A powerful bursting radio source towards the Galactic Center

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Transient astronomical sources are typically powered by compact objects and usually signify highly explosive or dynamic events\textsuperscript{1}. While radio astronomy has an impressive record of obtaining high time resolution observations\textsuperscript{2}, usually it is achieved in quite narrow fields-of-view. Consequently, the dynamic radio sky is poorly sampled, in contrast to the situation in the X- and \textgreek{g}-ray bands in which wide-field instruments routinely detect transient sources\textsuperscript{3}. Here we report a new transient source, GCRT J1745\textsuperscript{−}3009, detected in 2002 during a moderately wide-field radio transient monitoring program of the Galactic center (GC) region\textsuperscript{4,5} at 0.33 GHz. The characteristics of its bursts are unlike those known for any other class of radio transient. If located in or near the GC, its brightness temperature ($\sim 10^{16}$ K) and the implied energy density within GCRT J1745\textsuperscript{−}3009 vastly exceeds that observed in most other
classes of radio astronomical sources\textsuperscript{6}, and is consistent with coherent emission processes\textsuperscript{7} rarely observed. We conclude that GCRT J1745–3009 is the first member of a new class of radio transient sources, the first of possibly many new classes to be identified through current and upcoming radio surveys\textsuperscript{8}.

GCRT J1745–3009 is located approximately 1.25\degree south of the Galactic center (GC) and is notable for a series of $\sim 1$ Jy bursts, each with a duration of $\sim 10$ min., and occurring at apparently regular intervals of 1.27 hr. The variability of GCRT J1745–3009 is shown in the light curve of Figure 1, and the average burst light curve is shown in Figure 2. The light curves appear to be similar in shape, although the missing data during the first, second, and third bursts hinders a comprehensive comparison. GCRT J1745–3009 is located near the supernova remnant, SNR 359.1–00.5\textsuperscript{[9]}, and other prominent sources\textsuperscript{10,11}, as shown in Figure 3. GCRT J1745–3009 was detected using the Very Large Array radio telescope operating at a frequency of 0.33 GHz.

GCRT J1745–3009 is not detected between bursts with a 5\sigma upper limit of 75 mJy, determined by imaging the entire observation with the bursts removed. We also do not detect the source in 0.33 GHz, $\sim 1$-hr GC monitoring observations made earlier in 2002 and afterwards in 2003; the 5\sigma upper limit for detection in a bursting state is $\sim 250$ mJy with 5-min integrations, and in a quiescent state is $\sim 50$ mJy. Images made from three 6-hr observations in 1996 and 1998 have similar upper limits, and the combination of these images\textsuperscript{12} has a 15 mJy upper limit for quiescent emission.

The magnitude of errors in radio astronomical images typically increases with distance from
the center of the image. GCRT J1745−3009 is located only 14′ from the image center compared to the ∼3° field-of-view, and therefore, together with its detection at multiple frequencies around 0.33 GHz and in both circular polarizations, we consider the evidence to be very strong that the source is real. The bursts show no significant frequency dependence and no molecular-line masers are known to emit near 0.33 GHz; therefore, the lack of a frequency dependence suggests that GCRT J1745−3009 is not a maser.

GCRT J1745−3009 is unresolved in our observation. If we constrain its size to be less than $c\tau$, with $\tau \sim 2$ min. taken to be the decay time of the ∼ 1 Jy bursts, the energy density within the source as measured by the brightness temperature is $\sim 10^{12} \text{K} \left( \frac{D}{70 \text{ pc}} \right)^2$, where $D$ is the distance to the source. If the transient source is at the GC, ∼8.5 kpc distant, its brightness temperature far exceeds $10^{12} \text{K}$, the upper limit for incoherent synchrotron radiation produced by relativistic electrons gyrating in a magnetic field, and therefore its emission is likely coherent.

In principle, GCRT J1745−3009 could be located < 70 pc from us, in which case it could be either a coherent or an incoherent emitter. Known and hypothesized classes of “local” ($D < 70$ pc) sources that show flare activities include dwarf M-type (dMe) stars, brown dwarfs, and extrasolar planets. dMe flare stars emit coherent bursts produced through electron cyclotron maser emission. The bursts from flare stars show some similarities to the light curve of GCRT J1745−3009, but in contrast, they are detected in only one circular polarization at low frequencies (e.g., at 0.43 GHz for AD Leo and YZ CMi). Bursts of such highly circularly polarized radio emission are also predicted, by analogy to the giant planets in the solar system, from extrasolar giant planets.
However, no detections have been made in searches for such emission from known extrasolar planets at 0.33 GHz and 1.5 GHz, at comparable or better sensitivity limits to what we report here\textsuperscript{16}. We conclude that GCRT J1745–3009 is not likely to be a dMe flare star or an extrasolar planet.

Brown dwarfs also emit flares, apparently as a result of processes involving high magnetic fields\textsuperscript{17}. Four infrared sources detected in the \textit{Two Micron All Sky Survey}\textsuperscript{18} that lie within the $\sim 10''$ uncertainty of the transient’s radio position could possibly be brown dwarfs. However, their distances are unknown and their spectral colors, to the extent measured, are inconsistent with those of brown dwarfs\textsuperscript{19}.

Few radio flares from brown dwarfs have been detected\textsuperscript{20–22}, and none at low frequencies\textsuperscript{16}. Like the bursts from GCRT J1745–3009, the observed flares have time scales of minutes, and, for two of the brown dwarfs, LP944-20 and 2MASS 0036+18, they also have faster decay than rise times. In contrast to GCRT J1745–3009, however, no regular flaring pattern is evident for any of these sources, and they were observed only at high frequencies since emission is predicted to be self-absorbed at lower frequencies\textsuperscript{23}. The extent to which flares from brown dwarfs are self-absorbed at low frequencies is somewhat uncertain, though, since flares from only two objects (LP944-20 and DENIS 1048-3956) have been observed at multiple frequencies simultaneously, and these frequencies were much higher (4.8 and 8.5 GHz) than 0.33 GHz at which we detect GCRT J1745–3009. Furthermore, while, in contrast to the low-frequency bursts from GCRT J1745–3009, the observed flares from brown dwarfs at high frequencies are significantly
polarized (30–70%), the degree of polarization may be significantly reduced at low frequencies where self-absorption can become large\textsuperscript{24}.

We conclude, therefore, that we cannot rule out that GCRT J1745–3009 is a flaring brown dwarf. However, its detection at a low frequency, its regular flaring pattern, and significant detection in both circular polarizations, are all novel features in comparison to known characteristics of brown dwarfs. Hence, there is no compelling evidence for an identification as such.

While GCRT J1745–3009 is conceivably a “local” radio source belonging to one of the classes of objects considered above, it is much more likely that it is located significantly further from us. Assuming even a uniform distribution of transients, and not the vastly increasing spatial density of all astronomical objects toward the GC, the relative spatial volume covered by our wide-field observations results in an extremely small probability (6 × 10\textsuperscript{−7}) that GCRT J1745–3009 is located within 70 pc.

Many transient radio sources are also detectable at X-ray and \(\gamma\)-ray wavelengths. We have analyzed a serendipitous pointed observation about 32’ from GCRT J1745–3009 in the Rossi X-Ray Timing Explorer (RXTE) archive that runs between the third and fourth burst, though overlapping neither. No variable X-ray (2–10 keV) emission was seen and we place a conservative 25 mcrab upper limit on the flux of any interburst X-ray counterpart emission (1 mcrab \(\approx\) 2 \times 10\textsuperscript{−11} erg cm\textsuperscript{−2} s\textsuperscript{−1}). One of us (C.B.M.) performs regular scanning observations of the Galactic Bulge with RXTE. The closest of these were on 2002 September 25 and October 2. In both of these observations, 3\(\sigma\) upper limits on the X-ray flux from the source are 6 mcrab. A search of all of the Bulge
scans starting 1999 February finds one scan, on 2003 July 3, in which a 15 mcram (6.5σ) outburst was detected. However, possible confusion with other X-ray sources in the field-of-view (∼ 30') prevents a conclusive identification. Similarly, the γ-ray source 3EG J1744−301 was detected near the position of GCRT J1745−3009 during the 1990’s by the Energetic Gamma Ray Experiment Telescope, but the positional error on that source is also large (∼ 20') and the source is in a highly confused region with numerous diffuse and discrete sources of γ-ray emission25.

We next consider the possibility that the bursts from GCRT J1745−3009 could be relativistically beamed toward us as is the case for microquasars, which are accreting black holes in binary systems that occasionally power radio-bright relativistic jets (e.g., GRS 1915+105, whose apparent superluminal motion has a Lorentz factor of γ ∼ 526,27. While it is conceivable that relativistic beaming is responsible for the high calculated brightness temperature, the light curve of GCRT J1745−3009 does not resemble that for known microquasars or other sources of jet emission, most of which exhibit a fast rise and a slower decay and much longer time scales3. In addition, the apparent lack of a bright X-ray counterpart to the bursts argues strongly against accretion as the power source for the bursts.

Next, we consider radio pulsar origins for the source. A 77-min rotation period radio pulsar is excluded because the rotational energy loss rate from such a pulsar is insufficient to power the radio emission unless the magnetic field is extreme (> 10^{18} G) or the distance is unreasonably small (< 0.5 pc). Another conceivable option is that the 77 minutes is an orbital period and the outbursts are flux variations as a function of orbital phase similar to the pulsar PSR J0737−3039B28. This
scenario does not explain the transient behavior from the source or the lack of interburst emission, and favors a distance of order 1 kpc or less.

One other class of sources to consider are magnetars, neutron stars with immense \((10^{14} - 10^{15} \text{ G})\) magnetic fields whose radiation is powered by field decay\(^{29}\). Coherent emission from the magnetosphere of a magnetar addresses the energy budget difficulties seen in the pulsar models. An investigation of whether magnetars could produce the observed emission timescales and transient behavior is underway (K.S. Wood, P.S.R., S.D.H., T.J.W.L., & N.E.K. in preparation).

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Figure 1  The five detected bursts from the radio transient source, GCRT J1745−3009. The observation is continuous, with the time axis folded at multiples of 77.13 min. a, The first interval of the observation beginning at 20:50:00 on 30 September 2002 (TAI). b, The second interval. c, The third interval. d, The fourth interval. e, The fifth interval. The points connected by the heavy line are the detections in 30-s samples with typical error bars of 0.15 Jy shown. The arrows are 3σ upper limits for nondetections between bursts; no evidence of quiescent emission is found. Fluctuations of nearby sources are consistent with the noise level. The dashed vertical line is positioned at the fitted peak (see Figure 2) of the fourth burst as a reference. Note that several gaps in the data, including during the first three bursts, are due to radio frequency interference or when the phase calibrator was imaged. No anomalous behavior is seen for the calibrator. The 0.33 GHz, 7-hr observation was obtained with the CnB-configuration of the Very Large Array. The bandpass consists of thirty-one, 97 kHz wide channels for each of two intermediate frequencies (IF, 321.56 and 327.50 MHz). Both circular polarizations were imaged, but linear polarization measurements are not available for this observation. No circular polarization was detected (15%, 5σ upper limit)

Figure 2  Average light curve of GCRT J1745−3009 derived from the third, fourth, and fifth bursts. The peak times of the bursts, t₀, were determined for all but the second, most incompletely sampled burst, from exponential fits to their rise (Aₑ⁽ᵗ⁻ᵗ₀⁾/τ₁) and decay (Aₑ⁻⁽ᵗ⁻ᵗ₀⁾/τ₂) and have been subtracted from the light curve of each in order to construct the average. (While the first burst was included in the fit, it also is largely undersampled
and therefore not included in the average light curve.) The peak of the average light curve is arbitrarily placed at 0 min. Typical error bars (±0.11 Jy) are shown. The amplitude, $A$, and rise and decay time constants, $\tau_1$ and $\tau_2$, were constrained to be identical in the fits, yielding $A = 1.67 \pm 0.05$ Jy, $\tau_1 = 9.9 \pm 0.7$ min, and $\tau_2 = 1.9 \pm 0.5$ min. The difference between the peak times derived for the first and third bursts is $2 \times 77.3 \pm 0.2$ min., the third and fourth $77.6 \pm 0.3$ min., and the fourth and fifth $76.5 \pm 0.3$ min. A separate fit (solid curve) was made to the average light curve and yields parameters consistent with those listed above.

Figure 3  0.33 GHz radio image of the transient source, GCRT J1745−3009, and the surrounding region $\sim 1^\circ$ south of the Galactic center. GCRT J1745−3009 is located at (J2000) R.A. $17^h45^m05^s \pm 0.8^s$, Dec. $-30^\circ09'52'' \pm 10''$, indicated by the small box below the $\sim 20'$ diameter shell of the supernova remnant, SNR 359.1−00.5. Other sources in the image include the sources to the west which are part of Sgr E, the linear feature, The Snake, to the north, and The Mouse to the northeast of GCRT J1745−3009. The sensitivity and resolution of the image are 15 mJy beam$^{-1}$ and $48'' \times 39''$, respectively. We searched the entire $3^\circ$ field-of-view for other intra-observation transients and variable sources and found none. Note that GCRT J1745−3009 appears as only a 100 mJy source here since it is averaged over the five short $\sim 1$ Jy bursts and a total of $\sim 6$-hr of nondetections between bursts. Nondetections of quiescent and bursting emission at 0.33 GHz for other epochs are described in the text. We also do not detect quiescent emission in a 1.4 GHz observation from 2003 January, with a detection threshold of 35 mJy.
However, if GCRT J1745−3009 has a steep spectrum, as found for other radio transients (e.g., \( \alpha = -1.2, S_\nu \propto \nu^\alpha \) for the Galactic Center Transient\(^{30} \)) and coherent emitters such as radio pulsars (\( \alpha \sim -1.7 \)), it likely could have decayed significantly below the 2003 January detection threshold. Also, while no bursts were detected within the 1.4 GHz observations, these data were comprised of seven 3-min. “snapshots” taken every hour; given its 1.25 hr recurrence interval, GCRT J1745−3009 could have been missed easily in a bursting state. Similarly, most of the 0.33 GHz nondetection observations from 2002 and 2003 were only about an hour or less in duration, and therefore it is possible that GCRT J1745−3009 was and still is detectable in a bursting state.
