Thesis subject

Laboratory: Laboratoire d'astrophysique de Marseille (LAM)

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Title of the thesis subject: Simulations of X-ray emission from young stars, photoionised by coronal flares, for XRISM and NewAthena.

Description of the thesis subject:
Pre-main sequence, low-mass stars have a higher X-ray luminosity ($10^{28\text{-}31}$ erg s^{-1}) than the Sun at its cycle maximum (10^{27} erg s^{-1}) and intense flaring activity (up to $10^{32\text{-}33}$ erg s^{-1}). They are extremely active young suns, with most of their X-rays emitted by an active magnetic corona [1]. The rise of high-resolution X-ray spectroscopy strongly motivates new developments of spectral diagnostics for these astrophysical sources. A valuable spectral feature is the fluorescent Kα line of the neutral to low-ionised iron (Fe I–XVII) at 6.4 keV, which probes cool material located close to bright irradiating X-ray sources, from active galactic nuclei to X-ray binaries. This line is also detected in stars when the photospheric iron is ionised either by flare photons with energy larger than its K-shell ionisation potential (7.1 keV) or by collisions with energetic electrons. In the Sun, the emission of the iron $K\alpha_{1,2}$ doublet during X-ray flares is consistent with a photoionised photosphere [2], as computed by Monte Carlo (MC) simulations [3]. In active stars, this line was detected during bright flares [4, 5], where a photoionised photosphere is supported by MC simulations [6], predicting equivalent width of Fe 6.4 keV (EW) up to ~130 eV for iron solar abundance. However, a larger EW (~146 eV) was detected from an evolved protostar during a bright flare, suggesting that the inner accretion disk is also photoionised [7]; similar large EWs were observed from several young stars with accretion disks in the Orion nebula cluster [8, 9]. Much larger EWs were observed from another evolved protostar (~600 eV) [10] and from a flaring young protostar (~1.1 keV) [11], suggesting that the irradiating X-ray source was likely partly eclipsed. Moreover, the magnetic field along the accretion funnels could accelerate electrons that would ionise by collisions the iron of the inner circumstellar-disk [12].

Published MC simulations provide only EW [3, 6], which is sufficient for low-resolution X-ray spectroscopy with CCDs, but too coarse to fully exploit the higher resolution performed by microcalorimeters. Indeed, a 5 eV-resolution microcalorimeter at the focal plane of a large effective-area mirror is more sensitive to faint emission/absorption lines, which will allow for the first time the study of the iron $K\alpha_{1,2}$ doublet (13 eV separation) and its red wing (160 eV-width Compton shoulder) [13], the iron Kβ line and K-shell absorption threshold.

The PhD student will develop, using a public MC radiative transfer code [14], new simulations of a stellar photosphere photoionised by a coronal flare to produce a grid of reflected high-resolution X-ray spectra, for a set of physical parameters (iron abundance, flare temperature, elevation, viewing angle). The new simulated EWs will be compared to published, simulated EWs. The PhD student will then extend the simulation set-up to add the typical components observed around young stars (disk with accretion funnels, large envelope). These new simulated EWs will be compared to the observed EWs. From the computed iron fluorescent lines and threshold, spectral diagnostics will be determined to constrain the ionisation mechanism, the geometry, and the location of the fluorescent iron.

The artificial intelligence will be used to limit the computational cost: the PhD student will train an artificial neural-network with this grid of reflected spectra to emulate a reflected spectrum for any physical parameters [15]. Using in XSPEC [16] this machine-learning emulated, photoionisation model, the PhD student will assess the feasibility with XRISM/Resolve (JAXA, NASA, launched in 2023) and NewAthena/X-IFU (ESA, launch in 2037) [17] to detect in young stars the iron fluorescent lines and threshold, and to constrain the flare geometry and the location of the fluorescent iron.

The PhD student will have access to the LAM cluster and will benefit of the astrophysical data centre of Marseille (CeSAM) at LAM and its machine learning/deep learning division.

References:
[1] Sciortino 2022, in Handbook of X-ray and Gamma-ray Astrophysics; [2] Parmar et al. 1984, ApJ, 279, 866; [3] Bai 1979, SolPhys, 62, 113; [4] Osten et al. 2007, ApJ, 654, 1052; [5] Testa et al. 2008, ApJL, 675, L97; [6] Drake et al. 2008, ApJ, 678, 385; [7] Imanishi et al. 2001, ApJ, 557, 747; [8] Tsujimoto et al. 2005, ApJS, 160, 503; [9] Czesla & Schmitt 2010, A&A, 520, A38; [10] Hamaguchi et al. 2010, ApJL, 714, L16; [11] Grosso et al. 2020, A&A, 638, L4; [12] Pillitteri et al. 2019, A&A, 623, A67; [13] Odaka et al. 2016, MNRAS, 462, 2366; [14] Vander Meulen et al. 2023, A&A, 674, A123; [15] Matzeu et al. 2022, MNRAS, 515, 6172; [16] XSPEC; [17] Barret et al. 2023, Experimental Astronomy, 55, 373.