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THE PECULIAR INFRARED COUNTERPART OF GX 17+2

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ABSTRACT

We discuss the nature of the infrared (IR) counterpart of GX 17+2, one of the most luminous of the persistently bright X-ray binaries. *Chandra* HRC-S astrometry is consistent with either NP Ser (the original counterpart of GX 17+2 proposed by M. Tarenghi & C. Reina in 1972) or star "A" of E. W. Deutsch et al. as the counterpart of the X-ray source. However, we present Keck *K*-band observations that reveal a bright counterpart in the radio error circle of Deutsch et al. 0″.9 north of NP Ser itself. Furthermore, the position of this counterpart is consistent with that of star A to within 0″.1, implying an amplitude of variation of ∼25–33 between the Keck observations and the *Hubble Space Telescope* (*HST*) measurements of Deutsch et al. Subsequent Keck imaging also reveals star A in an "IR-faint" state ($K = 18.3$ mag, with a corresponding amplitude of variability of ∼22). In addition, archival Cerro Tololo Inter-American Observatory observations provide evidence for *K*-band variability, albeit of smaller amplitude. The *HST* and Keck *K*-band variations, however, do not appear to be accompanied by any changes in the overall X-ray luminosity of GX 17+2 as measured by contemporaneous (but not simultaneous) *Rossi X-Ray Timing Explorer* All-Sky Monitor observations. We propose instead that the large radio outbursts observed when the source is in the horizontal branch of its "Z" state are likely to give rise to synchrotron flares in the IR. The amplitude of the radio flares is in agreement with this scenario. Such IR variability, unrelated (directly) to X-ray reprocessing and the gross characteristics of the mass accretion rate, may be present in the IR flux of other low-mass X-ray binaries but harder to see owing to the intrinsically brighter IR fluxes of the longer period systems.

Subject headings: binaries: close — stars: individual (GX 17+2) — X-rays: stars

1. INTRODUCTION

GX 17+2 is one of the brightest of the persistent X-ray sources in the sky and a well-studied "Z" source. Such objects are characterized by the Z-shaped track they exhibit on the X-ray color-color diagram, the limbs of which are denoted as the horizontal, normal, and flaring branches. Each of these limbs has its own characteristic fast timing variability, e.g., quasi-periodic oscillations (see Wijnands et al. 1997 for the case of GX 17+2 itself).

Along with Cyg X-2, GX 17+2 belongs to the small class of bursting Z sources, and hence the accretor is a neutron star. Kuulkers et al. (2002) discuss the nature of these bursts in more detail and estimate a distance to the source of ∼8 kpc.

As discussed by Deutsch et al. (1999), the optical/infrared (IR) counterpart of GX 17+2 has been particularly difficult to identify; the optical candidate proposed by Tarenghi & Reina (1972), NP Ser, was cast into doubt by Naylor, Charles, & Longmore (1991) and conclusively excluded by the astrometry of Deutsch et al. (1999), who were able to show that the radio counterpart (e.g., Grindlay & Seaquist 1986) is displaced ∼0″.7 away from the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) image of NP Ser. Deutsch et al. (1999) suggested instead two faint stars ("A," $H \approx 19.8$ mag, and "B," $H \approx 20.8$ mag) within the radio error circle as possible candidates.

However, placing another well-studied Z source, Sco X-1 (dereddened $K = 11.5$ mag, $H-K \approx 0$ mag, distance $= 2.8$ kpc; Hertz & Grindlay 1984, Tokunaga 2000, Bradshaw, Fomalont, & Geldzahler 1999, respectively), at a distance of 8 kpc with a reddening of $A_H \approx 2$ mag predicts $H \approx 16.8$ mag for GX 17+2. Hence, the proposed infrared counterpart appears to be considerably underluminous. Nonetheless, there is nothing to suggest from these observations that GX 17+2 contradicts the paradigm that the optical and IR flux of bright low-mass X-ray binaries (LMXBs) is dominated by reprocessing of a fraction of the X-ray flux in the accretion disk and/or secondary star.

In order to establish the true IR counterpart of GX 17+2, we observed this system using the Keck I and Keck II 10 m telescopes, the 1.5 m telescope at the Cerro Tololo Inter-American Observatory (CTIO) in Chile, and the 3.5 m telescope at the Apache Point Observatory (APO). We present these observations in § 2 along with a brief discussion of the *Chandra* astrometric measurements. In § 3, we discuss the implications of our observations.

2. OBSERVATIONS

2.1. *K-Band Observations*

We observed GX 17+2 with the Near-Infrared Camera (NIRC; Matthews & Soifer 1994) on Keck I during 1999 June 26 (UT dates are used throughout this Letter). NIRC uses a 256 × 256 pixel InSb detector (with a scale of 0″.15 pixel^{-1}) and operates in imaging and low-resolution ($R \approx 60$–120) spectroscopic modes. We obtained a single grid of nine images of the field, with an integration time of 40 s per image. The data were reduced in the usual way (e.g., Callanan, McCarthy, & Garcia 2000).

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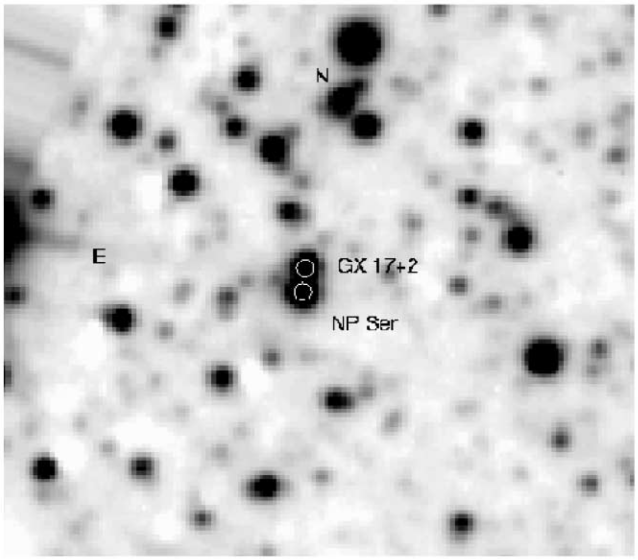

FIG. 1.—The 1999 June Keck NIRC *K*-band image of GX 17+2 in the IR-bright state. The circles denote the positions of NP Ser and GX 17+2 determined from our astrometry. The radii of the circles are 3 times the rms of the coordinate solution for the image.

Relative photometry was then performed on the summed, final image using DAOPHOT (Stetson 1987). The image was calibrated using the Persson et al. (1998) standards. To our surprise, we observed a bright counterpart in the Keck image ($K = 14.96 \pm 0.05$ mag; see Fig. 1), in the radio error circle of Deutsch et al. (1999), 0″.9 north of NP Ser itself (Callanan, Filippenko, & Garcia 1999). The *K*-band magnitude of NP Ser was measured to be 14.55 ± 0.05. Our grid of nine images spans a time interval of nearly 10 minutes, and there is no variability of GX 17+2 during this interval to within 5%.

Astrometry of the field was performed by first using four stars from the USNO catalog (Monet et al. 1998) to find coordinates for six stars common to both our archival CTIO images (see below) and the Keck image. As pointed out by Deutsch et al. (1999), NP Ser itself is in the USNO catalog, but as a consistency check it was not included among the four USNO stars. Nonetheless, our position for NP Ser derived from the Keck image agrees to within 0″.16 of the Deutsch et al. (1999) NICMOS position. Furthermore, the position of the bright *K*-band counterpart in the radio error circle agrees to within 0″.11 of the position of star A of Deutsch et al. (1999).

For an *H*-band reddening of ~2 mag (Deutsch et al. 1999), and an $H-K$ color range of 0–0.3 mag (early O through late M), the NICMOS observations of Deutsch et al. (1999) imply a *K* magnitude of ~18.5–18.8. Hence, star A appears to have brightened by ~3.5–3.8 mag between the 1997 August NICMOS observations of Deutsch et al. (1999) and our Keck observations, where the error here is dominated by the uncertain color of GX 17+2 during the *Hubble Space Telescope* (*HST*) observations. Remarkably, however, inspection of the *Rossi X-Ray Timing Explorer* (*RXTE*) All-Sky Monitor (ASM) light curves of GX 17+2 at the time of our observations and those of Deutsch et al. (1999) shows little, if any, difference in the mean X-ray luminosity between the two epochs (~50 counts s^{-1} with ~20% variability superposed). In particular, the contemporaneous ASM and *HST* observations are only ~1 hr apart (with 12 hr between our Keck observation and the corresponding ASM measurement).

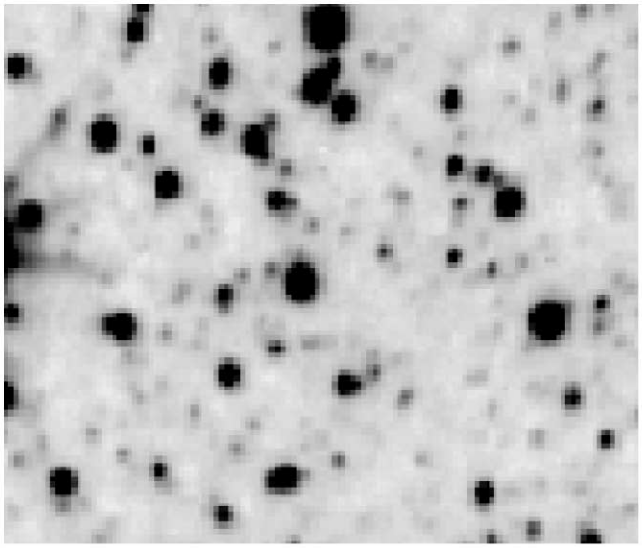

FIG. 2.—The 2000 July Keck II NIRSPEC SCAM *K*-band image of GX 17+2. The system is now in an IR-faint state. As in Fig. 1, north is up and east is to the left.

We also observed GX 17+2 using the Cerro Tololo Infrared Imager on the 1.5 m telescope at CTIO during 1995 June 12 and 13. This is a 256 × 256 pixel HgCdTe NICMOS-3 array with a variable pixel scale; for the observations presented here, a scale of 0″.65 pixel^{-1} was used. These data provide additional evidence for long-term variability of star A. Our 1995 June 12 image barely resolves NP Ser from GX 17+2, yielding magnitudes of 14.52 ± 0.05 and 15.64 ± 0.12, respectively. Unfortunately, the 1995 June 13 image is considerably shallower, and GX 17+2 is unresolved from NP Ser; the combined magnitude here is 14.65 ± 0.09. Hence, these images provide further evidence for substantial long-term IR variability of GX 17+2, as first suggested from the unresolved images of Naylor et al. (1991).

K-band observations using the 3.5 m telescope at the APO on 1998 September 27 (Anderson, Margon, & Deutsch 1999, although note that the date quoted was incorrect) resolved NP Ser and star A into two stars of comparable flux (to within $\lesssim$1 mag).

Finally, additional *K*-band observations (a grid of nine images, with 40 s exposure per image) using Keck II and the slit-viewing camera (SCAM) of the Near-Infrared Spectrometer (NIRSPEC; McLean et al. 1998) were obtained on 2000 July 22. This camera utilizes a 256 × 256 pixel HgCdTe IR array with a scale of 0″.18 pixel^{-1}. This image (see Fig. 2) shows GX 17+2 in an "IR-faint" state, with $K \approx 18.33 \pm 0.06$ mag, comparable to that inferred from the *HST* observations.

Taken together, the APO, Keck, and CTIO observations suggest that GX 17+2 may spend roughly equal amounts of time in IR-bright and IR-faint states. (See Table 1 for a list of all the IR observations.)

2.2. *X-Ray Observations*

Chandra also observed the field of GX 17+2 for 11 ks on 2000 March 8. The High-Resolution Camera (HRC)+Low-Energy Transmission Grating Spectrograph was used to provide both imaging and spectroscopic data. Details of the data reduction procedure can be found in Homer et al. (2001 and references therein); the spectra will be presented in a

TABLE 1
Infrared Observations

Telescope	UT Date	Filter	Exposure Time (s)
CTIO 1.5 m ……	1995 Jun 12.040	K_s	2700
	1995 Jun 13.093	K_s	270
Keck I …………	1999 Jun 26.474	K	360
Keck II ……….	2000 Jul 21.392	K	360

forthcoming paper. The astrometric measurements yield a position of $\alpha = 18^{\mathrm{h}}16^{\mathrm{m}}01\overset{\mathrm{s}}{.}8 \pm 0\overset{\mathrm{s}}{.}05$, $\delta = -14^\circ02'10\overset{''}{.}7 \pm 0\overset{''}{.}7$ (J2000.0; International Celestial Reference System). Here the errors are due to the uncertainty in the aspect solution as appropriate for the HRC-S (i.e., as determined from other HRC-S observations); unfortunately, in our case no additional sources in the (small) field of view could be used to make a boresight correction and refine the position and/or reduce the uncertainty.

Although this position is considerably more accurate than the *Einstein* HRI position (e.g., Deutsch et al. 1999), it is still formally consistent with either NP Ser or star A as the source of the X-ray flux. Hence, only the IR measurements are of sufficient accuracy to differentiate between them.

3. DISCUSSION

It is possible that the faint IR flux observed by Deutsch et al. (1999), and during our Keck II observation, was obtained during a deep eclipse; however, this appears to be ruled out by the lack of a similar variability in the contemporaneous X-ray light curve. More importantly, the extensive *EXOSAT*, *Ginga*, and *RXTE* observations of GX 17+2 (e.g., Kuulkers et al. 1997; Penninx et al. 1988; Homan et al. 2002) show no evidence for any eclipsing or dipping behavior and are entirely consistent with the Z source classification for this object. The IR variability that we measure appears to be inconsistent with the relatively stable nature of the X-ray light curve and X-ray heating as the origin of the IR flux (see de Jong, van Paradijs, & Augusteijn 1996 for a more detailed discussion of M_V vs. L_{X} for X-ray bright LMXBs). Thus, in what follows we seek alternative explanations for the origin of the variable IR flux of GX 17+2.

3.1. *Emission from an X-Ray–Driven Wind*

Van Paradijs et al. (1994) detected 10 μm emission from the LMXB GRO J0422+32 near the maximum of its outburst and suggested free-free emission from an X-ray–driven accretion disk wind as a possible origin. We believe that such emission is an unlikely source of the IR flux from GX 17+2 for two reasons: (1) we would expect an associated increase in the X-ray flux between the *HST* and Keck I epochs of observation, to generate the wind required to provide the increased IR flux; and (2) extending the calculations of van Paradijs et al. (1994) to the 2.2 μm flux of GX 17+2 shows that an accretion rate of $\sim 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ is required, for a distance of 8 kpc. This is alarmingly high for an LMXB. (See also the discussion in Fender 2001.)

3.2. *Synchrotron Emission*

Fender et al. (1997) have reported IR flaring activity from GRS 1915+105, with contiguous flaring at radio frequencies (15 GHz). The similarity of these IR and radio flares in amplitude and general morphology led these authors to suggest a common origin for both of them—synchrotron emission. Can such a mechanism, which is much less sensitive to the X-ray luminosity of the system, explain the observed IR behavior of GX 17+2?

Strong radio variability of GX 17+2 has been reported by Penninx et al. (1988). These observations (at wavelengths of 6 and 20 cm) were obtained simultaneously with X-ray measurements using *Ginga* and revealed that the strongest radio emission occurred when the source occupied the upper horizontal branch in its color-color magnitude diagram. The maximum flux density measured was 13.4 mJy (6 cm) and 22.8 mJy (20 cm), with a total amplitude of variability of 30 ± 5 and 40 ± 10, respectively. This amplitude of variability is reassuringly close to that observed in the IR. A spectral index of nearly zero (~ -0.2) is sufficient to provide a K-band flux of 1.6 mJy (corresponding to $K \approx 14$ mag), again consistent with synchrotron emission providing both the radio and IR emission. Furthermore, according to Kuulkers et al. (2002), GX 17+2 spends about equal amounts of time in the horizontal branch and flaring branch of the Z diagram, in agreement with the number of times it has been observed in an IR-bright and IR-faint state, although we suffer clearly here from small-number statistics.

Such IR variability, unrelated to X-ray reprocessing, may be present in the IR flux of other LMXBs. In many of these cases, however, synchrotron emission in the IR may be harder to see against the glare of IR emission generated by X-ray reprocessing in the longer period systems. As shown by van Paradijs & McClintock (1994), M_V (X-ray heating) is proportional to $P_{\mathrm{orb}}^{2/3}$—hence, we would expect synchrotron IR emission to be easier to detect in the shorter period systems.

If the IR flux measured by Deutsch et al. (1999) and ourselves (during the second Keck observation) is indeed generated by X-ray reprocessing, the low absolute magnitude combined with the high X-ray luminosity imply an extremely compact system (see also de Jong et al. 1996), reminiscent of 4U 1916−105 ($P_{\mathrm{orb}} \approx 50$ minutes) or the three ultracompact globular cluster LMXBs discussed by Deutsch, Margon, & Anderson (2000). This in turn would be inconsistent with the suggestion of Hasinger & van der Klis (1989) that all Z sources have evolved companions.

The absolute magnitude of GX 17+2 in its IR-bright state ($M_K \approx -0.5$ mag) is comparable to those of the Z sources Sco X-1, Cyg X-2, GX 340+0, and GX 349+2 (Jonker et al. 2000). By analogy with GX 17+2, a sizable fraction of the IR flux from these sources may also be due to synchrotron emission, especially when these sources inhabit the horizontal branch of their respective color-color magnitude diagrams. The compilation of Penninx (1989) shows, however, that GX 17+2 appears to exhibit the largest amplitude of radio variability among the Z sources, and hence we might expect its IR variability to be the most dramatic. In any case, simultaneous X-ray/radio and IR observations of these Z sources are clearly required to conclusively identify the origin of the IR emission in these systems.

Finally, we note that IR observations of quiescent X-ray novae have been used to constrain the mass ratio, inclination, and binary component masses (e.g., Shahbaz, Naylor, & Charles 1994). These measurements are based on the assumption that the secondary star in such systems dominates the IR emission. However, the presence of synchrotron emission would have a significant effect on these measurements and in turn on the masses inferred. Such contamination may, for example, explain the flickering observed in the quiescent K-band light curve of GRO J0422+32 (Callanan, Filippenko, & Garcia 2001).

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