The energy source of the anomalous X-ray pulsars (AXPs) is not well understood, hence their designation as anomalous. Unlike binary X-ray pulsars, no companions are seen, so the energy cannot be supplied by accretion of matter from a companion star. The loss of rotational energy, which powers radio pulsars, is insufficient to power AXPs. Two models are generally considered: accretion from a large disk left over from the birth process, or decay of a very strong magnetic field ($10^{15}$ G) associated with a magnetar. The lack of counterparts at other wavelengths has hampered progress, in our understanding of these objects. Here, we present deep optical observations of the field around 4U 0142+61, which is the brightest AXP in X-rays. The source has no associated supernova remnant, which, together with its spin-down time scale of $\approx 10^5$ yr (ref. 5), suggests that it may be relatively old. We find an object with peculiar optical colours at the position of the X-ray source, and argue that it is the optical counterpart. The optical emission is too faint to admit the presence of a large accretion disk, but may be consistent with magnetospheric emission from a magnetar.

The field around 4U 0142+61 was imaged in the V, R and I bands on 31 October 1994 using the Low-Resolution Imaging Spectrometer on the 10-m Keck I telescope on Mauna Kea, and in R and I on 6 September 1999 on the Keck II telescope. In 1994, the sky was not photometric and the seeing mediocre at 1 arcsec, but in 1999 the sky was photometric and the seeing 0.6 arcsec. Photometric
calibration was achieved with images obtained under photometric conditions on 23 July 2000 at the 60-inch telescope on Palomar Mountain.

Within the error circles of 4U 0142+61 (Figure 1), we find one faint stellar object with unusual colours (Figure 2). To understand its nature, and its relation to 4U 0142+61, we need to constrain the run of reddening with distance along the line of sight. We use two open clusters in this region of sky\(^7\) – NGC 654 (at an angular offset of 17\(^\prime\), distance of 2.7 ± 0.4 kpc and reddening \(A_V = 2.3 \div 3.4\)) and NGC 663 (30\(\prime\), 2.8 ± 0.4 kpc, 2.2 \(\div\) 3.1) – to infer that \(A_V \simeq 2.7\) at \(d = 2.7\) kpc. Furthermore, we use the bluest galaxy in our field (object G), with \(R = 25.6\), \(R - I = 1.3\). Because the intrinsic colour\(^8\) is unlikely to be bluer than \((R - I)_0 = 0.3\), the total Galactic reddening along this line of sight is constrained by \(E_{R-I} \lesssim 1.1\), or equivalently \(A_V \lesssim 5\).

From Figure 2, we see that most stars have brightnesses and colours consistent with those expected for low-mass stars at distances similar to the open clusters. Star A, however, is either too dim or too blue. It might be bluer because it is nearer and therefore less reddened. But then it would be too dim to be a main sequence star and too red to be a white dwarf. The latter can be seen by comparison to star D, which is probably a foreground white dwarf (Figure 2).

We proceed to estimate the temperature \(T\) and radius \(R\) of star A on the assumption that the object is located beyond the open clusters (i.e., \(d > 2.7\) kpc; 2.7 \(\lesssim\) \(A_V \lesssim 5\)); below we use \(d_5\), the distance normalized to 5 kpc. Bearing in mind the intrinsic variability in the shape of the reddening curve,\(^9\) we find a marginal fit for \(T \simeq 6000\) K and \(R \simeq 0.11d_5 R_\odot\) (\(A_V = 2.7\)), where \(R_\odot\) is the Sun’s radius; and increasingly better fits for \(T \simeq 10^4\) K and \(R \simeq 0.08d_5 R_\odot\) (\(A_V \simeq 4\)) up to \(T \gtrsim 10^5\) K and \(R \simeq 0.022d_5(T/10^5\) K\(^{-1/2}\) \(R_\odot\) (\(A_V \simeq 5.4\)). We note that for \(T \gtrsim 10^5\) K the optical bands fall in the Rayleigh Jeans tail and the colours do not vary with \(T\) any more. Because temperature and reddening compensate each other, the above scaling in the Rayleigh-Jeans limit actually holds to within 10% for any \(T \gtrsim 6000\) K.

For all temperatures, the radii are too small for star A to be a normal star within our Galaxy. The remaining possibility is that star A is a reddened but hot \((T \simeq 5 \times 10^5d_5^2\) K) white dwarf. This is extremely unlikely unless it is actually 4U 0142+61 itself, as we discuss below.

From the above, we conclude that in all likelihood star A is the optical counterpart to 4U 0142+61. Below, we discuss our observations in the framework of the models that have been proposed for AXPs. The optical extinction \(A_V\) to 4U 0142+61 is between 2.7 and 5.4 mag, as estimated from the X-ray
dust scattering halo and absorption column density, respectively\textsuperscript{10,11} (where the latter is likely the more reliable\textsuperscript{10}); therefore, the source must be at a distance exceeding $\sim 2.7$ kpc.

We first consider the possibility that AXPs are isolated neutron stars accreting matter from a disk, presumably composed of supernova debris.\textsuperscript{2,3} In this model, the optical emission arises in the accretion disk, mostly due to reprocessing of the X-ray irradiation\textsuperscript{12} (Figure 3). The isotropic X-ray luminosity of 4U 0142+61 is $L_X = 4\pi d^2 f_{\text{unabs}}^X = 1.8 \times 10^{36} d_5^3 \text{erg s}^{-1}$, where $f_{\text{unabs}}^X$ is the flux in the energy range 0.5–10 keV after correction for interstellar absorption (see Table 1). We can estimate the run of temperature with disk radius\textsuperscript{13} $r$ by $T(r) \simeq 5000 (f/0.25)^{2/7} d_5^{4/7} (r/R_\odot)^{-3/7} {\text{K}}$. Here, the factor $f$ parametrizes uncertainties in vertical disk structure and the fraction of impinging X-ray emission reflected by the disk.

The flux at a given frequency and for given inclination is obtained by integrating the emission from the accretion disk (assumed to be optically thick) from an inner radius, $r_{\text{in}}$, to an outer radius, $r_{\text{out}}$; see ref. 12 and Figure 3. For a simple estimate, we use that the optical flux will arise predominantly at those radii at which the emission peaks in the optical band, i.e., where $T \simeq 5000 \text{K}$. For 4U 0142+61, this would be at $r \simeq 1(f/0.25)^{2/3} d_5^{4/3} R_\odot$, which is much larger than the limit of $R \simeq 0.11 d_5 R_\odot$ derived above, and leads to a brightness much larger than observed (see Figure 3). Thus, this model is excluded.

The optical emission from the disk can be reduced by appealing to a larger $r_{\text{in}}$ or a smaller $r_{\text{out}}$. The former, suggested\textsuperscript{12} in the context of earlier limits,\textsuperscript{14} would result in extremely red emission (because of the absence of the hotter inner region). This is incompatible with the observations.

A reduced $r_{\text{out}}$ would follow naturally in a model less often considered, in which the AXPs are compact binaries.\textsuperscript{15} We find that our observations require $r_{\text{out}} \simeq 0.05 d_5^{10/11} (f/0.25)^{-2/11} R_\odot$; see Figure 3. This is very small, but not unprecedented: the X-ray binary with the tightest known orbit,\textsuperscript{16} 4U 1820–30 (an 11 min orbital period) has a similarly small radius and similarly high ratio of X-ray to optical flux; see Table 1. However, the X-ray spectrum of 4U 0142+61 is rather different from that of 4U 1820–30 and other accreting sources. Furthermore, such compact binaries are not expected to be associated preferentially with supernova remnants. Thus, we consider this model unlikely.

As mentioned, the optical data are consistent with a hot white dwarf. This would be expected in another model rarely considered, in which AXPs are massive and magnetized ($10^8$ G) white dwarfs
rotating on the verge of breakup, presumably formed in the merger of two ordinary, approximately 
0.6 \( M_\odot \) white dwarfs.\(^\text{17} \) In this model, the ultimate source of energy, as in radio pulsars, is rotation. 
For 4U 0142+61, the inferred rotational energy loss, \(-\dot{E}_{\text{rot}} = 4\pi^2 I \dot{P}/P^3 \approx 10^{37} \text{erg s}^{-1} \), is clearly sufficient to account for the X-ray luminosity; here, \( I = k M R^2 \approx 10^{60} \text{g cm}^2 \) is the moment of inertia appropriate for a hot white dwarf with mass \( M \approx 1.3 \ M_\odot \), radius \( R \approx 0.007 \ R_\odot \) and gyration constant \( k \approx 0.14 \). \( P \) is the spin period and \( \dot{P} \) its derivative. If some fraction \( \beta \) of \( \dot{E}_{\text{rot}} \) goes into heating, as might result if the white dwarf rotated differentially, we expect a surface luminosity 
\( L = 4\pi R^2 \sigma T^4 = -\beta \dot{E}_{\text{rot}} \), and thus a surface temperature 
\( T \approx 4 \times 10^5 (\beta/0.5)^{1/4} (k/0.14)^{1/4} (M/1.3 \ M_\odot)^{1/4} \text{K} \) (we note 
that \( T \) does not depend on \( R \)). This is sufficient to produce the optical emission for a source at 
\( d_5 = 0.6(R/0.007 \ R_\odot) \) (see Figure 3). We note that a possible descendant may already have been 
identified\(^\text{18} \): the 1.3 \( M_\odot \) white dwarf RE J0317−853 with \( P = 725 \text{ s} \), \( B \approx 5 \times 10^8 \text{ G} \), and a cooling age of a few \( 10^8 \) yr. In this model, however, what mechanism may cause the X-ray spectrum is unclear, 
the thermal emission being far too soft (see Figure 3). Furthermore, the association of other AXPs 
with supernova remnants again seems puzzling.

This leaves us with the magnetar model,\(^\text{4} \) in which both the power law component of the X-ray 
emission and the optical emission would be of magnetospheric origin. Unfortunately, there are no 
detailed models. Radio pulsars with X-ray and optical detections have rather smaller \( f_X/f_{\text{opt}} \) (see 
Table 1), but their X-ray spectra are unlike those of AXPs. From Figure 3, it appears that the 
simplest spectral energy distribution would be obtained if the extinction were near the high end 
\( (A_V \gtrsim 5) \), so that the emission could peak at a few \( 10^{16} \text{ Hz} \) (\( \sim 100 \text{ eV} \)) and be like a power law 
\( f_\nu \propto \nu^\alpha \) with index \( \alpha \approx 2 \) (or even 2.5) in the optical. This could arise if the magnetospheric 
emission is self-absorbed at optical frequencies. A possible problem for the magnetar model is the 
lack of X-ray emission from the one radio pulsar with similar \( P \) and \( \dot{P} \) (ref. 19). However, it may 
well be that, \( P \) and \( \dot{P} \) are not reliable measures of the strength of magnetic fields for AXPs and that 
other properties determine whether a source is an AXP.

In spite of the current uncertainties, the optical identification offer us new insights into these 
enigmatic objects and motivates new observations and searches for optical pulsations.
1. Mereghetti, S. in Proc. NATO ASI School “The neutron star - black hole connection” (eds Kouveliotou, C., van Paradijs, J. & Ventura, J.) in press (Kluwer Academic Publishers, Dordrecht, 1999). (astro-ph/9911252).

2. Marsden, D., Lingenfelter, R. E., Rothschild, R. E. & Higdon, J. C. Nature vs. nurture: The origin of soft gamma-ray repeaters and anomalous X-ray pulsars. Astrophys. J. , submitted (1999). (astro-ph/9912207).

3. Chatterjee, P., Hernquist, L. & Narayan, R. An accretion model for anomalous X-ray pulsars. Astrophys. J. 534, 373–379 (2000).

4. Thompson, C. & Duncan, R. C. The soft gamma repeaters as very strongly magnetized neutron stars. II. Quiescent neutrino, X-ray, and alfven wave emission. Astrophys. J. 473, 322–342 (1996).

5. Wilson, C. A., Dieters, S., Finger, M. H., Scott, D. M. & van Paradijs, J. Rossi X-ray timing explorer observations of the anomalous pulsar 4U 0142+61. Astrophys. J. 513, 464–470 (1999).

6. Oke, J. B., Cohen, J. G., Carr, M., Cromer, J., Dingizian, A., Harris, F. H., Labrecque, S., Lucinio, R., Schaal, W., Epps, H. & Miller, J. The Keck Low-Resolution Imaging Spectrometer. Publ. Astr. Soc. Pacific 107, 375–385 (1995).

7. Phelps, R. L. & Janes, K. A. Young open clusters as probes of the star formation process. 1: An atlas of open cluster photometry. Astrophys. J. 90, 31–82 (1994).

8. Fukugita, M., Shimasaku, K. & Ichikawa, T. Galaxy colors in various photometric band systems. Publ. Astr. Soc. Pacific 107, 945–958 (1995).

9. Cardelli, J. A., Clayton, G. C. & Mathis, J. S. The relationship between infrared, optical, and ultraviolet extinction. Astrophys. J. 345, 245–256 (1989).

10. White, N. E., Angelini, L., Ebisawa, K., Tanaka, Y. & Ghosh, P. The spectrum of the 8.7s X-ray pulsar 4U 0142+61. Astrophys. J. 463, L83–L86 (1996).

11. Predehl, P. & Schmitt, J. H. M. M. X-raying the interstellar medium: ROSAT observations of dust scattering halos. Astr. Astrophys. 293, 889–905 (1995).

12. Perna, R., Hernquist, L. & Narayan, R. Emission spectra of fallback disks around young neutron stars. Astrophys. J. 541, 344–350 (2000).
13. Vrtilek, S. D., Raymond, J. C., Garcia, M. R., Verbunt, F., Hasinger, G. & Kurster, M. Observations of Cygnus X-2 with IUE - Ultraviolet results from a multiwavelength campaign. *Astr. Astrophys.* **235**, 162–173 (1990).

14. Hulleman, F., van Kerkwijk, M. H., Verbunt, F. W. M. & Kulkarni, S. R. A deep search for the optical counterpart to the anomalous X-ray pulsar 1E 2259+58.6. *Astr. Astrophys.* **358**, 605–611 (2000).

15. Mereghetti, S. & Stella, L. The very low mass X-ray binary pulsars: A new class of sources? *Astrophys. J.* **442**, L17–L20 (1995).

16. Stella, L., White, N. E. & Priedhorsky, W. The discovery of a 685 second orbital period from the X-ray source 4U 1820 - 30 in the globular cluster NGC 6624. *Astrophys. J.* **312**, L17–L21 (1987).

17. Paczynski, B. X-ray pulsar 1E 2259+586 - A merged white dwarf with a 7 second rotation period? *Astrophys. J.* **365**, L9–L12 (1990).

18. Ferrario, L., Vennes, S., Wickramasinghe, D. T., Bailey, J. A. & Christian, D. J. EUVE J0317-855 A rapidly rotating, high-field magnetic white dwarf. *Mon. Not. R. astr. Soc.* **292**, 205–217 (1997).

19. Pivovaroff, M. J., Kaspi, V. M. & Camilo, F. X-ray observations of the high magnetic field radio pulsar PSR J1814-1744. *Astrophys. J.* **535**, 379–384 (2000).

20. Bessell, M. S. in *Proc. IAU Coll. 136, stellar photometry - current techniques and future developments* (eds Butler, C. J. & Elliott, I.) 22–39 (Cambridge University Press, Cambridge, 1992).

21. Schlegel, D. J., Finkbeiner, D. P. & Davis, M. Maps of dust infrared emission for use in estimation of reddening and cosmic microwave background radiation foregrounds. *Astrophys. J.* **500**, 525–553 (1998).

22. Rho, J. & Petre, R. X-ray imaging and spectroscopy of the supernova remnant CTB 109 and its associated pulsar 1E 2259+586. *Astrophys. J.* **484**, 828–843 (1997).

23. Middleditch, J., Pennypacker, C. R. & Burns, M. S. Optical color, polarimetric, and timing measurements of the 50 ms Large Magellanic Cloud pulsar, PSR 0540-69. *Astrophys. J.* **315**, 142–148 (1987).

24. Becker, W. & Truemper, J. The X-ray luminosity of rotation-powered neutron stars. *Astr. Astrophys.* **326**, 682–691 (1997).

25. Ögelman, H., Finley, J. P. & Zimmerman, H. U. Pulsed X-rays from the Vela pulsar. *Nature* **361**, 136–138 (1993).
26. Nasuti, F. P., Mignani, R., Caraveo, P. A. & Bignami, G. F. Photometry and proper motion of the Vela pulsar. *Astr. Astrophys.* **323**, 839–843 (1997).

27. Greiveldinger, C., Camerini, U., Fry, W., Markwardt, C. B., Ögelman, H., Safi-Harb, S., Finley, J. P., Tsuruta, S., Shibata, S., Sugawara, T., Sano, S. & Tukahara, M. Heated polar caps in PSR 0656+14 and PSR 1055-52. *Astrophys. J.* **465**, L35–L38 (1996).

28. Kurt, V. G., Sokolov, V. V., Zharikov, S. V., Pavlov, G. G. & Komberg, B. V. BVRI observations of PSR B0656+14 with the 6-meter telescope. *Astr. Astrophys.* **333**, 547–556 (1998).

29. Kurt, V. G., Komarova, V. N., Fatkhullin, T. A., Sokolov, V. V., Koptsevich, A. B. & Shibanov, Y. A. Photometric study of fields of nearby pulsars with the 6m telescope. *Bull. Special Astroph. Obs.* **49**, in press (2000). (astro-ph/0005500).

30. Chakrabarty, D. High-speed optical photometry of the ultracompact X-ray binary 4U 1626-67. *Astrophys. J.* **492**, 342–351 (1998).

31. Chakrabarty, D., Bildsten, L., Grunsfeld, J. M., Koh, D. T., Prince, T. A., Vaughan, B. A., Finger, M. H., Scott, D. M. & Wilson, R. B. Torque reversal and spin-down of the accretion-powered pulsar 4U 1626-67. *Astrophys. J.* **474**, 414–425 (1997).

32. Orlandini, M., Fiume, D. D., Frontera, F., del Sordo, S., Piraino, S., Santangelo, A., Segreto, A., Oosterbroek, T. & Parmar, A. N. BeppoSAX observation of 4U 1626-67: Discovery of an absorption cyclotron resonance feature. *Astrophys. J.* **500**, L163–L166 (1998).

33. Vrtilek, S. D., Helfand, D. J., Halpern, J. P., Kahn, S. M. & Seward, F. D. X-ray emission lines from three Galactic bulge sources. *Astrophys. J.* **308**, 644–654 (1986).

34. Sosin, C. & King, I. R. HST observations of the core of the globular cluster NGC 6624. *Astron. J.* **109**, 639–649 (1995).

35. Kulkarni, S. R. & van Kerkwijk, M. H. Optical observations of the isolated neutron star RX J0720.4-3125. *Astrophys. J.* **507**, L49–L53 (1998).

36. White, N. E., Mason, K. O., Giommi, P., Angelini, L., Pooley, G., Branduardi-Raymont, G., Murdin, P. G. & Wall, J. V. A 25 min modulation from the vicinity of the unusually soft X-ray source X0142+614. *Mon. Not. R. astr. Soc.* **226**, 645–654 (1987).

37. Motch, C., Belloni, T., Buckley, D., Gottwald, M., Hasinger, G., Pakull, M. W., Pietsch, W., Reinsch, K., Remillard, R. A., Schmitt, J. H. M. M., Trumpler, J. & Zimmermann, H. A ROSAT glance at the galactic plane. *Astr. Astrophys.* **246**, L24–L27 (1991).
38. Van den Berg, M. Verbunt, F. Spectroscopic confirmation of the optical identification of X-ray sources used to determine accurate positions for the anomalous X-ray pulsars 1E 2259+58.6 and 4U 0142+61. *Astr. Astrophys.* , submitted (2000).

39. Monet, D., Bird, A., Canzian, B., Dahn, C., Guetter, H., Harris, H., Henden, A., Levine, S., Luginbuhl, C., Monet, A. K. B., Rhodes, A., Riepe, B., Sell, S., Stone, R., Vrba, F. & Walker, R. *USNO-A V2.0, a catalog of astrometric standards.* U.S. Naval Observatory Flagstaff Station (USNOFS) and Universities Space Research Association (USRA) stationed at USNOFS (2000).

40. Baraffe, I., Chabrier, G., Allard, F. & Hauschildt, P. H. Evolutionary models for solar metallicity low-mass stars: mass-magnitude relationships and color-magnitude diagrams. *Astr. Astrophys.* **337**, 403–412 (1998).

41. Bergeron, P., Wesemael, F. & Beauchamp, A. Photometric calibration of hydrogen- and helium-rich white dwarf models. *Publ. Astr. Soc. Pacific* **107**, 1047–1054 (1995).

42. Stetson, P. B. DAOPHOT - A computer program for crowded-field stellar photometry. *Publ. Astr. Soc. Pacific* **99**, 191–222 (1987).

43. Stetson, P. B. Homogeneous photometry for star clusters and resolved galaxies. II. Photometric standard stars. *Publ. Astr. Soc. Pacific* **112**, 925–931 (2000).

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Table 1. Comparison with other high energy objects

Type of object: AXP: anomalous X-ray pulsar; PSR: radio pulsar; XRB: X-ray binary; INS: isolated neutron star.

Although RX J0720.4−3125 has a similar pulse period and X-ray to optical flux ratio, its X-ray spectrum is very different from those of the AXPs.

The observational data have been collected from the literature. A full set of references can be found on http://www.astro.uu.nl/~hulleman/u0142. The unabsorbed X-ray fluxes are for the energy range of 0.5–10 keV. They have been inferred from the best-fit spectral model with the help of the PIMMS software package. For 4U 1626−67, constant pulsed flux is assumed in the estimate of $(R−I)_0$, and for 4U 1820−30, we assumed $V−R=0$ to estimate $R$. For the conversion to fluxes, we used the Bessell zero points, where $V=0$ corresponds to 3600 Jy, $R=0$ to 3060 Jy, and $I=0$ to 2420 Jy. For reddening corrections, we used $(A_{VL}, A_R, A_I) = (1.015, 0.819, 0.594)A_V$, where $A_{VL}$, $A_R$, and $A_I$ are reddenings in the Landolt V, R, and I filters, and $A_V$ is the reddening in the Johnson V band; see Appendix C in ref. 21 for a discussion.

For reference, the final column lists estimated distances; the colons indicate the uncertainty, zero colons indicating a factor up to 1.5 uncertainty, one colon a factor two, two colons a factor three.
| Object         | Type | $P_{\text{spin}}$ (s) | $A_R$ | $R$  | $(V-R)_0$ | $(R-I)_0$ | $f_X^\text{unabs}$ (erg s$^{-1}$ cm$^{-2}$) | $f_X^\text{unabs}$/$\nu_R f_{\nu R}^\text{unabs}$ | $d$ (kpc) | ref. |
|----------------|------|-----------------------|-------|------|-----------|-----------|---------------------------------------------|------------------------------------------------|---------|-----|
| 4U 0142+61     | AXP  | 8.69                  | 4.4   | 24.98| -0.33     | 0.01      | $6.0 \times 10^{-10}$                       | $7.1 \times 10^3$                               | $> 2.7$  | 10  |
|                |      |                       | 2.1   |      |            |           |                                             | $5.9 \times 10^4$                               |          |     |
| 1E 2259+58.6   | AXP  | 6.97                  | 3.8   | $>25.7$|           |           | $1.8 \times 10^{-10}$                       | $\geq 7.2 \times 10^3$                           | $\geq 5$ | 14,22 |
| Crab           | PSR  | 0.033                 | 1.3   | 16.21| -0.06     | 0.35      | $4.0 \times 10^{-9}$                        | $2.5 \times 10^2$                               | 2        | 23,24 |
| Vela           | PSR  | 0.089                 | 0.3   | 23.93| -0.35     |           | $7.5 \times 10^{-12}$                       | $1.4 \times 10^3$                               | 0.4:     | 24,25,26 |
| PSR B0656+14   | PSR  | 0.38                  | 0.1   | 24.52| 0.36      | 0.69      | $1.5 \times 10^{-12}$                       | $6.1 \times 10^2$                               | 0.5:     | 27,28 |
| Geminga        | PSR  | 0.24                  | 0.1   | 25.4 | -0.20     |           | $3.9 \times 10^{-12}$                       | $3.6 \times 10^3$                               | 0.2:     | 24,29 |
| 4U 1626−67     | XRB  | 7.66                  | 0.2   | 18.68| -0.06     | 0.82:     | $2/8 \times 10^{-10}$                       | $3/14 \times 10^2$                               | 8::      | 30,31,32 |
| 4U 1820−30     | XRB  | 0.7                   | 18.87 |      |           |           | $8/16 \times 10^{-9}$                       | $1/2 \times 10^4$                               | 8        | 33,34 |
| RX J0720.4−3125| INS  | 8.39                  | 0.1   | 26.9 |           |           | $2.5 \times 10^{-12}$                       | $9.1 \times 10^3$                               | $< 0.4$  | 35  |
Figure 1. Keck images around the X-ray position of 4U 0142+61. The large panel shows an overview of the R-band image. Our candidate, A, as well as two other blue objects, D and G, are indicated with labels just to the right of their images. The small bottom panels are close-ups of the I-band images of A and G, which show that G is extended and probably a galaxy, while A is not. The panels on the right show the V, R, and I images around star A. The error circle indicates the X-ray position derived from analysis of Einstein HRI observations ($\alpha_{\text{J2000}} = 01^h46^m22^s03, \delta_{\text{J2000}} = +61^\circ 45'04''3$, 95% confidence level radius of 3.9 arcsec; ref. 36). The Einstein positions have proven to be highly reliable, but for comparison we display in the I-band panel also the error circles derived from observations with the EXOSAT LEIT (end figures 22.40 and 10.2; 4.8 arcsec radius; ref. 36) and ROSAT PSPC (21.93, 44'57''7; 6 arcsec radius). The ROSAT position of 4U 0142+61 was derived from archival data, using a boresight correction inferred from two other X-ray sources in the field, for which the optical counterparts are known$^{37,38}$ (LS I +61° 235 and LP 80-77; our technique is described in ref. 14). The astrometry was done as in ref. 14, by measuring 107 stars from the USNO-A2.0 catalogue$^{39}$ on a short R-band exposure (root-mean-square residuals of 0.26 arcsec in each coordinate, consistent with the USNO-A2.0 measurement errors). From the I-band image, we infer a position of star A of $\alpha_{\text{J2000}} = 01^h46^m22^s41, \delta_{\text{J2000}} = +61^\circ 45'03''2$. We estimate that this position is on the International Celestial Reference Frame to about 0.2 arcsec. The other images give consistent positions. Our 2σ upper limit to the proper motion is 0.03 arcsec yr$^{-1}$. 
Figure 2. Colour-magnitude and colour-colour diagrams for stars near the position of 4U 0142+61. For comparison, the magnitudes and colours expected for stars at the distance, reddening, and age of the nearby open cluster NGC 654 (2.7 ± 0.4 kpc, 2.7 mag, 50 Myr; ref. 7; solid line) are shown, as well as a cooling track for a 0.6 $M_\odot$ white dwarf at the same reddening and distance (dashed line). The arrows indicate the effect of increasing the reddening by $\Delta A_V = 1$. All optical images were corrected for sensitivity variations using dome flats, and a small correction for non-linearity of the detector was applied to the 1999 observations. For the 1999 I-band observations, a ‘fringe’ frame was constructed by taking the second-lowest value for each pixel from seven dithered images, which was subtracted from the individual images to remove interference patterns. Instrumental magnitudes were measured using the DAOPHOT II package on the 1994 V band and the 1999 R and I-band images, using only those regions not affected by scattered light from bright, overexposed stars. The 1994 V-band images were taken at a different pointing and rotation angle, which caused different parts on the sky to be affected by bleed trails, and so on. Therefore, we obtained V-band measurements only for stars in the central part displayed in Figure 1. The photometric calibration was done relative to the 60-inch data, which were calibrated in turn using exposures of the standard fields PG 1657−042 and NGC 7790. The R and I calibration was verified using Keck images of the standard field PG 0231+051. We estimate the uncertainties in the zero points of the magnitudes and colours to be about 0.03 mag. For star A, we find $R = 24.99 \pm 0.07$, $V - R = 0.63 \pm 0.11$, $R - I = 1.15 \pm 0.09$. By comparison with the 1994 images, we find that its brightness was constant to within 0.2 mag (2-$\sigma$) in R.
**Figure 3.** Energy distribution for 4U 0142+61. At low frequencies ($10^{14}$–$10^{15}$ Hz), the points marked V, R, and I indicate the observed V, R, and I-band fluxes. The vertical error bars reflect the uncertainties, while the horizontal ones indicate the filter bandwidths. The set of points above the measurements indicate dereddened fluxes for $A_V = 5.4$, as inferred from the X-ray column density.\textsuperscript{10,11} The errors include a 3\% uncertainty in the reddening correction.\textsuperscript{9} At high frequencies ($10^{17}$–$10^{18}$ Hz), the crosses show the incident X-ray spectrum as inferred from ASCA measurements.\textsuperscript{10} The diamonds show the spectrum after correction for interstellar absorption, and the two thick dashed curves show the two components used in the fit:\textsuperscript{10} a power law of the form $F_\nu = 103(h\nu/1\text{keV})^{-2.67} \mu\text{Jy}$ and a black body with $T = 4.4 \times 10^6$ K and $R = 12d_5$ km. The latter component is extrapolated to lower frequencies to show it cannot reproduce the optical fluxes. Drawn in thin solid lines are models for the optical emission. The curve marked disk is for an accretion disk that has inner radius equal to the corotation radius $R_{\text{co}} = (GM^2/4\pi^2)^{1/3} = 0.010 R_\odot$ (for $M = 1.4 M_\odot$, $P = 8.7$ s), outer radius of $10^{14}$ cm, and inclination of 60 degrees. Both irradiation and viscous heating are taken into account;\textsuperscript{13} the former dominates in the optical and the latter causes the bump in the ultra-violet. The calculation is for $d = 5$ kpc, but since the disk luminosity scales almost linearly with the X-ray luminosity, the result is not sensitive to distance. The optical fluxes expected in the accretion model are greatly in excess of those observed. Only for a truncated disk with a small outer disk radius, $r_{\text{out}} \lesssim 0.1d_5^{10/11}(f/0.25)^{-2/11} R_\odot$, can the observed fluxes be reproduced, as is shown by the dashed curve. The thin solid curves marked BB, H, and He are black body, pure hydrogen and pure helium white dwarf model atmospheres for $T = 4 \times 10^5$ K. The normalization to the optical data implies $R = 0.011d_5$, 0.017$d_5$ and 0.015$d_5 R_\odot$, respectively. None of the spectra can reproduce the X-ray emission.
