DEEP INFRARED OBSERVATIONS OF THE PUZZLING CENTRAL X-RAY SOURCE IN RCW 103\textsuperscript{1,2}

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ABSTRACT

The object 1E 161348—5055 (1E 1613) is a pointlike, soft X-ray source shining at the center of the 2000 yr old supernova remnant (SNR) RCW 103. It features a puzzling 6.67 hr periodicity and dramatic variability over a timescale of a few years. This, coupled with a young age and the lack of an obvious optical counterpart, makes 1E 1613 a unique source among all compact objects associated with SNRs. It could either be the first low-mass X-ray binary system discovered inside a SNR or a peculiar isolated magnetar with an extremely slow spin period. Analysis of archival VLT ISAAC and \textit{HST} NICMOS infrared observations unveils a very crowded field. A few sources are positionally consistent with the refined X-ray error region that we derived from the analysis of 13 \textit{Chandra} observations. To shed light on the nature of 1E 1613, we have performed deep IR observations of the field with the NACO instrument at the VLT, searching for variability. None of the candidates show clear modulation at 6.67 hr or have significant long-term variability. Moreover, none of the candidates stand out for peculiar colors with respect to the bulk of the field sources. We find no compelling reasons to associate any of the candidates with 1E 1613. On one hand, it is very unlikely that one of the candidates is a low-mass companion star to 1E 1613. On the other hand, if the X-ray source is an isolated magnetar surrounded by a fallback disk, we cannot exclude that the IR counterpart is hidden among the candidates. If none of the potential counterparts are linked to the X-ray source, 1E 1613 will remain undetected in the IR down to \(K_s > 22.1\), which will make its interpretation as an accreting binary system rather problematic.

\textit{Subject headings:} stars: individual (1E 161348—5055) — stars: neutron

\textit{Online material:} color figures

1. INTRODUCTION

The X-ray point source 1E 161348—5055 (1E 1613) was discovered with the \textit{Einstein} observatory close to the geometrical center of the very young (\(\sim 2000\) yr) shell-type supernova remnant (SNR) RCW 103 (Tuohy & Garmire 1980). The association of the point source with the SNR is very robust on the basis of good positional coincidence, with 1E 1613 lying within \(\sim 20''\) of the SNR center. Furthermore, \(\mathbf{H \beta}\) observations of this region (Reynoso et al. 2004) pointed to a spatial correlation of the two objects in view of their similar distance (\(\sim 3.3\) kpc). Historically, 1E 1613 was the first radio-quiet, isolated neutron star candidate with a thermal X-ray spectrum, no counterparts at other wavelengths, no pulsations, and no nonthermal extended emission. Since then, a handful of similar enigmatic sources, all characterized by a thermal X-ray spectrum, lack of standard pulsar activity, high X-ray–to–optical flux ratio (\(F_X/F_{\text{opt}} > 10^3\)), and general lack of pulsations, have been discovered inside young SNRs. Such sources, possibly the youngest members of the family of radio-quiet, isolated neutron stars (including the anomalous X-ray pulsars and soft gamma repeaters), were dubbed, as a class, “central compact objects” (CCOs; Pavlov et al. 2002); see De Luca (2007) for a recent review.

What makes 1E 1613 unique among CCOs is its very peculiar and puzzling temporal behavior. A factor of 10 variability on a timescale of a few years was already evident within the historical \textit{Einstein}/ROSAT/\textit{ASCA} data set (Gotthelf et al. 1999). This was confirmed by \textit{Chandra} ACIS observations, which showed that the source brightened by a factor of \(\sim 60\) between 1999 September (when the source’s flux was \(\sim 8 \times 10^{-13}\) erg cm\(^{-2}\) s\(^{-1}\) in the 0.5–8 keV energy range) and 2000 February (with a record flux of \(\sim 5 \times 10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\)), decreasing to \(\sim 10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\) (Sanwal et al. 2002) afterward. The analysis of \textit{Chandra} monitoring
observations showed that the source flux has been continuously fading since then (De Luca et al. 2006). The 1999 16 ks Chandra observation, performed when the source was in a “low state,” hinted at a possible $\sim$6.4 hr ($\sim$23 ks) periodicity (Garmire et al. 2000). However, subsequent Chandra and XMM-Newton observations found the source in an “active state” with a remarkably complex light curve, including dips, with an overall $\sim$20% modulation (Sanwal et al. 2002; Becker & Aschenbach 2002), and could not ultimately confirm its periodicity. The breakthrough came with a long, 90 ks XMM-Newton observation (De Luca et al. 2006), performed when the source was in a low state ($\sim 2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$), which clearly showed a 6.67 hr periodicity with a strong ($\sim 50\%$), almost sinusoidal modulation.

On the optical side, Very Large Telescope (VLT) observations of the crowded field of 1E 1613 performed with FORS1 and ISAAC identified a possible counterpart in a very red object ($I > 25, J \sim 22.3, H \sim 19.6,$ and $K_s \sim 18.5$) located within the Chandra error circle (Sanwal et al. 2002). The existence of this object was also confirmed by HST NICMOS follow-up observations (Mignani et al. 2004). A search for a counterpart in the far-IR with the Spitzer Space Telescope was also performed, with negative results (Wang et al. 2007).

As discussed by De Luca et al. (2006), the peculiar combination of long-term variability, 6.67 hr periodicity, young age, and underluminous optical IR counterpart settle the case for a unique phenomenology. It could be that 1E 1613 is a very young binary system, composed of a recently born compact object and a low-mass star in an eccentric orbit, powered by an unusual “double” (wind+disk) accretion mechanism. Very recently, a different binary scenario for 1E 1613 was proposed by Pizzolato et al. (2008). Alternatively, 1E 1613 could be a peculiar isolated object, e.g., a magnetar, dramatically slowed down, possibly by interaction with a debris disk (De Luca et al. 2006; see also Li [2007] for an update of the isolated magnetar model for 1E 1613). Both the binary system and the isolated object scenario are highly unusual and require nonstandard assumptions about the formation and evolution of compact objects in supernova explosions.

In order to shed light on the nature of the puzzling source 1E 1613, we have performed new, deep IR observations of the field with the VLT, with the main aim of identifying the source counterpart by means of a sensitive search for modulation at the expected 6.67 hr periodicity. We have also reanalyzed the archived VLT and HST observations (Sanwal et al. 2002; Mignani et al. 2004) in order to search for long-term variability of a possible counterpart. We presented a first account of our VLT results in Mignani et al. (2007). Since a precise position is of paramount importance for our counterpart search, we have first reassessed the 1E 1613 X-ray position using a set of Chandra archival data together with a very recent deep Chandra observation performed by our group (§ 3.1). Using our new position, we have analyzed our new IR VLT data, as well as the archival data (§§ 3 and 4). Results are discussed in § 5.

2. THE X-RAY POSITION OF 1E 1613

In order to maximize the identification chances, an improved X-ray position of the source is required. Although 1E 1613 has been extensively observed with Chandra, almost all data collected before 2002 are of little use to derive the source position owing to the presence of offsets in the astrometry, as computed by the aspect tool, and/or to source pile-up. Indeed, we found discrepancies among the reconstructed target coordinates that were much larger than the expected astrometric accuracy. Thus, we decided to rely only on Chandra data collected after 2002, for which no astrometric offsets are reported. Such data include 12 short (4–5 ks) observations with ACIS-S (Sanwal et al. 2002; De Luca et al. 2006), as well as a very recent, deep (80 ks) observation performed with HRC-S by our group. The short observations were performed with different roll angles, with the source at a large ($\sim 8^\circ$) off-axis angle in order to reduce pile-up effects. Data were retrieved from the Chandra X-ray Center (CXC) Science Archive. Calibrated (“level 2”) data were produced using the Chandra Interactive Analysis of Observations software (CIAO ver. 3.3). The target position was computed for each ACIS-S data set by performing a source detection in the 0.5–10 keV range using the wavdetect task. After averaging the target coordinates computed from each data set, we obtained $\alpha(J2000.0) = 16^h 17^m 36.228^s, \delta(J2000.0) = -51^\circ 02' 24.6''$ with an rms of 0.5$''$ and 0.25$''$ in right ascension and declination, respectively. The Chandra ACIS astrometric accuracy for sources at off-axis angles larger than 3$'$ is degraded with respect to the on-axis case because of PSF blurring, but no systematic studies of such an effect are available. Thus, we assume the observed rms on the source coordinates as the 1$\sigma$ uncertainty on the X-ray position. The target position in the deep HRC observation was computed in the same way, yielding $\alpha(J2000.0) = 16^h 17^m 36.232^s, \delta(J2000.0) = -51^\circ 02' 24.6''$ with a nominal 1$\sigma$ radial uncertainty of 0.41$''$, according to the CXC calibration team. The HRC coordinates are perfectly consistent with those computed using the 12 short ACIS-S observations. Combining the two measurements, we computed the best estimate of the source coordinates, i.e., $\alpha(J2000.0) = 16^h 17^m 36.23^s, \delta(J2000.0) = -51^\circ 02' 24.6''$ with a 1$\sigma$ uncertainty of 0.285$''$ and 0.185$''$ in right ascension and declination, respectively.

3. IR OBSERVATIONS AND DATA REDUCTION

3.1. The 2006 VLT NACO Observations

Our new set of IR observations was performed in visitor mode on 2006 May 23 and 24 with NaOnic (NACO), an adaptive optics (AO) imager and spectrometer mounted at the fourth unit telescope (UT4) of the ESO VLT at the Paranal Observatory, Chile. In order to provide the best combination of angular resolution and sensitivity, NACO was operated with the S27 camera giving a field of view of 28$'' \times 28''$ and a pixel scale of 0.027$''$. The only suitable reference star for the AO correction was the GSC-2 star S230213317483 ($V = 15.2$), located 21.1$''$ away from our target. For this reason, the resulting image quality was not optimal and appeared to be very sensitive to the atmospheric conditions. The Visual (VIS) dichroic element and wave-front sensor (4500–10000 Å) were used. Observations were performed in the $K_s$ ($\lambda = 2.18$ $\mu$m; $\lambda = 0.35$ $\mu$m) filter.

In order to continuously monitor the potential counterpart candidates within the Chandra error circle covering at least two 6.67 hr cycles, we obtained a total of 22 consecutive observations in the two nights (see Table 1). Each observation lasted about 2300 s and was split into sequences of short, randomly dithered exposures with Detector Integration Times (DITs) of 60 s. The air mass was mostly below 1.3, while the seeing was rarely below $\sim 0.8''$, affecting the performance of the AO. Sky conditions were photometric in both nights. Night (twilight flat fields) and day time-calibration frames (darks, lamp flat fields) were taken daily.
as part of the NACO calibration plan. Standard stars from the Persson et al. (1998) fields were observed in both nights for photometric calibration. The data were processed using the ESO NACO pipeline\(^6\) and the science images co-added.

\(^6\) See http://www.eso.org/observing/dfo/quality/NACO/pipeline.

### Table 1

| Time  | Filter | \(T\) (s) | Seeing (arcsec) | Air Mass |
|-------|--------|-----------|----------------|----------|
| 2006 May 24 |
| 00:49:53 | \(K_s\) | 2280 | 0.84 | 1.57 |
| 01:57:36 | \(K_s\) | 2040 | 0.64 | 1.36 |
| 02:45:14 | \(K_s\) | 1200 | 1.00 | 1.23 |
| 03:14:21 | \(K_s\) | 2280 | 1.02 | 1.18 |
| 04:04:24 | \(K_s\) | 2280 | 0.91 | 1.13 |
| 04:54:17 | \(K_s\) | 2280 | 0.81 | 1.12 |
| 05:44:25 | \(K_s\) | 1200 | 0.80 | 1.14 |
| 06:11:50 | \(K_s\) | 2280 | 0.90 | 1.16 |
| 07:02:02 | \(K_s\) | 720 | 1.06 | 1.24 |
| 07:19:58 | \(K_s\) | 2280 | 0.95 | 1.28 |
| 08:09:50 | \(K_s\) | 1920 | 1.00 | 1.44 |
| 08:56:06 | \(K_s\) | 360 | 0.89 | 1.67 |

| Time  | Filter | \(T\) (s) | Seeing (arcsec) | Air Mass |
|-------|--------|-----------|----------------|----------|
| 2006 May 25 |
| 00:55:12 | \(K_s\) | 2280 | 0.61 | 1.54 |
| 01:57:43 | \(K_s\) | 2280 | 0.66 | 1.34 |
| 02:47:40 | \(K_s\) | 2280 | 0.60 | 1.22 |
| 03:37:25 | \(K_s\) | 2280 | 0.65 | 1.15 |
| 04:27:26 | \(K_s\) | 2280 | 0.64 | 1.12 |
| 05:17:22 | \(K_s\) | 2280 | 0.62 | 1.12 |
| 06:08:53 | \(K_s\) | 2280 | 1.00 | 1.16 |
| 06:59:57 | \(K_s\) | 2280 | 0.96 | 1.24 |
| 07:50:24 | \(K_s\) | 600 | 0.72 | 1.38 |
| 08:06:16 | \(K_s\) | 2280 | 1.00 | 1.44 |

**Note.**—Given are the observation start time (UT), the filter, the exposure time, the average seeing, and the air-mass value.

### Table 2

| Date    | Time (UT) | Filter | \(T\) (s) | Seeing (arcsec) | Air Mass |
|---------|-----------|--------|-----------|----------------|----------|
| 2001 Apr 10 | 07:33:07 | \(J\) | 2000 | 0.68 | 1.12 |
| 2001 May 12 | 06:04:33 | \(K_s\) | 2000 | 0.95 | 1.13 |
| 2001 May 13 | 04:42:57 | \(K_s\) | 2000 | 1.00 | 1.13 |
| 2001 Jun 6 | 05:35:35 | \(K_s\) | 2000 | 1.41 | 1.12 |
| 2001 Jul 23 | 06:46:57 | \(H\) | 1000 | 0.64 | 1.28 |
| 2001 Jul 23 | 01:48:12 | \(H\) | 1000 | 1.04 | 1.34 |
| 2001 Jul 29 | 00:17:16 | \(H\) | 1000 | 0.98 | 1.18 |
| 2001 Jul 30 | 02:45:57 | \(H\) | 950 | 0.70 | 1.26 |
| 2001 Jul 30 | 03:14:54 | \(H\) | 1000 | 0.84 | 1.33 |
| 2001 Jul 30 | 03:43:08 | \(H\) | 1000 | 0.70 | 1.43 |
| 2001 Jul 30 | 00:27:13 | \(H\) | 1000 | 1.00 | 1.12 |
| 2001 Jul 30 | 01:04:19 | \(H\) | 1000 | 1.00 | 1.13 |
| 2001 Jul 30 | 01:32:56 | \(H\) | 1000 | 1.00 | 1.15 |
| 2001 Jul 30 | 02:01:25 | \(H\) | 1000 | 1.00 | 1.18 |

**Note.**—Given are the observing epoch, the observation start time (UT), the filter, the exposure time, the average seeing, and the air-mass value.

### Table 3

| Date    | Time (UT) | Filter | \(T\) (s) |
|---------|-----------|--------|-----------|
| 2002 Aug 15 |
| 02:25:38 | 160W | 2590 |
| 04:10:28 | 160W | 2590 |
| 06:05:15 | 160W | 2590 |
| 09:09:37 | 160W | 2590 |
| 11:12:32 | 110W | 935 |
| 12:40:18 | 205W | 1007 |

**Note.**—Given are the observation start time (UT), the filter, and the exposure time.

#### 3.2. VLT ISAAC Archival Data

IR observations of 1E 1613 were performed in service mode between 2001 April and July using the NIR spectrometer ISAAC mounted at the first unit telescope (UT1) of the VLT. The Short Wavelength camera was used, equipped with a Rockwell Hawaii 1024 \( \times \) 1024 pixel array, which has a projected pixel size of 0.148\(\) and a field of view of 152\(\) \(\times\) 152\(\).\) Observations were performed through the \(J\) (\(\lambda = 1.25 \mu m, \Delta \lambda = 0.29 \mu m\)), \(H\) (\(\lambda = 1.65 \mu m, \Delta \lambda = 0.30 \mu m\)), \(K_s\) (\(\lambda = 2.16 \mu m, \Delta \lambda = 0.27 \mu m\)) band filters. A total of 13 observations were performed in the \(H\) band with the aim of pinpointing the CCO counterpart through the detection of flux modulation, as suggested by the possible periodicity of the X-ray source hinted at by the early Chandra observations available at that epoch (Garmire et al. 2000). Additional pointings in the \(J\) and \(K_s\) bands were performed to study the colors of the candidate counterpart (see Table 2).

To allow for subtraction of the variable IR sky background, each observation was split into sequences of shorter dithered exposures (\(DIT = 20\) s in the \(H\) band and \(40\) s in the others). The total integration times per observation were \(2000\) s (\(J\) and \(K_s\) bands) and \(1000\) s (\(H\) band). All observations, with the exception of that of July 23, were taken under photometric conditions, with seeing often better than 1.0\(\) and air mass below 1.2. Twilight flat fields, dark frames, and images of standard stars from the Persson et al. (1998) fields were taken daily as part of the ISAAC calibration plan. The data were reduced and calibrated using the ESO ISAAC pipeline.\(^7\) For each exposure sequence, single frames were registered and co-added to produce a background-subtracted and cosmic-ray-free image.

#### 3.3. HST NICMOS Archival Data

IR observations of the field of 1E 1613 were performed on 2002 August 15 and October 8 with the HST. Observations were performed with NICMOS using the NIC2 camera (19.2\(\) \(\times\) 19.2\(\) field of view, 0.075\(\) pixel size) with the 110\(\) (\(\lambda = 1.128 \mu m, \Delta \lambda = 0.16 \mu m\)), 160\(\) (\(\lambda = 1.606 \mu m, \Delta \lambda = 0.11 \mu m\), and

\(^7\) See http://www.eso.org/observing/dfo/quality/ISAAC/pipeline.
205W ($\lambda = 2.071$ $\mu$m, $\Delta \lambda = 0.18$ $\mu$m) filters. To cope with visit scheduling constraints, the target had to be observed for 10 spacecraft orbits distributed over two different visits. In each visit, a sequence of six exposures (2590 s each) was performed in the 160W filter to search for variability of the originally proposed candidate counterpart (Sanwal et al. 2002), and two exposures in the 110W (935 s) and 205W (1007 s) filters were performed to derive color information (see Table 3).

To decrease the instrumental overheads, observations were taken in MULTIACCUM mode and split into sequences of 9 and 18 subexposures in the 110W filter and in the others, respectively. The data were downloaded from the European HST science archive\(^8\) after on-the-fly recalibration with the best reference files available, frame co-addition, and cosmic-ray filtering.

\(^8\) See http://www.stecf.org/archive/.
3.4. VLT and HST Astrometry

In order to precisely register the Chandra position on our IR images, we have refined the default image astrometry. We have computed the astrometric solution on the ISAAC images by fitting the positions and coordinates of 60 reference stars selected from the 2MASS catalog. The reference star positions have been computed by a two-dimensional Gaussian fitting procedure with accuracies of a few hundredths of a pixel. The astrometric fit was performed using the Starlink package ASTROM with a sixth-order polynomial to account for detector distortions and yielded a rms of $0.090''$ in both right ascension and declination.

Since very few 2MASS stars fall in both the narrow NICMOS ($19.2'' \times 19.2''$) and NACO ($28'' \times 28''$) fields of view, they do not provide an adequate primary reference grid. For this reason, in both cases we have computed the astrometric solution by using a secondary reference grid made up of 26 secondary stars identified in common with the ISAAC $K_s$-band image. The astrometric solutions computed for the NICMOS and NACO images thus yielded a rms of $0.042''$ and $0.040''$ coordinate$^{-1}$, respectively. By adding in quadrature the rms of the astrometric solution of the ISAAC image ($0.090''$ coordinate$^{-1}$), we thus end up with an overall uncertainty of $0.1''$ coordinate$^{-1}$ on the astrometry for both the NICMOS and NACO images. In all cases, we have accounted for the intrinsic $0.2''$ absolute astrometric accuracy of 2MASS.\footnote{See http://spider.ipac.caltech.edu/staff/hlm/2mass/overv/overv.html.}

Figure 1 shows the deepest VLT and HST images of the field of 1E 1613 with the computed Chandra position overlaid. Seven objects (labeled in the figure) are detected in the vicinity of the X-ray position; three of them are consistent with the 99% c.l. error region. In all cases, the objects’ profiles are pointlike and consistent with the instruments’ PSFs. We note that the originally proposed counterpart object 1 (Sanwal et al. 2002) is now only marginally consistent (at $3\sigma$ c.l.) with the position of 1E 1613. Due to field crowding, only the two brightest objects (1 and 2) are detected in the lower resolution VLT ISAAC image (Fig. 1, top left), while the faintest ones (3–7) are detected in the higher resolution HST NICMOS and VLT NACO images. Objects 1 and 2 are also detected in the VLT ISAAC $J$- and $K_s$-band images. All objects are detected in the HST NICMOS 160W and 205W bands, while only objects 1 and 2 are also detected in the 110W band, although the former is only marginally detected. This is likely due to the short exposure time (see Table 3) and to the fact that the 110W band is slightly bluer than the ISAAC $J$ band. The fact that objects 3–7 are all detected in the 160W and 205W

![Fig. 2.—Left, top to bottom: VLT NACO $K_s$-band light curves for candidate counterparts 1–6. The difference with respect to the average magnitude is plotted as a function of time. Horizontal dotted lines mark the rms variability for each source. Right, top to bottom: Folded VLT NACO $K_s$-band light curves for candidate counterparts 1–6. Crosses and squares represent flux measurements performed in the first and second night, respectively. Two phase intervals are plotted for clarity. Error bars in both panels account for statistical uncertainties only. The rms variability for each source, plotted in the left panel only, is representative of the random errors affecting our measurements (see text).]
bands but not in the 110W band suggests that they are very red and heavily absorbed. To be conservative, we consider all seven of the sources in our investigation.

4. DATA ANALYSIS

Due to field crowding and the faintness of most candidates, magnitudes for all observations were computed through PSF photometry, which, in this case, yields more accurate results than standard aperture photometry. We note that for the NACO observations the accuracy of the PSF photometry is affected by the quality of the AO correction, which was not optimal due to the relatively large offset of the guide star and the varying atmospheric conditions (§ 3.1). Since the NACO PSF is largely oversampled, to increase the signal-to-noise ratio the NACO images have been resampled with a $3 \times 3$ pixel window using the SWarp program. For the PSF photometry we used the suite of programs DAOPHOT, following the procedures described in Zaggia et al. (1997). To improve and maximize object detection we used as a reference the co-added and deeper VLT ISAAC H-band, HST NICMOS 160W, and VLT NACO $K_s$-band images (see Fig. 1) for each telescope/instrument data set to create a master list of objects which we registered on the single images and used as a mask for object detection. For each single image, the model PSF was then computed by fitting the profile of a number of bright but nonsaturated reference objects. Such a model PSF was used to measure object fluxes at the reference positions. Photometry calibration was applied using the zero points provided by the VLT and HST data reduction pipelines. Since the ISAAC and NACO zero points are by default computed through aperture photometry, the aperture correction was applied to the DAOPHOT magnitudes. For the VLT observation, air-mass correction was applied using the atmospheric extinction coefficients measured for the Paranal Observatory (Patat 2004).

4.1. Short-Term Variability

To search for short-term variability from the candidate counterparts we started from the VLT NACO data set, which is the only one to provide both complete coverage and accurate phase sampling of the 6.67 hr period of the X-ray source over at least two cycles (see Table 1). Using as a mask the master list created from the co-added $K_s$-band image, we ran DAOPHOT to compute the PSF photometry on the single images. The derived single-object catalogs were then matched and compared using the DAOPHOT routine allframe. To avoid systematic offsets induced by night-to-night zero-point fluctuations, the photometry of the second night was renormalized to that of the first night.

Magnitude differences with respect to the average value are plotted in Figure 2 (left) for all candidate counterparts for the two consecutive nights (May 23 and 24). Object 7 is not included, since it is not detected in the single images but only in the co-added one (see Fig. 1). Next, for each measurement we computed the corresponding phase with respect to the 6.67 hr X-ray period, assuming phase zero to be at MJD 53,879.0, and we folded the second night on the first one. The folded light curves are plotted in Figure 2 (right).

A large scatter of the flux measurements is apparent in both panels of Figure 2, where error bars account for statistical errors only. Such variability is generally erratic and not correlated with phase (Fig. 2). Indeed, visual inspection of the light curves of objects 1 and 3 would suggest a nearly sinusoidal variation, which, however, does not pass statistical tests. Considering source 1, a simple constant fails to reproduce the folded light curve ($\chi^2 = 3.9, 18$ dof). Adding a sine function does not yield a better description ($\chi^2 = 3.6, 16$ dof; such improvement has a 20% chance-occurrence probability), and adding a second harmonic does not improve the situation ($\chi^2 = 4.0, 14$ dof). Focusing on source 3, a constant fit yields $\chi^2 = 1.5$ (15 dof), while adding a sine function yields $\chi^2 = 1.0$ (13 dof). Such an improvement has a chance-occurrence probability of 3%, which is definitely too high to claim as evidence of modulation. Thus, none of the candidate counterparts show evidence for periodic modulation.

In order to estimate upper limits on short-term variability, a careful discussion of errors is required. Indeed, the apparent flux variations exceed the expected Poisson fluctuations among different measurements. A steady flux model is formally not consistent with most of the observed light curves (as seen above; e.g., for object 1 it yields $\chi^2 = 3.9, 18$ dof). Such a large scatter suggests that our relative photometry measurements are contaminated by random errors induced by, e.g., fluctuations in the atmospheric conditions, sky background, and seeing. Other sources of errors are the variations in the AO correction to the PSF, which depend both on the objects’ positions in the instrument field of view and on the correct guiding of the reference star. Furthermore, errors are also induced by the PSF fitting and background subtraction procedures. Other errors induced by the data reduction process and/or by glitches in detector performance should also to be taken into account. It is also interesting to note that the brightest source candidate (object 2, $K_s = 15.5$) shows a much smaller rms with respect to the other, much fainter ones ($K_s > 18$), implying that such errors are larger for sources with a lower signal-to-noise ratio. Since it would be extremely difficult to formally quantify all the above effects on the photometry of each single object, we decided to use an empirical approach. The results are shown in Figure 3, where, for all objects detected in the field, we have plotted the flux variation rms as a function of the average object’s flux. As already hinted in Figure 2, flux measurements for fainter sources are more scattered. In particular, the flux variation rms values of our candidate counterparts are fully consistent with those of field objects of comparable brightness. Thus, we conclude that none of the candidate counterparts show evidence for significant short-term variability or 6.67 hr modulation. Indeed, the measured flux variation rms can be interpreted as a $1\sigma$ upper limit to any possible variability. Such upper limits, together with the time-averaged magnitudes, are summarized in Table 4.

For completeness, we have analyzed the other available data sets which span different epochs and sample different source states. We have repeated our analysis using the VLT ISAAC H-band data set (see Table 2), which, unfortunately, provides repeated flux measurements only for the two brightest candidates (objects 1 and 2) with noncontinuous coverage and nonuniform sampling of the 6.67 hr X-ray period. We found that the apparent flux variations are compatible with the measured rms, suggesting also that random errors induced by fluctuations in the atmospheric conditions, sky background, and seeing dominate. As before, we assumed the measured flux variation rms as the $1\sigma$ variability upper limit (see Table 4). Finally, we have repeated our analysis using the HST NICMOS 160W data set, which provides repeated, atmosphere-free flux measurements, although with noncontinuous coverage and nonuniform sampling of the 6.67 hr X-ray period (see Table 3). Since the HST observations have been split into two different orbits separated by about 60 days, we first searched for variability in each visit. Once more, we could not find statistically significant evidence for variability. In particular, we found none for object 7.

10 See http://terapix.iap.fr/rubrique.php?id_rubrique=49.
i.e., the faintest of the candidates and the only one for which the repeated VLT NACO observations did not yield time variability information. While the uncertainty on the source period prevents folding of the light curves derived from different visits, by comparing the photometry of the two visits we found that the fluxes measured from the second one are systematically fainter by $\sim 0.1-0.2$ mag. Such an effect is probably due to the use of calibration frames noncontemporaneous with the observations (unfortunately, a single set of dark and flat-field frames is available for the two visits) and, possibly, to a nonoptimal correction for the “pedestal.”

The derived variability upper limits (see Table 4) are thus less constraining than those derived from the single visits, although, as expected, somewhat tighter than those derived from the analysis of the VLT NACO and ISAAC data sets.

### 4.2. Long-Term Variability

We have used the whole data set to search for indications of long-term IR variability on timescales of years possibly associated with the evolution of the X-ray source. As a reference, we have used the flux measurements in the closest passbands, i.e., those obtained from the VLT ISAAC $K_s$-band, *HST* NICMOS 205W, and VLT NACO $K_s$-band observations. Since we did not find any evidence for variability within the data set of each instrument,
for each data set we have generated time-averaged images. Unfortunately, a direct comparison is made difficult by the use of different instruments and filters. Passband transformations between the HST and Johnson filters can be computed using the synphot package of the Space Telescope Science Data Analysis Software (STSDAS). However, the results are affected by the uncertainty on the objects’ spectral type, which is a free parameter of the transformation equation. Since our spectral classification of the candidate counterparts relies mostly on one color, with only object 1 and 2 also detected in the VLT ISAAC J-band and the HST NICMOS 110W, we estimate that a straight passband transformation will introduce an unknown uncertainty into our flux estimates.

To solve the problem, as well as to account for other sources of systematics, we cross-matched the object catalogs obtained from the HST NICMOS 205W and the VLT ISAAC Ks-band observations (202 objects in common) and computed the correlation between the magnitudes measured in the two filters. The rms of the fit is ~0.05 mag (using 105 sources with H < 19.5 after 2 σ clipping), i.e., of the same order as our statistical photometric errors. We repeated the same procedure to compute the transformation between the VLT NACO and ISAAC Ks bands, and again we obtained an rms of ~0.05 mag (using 47 sources with $K_s < 17$ after 2.5 σ clipping). For all our candidates we then applied such empirical passband transformations in order to have all flux measurements consistently referred to the $K_s$ band.

We also checked the correlation for the bulk of the fainter sources, resolved only in the sharp HST NICMOS and VLT NACO images. The scatter is found to be somewhat higher at faint fluxes. The observed rms increases from 0.08 mag (for 19 sources in the $K_s$ 13–15.5 range) to ~0.4 mag (for 243 sources in the $K_s$ 18–20.5 mag range). The larger rms for fainter objects points to effects related to, e.g., passband transformation, air-mass corrections, and the effects discussed in § 4.1.

Figure 4 shows the derived long-term $K_s$-band light curve for all our candidates compared with the Chandra/XMM-Newton X-ray light curve obtained over the same time span. Note that, since only objects 1 and 2 were detected in the VLT ISAAC observations, for the fainter candidates the light curve is based on the HST NICMOS and VLT NACO points only. While the X-ray source was continuously fading, for most candidates there is no indication of IR variability on the year timescale. Object 6 apparently decreases by ~1 mag between 2002 August and 2006 May. However, we note that this object falls in the PSF wing of the much brighter object 2 (see Fig. 1), which might have affected our photometry. A possible ~0.7 mag flux decrease is also observed for objects 4 and 5 (with the latter being the only candidate to fall within the 68% c.l. X-ray error circle). However, in view of the larger uncertainties for fainter sources, as apparent from the scatter in the HST NICMOS–to–VLT NACO correlation, such evidence for variability should be taken with caution.

### 4.3. Color Analysis

We used the available multiband information to derive clues to the nature of the candidate counterparts. The single-band, single-epoch photometry catalogs derived with DAOPHOT were matched by allframe to create the multiband catalogs for the VLT ISAAC and HST NICMOS data sets. Single-epoch multiband catalogs were finally merged and magnitudes averaged. We note that since no time variability has been found in the VLT ISAAC and HST NICMOS observations (see § 4.1), the use of average magnitudes for each data set does not affect our color analysis. To make the comparison between the derived VLT ISAAC and HST NICMOS color-magnitude diagrams (CMDs) consistent, NICMOS 110W and 160W magnitudes have been transformed to the ISAAC J and H bandpasses using the same approach applied in the previous section. The available multiband photometry of our candidates is summarized in Table 5. The results of our color analysis are shown in Figure 5, where we plot the candidates’ photometry on the VLT ISAAC and HST NICMOS $(J, J - K_s)$ and $(H, H - K_s)$ CMDs built from the photometry of the field stars. As can be seen, nearly all candidates have colors consistent with the bulk of the field stellar population. The only possible exceptions are object 7, whose color determination is affected by the large photometry errors, and object 6, which seems to be slightly redder with respect to the CMD sequence, which has an average $H - K_s ~ 2$. However, this apparently peculiar deviation could be partly due to the lower statistics of the HST NICMOS CMD, where the redder part is poorly sampled. Indeed, objects with extreme $H - K_s$ appear less unusual in the much denser VLT ISAAC CMD. Furthermore, we warn here that object 6, as well as perhaps objects 4 and 5, might be variable on the long timescale (see § 4.2). Thus, its location in the CMD might not be fully representative.

### 4.4. Deep Imaging

No other candidates have been identified in our deep IR imaging within or close to the X-ray position apart from those indicated in Figure 1. We have used our deepest images of the field, i.e., those obtained from the co-addition of the repeated VLT ISAAC H-band, HST NICMOS 160W, and VLT NACO Ks-band observations, to set constraining upper limits on the flux of a hypothetically undetected CCO counterpart. We obtained $H \sim 23$

### Table 5

**Multiband Magnitudes for All Candidate Counterparts**

| ID | $J$       | $H$       | $K$       | $J$       | $H$       | $K$       | NACO $K$ |
|----|-----------|-----------|-----------|-----------|-----------|-----------|----------|
| 1  | 22.10 ± 0.10 | 19.36 ± 0.03 | 17.93 ± 0.02 | 22.10 ± 0.30 | 19.50 ± 0.02 | 17.98 ± 0.02 | 17.94 ± 0.03 |
| 2  | 17.94 ± 0.01 | 16.38 ± 0.01 | 15.49 ± 0.01 | 18.05 ± 0.01 | 16.38 ± 0.03 | 15.52 ± 0.02 | 15.42 ± 0.02 |
| 3  | ...        | ...        | ...        | ...        | ...        | ...        | ...      |
| 4  | ...        | ...        | ...        | ...        | ...        | ...        | ...      |
| 5  | ...        | ...        | ...        | ...        | ...        | ...        | ...      |
| 6  | ...        | ...        | ...        | ...        | ...        | ...        | ...      |
| 7  | ...        | ...        | ...        | ...        | ...        | ...        | ...      |

**Note:** Values are computed on the average images. To allow for easier comparison between different measurements, HST magnitudes have been normalized to the Johnson system (see text). Quoted uncertainties include statistical errors only.

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12 See http://stsdas.stsci.edu/cgi-bin/gethelp.cgi?synphot.sys.
5. DISCUSSION

Although our comprehensive study (astrometry, variability, multiband photometry) of the potential CCO counterparts did not single out a high-confidence candidate, position-wise, object 5 (inside the 68% c.l. region), objects 3 and 6 (inside the 99% c.l. region), and object 1 (marginally consistent at the ~3σ level) cannot be ruled out. On the other hand, objects 2, 4, and 7 may be disregarded. The field is very crowded, with a source density in the combined VLT NACO $K_s$ image of $>1.1$ objects arcsec$^{-2}$ at the sensitivity limit of $K_s \sim 22.1$. Before discussing the implications of our results for possible pictures of 1E 1613, we note that none of the possible candidates stand out for peculiar colors with respect to the field very red stellar population. The average $H - K \sim 2$ requires a large interstellar reddening, consistent with $A_V \sim 20-25$. Such a reddening is much larger than the value of $A_V \sim 3.3-6.6$ expected at the distance of the X-ray source, according to the measured $N_H$ of 1E 1613 (De Luca et al. 2006), the results of a neutral H study toward RCW 103 (Reynoso et al. 2004), and spectrophotometry of the SNR (e.g., Leibowitz & Danziger 1983). Thus, if one of the plausible candidates is indeed physically associated with 1E 1613, it must have very peculiar, red intrinsic colors.

In the frame of the binary system scenario for 1E 1613 (De Luca et al. 2006), in principle, one could expect the companion star to be significantly different from a main-sequence star of comparable mass. This could be the result of an early phase of irradiation by photons and charged particles from the newborn neutron star, which could have left the companion away from thermal equilibrium (the Kelvin-Helmholtz timescale to thermal relaxation would be much larger than the age of the system). Tidal interaction along a very eccentric orbit could also play some role. However, the hypothesis that any of the possible candidates could be the companion of 1E 1613 is very unlikely. The observed colors and magnitudes would require an unrealistically low temperature for the star ($\sim 1000-1500$ K), implying (at a distance of 3.3 kpc and for $A_V = 6.6$) a photospheric radius of $(1-2) \times 10^{11}$ cm, exceeding the Roche lobe dimension ($\sim 4 \times 10^{10}$ cm, assuming a $1.4 M_\odot$ neutron star, a $0.5 M_\odot$ companion, and an orbital period of 6.67 hr) and comparable to the systemic orbital separation ($\sim 1.5 \times 10^{11}$ cm under the same assumptions).

Within the isolated magnetar scenario (De Luca et al. 2006), a fallback disk is required in order to quench the neutron star rotation to a period of 6.67 hr in $\sim 2000$ yr. Could one of the possible candidates be the fallback disk itself? Recently obtained (Wang et al. 2006) evidence for a debris disk surrounding the anomalous X-ray pulsar 4U 0142+61 makes such a hypothesis not unrealistic (a faint IR source at the position of the CCO in Vela Jr. could also be related to a debris disk surrounding the compact object; see Mignani et al. 2007b). While the physics of the possible disk surrounding 4U 0142+61 is not understood (passive or viscous; Wang et al. 2006; Ertan et al. 2007), we note that the colors of our candidates are similar to those of the case of 4U 0142+61, but their $F_K/F_H$ ratio [in the range $(0.7-2) \times 10^{-3}$ at the epoch of the NACO observations] is about 1 order of magnitude larger. The upper limits to the far-IR emission set by Wang et al. (2007) are not constraining.

Unfortunately, mostly because of the faintness of the IR sources, results of the temporal analysis could not offer conclusive clues. The upper limits we could set did not place stringent constraints. They could be consistent with a binary scenario, since any orbital modulation would obviously depend on the inclination of the system with respect to the plane of the sky. On the other hand, the isolated neutron star scenario does not allow for firm predictions about a possible IR periodicity.

We also tried to exploit the source long-term fading seen in X-rays between the NICMOS and NACO observations looking...
for long-term variability to pinpoint the IR counterpart of 1E 1613. In the binary scenario, IR variability could be due to the reprocessing of the compact source X-ray radiation by the companion star (and possibly by an accretion disk, if any). The same could be true for the isolated magnetar scenario: X-ray reprocessing taking place in a fallback disk. We stress yet again that in both pictures the effect would be strongly dependent on the geometry of the system with respect to the line of sight. Indeed, we have obtained evidence for a possible ~1 mag fading of one of the candidates, which yields a constant $F_{Ks}/F_X$ ratio in case of association with 1E 1613. However, in view of the scatter seen in the correlation of NICMOS and NACO photometric measurements for sources of comparable magnitude, such possible evidence for IR variability is not strong enough to claim an identification.

With no compelling reasons to associate any of the possible candidates with 1E 1613, we explore the implications of a source non-detection down to $K_s > 22.1$. Considering the binary scenario, accounting for uncertainties on the distance and reddening, such an upper limit is only consistent with an M6–M8 dwarf, i.e., a very underluminous companion. It is rather unlikely that such a small star may power the mechanism proposed by De Luca et al. (2006), where accretion of wind from the companion modulated along an eccentric orbit explains the phenomenology of the low state. Such a picture would require an accretion rate of $\sim 10^{-13} M_{\odot} \, yr^{-1}$, implying a red dwarf wind mass loss larger by at least a factor of a few, which seems somewhat too high for such a small star. Thus, an alternative process is required to explain the X-ray phenomenology. Even the survival of the supernova explosion of a binary system with such an extreme mass ratio seems problematic. It would require an ad hoc kick for the neutron star to avoid disruption of the system.

On the other hand, the lack of an IR counterpart fits well within the isolated magnetar scenario. The upper limit to the ratio $F_{K_s}/F_X < 1.5 \times 10^{-4}$ (at the epoch of the NACO observation) is fully consistent with the values observed for all magnetars identified in the IR (see, e.g., Fesen et al. 2006), including 4U 0142+61 (Wang et al. 2006). In the isolated magnetar scenario, we cannot rule out the possibility that one of the candidate sources is the residual disk surrounding 1E 1613. However, Occam’s razor argues against such a conclusion, since all possible candidates are undistinguishable from normal, background stars.

Recent Swift monitoring of 1E 1613 shows that the X-ray source continued to fade in the 2006–2007 time interval, and that its flux is approaching the 1999 preoutburst level (see Fig. 4). Historical observations point to a large flux variability over an ~10 yr timescale (Gotthelf et al. 1999; De Luca et al. 2006), so that a rebrightening is likely to occur. A factor of ~100 increase in the X-ray luminosity (as in the 1999–2000 outburst) would yield a dramatic change in the irradiation of any possible object/structure (companion star/fallback disk) linked to 1E 1613. Thus, if a new outburst from 1E 1613 occurs, a fast follow-up in the IR will be crucial in order to conclusively address the issue of the IR counterpart for 1E 1613 and to shed light on its nature. The images described in this work will be a reference to search for the variability of the counterpart.

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