Optical pulsations from the anomalous X-ray pulsar 1E 1048.1−5937

V. S. Dhillon,1,T. R. Marsh,2 S. P. Littlefair,1 C. M. Copperwheat,2 P. Kerry,1 R. Dib,3 M. Durant,4 V. M. Kaspi,3 R. P. Mignani5 and A. Shearer6

1Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH
2Department of Physics, University of Warwick, Coventry CV4 7AL
3Department of Physics, McGill University, Montreal, Quebec H3A 2T8, Canada
4Instituto de Astrofísica de Canarias, 38 200 La Laguna, Tenerife, Spain
5Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT
6Centre for Astronomy, National University of Ireland, Galway, Newcastle Rd., Galway

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ABSTRACT

We present high-speed optical photometry of the anomalous X-ray pulsar 1E 1048.1−5937 obtained with ULTRACAM on the 8.2-m Very Large Telescope in 2007 June. We detect 1E 1048.1−5937 at a magnitude of $i' = 25.3 \pm 0.2$, consistent with the values found by Wang et al. and hence confirming their conclusion that the source was approximately 1 mag brighter than in 2003–06 due to an on-going X-ray flare that started in 2007 March. The increased source brightness enabled us to detect optical pulsations with an identical period (6.458 s) to the X-ray pulsations. The root-mean-square (rms) pulsed fraction in our data is 21 ± 7 per cent, approximately the same as the 2–10 keV X-ray rms pulsed fraction. The optical and X-ray pulse profiles show similar morphologies and appear to be approximately in phase with each other, the latter lagging the former by only 0.06 ± 0.02 cycles. The optical pulsations in 1E 1048.1−5937 are very similar in nature to those observed in 4U 0142+61. The implications of our observations for models of anomalous X-ray pulsars are discussed.

Key words: stars: neutron – pulsars: individual: 1E 1048.1−5937.

1 INTRODUCTION

The anomalous X-ray pulsars (AXPs) are a small group1 of isolated neutron stars in which the X-ray luminosity far exceeds the energy available from the spin-down. The AXPs are generally believed to be magnetars, in which the excess luminosity is powered by the decay of an ultra-strong magnetic field, in excess of $10^{14}$ G (see Woods & Thompson 2006). An alternative explanation is the fallback disc scenario, in which some of the supernova ejecta fails to escape and forms an accretion disc around the neutron star, providing an extra source of energy to power the X-ray emission (van Paradijs, Taam & van den Heuvel 1995; Chatterjee, Hernquist & Narayan 2000; Alpar 2001).

One way of discriminating between the magnetar and fallback disc models is via optical observations. The magnetar model predicts any optical emission must be non-thermal and magnetospheric in origin. Four plausible mechanisms have been considered – coherent plasma emission, synchrotron emission from electrons with high Lorentz factors, cyclotron emission from ions in the outer magnetosphere and curvature emission from bunched electron-positron pairs in the inner magnetosphere [see Beloborodov & Thompson (2007) and references therein]. The simplest form of the fallback disc model, on the other hand, predicts any optical emission is produced by reprocessing of the X-ray light in the disc and/or thermal emission from the disc (Perna, Hernquist & Narayan 2000).

The first AXP to be detected in the optical part of the spectrum was 4U 0142+61 (Hulleman, van Kerkwijk & Kulkarni 2000). Optical pulsations were discovered in 4U 0142+61 by Kern & Martin (2002), and the fact that these pulsations have the same period, morphology and phase as the X-rays, but with 5–7 times greater pulsed fraction, was reported by Dhillon et al. (2005). These results provided strong support for the magnetar model – pulsed optical emission is indicative of a magnetospheric origin and disc reprocessing is unlikely in this case, as the optical pulsed fraction is higher than the X-ray pulsed fraction and there is no time delay between the two. Although it is possible to contrive ways in which the fallback disc model is consistent with the optical pulsations observed in 4U 0142+61, for example by assuming that the X-ray pulse profile that we observe is different to the X-ray radiation seen by the disc due to orientation or beaming effects or by invoking a hybrid disc-magnetosphere model [see Ertan et al. (2007) and references therein], the weight of evidence from the optical and other
wavelengths lies heavily on the side of the magnetar model [see Mereghetti (2008) for a recent review].

The detection of optical pulsations in other AXPs would provide valuable confirmation, or otherwise, of the results for 4U 0142+61 discussed above. Only one other AXP has been unambiguously identified in the optical\(^1\): 1E 1048.1−5937 (Durant & van Kerkwijk 2005). In this paper, we report on the first detection of optical pulsations from AXP 1E 1048.1−5937, obtained only \(\sim 3\) months after a bright X-ray flare in 2007 March.

2 OBSERVATIONS AND DATA REDUCTION

The observations of 1E 1048.1−5937 presented in this paper were obtained with ULTRACAM (Dhillon et al. 2007) at the Nasmyth focus of Melipal, the 8.2-m Unit 3 of the Very Large Telescope (VLT) in Chile. ULTRACAM is a CCD camera designed to provide imaging photometry at high temporal resolution in three different colours simultaneously. The instrument provides a 2.66 arcmin field on its three \(1024 \times 1024\) E2V 47−20 CCDs (i.e. 0.156 arcsec pixel\(^{−1}\)). Incident light is first collimated and then split into three different beams using a pair of dichroic beam splitters. For the observations presented here, one beam was dedicated to the Sloan Digital Sky Survey (SDSS) \(u'\) filter (3543 Å), another to the SDSS \(g'\) (4770 Å) filter and the third to the SDSS (7625 Å) \(i'\) filter. Because ULTRACAM employs frame-transfer chips, the dead-time between exposures is negligible: we used ULTRACAM in its two-windowed mode, each of \(250 \times 200\) pixel, resulting in an exposure time of 0.963 s and a dead-time of 0.024 s. A total of 11 095 frames of 1E 1048.1−5937 were obtained on the night of 2007 June 9, with each frame time-stamped to a relative (i.e. frame-to-frame) accuracy of \(\sim 50\) \(\mu\)s and to an absolute accuracy of \(\sim 1\) ms using a dedicated GPS system (see Dhillon et al. 2007). Observations of the SDSS standard G163-51 (Smith et al. 2002) were also obtained to flux calibrate the data. The night was photometric, with no moon and standard G163-51 (Smith et al. 2002) were also obtained to flux calibrate the data.

As part of a long-term monitoring project, 1E 1048.1−5937 has been observed regularly (up to three times per week) since 1997 with the Proportional Counter Array (PCA) on board the Rossi X-ray Timing Explorer (RXTE) [Kaspi et al. 2001; Gavriil & Kaspi 2004; Dib et al. (2009)]. The X-ray spin frequency and frequency derivative of 1E 1048.1−5937 for the night of our VLT observations (MJD 54260) are given in Table 1. For the first light-curve extraction technique, we shifted and added each of the 11 095 ULTRACAM frames into 10 evenly spaced phase bins using the epoch and spin frequency given in Table 1, resulting in 10 high signal-to-noise data frames. An optimal photometry algorithm (Naylor 1998) was then used to extract the counts from 1E 1048.1−5937 and an \(i'\) \(\sim 17\) comparison star \(\sim 12\) arcsec to the south-east of the AXP (see Fig. 1), the latter acting as the reference for the profile fits and transparency-variation correction. The position of 1E 1048.1−5937 relative to the comparison star was determined from a sum of all the images, and this offset was then held fixed during the reduction so as to avoid aperture centroiding problems. The sky level was determined from a clipped mean of the counts in an annulus surrounding the target stars and subtracted from the object counts.

2.2 Technique (ii)

The second approach we took to light-curve extraction was identical to that described above, except we omitted the phase-binning step and simply performed optimal photometry on the 11 095 individual ULTRACAM data frames followed by a periodogram analysis of the resulting time series. In other words, we made no assumption about the spin period of 1E 1048.1−5937.

3 RESULTS

3.1 Magnitudes

We were unable to detect 1E 1048.1−5937 in \(u'\) and \(g'\), at a 3 \(\sigma\) detection limit of \(u' > 25.7\) and \(g' > 27.6\), respectively. This is unsurprising given the high visual extinction to the object (\(A_V = 4.9\); Durant & van Kerkwijk 2006). We did, however, clearly detect 1E 1048.1−5937 in \(i'\) at a magnitude of \(i' = 25.3 \pm 0.2\), as shown in

| Table 1. X-ray ephemeris for 1E 1048.1−5937 (Dib et al. 2009). The epoch of the frequency and frequency derivative measurements given below falls on the same night as our VLT observations (2007 June 09 = MJD 54260). BMJD refers to the Barycentric-corrected Modified Julian Date on the Barycentric Dynamical Time-scale (TDB). The errors on the last two digits of each parameter are given in parentheses. This ephemesis is valid for BMJD 54 229.0 − 54 280.0. |
|---|---|---|
| \(\nu\) (Hz). | \(\nu\) (10\(^{−13}\) Hz s\(^{−1}\)). | Epoch (BMJD). |
| 0.154847 9469(4) | −5.413(53) | 54 260.0 |

Figure 1. Left-hand side: summed \(i'\)-band image of the field around 1E 1048.1−5937, with a total exposure time of 10 684 s. For clarity, only a portion of one of the two ULTRACAM windows is shown. The positions of 1E 1048.1−5937 and the comparison star are indicated by circles near the centre and bottom of the image, respectively. The central box shows the portion of the field that is plotted at a higher contrast on the right-hand side. The orientation of the image is marked on the upper right-hand side. The pixel scale is 0.156 arcsec pixel\(^{−1}\), hence the field of view in this image is 36 \(\times\) 30 arcsec\(^2\). The vertical banding is due to residual bias structure. Right-hand side: higher contrast plot of a 7.5 \(\times\) 7.5 arcsec\(^2\) field around 1E 1048.1−5937, highlighting the detection of the pulsar in the \(i'\) band.

\(^{1}\) *See Durant & van Kerkwijk (2005).*
3.2 Pulse profiles

The two data reduction techniques described in Section 2 result in two different pulse profiles for 1E 1048.1−5937.

3.2.1 Technique (i)

The first technique produced the pulse profile shown by the solid line in the top panel of Fig. 2. The pulse profile exhibits a broad, single-humped structure with a peak around phase 0.5 and a minimum around phase zero. There is a great deal of similarity in the morphology of the optical pulse profile shown in the top panel of Fig. 2 and the 2–10 keV X-ray pulse profile shown below it, where the latter is the average of the X-ray light curves in the period 2007 May 23 to June 21 obtained as part of the RXTE monitoring campaign described by Dib et al. (2009), with a total effective integration time of 59.5 ks. Both profiles show the same broad, single-humped morphology. Moreover, since the X-ray light curve shown in Fig. 2 has also been phased using the ephemeris given in Table 1, it can be seen that the optical and X-ray pulse profiles are approximately in phase with each other. To quantify this, the optical pulse profile was cross-correlated with the X-ray pulse profile. The resulting peak in the cross-correlation function was fitted with a Gaussian to derive a phase shift of $-0.06 \pm 0.02$ cycles (i.e. $-0.39 \pm 0.13$ s), where a negative phase shift implies that the X-ray pulse profile lags the optical pulse profile. This phase shift is only significant at the 3$\sigma$ level, due to the low signal-to-noise and time resolution of the optical data, and additional data will be required in order to confirm that the phase shift is different from zero (discounting the unlikely situation in which the time delay is approximately equal to some multiple of the spin period).

It should be noted that the morphology of the X-ray pulse profile in 1E 1048.1−5937 does not appear to be energy sensitive; the shapes of the 2–4 and 6–10 keV pulse profiles are virtually identical to the 2–10 keV pulse profile shown in Fig. 2, even though the 6–10 keV band is composed primarily of non-thermal photons whereas the 2–4 keV band is composed of both thermal and non-thermal photons (F. Gavriil, private communication).

The modulation amplitude of the pulses presented in Fig. 2 can be measured using a peak-to-trough pulsed fraction, $h_{\text{pt}}$, defined as follows:

$$h_{\text{pt}} = \frac{F_{\text{max}} - F_{\text{min}}}{F_{\text{max}} + F_{\text{min}}},$$

where $F_{\text{max}}$ and $F_{\text{min}}$ are the maximum and minimum flux in the pulse profile, respectively. We find a value of $h_{\text{pt}} = 52 \pm 15$ per cent. The peak-to-trough pulsed fraction defined in equation (1) effectively adds any noise present in the light curve to the true pulsed fraction, thereby tending to increase the resulting measurement. A more robust estimate is given by the root-mean-square (rms) pulsed fraction, $h_{\text{rms}}$, defined as follows:

$$h_{\text{rms}} = \frac{1}{\bar{y}} \left[ \frac{1}{n} \sum_{i=1}^{n} (y_i - \bar{y})^2 - \sigma^2 \right]^{1/2},$$

where $n$ is the number of phase bins per cycle, $y_i$ is the number of counts in the $i$th phase bin, $\sigma$ is the error on $y_i$ and $\bar{y}$ is the mean number of counts in the cycle. As expected, measuring the optical pulsed fraction in this way gives a lower value of $h_{\text{rms}} = 21 \pm 7$ per cent.

For comparison, the 2–10 keV X-ray rms pulsed fraction at the same epoch as the optical observations was $h_{\text{rms}} = 28.7 \pm 0.5$ per cent. Since it is not possible to measure the rms pulsed fraction directly from the RXTE pulse profile due to the uncertain background (see caption to Fig. 2), we derived this value as follows. We first averaged the rms pulsed flux, defined as the product of the total flux and the rms pulsed fraction, measured with RXTE between 2007 June 7 and June 12 (Dib et al. 2009). This value, which is background independent, was identical to that measured with Chandra on 2007 April 28 by Tam et al. (2008), who also find a strong anticorrelation between total flux and rms pulsed fraction. Hence, if the pulsed flux was the same for the RXTE and Chandra observations, we can be confident that the rms pulsed fraction was the same as well, and hence we have adopted the Chandra rms pulsed fraction from the 2007 April 28 observation of Tam et al. (2008).
4 DISCUSSION AND CONCLUSIONS

The results presented in Section 3 demonstrate conclusively that we have detected optical pulsations from 1E 1048.1−5937 on the X-ray spin period.

It is instructive to compare the optical light curve of 1E 1048.1−5937 with that of the only other AXP to have been studied in this way – 4U 0142+61 (Dhillon et al. 2005). Both objects show optical pulsations on the X-ray spin period, which is 6.458 s in the case of 1E 1048.1−5937 and 8.688 s in 4U 0142+61. Both objects show optical pulsations with similar morphologies to their 2−10 keV X-ray light curves, with 1E 1048.1−5937 exhibiting a single-humped pulsation and 4U 0142+61 a double-humped pulsation. Both objects exhibit optical pulsations which are approximately in phase with the X-ray pulsations, with 1E 1048.1−5937 showing only marginal evidence for the optical leading the X-rays and 4U 0142+61 showing only marginal evidence for the optical lagging the X-rays. Even the optical pulsed fractions of the two objects are similar, with values of $h_{\text{pt}} = 52 \pm 15$ per cent and $h_{\text{rms}} = 21 \pm 7$ per cent in 1E 1048.1−5937, and $h_{\text{pt}} = 58 \pm 16$ per cent and $h_{\text{rms}} = 29 \pm 8$ per cent in 4U 0142+61.

The only major difference when comparing this study of 1E 1048.1−5937 with Dhillon et al.’s (2005) study of 4U 0142+61 is the ratio of the optical to X-ray pulsed fraction: in 1E 1048.1−5937 it is approximately unity, whereas in 4U 0142+61 the optical pulsations had an rms pulsed fraction 5−7 times that of the X-rays. However, whereas the optical and X-ray pulsed fractions for 1E 1048.1−5937 were measured contemporaneously, those of 4U 0142+61 were not. The X-ray pulsed fractions of 4U 0142+61 reported by Dhillon et al. (2005) were quoted from the work of Patel et al. (2003), which obtained their Chandra data in 2000, over two years prior to the optical observations. We now know from the work of Dib, Kaspi & Gavriil (2007), however, that 4U 0142+61 exhibited an increase in its pulsed light of 36 per cent in the 2−10 keV band between 2002 and 2004. Hence, it is possible that at least part of the discrepancy between the optical/X-ray pulsed fraction ratio in 1E 1048.1−5937 and 4U 0142+61 is due to variability in the latter source. This hypothesis is further supported by the fact that Dhillon et al. (2005) measured a value of $h_{\text{pt}} = 58 \pm 16$ per cent in 2002 September, whereas Kern & Martin (2002) measured $h_{\text{pt}} = 27 \pm 8$ per cent in 2001 November, although there are other possible reasons for this discrepancy (see Dhillon et al. 2005 for a discussion).

It is also possible that the discrepancy between the optical/X-ray pulsed fraction ratio in 1E 1048.1−5937 and 4U 0142+61 is due to variability in 1E 1048.1−5937: as discussed in Section 3.2.1, the X-ray pulsed fraction of 1E 1048.1−5937 is inversely proportional to the total 2−10 keV flux. The optical pulsed fraction might not vary in the same way, implying that the optical/X-ray pulsed fraction ratio in 1E 1048.1−5937 could be variable and we just happened to observe it when it was unity.

Viewed in isolation, the data on 1E 1048.1−5937 presented in this paper do not allow us to discriminate between the magnetar and fallback disc models, as the optical and X-ray pulsed fractions are approximately equal, although the tentative evidence we present for the optical pulses leading the X-rays is irreconcilable with reprocessing. Arguably, the most important result of this paper, however, is that it confirms the existence of pulsated optical light in a second AXP, 1E 1048.1−5937, thereby demonstrating that the properties of the optical emission in 4U 0142+61 are not unique. The observed similarities between the optical and X-ray emission in both 1E 1048.1−5937 and 4U 0142+61 indicate that closely related populations of particles, located in the same region of the...
magnetosphere, are probably responsible for the emission. This paper has also highlighted the way forward for time-resolved optical studies of these incredibly faint objects, as the data presented in this paper would have been unobtainable had 1E 1048.1−5937 been in a faint state. By targeting observations during bright X-ray states, it should be possible to study other AXPs, and possibly also soft gamma repeaters, in the optical part of the spectrum, although this will still require access to sensitive, high-speed cameras like ULTRACAM on the world’s largest telescopes.

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