

X-ray Astrophysics

Research projects

Department of Physics, NKUA 2026

Each project uses public data from X-ray observatories and builds on the tools of the lab exercise. The goal is a short report with one main result (a measurement with its uncertainty) and a comparison with the literature. The references listed for each project are the starting point; the full list is at the end.

1 Dust tomography with X-ray rings

When an X-ray source produces a bright, short flare, part of its photons is scattered by dust grains along the line of sight. These photons travel a longer path and reach us later, from a ring around the source: an X-ray light echo. Photons scattered by one thin dust cloud arrive at the same angle θ , so each cloud makes one ring, and the ring grows with time. For small angles the geometry of Fig. 1 gives

$$\theta(t) = \sqrt{\frac{2c \Delta t (1-x)}{x D}}, \quad (1)$$

where Δt is the time since the flare. If D is known, the size of each ring gives the distance to a dust cloud.

In June 2015 the black-hole binary V404 Cyg ($D \simeq 2.4 \text{ kpc}$, [3]) had one of the brightest outbursts seen in X-rays. *Swift*/XRT and *Chandra* observations in the following weeks show at least five concentric rings [1].

What you will do. Download *Swift*/XRT and/or *Chandra* observations of V404 Cyg from HEASARC, make images and radial profiles around the source, identify the rings and measure their angular radius. Then follow one of two directions:

- **Time evolution:** measure the rings in several observations, check that $\theta \propto \sqrt{\Delta t}$, and use Eq. (1) to find the distance of each dust cloud.
- **Ring structure:** study the rings in one deep observation and compare the dust layers with measurements of the interstellar medium in the same direction (e.g. 3D dust/extinction maps).

A minimum result is the distance of one dust cloud with its uncertainty, compared with [1].

Data: *Swift*/XRT, *Chandra*/ACIS (HEASARC) **Start with:** [1, 2]

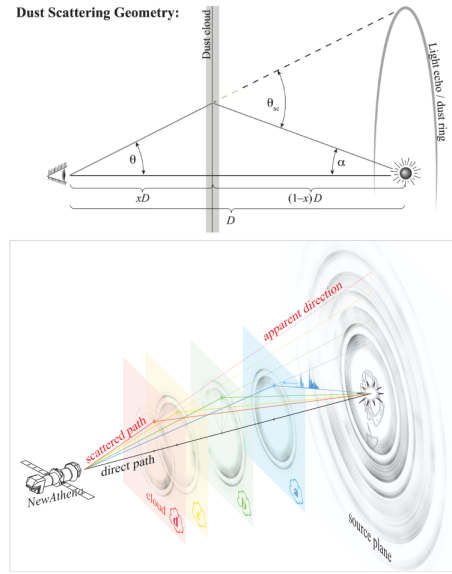


Figure 1: Top: dust-scattering geometry. The observed angle of the echo, θ , depends on the source distance D , the relative distance of the dust $x \equiv D_{\text{dust}}/D$ and the time delay Δt ; photons are scattered by $\theta_{\text{sc}} \geq \theta$. Bottom: several dust clouds along the line of sight produce several rings. Adapted from [2].

2 Spin and magnetic-field evolution of a young neutron star

The spin of an accreting neutron star depends on its magnetic field, on the mass-accretion rate and on time. Usually we know only the present spin period and luminosity, not how old the system is. A neutron star found inside its own supernova remnant is special: the size of the remnant gives an age. For a remnant in the Sedov phase, the radius grows as $R_{\text{SNR}} \propto (Et^2/\rho)^{1/5}$, where E is the explosion energy and ρ the density of the surrounding gas.

XMMU J050722.1–684758 in the Large Magellanic Cloud is a Be/X-ray binary pulsar located close to the centre of the remnant MCSNR J0507–6847 (Fig. 2). Its spin period is long, while the remnant is young [4]. How can a neutron star spin down so much in so little time? With the tools of the lab (Alfvén radius R_m , corotation radius R_{co} , accretion torque) the star passes through three stages:

- **ejector:** the pulsar wind keeps the gas away, and the star spins down as a radio pulsar;
- **propeller:** $R_m > R_{\text{co}}$, the field throws the gas out and the star spins down fast;
- **accretor:** $R_m < R_{\text{co}}$, the gas reaches the surface and the star approaches the equilibrium period where $R_m \simeq R_{\text{co}}$.

What you will do. Measure the spin period of the pulsar from the *XMM-Newton* data, and estimate the age of the remnant from its size. Then write a short Python code that follows $P(t)$ through the three stages for a constant accretion rate (taken from the observed L_X), for a grid of magnetic fields B and initial periods. Find which B bring the star to the observed period within the age of the remnant, and test simple assumptions such as a decaying magnetic field. A minimum result is a plot of $P(t)$ for a few values of B , with the observed P and age range marked, and the range of B that is consistent with the data.

Data: *XMM-Newton* (archive), modelling in Python **Start with:** [4, 5]

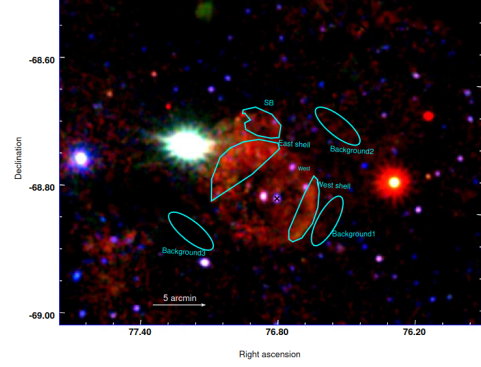


Figure 2: *XMM-Newton* RGB image of the supernova remnant MCSNR J0507–6847 in the LMC (red 0.3–0.7, green 0.7–1.1, blue 1.1–4.2 keV). Cyan: regions for spectral extraction. The cross marks the Be/X-ray binary pulsar XMMU J050722.1–684758; a nearby point source is a background AGN. From [4].

3 A contracting white dwarf?

The spin of a compact object can change for several reasons. In accreting neutron stars, like the one in the lab, the main cause is the torque of the accreted matter. A white dwarf (WD) is much larger, so its moment of inertia is much larger, and the spin-up from accretion is expected to be very small. An alternative explanation for an observed spin-up is that the WD itself is contracting: if its angular momentum $J = I\Omega$ is conserved while its radius R decreases, then for $I \propto MR^2$

$$\frac{\dot{P}}{P} = 2 \frac{\dot{R}}{R}. \quad (2)$$

Such a contraction is expected for young WDs, or after the outer layers are heated by nuclear burning, e.g. after a nova [7].

1RXS J050526.3–684628 in the LMC is a supersoft X-ray source: a WD that still burns hydrogen on its surface, decades after a nova eruption [6]. Its X-ray flux is pulsed (Fig. 3).

What you will do. Use the timing tools of the lab on two *XMM-Newton* observations taken a few years apart: fold the light curve, measure the period in each observation and estimate $\dot{P}$. Then (a) compute the largest spin-up that accretion can give, using the observed luminosity and the formulas of the lab guide, and (b) use Eq. (2) to find the contraction rate $\dot{R}$ needed to explain the measurement. A minimum result is $\dot{P}$ with its uncertainty and a comparison of the two explanations.

Data: *XMM-Newton*/EPIC (two epochs) **Start with:** [6, 7]

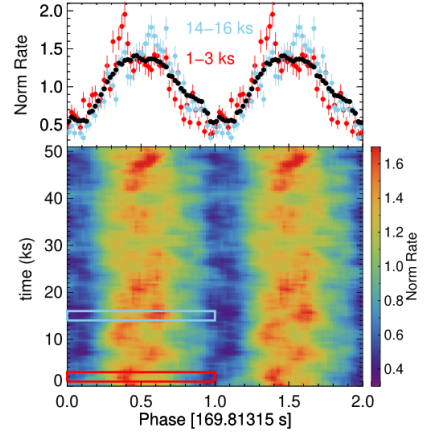


Figure 3: Pulse profile of the supersoft source 1RXS J050526.3–684628 from one *XMM-Newton* observation. Top: average profile (black) and two 2-ks intervals. Bottom: dynamic profile, i.e. pulse phase versus time. From [6].

4 Thermonuclear bursts on neutron stars

In low-mass X-ray binaries a neutron star accretes matter from a companion star. The hydrogen and helium pile up on its surface until the layer reaches a critical density and temperature, and then burn unstably in a few seconds: a thermonuclear or type I X-ray burst (Fig. 4). Nuclear burning releases a few MeV per nucleon, while accretion releases $GM/R \sim 200$ MeV per nucleon. The ratio

$$\alpha = \frac{E_{\text{persistent}}}{E_{\text{burst}}} = \frac{\langle L_{\text{pers}} \rangle t_{\text{rec}}}{4\pi d^2 f_{\text{b}}} \quad (3)$$

of the accretion energy between two bursts to the burst energy therefore tells us about the fuel that burns (t_{rec} is the recurrence time and f_{b} the burst fluence) [8]. The brightest bursts reach the Eddington limit and can be used to estimate the distance.

What you will do. Starting from archival event files (FITS), build light curves in Python, find the bursts and measure their rise and decay times, peak count rate and fluence. Convert to energy for a given distance, measure the persistent emission between bursts and compute α . Compare with the values expected for burning of hydrogen and/or helium. A minimum result is a table of the bursts with their properties and α with its uncertainty.

Data: archival X-ray event files (FITS) **Start with:** [8]

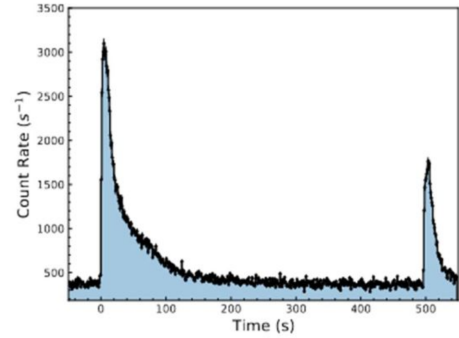


Figure 4: X-ray light curve with two thermonuclear (type I) bursts: a fast rise in a few seconds and a slower decay, on top of the persistent emission from accretion.

5 Spin-up and orbit of a Be/X-ray binary pulsar in outburst

In Be/X-ray binaries the neutron star moves on an eccentric orbit around a Be star and accretes from its decretion disc, often in outbursts that last weeks to months. During an outburst the pulsar spins up, exactly as NGC 300 ULX-1 in the lab, but now we can follow the spin and the luminosity day by day. The *Fermi* Gamma-ray Burst Monitor (GBM) measures the pulse frequency and pulsed flux of many such pulsars [10], and *Swift*/BAT monitors their flux.

The observed frequency changes for two reasons: the accretion torque and the Doppler shift from the orbital motion,

$$2\pi I \dot{\nu}_{\text{int}} = n \dot{m} \sqrt{GM R_m},$$

$$\nu_{\text{obs}}(t) = \nu_{\text{int}}(t) \left[1 - \frac{v_r(t)}{c} \right], \quad (4)$$

where $\dot{m}$ follows the observed luminosity, R_m depends on B , n is a dimensionless torque factor and v_r is the radial velocity of the neutron star in its orbit. Fitting both effects together gives the magnetic field and the orbital parameters (period, projected semi-major axis, eccentricity) [9] (Fig. 5).

What you will do. Choose a Be/X-ray binary outburst from the GBM pulsar pages, download the frequency history and the GBM/BAT flux, and convert flux to luminosity for a known distance. Write a model of Eq. (4) in Python, starting from a circular orbit, and fit it to the data. A minimum result is the orbital period and the magnetic field with their uncertainties, compared with the literature.

Data: *Fermi*/GBM pulsar data, *Swift*/BAT monitor **Start with:** [9, 10]

Tools

All projects use Python (numpy, matplotlib, astropy), an image viewer such as DS9, and, where needed, TOPCAT and the standard mission software (HEASoft). Reading research papers in English is part of every project.

References

- [1] Vasilopoulos G., Petropoulou M., 2016, *The X-ray dust-scattered rings of the black hole low-mass binary V404 Cyg*, MNRAS, 455, 4426. <https://ui.adsabs.harvard.edu/abs/2016MNRAS.455.4426V>
- [2] Heinz S., et al., 2015, *Lord of the Rings: A Kinematic Distance to Circinus X-1 from a Giant X-Ray Light Echo*, ApJ, 806, 265. <https://ui.adsabs.harvard.edu/abs/2015ApJ...806..265H>
- [3] Miller-Jones J. C. A., et al., 2009, *The first accurate parallax distance to a black hole*, ApJ, 706, L230. <https://ui.adsabs.harvard.edu/abs/2009ApJ...706L.230M>

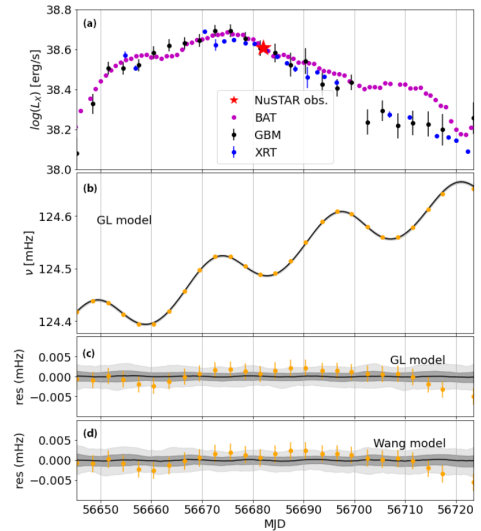


Figure 5: The 2014 outburst of RX J0520.5–6932. (a) Luminosity from *Fermi*/GBM, *Swift*/BAT and XRT. (b) Spin frequency from GBM with a model of accretion torque plus orbital motion (Ghosh & Lamb). (c,d) Residuals for two torque models. From [9].

- [4] Maitra C., Haberl F., Maggi P., et al., 2021, *XMMU J050722.1–684758: discovery of a new Be X-ray binary pulsar likely associated with the supernova remnant MCSNR J0507–6847*, MNRAS, 504, 326. <https://ui.adsabs.harvard.edu/abs/2021MNRAS.504..326M>
- [5] Haberl F., et al., 2012, *SXP 1062, a young Be X-ray binary pulsar with long spin period. Implications for the neutron star birth spin*, A&A, 537, L1. <https://ui.adsabs.harvard.edu/abs/2012A&A...537L...1H>
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- [7] Popov S. B., et al., 2018, *A young contracting white dwarf in the peculiar binary HD 49798/RX J0648.0–4418?*, MNRAS, 474, 2750. <https://arxiv.org/abs/1711.02449>
- [8] Strohmayer T., Bildsten L., 2006, *New views of thermonuclear bursts*, in Lewin W., van der Klis M., eds, Compact Stellar X-ray Sources, Cambridge University Press, p. 113. <https://arxiv.org/abs/astro-ph/0301544>
- [9] Karaferias A. S., Vasilopoulos G., Petropoulou M., Jenke P. A., Wilson-Hodge C. A., Malacaria C., 2023, *A Bayesian approach for torque modelling of BeXRB pulsars with application to super-Eddington accretors*, MNRAS, 520, 281. <https://arxiv.org/abs/2211.16079>
- [10] Malacaria C., et al., 2020, *The ups and downs of accreting X-ray pulsars: decade-long observations with the Fermi Gamma-ray Burst Monitor*, ApJ, 896, 90. Data: <https://gamma-ray.msfc.nasa.gov/gbm/science/pulsars.html>