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Author(s)	P.R. den Hartog
Faculty	FNWI: Astronomical Institute Anton Pannekoek (IAP)
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Chapter 5

The first multi-wavelength campaign of AXP 4U 0142+61 from radio to hard X-rays

P. R. den Hartog[1], *L. Kuiper*[1], *W. Hermsen*[1,2], *N. Rea*[1], *M. Durant*[3], *B. Stappers*[4,2], *V. M. Kaspi*[5] *and R. Dib*[5]

[1] SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
[2] Astronomical Institute, University of Amsterdam, Kruiskade 403, 1098 SJ Amsterdam, The Netherlands
[3] Department of Astronomy & Astrophysics, University of Toronto, 60 Saint George Street, MP 1404D Toronto, ON M5S 3H8, Canada
[4] ASTRON The Netherlands Foundation for Research in Astronomy, P.O. Box 2, 7990 AA, Dwingeloo, The Netherlands
[5] Physics Department, McGill University, 3600 University Street, Montreal, PQ H3A 2T8, Canada

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Abstract

For the first time a quasi-simultaneous multi-wavelength campaign has been performed on an Anomalous X-ray Pulsar from the radio to the hard X-ray band. 4U 0142+61 was an INTEGRAL target for 1 Ms in July 2005. During these observations it was also observed in the X-ray band with Swift and RXTE, in the optical and NIR with Gemini North and in the radio with the WSRT. In this paper we present the source-energy distribution. The spectral results obtained in the individual wave bands do not connect smoothly; apparently components of different origin contribute to the total spectrum. Remarkable is that the INTEGRAL hard X-ray spectrum (power-law index 0.79 ± 0.10) is now measured up to an energy of $\sim$230 keV with no indication of a spectral break. Extrapolation of the INTEGRAL power-law spectrum to lower energies passes orders of magnitude underneath the NIR and optical fluxes, as well as the low $\sim$30 μJy (2σ) upper limit in the radio band.

5.1 Introduction

Anomalous X-ray Pulsars (AXPs) are young rotating isolated neutron stars (for a review in this volume, see Kaspi 2007). Currently there are 8 AXPs known and there are a few more candidates (Woods & Thompson 2006). These objects are called anomalous, because their X-ray luminosities exceed by far the available total energy released by rotational energy loss. The energy output is believed to originate from an immense energy reservoir stored in a toroidal magnetic field within the Neutron Star. The surface magnetic fields, inferred from their periods and period derivatives, are of the order of $10^{14} - 10^{15}$ G. Therefore, AXPs are believed to be magnetars, as originally proposed for the Soft Gamma-ray Repeaters (SGRs, see Duncan & Thompson 1992; Thompson & Duncan 1995, 1996). Both AXPs and SGRs are well studied objects in the X-ray band for energies below 10 keV. However, little was known about their persistent emission in the hard X-ray band ($>$10 keV). In 2004 INTEGRAL discovered hard X-ray emission from the position of 1E 1841-045 (Molkov et al. 2004). Kuiper et al. (2004a) showed unambiguously that the hard X-rays originated from the AXP by extracting a pulsed hard X-ray signal from the source using archival RXTE data. After INTEGRAL discovered hard X-rays from two other AXP locations, namely from 1RXS J1708-4009 (Revnivtsev et al. 2004a) and 4U 0142+61 (den Hartog et al. 2004a), Kuiper et al. (2006) also showed for these and for a fourth AXP (1E 2259+586) pulsed hard X-ray emission using archival RXTE data. That means that presently already for 4 of the 8 established AXPs hard X-ray emission has been detected and this can now be considered to be a common characteristic, which is not yet understood.

In this paper we focus on the AXP 4U 0142+61. This AXP was discovered by the Uhuru X-ray observatory in the early seventies (Giacconi et al. 1972; Forman et al. 1978). The spin period of 8.7 s was found by Israel et al. (1994). They realised that the X-ray luminosity is too high to be explained by rotational energy loss. Like for the other AXPs, there is no proof for a companion, nor for an active (i.e. accreting) disk that could explain the high X-ray luminosity of 4U 0142+61. The passive (i.e. non accreting) debris disk discovered by Wang et al. (2006) does not power the X-ray emission. The X-ray luminosities recently measured with e.g. XMM-Newton and Chandra are of the order of 10^{35} erg cm^{-2} s^{-1}(2–10 keV, see Patel et al. 2003; Göhler et al. 2005), assuming a distance of 3.6 kpc (Durant & van Kerkwijk 2006a). The X-ray spectra (0.5–10 keV) of AXPs are soft and are commonly fitted with a black-body and a power-law model. The inclusion of the power-law component is required to fit excess photons with energies above $\sim$3 keV. For 4U 0142+61, the best fit parameters are a black-body temperature of kT $\sim$0.4 keV and a power-law photon index of Γ $\sim$3.4.

4U 0142+61 was detected by den Hartog et al. (2006) in hard X-rays up to 150 keV in 1.6 Ms of INTEGRAL observations (see also Kuiper et al. 2006). The 20–150 keV flux was measured to be $(9.7 \pm 0.9) \times 10^{-11}$ erg cm^{-2} s^{-1}. The total spectrum could be fitted with a power-law model with photon index $\Gamma = 0.73 \pm 0.17$. They also revisited the Compton Gamma-Ray Observatory (COMPTEL) archives (0.75–30 MeV, see Schönfelder et al. 1993) and determined flux upper limits at the location of the AXP. These limits put constraints on the extrapolation of the hard X-ray power law. Assuming that the hard X-ray flux is stable, a spectral break has to occur in the hard X-ray regime below $\sim$750 keV in order for the spectrum not to be in conflict with the COMPTEL upper limits. den Hartog et al. (2006) and Kuiper et al. (2006) were not able to measure such a break, but a hint was found with a 2.3σ fit improvement when a high-energy cutoff was added to the power-law model by den Hartog et al. (2006). The indication for the cutoff was found at an energy of 73 ± 15 keV.

A close connection may exist between the production of non-thermal hard X-rays and radio emission. However, until recently all AXPs were radio quiet. For AXP 1E 2259+58 the detection of radio emission has now been claimed by Malofeev et al. (2005), but the observations and analysis were difficult and confirmation is required. Halpern et al. (2005) discovered transient radio emission from the transient AXP XTE J1810-197 which appeared sharply modulated at the rotation period with peak flux densities $>$1 Jy (Camilo et al. 2006), orders of magnitude brighter than the reported upper limits for this or any other AXP. Gaensler et al. (2001) have observed 4U 0142+61 with the VLA (1.4 GHz), but only a 5σ upper limit of 0.27 mJy could be extracted from the data.

4U 0142+61 was the first AXP for which an optical counterpart was discovered (Hulleman et al. 2000). Kern & Martin (2002) found that the optical emission is pulsed for a considerable fraction. Hulleman et al. (2000) showed for the first time that it is not possible to understand the optical and NIR measured fluxes with respect to the X-ray fluxes. There is an optical and NIR excess that can not be explained by the Rayleigh-Jeans tail from the X-ray black body. Moreover the optical and NIR emissions seem to be non thermal and exhibit more variability than seen in the X-rays (Hulleman et al. 2004; Israel et al. 2004b; Morii et al. 2005a; Durant & van Kerkwijk 2006c).

We present the first quasi-simultaneous multi-wavelength observation campaign to study 4U 0142+61 from the radio up to hard X-rays.

5.2 Multi-wavelength campaign

For June–July 2005, 1 Ms INTEGRAL (20–300 keV) dedicated 4U 0142+61 observations were scheduled. With these observations, we tried to get, nearly simultaneously, as much wavelength-band coverage of 4U 0142+61 as possible. An approved 12 hour radio observation with the WSRT (21 cm) was rescheduled to overlap with the INTEGRAL observations. A regular RXTE (2–250 keV) monitoring observation also fell in the INTEGRAL time line. For an X-ray imaging observation a Target of Opportunity (ToO) was granted with Swift (0.2–10 keV). Finally, optical and NIR observations were requested and approved in the Directors' Discretionary Time (DDT) on Gemini North. During two nights 4U 0142+61 was imaged in the K_s and r' bands. Unfortunately it was not possible to schedule the K_s and the INTEGRAL observations contemporaneous (see Table 5.1).

5.2.1 Hard X-rays: INTEGRAL

The INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL; Winkler et al. 2003) is ESA's currently operational hard X-ray/soft gamma-ray space telescope. For the study of AXPs the low-energy detector of IBIS, called ISGRI (20–300 keV Lebrun et al. 2003), has proven itself to be of great importance. The serendipitous discovery of AXPs in the INTEGRAL energy band was a result of the combination of long exposure times and the 29° wide FOV of IBIS.

For this work we have analysed 1 Ms of observations of 4U 0142+61 performed between June 29 and July 17, 2005. The data were screened for solar flares and erratic count rates resulting from passes through the Earth's radiation belts. After screening the net exposure was 868 ks (Table 5.1). The observations consist of 265 pointings (Science Windows, ScWs) which can last up to one hour. The ScWs have been analysed separately with the official INTEGRAL software OSA 5.1 (see Goldwurm et al. 2003, for IBIS-ISGRI scientific data analysis) in 20 energy bands between 20 keV and 300 keV with exponential binning. These analyses result in sky images for every ScW in 20 energy bands. The spectrum was built up by averaging the count rates from each ScW, weighted by the variance. For the conversion into flux values, the spectrum was normalized to the known total Crab spectrum (nebula and pulsar) using a

Table 5.1: *Multi-wavelength campaign measurements*

Obs	Time span	Exposure
WSRT	July 2, 2005	12 h
Gemini K_s	July 26, 2005	1125 s
Gemini r'	July 13, 2005	2400 s
Swift	July 11 – 12, 2005	7400 s
INTEGRAL	June 29 – July 17, 2005	868 ks

curved power law as determined by Kuiper et al. (2006).

4U 0142+61 is detected up to 230 keV with a 3.0σ significance in the 150–230 keV energy band. The total spectrum shown in Fig. 5.1 was fitted with a power-law model resulting in a photon index $\Gamma = 0.79 \pm 0.10$. The quality of the fit is good with a reduced chi square χ^2_r= 1.12 for 16 degrees of freedom. The 20–230 keV flux is $(17.0 \pm 1.4) \times 10^{-11}$ erg cm^{-2} s^{-1}.

Our new total spectrum shows that this AXP is now detected at even higher energies than reported earlier, without an indication for a spectral break. The hint for a break found by den Hartog et al. (2006) is not confirmed in this data set.

5.2.2 Soft X-rays

5.2.2.1 Swift

The Swift-XRT (0.2–10 keV; Burrows et al. 2005) observation was performed on July 11–12, lasting 8500 s. Of this observation 7400 s of data were taken in the Photon-Counting mode and were analysed with the FTOOLS `xrtpipeline`, version build-14 under HEADAS 6.0 (Hill et al. 2005). Photons were extracted from an annular region (3 pixels inner radius, 30 pixels outer radius) in order to avoid pile-up contamination. Background spectra were taken from close-by source-free regions.

As mentioned in Sect. 5.1, AXP spectra in the X-ray domain (< 10 keV) can usually be fitted satisfactorily with a black-body and a power-law model. When we use this canonical model the fit results are: $N_{\rm H} = (1.01 \pm 0.10) \times 10^{22}{\rm cm}^2$; $kT = (0.400 \pm 0.012)$ keV; $\Gamma = 2.7 \pm 0.3$; χ^2_r= 0.97 (dof = 573). These parameters yield an unabsorbed flux of $(3.9 \pm 0.2) \times 10^{-10}$ erg cm^{-2} s^{-1} in the 0.7–6.0 keV band, or $(7.8 \pm 0.5) \times 10^{-11}$ erg cm^{-2} s^{-1} in the more commonly used 2–10 keV band. Such a model fits the measured X-ray spectrum well, but systematically overestimates the flux at the lower X-ray energies. Furthermore it seems meaningless for extrapolation to the NIR window. In particular, the soft power-law component dominates the black-body component for energies less than $\sim$1.5 keV, meaning that also the $N_{\rm H}$ estimate is affected and estimated too high.

Alternatively, we used a double black-body model to fit the measured spectrum, yielding an acceptable fit (χ^2_r= 0.98; dof = 573) with an excellent fit at the lower X-ray energies, but underestimating the higher X-ray energies (> 4.5 keV). The two temperatures are 0.38 ± 0.02 keV and 0.78 ± 0.10 keV and the $N_{\rm H}$ is $(0.61 \pm 0.03) \times 10^{22}{\rm cm}^{-2}$. The unabsorbed flux is $(2.11 \pm 0.06) \times 10^{-10}$ erg cm^{-2} s^{-1} in the 0.7–6.0 keV band and $(6.94 \pm 0.29) \times 10^{-11}$ erg cm^{-2} s^{-1} in the 2–10 keV band. Arguably, this model is again canonical, but it is more appropriate for extrapolation to the NIR, which is shown in Fig. 5.1.

5.2.2.2 Rossi-XTE

4U 0142+61 monitoring data of the PCA (2–60 keV; Jahoda et al. 1996) on board the Rossi X-ray Timing Explorer (RXTE, Bradt et al. 1993) were used to create a phase-coherent timing solution valid during the multi-wavelength campaign (see Gavriil & Kaspi 2002, for a detailed description and use of the AXP-monitoring campaign). This ephemeris is essential for INTEGRAL timing analysis (c.f., den Hartog et al. 2008a). In this work it is used for the WSRT observation in order to reduce the number of trials in the search for a (possible) weak pulsed radio signal. Data from RXTE-observation IDs 90076 and 91070 were analysed with the pulsar-timing software package TEMPO[1]. The resulting ephemeris is valid between MJD 53251 and MJD 53619, with the following characteristics: Epoch MJD 53420.0, $\nu = 0.1150929855(7)$ Hz, $\dot{\nu} = -2.639(8) \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$ and $\ddot{\nu} = 3(2) \times 10^{-23}\,\mathrm{Hz\,s^{-2}}$.

5.2.3 Optical & NIR: Gemini

The field of 4U 0142+61 was imaged in the K_s band with the Near Infrared Imager (NIRI; Hodapp et al. 2003) on Gemini North, Hawaii, in the night of July 26th, 2005. NIRI has standard broad-band and narrow-band filters covering 1–5μm.

The final image was created by subtracting dark frames from each science frame, dividing by a flat field derived from the images themselves, and then aligning and stacking all the images. The photometry was measured using the PSF-fitting package DAOPhot (Stetson 1987), and calibrated against the photometry provided for several field stars in Hulleman et al. (2004). The K_s magnitude was found to be 19.96(10).

Optical r'-band images were obtained on the night of July 13th, 2005 using the Gemini-North Multi-Object Spectrograph (GMOS-N; Hook et al. 2004). We subtracted the bias and divided by screen flats, before stacking and photometering the images. For the calibration, the photometry listed in Hulleman et al. (2004) was used, interpolating between the R and V-bands using the relationship in Smith et al. (2002). We find for 4U 0142+61 $r' = 25.42(6)$, where the statistical uncertainty in the measurement and the uncertainty in the calibration of the photometry zero-point are similar.

5.2.4 Radio: WSRT

Using the Westerbork Synthesis Radio Telescope (WSRT) we have searched for both pulsed and unpulsed radio emission. An observation of 12 hour duration was carried out at a frequency of 1380 MHz ($\sim$ 21 cm) with a bandwidth of 80 MHz. Using the synthesis data a map was made using standard routines in the MIRIAD[2] package. In the resulting map (rms $\sim$30 μJy) no source was detected at the location of 4U 0142+61 leading to a 3σ upper limit on its flux of $\sim$90 μJy. Simultaneously we also summed the signals from all 14 dishes of the WSRT coherently to form a so-called tied array. The data were then sent to the Pulsar Machine PuMa (Voûte et al. 2002) which formed a digital filter bank with 512 channels and a sampling time of 409.6 μs. As the dispersion measure in the direction of the source was unknown, we tried many trial dispersion measures and then folded each one with the RXTE ephemeris (see Sect. 5.2.2.2). Each resultant profile was then inspected to determine if there

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[1] http://pulsar.princeton.edu/tempo

[2] http://www.atnf.csiro.au/computing/software/miriad/

was a significant detection. We also performed a standard pulsar search analysis on the full data set. Neither the folding nor the search revealed any significant detection of radio pulsations. A 5σ upper limit was determined at $77 \times \sqrt{(d/1-d)}\mu\mathrm{Jy}$ where d is the duty cycle of the pulsar. Using $d = 0.5$, a typical value in the X-ray regime, the 3σ upper limit is $\sim$46 μJy. It has to be noted that for this analysis the whole observation was used. A finer analysis like performed by Halpern et al. (2005) and Camilo et al. (2006) who discovered the transient AXP XTE J1810-197 as a bright transient radio source in smaller intervals is still ongoing. However 4U 0142+61 has not exhibited the same sort of transient behaviour in X-rays like XTE J1810-197, specially it has not shown any large outburst, and therefore the radio characteristics of these sources might be very different.

5.3 Multi-wavelength Source-Energy Distribution

In Fig. 5.1 the quasi-simultaneous multi-wavelength Source-Energy Distribution (SED) is presented covering roughly 10 orders of magnitude in photon energy. In the lower left corner the WSRT (1380 MHz) continuum (upper arrow) and timing (lower arrow) 2σ upper limits are shown. The Gemini K_s (2.15 μm) and r' (0.6 μm) data points are dereddened assuming $A_V = 3.6$ as determined by Durant & van Kerkwijk (2006b). The Swift-XRT spectrum between 0.7 keV and 6 keV is corrected for absorption with $N_{\mathrm{H}} = 0.61 \times 10^{22}\mathrm{cm}^{-2}$. Also shown is the corresponding double black-body fit (solid line), extrapolated towards lower energies (dotted line). The INTEGRAL flux values between 20 keV and 230 keV show the hard X-ray spectrum for this AXP. The power-law fit (solid line) is also extrapolated to lower energies (dashed line).

Significant flux variability has been reported in the optical, NIR and soft X-ray bands (Durant & van Kerkwijk 2006c), therefore in this quasi-simultaneous spectrum we can investigate better how the fluxes in the different bands relate to each other.

5.4 Discussion

The results for the different wave-band measurements render separately no surprises. The Swift-XRT spectrum shows a typical soft AXP spectrum and NIR and optical magnitudes are around the earlier reported values. The INTEGRAL spectrum is in agreement with previously found results, however, thanks to the high effective exposure in this dedicated observation the maximum energy up to which 4U 0142+61 could be detected is now higher, namely 230 keV. The spectrum, described with a power-law model with photon index $\Gamma = 0.79 \pm 0.10$ and luminosity $8.7 \times 10^{34}\,\mathrm{erg\,s}^{-1}$ (20–100 keV, d = 3.6 kpc) can be compared with the spectral results reported earlier by den Hartog et al. (2006) using an independent data set: $\Gamma = 0.73 \pm 0.17$ and luminosity $8.5 \times 10^{34}\,\mathrm{erg\,s}^{-1}$ (20–100 keV, d = 3.6 kpc). Kuiper et al. (2006) derived $\Gamma = 1.05 \pm 0.11$ and luminosity $8.1 \times 10^{34}\,\mathrm{erg\,s}^{-1}$ (20–100 keV, d = 3.6 kpc). All these findings are within errors in agreement. Therefore there is no evidence for long-term time variability at hard X-ray energies yet.

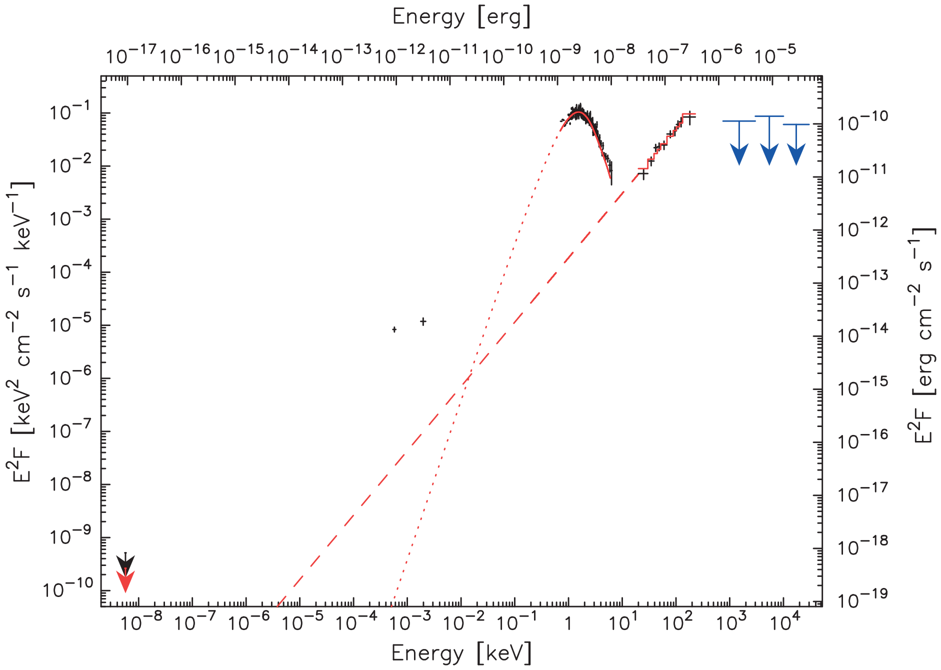

Figure 5.1: *Source-energy distribution of 4U 0142+61 from radio up to gamma-ray energies. For observation details, see Sect. 5.3. The WSRT radio limits are shown for the continuum emission (top arrow) and the pulsed emission (lower arrow). Extrapolations to lower energies are shown for the Swift-XRT double black-body fit (dotted line) and for the INTEGRAL power-law fit (dashed line). It can be seen that neither the soft X-ray nor the hard X-ray spectral fits extrapolate to the Optical and NIR fluxes. An optical-NIR excess orders of magnitude above these extrapolations is evident. The COMPTEL upper limits at MeV energies do not belong to the multi-wavelength campaign.*

den Hartog et al. (2006) published 2σ flux upper limits for 4U 0142+61 in the 0.75–30 MeV window analysing COMPTEL data collected over the years 1991–2000. These observations are obviously not contemporaneous to the multi-wavelengths campaign reported here, but the apparent stability at hard X-ray energies seems to justify a direct comparison of the COMPTEL upper limits with the hard X-ray spectrum measured with INTEGRAL. Thus assuming that the hard X-ray emission is stable, Fig. 5.1 clearly shows that the hard X-ray / soft gamma-ray spectrum of 4U0142+61 has to break between $\sim$ 200 keV and 750 keV in order not to be in conflict with the COMPTEL upper limits. If we were to assume that by chance 4U0142+61 was in a low state at MeV energies during the long COMPTEL observations, it would be remarkable that also for the other AXPs detected similarly by INTEGRAL (1E 1841-045 and 1RXS J1708-4009) no signal was found at MeV energies during the many observations that they were in