

Optical and Infrared Observations of Anomalous X-ray Pulsars

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Abstract. The detection of optical/infrared counterparts to Anomalous X-ray Pulsars (AXPs) has greatly increased our understanding of these systems. Models for the AXP phenomenon were based upon their X-ray emission, and all but the *magnetar* model made predictions for the optical/infrared that have now been falsified. With detections in hand, detailed studies of the optical/infrared to X-ray flux ratios, variability, and the spectral energy distributions have become possible. We present new data on two AXPs taken with Keck and Magellan, and compare the results with predictions made in the context of the magnetar model, in which the emission is due to ion currents flowing in the $\gtrsim 10^{14}$ G magnetosphere of young neutron stars.

1. Introduction

Anomalous X-ray Pulsars (AXPs) have been classified as a distinct category of neutron stars on the basis of observational properties which they share in common. They were detected as X-ray sources with long (~ 10 s) pulse periods. The term *anomalous* refers to the fact that the power associated with rotational energy loss through spin-down is not sufficient to produce the observed luminosities, nor were they obviously associated with binary companions.

If they are short-lived, as supernova remnant associations suggest, then AXPs along with the Soft Gamma-ray Repeaters (SGRs) and Dim Isolated Neutron Stars (DINs) hint at a large population of neutron stars which differ considerably from the radio pulsars and X-ray pulsars in binaries.

The earliest models were based purely on the X-ray properties of AXPs, but with the identification and photometry of the first optical and infrared counterparts, it became possible to test these models against the measured flux ratio F_X/F_{IR} .

Currently, the front-runner to explain these objects is the *magnetar* model (Thompson & Duncan 1996), in which AXPs are neutron stars with dipole magnetic fields of order $B \gtrsim 10^{14}$ gauss, the decay of which supplies the energy for the observed luminance. Thus they are thought to be very similar objects to the SGRs when in quiescence, although bursting activity has now been seen from AXPs also. This brings into view the prospect of probing the physics of

super-QED field physics. One would expect to see variation in the optical or IR, if the emission at those wavelengths is directly related to the processes causing the bursting activity.

Since these first measurements, further optical and infrared observations have been undertaken. It is now starting to be possible to construct spectral energy distributions and to look for broad features. In this way, we can gain more information and another handle on these intriguing objects.

2. AXP 4U 0142+61

Optical and infrared images were taken of the field of AXP 4U 0142+61 using LRIS and NIRC at Keck respectively.

The object was clearly seen in the V , R , I , K and K_s bands, but after two hours of integration there was only a marginal (2σ) detection in the B band, which could be seen either as a tentative detection or a hard upper limit in magnitude. In Figure 2, the spectral energy distribution (SED) of 4U 0142+61 is shown from the infrared to the X-ray, de-reddened with an $A_V = 5.1$, as inferred from the X-ray column density of hydrogen.

The points to note are that the optical/IR spectral points do not match extrapolations of the blackbody + power law spectrum which was fit to the X-ray (White et al. 1996); there appears to be a break in the continuum in B ; there is a marked difference between the K and K_s bands which, due to their spectral proximity, is most easily attributed to variability (since the respective measurements were taken over two and a half years apart). Conversely, the optical flux appears to have been stable.

The choice of reddening has a marked impact on the shape of the SED, but the above three statements remain valid for the range of A_V that has been suggested, i.e. $A_V = 2.6$ from a nearby OB association (Hulleman et al. 2001) to 5.1 from the Hydrogen column inferred from the X-ray spectrum (Patel et al. 2003). Full details of these results are presented in Hulleman, van Kerkwijk & Kulkarni (2004).

3. AXP 1E 1048.1–5937

Optical and infrared images were taken of AXP 1E 1048.1–5937 using MagIC and PANIC on the Magellan II (Clay) telescope, Las Campanas and using ISAAC at VLT. See Figure 1 for the I - and K_s -band images. The analysis is still ongoing, and the results presented here are thus preliminary.

The object was detected in the I band at an apparent magnitude of $I = 26.6 \pm 0.15$ with an exposure time of more than two hours and superb seeing conditions of $0''.3$. This may fairly be said to be at the limits of what is possible at the current time. Also, it is worth noting that our K_s band magnitude of 21.2 ± 0.4 is already fainter than that which was measured by Wang & Chakrabarty (2002), but consistent with the upper limits measured by Israel et al. (2002). Thus the hope is clearly that here we are seeing the AXP in its quiescent state.

See again Figure 2 where the points for this AXP are also plotted, de-reddened with $A_V = 5.8$ (Wang & Chakrabarty 2002). We see that the gradient

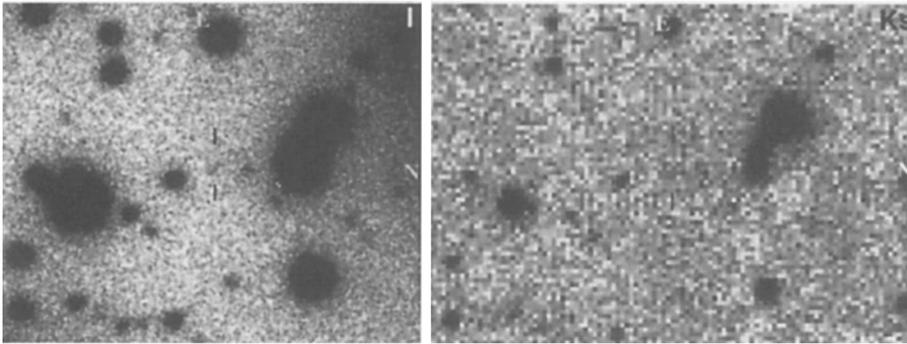


Figure 1. I - and K_s -band image of 1E 1048.1–5937, taken with MagIC and PANIC on Magellan II (Clay) at LCO. The AXP’s position as found by e.g. Wang & Chakrabarty (2002) is indicated by two dashes. It is clearly visible, but very faint.

of the spectrum from K_s to I is now different to what was seen before, different to 4U 0142+61; and that the infrared emission has varied considerably.

4. Implications

The results above seem to suggest that the optical emission seems stable whereas the near infrared emission is highly variable. This in turn suggests that the source for the optical and the infrared emission is different, and perhaps that the latter is related in some way to, or more influenced by, bursting activity.

The *magnetar* model gives a qualitative explanation for the optical/IR flux, in terms of ion currents flowing through the magnetosphere which maintain the global twist in the magnetic field. If this is so, then one would expect a relationship between the torque working on the star and the optical flux. Thus the comparison of optical emission to the spin down history of the AXPs will yield this relationship, and so it is vital that both optical and X-ray monitoring are continued.

There is also the suggestion that the magnetar model may be able to explain the spectral break (seen in the B band of 4U 0142+61) coming from a particular radius in the magnetosphere, with a weak break-frequency dependence on the magnetic field ($\nu_{\text{break}} \propto B^{1/5}$). This is can be verified with further photometry.

References

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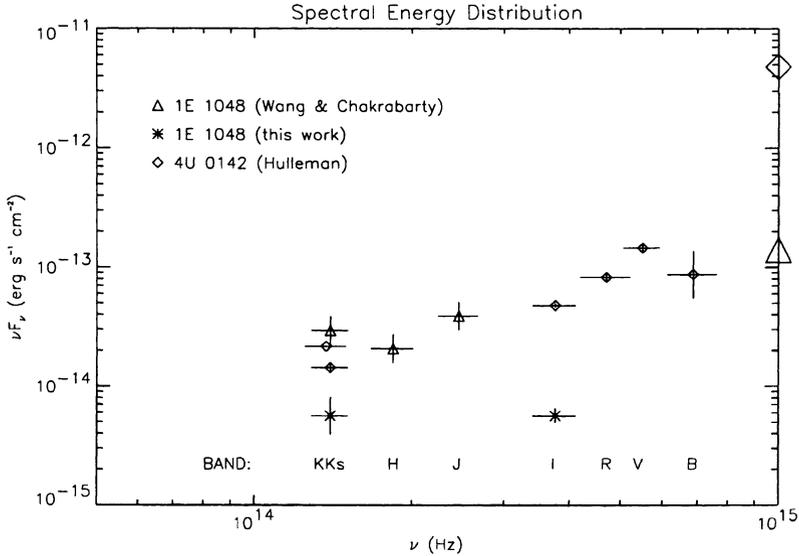


Figure 2. The spectral energy distributions of the two AXPs in infrared and optical. The two larger symbols on the right-hand axis indicate the $\nu F_\nu/10^2$ of the X-ray emission for each object. Not shown are the limits for 1E 1048.1–5937 (Israel et al. 2002).

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