Thesis subject

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Subject’s title: Preparation to stellar high-resolution X-ray spectroscopy with the microcalorimeters aboard *XRISM* and *NewAthena*: simulations of stellar photosphere and circumstellar material, photoionised by coronal X-ray source to constrain the ionisation mechanism, the flare geometry and the fluorescent-iron location.

Subject description: Young, low-mass stars are conspicuous X-ray emitters. Their high luminosities (~10^{28-31} erg s^{-1}) in X-rays compared to the solar maximum (~10^{27} erg s^{-1}) and intense X-ray flaring activity (up to ~10^{32-33} erg s^{-1}) make them appear as extremely active young suns in the X-ray domain [1]. The analogy with solar activity has been quite successful in ascribing most of the X-ray emission to an active magnetic corona. Progress in sensitivity and spectral resolution in the X-ray domain will be a great leap for our knowledge of the X-ray emission from young, low-mass stars and protostars. In particular, the fluorescent Kα emission line at 6.4 keV of the neutral to low-ionised (Fe I-XVII) iron is a valuable feature to probe any cool material located close to a bright irradiating X-ray source.

The Fe Kα 6.4 keV line was predicted in solar coronal flares, which produce energetic electrons that can ionise by collisions the K shell of the neutral iron of the cooler photosphere [2], and observed with Bragg crystal spectrometer aboard *OSO III* [3]. The photoionisation by X-rays with energy larger than the iron K-shell ionisation potential (~7.1 keV) was then proposed as an other production channel of this line [4, 5]. The systematic study during solar flares of the iron $K\alpha_{1,\,2}$ (~6.404, ~6.391 keV) doublet, resolved by *Solar Maximum Mission*, has shown that the Monte Carlo (MC) simulations of the photoionisation of the solar photosphere by a coronal X-ray source [6] reproduce the observed emission [7].

This iron emission line was also detected in active stars during bright flares that triggered the *Burst Alert Telescope* aboard *Swift* allowing a fast *XRT* follow-up of the X-ray emission [8], or observed by *Chandra* [9]. In these stellar flares, the X-ray photoionisation of the photosphere is the production channel favored by MC simulations, which predict for iron solar abundance, Fe 6.4 keV equivalent widths (EWs) lower than ~130 eV [10].

This iron emission line was detected for the first time from a young stellar object (YSO) with *Chandra* during a bright flare from an evolved protostar peaking to a larger EW value (~146 eV), suggesting that the inner accretion disk is also photoionised [11]. In the Orion Nebula cluster, *Chandra* also observed similar large EW values (~140 eV in average) in several YSOs [12,13]. Much larger EW values were also observed from the protostar V1647 Ori (~600 eV [14]) and during the X-ray flare from a young protostar (~1.1 keV [15]), suggesting that the irradiating X-ray source was likely partly eclipsed. It has also been proposed in YSOs that electrons could be accelerated by the magnetic field along the accretion funnels to produce collisional ionisation of the stellar photosphere [16].

MC simulations of stellar photosphere irradiated by coronal X-rays were made for low-resolution CCD spectroscopy [6, 10], therefore, only provide EWs for a grid of parameters (iron abundance, flare temperature, elevation, viewing angle). Thanks to their higher spectral resolution and grazing mirrors with larger effective area, X-ray microcalorimeters are more sensitive than CCDs to faint emission/absorption lines, which will allow us for the first time to investigate: the iron resolved $K\alpha_{1,\,2}$ doublet (~13 eV separation) and its red wing (~160 eV-width Compton shoulder [17]); the iron $K\beta$ emission line; and the iron K-shell absorption threshold (~7.1 keV), which is the smoking gun of photoionisation.

The PhD student will first have to develop new MC simulations of a stellar photosphere irradiated by a coronal X-ray source to produce reflected high-resolution X-ray spectra for a set of physical parameters (hereafter the reflected-spectra grid). These simulations will be designed and computed with the public MC radiative transfert code, *Geant4* [18]. The PhD student will then extend the simulation set-up to the typical material components observed around YSOs (disk with accretion funnels, envelope). The simulated EWs will be compared to the literature values. From the computed iron absorption line and emission lines, the PhD student will determine spectral diagnostics to constrain the ionisation mechanism, the flare geometry, and the fluorescent-iron location.

To limit the computational cost of the reflected-spectra grid, the PhD student will use artificial intelligence by applying supervised machine learning: an artificial neural network will be built to emulate for any physical parameters a reflected spectrum from the reflected-spectra grid [19]. Using this machine-learning emulated photoionisation model in the worldwide standard *XSPEC* [20], the PhD student will assess the feasibility to detect the iron K-shell absorption threshold and Kβ emission line, and to constrain the flare geometry and the location of the fluorescent iron, with *RESOLVE* aboard *XRISM* (*NASA*, *JAXA*; launched on Sep. 7, 2023) and *X-IFU* aboard *NewAthena* (*ESA*'s large mission, 2037) [21].

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

Bibliography: [1] Sciortino 2022 in *Handbook of X-ray and Gamma-ray Astrophysics*; [2] Acton 1965, Nature, 207, 4998; [3] Neupert et al. 1967, ApJL, 149, L79; [4] Neupert et al. 1969, SolPhys, 6, 183; [5] Doschek et al. 1971, ApJ, 170, 573; [6] Bai 1979, SolPhys, 62, 113; [7] Parmar et al. 1984, ApJ, 279, 866; [8] Osten et al. 2007, ApJ, 654, 1052; [9] Testa et al. 2008, ApJL, 675, L97; [10] Drake et al. 2008, ApJ, 678, 385; [11] Imanishi et al. 2001, ApJ, 557, 747; [12] Tsujimoto et al. 2005, ApJS, 160, 503; [13] Czesla & Schmitt 2010, A&A, 520, A38; [14] Hamaguchi et al. 2010, ApJL, 714, L16; [15] Grosso et al. 2020, A&A, 638, L4; [16] Pillitteri et al. 2019, A&A, 623, A67; [17] Odaka et al. 2016, MNRAS, 462, 2366; [18] *Geant4*; [19] Matzeu et al. 2022, MNRAS, 515, 6172; [20] *XSPEC*; [21] Barret et al. 2023, Experimental Astronomy, 55, 373.