A search for the optical/infrared counterpart of the anomalous X-ray pulsar 1E 1841–045

S. Mereghetti,1 R. P. Mignani,2 S. Covino,3 S. Chaty,4 G. L. Israel,5† R. Neuhäuser,6 H. Plana7 and L. Stella5†

1Istituto di Fisica Cosmica del CNR, Via Bassini 15, I-20133 Milano, Italy
2ESO, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany
3Osservatorio Astronomico di Merate, v. E. Bianchi 46, I-22055 Merate (LC), Italy
4Department of Physics and Astronomy, The Open University, Walton Hall, Milton Keynes MK7 6AA
5Osservatorio Astronomico di Roma, Via Frascati 23, I-00040 Monteporzio Catone (Roma), Italy
6MPI Extraterrestrische Physik, D-85740 Garching, Germany
7Observatorio Astronómico Nacional, Apartado Postal 877, 22800 Ensenada, BC, México

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ABSTRACT
We have carried out a search for the optical and infrared counterpart of the anomalous X-ray pulsar 1E 1841–045, which is located at the centre of the supernova remnant Kes 73. We present the first deep optical and infrared images of the field of 1E 1841–045, as well as optical spectroscopy results that exclude the brightest objects in the error circle as possible counterparts. A few of the more reddened objects in this region can be considered as particularly interesting candidates, in consideration of the distance and absorption expected from the association with Kes 73. The strong interstellar absorption in the direction of the source does not allow us to exclude completely the presence of main-sequence massive companions.

Key words: pulsars: individual: 1E 1841–045 – X-rays: stars.

1 INTRODUCTION
The X-ray source 1E 1841–045 was discovered with the Einstein Observatory in 1979 (Kriss et al. 1985) at the centre of the supernova remnant Kes 73 (G27.4±0.0), and studied in more detail with ROSAT (Helfand et al. 1994). Kes 73 is a young supernova remnant that shows a shell morphology in the radio band, without any evidence for a central synchrotron nebula originating from a rotation-powered pulsar. The most likely interpretation for 1E 1841–045, on the basis of these earlier observations, was that of an accretion-powered system.

Recent data obtained with ASCA led to the discovery of a periodicity at 11.8 s and a period derivative of $4 \times 10^{-11} \text{s}^{-1}$ (Vasisht & Gotthelf 1997). The corresponding characteristic age $\tau = P/2P \sim 4700 \text{yr}$ is consistent with that of Kes 73, thus strengthening the association. The X-ray spectrum of 1E 1841–045 is very soft (power-law photon index $\sim 3.4$), and its luminosity has remained remarkably constant at a level of $\sim 3 \times 10^{35} \text{erg s}^{-1}$ (for $d = 7 \text{kpc}$) during all the observations carried out till now (Gotthelf, Vasisht & Dotani 1999).

On the basis of these observational properties, 1E 1841–045 can be included in the class of anomalous X-ray pulsars (AXPs, Mereghetti & Stella 1995). These pulsars, while clearly not powered by the rotational energy losses, are characterized by soft spectra, periods in a narrow range (6–12 s), secular spin-down, absence of massive companions and no radio emission (see Mereghetti 2000 for a review). Three of the six known AXPs are associated with supernova remnants (SNRs).

The AXPs are clearly very different from the more common accreting X-ray pulsars usually found in high-mass X-ray binaries, and their nature is still uncertain. Several models (involving both binary systems and isolated objects) have been proposed, but up to now the only reasonably well-established fact is that AXPs are yet another manifestation of neutron stars.

Here we report a study of the possible counterparts of 1E 1841–045 based on deep optical and infrared observations of its small error region.

2 OBSERVATIONS
Several observations of the field of 1E 1841–045 were carried out using different European Southern Observatory (ESO) telescopes at La Silla from 1993 to 1999. Table 1 gives a log of the observations that are described in more detail in the following subsections.

2.1 Optical imaging
Images in the V and R filters were obtained with the 3.5-m NTT in...
1993 June, using the first generation of the ESO Multi Mode Instrument (EMMI) operated in imaging mode with the red-sensitive CCD. The detector, a 2048 × 2048 Loral/Lesser (ESO CCD No. 40) with a pixel size of 0.35 arcsec.

The field of 1E 1841–045 was observed in the Bessel filter using ESO/MIDAS 98NOV version. Calibration was performed by standard stars observed, as far as possible, in the same condition of the scientific frame. While the relative magnitude values from these data are quite accurate (~0.01–0.02 mag), it was not possible to derive a precise absolute calibration because most of the observations were carried out in non-photometric conditions. Therefore, in order to obtain the absolute calibration, we reobserbed the field in the $B$, $V$ and $R$ filters under photometric conditions using the 1.5-m telescope of the Observatorio Astronómico Nacional at San Pedro Mártir (Baja California, Mexico) equipped with a 1024 × 1024 CCD detector with a pixel scale of 0.24 arcsec pixel$^{-1}$. This allowed us to obtain the results summarized in Table 2. The Gunn $r$ photometry was calibrated by means of a standard star observed in the $R$ band and the average relations between $tegr$ and UBVR systems (Kent 1985).

### 2.2 Infrared imaging

Near-infrared observations have been carried out at the New Technology Telescope (NTT) using Son of Isaac (SOFI). The SOFI instrument is an infrared spectrograph and imaging camera with a HgCdTe 1024 × 1024 array and a pixel size of 18.5 $\mu$m. The camera was operated with a f.o.v. of 4.94 × 4.94 arcmin$^2$ and a corresponding pixel scale of 0.292 arcsec. Images have been taken through the wide-band $J$ ($\lambda = 1.247 \mu$m; $\Delta\lambda = 0.290 \mu$m) and $K_s$ ($\lambda = 2.162 \mu$m; $\Delta\lambda = 0.275 \mu$m) filters with exposure times of 60$s$. The typical seeing for these observations was ~0.7 arcsec. After taking each image of the object, an image of the sky was acquired, to permit the subtraction of the sky. The images were further treated by removal of the dark current, flat field and bright infrared sky.

### 2.3 Optical spectroscopy

Spectroscopy of the brightest candidate counterparts (objects A and B) was obtained at the 1.5-m ESO spectrographic telescope during 1998 July, using a B&C Spectrograph. The exposure time was 20 min; the slit width was 2 arcsec. The spectra covered the wavelength range 4000–8000 Å with a resolution of ~10 Å (FWHM). Spectra were flux-calibrated under non-photometric conditions, so that just the relative intensities are reliable.

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Figure 1. $R$-band image of the field of 1E 1841–045 obtained with the NTT/EMMI in 1993. Here and in the following images North is to the top and East to the left. The two error circles have radii of 3 arcsec.

Figure 2. Deep $R$-band image of the same field shown in Fig. 1. The colour scale has been stretched to show the faintest stars better.
3 RESULTS

An $R$-band image of the field of 1E 1841–045 is shown in Fig. 1. The two error circles are centred at the positions obtained with the ROSAT HRI, RA = 18$^\mathrm{h}$41$^\mathrm{m}$19$^\mathrm{s}$2, Dec. = −04$^\circ$56′12″5′′ (J2000, Helfand et al. 1994) and with the Einstein HRI, RA = 18$^\mathrm{h}$41$^\mathrm{m}$19$^\mathrm{s}$0, Dec. = −04$^\circ$56′08″9′′ (J2000, Kriss et al. 1985). Both positions were reported with uncertainties of 3 arcsec, but possible errors in the boresight of the satellites cannot be excluded. For this reason we considered all the objects within ~10 arcsec from the nominal positions. Our astrometry, computed with the astrom software (Wallace 1990) on a short-exposure EMMI image by using as a reference a set of stars from the DSS2, has an overall accuracy of ~1 arcsec.

Several objects are present within or close to the error circles. Their magnitudes are reported in Table 2. A deeper image is shown in Fig. 2.

The spectra for the brightest objects, B and A, are shown in Fig. 3. Classification was performed by comparison with the spectral library of Silva & Cornell (1992). Based on this we classify star B as a F6–7 III and star A as A5–8 V. Both spectra are quite reddened. From the equivalent width (EW) of the Na I lines, we can estimate an interstellar absorption larger than $A_V > 1.5$ for both stars (Munari & Zwitter 1997).

The infrared image in the $K_s$ band is shown in Fig. 4. Thanks to the less severe absorption at long wavelengths, these data give the deeper view of the region, revealing several objects undetected in the visible band.

4 DISCUSSION

The distance of Kes 73 was determined by means of the 21-cm absorption measurements by Sanbonmatsu & Helfand (1992), who obtained a value of 6–7.5 kpc. These authors also estimated an $\mathrm{H}_1$ column density to the source of $\sim 5 \times 10^{21}$ cm$^{-2}$. The equivalent hydrogen column density obtained from X-ray spectral fits of 1E 1841–045 and Kes 73 is in the $\sim 1.5–3 \times 10^{22}$ cm$^{-2}$ range (Gotthelf & Vasisht 1997). It is thus clear that we can expect a significant reddening for the optical counterpart of 1E 1841–045. For instance assuming $N_{\mathrm{H}} = 2 \times 10^{22}$ cm$^{-2}$ and using the average relation $N_{\mathrm{H}} = 1.79 \times 10^{21} A_V$ cm$^{-2}$ (Predehl & Schmitt 1995) we expect $A_V \sim 11$ (note however that there is a large scatter around the above average relation).

The two brightest objects we studied (A and B) are normal stars...
without any distinctive feature in their spectra that might suggest an association with an X-ray pulsar. Their magnitudes and colours also indicate a relatively small distance of $\sim 3$ kpc.

The colour-magnitude diagram based on the $V$ and $R$ NTT observations is shown in Fig. 5. The circles indicate the objects within or close to the error regions; their magnitudes are given in Table 2. None of these objects possesses especially unusual colours. The $V - R$ colour–magnitude diagram, which shows a clearly defined sequence, is very similar to that of a star cluster, indicating that most of the stars that we observed have similar distance and reddening.

The possible presence of a star cluster would be particularly interesting; however, a more likely explanation is that we are looking at stars belonging to one of the spiral arms of our Galaxy. In fact, the line of sight toward Kes 73 intercepts Arm 3 at $\sim 2.5$–3 kpc (see, e.g., Taylor & Cordes 1993) and then is almost tangential to Arm 2 for distances between $\sim 5$ and $\sim 8$ kpc. For comparison, the line corresponding to a main sequence with a value of reddening of 2.5 and distance 2.5 kpc is also plotted in Fig. 5. It is clear that most of the points in the diagram correspond to stars in the spiral arm at $\sim 2.5$–3 kpc, while only a few farther objects are visible owing to the strong reddening in the Galactic plane. Therefore, if we trust the association between 1E 1841–045 and the SNR at $d = 7$ kpc, most of the objects seen in the optical images are likely foreground stars much closer than Kes 73.

The presence of a large number of stars with similar values of distance and reddening is also evident from the IR colour–magnitude plot shown in Fig. 6. Here objects consistent with a red giant branch are also visible, as well as many other more distant and/or reddened stars that are not seen in the optical bands. The objects within or close to the error boxes of 1E 1841–045 are indicated with diamonds. Three of them are very reddened (G, 5 and 19), with colours not compatible with main-sequence stars. They are probably very distant giant or supergiant stars. In particular, while stars G and 5 are quite distant from the error regions of 1E 1841–045, star 19 should be considered as a potentially interesting candidate counterpart.

Many accreting pulsars have supergiant OB companions. However, the IR magnitudes of object 19 does not support an early-type star. OB supergiants have typically $J - K$ in the $-0.2$ to $0.1$ range (Johnson 1966; Ruelas-Mayorga 1991) therefore a very high absorption ($A_v \approx 25–30$) is required by the observed value of $(J - K) = 5.24 \pm 0.12$, as well as a distance placing it at the edge of the Galaxy, well beyond Kes 73. The possibility of a

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Optical colour–magnitude diagram for the stars in a $3\text{arcmin} \times 3\text{arcmin}$ field around the position of 1E 1841-045. The circles mark the stars within or close to the error circles. Note that the stars brighter than $R \sim 18$ are partly saturated, and their profile-fitted magnitudes are to be considered cautiously. A Pop.I MS at 2.5 kpc and with a reddening $A_V \sim 2.5$ gives a good fit of the data, in agreement with the spectroscopic estimate for star A. The segment in the upper right corner indicates the direction of reddening (the length corresponds to $A_v = 1$ mag).

![Figure 6](https://example.com/figure6.png)

**Figure 6.** IR colour–magnitude diagram for the stars in the region of 1E 1841–045. The expected positions for main-sequence stars (full lines) and red giants (dashed lines) for selected values of the distance and reddening are also indicated. The diamonds mark objects close to or within the 1E 1841-045 error boxes. The segment in the upper right corner indicates the effect of reddening resulting from $A_v = 10$ mag.

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Be system seems also unlikely: though a smaller distance is allowed (e.g. $\sim 10\,\text{kpc}$ for a B5) still a very large $A_V$ would be required (of course, a smaller $A_V$ could be assumed in the presence of substantial IR emission from circumstellar dust). A more plausible explanation for star 19 is that of a very reddened giant at $d \approx 8\,\text{kpc}$.

Some models for AXPs involve isolated neutron stars accreting from residual discs (van Paradijs, Taam & van den Heuvel 1995; Ghosh, Angelini & White 1997; Chatterjee, Hernquist & Narayan 1999). Although it is unclear whether such discs can actually be formed (e.g. in the evolution of Thorne–Zytkow objects or as a result of material fallback after a supernova explosion), and whether they can explain all the observed properties of the AXP, Perna, Hernquist & Narayan (2000) made some predictions on the emitted optical and IR spectra. Very different optical and IR colours can be obtained by the models presented by these authors, as a function, e.g., of the neutron star age and magnetic field, inclination and mass of the disc, importance of re-irradiation of the pulsar X-ray flux, etc. Therefore it is not surprising that the current data neither support nor weaken such models. For instance, the values $K \sim 17$ and $V \sim 28$ predicted by Perna et al. for 1E 1841–045 assuming an age of $\sim 4000\,\text{yr}$, $B = 8 \times 10^{12}\,\text{G}$, a disc mass of $0.005\,\text{M}_\odot$ and an inclination of $60^\circ$ are consistent with several of the objects visible in our IR data and below the detection threshold in the optical.

5 CONCLUSIONS

The optical limits on the possible counterparts of other AXPs have allowed us to rule out the presence of a (non-degenerate) massive companion (see Mereghetti 2000 and references therein). Unfortunately, we cannot do the same yet for 1E 1841–045, based on the observations presented here. However, an OB supergiant companion seems unlikely, as it requires values of the distance and/or absorption much in excess of those estimated for 1E 1841–045 to be compatible with the objects we found. Massive main-sequence stars cannot be excluded. For instance a B5 star at $\sim 7\,\text{kpc}$ and with $A_V \sim 8$ would have $J$ and $K$ magnitudes fully consistent with e.g. those of star H. Although the optical and IR data cannot exclude the possibility that 1E 1841–045 is a Be binary, its X-ray properties are very different from those of such a class of sources, which are characterized by hard X-ray spectra, significant variability and erratic long-term evolution in the spin period.

None of the objects we studied has peculiar characteristics that might suggest a possible connection with 1E 1841–045. However, if this source is indeed associated with Kes 73 and therefore subject to a significant reddening, we have discovered within its error region a promising candidate (star 19) deserving further spectroscopic study. We expect that the data presented here will represent a useful reference to facilitate the identification task, once the positional accuracy of 1E 1841–045 is much improved by observations with the new generation X-ray satellites Chandra and Newton XMM.

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