

## ACCURATE X-RAY POSITION OF THE ANOMALOUS X-RAY PULSAR XTE J1810–197 AND IDENTIFICATION OF ITS LIKELY INFRARED COUNTERPART<sup>1</sup>

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Received 2003 November 11; accepted 2004 January 15; published 2004 February 19

### ABSTRACT

We report the accurate subarcsecond X-ray position of the new anomalous X-ray pulsar (AXP) XTE J1810–197, derived with a *Chandra* High Resolution Camera Target of Opportunity observation carried out in 2003 November. We also report the discovery of a likely IR counterpart based on a Very Large Telescope (IR band) Target of Opportunity observation carried out in 2003 October. Our proposed counterpart is the only IR source ( $K_s = 20.8$ ) in the X-ray error circle. Its IR colors as well as the X-ray/IR flux ratio are consistent with those of the counterparts of all other AXPs (at variance with field star colors). Deep Gunn *i*-band images obtained at the 3.6 m ESO telescope detected no sources down to a limiting magnitude of 24.3. Moreover, we find that the pulsed fraction and count rates of XTE J1810–197 remained nearly unchanged since the previous *Chandra* and *XMM-Newton* observations (2003 August 27 and September 8, respectively). We briefly discuss the implications of these results. In particular, we note that the transient (or at least highly variable) nature of this AXP might imply a relatively large number of hidden members of this class.

*Subject headings:* infrared: stars — pulsars: general — pulsars: individual (XTE J1810–197) — stars: neutron — X-rays: stars

### 1. INTRODUCTION

Despite their limited number, anomalous X-ray pulsars (AXPs) are one of the most intensively studied Galactic high-energy sources. Since these sources were first proposed as a separate class (Mereghetti & Stella 1995; van Paradijs, Taam, & van den Heuvel 1995), their number has grown slowly, and there are now five confirmed AXPs plus two candidates. These sources are relatively slowly rotating, spinning-down, radio-quiet X-ray pulsars with no evident signature for binary motion and X-ray luminosity exceeding the rotational energy loss by a large factor (see Israel, Mereghetti, & Stella 2002a and Mereghetti et al. 2002 for a review). AXPs have been linked to soft gamma repeaters (SGRs) because of similar timing properties, namely, spin periods ( $P$  in the 5–12 s range) and large period derivatives ( $\dot{P} \sim 10^{-11}–10^{-12} \text{ s s}^{-1}$ ). It is now commonly believed that SGRs are magnetars, isolated neutron stars powered by the decay of their strong, supercritical magnetic fields of  $B > 10^{14}$  G (Duncan & Thompson 1992; Thompson & Duncan 1995; Kouveliotou et al. 1998). The same model has been applied to AXPs. Nonetheless, there is a growing group of radio pulsars (Camilo et al. 2000; McLaughlin et al. 2003) with comparably long periods

and inferred magnetic field strengths approaching  $10^{14}$  G. These radio pulsars possess no special attribute linking them to either AXPs (no steady bright quiescent X-ray emission; Pivovarov, Kaspi, & Camilo 2000) or SGRs (no bursting episodes). Thus, periodicity alone does not appear to be a sufficient attribute for classification. Correspondingly, a very high magnetic field strength cannot be the sole factor governing whether a neutron star is a magnetar, a radio pulsar, or an accreting neutron star.

The recent detection of X-ray bursts from 1E 2259+586 and 1E 1048.1–5937 has strengthened the connection of AXPs with SGRs (Kaspi & Gavriil 2002; Gavriil, Kaspi, & Woods 2002). At the same time, the study of the former sources resulted in the identification of new observational properties. In the case of 1E 2259+584, IR variability of the counterpart was detected a few days after an episode of strong X-ray bursting activity (Kaspi et al. 2003). IR variability of the counterpart to 1E 1048.1–5937 was also detected; this might be related to the X-ray variability that was observed from this source (Israel et al. 2002b). These findings have opened a new perspective in the field, challenging the predictions of current models. It is not yet clear which specific physical parameter(s) differentiate(s) AXPs from SGRs (if any).

A pronounced X-ray variability seems to be the main new characteristic of the recently proposed member of this class of pulsars, namely, XTE J1810–197 (also known as CXOU J180951.1–194351; Gotthelf et al. 2004, hereafter G04). The source was discovered with the *Rossi X-Ray Timing Explorer* (*RXTE*) in 2003 July at an absorbed flux level of  $\sim 5.5 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$  (2–10 keV;  $N_{\text{H}} = 1 \times 10^{22} \text{ atoms cm}^{-2}$ ; Markwardt et al. 2003a; Ibrahim et al. 2004). Subsequent re-examination of archival data showed that the source was present in the *RXTE* Proportional Counter Array data since 2003 February with a flux of  $\sim 8.64 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$  (2–10 keV). The source shows a soft two-component spectrum, pulses at a period  $P$  of 5.5 s, and a period derivative  $\dot{P}$  of  $1.8 \times 10^{-11} \text{ s s}^{-1}$  (Markwardt et al. 2003b; Ibrahim et al. 2004; Tiengo & Mereghetti 2003). No relatively bright optical ( $I > 21.3$ ) and IR ( $K = 17.5$ ) counterpart was found in the 2.5 radius error circle

<sup>1</sup> The results reported in this Letter are partially based on observations carried out at ESO, Cerro Paranal, Chile (072.D-0297).

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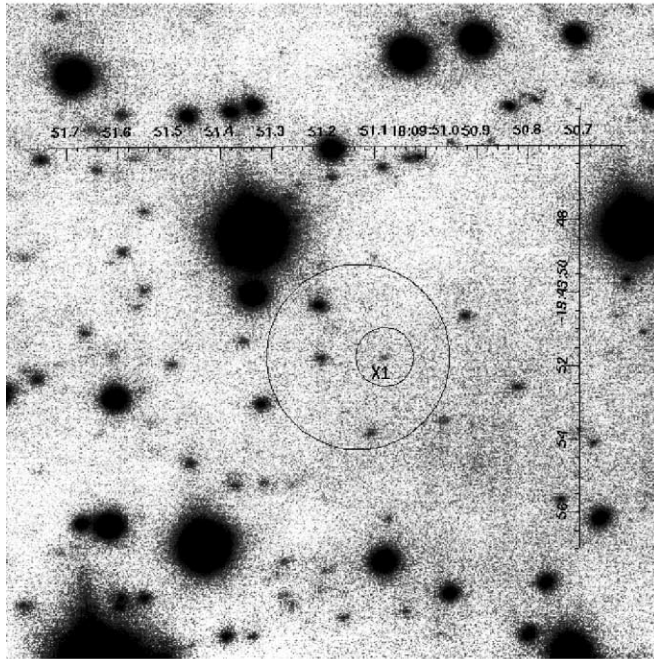


FIG. 1.—Near-IR  $K'$ -band image of the region including the position of XTE J1810–197, taken with NAOS-CONICA mounted on VLT UT4 Yepun on 2003 October 7. The two *Chandra* uncertainty circles ( $2''.5$  and  $0''.8$  radius at  $1\sigma$  and 90% confidence level, respectively) are shown. The proposed IR counterpart is marked with X1. Coordinates are right ascension (hours, minutes, seconds) and declination (degrees, arcminutes, arcseconds; equinox J2000.0).

obtained with *Chandra* in 2003 August ( $1\sigma$  confidence level; G04; Ibrahim et al. 2004).

In this Letter, we present the results from *Chandra* and Very Large Telescope (VLT) Target of Opportunity observations of XTE J1810–197 that we obtained in the fall of 2003. These led to a subarcsecond accurate X-ray position for XTE J1810–197 and to the identification of its likely IR counterpart. Preliminary results from this study were reported in Israel et al. 2003 (posted on 2003 November 4). We found that the optical/IR colors and broadband spectrum of this pulsar are similar to those of AXPs, strongly suggesting that XTE J1810–197 belongs to the same class. Based on these findings and on the X-ray variability previously reported for this pulsar (Ibrahim et al. 2004), we conclude that XTE J1810–197 represents the first confirmed AXP showing a transient behavior (in the X-ray band).

## 2. CHANDRA OBSERVATIONS

The field of XTE J1810–197 was observed by *Chandra* with the High Resolution Camera Imager (HRC-I; Zombeck et al. 1995) on 2003 November 1 for an effective exposure time of 2866 s. Data were reduced with CIAO version 3.0.1 and analyzed with standard software packages for X-ray data (Ximage, Xronos, etc.). Only one source was detected in the HRC-I (see Israel et al. 2002b for details on the detection algorithm). The source has the following coordinates: R.A. =  $18^{\text{h}}09^{\text{m}}51^{\text{s}}.08$ , decl. =  $-19^{\circ}43'51''.74$  (statistical uncertainty of  $0''.13$ ; equinox J2000.0), with a total uncertainty circle radius of  $0''.7$  (90% confidence level; Israel et al. 2003). The position is consistent with that of the previous *Chandra* observation (G04). Photon arrival times were extracted from a circular region with a radius of  $1''.5$ , including more than 90% of the source photons, and corrected to the barycenter of the solar system. Coherent pulsations at a period of about 5.5 s were detected, confirming that the source

was indeed XTE J1810–197. To refine the period determination, we adopted a phase fitting technique. The best pulse period was determined to be  $P = 5.5391 \pm 0.0004$  s (90% confidence level). The pulsed fraction in the HRC-I energy band was  $49\% \pm 2\%$  (semiamplitude of modulation divided by the mean source count rate). The latter value is consistent with that reported by G04 ( $46\% \pm 3\%$  using our pulsed fraction definition). The source count rate was  $1.04 \pm 0.04$  counts  $\text{s}^{-1}$ , marginally lower than the previous *Chandra* observations carried out 66 days earlier ( $0.96 \pm 0.04$  counts  $\text{s}^{-1}$ ; G04).

Finally, the spatial profile was found to be in good agreement with the expected *Chandra* point-spread function (PSF) for an on-axis source (see Israel et al. 2002b for details).

## 3. OPTICAL/IR OBSERVATIONS

Data were acquired at VLT-UT4 Yepun with the Nasmyth Adaptive Optics System and the High Resolution Near IR Camera (NAOS-CONICA) on 2003 October 7. The pixel size of the camera is  $0''.027$ , and the FWHM is approximately 6 pixels. Images have been reduced with instrument-specific pipelines and then co-added. A total of 21 images (effective exposure time of each frame is 120 s, obtained by averaging three exposures of 40 s on the chip) in  $H$  and  $K_s$  filters were used for the analysis. Zero points (ZPs) were obtained by using the standard S234-E from the catalog of Persson et al. (1998), producing the following values:  $ZP(H) = 23.80$ ,  $ZP(K_s) = 22.91$ . Thanks to adaptive optics, we obtained an on-axis source PSF of  $\sim 0''.15$ , and we inferred a limiting magnitude (signal-to-noise ratio [S/N]  $\sim 3$ ) of 22.5 ( $H$ ) and 21.5 ( $K_s$ ). A preliminary catalog for the objects in the field was obtained by co-adding  $H$  and  $K_s$  images. Magnitudes and positions of detected stars in the co-added images were derived by means of aperture photometry and centroid determination (Stetson 1990).

Optical observations were carried out on 2003 October 12 with EFOSC2 at the 3.6 m ESO telescope (La Silla). The night was clear with variable seeing (between  $0''.7$  and  $1''.5$ ). The XTE J1810–197 field was imaged with 21 exposures of 240 s each using the Gunn  $i$  filter (central wavelength 803.4 nm; FWHM of 151 nm). The ZP for the night is extracted from the tabulated Johnson and Cousins  $I$  magnitudes for the standard field, and its value is:  $ZP(I) = 23.85$  (Landolt 1992). Data were flat field-corrected and fringe pattern-subtracted. Using an S/N = 3 threshold, a PSF area of 11 pixels, and the average of the tabulated extinction values for La Silla, the  $I$  limiting magnitude was  $24.30 \pm 0.03$ .

To register the *Chandra* coordinates of XTE J1810–197 on our IR images, we computed the image astrometry using, as a reference, the positions of stars selected from the GSC2.2 and 2MASS catalogs, which has an intrinsic absolute accuracy of about  $0''.2$ – $0''.4$  (for GSC2.2 and depending on magnitude and sky position of stars). After taking into account the uncertainties in the source X-ray coordinates ( $0''.7$ ), the rms error of our astrometry ( $0''.06$ ), and the propagation of the intrinsic absolute uncertainties on the catalog coordinates (we assumed a value of  $\sim 0''.3$ ), we estimated an accuracy of about  $0''.8$  to be attached to the XTE J1810–197 position. Figure 1 shows a region of  $18'' \times 18''$  around the XTE J1810–197 position in the  $K_s$ -band VLT image (the  $1\sigma$  confidence level uncertainty circle reported by G04 is also superposed).

## 4. DISCUSSION

The 3.6 m ESO data show no object within the new *Chandra* uncertainty circle down to a  $I$  limiting magnitude of 24.3

(S/N  $\sim 3$ ). On the other hand, only one faint pointlike object is present in the VLT  $H$  and  $K_s$  frames (marked X1 in Fig. 1;  $H = 22.0 \pm 0.1$ ,  $K_s = 20.8 \pm 0.1$ ). Note that the probability of finding by chance an object unrelated to the X-ray source within the *Chandra* uncertainty region is of the order of  $\sim 50\%$  (number of detected sources normalized to the area of the *Chandra* error circle). No further object was detected in the *Chandra* circle down to a limiting  $K_s$  magnitude of about 22.5 (S/N  $\sim 1.5$ ). The colors of the IR source,  $H - K_s = 1.2$  and  $i - K_s > 3.5$ , are at variance with those of field stars that lie far from nearby stars in a color-color diagram. On the contrary, the IR colors are similar to those of other AXP counterparts. As an example, the persistent optical/IR emission of 4U 0142+614 has  $H - K_s = 1.1$  and  $I - K_s = 3.8$  colors (Hulleman, van Kerkwijk, & Kulkarni 2000; Israel et al. 2003), while the “outbursting” IR emission of 1E 1048.1–5937 has  $H - K_s = 1.4$  (Wang & Chakrabarty 2002; note, however, that the extinction in the direction of the three objects is different). These findings make the association of this object with XTE J1810–197 quite probable.

In order to further test the hypothesis of the AXP nature of XTE J1810–197, we studied the IR-to-X-ray spectrum. We retrieved the *XMM-Newton* archival data on XTE J1810–197 obtained on 2003 September 8 and extracted and fitted the European Photon Imaging pn Camera (EPIC-pn) spectrum by adopting the power law plus blackbody spectral model described by G04. We plot the IR/optical through X-ray data of XTE J1810–197 in Figure 2. A value of  $A_V = 5.9 \pm 0.3$  was used to infer the unabsorbed IR fluxes and their uncertainties [this was derived from the  $N_H$  inferred from the *XMM-Newton* spectra and  $A_V = N_H / (1.79 \times 10^{21} \text{ cm}^{-2})$ ; Predehl & Schmitt 1995]. Note that the count rate, and thus flux, of the second *Chandra* data set of XTE J1810–197 was nearly unchanged with respect to the previous *Chandra* and *XMM-Newton* observations; we are thus justified in combining the IR-to-X-ray measurements plotted in Figure 2 (we assumed that the spectral parameters did not change, as suggested also by the constant pulsed fraction level between the two *Chandra* observations). It is evident from Figure 2 that the  $F_X/F_{\text{IR}}$  ratio is larger than  $10^3$  and similar to those of other AXPs (for a comparison, see Fig. 2 of Israel et al. 2004; note, however, that the  $F_X/F_{\text{IR}}$  ratio is also consistent with that of low-mass X-ray binaries as in the case of all the other AXPs).

The relatively high pulsed fraction of XTE J1810–197 is not unusual for AXPs: in fact, 1E 1048.1–5937 has a higher pulsed fraction and in addition shows flux variability both in the X-ray and IR bands (Oosterbroek et al. 1998; Israel et al. 2002b). All the above findings and similarities with known members of the AXP class clearly indicate that XTE J1810–197 is an AXP, the one possessing the highest degree of X-ray flux variability seen so far (a factor of about 100 between quiescent and outburst peak fluxes). The candidate AXP AX J1844–0258 might be another example of variable/transient AXP (TAXP; Torii et al. 1998; Gotthelf & Vasisht 1998). However, AX J1844–0258 was caught in a high state only once and no  $P$  measurement is available in order to definitively assess the AXP nature of this source. We note that the quiescent *XMM-Newton* and *BeppoSAX* spectrum of AX J1844–0258 has a 0.5–10 keV absorbed flux of  $\sim 3 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$  (Israel et al. 2004), quite similar to that of XTE J1810–197 as seen by *ROSAT* in 1993 ( $\sim 5 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$ ; G04). In addition, as in the case of XTE J1810–197, no pulsations were detected for AX J1844–0258 in the quiescent phase (although poor statistics prevented setting any sensitive upper limit; G. L. Israel et al. 2004, in preparation).

Regardless of whether or not AX J1844–0258 is an AXP,

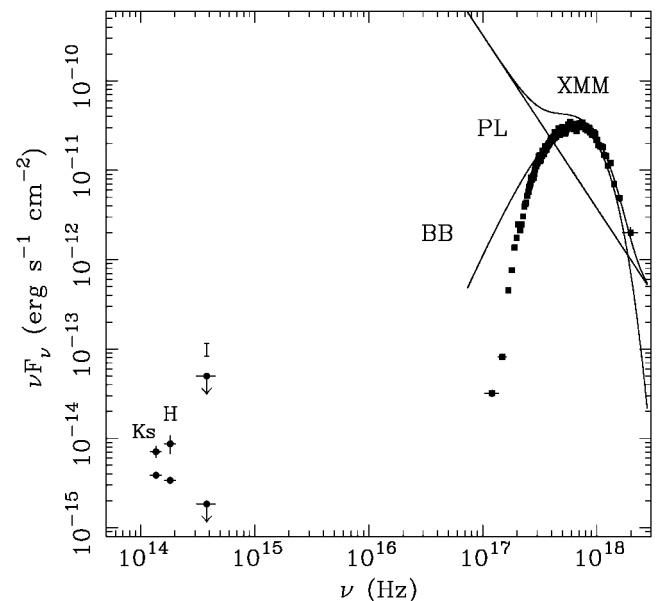


Fig. 2.—Broadband energy spectrum of XTE J1810–197. X-ray raw data are taken from the EPIC-pn instrument on board *XMM-Newton* (filled squares), while the solid upper curves are the unabsorbed fluxes for the blackbody (BB), the power law (PL), and the sum of the two components. On the lower left corner of the plot are the optical/IR fluxes/upper limits: lower points are absorbed values, while upper points are unabsorbed values for  $A_V = 5.9$ .

the existence of at least one TAXP clearly points to a larger number of hidden members of the AXP class in the Galaxy. As suggested by G04, some of them might be the radio-quiet X-ray unpulsed central compact objects (CCOs) found in an increasing number of supernova remnants. Other AXPs might spend a large fraction of the time in a quiescent state and therefore might remain unidentified as AXPs. There are at least two important new facts that should be taken into account in the comparison with models: (1) the X-ray flux variability of more than 2 orders of magnitude and (2) the nondetection of X-ray pulsations in the quiescent state of XTE J1810–197 during a 1996 *ROSAT* observation. Variations in the persistent X-ray emission are common in neutron stars accreting from a companion (White, Nagase, & Parmar 1995). The IR measurements presented in this Letter for XTE J1810–197 rule out any hypothetical main-sequence companion star from O to F spectral types and are comparable to those set for other, more “standard,” AXPs (Mereghetti, Israel, & Stella 1998; Wilson et al. 1999). However, a lighter companion cannot be ruled out (as in the case of all the other AXPs) and would imply an extremely small and virtually undetectable Doppler shift in the pulsations (similar, e.g., to the 42 minute orbital period binary system hosting the 7 s pulsar 4U 1626–67; Chakrabarty 1998).

If the two transient objects discovered so far do belong to the same class of SGRs and AXPs, then one would likely interpret the observations within the context of the magnetar model. The magnetar model as currently formulated does not make specific predictions for on/off states of the pulsars as well as for their IR fluxes. Variations in the quiescent emission have been observed following an X-ray burst in 1E 2259+586 (Woods et al. 2004). Soon after the burst, the persistent X-ray flux was a factor of about 20 higher, the temperature also higher, and the blackbody radius much smaller than in the low quiescent state. Some of the 1E 2259+586 properties in the quiescent emission before and after the burst are consistent (at least qualitatively) with the those of XTE J1810–197 in its low and high state. Moreover,

the slow decay of the “high-state” X-ray emission of XTE J1810–197 is found to be in the range of those of SGR 1627–41 and SGR 1900+14 (Ibrahim et al. 2004; Kouveliotou et al. 2003) for a power-law decay; therefore, we cannot rule out that XTE J1810–197 is an SGR. In this respect, we note that if XTE J1810–197 were proven to be an SGR, our proposed IR candidate would be the first ever for an SGR.

If XTE J1810–197 were an isolated object, then (a hypothetical) accretion would have to proceed through a fallback disk (Chatterjee, Hernquist, & Narayan 2000; Alpar 2001). While short-term, small-scale fluctuations are expected in this case, by analogy with most accreting neutron star systems, large-scale variations might require special conditions. In particular, as the object spins down, it might occasionally switch from a propeller phase to an accretion phase. During the propeller phase, accretion is inhibited, and the star should be bright in X-rays owing to its thermal emission. Indeed, in its low state, XTE J1810–197 had an X-ray luminosity of the order of a few times  $10^{33}d_5$  ergs  $s^{-1}$ , which is typical of other known thermal emitting sources (e.g., Becker & Trümper 1997). Moreover, in its low state, the pulsed fraction of XTE J1810–197 (if any) decreased considerably, suggesting emission from the whole surface of the star as expected in a cooling object (G04). Note that in a more general scenario, the CCOs would be AXPs in the above described state. If the high state is due to resumed accretion onto the magnetic poles, then larger pulsed fractions would be naturally explained. The accretion luminosity could be much higher than the thermal emission and would dominate the emitted spectrum. These properties appear consistent with those of XTE J1810–197, and the properties of the IR counterpart could be explained in terms of a fallback disk the size of approximately less than a few times

$10^{10}$  cm (using the spectral models of Perna, Hernquist, & Narayan 2000 and Perna & Hernquist 2000). However, the X-ray flux decay reported by Ibrahim et al. (2004) would be hardly accounted by the fallback model unless the accretion rate were decreasing very rapidly. Moreover, the above active phase is expected to occur just once in the AXP life (with a duration longer than the  $\sim 1$  yr observed in XTE J1810–197 and possibly AX J1844–0258; Chatterjee et al. 2000).

The pronounced long-term X-ray flux and pulsed fraction variability of XTE J1810–197 might be more easily explained in the framework of a pulsar in a binary system with a light companion. In fact, we note that the quiescent luminosity of XTE J1810–197 (and AX J1844–0258) is similar to that already observed from transient binary system pulsars (Campana et al. 2002), together with the pulsed fraction decrease in the on/off transitions (Campana et al. 2001). However, in the binary scenario, the short X-ray bursts displayed by AXPs and, especially, SGRs would be difficult to explain (see Mereghetti et al. 2002 for more details).

We thank Harvey Tananbaum for making the *Chandra* HRC-I observation possible through the *Chandra* Director’s Discretionary Time program and Michael Juda for help during the *Chandra* scheduling phase. We also thank the ESO Director’s Discretionary Time Committee for agreeing to extend our original program, allowing us to trigger the VLT observations, and Lowell Tacconi-Garman for his help and patience during the OB submission phase. This work is partially supported through ASI and Ministero dell’Università e Ricerca Scientifica e Tecnologica (MURST-COFIN) grants.

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