Time-varying X-ray emission from stellar flares and its impact on disk evolution

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Short Abstract

X-rays have significant impacts on cold, weakly ionized protoplanetary disks by increasing the ionization rate and driving chemical reactions. Stellar flares are explosions that emit intense X-rays and are the unique source of hard X-rays with an energy of ≳ 10 keV in the system. Hard X-rays should be carefully taken into account in models as they can reach the disk midplane. However, previous models are insufficient to predict the hard X-ray spectra because of the simplification in flare models. We develop a model of X-ray spectra of stellar flares based on observations and flare theories. The flare temperature and nonthermal emissions are modeled as functions of flare energy, which allows us to better predict the hard X-ray photon flux than before. Using our X-ray model, we conduct radiative transfer calculations to investigate the impact of flare hard X-rays on disk ionization. We demonstrate that X-ray photons with ≳ 10 keV penetrate down to the midplane to increase the ionization rates more than galactic cosmic rays. These results emphasize the importance of stellar flares on the disk evolution.

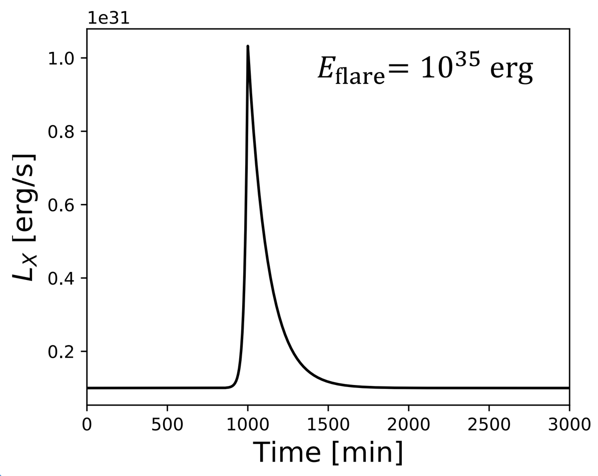
Motivation : How do the X-rays from stellar flares affect the ionization condition in protoplanetary disks?

- Stellar UV & X-ray radiations impact on disk evolution via photoevaporation and photoionization. e.g., Walsh+12, Ercolano & Glassgold 13, Nakatani+22
- The ionization activates non-ideal MHD effects (e.g., Wardle 07, Bai 17) and chemical reactions (e.g., Henning+10, Waggoner & Cleeves 22) in disks.

→ **Stellar ionizing radiation is quite important to understand the disk physical/chemical structures and their evolution.**

X-ray model of Stellar Flares

- Flares are the unique source of hard X-rays (≳10 keV) in protoplanetary disk systems.
- Previous models underestimate the flare hard X-rays. We model stellar flares based on flare theory and observations.



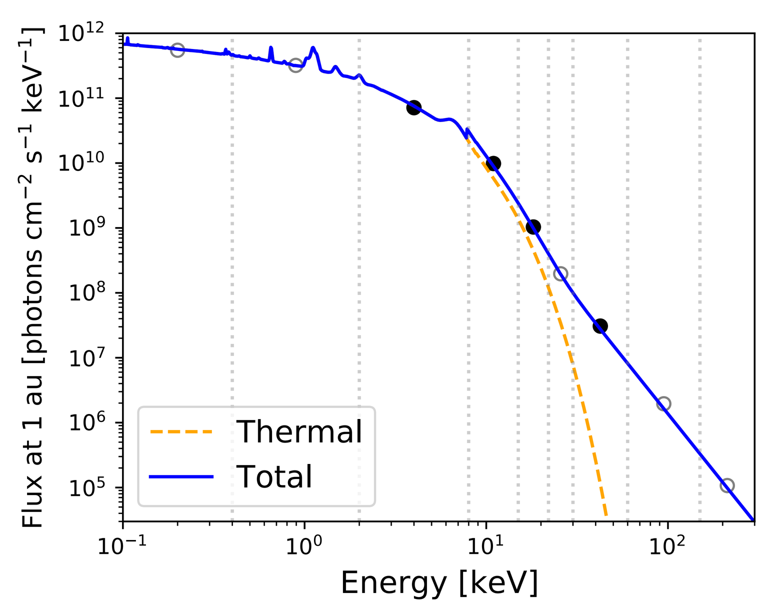
X-ray light curve for a given E_{flare}

$L_X = L_{X,peak} \times \exp(t/\tau)$ Getman+08, Aschwanden+12

- $t < t_{peak}$: $\tau = \tau_{rise} \propto E_{flare}^{1/3}$ Maehara+15
- $t \geq t_{peak}$: $\tau = -\tau_{decay} \propto -\tau_{rise}^{0.44}$ Getman+21

X-ray spectrum for a given E_{flare} – thermal + nonthermal components

Spectrum at the peak of flare with $E_{flare} = 10^{35}$ erg



Photon flux : $F_{total} = \alpha F_{th} + \beta F_{nth}$

- F_{th} is computed by Chiantipy using T_{flare} & EM

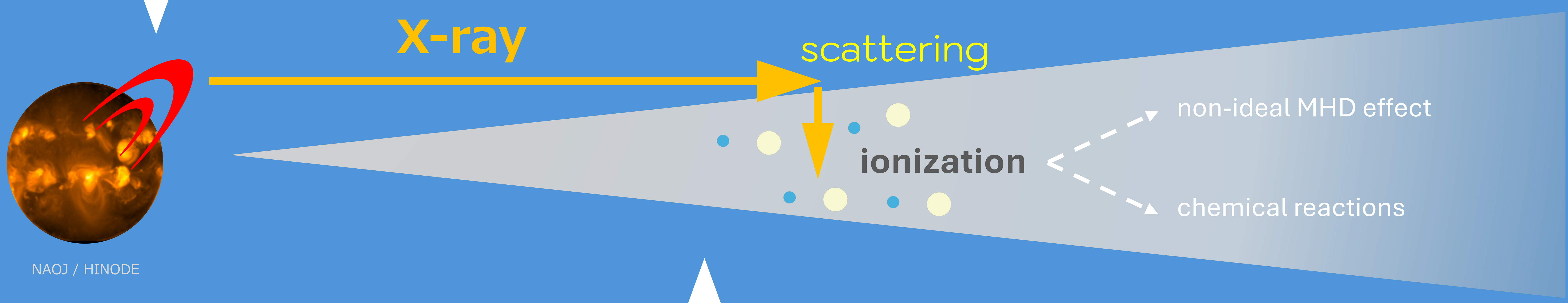
$T_{flare} \propto E_{flare}^{2/21}$ Yokoyama & Shibata 98; Shibata+13

$EM \propto T_{flare}^{8.5}$ Shibata & Yokoyama 99, 02

- F_{nth} is modeled with a single power-law formulation Grigis & Bentz 04, Oka+18

$F_{nth} = A\, E^{-\gamma}$ at $E > E_{lc}$

Our model can better predict T_{flare} & hard X-ray photon flux than before.



Radiative Transfer Calculation of a Disk around a T Tauri Star

Radiative transfer by RADMC-3D code (Dullemond+2012)

- We perform the **monochromatic Monte Carlo runs** to obtain the mean intensity.
- Star : a classical T Tauri star ($M_* = 0.5\, M_\odot, R_* = 2.0\, R_\odot, T_{eff} = 4000$ K)

Disk : $M_d = 0.01 M_\odot$, dust-to-gas mass ratio =0.01, dust size = $0.1\, \mu m$

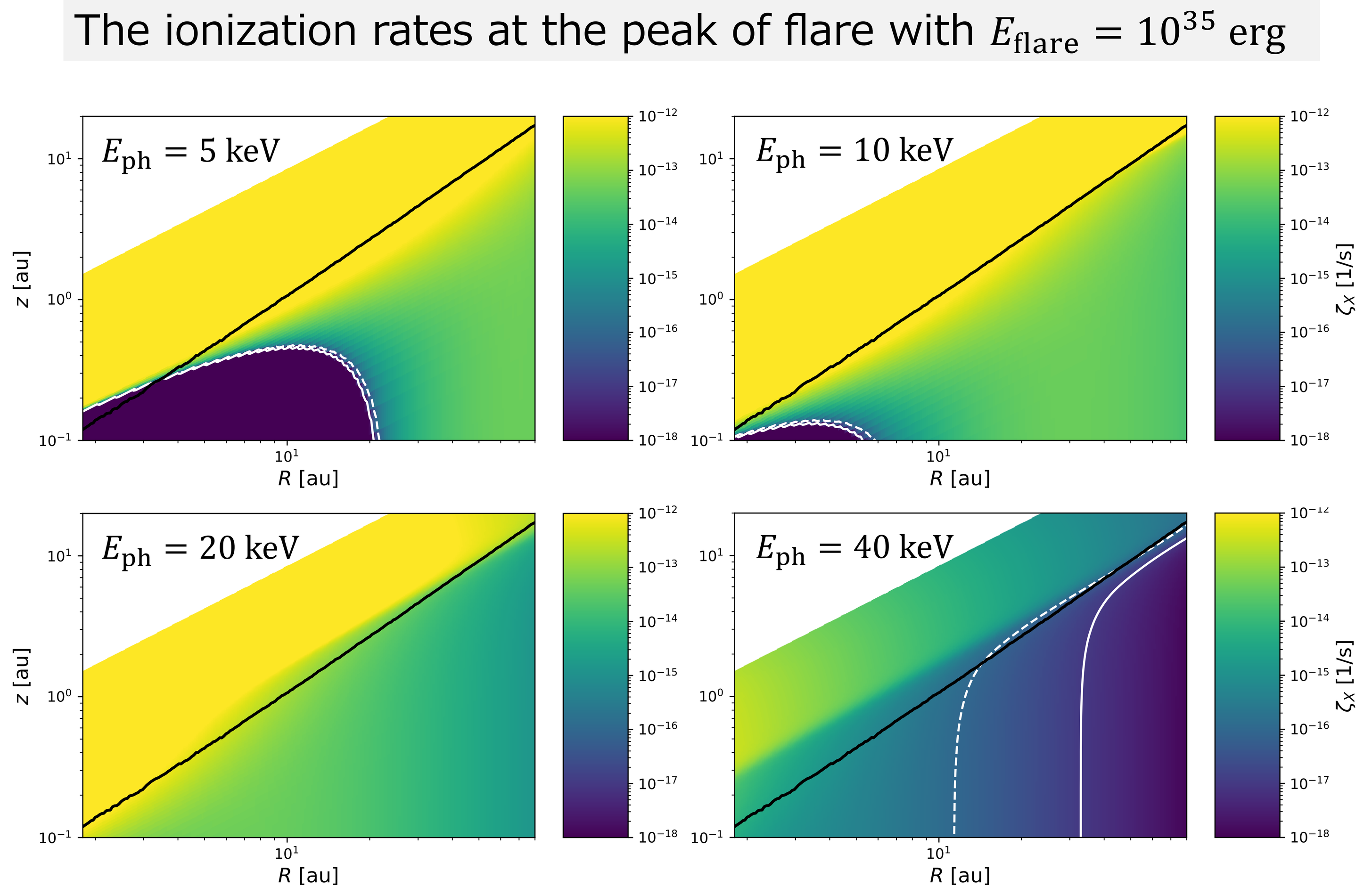
Result : Spatial structures of the ionization rate

- **Ionization rate ζ_X** is calculated using **mean intensity** : $\zeta_X = 4\pi \int \sigma_X J_X / \Delta\epsilon\, dE$
- **X-rays with the energy of 20 keV enhance ζ_X in the widest range of radii.**

Photons with 5 & 10 keV cannot penetrate the inner disk due to the absorption.

Photons with 40 keV contribute to the ionization only at inner radii because of the small photon flux.

The ionization rates at the peak of flare with $E_{flare} = 10^{35}$ erg



- We constructed a model of X-ray spectra of stellar flares based on solar/stellar theories and observations.
- We found that flare X-rays significantly affect the ionization rate at the disk midplane in a wide range of radii.
- **If you get interested in our work, please check our paper on arXiv.org ! (submitted to ApJ)** → → →

-- we also discuss the time-averaged effect from multiple flares on disk ionization