A&A 438, L1–L4 (2005)
DOI: 10.1051/0004-6361:200500138

Astronomy & Astrophysics

Discovery and monitoring of the likely IR counterpart of SGR 1806–20 during the 2004 γ-ray burst-active state★

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Received 7 April 2005 / Accepted 4 June 2005

Abstract. The sky region including the Chandra position of SGR 1806–20 was monitored in the IR band during 2004, following its increased high energy bursting activity. Observations were performed using NAOS-CONICA, the adaptive optics IR camera mounted on Yepun VLT, which provided images of unprecedented quality (*FWHM* better than 0.″1). After the 2004 December 27th giant flare, the source position has been nailed by VLA observations of its radio counterpart, reducing the positional uncertainty to 0.″04. Using IR data from our monitoring campaign, we discovered the likely IR counterpart to SGR 1806–20 based on positional coincidence with the Chandra and VLA uncertainty regions and flux variability of a factor of about 2 correlated with that at higher energies. We compare our findings with other isolated neutron star classes thought to be related, at some level, with SGRs.

Key words. pulsar: individual: SGR 1806–20 – stars: neutron – stars: imaging – infrared: stars – X-rays: stars

1. Introduction

Soft Gamma-ray Repeaters (SGRs) were discovered in the seventies through the detection of short (<1s), recurrent, and intense bursts of high energy emission peaked in the soft γ rays. Only four confirmed SGRs are known, three in the Galaxy and one in the Large Magellanic Cloud (for a review see e.g. Woods & Thompson 2004). The detection of a ~8 s periodicity in the decaying tail of a very intense (~10^{44} erg) and long (several minutes) event, known as giant flare, from SGR 0526–66 on 1979 March 5th (Mazets et al. 1979) suggested the association of SGRs with neutron stars. A small sample of peculiar X-ray pulsars, namely the Anomalous X-ray Pulsars (AXPs) has been proposed to be closely related to SGRs based on similar properties, namely their period P (in the 5–12 s range), their period derivative $\dot{P}$ (10^{-10}–10^{-13} s s^{-1} range), and X-ray bursts (Kouveliotou et al. 1998; Kaspi et al. 2003; Gavriil et al. 2002).

Both SGRs and AXPs have been proposed to be powered by the decay of strong magnetic fields that characterise these neutron stars ($B \sim 10^{14}$–10^{15} G; Duncan & Thompson 1992; Thompson & Duncan 1995). The "magnetar" model is founded on two observational facts: firstly, the rotational energy loss inferred from the SGR and AXP spin-down is insufficient to power their persistent X-ray luminosity of ~10^{34}–10^{36} erg s^{-1}; secondly, there is no evidence for a companion stars which could provide the mass to power the X-ray emission through accretion.

Bursting activity from SGR 1806–20 resumed at the end of 2003 displaying an increase in both the γ-ray burst rate and the hard X-ray persistent emission (Mereghetti et al. 2005a) throughout 2004, and culminating with the giant flare of 27th December 2004 (Borkowski et al. 2004), during which ~10^{47} erg were released (for a distance of about 10 kpc; Cameron et al. 2005; McClure-Griffiths & Gaensler 2005). Few days after this event, SGR 1806–20 was observed and detected in the radio band for the first time, providing very accurate positions (VLA; Cameron et al. 2005; Gaensler et al. 2005).

In this work we report on the results of an extended Target of Opportunity (ToO) observational campaign on SGR 1806–20 carried out during 2004 with the ESO VLT. In particular, we report on the likely discovery of the IR counterpart to SGR 1806–20 based on positional coincidence with the radio and Chandra positions and flux variability. (Preliminary

★ The results reported in this Letter are based on observations carried out at ESO, VLT, Chile (programs 072.D–0297, 073.D–0381 and 274.D–5018).

Table 1. Journal of the VLT NACO IR 2004 observations for the field of SGR 1806–20.

2004 Start UT (MM DD / HH : MM)	Filter	Exposure (s)	*FHWM* (″)	*K*s mag for object A
03 10 / 09 : 00	*K*s	1200	0.14	contaminated
03 17 / 08 : 14	*J*	1980	0.21	–
03 17 / 08 : 53	*K*s	1800	0.10	20.01 ± 0.14
03 17 / 09 : 33	*H*	1800	0.14	–
03 18 / 07 : 35	*K*s	3600	0.09	20.09 ± 0.15
06 13 / 03 : 38	*K*s	3600	0.11	20.26 ± 0.26
06 19 / 04 : 51	*K*s	6120	0.11	19.94 ± 0.13
08 10 / 02 : 50	*K*s	2640	0.12	contaminated
08 11 / 03 : 04	*K*s	5160	0.10	19.48 ± 0.12
09 07 / 23 : 56	*K*s	5240	0.09	19.70 ± 0.08
10 05 / 23 : 45	*K*s	5160	0.11	19.32 ± 0.16

results were reported in Israel et al. 2004, 2005a,b, before and independently from Kosugi et al. 2005). We briefly compare the IR emission properties of SGR 1806–20 with those of related objects.

2. NAOS-CONICA observations at VLT

The observations presented here were performed as part of an ESO Target of Opportunity program extending over October 2003–September 2004, and a Director Discretionary Time observation on October 2004. Observations were triggered following the detection of intense γ-ray bursts or during epochs of increased burst rate (Götz et al. 2004; Golenetskii et al. 2004a,b). The data were acquired at Yepun VLT with the Nasmyth Adaptive Optics System and the High Resolution Near IR Camera providing a pixel size of $0\farcs027$ (NAOS-CONICA; see Table 1 for details). For all observations we used an exposure time of 40 s and a number of frames per image of 3 with a random offset of 7″ among images in order to perform background subtraction of the variable IR sky. VLT NACO science images were reduced based on the standard tools provided by the ESO – Eclipse package (Devillard 1997). As a result of the presence of the *K*s = 8.9 mag object LBV 1806–20 (see Eikenberry et al. 2004) close to the edge of the NACO field of view (FOV), artificial ring-like ghost structures were clearly detected in the image at coordinates RA = $18^{h}08^{m}40\fs31$; Dec = $-20°24'41\farcs21$ (equinox 2000), 13″ away from the LBV 1806–20 position. In order to reduce as much as possible the effects of contamination due to nearby objects, relative aperture and Point Spread Function (PSF) photometry was obtained within narrow annuli (about 1–1.5 *FWHM* depending on the seeing conditions), while the background was evaluated close to the object under analysis. Absolute photometry was derived by analysis of the best seeing frames. Finally, we cross-checked our absolute magnitudes by means of archival ISAAC data of the same region and about 100 isolated stars taken from the 2MASS catalog and within the instrument FOV: the results were in agreement to within 0.05 *K*s magnitudes.

In order to register the Chandra and VLA coordinates of SGR 1806–20 on our IR images, we obtained the image astrometry by using the positions of about 10 stars selected from the 2MASS catalogs and within the ∼30″ × 30″ NACO FOV of final images. The residual in the fit was of $0\farcs06$ in each coordinate, converting to ∼$0\farcs1$ once the 2MASS absolute accuracy was included[1]. Figure 1 shows the ∼$1\farcs5 \times 1\farcs5$ *K*s band region around the Chandra and VLA positions (1σ confidence level radius of $0\farcs3$, $0\farcs04$, respectively; Kaplan et al. 2002; Gaensler et al. 2005). However, given that the Gaensler et al. (2005) radio position refers to about 20 days after the giant flare of SGR 1806–20, and that the source from which is originating the radio emission is moving at about 4 mas/day (Taylor et al. 2005), we also plot the VLA position obtained after 7 days by Cameron et al. (2005; 1σ radius if $0\farcs1$), corrected for about 30 mas in right ascension (following Taylor et al. 2005); this corresponds to a final 1σ confidence level radius of $0\farcs14$. Source *A*, a relatively faint (*K*s ∼ 20) object, at the sky position RA = $18^{h}08^{m}39\fs337$, Dec = $-20°24'39\farcs85$ (equinox 2000, 90% uncertainty of $0\farcs06$), is found to be consistent with the Chandra and VLA positional uncertainty circles superimposed on our IR astrometry-corrected frame. Objects *B* and *C* (∼$0\farcs23$ and $0\farcs27$ away from *A*, respectively; by looking at the contour lines, we note that object *B* might be the blend of two unresolved objects) are only marginally consistent with the X-ray and radio positions, even though statistically plausible. Object *A* was not detected in the *J* and *H* images; 3σ upper limits of magnitude 21.2 and 19.5 were derived, respectively. We note that the SGR 1806–20 IR counterpart *A* (*K*s magnitudes are listed in Table 1) plus objects *B* and *C* (*K*s = 19.07 ± 0.04 and 18.77 ± 0.04, respectively) are all within a radius of ∼$0\farcs25$ from the VLA positions, and consistent with being unresolved components of candidate *B* in the IR images of Eikenberry et al. (2001; *K* = 18.6 ± 1.0).

Light curves of the *A*, *B* and *C* objects marked in Fig. 1 are shown in Fig. 1 (right plot). Candidate *A* is the only one showing a clear brightening (a factor of ∼2) in the IR flux between June and October 2004. Objects *B* and *C* show a fairly constant flux[2]. The upper panel of Fig. 1 (right plot) shows the closest reference star ($1\farcs6$ away form the target) used for relative photometry across *K*s images: the object is constant to within the photometric uncertainties. We thus conclude that object *A* is variable. We checked for a similar variability also in the X-ray flux of SGR 1806–20. Both the XMM-Newton (Mereghetti et al. 2005b) and INTEGRAL (Mereghetti et al. 2005a) persistent fluxes of SGR 1806–20 showed an increase across the two semesters of 2004 by a factor of $1.94^{+0.01}_{-0.02}$ and $1.7^{+0.4}_{-0.3}$ in the 2–10 keV and 20–100 keV bands, respectively[3]. During the same time interval the NACO *K*s flux increased by a factor of $2.4^{+0.9}_{-0.5}$, consistent with high energy flux variations.

[1] http://www.ipac.caltech.edu/2mass/releases/allsky/doc

[2] For the faintest component of blended object B we can reasonably exclude any IR variability, similar to that shown by *A*, for any *K*s magnitude brighter than about 22.5.

[3] For the 2–10 keV 2004 first semester flux we assumed that of October 2003, based on the unvaried INTEGRAL flux between October 2003 and February–April 2004.

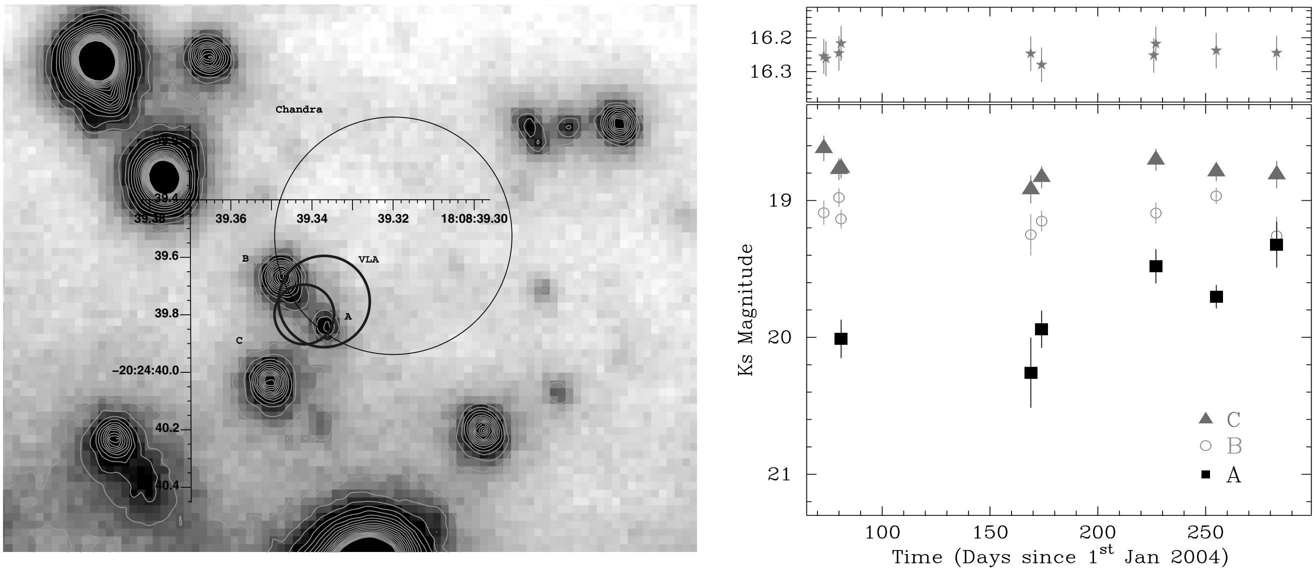

Fig. 1. IR NACO *K*s band image (*left panel*; 18th June 2004 dataset) close-up of the 1.″5 × 1.″5 portion of the sky around the 1σ Chandra and VLA uncertainty circles (radius of 0.″3, 0.″04 and 0.″1, respectively) with the proposed counterpart marked with A. Coordinates are RA (h m s) and Dec (° ′ ″; equinox J2000). Isophotal contour lines are also drawn for clarity. *K*s light curves (*right panel*) for a number of selected sources: the proposed counterpart to SGR 1806–20 (*A*) with two nearby objects (*lower panel*), and the closest reference (isolated and bright) star (*upper panel*) we used for relative photometry among *K*s frames. Flux variability is clearly detected only for object *A*.

This further supports the identification of object A as the correct IR counterpart of SGR 1806–20.

Recently, independent from our work, the object *A* has been proposed as the IR counterpart to SGR 1806–20 (Kosugi et al. 2005; their object *B*3). A comparison of their photometry with our shows that nearly all the *K*s magnitudes have an offset of about 0.2, with the important exception of objects *A* and *C* which are 1.6 and 0.6 *K*s magnitudes brighter than the corresponding objects *B*3 and *B*1 in Kosugi et al. (2005), respectively. Even though we do not have a clear explanation for the observed differences, we note that in our images we did not see any evidence for (i) a brightening of objects *B* and *C*, and (ii) an increase of the local background around object *A* (based on our best datasets with $FWHM \leq 0.''1$), in contrast to Kosugi et al. (2005). An unusually high background level (regardless of its origin) may of course result in a flux underestimation of a source that lies in the same area.

3. Discussion

The deep and high spatial resolution NACO images allowed us to identify the likely IR counterpart of SGR 1806–20, and monitor its IR flux for seven months in 2004, during which an increase by a factor of ~2 was detected, correlated with the flux in the high energy bands. In fact, the IR flux of SGR 1806–20 was fairly constant until mid-June 2004, while it grew rapidly between June ($Ks = 20.01 \pm 0.14$) and October 2004 ($Ks = 19.32 \pm 0.16$; 1σ uncertainties; these values override the preliminary ones reported in Israel et al. 2005b).

IR variability has been detected in nearly all AXPs with known IR counterpart. In particular, for 1E 1048.1−5937, XTE J1810−197 and 1E 2259+586, IR variability has been found, or suspected, to be correlated with the persistent X-ray emission (Israel et al. 2002; Rea et al. 2004; Tam et al. 2004). Based on the NACO results we can conclude that the IR/X-ray correlation observed in AXPs also holds for SGR 1806–20. The total fluence of the IR enhancement between June and October 2004 is about 10^{41} erg (we assumed $A_V = 29 \pm 2$; see Eikenberry et al. 2004), a factor of about 100 smaller than that in the 2–10 keV band.

Based on the above reported findings we note that the SGR 1806–20 emission varies in a similar fashion (in terms of timescale and amplitude of variation) over more than five orders of magnitude in photon energy. The similar flux variation in the IR and X-ray bands suggests that the emission in the two bands has a similar, if not the same, origin. Moreover, it has become evident that X-ray flux enhancement of the persistent emission of SGRs is correlated with their burst rate, making it difficult to compare the fluxes among different SGRs without knowing their burst history (see Woods & Thompson 2004). Tam et al. (2004) argued that IR thermal surface emission (within the magnetar model) is ruled out during the correlated X-ray/IR flux decay phases of 1E 2259+586 (implausibly high implied brightness temperature), suggesting the magnetospheric origin for the IR enhancement. Alternatively, the IR flux can be due to reradiation by material in the vicinity of the the pulsar. This model naturally predicts a correlation between the the IR and the X-ray flux (Perna et al. 2000; Rea et al. 2004).

This is the first time that the broad band energy properties of an SGR can be compared, over a similar energy band, with those of other classes of isolated neutron stars, such as AXPs and radio pulsars. In Fig. 2 we show the "nearly simultaneous" broad band energy spectrum of SGR 1806–20 from the IR to γ rays (high energy data are taken form Mereghetti et al. 2005a; see caption for details). The high energy part of

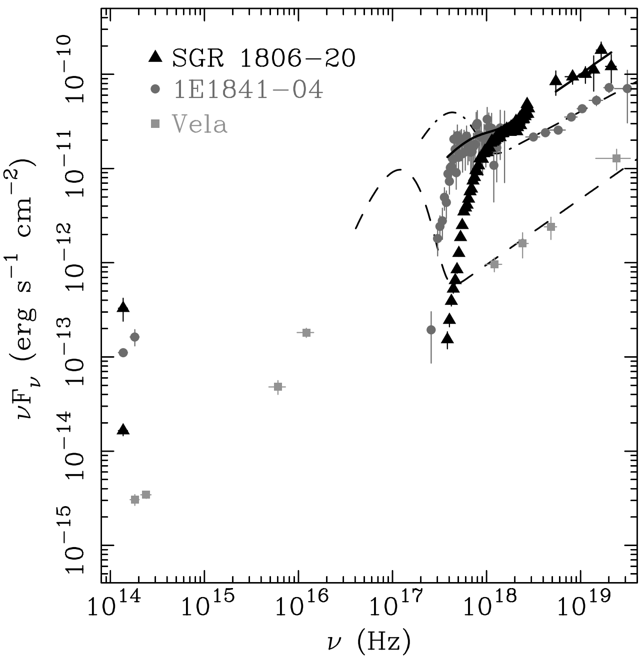

Fig. 2. Broad band energy spectrum of SGR 1806–20 (triangles) and, as a comparison, the AXP 1E 1841−045 (circles) and the radio pulsar Vela (squares). In the case of SGR 1806–20 and 1E 1841−045 high energy data are taken from XMM-Newton (Mereghetti et al. 2005b; referring to 6th October 2004 for SGR 1806–20), Chandra (for 1E 1841−045) and INTEGRAL (Mereghetti et al. 2005a; 21st September–14th October 2004 for SGR 1806–20). Absorbed and unabsorbed IR fluxes (A_V = 29±2, 5th October 2004 NACO observation) are shown in the case of SGR 1806–20, unabsorbed (A_V = 13 ± 1) IR fluxes are instead reported for the likely candidate of 1E 1841−045 (circles; Israel et al. 2005, in preparation). All the data for Vela are taken form literature (Kaspi et al. 2004, and references therein). Solid curves (continuous, stepped and dot-stepped) are the unabsorbed fluxes for the black body plus power law model used to fit the high energy part of spectra.

the spectrum is clearly consistent with being non-thermal emission (a power-law model is generally used) from the source. We also plot the spectrum from the AXP 1E 1841−045, for which 20–200 keV band data are available (Kuiper et al. 2004); a similar non-thermal component is displayed by the source. Non-thermal components are also seen in radio pulsars and modelled with power-law components (see Kaspi et al. 2004, for a recent review). In some cases there is a smooth connection between optical, X-rays and γ-ray emission (Crab), while in other cases the extrapolation is plausible (Vela; see Fig. 2). It is worth noting the similar flux ratios in the IR and hard X-ray bands for the three objects, and the significant difference of the characteristic temperature of thermal soft X-ray components between radio pulsars (≤0.1 keV) and SGRs/AXPs (0.4–0.8 keV for a BB fit and 0.2–0.5 keV for a magnetic atmosphere fit, Perna et al. 2001), suggesting a significantly larger energy injection on the neutron star surface in "magnetar" candidates than in radio pulsars.

Future detailed multi-wavelength observations campaigns of AXPs and SGRs will likely help clarifying the link between IR and high energy bands. Furthermore, the detection of the quiescent IR flux level of SGR 1806–20 will allow to compare the net energy released by the source in the IR and X-ray/γ-ray bands during its bursting active phase.

Acknowledgements. We thank the ESO Director's Discretionary Time Committee for accepting the observation of SGR 1806–20 few hours after the 5th October 2004 intense X-ray burst. We are also indebted with VLT personnel for their continuous help in optimising and performing the NACO observations. We thanks D. Dobrzycka and W. Hummel for their help in clarifying the artificial nature of the rings in the NACO images. This work was partially supported through Agenzia Spaziale Italiana (ASI), Ministero dell'Istruzione, Università e Ricerca Scientifica e Tecnologica (MIUR – COFIN), and Istituto Nazionale di Astrofisica (INAF) grants. N.R. is supported by a Marie Curie Training Grant (HPMT-CT-2001-00245).

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