Science and Technology Facilities Council
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APPLICATION FOR TELESCOPE TIME (OPTICAL AND INFRARED)

1 TELESCOPE *(AAT, UKST, WHT, INT or UKIRT)*	WHT	Reference:	Date Stamp:
2 SEMESTER	2009A	3 SCIENTIFIC CATEGORY	3

4 COORDINATED PATT PROPOSALS: *AAT:*☐ *UKST:*☐ *WHT:*☐ *INT:*☐ *UKIRT:*☐ *JCMT:*☐ *GEMINI:*☐ *LT:*☐ *MERLIN:*☐

5 PRINCIPAL APPLICANT

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Is the applicant a possible observer? Y

6 COLLABORATORS

Name:	Institute:	Observer?
H. Campbell	University of Sussex	N
K. Romer	University of Sussex	N
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B. Hoyle	University of Portsmouth	N

7 SHORT TITLE OF PROPOSAL *(maximum 12 words)*

Investigating radio-silent Isolated Neutron Star candidates detected in the XMM Cluster Survey

8 SUMMARY OF PROPOSED OBSERVATIONS

ROSAT observations discovered a group of seven, *radio-silent*, dim, and middle-aged Isolated Neutron Stars (a.k.a. XDINSs) with steady and thermal X-ray emission, ascribed to the cooling of the stellar surface. XDINSs are thus considered ideal test cases to probe models of the neutron star interior. Recently, the high magnetic fields ($\approx 10^{13-14}$ G) inferred from the detection of X-ray spectral features suggested that XDINSs are indeed a later evolutionary stage of *magnetars*, young, hyper-magnetized ($B \sim 10^{14-15}$ G), and bursting INSs. Here we request WHT observations of XDINS candidates selected in the *XMM Cluster Survey* based on their soft X-ray spectra and lack of SDSS counterparts. This will push our limits down to magnitude $\sim 26-27$ and to X-ray–to–optical flux ratios of $\approx 10^3$ certifying these sources as XDINSs, the first identified since the *ROSAT* era.

9 FOCAL STATION, INSTRUMENT AND DETECTOR

Focal station:	Instrument:	Detector(s):	Gratings/Filters:
prime	Prime Focus Camera	EEV 2k4k CCDs	BVI

10 OBSERVING TIME REQUESTED THIS SEMESTER

	Dark:	Grey:	Bright:	specify nights *or* weeks:
Time requested this semester	3			N
Minimum useful allocation this semester	3			

UKIRT applicants requiring dark time must justify this in section 18

11 COMPLETE THIS SECTION ONLY IF THIS IS A LONG TERM PROPOSAL

	Dark:	Grey:	Bright:	specify nights *or* weeks:
Total time requested				

Justification for long term status must be given in section 17

Text fonts must *not* be smaller than the style-file defaults

Preferred dates:	March
Impossible dates: *Give justification for impossible dates*	
If observations are to be simultaneous with other telescopes or satellites, give details:	
Any other scheduling constraints: *Include likely clashes with other time applications, constraints on lunar position or quarter, instrument preparation requirements, etc*	The observing nights should be preferably allocated around March 26 in order to match the requested dark time conditions and the requested constraints for target visibility (see Box 18)

13 SERVICE OBSERVING

yes: [ ] no: [x] maybe: [ ]

14 SUPPORT ASTRONOMER REQUESTED AT TELESCOPE

every night: [ ] no: [ ] first night only: [x]

15 LIST OF PRINCIPAL TARGETS

Object(s):	RA(h,m):	Dec(degs):	Mag(type):	Colour:	Exp. Time:
XCS1	11:17:41.002	+07:53:57.66	g> 22.5		3 hours
XCS2	10:51:20.472	+33:54:18.83	g> 22.5		3 hours
XCS3	14:36:05.945	+48:47:05.57	g> 22.5		3 hours
XCS4	13:10:47.731	+37:02:04.45	g> 22.5		3 hours
XCS5	13:18:30.329	+32:41:16.58	g> 22.5		3 hours
XCS6	13:51:26.071	+64:20:10.93	g> 22.5		3 hours
XCS7	09:20:31.721	+30:33:06.23	g> 22.5		3 hours

16 LIST ALL SIMILAR/SUPPORTING APPLICATIONS TO ANY PATT OR OTHER TIME ASSIGNMENT COMMITTEE

You must include a brief description of any other applications whose targets or science goals are similar to those requested here

Telescope/satellite:	Title/Description of programme:

X-ray observations performed by *ROSAT* in the 1990s, pinpointed a class of soft, *radio-silent* X-ray sources characterized by thermal ($kT \sim 50 - 100$ eV) spectra, extreme X-ray–to–optical flux ratios ($> 10^3$), low hydrogen column densities ($N_H \approx 10^{20}$ cm^{-2}), and lack of supernova remnant (SNR) associations (see Haberl 2007 and van Kerkwijk & Kaplan 2007 for recent reviews). While such properties qualify these sources as nearby, faint ($L_X \approx 10^{30}$–10^{31} erg s^{-1}) isolated neutron stars (hence dubbed X-ray Dim INS, or XDINSs), the source powering their X-ray emission has been unidentified for a long time. Their thermal spectra and radio silence initially suggested that XDINSs were old, extinguished radio pulsars accreting from the interstellar medium (ISM) via Bondi-Hoyle accretion. However, at least for some XDINSs, their inferred space velocities were found too high to allow for accretion. On the other hand, their soft X-ray spectra were compatible with XDINSs being middle-aged (~ 1 Myr), cooling neutron stars. This put XDINSs among the best targets to study the thermal evolution of the neutron star surface and, ultimately, to probe its internal structure and composition. Perspectives became more intriguing after the discovery of X-ray pulsations ($P = 3$–12 s) and after finding that the XDINS optical fluxes exceed by a factor of ≈ 10 (or more) the low-energy extrapolation of the X-ray spectra (see, e.g. Kaplan 2008) closely following, at least in the best studied cases, a Rayleigh-Jeans distribution. This might imply a non-uniform star surface temperature distribution (e.g. Pons et al. 2002), with the optical emission coming from a larger and cooler region than that producing the X-rays. Our vision of XDINSs was further twisted when *XMM* revealed, in nearly all of them, broad ($EW \approx 10$–100 eV) absorption features at $E_{\rm line} \approx 0.2$–0.7 keV (see Haberl 2007 and references therein) superimposed on the thermal continuum. These features, likely due to the proton cyclotron resonance and/or to bound-free, bound-bound transition in H,H-like and He-like atoms, imply magnetic fields of $\approx 10^{13} - 10^{14}$ G. These estimates were independently confirmed by the measurement of the period derivative $\dot{P}$ in some XDINSs, which yielded, assuming magneto-dipolar spin-down, $B \sim 2 - 3 \times 10^{13}$ G (van Kerkwijk & Kaplan 2007; van Kerkwijk & Kaplan 2008). Interestingly, magnetic fields of $\approx 10^{14}$ G are not far from those of some younger (a few kyears), tipically radio-silent, INSs discovered in X/γ-rays,i.e. the *magnetars* (see Mereghetti 2008 for a recent review) whose high energy emission is believed to be powered by their ultra-strong magnetic fields (Duncan & Thompson 1992; Thompson & Duncan 1995). While apparently dissimilar in both their high-energy behavior and age, with magnetars featuring bursting/transient X/γ-ray emission and non-thermal spectral tails, their similar long pulsation periods and magnetic fields tantalizingly suggests that the two classes are evolutionary linked.

The only XDINSs identified so far are still the seven sources (a.k.a. "The Magnificent Seven", Popov 2006) originally discovered by *ROSAT*. Systematic XDINSs searches are now being performed both in the *XMM* (Pires & Motch 2008) and *Chandra* (Mignani et al., in progress) X-ray archives. Recently, a few candidate XDINSs have been identified in the *XMM Cluster Survey* (XCS; Romer et al. 2001). A first sample of point-like X-ray sources was initially selected from the XCS data (see, e.g. Fig. 1), based on the similarities of their spectral parameters and those of the "Magnificent Seven", i.e. hardenss ratio $HR < -0.2$, $N_H \approx 10^{20}$ cm^{-2}, and fluxes $\approx 10^{-15}$ erg cm^{-2} s^{-1}. The sample was further screened to filter out X-ray sources with possible optical counterparts detected in one of the bands of the Sloan Digitized Sky Surveys (SDSS) within a generous matching radius of 15 arcsec (Fig. 2). This produced a final working list of seven, point-like XCS sources with XDINS-like X-ray spectra and no SDSS optical counterparts. These X-ray sources were further checked against all optical, infrared, and radio catalogues available in the *Simbad* and *NED* databases to ensure that they have no detected counterpart at these wavelengths (Campbell et al. 2008, in preparation). No optical/UV counterpart was found in the *XMM/Optical Monitor* observations. Aim of this proposal is to perform the first, deep optical observations of our XDINS candidates with the WHT. While their soft X-ray spectra already represent an important piece of evidence, the upper limits on their optical fluxes obtained from the SDSS ($g \geq 22.5$) are not deep enough to tightly constrain their X-ray–to–optical flux ratios which are still a factor of ~ 100 above the values typical for INSs. BVI photometry with the Prime Focus Camera will enable us to classify potential counterparts detected within the error circles and to filter out spurious matches with fore/background objects. In this way we will be able to single out sources with *no* optical counterpart down to magnitude $\sim 26 - 27$, corresponding to X-ray–to–optical flux ratios of $\approx 10^3$. This would certify at least some of our candidates as XDINSs, the first discovered since the *ROSAT* era.

Give details of the technical feasibility of the proposal (S/N,etc) AND any non-standard technical requirements

We plan to perform our observations of all our XDINS candidates (see Box 15) using the Prime Focus Camera on WHT. We preferred this instrument with respect to the Auxiliary Port Imager (API) because of its slightly higher throughput and of its larger field of view (16.2 × 16.2 arcmin). Since the Prime Focus Camera is equipped with a mosaic CCD detector, our targets will be centred in one of the two chips.

We note that, since our targets are point-like, in principle the size of the field of view would not be an issue. However, the smaller API field of view (2.2 arcmin diameter) does not include a sufficient number of reference stars (either from the GSC2 or USNO-B1.0 catalogues), to compute an accurate image astrometry. Furthermore, the larger field of view of the Prime Focus Camera makes it possible to include the positions of a few serendipitous X-ray sources detected in the *XMM* observations. This will enable us to match the position of these sources with those of their optical counterparts detected in the Prime Focus Camera images and to compute the boresight correction to be applied to the default *XMM* coordinates of our targets, which have an average radial positional uncertainty of $\approx 3''$. Here we stress that, given the X-ray–to–optical flux ratio of $\approx 10^3$ typical of INSs, none of our XDINS candidates would be detected in the Prime Focus Camera images, unless it has an anomalously high optical excess (as seen, e.g. in the XDINS RBS 1774; Zane et al. 2008). *We thus expect to single out high confidence XDINSs from those candidates for which we find no optical counterpart.* To this aim, an accurate astrometry is an issue since it allows to avoid possible mismatches due to an incorrect registration of the X-ray coordinate grid into the optical one. As a safe measure, for each of our targets we plan to perform observations in the B, V, and I bands to filter out possible spurious matches with fore/background objects detected within the boresight corrected X-ray error circles. Thanks to the low interstellar extinction ($E(B-V) \approx 0.02$) derived from the $N_H \approx 10^{20}$ cm^{-2} measured along the line of sight of our targets, the observed object colors will provide a preliminary, but reliable enough, spectral classification which will enable us to determine whether or not they are associated to our targets.

We have used the Prime Focus Camera Exposure Time Calculator to estimate the total number of nights requested, assuming an airmass of 1.3, a seeing of 1.0", and dark sky conditions. We found that with a 3600 s integration in each band we can reach $\approx 3\sigma$ limiting magnitudes of $B \sim 27$, $V \sim 26.5$, and $I \sim 25.2$. We remind that the derived constraints on the X-ray–to–optical flux ratios are crucial to single out high confidence XDINSs from our candidates. For this reason, we aim at reaching the faintest possible limiting magnitudes in all the requested bands, which obviously requires dark time conditions. Indeed, relaxing our constraint to grey time conditions would yield, for the same values of airmass and seeing assumed above, limiting fluxes about one magnitude brighter in both the B and V bands, which corresponds to a factor ~ 2.5 in terms of X-ray–to–optical flux ratio.

To summarize, we thus need 3 hours integration time per target (over all the bands), which corresponds to a total of 21 hours for all targets in our list. Each integration will be split in shorter dithered exposures to allow for cosmic rays filtering and bad pixel rejection, which adds a total overhead of 0.12%-0.16% per target depending on the CCD readout speed. Including additional overheads for telescope pointings, guide star acquisition, night time calibrations, etc., and accounting for the target visibility (see below), we estimate that three nights are required to complete our observing program. By using the *Star*-family tools we have determined the optimal visibility window for our targets according to the required dark sky conditions and airmass constraints. We found that the optimal window falls around March 26 2009, i.e. coincident with the New Moon, when all our targets are visible with an airmass better than 1.3 for at least three hours per night.

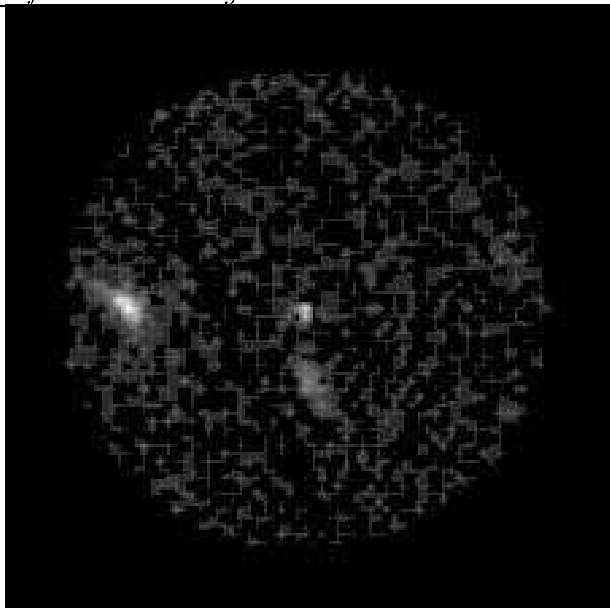

Fig.1 - 1.5 × 1.5 arcmin cutout of the 200 ks *XMM/EPIC-pn* image of one of our XDINS candidates (Campbell et al. 2008) selected from the *XMM Cluster Survey* (Romer et al. 2001). The candidate (XCS1 in our list) is the X-ray source right at the center of the field of view.

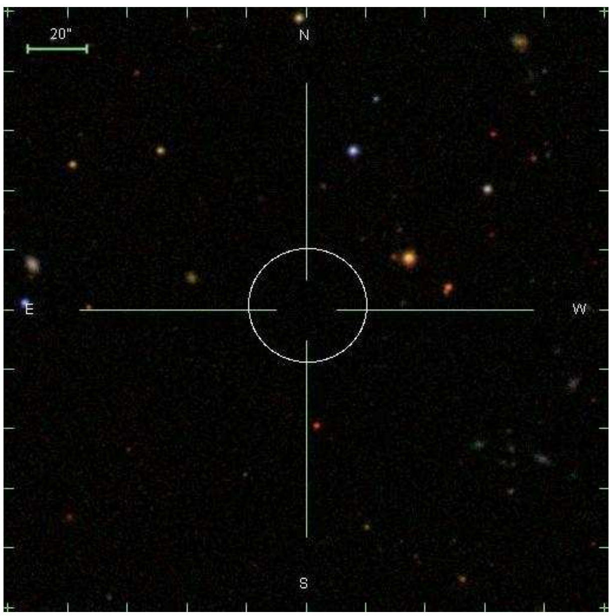

Fig.2 - Composed multicolor SDSS image of the field around the XDINS candidate shown in Fig.1. The circle, of radius 15 arcsec (corresponding to ∼ 5 times the radial positional uncertainty on the X-ray source), marks the area where no candidate optical counterparts are found.

References

- Duncan, R.C., & Thompson, C. 1992, ApJ, 392, L9
- Haberl, F. 2007, AP&SS, 308, 181
- Kaplan, D.L. 2008, Proc. of "40 Years of Pulsars", AIP, 983, 331
- Mereghetti, S., 2008, A&A Rev., in press,[arXiv:0804.0250]
- Pires, A.M. & Motch, C., 2008, Proc. of "40 Years of Pulsars", AIP, 983, 363
- Pons, J.A., et al. 2002, ApJ, 564, 981
- Popov, S. B., Turolla, R., Possenti, A., 2006, MNRAS, 369, L23
- Romer A. K., Viana P. T. P., Liddle A. R., Mann R. G., 2001, ApJ, 547, 594
- Thompson, C., & Duncan, R.C. 1995, MNRAS, 275, 255
- van Kerkwijk, M.H., Kaplan, D.L. 2007, AP&SS, 308,191
- van Kerkwijk, M.H. & Kaplan, D.L. 2008, ApJ, 673, L163
- Zane, S., Mignani, R.P., Turolla, R., et al., 2008, ApJ, 682, 487

If instrumentation or setup differs from main programme, give full details

Our programme focus on observing all candidates in our target list (box 15). No other suitable targets of the same class exist, or are observable from the WHT in period 2009A. If the atmospheric conditions were to turn worse than expected, we will stick to the planned schedule but we will either reduce the number of bands or the number of targets to increase the exposure time and compensate for the varied observing conditions.

20 RELATED PATT APPLICATIONS OVER THE LAST FOUR SEMESTERS *(including unsuccesful applications)*

PATT reference:	Award:	Clear nights:	Comments:

21 PUBLICATIONS BASED ON PATT TIME PUBLISHED DURING THE LAST FOUR SEMESTERS *(maximum 6)*

22 EXPERIENCE OF INTENDED OBSERVERS WHO HAVE NOT PREVIOUSLY USED THIS TELESCOPE

The PI has a well established record of observations both with the ESO telescopes (the 2.2m, the 3.6m, the NTT, and the VLT), with the HST, the CFHT, and the LBT, for a total of more than 150 programmes approved. In particular, the PI has been for two years ESO Survey Scientist and for four years VLT Instrument Operation Scientist.

23 COMPLETE IF THE OBSERVATIONS ARE PRIMARILY FOR A STUDENT RESEARCH TRAINING PROGRAMME

Name of student:

Project title:

24 COMPLETE IF THE OBSERVATIONS ARE ASSOCIATED WITH A CURRENT STFC RESEARCH GRANT

Name of principal investigator:

Grant title:

Grant number:

25 NON-STANDARD TRAVEL AND SUBSISTENCE REQUIREMENTS *(UK observers only)*

Justify requests for travel and subsistence for more than one person:

Details of any other expenditure (eg freight, remote observing):

PATT2 LaTeX style file v3.7 10 February 2008.