundary is reduced.) Second, none of the models require a large number of clouds ($N_0 < 10$). Significantly, although the models were fit only to the 10μm spectral region, the predicted spectral energy distribution from 2–60μm agrees well with other measurements obtained over small physical scales. While much of the larger-scale emission may ultimately be due to the AGN, it does not represent the torus alone. Finally, because the reprocessed torus spectrum scales with the intrinsic AGN luminosity, we recover $L_{bol} \approx 2 \times 10^{45}\,\mathrm{erg\,s^{-1}}$ from this very obscured Seyfert 2, in which the AGN is not viewed directly.

5. POLARIZATION

The polarization signature in AGN depends strongly on the distribution of dusty material around the central engine and specifically the alignment of the dust grains. The degree and polarization angle at a particular wavelength, along with comparisons at different wavelengths from any non-symmetric distribution is diagnostically powerful. Currently, NGC 1068 is the only AGN for which MIR imaging polarimetry has been published.[25, 26] Our recent imaging polarimetry result through a narrow band 9.7μm filter using Michelle on the Gemini North Telescope shows complex polarization structures on sub-arcsecond scales (Figure 5). We find three different components. The first extends $\sim 1''$ north of the MIR peak and is coincident with the inner regions of the radio jet.

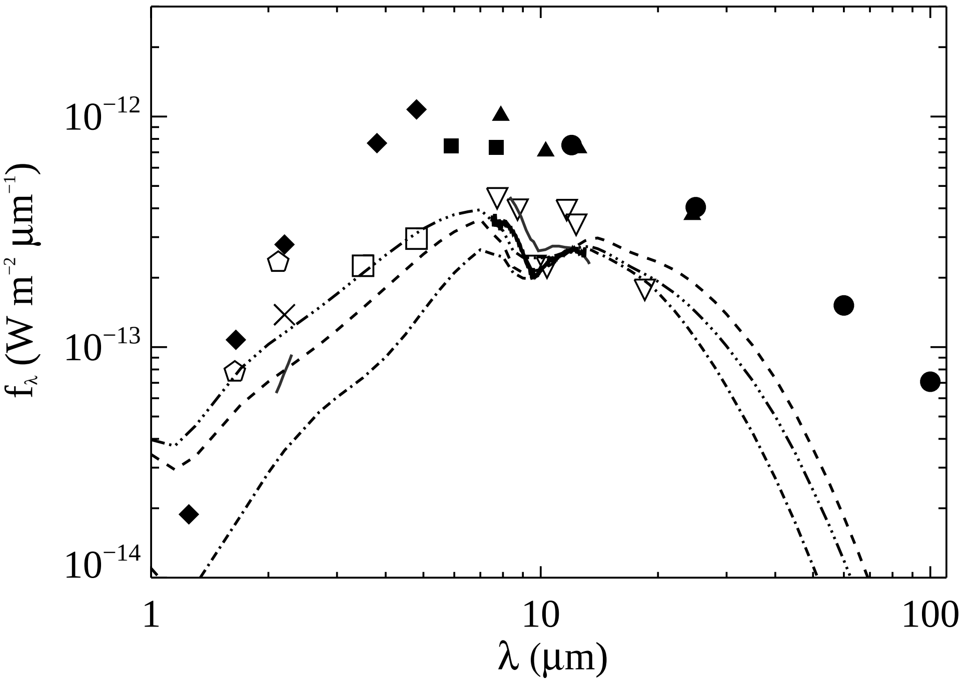

Figure 4. Comparison of observed nuclear spectrum if NGC 1068 (heavy solid line) and fitted models with results from the literature.[15] The models were fit only to the 10μm spectrum, which isolates the torus emission, yet they agree with small aperture measurements (open symbols) obtained over a range of wavelengths. In contrast, large aperture measurements (filled symbols) show significant extra-nuclear flux.

The polarization is aligned approximately north-south, likely arising through dichroic emission of dust entrained in the jet and narrow line emitting regions. The second region is diffuse, partially enclosing the nucleus and extending south, east, and west of the nucleus, with position angle of polarization PA$\sim 35°$. Finally, because the degree of polarization is a minimum very close to the MIR flux peak, we infer the presence either of an unresolved polarized component with a PA approximately orthogonal to the extended emission, which reduces the net polarization, or a bright unpolarized source. We associate this component with the compact torus itself.

The polarization PA of the MIR extended emission is nearly orthogonal to that measured in the near-infrared,[27] and the PA flips by 90° between 4 and 5μm.[28] These results are consistent with the transition from dichroic absorption to dichroic emission of the same aligned dust grains.

With CanariCam, the limiting flux for spectropolarimetry at 10μm will be about 0.3 Jy (to identify $\Delta p \sim 0.5\%$ in an few hours) at resolving power $R \sim 30$. In contrast to the limited candidate pool for spectropolarimetry of AGN on 4m class telescopes, we will be able to study several using CanariCam. Because spectropolarimetry reveals solid state features, we should be able to discriminate between thermal and non-thermal emission, which is particularly important in the radio galaxies, where the latter is significant. Overall, polarimetry with CanariCam will provide a useful tool to disentangle the intrinsic emission of the central engine from the effects of the surrounding dust.

6. SCIENCE TEAM PROGRAM

The dusty torus that is characteristic of the immediate AGN environment is critically tied to central questions black hole accretion and growth in the context of galaxy evolution. Studies of individual galaxies, such as those described above, are essential first steps in describing the physical properties of the torus in particular cases. To identify the characteristic conditions of accreting black holes generally, we require systematic investigations of

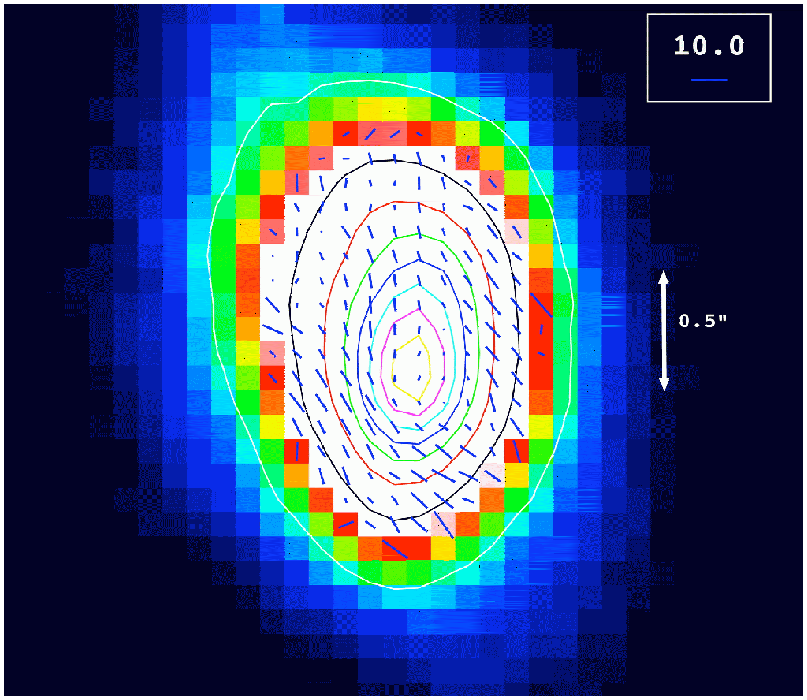

Figure 5. Imaging polarimetry of NGC 1068, obtained through a 9.7μm filter using Michelle on the Gemini North Telescope. The plotted polarization vectors indicate the PA of the polarization (the direction of electric field), and their length is proportional to the degree of polarization; the length of 10% polarization is shown in the inset at the upper right. We identify three physical components on different spatial scales.

samples of AGN. Los Piratas will begin this work with approximately 100 hours of Guaranteed Time devoted to AGN science using CanariCam on the GTC.

We will test the hypothesis that accretion activity level is a fundamental parameter that determines the physical conditions broadly in AGN. We use intrinsic hard X-ray luminosity as a proxy for AGN activity, initially assuming that the bolometric correction is the same in all AGN. (Although the Eddington ratio, the ratio of bolometric luminosity to Eddington luminosity, rather than absolute luminosity is likely the underlying critical property, measurements of the latter are available for a wide variety and large number of AGN.) We have identified an initial sample of 39 galaxies that span activity level from LINERs on the low end to quasars at the highest levels, including some comparison examples of non-AGN star-forming galaxies. We will measure the torus properties, including typical number of clouds and their distribution in scale height and radial extent. We will consider whether the dust distribution in the unifying clumpy torus is a function of the AGN luminosity or other characteristics of these galaxies. In addition to the "activity" axis, we will address grand unification of AGN, exploring possible differences of radio loudness, optical type (1 or 2), and presence of nuclear star formation. Theoretical models suggest that the torus may no longer be sustained at low luminosity,[29] raising the possibility that even LINERs containing accreting supermassive black holes cannot be fully "unified" with other types of AGN.

The sample favors MIR-bright objects, for feasibility. It is distance-limited (< 50 Mpc) to take full advantage of CanariCam's spatial resolution, so we will also investigate dust located in extended narrow emission line regions and its connection to the smaller scale of the torus. We will quantify physical properties of the torus using the clumpy models, and simultaneously test the applicability of these models to the AGN generally. We expect the unique abilities of the CanariCam/GTC system used this program, combined with the outstanding capabilities offered by the Gemini, VLT, and Subaru MIR facilities (Michelle, T-ReCS, VISIR, and COMICS), will allow us to probe the activity axis with unprecedented finesse. Through detailed understanding of the torus and AGN activity effects, we will address the fueling process and its relationship to (or even creation of) the torus, the interaction with the host galaxy, and dust chemistry in other galaxies. Such information is crucial to understand in the local universe for application to more distant objects. The next generation of ground- and space-telescopes will probe the distant universe to explore galaxy and AGN formation, where black hole and AGN evolution may be evident, so understanding local objects is essential preparation. The program of observations outlined in this paper will form the basis of such a comprehensive study.

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