VARIABLE INFRARED EMISSION FROM THE SUPERMASSIVE BLACK HOLE
AT THE CENTER OF THE MILKY WAY

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ABSTRACT

We report the detection of a variable point source, imaged at \(L'\) (3.8 \(\mu\)m) with the Keck II 10 m telescope’s adaptive optics system, that is coincident to within 18 mas (1 \(\sigma\)) of the Galaxy’s central supermassive black hole and the unique radio source Sgr A*. While in 2002 this source (Sgr A* IR) was confused with the stellar source S0-2, in 2003 these two sources are 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 dereddened flux density of 4–17 mJy; 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 minutes. 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. 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 \(\mu\)m flux density variations implies that the emission arises quite close to the black hole, within 5 AU, or 80 \(R_s\). We suggest that both the variable 3.8 \(\mu\)m emission and the X-ray flares arise from the same underlying physical process, possibly the acceleration of a small population of electrons to ultrarelativistic energies. In contrast to the X-ray flares, which are only detectable \(\sim 2\%\) of the time, the 3.8 \(\mu\)m emission provides a new, constantly accessible window into the physical conditions of the plasma in close proximity to the central black hole.

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

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1. INTRODUCTION

At the center of the Milky Way lurks a supermassive black hole (SMBH) whose presence and mass, \(\sim 4 \times 10^6\ M_\odot\), have been ferreted out through its strong gravitational field (e.g., Ghez et al. 2003a, 2003b; Schödel et al. 2002, 2003) but whose associated radiative emission has remained more elusive. For decades it was only detected at radio wavelengths (see, e.g., Melia & Falcke 2001), where it appears to show low-amplitude intensity variations with a quasi-periodicity of \(\sim 106\) days (Zhao, Bower, & Goss 2001). Recent observations detected it at X-ray wavelengths, where it appears to be composed of the following two distinct components (Baganoff et al. 2001, 2002, 2003; Goldwurm et al. 2003; Porquet et al. 2003): (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 (\(\sim 10\) pc), and (2) an unresolved variable component, which has a flux density that rises above the quiescent level by an order of magnitude for \(\sim 1\) hr approximately once a day. These detections at opposite ends of the electromagnetic spectrum, along with existing infrared (IR) limits (e.g., Serabyn et al. 1997; Morris et al. 2001; 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, \(10^{-3} L_{\text{Edd}}\).

Detection of emission at IR wavelengths would be a very powerful constraint for the proposed models of the accretion flow onto the SMBH as well as possible outflows (e.g., Markoff et al. 2001; Liu & Melia 2002; Yuan, Quataert, & Narayan 2003). At mid-IR wavelengths (\(\sim 8\ \mu\)m), the detectability of a source is limited by thermal emission from dust (Stolovy, Hayward, & Herter 1996; Morris et al. 2001). At near-IR wavelengths (1–2 \(\mu\)m), detection of an associated point source is difficult because of the confusion with stellar sources (e.g., Close, McCarthy, & Melia 1995; Genzel et al. 1997; 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 Letter, we present new \(L'\) (3.8 \(\mu\)m) images from the W. M. Keck II 10 m telescope of the Galactic center showing a near-IR counterpart to Sgr A*. In § 2 we describe the observations, and in § 3 we summarize the data analysis. In § 4 we report the detection of a new \(L'\) source and its properties. Finally, in § 5 we discuss possible emission mechanisms for the new source and conclude that it is indeed associated with the SMBH.

2. OBSERVATIONS

Adaptive optics \(L'\) (\(\lambda_0 = 3.8\ \mu\)m and \(\Delta \lambda = 0.7\ \mu\)m) bandpass observations of the Galactic center were obtained with the W. M. Keck II 10 m telescope using the facility near-infrared camera, NIR2C (K. Matthews et al. 2004, in preparation) on the following four nights: 2002 May 31 and 2003 June 10, 16, and 17 (UT). The positions of IRS 16 NE, NW, and SW with respect to IRS 16 C in the final map (see § 3) compared with that reported in Ghez et al. (2003b) established a plate scale of 9.93 \(\pm\) 0.05 mas pixel\(^{-1}\), corresponding to a field of view
of 10′′2 × 10′′2 for NIRC2’s narrow field camera. 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 0.2–0.5 s
collected exposures with an effective exposure on the sky of
20–60 s, were collected using a five position dither pattern with
offsets of ~1′′.

3. DATA ANALYSIS

The standard image reduction steps of sky subtraction, flat
fielding, and bad pixel removal were carried out on each image.
Visual inspection of the reduced individual images eliminated
those that were degraded by poor adaptive optics tip-tilt cor
rections, which occasionally generated double-peaked point
spread functions (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 of the selected images
were registered and averaged together using the centroid of
IRS 16 C’s light distribution.

Sources were identified, and their positions and relative in
tensities were quantified using the PSF fitting program
StarFinder (Dinoliti et al. 2000). Three bright point sources
(IRS 16 C, 16 NW, and 33 N) were entered into StarFinder’s
algorithm for generating a model PSF. Uncertainties in this
process were established by dividing the data set into inde
pendent maps composed of two to three frames, rerunning this
procedure on each map, and taking rms values for the astro
metric and relative photometric values. This also allowed us
to examine the data set for shorter timescale flux density
variations.

Measurements reported here are photometrically calibrated
based on absolute $L$ photometry for several bright stars within
our field of view obtained by Simons & Becklin (1996). From
the eight stars in common, we selected the following four stars,
which are not known to be variable or spatially extended at
$L$ or at $K$ (2.2 μm), as calibration sources: IRS 16 NE (7.77 mag),
IRS 16 SW-E (8.30 mag), IRS 16 NW (8.87 mag), and IRS 16
C (also labeled IRS 16 C-W; 8.91 mag). Our multiple mea
surements of these sources reveal no evidence of 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
calibration sources. All the reported measurements are based on
a zero point of 248 Jy for the $L$ magnitude scale (Tokunaga
2000).

The inferred position of the SMBH in the $L$ maps is based
on its dynamically determined position. Using the orbital so
lutions for S0-1, S0-2, S0-3, and S0-4 reported in Ghez et al.
(2003b), we localize the SMBH 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 SMBH’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). 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 SMBH. 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), that are comparably bright (L' ≤ 13.6 mag), and that
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 σ) to 13.38 mag by 2003 June
17, with a factor of 2 (12 σ) change occurring between June
16 and 17. A subdivision of the data into shorter time blocks
of 60 s exposures, which correspond to an elapsed time of 100–
250 s depending on how images were selected (see § 3), shows
significant substructure (see Fig. 2); on 2003 June 17, the new
source is observed to have dimmed by a factor of 2, with a
significance of 5 σ. This also increases the range of intensity
variations observed over a week to a factor of 4. Table 1 pro-
vides a summary of this source’s measured properties, which
includes its position with respect to the SMBH as well as its
apparent magnitude and dereddened flux density at 3.8 μm.

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 SMBH with a projected separation of a mere 14 mas
(Ghez et al. 2003a, 2003b; Schödel et al. 2003). This confused
the identification of the L' source in this first epoch map as
well as those obtained at the Very Large Telescope on 2002
August 29 (Clénet et al. 2003; Genzel et al. 2003).7 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
Fig. 1). Since S0-2 shows no evidence of significant variability
in the K band, where there is negligible confusion with other
sources (Ghez et al. 2003b), we use the L' magnitude of S0-2
measured in 2003 June 16 and 17, when the contrast between
S0-2 and the new source is smallest (∆L'_{0.02} = 13.07), to sub-
tract the S0-2 contamination from the new source in 2002 May
31. This results in an inferred brightness of L' = 13.2 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.

5. DISCUSSION AND CONCLUSIONS

The newly identified L' source has several properties that
indicate that it is affiliated with the SMBH. First, its location
on the plane of the sky is coincident with the SMBH to within
18 mas (1 σ). Second, it appears to be a stationary source with
an upper limit on its transverse motion of 700 km s
−1, which
differs from the proper motions of greater than 6000 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 ob-
served on timescales as short as 40 minutes. Fourth, it is an
extremely red object. In the K band, a stationary source con-
sistent with the location of the dynamical center would have
to be fainter than at least K ~ 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 submillimeter de-
tections (e.g., Falcke et al. 1998; Zhao et al. 2003) and 2.2 μm
limits (Hornstein et al. 2002) shown in Figure 3. We conclude
that the new L' source is associated with the SMBH or, equiva-
ently, Sgr A*, and therefore we refer to it as Sgr A* IR.

Several mechanisms associated with an SMBH can give rise
to IR variability, including gravitational lensing (e.g., Alexan-
der & Loeb 2001), disk illumination (Cuadra, Nayakshin, & Sunyaev
2003), star-disk collisions (Nayakshin & Sunyaev 2003), and
physical processes in the SMBH’s accretion flow (e.g., Markoff

Fig. 3.—Spectral energy distribution for Sgr A*. The new 3.8 μm 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-IR limits (Serabyn et al. 1997) and 2 μm limits (Hornstein et al.
2002) are depicted as arrows, and X-ray flux densities in a steady state and
variable (dotted curve: SSC model; solid curve: synchrotron-only model) of
Sgr A* taken from Yuan et al. (2003, 2004).

TABLE 1

| Offset from | Dynamical | Center |
|-------------|---------|--------|
| UT Date     | UT Time | L'     | F_{v, dereddened} | ∆R.A. | ∆Decl. |
| 2002 May 31 | Average | 13.23 ± 0.10 | 6.9 ± 0.7 | 0 ± 6 | -7 ± 7 |
| 11:29       |         | 12.78 ± 0.18 | 10.35 ± 1.9 | ...   | ...    |

Note.—Table 1 is published in its entirety in the electronic edition of the
Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
et al. 2001; Liu & Melia 2002; Yuan et al. 2003, 2004). Assuming that we are witnessing a single phenomenon, the observed short timescales for the variations, ~40 minutes, rule out the first two possibilities, and the longer timescales eliminate the third. We therefore suggest that the detected 3.8 μm emission emanates from either an accretion flow or an outflow quite close to the SMBH, within 5 AU or, equivalently, 80 Ṙ. While the shortest timescale variations observed at 3.8 μm are comparable to the X-ray flare timescales (Baganoff et al. 2001, 2002; 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. Nonetheless, the similarity in the timescales for variations at 3.8 μm and at X-ray wavelengths leads us to suggest that the variable 3.8 μm emission is produced by a mechanism related to that which produces the X-ray flares. We presume any associated variable X-ray emission during our observations was below the quiescent level.

Several models of the flared X-ray emission have been proposed, invoking physical processes such as elevated accretion rates or enhanced electron acceleration from MHD turbulence, reconnection, or weak shocks and emission mechanisms including bremsstrahlung, synchrotron, and inverse Compton radiation (Markoff et al. 2001; Liu & Melia 2001, 2002; Yuan et al. 2003, 2004). Models that account for the low variability amplitude at radio frequencies generally invoke acceleration of some fraction of the electrons into the power-law tail of the electron energy distribution (Markoff et al. 2001; Liu & Melia 2001, 2002; Yuan et al. 2003). For the two cases that produce 3.8 μm emission via synchrotron emission, the SSC model predicts correlated IR and X-ray flares, while the synchrotron-only model can more readily allow for an IR-only flare, depending on the spectrum of the accelerated electron energy distribution. It therefore appears at present that the synchrotron-only model best fits the available data (e.g., Yuan et al. 2004). Furthermore, in contrast to the X-ray flares, which suggest that processes giving rise to a high-energy power-law tail in the electron energy distribution occur infrequently (±2% of the time), the persistently detected variable 3.8 μm emission suggests that such processes are in effect much more often. More generally, the 3.8 μm emission opens up a continuously accessible window for studying the conditions and physical processes within the plasma that is either accreting onto or outflowing from the central black hole.

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REFERENCES

Alexander, T., & Loeb, A. 2001, ApJ, 551, 223
Baganoff, F. K., et al. 2001, Nature, 413, 45
———. 2002, BAAS, 34, 1153
———. 2003, ApJ, 591, 891
Clénet, Y., et al. 2003, A&A, in press (astro-ph/0312108)
Close, L., McCarthy, D. W., & Melia, F. 1995, ApJ, 439, 682
Cudja, J., Nayakshin, S., & Sunyaev, R. 2003, A&A, 411, 405
Dionati, E., Bendinelli, O., Bonaccini, D., Close, L., Currie, D., & Parmeggiani, G. 2000, A&AS, 147, 335
Falcke, H., Goss, W. M., Matsuo, H., Teuben, P., Zhao, J.-H., & Zylka, R. 1998, ApJ, 499, 731
Genzel, R., Eckart, A., Ott, T., & Eisenhauer, F. 1997, MNRAS, 291, 219
Genzel, R., et al. 2003, ApJ, 594, 812
Ghez, A. M., et al. 2003a, ApJ, 586, L127
Ghez, A. M., Salim, S., Hornstein, S. D., Tanner, A., Morris, M., Becklin, E. E., & Duchêne, G. 2003b, ApJ, submitted (astro-ph/0306130)
Goldwurm, A., Brion, E., Goldoni, P., Ferrando, P., Daigne, F., Decourchelle, A., Warwick, R. S., & Predehl, P. 2003, ApJ, 584, 751
Hornstein, S. D., Ghez, A. M., Tanner, A., Morris, M., Becklin, E. E., & Wizinowich, P. 2002, ApJ, 577, L9
Liu, S., & Melia, F. 2001, ApJ, 561, L77
———. 2002, ApJ, 566, L77
Markoff, S., Falcke, H., Yuan, F., & Biermann, P. L. 2001, A&A, 379, L13
Meila, F., & Falcke, H. 2001, ARA&A, 39, 309
Moneti, A., Stolovy, S., Blommaert, J. A. D. L., Figer, D. F., & Najarro, F. 2001, A&A, 366, 106
Morris, M., Tanner, A. M., Ghez, A. M., Becklin, E. E., Coteira, A., Werner, M. W., & Ressler, M. E. 2001, BAAS, 33, 841
Nayakshin, S., & Sunyaev, R. 2003, MNRAS, 343, L15
Porquet, D., Predehl, P., Aschenbach, B., Grosso, N., Goldwurm, A., Goldoni, P., Warwick, R. S., & Decourchelle, A. 2003, A&A, 407, L17
Rieke, G. H., Rieke, M. J., & Paul, A. E. 1989, ApJ, 336, 752
Schödel, R., Genzel, R., Ott, T., Eckart, A., Mouawad, N., & Alexander, T. 2003, ApJ, 596, 1015
Schödel, R., et al. 2002, Nature, 419, 694
Serabyn, E., Carlstrom, J., Lay, O., Lis, D. C., Hunter, T. R., & Lacy, J. H. 1997, ApJ, 490, L77
Simons, D. A., & Becklin, E. E. 1996, AJ, 111, 1908
Stolovy, S. R., Hayward, T. L., & Herter, T. 1996, ApJ, 470, L45
Tokunaga, A. T. 2000, in Allen’s Astrophysical Quantities, ed. A. N. Cox (New York: Springer)
Yuan, F., Quataert, E., & Narayan, R. 2003, ApJ, 598, 301
———. 2004, ApJ, in press (astro-ph/0401429)
Zhao, J.-H., Bower, G. C., & Goss, W. M. 2001, ApJ, 547, L29
Zhao, J.-H., Young, K. H., Herrnstein, R. M., Ho, P. T. P., Tsutsui, T., Lo, K. Y., Goss, W. M., & Bower, G. C. 2003, ApJ, 586, L29