

X-ray Astrophysics Laboratory

Measuring the magnetic field of a neutron star in an ultraluminous X-ray pulsar (ULX pulsar): NGC 300 ULX-1

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Overview

The aim of this exercise is to estimate the magnetic field B at the surface of the neutron star (NS) in NGC 300 ULX-1 by combining **our own measurements** (timing analysis of NuSTAR data) with **values from the literature and from catalogues** (distance, flux, bolometric correction). The analysis chain is:

Step	What we measure / estimate	Source
1	Frequency $\nu(t)$ in successive time segments $\rightarrow$ rate of change $\dot{\nu}$	Our own (NuSTAR, Jupyter notebook) — Part 1
2	Flux $F_X \rightarrow$ luminosity $L_X = 4\pi d^2 F_X \rightarrow$ bolometric L_{bol}	XMM-Newton catalogue, Simbad/NED, literature — Part 2
3	Mass accretion rate $\dot{m}$ from L_{bol}	Theory (eq. [3])
4	Magnetic field B from ν , $\dot{\nu}$, $\dot{m}$	Theory (eqs. [1], [5], [6], [7]) — Part 3

A key goal is to understand **how uncertainties propagate** when we combine measurements from different sources: which ones carry a statistical error and which ones are assumptions (systematic uncertainties), and which of them “dominates” the final result.

Chapter 1 contains the theory (to be read before the lab) and Chapter 2 the lab steps and the instructions for the report.

Chapter 1

Theory

1.1 Introduction to X-rays

X-ray observatories produce several kinds of data. Because X-rays are very high-energy electromagnetic radiation, X-ray detectors record **individual photons** (the particle nature of light). For each photon (an “event”) the detector records its **position** on the detector (and hence on the sky), its **arrival time** and a measurement of its **energy**.

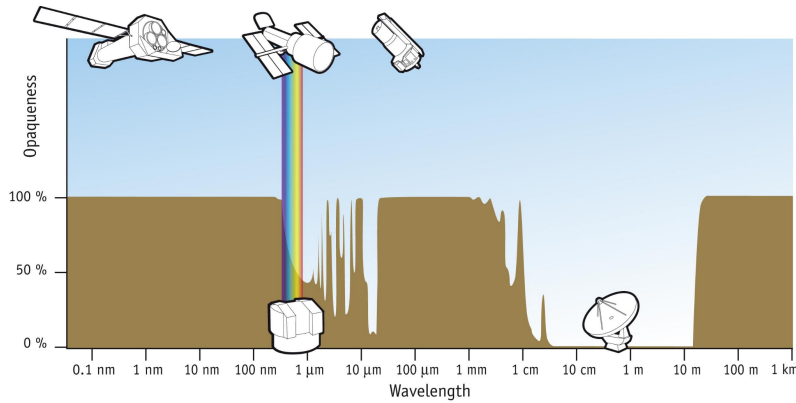


Figure 1: The Earth’s atmosphere absorbs X-rays; this is why we can only observe them from space.

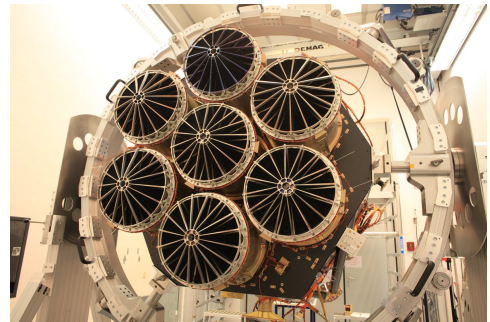
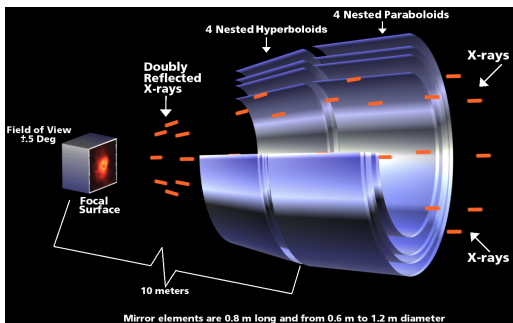


Figure 2: X-rays are focused with Wolter-I telescopes: a combination of parabolic and hyperbolic mirrors on which the X-rays arrive almost parallel to the surface (grazing incidence) and are reflected. To increase the effective area, many coaxial mirror shells are nested inside each other (left: the Chandra mirror assembly). Right: the 7 telescope modules of eROSITA. Even a point source is imaged as a “blob” on the camera; this distribution is called the point spread function (PSF). Its width depends on the quality of the mirrors and differs strongly between telescopes: from $\sim 0.5''$ (Chandra) to $\sim 15''$ (XMM-Newton) and $\sim 1'$ (NuSTAR, half-power diameter). [Image credit: SAO, MPE.]

Images

Images are the most accessible product of X-ray missions. The primary product of an X-ray detector, however, is the **event file**: a table in which every row is one photon, with columns such as position (X, Y), arrival time (TIME) and energy (PI). An image is obtained by making a two-dimensional histogram of the positions, i.e. by counting how many photons fell on each pixel. From the same file, using other columns, we build spectra (a histogram of energy) and

light curves (a histogram of time).

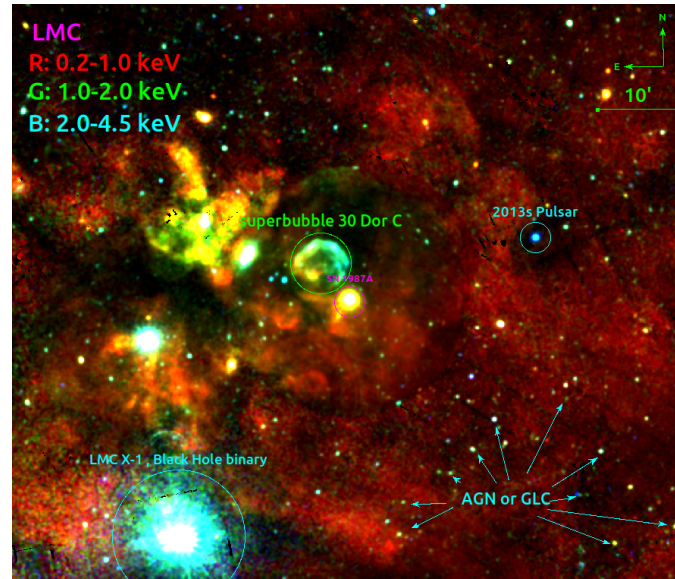


Figure 3: X-ray mosaic of a region of the Large Magellanic Cloud. One can see diffuse hot gas, point sources (pulsars, binaries, background active galactic nuclei) and extended sources such as supernova remnants. Note that the brightest point sources look larger (why? think about the PSF of Figure 2). The colours are “false colours”: they correspond to the flux in specific energy bands (red 0.2–1 keV, green 1–2 keV, blue 2–4.5 keV). [Image credit: G. Vasilopoulos.]

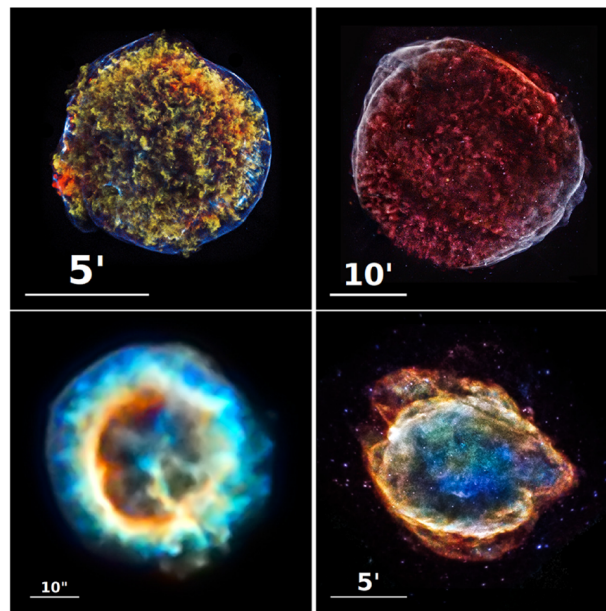


Figure 4: Chandra X-ray images of supernova remnants (SNR). Clockwise from top left: Tycho, SN 1006, G299.2–2.9 and 1E 0102.2–7219. Low-, medium- and high-energy X-rays are shown in red, green and blue, respectively. Synchrotron emission is visible as thin blue filaments in Tycho and SN 1006. The physical scale differs between the images (white bars). [Credit: Chandra X-ray Observatory, <https://chandra.si.edu>]

Spectra

A spectrum is the distribution of radiation as a function of wavelength, frequency or energy. In X-rays the observed spectrum is essentially a **histogram of photon energies**. X-ray spectra

allow us to determine the temperature, density and chemical composition of hot plasmas (stellar coronae, supernova remnants, galaxy clusters). In sources powered by accretion onto compact objects (white dwarfs, neutron stars, black holes), the strong continuum illuminates the surrounding material and produces emission and absorption lines. Optically thin hot plasmas show emission lines from K-shell transitions of almost all abundant elements (from C to Zn) and from L-shell transitions of heavier elements (e.g. Fe-L).

By combining images and spectra we build detailed physical models, e.g. of a galaxy cluster or of the region around a black hole.

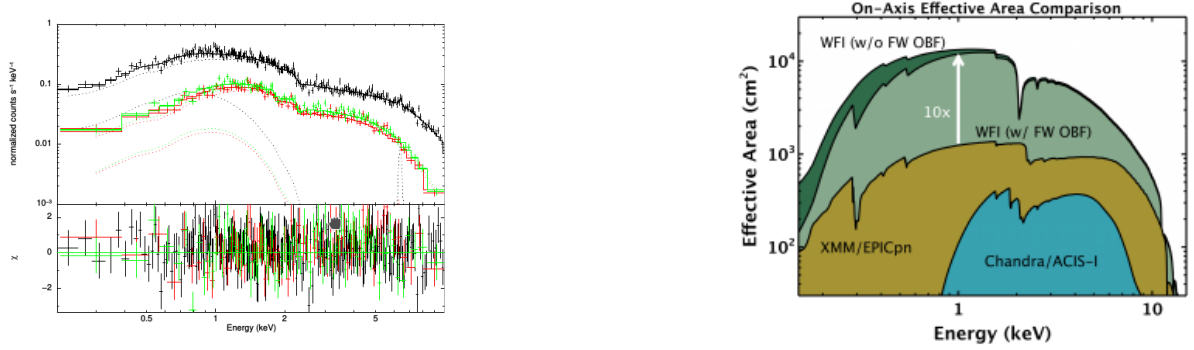


Figure 5: Left: three X-ray spectra fitted with the same model (a blackbody, dominant below ~ 2 keV, plus a power law). The power law does not look like a straight line because we see the spectrum **as recorded by the instrument**, not the intrinsic spectrum of the source: the effective area of the telescope (mirror reflectivity $\times$ detector quantum efficiency) depends strongly on energy. Right: the effective area of three instruments — XMM-Newton/EPIC-pn, Chandra/ACIS-I and the Wide Field Imager of (New)Athena (NewAthena is planned for launch in 2037). Note the drop in efficiency at high energies and the sharp **absorption edges** caused by the materials of the telescope and detector themselves (e.g. C-K at ~ 0.28 keV, O-K at ~ 0.53 keV, Si-K at ~ 1.84 keV and Au-M at ~ 2.2 keV from the mirror coating).

Light curves

Because the arrival time of each photon is recorded, we can study how the emission of a source changes with time. To do so we build a **light curve**, i.e. a histogram of photons as a function of time. Variability is seen, for example, in X-ray binaries and in active galactic nuclei (AGN). It can be periodic (e.g. the orbital period or the spin period of a NS), quasi-periodic, or stochastic (noise).

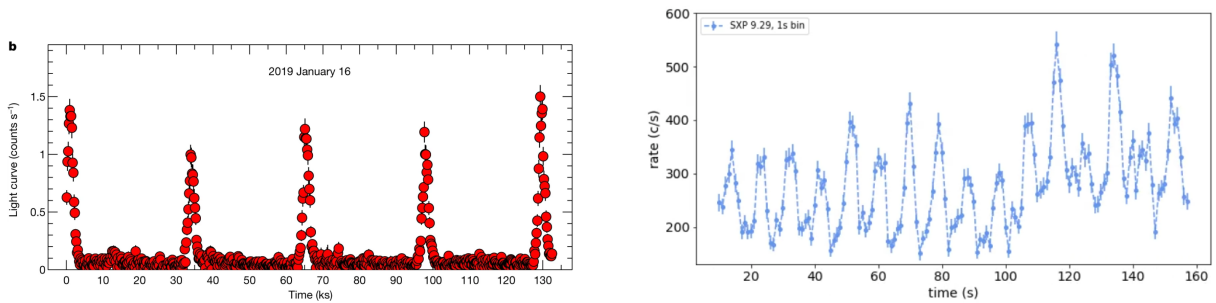


Figure 6: Left: light curve of the galactic nucleus GSN 069, which shows quasi-periodic eruptions (QPEs; Miniutti et al. 2019). Their origin is still an open question. Right: periodic signal from a neutron star in a binary system in the Small Magellanic Cloud; the pulse period is the spin period of the NS.

1.2 X-ray pulsars and ultraluminous X-ray sources (ULX)

X-ray binaries and pulsars

Binary systems in which a compact object accretes matter from a companion star are called X-ray binaries (XRBs). If the compact object is a NS with a strong magnetic field ($B \sim 10^{12}\text{--}10^{13}$ G), close to the NS the matter follows the magnetic field lines and ends up at the magnetic poles. There, hot spots (or “accretion columns”) form that emit X-rays. Because the magnetic axis is not aligned with the spin axis, the hot spots move in and out of our line of sight as the star rotates, producing periodic pulses: we have an **X-ray pulsar**.

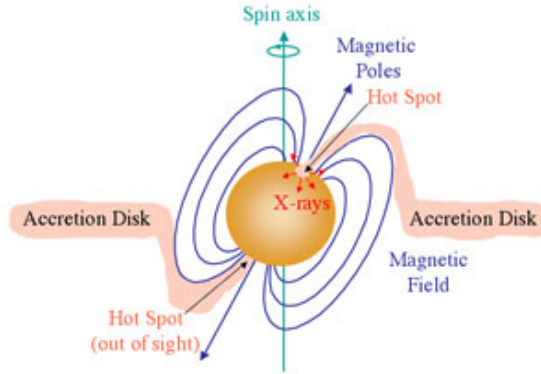


Figure 7: Sketch of an X-ray pulsar: the spin axis and the magnetic axis are inclined, so the hot spot emitting X-rays “rotates” in and out of view. The companion star is not shown.

Known X-ray pulsar periods range from ~ 1.7 ms (millisecond pulsars in low-mass systems) to several hours. Very slow pulsars are usually found in systems where the NS is fed by the stellar wind of a supergiant; their period is set by the balance of the torques acting on the magnetosphere, which depends on B and on the mass accretion rate.

Unlike radio pulsars (see the High-Energy Astrophysics course), which spin down continuously by losing energy through magnetic dipole radiation and a wind of relativistic particles, many X-ray pulsars **spin up**. Some show a fairly steady spin-up, others alternate between spin-up and spin-down. The difference is due to accretion: the matter reaching the NS carries angular momentum, so the NS can gain, lose or keep angular momentum depending on how mass is transferred (Roche-lobe overflow, an accretion disc, a stellar wind, or episodic accretion near periastron of an eccentric orbit). An isolated radio pulsar has no such mechanism and can only lose angular momentum.

Ultraluminous X-ray sources (ULX) and ULX pulsars

Ultraluminous X-ray sources (ULXs) are off-nuclear point sources in galaxies with observed luminosity $L_X \gtrsim 10^{39}$ erg/s, i.e. above the Eddington limit of a NS (see eq. [4]). For years they were considered candidate intermediate-mass black holes. In 2014 pulsations were discovered from M82 X-2 (Bachetti et al. 2014), showing that at least some ULXs are powered by **neutron stars** accreting far above the Eddington limit. Only a few such ULX pulsars (ULXPs) are known today.

In the source we will study, **NGC 300 ULX-1**, pulsations with a period of ~ 31.6 s and an extremely fast spin-up were discovered in 2018, in simultaneous XMM-Newton and NuSTAR observations from December 2016 (Carpano et al. 2018).

1.3 Accretion, magnetosphere and torques

Mind the units. X-ray astrophysics usually works in cgs units (L in erg/s, $\dot{m}$ in g/s, B in gauss). The relations below are also given in SI (as in Carroll & Ostlie), where B is in tesla ($1 \text{ T} = 10^4 \text{ G}$) and μ_0 appears. **Do not mix unit systems** in the same calculation. The “normalised” relations ([1], [2]) do not depend on the unit system.

Keplerian disc

Matter coming from the companion star has angular momentum and does not fall radially onto the compact object. Instead, it forms an accretion disc in which matter moves on nearly circular orbits with the local Keplerian velocity $v_K = \sqrt{GM/r}$ and angular velocity $\Omega_K = \sqrt{GM/r^3}$.

Magnetosphere and Alfvén radius

Let us estimate the characteristic radius inside which the magnetic field of the NS controls the flow of matter. This region is called the **magnetosphere**. We compare the magnetic energy density (pressure), $u_B = B^2/2\mu_0$ (SI) or $B^2/8\pi$ (cgs), with the kinetic energy density of the matter, $u_{kin} = \rho v^2/2$. We assume a dipole field, $B(r) = B_s(R/r)^3$, where B_s is the surface field (at the magnetic equator) and R the NS radius, and that matter falls radially in free fall with $v_{ff} = \sqrt{2GM/r}$. Mass continuity (spherical infall) gives $\dot{m} = 4\pi r^2 \rho v_{ff}$. Setting $u_B = u_{kin}$ and solving for r gives the Alfvén radius:

$$R_A = \left(\frac{8\pi^2 B_s^4 R^{12}}{\mu_0^2 GM \dot{m}^2} \right)^{1/7} \quad (\text{SI}), \quad R_A = \left(\frac{\mu^4}{2GM \dot{m}^2} \right)^{1/7} \quad (\text{cgs, } \mu = B_s R^3),$$

where μ is the magnetic dipole moment. In normalised form:

$$R_A \simeq 1.8 \times 10^3 \left(\frac{B_s}{10^{12} \text{ G}} \right)^{4/7} \left(\frac{R}{10 \text{ km}} \right)^{12/7} \left(\frac{M}{1.4 M_\odot} \right)^{-1/7} \left(\frac{\dot{m}}{10^{-8} M_\odot \text{ yr}^{-1}} \right)^{-2/7} \text{ km} \quad [1]$$

(see Carroll & Ostlie, ch. 18). The Alfvén radius shrinks as the accretion rate increases. For a disc, the inner edge of the disc (the magnetospheric radius) is written as $R_m = \xi R_A$, with a dimensionless factor $\xi \sim 0.3$ – 1 . The value $\xi = 1$ corresponds to spherical infall; for a thin disc $\xi \approx 0.5$ is commonly used (Ghosh & Lamb 1979). **In this exercise we use $\xi = 0.5$ as the baseline value and treat the range 0.3–1 as a source of systematic uncertainty.** At R_m the matter leaves the disc and follows the magnetic field lines onto the NS.

Corotation radius and the propeller effect

The magnetic field lines corotate with the NS at angular velocity $\Omega = 2\pi/P$, where P is the spin period. Matter at the inner edge of the disc moves with the Keplerian angular velocity $\Omega_K(R_m)$. For matter to be “loaded” onto the field lines and accreted onto the NS, it must rotate **faster** than the magnetosphere, $\Omega_K(R_m) > \Omega$. Otherwise the magnetosphere rotates faster than the matter, the centrifugal barrier stops accretion and the matter is ejected (the propeller effect). The necessary condition for accretion is therefore $R_m < R_{co}$, where the corotation radius R_{co} is defined by $\Omega_K(R_{co}) = \Omega$:

$$R_{co} = \left(\frac{GMP^2}{4\pi^2} \right)^{1/3} \simeq 1.7 \times 10^3 \left(\frac{P}{1 \text{ s}} \right)^{2/3} \left(\frac{M}{1.4 M_\odot} \right)^{1/3} \text{ km} \quad [2]$$

A useful quantity is the dimensionless “fastness” parameter $\omega_s = \Omega/\Omega_K(R_m) = (R_m/R_{co})^{3/2}$. For $\omega_s \ll 1$ the NS is a “slow rotator” and receives the maximum spin-up torque; for $\omega_s \rightarrow 1$ it approaches equilibrium, and for $\omega_s > 1$ it is in the propeller regime.

Mass accretion and luminosity

Accretion onto a compact object is one of the most efficient ways of producing energy. In our case the matter releases energy in two stages. In the disc, down to its inner edge R_m , half of the gravitational energy, $GMm/(2R_m)$, is radiated, while the other half remains as kinetic energy of the orbital motion (virial theorem). Inside R_m the matter follows the magnetic field lines and falls almost freely onto the NS surface, where all its kinetic energy is converted into heat and radiation. The total energy per unit mass is GM/R , as if the matter had started at infinity; the disc contributes only a fraction $R/(2R_m)$, which is negligible since $R_m \gg R$. Hence, if all the energy is radiated (and isotropically):

$$L_{acc} = \frac{GM\dot{m}}{R} \Rightarrow \dot{m} = \frac{L_{bol} R}{GM} \quad [3]$$

Note that in ULXs part of the energy may be lost in outflows, or may not be radiated isotropically (geometric beaming); these are additional sources of uncertainty in eq. [3].

The Eddington limit

One of the best-known astrophysical applications of Thomson scattering is the Eddington limit: the luminosity at which radiation pressure on electrons balances gravity acting on protons (for fully ionised hydrogen):

$$L_{Edd} = \frac{4\pi GMm_p c}{\sigma_T} \simeq 1.26 \times 10^{38} \left(\frac{M}{M_\odot} \right) \text{ erg s}^{-1} \quad [4]$$

i.e. $\approx 1.8 \times 10^{38}$ erg/s for a $1.4 M_\odot$ NS. This limit assumes spherical symmetry and ignores the magnetic field. In a NS with a very strong B the matter is channelled into accretion columns, radiation escapes mainly through their sides, and the effective scattering cross-section can be smaller than σ_T ; the limit can therefore be exceeded substantially, as in ULX pulsars.

Torques and spin-up

The interaction of the disc with the NS through its magnetic field transfers angular momentum and changes the spin rate. The main torque due to accretion follows from the angular momentum per unit mass of Keplerian matter at R_m , $\sqrt{GMR_m}$:

$$N_{acc} = \dot{m} \sqrt{GMR_m} \quad [5]$$

In this exercise we assume that the total torque equals the accretion torque, $N_{tot} = N_{acc}$. This assumption is reasonable only if the NS is a “slow rotator” ($\omega_s \ll 1$, i.e. $R_m \ll R_{co}$). From conservation of angular momentum, $N_{tot} = I \dot{\Omega}$, so:

$$\dot{\nu} \equiv \frac{\dot{\Omega}}{2\pi} = \frac{N_{tot}}{2\pi I} \quad [6]$$

where I is the moment of inertia of the NS. We can approximate it with that of a uniform sphere, $I = \frac{2}{5}MR^2 \approx 1.1 \times 10^{45} \text{ g cm}^2$ for $1.4 M_\odot$ and 10 km (realistic NS models give $I \sim (1-2) \times 10^{45} \text{ g cm}^2$). Frequency and period are related by $\nu = 1/P$ and $\dot{\nu} = -\dot{P}/P^2$.

Calculating B

From eqs. [1], [5] and [6], with $R_m = \xi R_A$ and $N_{tot} = N_{acc}$, we can express the surface magnetic field of the NS in terms of $\dot{\nu}$ and $\dot{m}$. The idea is simple: eq. [6] combined with eq. [5] gives the

R_m needed to explain the measured $\dot{\nu}$,

$$R_m = \frac{1}{GM} \left(\frac{2\pi I \dot{\nu}}{\dot{m}} \right)^2,$$

and then eq. [1] (with $R_A = R_m/\xi$) gives B_s . The result, in cgs units ($\mu = B_s R^3$), is:

$$B_s = 2^{1/4} (2\pi)^{7/2} G^{-3/2} M^{-3/2} R^{-3} I^{7/2} \xi^{-7/4} \dot{\nu}^{7/2} \dot{m}^{-3} \quad [7]$$

You will use eq. [7] in the analysis. Before the lab, think about it: how does B_s depend on $\dot{\nu}$, $\dot{m}$, R , M (NS radius and mass) and ξ ? If $\dot{m}$ is uncertain by a factor of 2, how uncertain is B_s ?

Chapter 2

Lab steps

Exercise: Mass accretion and angular-momentum change in a ULX pulsar. We will study **NGC 300 ULX-1**, also known as SN 2010da. The theory needed is in Chapter 1 (Section 1.3).

Part 1: Timing analysis — spin-up of the neutron star

Done in the lab (Jupyter notebook). Read the steps and the notebook before the lab.

Repository: https://github.com/gevas-astro/EKPA_LAB2022W_XRay — notebook: LAB_Xray_walkthrough_2026.ipynb

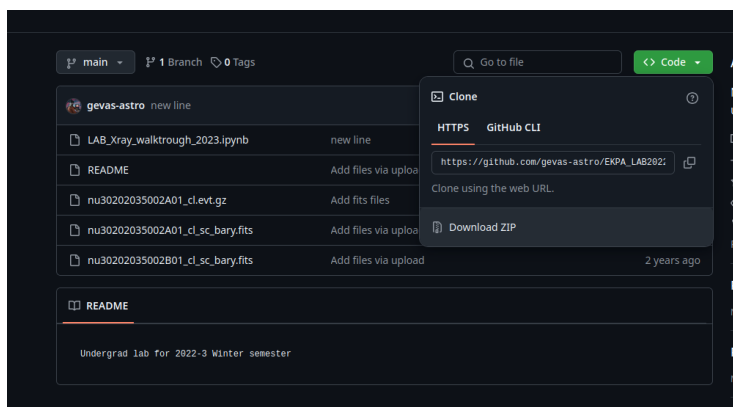


Figure 8: The lab repository on GitHub. From the “Code” button choose “Download ZIP”.

Steps:

1. Create a working folder named with your initials and student ID (e.g. AB2020007). Download the repository from GitHub as a zip file and unzip it inside your working folder. Instructions for the software (conda, Jupyter, python) are given in the lab handout.
2. The data are NuSTAR photon lists (files `*_cl.evt.gz` and `*_cl_sc_bary.fits`, for the two detectors FPMA and FPMB). The `bary` files have arrival times corrected to the Solar System barycentre. Check the observation date in the file header (keyword `DATE-OBS`); you will need it in Part 2.
3. Select the source photons (a circular region around the source) and energies 3–30 keV ($E = 0.04 \times \text{PI} + 1.6$ keV).
4. Build the light curve and look at it. You will notice periodic gaps: think about where they come from (NuSTAR’s orbit around the Earth).
5. Search for a periodic signal with the **epoch folding** method: for each trial frequency we “fold” the photons in phase, build the pulse profile and compute the χ^2 of the profile against a flat (constant) model. The correct frequency is the one that **maximises** χ^2 (the profile deviates most from flat). We will use both ready-made functions (Stingray) and a simple function of our own.

6. The observation lasts ~ 300 ks (~ 3.5 days). During this time the period changes, so a search over all the data at once is not accurate enough. Split the data into shorter segments (as many as you consider appropriate) and find the frequency in each segment. **Careful:** the orbital gaps (~ 96 min) produce secondary peaks (aliases) in the periodogram at $\sim 1/(96 \text{ min}) \approx 1.7 \times 10^{-4}$ Hz from the main peak. Make sure you pick the correct peak in each segment.
7. Plot frequency versus time and fit a linear model $\nu(t) = \nu_0 + \dot{\nu}(t - t_{ref})$. Choose t_{ref} at the middle of the observation. The fit gives the spin-up rate $\dot{\nu}$ and its error.

The $\nu(t)$ plot with the fit, and the value of $\dot{\nu}$ with its error, go into your report.

Part 2: Flux, luminosity and accretion rate

Third 45-minute session of the lab; can be finished at home.

In this part we estimate the accretion rate $\dot{m}$ indirectly, from the luminosity of the source, and examine how much the result depends on where the data come from. At every step write down the value you use, where it comes from, and how uncertain it is.

2a. Distance

1. In Simbad (<https://simbad.cds.unistra.fr/simbad/>) search for the source (basic search) and for its host galaxy, NGC 300.
2. On the galaxy's page, under "Collections of Measurements $\rightarrow$ distance", you will find many distance measurements (Figure 9). A more complete collection is available in NED (<https://ned.ipac.caltech.edu>), under redshift-independent distances.
3. **Which distance do you choose, and why?** Each measurement is based on a different method (e.g. Cepheid variables, the tip of the red giant branch — TRGB) and has a different precision. The smallest quoted uncertainty does not necessarily mean the most reliable value. Write down the range of values: you will use it as an estimate of the systematic uncertainty.

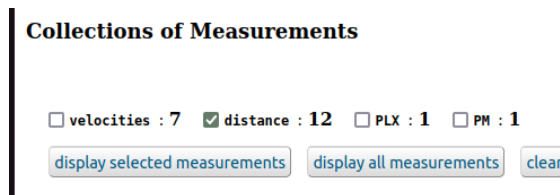
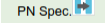


Figure 9: Screenshot from Simbad: there are many distance measurements for NGC 300.

2b. Flux from the XMM-Newton catalogue

1. Go to XCatDB (<https://xcatdb.unistra.fr>, <https://xcatdb.unistra.fr/alixcatdb/>), an online database with the XMM-Newton source catalogue and analysis products (images, spectra, light curves).
2. Search for the source by name (e.g. "SN 2010da") or by its coordinates in the search field (Figure 10), and select it on the map (Figure 11).

3. Under “Details” you can see the XMM-Newton observations and the flux ($\text{ergs}^{-1} \text{cm}^{-2}$) in each one; under “Gallery” there are spectra and light curves (Figure 12, and the icon  for the spectrum).
4. We are interested in observations **0791010101** and **0791010301**. **Check their dates** (and durations) and compare them with the date of the NuSTAR observation of Part 1 (keyword DATE-OBS): are they simultaneous? This matters because the luminosity of the source varies; the flux must correspond to the same period as the measurement of $\dot{\nu}$.
5. **Write down the catalogue flux** F_{XMM} (0.2–12 keV band) for the two observations.

Careful — what exactly is the catalogue flux? In the 4XMM catalogue the “total” flux refers to the 0.2–12 keV band and is computed from the count rate assuming a **generic** spectrum (a power law with photon index 1.7 and low absorption, $N_H = 3 \times 10^{20} \text{cm}^{-2}$); it is the **observed** (absorbed) flux.



Figure 10: Name (sn2010da) or coordinate search field in XCatDB.

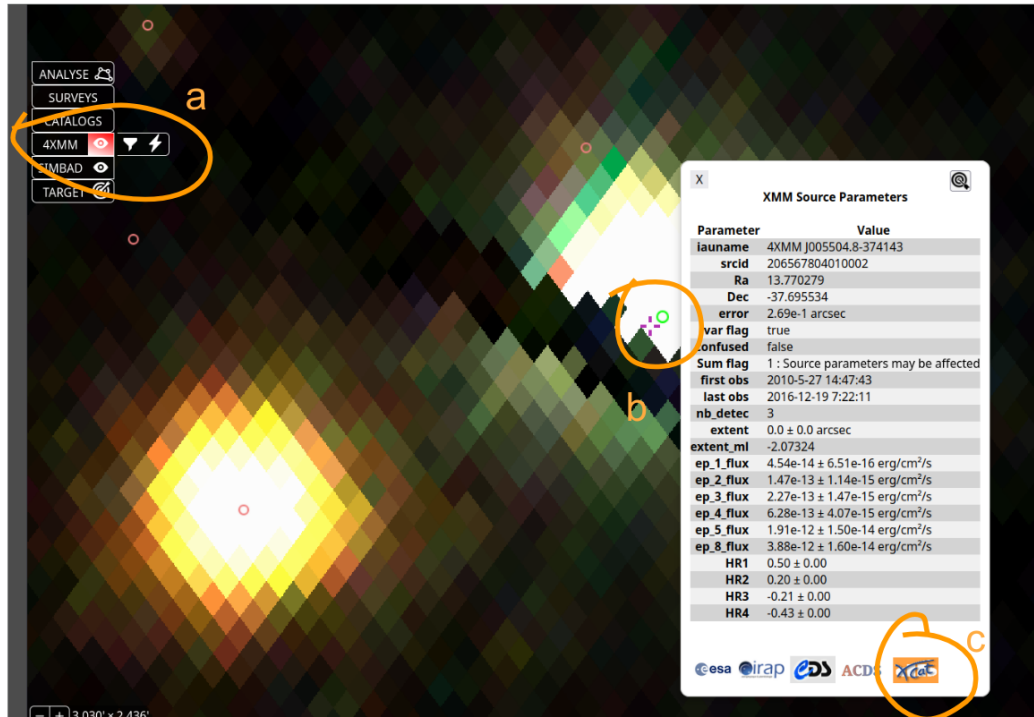


Figure 11: The sky region around NGC 300 ULX-1 (SN 2010da). Steps: (a) on the left select the 4XMM catalogue, (b) select our source, (c) click on the XCat icon.

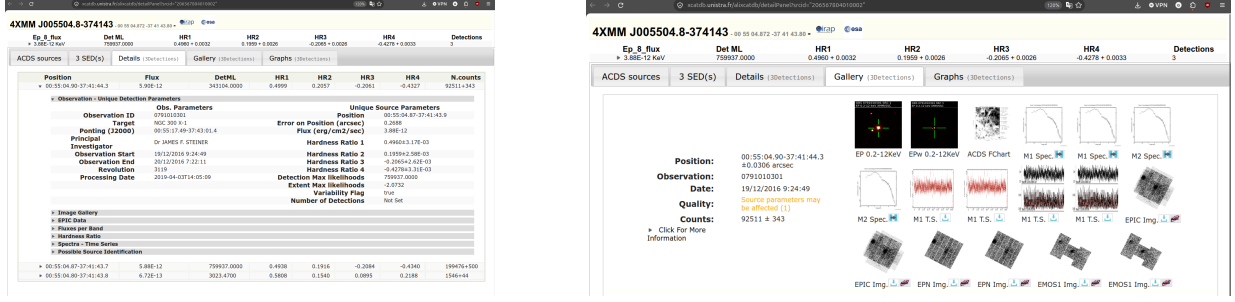


Figure 12: The “Details” and “Gallery” tabs in XCatDB.

2c. Flux from broadband spectral analysis

XMM-Newton measures in a limited energy band, while the spectrum of the source extends to higher energies (as the NuSTAR data show). Estimating the total flux requires a broadband spectral analysis. Carpano et al. (2018) analysed the simultaneous XMM-Newton and NuSTAR spectra and estimated a bolometric luminosity $L \approx 4.7 \times 10^{39}$ erg/s for a distance of 1.88 Mpc. This corresponds to a flux $F_{broad} \approx 1.1 \times 10^{-11}$ erg s $^{-1}$ cm $^{-2}$, which we take as an estimate of the bolometric flux, with an uncertainty of $\sim 10\%$ due to the spectral modelling. Use this flux together with your own choice of distance.

Compute the ratio F_{XMM}/F_{broad} . This ratio is essentially a bolometric correction: what fraction of the total flux does the catalogue “see”? Why do the two values differ? (Think about the energy band, absorption and the generic spectral model assumed by the catalogue.)

2d. Luminosity and accretion rate

Compute the luminosity $L = 4\pi d^2 F_{broad}$ and, from eq. [3], the accretion rate $\dot{m}$ (in g/s and in $M_{\odot}$ /yr). Repeat with F_{XMM} , as if we did not have the broadband spectrum.

Part 3: Magnetic field

We assume that the whole torque is due to accretion (eq. [5]).

1. From eq. [7], with $\dot{\nu}$ from Part 1, $\dot{m}$ from 2d and $\xi = 0.5$, $M = 1.4 M_{\odot}$, $R = 10$ km, $I = \frac{2}{5}MR^2$, compute B_s .
2. Repeat with the $\dot{m}$ obtained from F_{XMM} . How much does B_s change? Explain this in terms of the dependence of B_s on $\dot{m}$ in eq. [7].
3. **Uncertainties.** For each quantity in Table 1, compute how much B_s changes at the ends of its range, keeping the others fixed. Which one dominates?
4. Is the value of B_s reasonable? Compare with typical X-ray pulsars (10^{12} – 10^{13} G) and magnetars (10^{14} – 10^{15} G).

Table 1: Uncertainty budget for B_s .

Quantity	Range	Effect on B_s
$\dot{\nu}$	$\pm 1\sigma$ from the fit	
distance d	range of values in Simbad	
flux F_{broad}	$\pm 10\%$	
ξ	0.3–1	
M	1.4–2.8 $M_\odot$	

Rules

- The lab starts at 14:00; with the academic quarter, the class starts strictly at 14:15. Late arrival has consequences (possibly an absence and a repeat session).
- Reports must be submitted by the deadline set at the end of the four-hour session (usually 1 week). Late submission carries a grade penalty.
- You may discuss the steps, interpretations and problems of the analysis with your classmates. However, to benefit from the lab, work on the programming part (notebook) as independently as you can; every student completes the steps in their own notebook.
- **Use of AI tools:** AI tools (e.g. ChatGPT, Claude) and the internet may be used to help with the code. The text of the report, the calculations and the interpretation of the results must be your own. State briefly (e.g. in a footnote) whether and how you used such tools. Be prepared to explain every step of your work orally.
- The report is written individually, without copying content (numbers, figures, text) from other reports. On plagiarism: <https://eclass.uoa.gr/modules/document/file.php/PHS387/plagiarism%20AUTH.pdf>

Report

Format and content:

- **Length: up to 2 pages (11–12 pt).** No theory is needed; but if you use an analytic relation, write it down and explain its terms. You do not need to submit code.
- **Required figures:** (I) a periodogram (period-search results), ideally for more than one segment; (II) the evolution of the frequency (or period) with time for the NuSTAR observation, with the fitted model. You may add any other figure you find useful. **All figures must have a caption, units on the axes, and be referred to in the text.**
- **Theory:** you may use eq. [7] for B_s directly (you may verify it by derivation), provided you explain every term of the relation in your report.
- **Results:** the rate $\dot{\nu}$ (and $\dot{P}$) with its error, $\dot{m}$, and as the final result B_s with its uncertainty. Where possible, separate the statistical error from the systematic uncertainty. Is the value of B_s reasonable? Compare with typical values for X-ray pulsars (10^{11} – 10^{13} G) and magnetars (10^{14} – 10^{15} G).
- **Uncertainties.** For your measurements, apply error theory (error propagation). In the analysis, however, we also make assumptions or use values from the literature; there, error

propagation may not apply, but you must state the impact of each assumption. If a parameter takes values in a range $[A_{\min}, A_{\max}]$, compute how the final result is affected. Include Table 1 from Part 3. **What is the largest source of uncertainty?**

- **References:** for every value you did not measure yourselves (e.g. distance, flux), give its source. The reference can be in the text (e.g. “Carpano et al. 2018”) or as a footnote with a URL.

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