A SEARCH FOR THE NEAR-INFRARED COUNTERPART TO GCRT J1745–3009

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ABSTRACT

We present an optical/near-infrared search for a counterpart to the perplexing radio transient GCRT J1745–3009, a source located ∼1° from the Galactic center. Motivated by some similarities to radio bursts from nearby ultracool dwarfs, and by a distance upper limit of 70 pc for the emission to not violate the $10^{12}$ K brightness temperature limit for incoherent radiation, we searched for a nearby star at the position of GCRT J1745–3009. We found only a single marginal candidate, limiting the presence of any late-type star to >1 kpc (spectral types earlier than M9), >200 pc (spectral types L and T0–T4), and >100 pc (spectral types T4–T7), thus severely restricting the possible local counterparts to GCRT J1745–3009. We also exclude any white dwarf within 1 kpc or a supergiant star out to the distance of the Galactic center as possible counterparts. This implies that GCRT J1745–3009 likely requires a coherent emission process, although whether or not it reflects a new class of sources is unclear.

Subject headings: Galaxy: center — infrared: stars — radio continuum: general — stars: low-mass, brown dwarfs — stars: variables: other

Online material: color figures

1. INTRODUCTION

A blind search program using the Very Large Array (VLA) at 330 MHz (90 cm), made possible by new wide-field radio imaging techniques, has resulted in the discovery of two radio transients near the Galactic center (GC). One of these, GCRT J1745–3009, exhibits dramatic 1 Jy outbursts that last about 10 minutes and have a recurrence interval of about 77 minutes (Hyman et al. 2005).

GCRT J1745–3009 exhibited five bursts at 330 MHz, each lasting about 10 minutes, at apparently regular intervals of 77.1 minutes during a 7 hr VLA observation in 2002 September. After several nondetections during the summer of 2003, a single burst was detected during a short Giant Metrewave Radio Telescope (GMRT) observation in 2003 September (Hyman et al. 2006), confirming that it is recurrent. It has since also been faintly detected in an additional GMRT observations from 2004, where it had a very steep nonthermal radio spectrum across the 32 MHz bandpass (Hyman et al. 2007). It is at Galactic coordinates $l = 358.89^\circ$, $b = -0.54^\circ$, so it may be as close as 180 pc to the GC, although the distance of GCRT J1745–3009 from the Earth is completely unknown. If it is at a distance $d > 70$ pc from the Earth, then the radio flux density combined with the rapid (~2 minutes) decay of the bursts constrains its brightness temperature to exceed the $10^{12}$ K limit for incoherent synchrotron radiation (Readhead 1994) and thus it is very likely a coherent emitter. The positional coincidence with the GC, along with the greatly increasing source density near the center, suggests it is at a distance of about 8 kpc, but this could be a selection effect because all the fields searched for transients in this program were in that direction. Consequently, it is very important to rule out local classes of sources as possible explanations.

Among the many possibilities discussed for the origin of GCRT J1745–3009, several involved low-mass stars or substellar objects (brown dwarfs [BDs]), which we generically call ultracool dwarfs. These were initially rejected as being unlikely or inconsistent with the observations (Hyman et al. 2005). However, additional observations are required to strengthen the case against the ultracool dwarfs and to confirm that the radio source is indeed a new type of source. Alternative models have also been proposed, ranging from a nulling pulsar (Kulkarni & Phinney 2005), to a double pulsar (Turolla et al. 2005), a transient white dwarf (WD) pulsar (Zhang & Gil 2005), and a precessing radio pulsar (Zhu & Xu 2006), but these will largely be constrained through other observations.

A number of BDs and late-type stars have now been detected at GHz frequencies, in many cases despite the absence of flaring optical or X-ray emission that would accompany radio emission from normal stars (see Berger 2006 for a review). These objects exhibit a range of nonthermal flaring behaviors, from strong, narrowband, fully polarized, bursting emission with frequency drifts (Burgasser & Putman 2005), to periodic bursts suggestive of pulsar-like beaming (Hallinan et al. 2007), to order-of-magnitude variations spanning years (Antonova et al. 2007). In particular, the behavior found by Hallinan et al. (2007) for the M9 dwarf TVLM 513–46546 is reminiscent of GCRT J1745–3009: bright bursts of coherent emission that follow the 2 hr rotation of the star.
Although the bursts are orders of magnitude weaker than those seen for GCRT J1745−3009, the observations differ by an order of magnitude in wavelength, and there are no current limits on the radio behavior of ultracool dwarfs at meter wavelengths.

We then have two independent but complementary motivations for searching for a counterpart to GCRT J1745−3009 in the near-infrared (near-IR) and optical bands. First, we wish to see if there is any possible counterpart closer than 70 pc; otherwise, we must conclude that the emission from GCRT J1745−3009 is coherent. Second, given the similarity between it and TVLM 513−46546, we wish to see if GCRT J1745−3009 is associated with a nearby ultracool dwarf, although such an object could be more distant than 70 pc, as they can emit coherently. A single ultracool dwarf in the error circle of GCRT J1745−3009 would be strong evidence that it is the counterpart, even in the absence of a precise position, as one expects <1 such object in a 2’ field (Reid et al. 1999; Caballero et al. 2008). We concentrated on the near-IR for several reasons: (1) if the source is at the distance of the GC, the average $K$-band extinction, $A_K$, at this position is approximately 2−3 mag, corresponding to a visual extinction of $\geq$20 mag (see, e.g., Dutra et al. 2003); (2) if the source is a relatively nearby late-type star, it would be intrinsically red; and (3) the field toward the GC is very crowded, and near-IR observations often have better seeing than bluer bands. We augmented the traditional near-IR bands ($JHKs$) with the $I$ band to aid in color discrimination (see below).

The structure of this paper is as follows. First, to aid the analysis that follows, we update our determination of the radio position of GCRT J1745−3009 in §2. We then describe our optical and near-infrared data in §3. The primary analysis is in §4, where we attempt to constrain any ultracool dwarf counterpart to GCRT J1745−3009. Following this, in §5 we also examine what constraints on other types of counterparts we can determine from our data. Finally, we give our conclusions in §6.

2. AN UPDATED RADIO POSITION

Before we search for counterparts at other wavelengths, we need to use the most accurate position possible for GCRT J1745−3009, and we must correct for the significant ionospheric refraction prevalent at low frequencies. We therefore present a revised analysis of the radio position of GCRT J1745−3009. This position was obtained by registering the 330-MHz 2003 and 2004 GMRT images with respect to the revised 6 and 20 cm source positions determined by White et al. (2005) in their reanalysis of the Galactic Plane Radio Survey (GPRS) of 586 compact sources (Zoonematkermani et al. 1990; Helfand et al. 1992; Becker et al. 1994). Our previous reports on GCRT J1745−3009 used either the initial GPRS survey or the much lower resolution NRAO VLA sky survey (Condon et al. 1998) to register the 330 MHz images.

We compared 13 and 19 sources within the primary beams of the 2003 and 2004 observations, respectively, with their 5 and 1.4 GHz (6 and 20 cm) counterparts. Five of the sources were detected at both 5 and 1.4 cm, and the average source positions were calculated for these. The 6 or 20 cm coordinates of the other 27 sources were shifted by half of the average difference (0.018° ± 0.059° in right ascension and 0.64° ± 0.81° in declination) we found between the 5 and 1.4 GHz positions of the five sources mentioned above and three others that were not detected at 330 MHz.

The position correction is determined to be 0.185° ± 0.071° in right ascension and $-2.87''$ ± $0.92''$ in declination for the 2003 observation and 0.013° ± 0.052° in right ascension and $-2.88''$ ± $0.77''$ in declination for the 2004 observation. The measured position of GCRT J1745−3009 was corrected by these differences at each of the two epochs. After correction, the two positions are consistent at roughly the 1 σ level, as shown in Figure 1. A weighted average of the two yields a position of R.A. = 17°45′50.15″, decl. = −30°09′52.79″ (J2000.0), with a 1 σ uncertainty of ±0.7″ on each coordinate. To be conservative and allow for astrometric frame uncertainties (which should be $\approx0.2''$ in each coordinate; see below), we use a position uncertainty in the near-IR of 1′′, and consider objects within 3 $\sigma$ (3′′ radius) of the position of GCRT J1745−3009.

3. OPTICAL AND INFRARED OBSERVATIONS AND REDUCTION

We obtained near-infrared ($JHKs$ bands, covering wavelengths 1.2−2.1 $\mu$m) photometric observations of GCRT J1745−3009 in the summer of 2005 with both PANIC on the Magellan I/Baade telescope and NIRI on the Gemini North telescope: see Table 1 for details. We also observed GCRT J1745−3009 in the $J$ band (0.8 $\mu$m) in 2006 with Magellan.

The near-infrared (PANIC and NIRI) reduction was similar for both instruments. For NIRI, there is an IRAF package to reduce the data available from the NIRI Web site.10 We proceeded through the steps of this package, flat-fielding the data, subtracting the sky, shifting the images, and adding them together. For PANIC, we used our own routines in PyRAF, but the steps were similar.

We referenced the astrometry and photometry of the PANIC data to the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006). For the astrometry, we used 210 2MASS stars that we identified as not blended or badly saturated for the $J$ and $H$ bands and 135 stars for the $K_s$ band, getting rms residuals of 0.11″ in each coordinate. The net uncertainty is $\approx0.2''$ in each coordinate, dominated by the $\approx0.15''$ uncertainty in the tie between 2MASS and the International Celestial Reference System (ICRS). We used fewer stars for photometry, since we avoided sources that showed any signs of saturation or significant nonlinearity in the data. However, we still used $\gtrsim$30 stars in the $K_s$ band and $\gtrsim$100 stars in the $J$ and $H$ bands. We estimate zero-point uncertainties of 0.1 mag for the $K_s$ band and 0.05 mag for the $J$ and $H$ bands, with the larger uncertainty at $K_s$ coming from the smaller number of stars and the greater effects of saturation.

For the NIRI data, we used 116 2MASS stars for the astrometry, and obtained rms residuals of 0.09″ in each coordinate. For the photometry, we tried to reference it to 2MASS and found zero-point magnitudes reasonably close to those in the NIRI manual, but many of the 2MASS stars showed some signs of saturation, and therefore we wanted to check with another method of calibration. We used an observation of the standard star FS 140. We corrected for the difference in air mass between the standard star observation and the observations of GCRT J1745−3009 using the extinction coefficients listed for the Keck telescope11 (also on Mauna Kea), although these corrections were minor. There might have been some small variations in extinction due to clouds over the course of the night (from the Canada France Hawaii Telescope sky probe). Overall, the zero-point magnitudes from both methods agreed to within 0.1 mag, and measurements of stars from PANIC and NIRI agreed to within this limit as well. We therefore assign a zero-point uncertainty of 0.1 mag to all of the NIRI data.

For the $I$-band data, we did standard reduction in IRAF by subtracting overscan regions, merging the data from four amplifiers, and flat-fielding the data with twilight flats. We registered the astrometry to that of the PANIC $K_s$-band image, using 248 stars that

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10 See http://www.us-gemini.noao.edu/sciops/instruments/niri/NIRIIndex.html.
11 See http://www.us-gemini.noao.edu/sciops/instruments/niri/standards/UKIRT-fs.html.
were not blended or badly saturated, and obtained rms residuals of $0.07''$ in each coordinate. For photometry, we used observations of the standard fields L113-339 and NGC 6093 (Landolt 1992; Stetson 2000), and we estimate a zero-point uncertainty of 0.1 mag.

4. SEARCH FOR AN ULTRACOOL DWARF

When we consider seeing and depth, our best set of images in the near-IR are the NIRI images in $J$ and $H$ bands, and the PANIC $K_s$-band image: unless otherwise noted, all references to $J$, $H$, and $K_s$-band images refer to those. We show the best near-IR images plus the $I$-band image in Figure 1. The other near-IR data are mostly useful as a check, but we note that we see no variability in the sources within the error circle over the 1–2 day span between the observations.

Since the $K_s$-band image shows by far the most objects and has the best seeing, we computed aperture photometry for all of the sources in that image using SExtractor (Bertin & Arnouts 1996). We then used those source positions to run SExtractor on the $I$, $J$, and $H$ images, generating a set of source photometry in four bands, which we supplemented with 2MASS photometry for the sources that were saturated on our images. We repeated this procedure but starting this time from the $I$-band image: this picked up many fewer sources, but they sample a larger range in color space.

Overall, we found $3\sigma$ limiting magnitudes for the $I$, $J$, $H$, and $K_s$ images, generating a set of source photometry in four bands, which we supplemented with 2MASS photometry for the sources that were saturated on our images. We repeated this procedure but starting this time from the $I$-band image: this picked up many fewer sources, but they sample a larger range in color space.

For the sources in the $3\sigma$ error circle we were more careful about the photometry. We used PSF fitting routines from DAOPHOT (Stetson 1987) within IRAF. For each band, we modeled the PSF

![Fig. 1.—Images of the field of GCRT J1745–3009. We show our best images in the $I$ (top left), $J$ (top right), $H$ (bottom left), and $K_s$ (bottom right) bands. We give the individual error circles from the 2003 and 2004 observations ($J$ band only), as well as the weighted average. The error circles on the average position have radii of $1''$ and $3''$, corresponding to $1$ and $3\sigma$ uncertainties. North is up, and east to the left. The three objects with $I$-band detections from Table 2 are labeled in the $I$-band image. [See the electronic edition of the Journal for a color version of this figure.]

### TABLE 1
**Observation Summary**

| Date         | Telescope          | Instrument | Band        | Exposure (s) | Seeing (arcsec) |
|--------------|--------------------|------------|-------------|--------------|-----------------|
| 2005 Jul 12  | Magellan I/Baade   | PANIC      | $K_s$ (2.1 μm) | 1800         | 0.4             |
| 2005 Jul 13  |                    |            | $J$ (1.2 μm)  | 1920         | 0.8             |
| 2005 Jul 14  |                    |            | $H$ (1.6 μm)  | 2460         | 0.7             |
| 2005 Jul 14  | Gemini North       | NIRI       | $J$ (1.2 μm)  | 840          | 0.5             |
|              |                    |            | $H$ (1.6 μm)  | 840          | 0.5             |
|              |                    |            | $K_s$ (2.1 μm) | 780          | 0.4             |
| 2006 Jun 20  | Magellan II/Clay   | MagIC      | $I$ (0.8 μm)  | 3660         | 0.4             |

**Notes.—** PANIC is Persson’s Auxiliary Nasmyth Infrared Camera on the 6.5 m Baade (Magellan I) telescope (Martini et al. 2004). NIRI is the Near-Infrared Imager on the 8 m Gemini North telescope (Hodapp et al. 2003). MagIC is the Raymond and Beverly Sackler Magellan Instant Camera on the 6.5 m Clay (Magellan II).
from an ensemble of about 50 stars that were well separated from all neighbors and where our aperture photometry was not corrupted by any bad pixels or cosmic rays. We then iteratively fit the PSF models to the sources within the error circle, identifying the brighter objects, subtracting them, and then examining the residual image for any fainter neighbors. What is most striking about the images is the crowding at \( K_s \) compared to the relatively empty field at \( I \): we detect at least 26 sources in the former, compared to only three in the latter.

For the 15 objects with detections in at least two bands, we give the PSF photometry in Table 2 (also see Fig. 2), where we have attempted to combine the photometry from the different images even though it is not always perfectly clear how to do so given the differences in seeing and brightness. For instance, in the \( K_s \)-band image object A is relatively bright, but is surrounded by a number of nearby objects that are \( >1 \) mag fainter. However, in the \( J \)-band image all of those objects are blended together, and so we ascribe all of the flux to object A in that band. It is clear that we have detected sources fainter than the nominal limiting magnitudes given above. There may be some additional faint objects remaining in the \( K_s \)-band image that we could have included, but none of these is detected in any other band, so they are of limited utility in our attempt to find a counterpart to GCRT J1745–3009.

To define the sort of object that we are searching for, we consider the results of Reid et al. (2001), Dahn et al. (2002), and Vrba et al. (2004). Together, these papers discuss the classification and absolute photometry of cool dwarf stars and BDs. They establish the broadband colors as a function of spectral type for stars with spectral types ranging from late M through T (also see Caballero et al. 2008), which draws data from many of the same sources and gives distance limits similar to those presented here). In particular, Dahn et al. (2002) include photometry in the \( IJHK_s \) bands. We note, however, that there may be difficulties in comparing our photometry with results from the literature, especially in the \( I \) band. That is because, as is discussed by Dahn et al. (2002), the majority of the flux from cool stars in that bandpass is at the very red edge, and therefore details of the filter cutoff and the detector response become quite important. When calibrated, as we did, with an ensemble of stars of a range of moderate spectral types, the calibration may have errors when applied to very red objects. We did not have sufficient calibration data to solve for color or extinction terms. We must therefore allow for additional zero-point uncertainties when examining potential BDs in the \( I \) band; this should be less than a few tenths of a magnitude for stars earlier than L5, but for later stars could even be \( >1 \) mag (A. Burgasser 2008, private communication). There are also differences between the near-IR filters used (Caltech [CIT] vs. 2MASS, usually), but those are generally smaller than our zero-point uncertainties (Carpenter 2001; Dahn et al. 2002).

Objects with spectral types down to late L have absolute \( I \) magnitudes of \(<19\), absolute \( J \) magnitudes of \(<15\), and \( K_s \) magnitudes of \(<13\) or so. The \( J - I \) color for those objects ranges from \( \approx 2.5 \) at the bright end to \( \approx 4 \) at the faint end, while \( J - K_s \) goes from 1 to 2 over the same range. For later type stars, the absolute \( K_s \) magnitude increases to about 16.5 at T9 (\( M_I \) increases to about

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**TABLE 2**

| ID | \( \alpha_{2000.0} \) | \( \delta_{2000.0} \) | \( I \) | \( J \) | \( H \) | \( K_s \) |
|----|------------------|------------------|------|------|------|-------|
| A  | 17 45 05.09      | -30 09 52.8      | 24.25(4) | 18.50(2) | 16.36(2) | 15.95(6) |
| B  | 17 45 05.21      | -30 09 52.2      | 25.36(10) | 18.26(2) | 15.30(1) | 14.19(3) |
| C  | 17 45 05.04      | -30 09 51.3      | 23.05(1) | 21.05(7) | 19.16(8) | 19.10(15) |
| D  | 17 45 05.23      | -30 09 54.4      | ... | 19.19(3) | 16.27(1) | 15.07(3) |
| E  | 17 45 05.28      | -30 09 51.6      | ... | 22.40(24) | 18.55(7) | 17.04(5) |
| F  | 17 45 05.11      | -30 09 51.6      | ... | 21.50(9) | 18.72(5) | 17.49(6) |
| G  | 17 45 05.17      | -30 09 50.0      | ... | 20.39(6) | 17.38(5) | 16.19(4) |
| H  | 17 45 05.11      | -30 09 54.4      | ... | ... | 18.46(7) | 17.36(5) |
| I  | 17 45 05.21      | -30 09 55.3      | ... | ... | 18.56(5) | 17.05(6) |
| J  | 17 45 04.99      | -30 09 52.4      | ... | ... | 19.10(9) | 17.66(7) |
| K  | 17 45 05.14      | -30 09 50.8      | ... | ... | 19.79(8) | 18.43(6) |
| L  | 17 45 05.20      | -30 09 50.6      | ... | ... | 18.52(4) | 17.28(5) |
| M  | 17 45 05.10      | -30 09 50.4      | ... | ... | 19.93(10) | 18.10(5) |
| N  | 17 45 05.26      | -30 09 53.9      | ... | ... | 19.09(7) | 17.62(5) |
| O  | 17 45 05.13      | -30 09 52.5      | ... | ... | 18.52(7) | 17.72(8) |

**Notes.**—See Fig. 2. The quantities in parentheses are 1σ statistical uncertainties on the last digit only: there are additional zero-point uncertainties of 0.1 mag. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* These objects are within 1′′ of the radio position of GCRT J1745–3009.

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Fig. 2.—PANIC \( K_s \) image of the field of GCRT J1745–3009. Again, the error circles have radii of 1′′ and 3′′, corresponding to 1 and 3σ uncertainties. We label and put diamonds on all of the sources with detections in at least two bands (Table 2), and put crosses on the remaining objects with only \( K_s \)-band detections. [See the electronic edition of the Journal for a color version of this figure.]
22 and $M_J$ increases to about 17), and the stars become redder in $I - J$ (up to about 5.5), but they become bluer in $J - K_s$ (to about 0). See Figure 3.

4.1. Implications of Nondetections

In searching for a nearby, ultracool counterpart to GCRT J1745–3009, we first treat all objects detected in the error circle as unrelated background stars (we examine the validity of this assumption in § 4.2). This enables us to make some general statements about the field and to derive some useful relations. We assume that any extinction will be minimal: at the distances of interest here (≤300 pc), we expect $A_V \approx 0.2$ mag or so (based on Drimmel et al. 2003), which translates to an extinction of $\lesssim 0.02$ mag at $K_s$.

We start our examination with the $I$-band image: while there are calibration uncertainties, the depth of the image and the lack of crowding make it preferable. The PSF fitting and subtraction did not reveal any fainter objects in the error circle, and the background is regular enough that we are not dominated by confusion. Using the data from Dahn et al. (2002) we derive the absolute $I$ magnitude as a function of distance $d$ that a nondetection in the $I$ band implies

$$M_I(M, L) \approx 10.5 + 0.45ST,$$

where $ST = 7$ for spectral type M7, 10 for spectral type L0, and goes up to 20 for spectral type T0; the dispersion is about 0.5 mag, and it is not valid for later spectral types. We use this with our $I$-band detection threshold of $I \approx 26$ to limit the spectral type as a function of distance $d$ that a nondetection in the $I$ band implies

$$ST_{nondet}I(M, L) \gtrsim 23.4 - 11.1 \log_{10}\left(\frac{d}{100 \text{ pc}}\right).$$

So for no detection in the $I$ band, we can exclude almost all M and L type objects out to 200 pc. Even with the scatter on the $M_I(ST)$ relation and the calibration uncertainties, this should be a relatively robust result. More typical main-sequence stars (spectral...

Fig. 3.—Color-magnitude diagrams for the field of GCRT J1745–3009. We plot $I - J$ (top left), $J - K_s$ (top right), and $H - K_s$ (bottom) color versus $K_s$ magnitude. The points are objects from the field, the filled circles are the objects from the 3σ error circle (with the objects that have $I$-band detections labeled according to Table 2), and the squares are the objects from Dahn et al. (2002) shifted to a distance of 100 pc. Reddening vectors for $A_V = 5$ mag are also plotted. [See the electronic edition of the Journal for a color version of this figure.]

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types K and earlier) are excluded closer than about 5 kpc (see discussion of object C in §4.2).

Moving to the $J$ band, we still detect only seven objects. Here the PSF subtraction did reveal fainter objects, and we have included them to the best of our ability. With an approximate upper limit of $J < 21$ and the relation from Dahn et al. (2002), $M_J(M, L) \approx 8.38 + 0.341$ST, we can again limit

\[
ST_{\text{non-det},J} = 22.4 - 14.7 \log_{10} \left( \frac{d}{100 \text{ pc}} \right), \tag{3}
\]

so the implications are similar. For later spectral types, we can use the comparable relation from Vrba et al. (2004) for T dwarfs, and we limit possible objects to later than T7 or so at 100 pc and and later than T4 or so at 200 pc (the relation is more complicated than the linear forms above, so we do not give a simple expression).

TVLM 513—46546, the pulsating dwarf found by Hallinan et al. (2007), is of spectral type M9 (ST = 9) and at a distance of 10.5 pc (Leggett et al. 2007). To have such an object be fainter than our $J$-band limit would require a distance of $>2$ kpc, although this will be somewhat of an over estimate, since for $>0.5$ kpc the extinction will start to contribute. Assuming an average extinction in the $J$ band of $\sim 1$ mag kpc$^{-1}$, we can still exclude an M9 star within 1.3 kpc. The observed flux density from TVLM 513—46546 peaks at a few mJy at frequencies of 4 and 8 GHz (8 and 4 cm). In comparison, bursts from GCRT J1745—3009 have peak flux densities of $\sim 1$ Jy at 330 MHz, although this has been observed to vary by a factor of $\sim 10$ (Hyman et al. 2007). Scaling TVLM 513—46546 to 1 kpc, we would expect peak flux densities of $<1$ Jy at 5 GHz (6 cm); having the flux density be $\sim 1$ Jy at 330 MHz would require an average spectral index of $\alpha \sim 5$ over more than a decade of frequency (where $S_\nu \propto \nu^\alpha$), inconsistent with typical spectral indices observed from M dwarfs (0 to $-1$; Güdel et al. 1993). Similar conclusions come from comparison with the L3.5 dwarf 2MASS J00361617+1821104 observed by Berger et al. (2005) which has a 3 hr periodicity in the radio (implied spectral index $\sim -6$ for a flux density of $\sim 1$ Jy at 330 MHz). This is far steeper than almost any known source (e.g., Kaplan et al. 2000) and inconsistent with the flat-spectrum bursts from TVLM 513—46546 (Hallinan et al. 2006) and dwarf stars in general (Güdel & Benz 1996), although such steep emission should be possible (Erickson 1999), and the bursts for GCRT J1745—3009 reported by Hyman et al. (2007) do have a very steep spectral index of $\alpha = -13.5$ across a narrow (32 MHz) band-pass. Bastian et al. (1990) found a similarly steep spectrum across a $\sim 40$ MHz bandpass for the dMe star AD Leo at 1.4 GHz (20 cm), but the spectrum here has opposite sense ($\alpha = +12$). In both cases it seems difficult to extrapolute the steep spectra over a wide range in frequency, but the similarity may point to band-limited emission from both sources.

### 4.2. Examinations of Detected Objects

We now examine the objects that we did detect in the 3σ error circle around the position of GCRT J1745—3009. We start with the objects detected in $I$ band: as we discussed above, a non-detection in the $J$ band generally rules out objects of interest, at least for spectral types earlier than L9 or so.

In the $I$ band, there are three objects that we detect: A, B, and C (Table 2 and Fig. 2). We plot them, along with the other objects from the field, in Figure 3. The first two objects are quite bright in the longer wavelengths, but faint in the $I$ band ($I - K_s = 8.3$ and $I - J = 5.8$ for A; $I - K_s = 11.2$ and $I - J = 7.1$ for B). In both of those cases, the colors are generally too red for any sort of nearby, low-mass star or ultracool dwarf, as we would not expect anything with $J - K_s > 2$ or $I - K_s > 6$, as discussed above. Instead, these objects are most likely distant, reddened giant stars that are consistent with the bulk of the objects in the field (see Fig. 3).

Object C is more interesting. It is in the right color range ($J - K_s = 4.0$, $I - J = 2.0$) to be an ultracool dwarf. However, the colors are a bit contradictory, as can be seen from comparison with the ultracool dwarfs plotted in Figure 3. From the $J - K_s$ color, we could guess a spectral type around late L, but the $I - J$ color implies a much earlier object (early M). The $H - K_s$ color is also bluer than expected for a late L object, but given the blueward trend for T0 and later, it could be a T dwarf. Some of these discrepancies could be due to the difficulty in applying our $J$-band calibration to a red object, but the $H - K_s$ and $J - K_s$ implications differ as well. Based on the $M_{K_s}(ST)$ relation from Vrba et al. (2004) object C would have spectral type

\[
ST_C \approx 21.6 - 15.4 \log_{10} \left( \frac{d}{100 \text{ pc}} \right) \tag{4}
\]

(this relation is really only valid for L dwarfs). So for the nominal distance of 100 pc, we would expect a very late L/early T object (again neglecting extinction).

Fitting all of the objects in Dahn et al. (2002) and Vrba et al. (2004) to our data and restricting the fit to $JHK_s$, the best fits are for spectral types around L5 (Fig. 4) and distances around 200 pc.
(roughly consistent with the relation above). There are systematic
deviations between the catalog objects and C, where they un-
derpredict the J- and K-band magnitudes (typically by about
0.3 mag) and overpredict the H-band magnitude (by a similar
amount). These differences are systematic in direction, but are
not greatly larger than the variation within the brown-dwarf se-
quence (typically <0.25 mag; Dahn et al. 2002; Vrba et al. 2004).
Perhaps this variation can be attributed to poor calibration of
the other bands, although our checks with 2MASS stars had much
smaller residuals (<0.1 mag). The catalog photometry was gen-
erally in the CIT photometric system, and we converted it to the
2MASS system using the transformations from Carpenter (2001).
For most colors, the differences are small, but those transforma-
tions were not necessarily appropriate for L or T dwarfs. For the
reddest stars there could be deviations of ~0.1 mag between
J band in the two systems, which would not really reconcile the
differences discussed above, but could help in some cases. Per-
haps age or metallicity could be the culprits, although they are un-
likely to be significant for objects in the Galactic plane but outside
of star clusters. A small amount of reddening helps the fit, but we
cannot accommodate very much reddening without being un-
physical given the distance.

Much more significant is the difference in I-band magnitude
for the data from Dahn et al. (2002). Fitting only the JHKs bands
as discussed above, we find that our I-band measurement is
~1.5 mag brighter than the catalog objects (such as the fit in
Fig. 4). If we fit all four bands, the quality of the fit gets con-
siderably worse, with deviations of >0.5 mag common, and
the best fits move to earlier type stars (late M to L0) at greater
distances. These deviations are far larger than what is seen
among brown dwarfs, and do not seem like they can be easily
accommodated by reddening, metallicity, or calibration issues.
It may be that there is a disk or other complication that
gives rise to different colors and explains the radio emission,
but without additional details this would be very difficult to
constrain.

However, object C is also quite compatible with being a main-
sequence star (Fig. 4). We get a roughly reasonable fit for all four
bands (residuals of 0.25 mag or so) using the main-sequence pho-
tometry from a late K/early M star at ~6 kpc with $A_F \approx 5$ mag
(Cox 2000; Kurucz 1993; Baraffe et al. 1998). Allowing for diffi-
culties in the reddening law and metallicity, such a classification
seems reasonable.

Beyond the J band, all of the objects detected at J but not I are
similar in colors to object B, with very red colors indicative of
distant, reddened giant stars.

5. CONSTRAINTS ON OTHER SOURCE TYPES

5.1. A White Dwarf

Zhang & Gil (2005) proposed a model for GCRT J1745−3009
where it was a "white dwarf pulsar": a rotating, magnetized WD
that, in analogy with traditional pulsars, emits light due to con-
version of rotational energy to electromagnetic waves/particles
through a strong magnetic field. At the wavelengths considered
here, WDs generally have neutral colors ($J - K_s \approx 0$, etc.), since
they are moderately well approximated by warm-to-hot black-

corps with effective temperatures >5000 K (e.g., Bergeron et al.
1995, 1997, 2001; Wachter et al. 2003; Holberg & Bergeron 2006;
Hoard et al. 2007) and the magnitudes we are using are based on
Vega, another hot blackbody. While approximate, this should be
accurate to ±0.5 mag or so. Based on this, none of the objects
detected in the I band is consistent with being a WD.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig5}
\caption{Distance limits for any white dwarf in the error circle of GCRT
J1745−3009, based on the I-band non-detection. We plot contours as a function
of WD radius (in units of the solar radius) and effective temperature. The contours
are labeled by the distance limits in kpc, assuming an average extinction
of 1 mag kpc$^{-1}$. The points are the cool WDs from Bergeron et al. (2001).}
\end{figure}

We next determine a distance limit inside of which there are
no WDs. For the I-band magnitude of a WD with radius $R$, effec-
tive temperature $T_{\text{eff}}$, and distance $d$, we have

\begin{equation}
I_{\text{WD}}(R, T_{\text{eff}}, d) = I_0 - 2.5 \log_{10} \left[ \frac{R}{R_0} \right]^2 \left( \frac{d}{d_0} \right)^{-2} \left( \frac{T_{\text{eff}}}{T_{\text{eff},0}} \right)^2 \right] + A_I,
\end{equation}

where $I_0$ is the magnitude of some fiducial object with radius
$R_0$, effective temperature $T_{\text{eff},0}$, and distance $d_0$, and $A_I$
the extincion at the I band (and the same for the other bands). This
assumes that we are on the Rayleigh-Jeans portion of the spectrum,
which is largely true for $T_{\text{eff}} > 5000$ K and wavelengths redward
of the I band, and takes care of the bolometric corrections needed
to transform a blackbody into observed bands. For the fiducial
values, we use the average of the objects from the sample of
Bergeron et al. (2001): $R_0 = 0.012$ $R_\odot$, $T_{\text{eff},0} = 7100$ K, $d_0$
= 10 pc, and $(I_0, J_0, H_0, K_0) \approx 12.9$. In reconstructing the values
from that sample, choice of a fiducial gives the other sources to
an accuracy of ±0.4 mag, comparable to the scatter of the WD
sample of Wachter et al. (2003) in the color-color plane (we are
also mixing WDs of different surface composition, but the dif-
ferences at wavelengths of interest are small).

We can then use these relations to limit WDs in the error circle
of GCRT J1745−3009. Since the limiting magnitude is highest
for the I band, that is the most constraining. Here we need to take
the extinction into account more explicitly, since the distances
are >500 pc and it will be significant. Assuming an average extinc-
tion of 1 mag kpc$^{-1}$, we find the distance limits plotted in
Figure 5. The limits are a function of WD radius and effective tem-
perature, but for typical temperatures (5000−20,000 K) and radii
(0.01 $R_\odot$) our I-band limit implies no WD closer than 2 kpc. We
compare this lower limit with the nominal distance upper limit of
0.8 kpc derived by Zhang & Gil (2005) for a WD pulsar (with the
constraint that the radio luminosity not exceed the rate of rota-
tional energy loss), and see that their basic model is not consistent
with our observations.
There are also occasional WDs that are considerably cooler (e.g., \( \approx 3500 \text{ K} \) for the source from Hodgkin et al. 2000) and which can have bizarre near-infrared colors (\( I - J \approx 0 \) but \( J - K \approx -1.4 \) for the same object). Such objects tend to be quite blue in the near-IR, despite their cool temperatures. The near-IR flux is considerably less than one would predict from the optical blackbody, with a deficit of more than one order of magnitude at 2 \( \mu \text{m} \). The \( I \) band is better behaved, but the data are still 1.5 mag fainter than our simplistic prediction above. Even so, none of the objects that we detected would be consistent with a cool WD since they all have red \( J - K_s \), and our \( I \)-band limit still constrains such an object to be more distant than \( \approx 1.4 \text{ kpc} \).

### 5.2. A Star at the Galactic Center

We can also see what limits our data can place on a possible stellar object at the GC. Here extinction is the largest unknown. We begin by assuming \( A_I \approx 20-30 \text{ mag} \) at a distance of 8.5 kpc (e.g., Dutra et al. 2003), but there could be a wide range of possible extinctions (both in total column density and in variation with wavelength; e.g., Nishiyama et al. 2006; Gosling et al. 2006, 2007) due to local clouds.

With such a combination, our data are not very constraining. We can largely exclude supergiants based on the expected \( K_s \) magnitudes: the faintest (which are actually the hottest, such as B0I) would have \( K_s \approx 12 \) (based on Cox [2000], although we note that supergiants have a wide observed range in luminosity), while the brightest star we find in the error circle has \( K_s = 14.2 \) (object B). So we would need 2 additional magnitudes of extinction at 2 \( \mu \text{m} \), or \( \approx 20 \) additional magnitudes at the \( V \) band (e.g., Mathis 1990), for a total \( A_V \approx 50 \text{ mag} \). This is larger than we would expect, although not completely unreasonable. It would, however, be rather redder than what we observe for object B: we find \( H - K_s = 1.1 \), but a supergiant with \( A_V = 50 \text{ mag} \) would have \( H - K_s \approx 3 \). Variations in the extinction law \( A_H/A_K \) would have to be far larger than observed (e.g., Nishiyama et al. 2006; Gosling et al. 2007) to agree with the data. Later type supergiants would have even worse agreement. They are brighter in the \( K_s \) band, so we would need additional extinction to get them to agree with our observed magnitude. But they are also redder, and with that additional extinction they would be redder still, such that a K0I star would have \( H - K_s = 6 \) (and would require \( A_V \approx 80 \text{ mag} \)).

For other luminosity classes, however, we can say very little. There are certainly giant stars at the GC consistent with objects in the error circle, and main-sequence stars are even easier to accommodate. We cannot exclude any of the canonical mass donor stars of low-mass X-ray binaries or cataclysmic variables (G–M main-sequence stars) at the distance of the GC. For instance, object B is generally consistent with a K2 III star at 8.5 kpc and with an extinction of \( A_V \approx 19 \text{ mag} \), although other possibilities are certainly possible given the degeneracies between reddening and spectral type, especially if one allows for a changing extinction law.

### 6. DISCUSSION AND CONCLUSIONS

We have examined relatively deep images of the field of GCRT J1745–3009 taken under good conditions (seeing better than 0.5") meant to search for a possible nearby counterpart to the radio transient. Such an object would have to be at a distance <70 pc in order to not violate the 10^{12} K brightness temperature limit on incoherent sources. Beyond that, we searched for nearby ultracool dwarfs at a range of distances.

Examining data at wavelengths from 0.8 to 2.1 \( \mu \text{m} \), we find that the field changes dramatically. Only three objects are detected at the shortest wavelength, compared to more than 20 at the longest wavelength. Two of the three sources detected at 0.8 \( \mu \text{m} \) are background giant stars. The third (object C) is most likely a late-type K star at a moderate distance (~6 kpc). We cannot entirely rule out the possibility that it is an object of type ~L5, but this is not consistent with the \( K \)-band photometry and would still be at a distance of ~200 pc: farther than the 100 pc limit discussed above. If it is of a late K type, object C is unlikely to be the source of the radio emission. While isolated K stars typically do not show strong radio flares, it is possible but generally at fainter flux levels (Güdel 2002). Given the radio luminosities typically seen (~10^{23} erg s^{-1}; Güdel 2002), it would be far too faint to be the source of the radio emission from GCRT J1745–3009. However, the radio luminosities seen to date for K stars may not include the brightest transient events.

Some K stars in binaries (e.g., RS CVn binaries; Güdel 2002) also show coherent radio flares. Such objects have peak fluxes of <1 Jy, even at relatively low radio frequencies (e.g., van den Oord & de Bruyn 1994), and for the distances implied for object C (possibly underestimated if it is a binary, especially if it is evolved like the K star in the prototypical RC CVn binary HR 1099) it would again be far too faint.

If we have not detected the counterpart, we use constraints from the shorter wavelengths, where the field is much less crowded, to limit the presence of any low-mass object. For distances of <100 pc, we can exclude stars earlier than T7 (with related limits of stars earlier than T4 at 200 pc, M9 at 1.3 kpc, M5 at 2 kpc, etc.) or so based on the \( I \)- and \( J \)-band photometry.

Our search is limited by the sample of comparison objects that we used: nearby ultracool dwarfs with good photometry and (often) astrometry. We therefore cannot exclude the possibility that object C is some peculiar type of ultracool dwarf, where the mismatch in the \( I \) band reflects some intrinsic difference of this object, but we require additional constraints to be able to decide conclusively one way or the other. While the source is bright enough at the \( K_s \) band for spectroscopy with large telescopes, \( I \)-band spectroscopy is likely to prove most productive, as the source is much easier to isolate from the nearby objects. Additional photometry will suffer from the near degeneracy between effective temperature and reddening seen in Figure 4 and the difficulty of calibrating data where the spectrum is dropping so sharply, but spectra should be able to distinguish cleanly between the largely featureless spectrum of a late-K/early-M star and the deep metal hydride absorption of an L dwarf. Our conclusions are also dependent on a lack of significant variability: fluctuations of <0.5 mag would not change things, but larger variations might. We see good agreement between the two sets of near-IR data (from PANIC and NIRI). However, those data were taken within two nights of each other. Variations over longer timescales, such as the \( \approx 1 \text{ yr} \) between the near-IR and optical observations, or even short flares, could still be present, although we note that we compared our data with photometry of the three sources (A, B, and D) within the error circle that are visible in the UKIRT Infrared Deep Sky Survey (UKIDSS) Galactic Plane Survey Data Release 3 (see Lawrence et al. 2007; Lucas et al. 2007) taken 2 years after our near-IR data and see no sign of variability at levels \( \approx 0.3 \text{ mag} \); below that, it is difficult to compare given the differences in calibration, seeing, and photometric technique. Additional monitoring could help address this issue.

With the same data, we have attempted to constrain other source types as possible counterparts to GCRT J1745–3009. We find that no white dwarf nearer than \( \approx 1.5 \text{ kpc} \) could be present in the error circle, nor could there be a supergiant star at the distance of the Galactic center. However, both of those conclusions have the same
limitations as that discussed above. Namely, we searched for objects that resemble other, known objects. If the radio emission from GCRT J1745—3009 really marks it as a unique object than the counterpart that we seek could have dramatically different properties. The presence of a binary companion, accretion disk, or other anomaly could also complicate things (e.g., Hoard et al. 2007), although most such additions to the system would make it brighter and hence would still largely be ruled out.

With all of the analysis above, we have excluded virtually any white dwarf or nondegenerate star as counterpart to GCRT J1745—3009 within 100 pc, and many sources are excluded within 1 kpc. We are therefore left with the conclusion that GCRT J1745—3009 likely emits via a coherent process. What this means, however, is unclear. Coherent emission with brightness temperatures as high as 10^{13} K (e.g., Slee et al. 2008; Osten & Bastian 2008) and sometimes higher have been seen from isolated stars and binaries, either relating to magnetic activity from the stars or from interaction between the members of the binary (Gu¨ del 2002; Osten 2008). The emission seen from GCRT J1745—3009 does not really resemble the known radio emission from such sources, although this may reflect the limitations of our observations. As discussed above, most sources have been observed to be significantly fainter than GCRT J1745—3009, but the comparison may be unfair since the behavior across such a wide range of frequencies and timescales is not known. If we remove the flux/luminosity constraints, the emission from GCRT J1745—3009 is actually not dissimilar to some ultracool dwarfs (such as the results of Berger et al. [2005] and Hallinan et al. [2006]). Time-resolved analysis at frequencies of <500 MHz (>60 cm) have been rare, especially in recent years (e.g., van den Oord & de Broun 1994), and we really do not know how known radio sources behave there. It seems likely that either GCRT J1745—3009 represents new low-frequency behavior from a known class of sources, or that it is indeed the first member of a new class.

Searches for counterparts to GCRT J1745—3009 at other wavelengths (especially X-rays, where the searches so far have not been very constraining; Hyman et al. 2005), along with further characterization of the radio properties of both GCRT J1745—3009 and other transient sources, are required to help elucidate its nature.

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