Variable Infrared Emission from the Supermassive Black Hole at the Center of the Milky Way

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\textbf{ABSTRACT}

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We report the detection of a variable point source, imaged at L’(3.8 μm) with the W. M. Keck II 10-meter telescope’s adaptive optics system, that is coincident to within 6 mas (1 σ) to the Galaxy’s central supermassive black hole and the unique radio source Sgr A*. While in 2002 this source (SgrA*-IR) was confused with the stellar source S0-2, in 2003 these two sources are now separated by 87 mas allowing the new source’s properties to be determined directly. On four separate nights, its observed L’ magnitude ranges from 12.2 to 13.8, which corresponds to a flux density of 0.7 - 3 mJy, observed, and 4 - 17 mJy, dereddened; no other source in this region shows such large variations in flux density - a factor of 4 over a week and a factor of 2 over 40 min. In addition, it has a K-L’ color greater than 2.1, which is at least 1 mag redder than any other source detected at L’ in its vicinity. Between 2002 and 2003, the new source has no significant proper motion with a 1 σ upper limit of 300 km s⁻¹, which is a factor of ≳ 20 smaller than that of the stellar sources measured within 10 mas of the dynamical center. Based on this source’s coincidence with the Galaxy’s dynamical center, its lack of motion, its variability, and its red color, we conclude that it is associated with the central supermassive black hole. The short timescale for the 3.8 μm flux density variations implies that the emission arises in the accretion flow on physical size scales smaller than 5 AU, or 80 Rₜ for a 4×10⁶M☉ black hole. We suggest that the 3.8 μm emission mechanism is synchrotron emission from the same population of electrons that gives rise to the X-ray flares, which implies that processes that can give rise to a high-energy power-law tail in the electron energy distribution are much more common than previously thought. In contrast to the X-ray flares which are only detectable ∼2% of the time, the 3.8 μm emission provides a new, constantly accessible, window into the physical conditions of the material being accreted onto the central black hole.

Subject headings: black hole physics – Galaxy:center – infrared:stars – techniques:high angular resolution

1. Introduction

At the center of the Milky Way lurks a supermassive black hole, whose presence and mass, ∼4×10⁶M☉, has been ferreted out through its strong gravitational field (e.g., Ghez et al. 2003a,b; Schödel et al. 2002, 2003), but whose associated radiative emission has remained more elusive. The most secure detection of radiation associated with the Galactic black hole is at radio wavelengths, where Sgr A* is detected as a nonthermal, compact, low-velocity
source (e.g., Beckert et al. 1996; Serabyn et al. 1997; Rogers et al. 1994; Backer & Sramek 1999; Reid et al. 1999, 2003a) that lies at $\sim 13 \pm 10$ mas from the Galactic dynamical center (Reid et al. 2003b; Ghez et al. 2003b). Furthermore, monitoring of Sgr A* suggests that it is a variable source with a quasi-periodicity of 106 d at radio wavelengths (Zhao, Bower, & Goss 2001). More recently, an X-ray source coincident, within $0''27 \pm 0''18$, with Sgr A* and the Galaxy’s dynamical center has been discovered (Baganoff et al. 2003a).

Subsequent work revealed two distinct components in the X-ray emission associated with Sgr A*: (1) a steady state, which has been stable to within $\sim 10\%$ over the past 4 years and which is spatially resolved with a size that corresponds to the Bondi radius ($\sim 1''$), and (2) an unresolved variable component, which has a flux density that rises above the quiescent level by an order of magnitude for one to a few hours approximately once a day (Baganoff et al. 2001, 2003b; Goldwurm et al. 2003; Porquet et al. 2003). While there are no sure detections of emission associated with the central black hole between these two wavelength extremes, existing infrared limits (e.g., Hornstein et al. 2002) reveal that overall, Sgr A* is remarkably weak, with a bolometric luminosity of only $10^{36}$ ergs s$^{-1}$ or, equivalently, $10^{-9}L_{Edd}$.

Detection of emission at infrared wavelengths would be a very powerful constraint for the proposed models of the accretion flow onto the central black hole as well as possible outflows (e.g., Markoff et al. 2001; Liu & Melia 2002; Yuan et al. 2003). At mid-infrared wavelengths ($\gtrsim 8$ $\mu$m), the detectability of a source is limited by thermal emission from dust (Stolovy et al. 1996; Morris et al. 2001). At near-infrared wavelengths (1-2 $\mu$m), a clear detection of an associated point source is difficult due to the confusion with stellar sources (e.g., Close et al. 1995; Genzel et al. 1997; Stolovy et al. 1999; Hornstein et al. 2002). In the 3-5 $\mu$m window, the stellar and dust emission are both declining, potentially allowing an unambiguous detection of a radiative counterpart at a wavelength intermediate to the radio and X-ray regimes.

In this paper, we present new L'(3.8 $\mu$m) images from the W. M. Keck II 10-meter telescope of the Galactic center showing a near-infrared counterpart to Sgr A* at the dynamical center of the Galaxy. Section 2 describes the adaptive optics observations and Section 3 summarizes the data analysis, including how sources are identified and characterized. Section 4 reports the detection of a new L’ source and its properties. Finally, Section 5 discusses possible emission mechanisms for the new source and concludes that it is indeed associated with the central black hole.
2. Observations

Adaptive optics L’ (λ = 3.776 μm and Δλ = 0.700 μm) bandpass observations of the Galactic center were obtained with the W. M. Keck II 10-meter telescope using the facility near-infrared camera, NIRC2 (Matthews et al., in prep) on 2002 May 31, 2003 June 10, and 2003 June 16 & 17 (UT). The positions of IRS 16NE, NW, and SW with respect to IRS 16C in the final map (see §3) established a plate scale of 9.93 ± 0.05 mas pix$^{-1}$, consistent with the 9.942 mas pix$^{-1}$ internal measurement made as part of the instrument’s labratory characterization and corresponding to a field of view of 10′′2 × 10′′2 for NIRC2’s narrow field camera, based on the absolute astrometry for these sources reported in Ghez et al. (2003b). Using an R=13.2 mag natural guide star located 30″ from Sgr A*, we were able to achieve a resolution as high as 80 mas, which corresponds to the diffraction limit, and Strehl ratios as high as ∼0.4. Each night, several images, composed of 0.2 to 0.5 sec coadded exposures with effective exposure on the sky of 20 to 60 sec, were collected using a 5 position dither pattern with offsets of ∼1 arcsec. Observations of a dark spot of sky were obtained in the same manner.

3. Data Analysis

The following standard image reduction steps were carried out: 1) an average of the sky observations was subtracted from each image to remove thermal emission from the sky, telescope structure, and adaptive optics system, 2) the images were flat fielded using the average sky image, and 3) bad pixels were removed by interpolation with their nearest neighbors. Visual inspection of the individual images eliminated those that were degraded by poor adaptive optics tip-tilt corrections, which occasionally generated double peaked PSFs. Inclusion in the final map for the remaining images was based on their estimated Strehl ratios, which were required to be ≥0.2. All the calibrated images were registered and averaged together using the centroid of IRS 16C’s light distribution.

Sources are identified and their positions and relative intensities are quantified using the point spread function (PSF) fitting program StarFinder, which was developed for the specific application of carrying out astrometry and photometry on adaptive optics images of crowded stellar fields (Diolaiti et al. 2000). Three bright point sources (IRS 16C, 16NW, and 33N) were entered into StarFinder’s algorithm for generating a model PSF. StarFinder cross-correlates the generated PSF with the image and correlation peaks above a user defined correlation threshold, typically ≥0.7 in this analysis, are considered to be source detections. Visual inspection of residual images, the original image with a model of the detected stellar population removed, shows that this correlation threshold is quite conservative. Uncertain-
ties in this process are established by dividing the data set up into independent maps composed of 2 to 3 frames, re-running this procedure on each map, and taking root-mean-square values for the astrometric and relative photometric values. This also allows an examination of the data set for shorter timescale flux density variations.

Simons & Becklin (1996) derived absolute photometry within the L’ bandpass for several of the bright stars within our field of view, allowing the measurements reported here to be photometrically calibrated. Among the 8 stars in common between the two data sets, 4 are known to be variable at L’ or at K (2.2 µm) and are therefore excluded; IRS 16CC (also labeled 16C-E) varied by more than 1.3 magnitudes at 3 µm between the measurements reported by Blum, Sellgren, & Depoy (1996) and those made by Simons & Becklin (1996), IRS 29N, 16SW-W, and 21 appear to be variable at 2 µm (Ott et al. 1999; Hornstein et al. 2002), and IRS 21 is also an extended source (Tanner et al. 2002). The remaining sources that are used to calibrate the data set presented here are IRS 16NE (7.77 mag), IRS 16SW-E (8.30 mag), IRS 16NW (8.87 mag), and IRS 16C (also labeled IRS 16C-W; 8.91 mag). Our multiple measurements of these 4 reference sources reveal no evidence for variability, confirming their suitability as local standards. We estimate the uncertainty in the apparent magnitude calibration for each image to be 0.1 mag from the standard deviation of the mean of the reference stars. All the reported measurements assume a zero point of 248 Jy for the L’ magnitude scale (Tokunaga 2000).

Both the position of the radio source Sgr A* and the dynamical center provide estimates of the black hole’s location in the L’ maps. Since the position of the dynamical center and that of Sgr A* agree, but the former is a factor of 5 more precise (Ghez et al. 2003b), we use the location of the dynamical center to estimate the position of the Galaxy’s central supermassive black hole in the analysis presented here. Using the orbital solutions for S0-1, S0-2, S0-3 and S0-4 reported in Ghez et al. (2003b), we localize the Galaxy’s dynamical center in each of the L’ images to within ± 5-10 mas, where these uncertainties are limited by inaccuracies in the centroids of the stars in the L’ maps.

4. Results

Figure 1 shows a 1″2 × 1″2 region of the combined images centered on the black hole’s location for each of the four nights reported here. In 2003, a new source is detected. With the exception of this new source all other detected L’ sources in Figure 1 are coincident with stars detected at 2.2 µm (Ghez et al. 2003b); a complete description of the L’ sources can be found in Wright et al. (in prep). The new source distinguishes itself in several ways. It is an unresolved point source that has a negligible average offset of 12 ± 6 mas from the dynamical
center. In contrast to stars in its vicinity, the new L' source is remarkably variable. This is shown in Figure 2, which plots the new source’s dereddened flux density along with that of all sources that are nearby ($r < 0''5$), are comparably bright (L' $\lesssim 13.6$ mag), and do not suffer from confusion; all the sources are dereddened assuming an L’ extinction of 1.83 mag, which is based on a visual extinction of 30 mag from Rieke, Rieke, & Paul (1989) and an extinction law from Moneti et al. (2001). On 2003 June 10 the new source was at its brightest at 12.28 mag and then it dimmed by a factor of 3 (13 $\sigma$) to 13.38 mag by 2003 June 17, with a factor of 2 (12 $\sigma$) change occurring between June 16 and 17. Subdivision of the data into shorter time blocks of 60 second exposures, which correspond to elapsed time of 100 - 250 seconds depending on how images were selected (see §3), shows significant substructure (see Figure 2); on 2003 June 17 the new source is observed to have dimmed by a factor of 2, with a significance of 5 $\sigma$. Table 1 provides a summary of this source’s measured properties, which includes its position with respect to the dynamical center as well as its apparent magnitude and dereddened flux density at 3.8 $\mu$m.

In our 2002 map, the new L' source is blended with the star S0-2, which at this time was experiencing its closest approach to the central black hole with a projected separation of a mere 14 mas and a proper motion of 170 mas yr$^{-1}$, or equivalently 6600 km s$^{-1}$ (Schödel et al. 2002, 2003; Ghez et al. 2003a,b; Eisenhauer et al. 2003). This confused the identification of the L’ source in this first epoch map, as well as those obtained at the VLT on 2002 August 29 (Clenet et al. 2003, Genzel et al. 2003). In our 2003 maps, S0-2 is 87 mas away from the dynamical center and is clearly separated from the newly identified L’ source (see Figure 1). Since S0-2 shows no evidence for significant variability in the K-band, where there is negligible confusion with other sources (Hornstein et al., in prep), we use the L’ mag of S0-2 measured in 2003 June 16 & 17, when the contrast between S0-2 and the new source is smallest, ($<L'_{S0-2}> = 13.27$) to subtract the S0-2 contamination to the new source in 2002 May 31. This results in an inferred brightness of L’=13.0 mag, which is close to the average of the values measured in 2003 June. A comparison of the 2002 position with the average 2003 position limits its proper motion to 400 ± 300 km s$^{-1}$.

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5 Based on the L’ values for stellar sources within the central 0''7, there is a significant zero-point offset between our reported values and what is presented by Clenet et al. (2003) and Genzel et al. (2003); using stellar sources in common within the central 0''7, we measure the offsets to be L’$_{Keck} = L’_{Genzel} + 0.82$ mag and L’$_{Keck} = L’_{Clenet} + 0.37$ mag. This is primarily a consequence of variable and/or extended sources being included in their sample of reference sources (see §3 and Wright et al, in prep); Clenet et al. (2003) use IRS 16C, 29N, 16CC, 21, 33SE, and MPE+1.6-6.8 and Genzel et al. (2003) restrict their analysis of the same data set to IRS 16CC and 33N.
5. Discussion & Conclusions

The newly identified L’ source has several properties that indicate that it is affiliated with the central black hole. First, its location on the plane of the sky is coincident with the dynamical center to within 6 mas (1 σ). Second, it appears to be a stationary source with an upper limit on its transverse motion of 300 km s$^{-1}$, which differs from the proper motions of $>6,000$ km s$^{-1}$ for other sources that have come within 10 mas of the dynamical center (Ghez et al. 2003b; Schödel et al. 2003). Third, it is a variable source with significant flux density changes observed on timescales as short as 40 min. Fourth, it is an extremely red object. In the K-band, a stationary source consistent with the location of the dynamical center would have to be fainter than at least K $\sim$ 15.5 mag to be consistent with the observations of Ghez et al. (2003b) and Hornstein et al. (2002). The K-L color of the new source must therefore be greater than 2.1 mag, which is at least 1.0 mag redder than all the nearby stars used as comparison stars in Figure 2. Such a red color is expected for Sgr A* from the sub-millimeter detections (e.g., Falcke et al. 1998; Zhao et al. 2003) and 2.2 $\mu$m limits (Hornstein et al. 2002) shown in Figure 3. We conclude that the new L’ source is associated with the central black hole or, equivalently, Sgr A*, and therefore refer to it as SgrA*-IR.

Several mechanisms associated with a central black hole can give rise to infrared variability, including gravitational lensing (e.g., Alexander & Loeb 2001), disk illumination (Cuadra, Nayakshin, & Sunyaev 2003), star-disk collisions (Nayakshin & Sunyaev 2003), and physical processes in the black hole’s accretion flow (e.g., Markoff et al. 2001; Liu & Melia 2002; Yuan, Quataert, & Narayan 2003). Assuming that we are witnessing a single phenomenon, the observed short timescales for the variations, $\sim$40 min, rule out the first two possibilities and the longer timescales eliminate the third. We, therefore, suggest that the detected 3.8 $\mu$m emission emanates from the accretion flow from a physical size scale $\lesssim$ 5 AU, or equivalently 80 R$_s$ for a 4×10$^6$M$_\odot$ black hole. While the shortest timescale variations observed at 3.8 $\mu$m are comparable to the X-ray flare timescales detected by Chandra & XMM (Baganoff et al. 2001, 2003b; Goldwurm et al. 2003; Porquet et al. 2003), the probability that such an X-ray flare occurred during any of these observations is less than 0.05 and the probability that such X-ray flares occurred or were in progress during all of our observations is less than 10$^{-7}$. We therefore presume that during our observations that the X-ray emission was dominated by its extended steady state flux and that any possible emission from the unresolved variable X-ray source was below this quiescent level. The 3.8 $\mu$m measurements show no evidence of a steady state.

The similarity in the timescales for variation at 3.8 $\mu$m and at X-ray wavelengths lead us to suggest that the 3.8 $\mu$m emission is produced by a mechanism related to that which produces the X-ray flares. As first suggested by Markoff et al. (2001), the flared X-ray
emission is likely to arise from enhanced electron heating or acceleration, due to MHD turbulence, reconnection, or weak shocks, which can promote some fraction of the electrons into the power-law tail of the electron energy distribution. If energetic enough ($\gamma \sim 10^6$), these electrons might account for the X-ray flares as synchrotron emission, although the energy requirement for the electrons is not as demanding if the X-rays are produced by synchrotron-self Compton (SSC) upscattering of sub-mm and infrared synchrotron photons (Yuan et al. 2003). The SSC models produce a significant amount of 3.8 $\mu$m emission from the direct synchrotron emission (e.g., Markoff et al. 2001; Yuan et al. 2003). We propose that synchrotron emission is the mechanism giving rise to the 3.8 $\mu$m emission detected in our observations (see Figure 3). In this case the variability may be induced by small changes in the fraction of electrons in the high-energy power-law tail of the electron energy distribution or by changes in the value of the power-law (Yuan et al. 2003). Furthermore, we suggest that, due to geometrical, radiative transfer, or density effects that can suppress the SSC emission, this does not always generate a detectable X-ray flare. Presumably the X-ray flux density emerging from this non-thermal plasma located very close to the black hole is variable, but it is dominated by the steady state X-ray emission. If the SSC model is applicable, the same population of electrons can be responsible for both the 3.8 $\mu$m emission and the X-ray flares. This would imply that processes that can give rise to a high-energy power-law tail in the electron energy distribution are much more common than previously thought. It is now clear that the 3.8 $\mu$m emission is a powerful tool for studying the state of the plasma that ultimately gives rise to the stronger, but infrequently detectable X-ray flares. Furthermore, since this plasma appears to be detectable at all times at 3.8 $\mu$m, as opposed to only $\sim 2\%$ of the time at X-ray wavelengths, the 3.8 $\mu$m emission opens up a continuously accessible window for studying the accretion flow onto the central black hole.

The authors thank Joel Aycock, Randy Campbell, Grant Hill, Chuck Sorensen, Marcos van Dam, and Cynthia Wilburn at the Keck Observatory for their help in obtaining the observations. Support for this work was provided by the National Science Foundation grant AST-9988397 and the National Science Foundation Science and Technology Center for Adaptive Optics, managed by the University of California at Santa Cruz under cooperative agreement No. AST-9876783. The W.M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. The authors also wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.
REFERENCES


\textsuperscript{AAS LATEX macros v5.0.}
Table 1. Summary of SgrA*-IR’s 3.8 μm properties

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<td>(mag)</td>
<td>(mJy)</td>
<td>ΔRA (mas)</td>
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³Since the new L’ source coincided with S0-2 in 2002, the reported magnitude has had the flux density observed for S0-2 in 2003 removed (see §4).
Fig. 1.— A 1.2″ × 1.2″ region of the L’(3.8 µm) Galactic center images obtained with the adaptive optics systems on the W. M. Keck II 10-meter telescope during the nights of 2002 May 31, 2003 June 10, 2003 June 16, and 2003 June 17. In each image, a cross denotes the dynamically determined position of the central black hole and its uncertainties. An L’ source, SgrA*-IR, is coincident with this position in all images; while in 2002 SgrA*-IR is blended with the stellar source S0-2, S0-2’s significant orbital motion makes it well resolved from SgrA*-IR in the 2003 images. Clear intensity variations are detectable in these nightly images, in which SgrA*-IR is at its brightest in 2003 June 10, when it dominates over S0-2, and its faintest in 2003 June 17, when it is somewhat dimmer than S0-2. The 5 comparison stars, whose photometry is plotted in Figure 2, are circled with dashed lines.
Fig. 2.— Dereddened 3.8 \( \mu \)m flux densities for SgrA*-IR (top) and 5 nearby stellar sources of similar brightness (bottom). A panel of 80 minutes for each of the four nights of observations is shown. The comparison sources are S0-1 (cyan circles), S0-3 (red triangles), S0-4 (green squares), S0-6 (blue asterisks), S0-11 (magenta stars). While the stellar sources show no significant variation, SgrA*-IR has varied by a factor of 3 over the course of a week, 2003 June 10-17, and a factor of 2 within 40 minutes on the night of 2003 June 17.
Fig. 3.— The spectral energy distribution for Sgr A*. The new 3.8 $\mu$m flux density measurements are plotted as two filled circles delimiting the range of observed values. Other measurements from the literature are plotted with the following symbols: radio data appear as diamonds (Falcke et al. 1998) and triangles (Zhao et al. 2003), mid-infrared limits (Serabyn et al. 1997) and 2 $\mu$m limits (Hornstein et al. 2002) are depicted with arrows, and X-ray flux densities in steady state and a flaring state are plotted as bowties (Baganoff et al. 2001; 2003). The curve shown is a model from Yuan et al. (2003), in which 3.8 $\mu$m emission arises from synchrotron emission from the same population of electrons that can produce X-ray flares via synchrotron-self Compton upscattering of infrared synchrotron photons.