A direct image of the obscuring disk surrounding an active galactic nucleus

Jack F. Gallimore*, Stefi A. Baum†
& Christopher P. O'Dea†

* Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, D-85740 Garching bei München, Germany

† Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland 21218, USA

Active galactic nuclei (AGN) are generally accepted to be powered by the release of gravitational energy in a compact accretion disk surrounding a massive black hole^{1,2}; such disks are also thought necessary to collimate the powerful radio jets seen in some AGN³. The unifying classification schemes for AGN further propose that differences in their appearance can be attributed to the opacity of the accreting material, which may obstruct our view of the central region of some systems. The popular model for the obscuring medium is a parsec-scale disk of dense molecular gas⁴, although evidence for such disks has been mostly indirect, as their angular size is much smaller than the resolution of conventional telescopes. Here we report direct images of a parsec-scale disk of ionized gas within the nucleus of NGC1068, the archetype of obscured AGN. The disk is viewed nearly edge-on, and individual clouds observed within the ionized disk are opaque to high-energy radiation, consistent with the unifying classification schemes. The projected axes of the disk and AGN are aligned, from which we infer that the ionized gas disk traces the outer regions of the long-sought inner accretion disk.

The nucleus of the galaxy NGC1068 hosts the archetypal example of an obscured AGN. The popular model for the obscuring medium is a parsec-scale, molecular disk surrounding the AGN⁵, perhaps ultimately feeding an accretion disk^{6,7}. One difficulty for observational tests has been that the location of the obscured, central ionizing source is unknown. It has been argued on several grounds that the radio source S1 marks the location of the hidden AGN in NGC1068 (refs 8, 9). Located at the southern end of the arcsecond-scale radio jet, S1 is an unusual radio source in two respects. First, in contrast with the rest of the radio jet, its radio spectrum is relatively flat (spectral index $\alpha = +0.3$; $S_\nu \propto \nu^\alpha$ (ref. 8)), and second, it is a source of H₂O and OH maser emission¹⁰, which distinguishes regions of peculiarly warm (1,000 K) and dense ($\geq 10^8$ molecules cm⁻³) molecular gas. We argued that S1 might trace emission from molecular clouds defining the inner surface of the proposed obscuring disk, whose surfaces would be exposed directly to the central X-ray source and are therefore hot and highly ionized⁸.

We made two predictions for very-long-baseline interferometry (VLBI) observations⁸. First, S1 should resolve into a parsec-scale, linear radio structure, tracing the profile of an edge-on disk or 'torus' projected onto the sky, and located within the warm, molecular disk mapped in part by H₂O masers¹⁰. Second, the mean surface brightness of S1, in temperature units corresponding to an equivalent blackbody radiator (brightness temperature), should be $T_b \approx 10^6$ K for scattering-diffused emission or thermal free-free emission⁸.

To test these predictions, we have imaged the subarcsecond radiostructure of NGC1068 using the 10-station Very Large Baseline Array (VLBA), augmented by the phased, 26-element Very Large Array (VLA). The new images are displayed in Fig. 1. A single, deep (8.8 h on-source) integration was obtained at 8.4 GHz only. The observations and data reduction followed standard techniques with

exceptions as follows. On continental-scale baselines, NGC1068 is not sufficiently bright at 8 GHz to calibrate interferometric fringes within averaging times comparable to the atmospheric coherence time. Instead, we measured fringe-rate and fringe-delay corrections from short scans of the nearby calibrator source 0237 – 027. Less than 0.2% of the data (one out of a total of nearly 600 baseline-hours) were affected by phase rotations resulting from fringe solution ambiguities, and the radio sources S1, C and NE were

Figure 1 VLBI images of the radio component S1 of NGC1068. The total recovered flux of the 'hot zone' (HZ) is 6.9 mJy, or ~60% of the flux anticipated by a power-law interpolation of the 5-GHz and 22-GHz measurements of Gallimore *et al.*¹⁴. In contrast, less than a total of ~1 mJy arises from compact structures lying outside the HZ but within S1. Owing to an instability in the deconvolution algorithm used to produce this image, some of the compact sources may be artificially enhanced at the expense of the diffuse emission²⁸. The compact sources are nevertheless real, as they are also distinguishable on the unprocessed images. δ , declination; α , right ascension. Top panel, naturally weighted image of S1; the beam size (full-width at half-maximum, FWHM), indicated by the black ellipse in the lower right-hand corner, is 2.5×1.4 mas. We have marked and labelled the HZ and the local jet axis towards radio jet component C. Note that, in projection, the extent of the HZ and the direction of the radio jet are at right angles to each other, suggesting a common symmetry axis. Scaled logarithmically, the contour levels are ± 0.10 (2.5 σ), 0.22, 0.35, 0.47 and 0.59 mJy beam⁻¹, or $\pm 0.49, 1.1, 1.7, 2.3$ and 2.9 in brightness temperature units of 10^6 K. Bottom panel, uniformly weighted image of the HZ; the beam size (FWHM) is 2.3×1.1 mas. The contour levels are ± 0.16 (2.5 σ), 0.24, 0.36 and 0.54 mJy beam⁻¹, or $\pm 1.1, 1.6, 2.5, 3.7$ in units of 10^6 K.

clearly detected on the initial maps. The resulting, fringe-calibrated data were coherent over sufficiently long intervals to allow self-calibration, and so we removed the residual phase wraps using five iterations of phase-only self-calibration. In order to focus specifically on the nuclear emission, the VLBA images of NE and C will be presented elsewhere. Here we focus on the 'hot zone' (HZ), the brighter, central region of S1, and also defer discussion of fainter radio emission to future work.

The HZ comprises nine distinguishable compact sources, each of total flux density $S_\nu \approx 0.65$ mJy ($1 \text{ mJy} = 10^{-26} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$), embedded in diffuse emission. These observations only marginally resolve the individual compact sources. Based on gaussian model fits and image moment analysis, the deconvolved source sizes are typically ~ 1 milliarcsecond (mas), or ~ 0.07 pc at the distance of NGC1068. These measurements are, however, uncertain owing to confusion between neighbouring sources, blurring due to residual phase errors, and possible enhancement by deconvolution. We also estimated limits on the source sizes based on inspection of the interference fringes. Less than half (~ 3 mJy) of the recovered flux of the HZ is detected on baselines corresponding to angular sizes $< 2 \times 1$ mas; at least half of the flux from the HZ must therefore arise from structures ≥ 1 mas in size, consistent with measurements of the synthesized image. This limit is conservative, as 1–2 mJy worth of milliarcsecond-scale components are also detected towards components NE and C. Any one or two of these compact sources may be smaller than 1 mas, but this caveat will not affect the main conclusions.

The compact sources trace a slightly curving line along a position angle of 110° , measured east of north. The HZ is therefore nearly at right angles to the collimation axes defined by the local radio jet and polarization axes, the latter describing the collimation axis for escaping ionizing radiation¹¹. This geometry is fully consistent with our prediction that the radio emission from S1 traces emission not from a streaming jet but rather from gas in an ionized disk surrounding the AGN. We next consider the implications of this disk model, making the simplifying assumption that the HZ gas lies at a common radius, ~ 0.3 – 0.5 pc, from the AGN.

Opaque synchrotron emission is the conventional explanation for flat-spectrum radio sources, but the brightness temperatures over the HZ are too low for synchrotron self-absorption¹². There are two likely alternatives, illustrated in Fig. 2, each being a variation on emission from ionized gas in a disk⁸. The first is synchrotron emission from a synchrotron-opaque, compact radio source, presumably the AGN, which is not viewed directly but in reflection by electron-scattering from the ionized gas disk.

The limits for this model are set by requiring that the electron scattering opacity (τ_e) must exceed the opacity to free-free absorption (τ_{ff}), and that the hidden radio source must not be so luminous that it would have been detected in reflection on larger scales. Based on the sensitivities of our radio continuum images⁸ and the reflecting properties of the electron-scattering mirror¹³, we estimate that the hidden radio source can be no brighter than $S_\bullet \approx 3.5$ Jy. We estimated limits on the plasma properties by exploring a grid of electron densities n_e , electron temperatures T_e and cloud thicknesses l (and the corresponding value $S_\bullet$ appropriate for a given τ_e) and rejecting those values where $\tau_{ff} > 0.5\tau_e$ and $S_\bullet > 3.5$ Jy. We find that the reflection model can be satisfied for $T_e \geq 10^{6.7}$ K, $10^{6.2} \leq n_e < 10^{6.6}$ electrons cm^{-3} and $0.007 \leq l \leq 0.07$ pc (the upper limit set by the measured sizes). We also estimate that, assuming that thermal absorption is negligible, the flux density of any hidden compact radio source must be $0.8 \leq S_\bullet \leq 3.5$ Jy.

The second model is direct, thermal free-free emission from ionized gas inside the obscuring disk. Appropriate for the integrated radio spectrum^{9,14}, we assume for this thermal model a mean opacity of $\tau_{ff}(8.4 \text{ GHz}) = 0.5$ through the HZ plasma. Using the free-free opacity approximations of Mezger and Henderson¹⁵, we estimate $10^{6.5} \leq T_e \leq 10^{6.8}$ K and $n_e \geq 10^{6.8} \text{ cm}^{-3}$ ($T_e/10^7 \text{ K}$)^{1.35} ($l/0.07 \text{ pc}$)^{0.5}.

The plasma conditions in either the thermal or reflection models are plausible given the extreme environment. For comparison, particle densities in the molecular region of the disk are estimated to be $n_{\text{H}_2} \approx 10^8$ molecules cm^{-3} (refs 7, 16), and photoionization heating can drive T_e up to the limit bounded by inverse Compton cooling, $T_c \approx 10^7$ – 10^8 K (refs 7, 17). On the other hand, it is not clear how such a dense medium can remain heated to temperatures so near the Compton limit. For instance, photoionization heating of dense plasmas can support only $T_{\text{cool}} \approx 10^4$ – 10^6 K (refs 7, 18), unless the ionizing spectrum is much harder (more luminous in X-rays) and overall more luminous than current estimates¹⁹. A promising alternative is heating by mixing with a hot, intercloud medium²⁰, a $T_{\text{hot}} \approx 10^7$ – 10^8 K plasma proposed to confine optical emission-line clouds in the nuclear environment¹⁷. The temperatures in the mixed plasma would be $T_e \approx \sqrt{T_{\text{cool}} T_{\text{hot}}}$ (ref. 21), or $T_e \approx 10^{6.5}$ K, to within factors of a few. In addition, fast shocks, such as those driven by winds or the radio jet, or internal shocks arising at cloud–cloud collisions, might at least briefly support such high temperatures. Understanding the energy budget of the HZ will be a challenge for follow-up research.

Relevant specifically to AGN unifying schemes, the column density through the HZ clouds may be as high as $n_e l \approx 10^{24} \text{ cm}^{-2}$,

Figure 2 Diagrams of our model of the AGN of NGC1068 and its environs. Left panel, cartoon depicting the obscuring disk as viewed along our sight-line. The AGN is hidden from direct view, but we see reprocessed and scattered emission from the surrounding disk (illuminated material at the centre of the cartoon). Right panel, higher magnification plan view of the central part of our model (indicated by the white box in the left-hand panel). Shown are the relative locations of the 10^6 K 'hot zone' (HZ), detected in these observations, the warm transition zone, traced by H_2O maser emission and H I absorption¹⁰, and an outer, cooler molecular zone, which still eludes direct detection. It has been argued that the innermost region may be filled with a hot (10^8 K), intercloud medium¹⁷, which might be a source of heat for the HZ. This cartoon also illustrates two possible contributions to the observed radio emission: (1) scattered non-thermal emission originating at the AGN and (2) direct free-free emission from the HZ.

sufficient to absorb virtually all of the incident X-ray emission from the AGN²². This result, and the fact that the disk is viewed nearly edge-on, support the idea that the HZ traces ionized gas lying within the obscuring disk of NGC1068. One difficulty is that the covering fraction of the compact sources, $\sim 5\text{--}10\%$, is much smaller than required generally to explain the fraction of directly viewed AGNs²³ (the covering fraction is the portion of a sphere surrounding an AGN which is covered by obscuring clouds). However, the model can be reconciled if the geometric thickness of the obscuring medium increases with radius²⁴, and the HZ traces only emission from disk material nearest the AGN. Alternatively, the obscuring disk might instead be thin but highly warped²⁵, and again the HZ marks only the most central region of the disk.

Turning to the broad-band properties of the disk, the HZ plasma must also be a source of line and continuum emission up to soft X-ray energies. To determine whether the optical–X-ray spectrum of the HZ might be distinguished from neighbouring emission-line regions and the AGN proper, we modelled the HZ spectrum using the CLOUDY photoionization code²⁶, programmed to emulate a cooling plasma with the properties of the HZ, and normalized to the observed radio flux. We find that, in broad agreement with Pier and Voit⁷, the HZ contributes $\leq 10\%$ to the observed optical–ultraviolet emission lines of NGC1068 and $\leq 1\%$ to the optical–ultraviolet continuum. On the other hand, the HZ should contribute significantly to the soft X-ray spectrum of the nucleus were the AGN viewed along an unobscured sight-line. We estimate that free–free emission from the HZ may contribute $\geq 10\%$ of the AGN continuum in soft X-rays (photon energies $\sim 1\text{--}2\text{ keV}$). Moreover, the predicted soft X-ray line emission exceeds that observed towards NGC1068²⁷ by a factor of ≥ 100 . This observed diminution is approximately that expected for obscured X-ray emission viewed only in reflection¹⁹. Therefore, this result can be reconciled if the HZ is also heavily obscured over optical–soft X-ray wavebands. The implication is that, if the AGN unifying schemes hold generally, the disks surrounding unobscured AGN should be luminous soft X-ray emission-line sources. To our knowledge, there has as yet been no analysis of the soft X-ray line emission from unobscured AGN (that is, Seyfert 1 AGN). The detection of soft X-ray lines characteristic of a $10^6\text{--}10^7\text{ K}$ plasma in unobscured AGN would lend self-consistency to the obscuring disk model.

The present observation is, to our knowledge, the first direct image of a parsec-scale, ionized gas disk surrounding an AGN. Simple models for the radio emission further provide direct estimates of the physical properties of a parsec-scale disk, and the results are consistent with the predictions of AGN unifying schemes. However, we also find that photoionization heating is insufficient to support the high plasma temperatures in the disk, and so the challenge remains to model the energy budget in accord with the observed radio emission. Equally important is how the HZ might fit into the standard, infall model for AGN². The HZ is orientated nearly at right angles to the radio jet. The observed orientation suggests that, within the HZ, internal, viscous dissipation drives the fuelling of the AGN rather than external torques. In this regard, the HZ may be considered to define the outer extent of the long-sought accretion disk powering the AGN. □

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Correspondence and requests for materials should be addressed to J.E.G. (e-mail: jfg@hethp.mpe-garching.mpg.de).

Core formation on Mars and differentiated asteroids

Der-Chuen Lee and Alex N. Halliday

Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109-1063, USA

Meteorite chronometry based on the ^{182}Hf – ^{182}W system can provide powerful constraints on the timing of planetary accretion and differentiation^{1–4}, although the full potential of this method has yet to be realized. For example, no measurements have been made on the silicate-rich portions of planets and planetesimals other than the Earth and Moon. Here we report tungsten isotope compositions for two eucrites, thought to be derived from asteroid 4 Vesta, and from eight other basaltic achondritic meteorites that are widely considered to be from Mars. The eucrites, which are among the oldest differentiated meteorites, yield exceedingly radiogenic tungsten, indicating rapid accretion, differentiation and core formation on Vesta within the first 5–15 Myr of Solar System history, whereas the range of radiogenic tungsten measurements on the martian meteorites points towards tungsten depletion via melting and core formation within the first 30 Myr of the Solar System. The survival of tungsten isotope heterogeneity in the martian upper mantle implies that no giant impacts or large-scale convective mixing took place since this time. These results contrast with those obtained for the Earth–Moon system^{2,3} for which accretion and core formation related to