Time-resolved Spectroscopy of Stellar Flare Dynamics with Chandra X-ray Data

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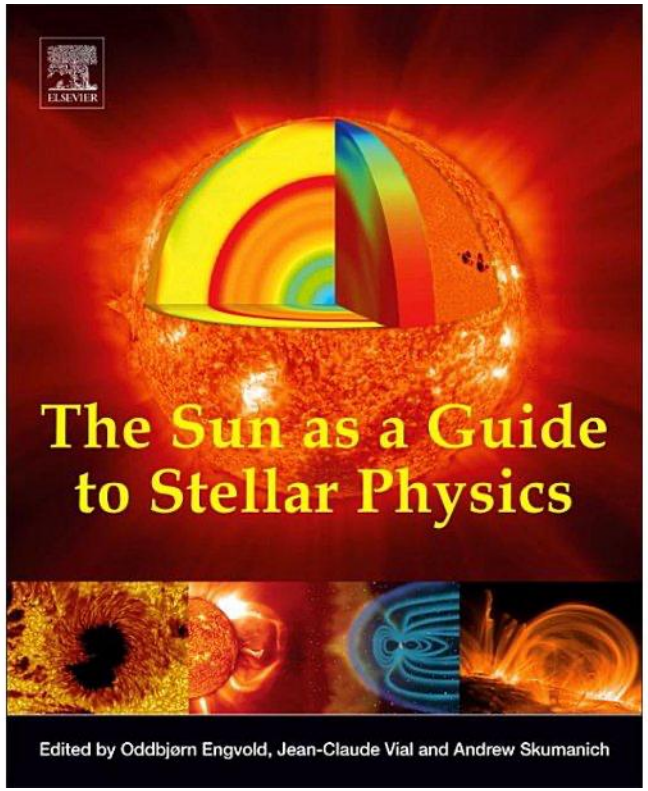
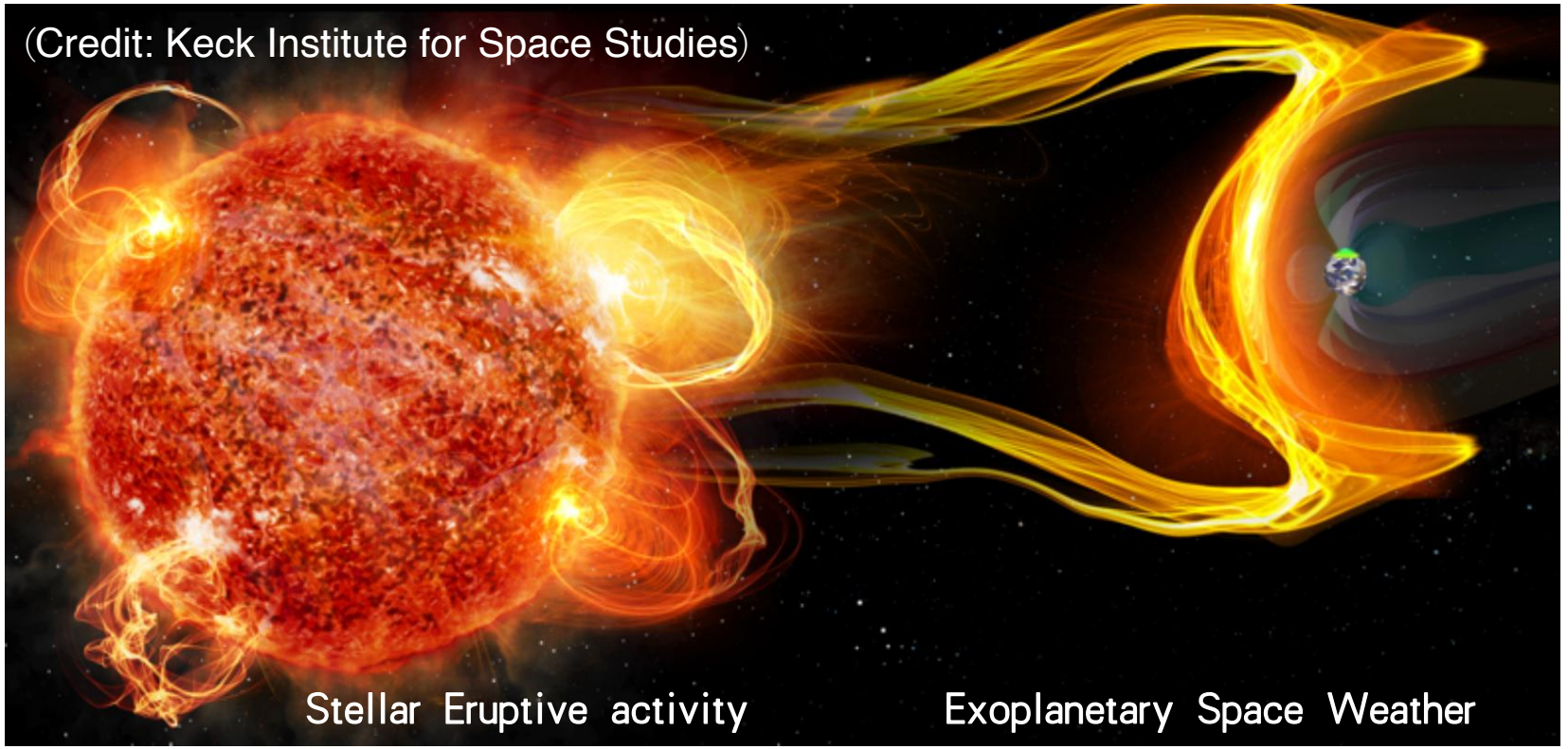
Solar–stellar Connections

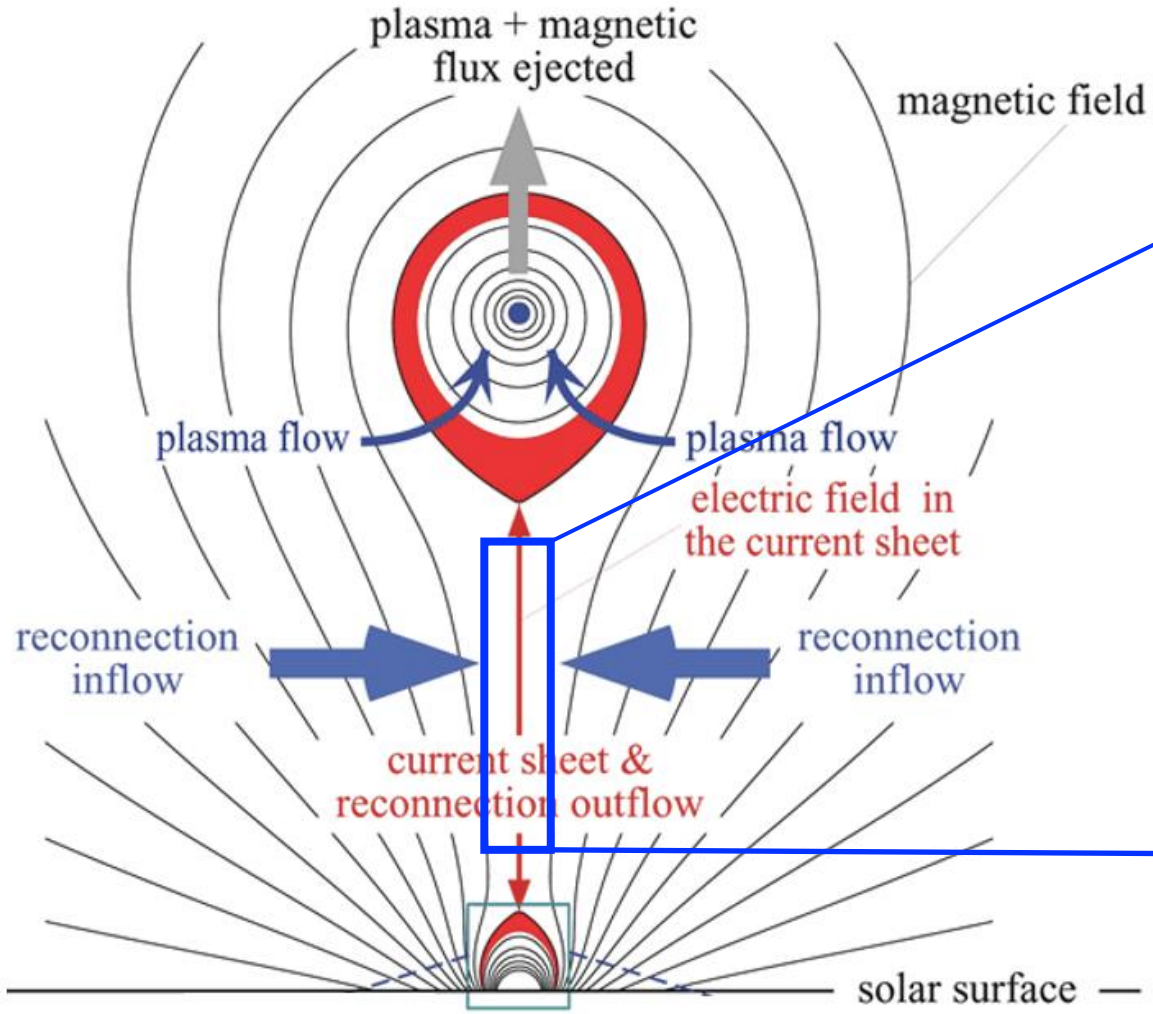




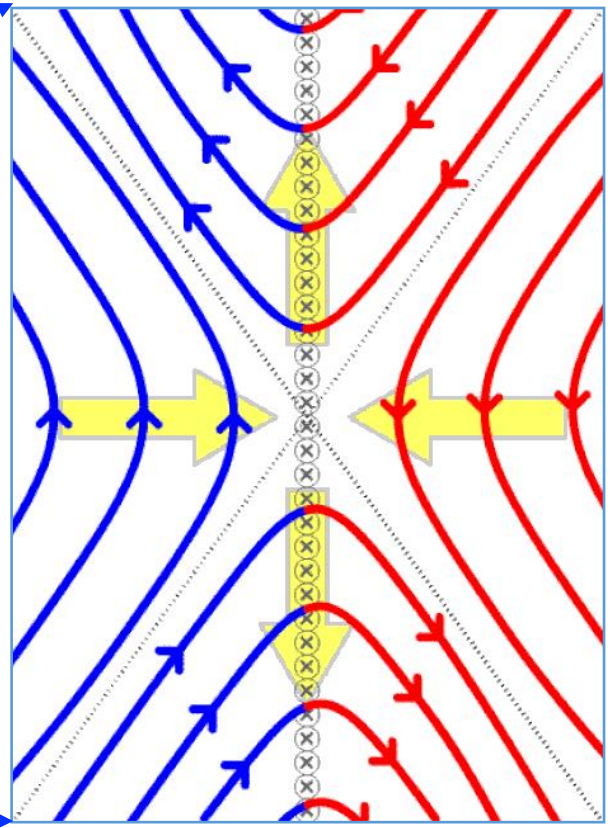
Whether stellar flares (especially on M dwarfs) share a same mechanisms with solar flares?
Whether they are associated with CMEs leading to extreme exoplanetary space weather ?

(see Airapetian et al. 2020)

The standard flare model



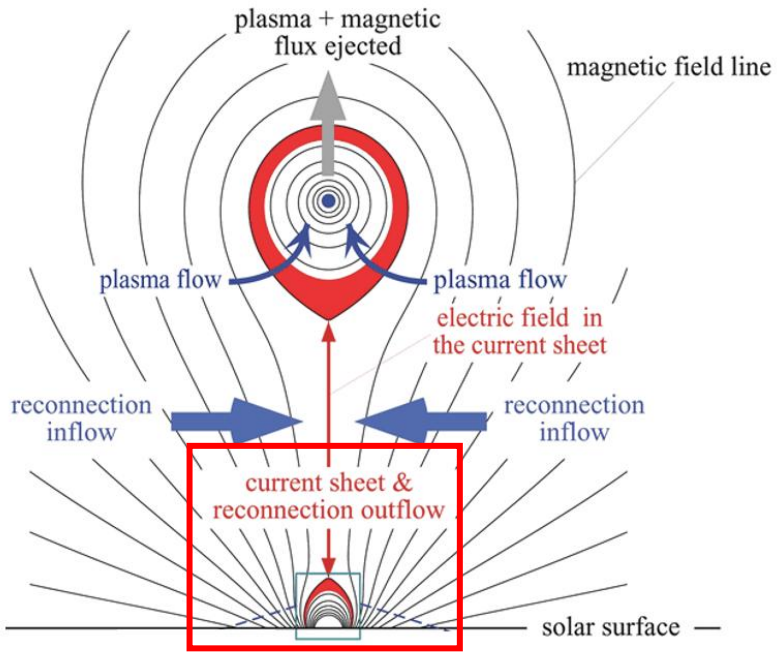
(Lin & Forbes 2000; Lin 2004)



Magnetic Reconnection

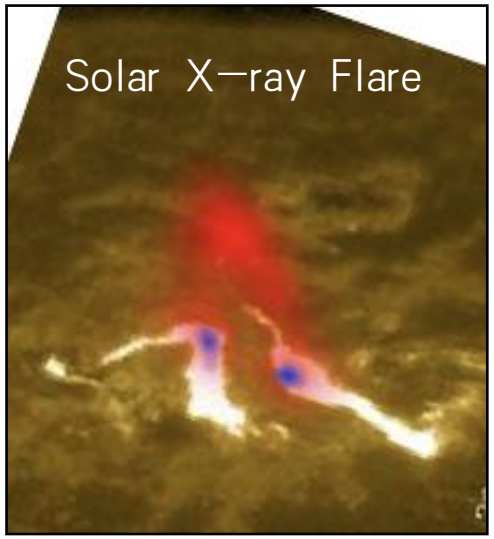
The Central Engine of Energy Release in Solar Eruptions

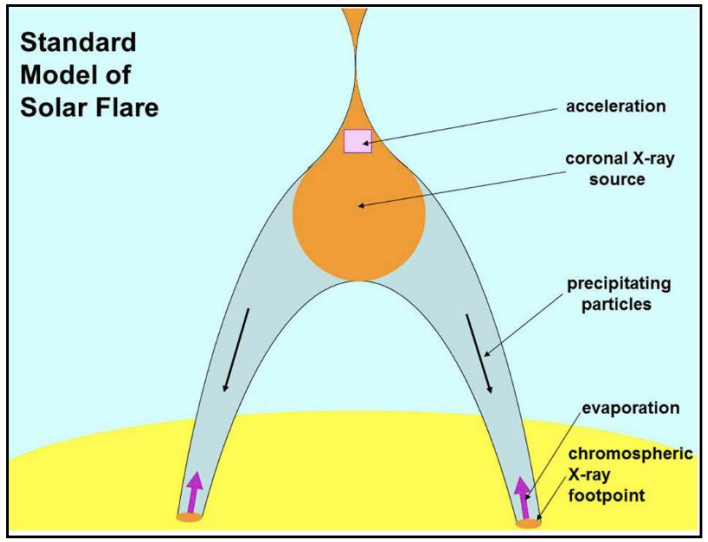
The standard flare model



(Lin & Forbes 2000; Lin 2004)

Chromospheric evaporation





(Benz 2017)

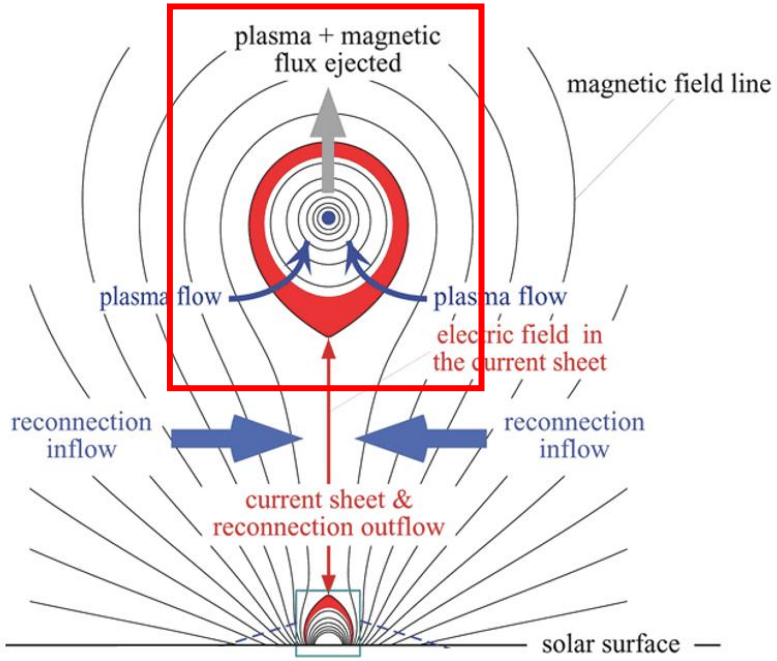
On the Sun, chromospheric evaporation have been well observed by imaging and spectroscopy
(e.g., Milligan et al. 2006, 2008; Li et al. 2011, 2015ab, 2017, 2019; Tian et al. 2014, 2015, 2018; Zhang et al. 2013; 2016; 2019)

On Stars, chromospheric evaporation are still poorly observed, especially in EUV and X-rays.

- only predicted by indirect evidence: Neupert effect, density variation etc.

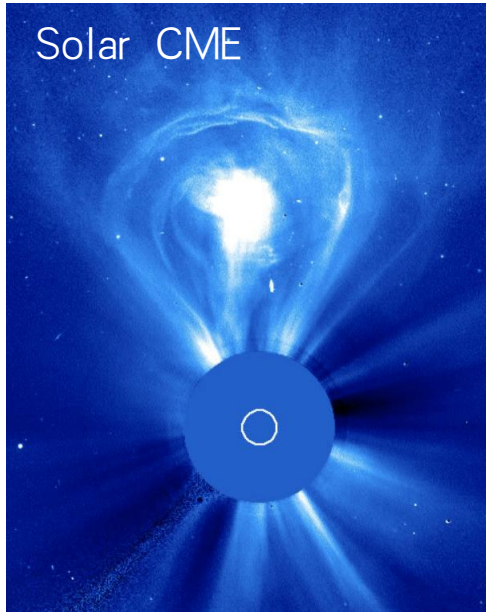
(e.g., Hawley et al. 1995; Güdel et al. 1996; 2002; Laming & Hwang 2009; Güdel & Nazé 2009, 2010; Linsky 2019)

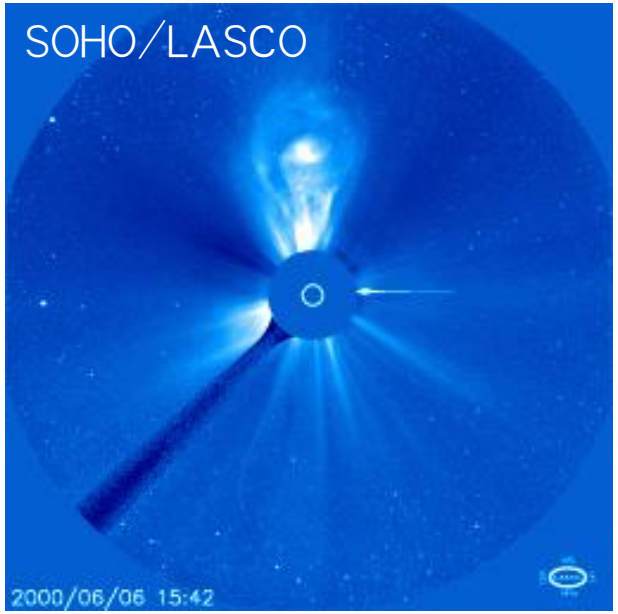
The standard flare model



(Lin & Forbes 2000; Lin 2004)

Coronal Mass ejections (CMEs)





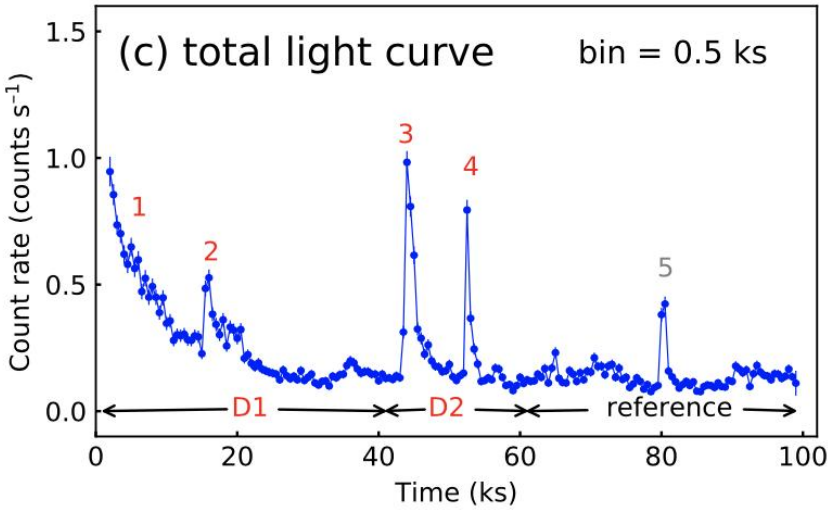
On the Sun, CMEs have been routinely detected by the solar white-light coronagraphs (e.g., Brosius 2003; Teriaca et al. 2003; Milligan et al. 2006; Milligan 2008; Li et al. 2015; Tian et al. 2015; Zhang et al. 2016)

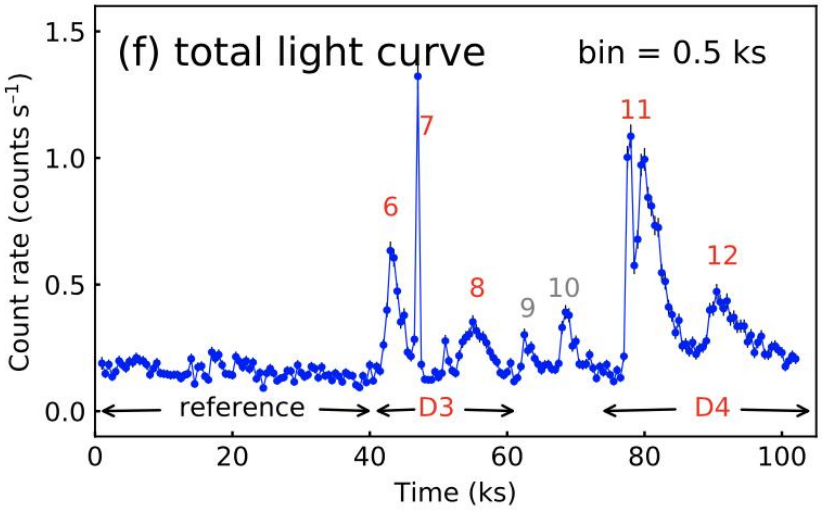
On other stars, imaging the stellar coronae is impossible at least in the foreseeable future.

- many attempts have been made to detect stellar CMEs (e.g., Moschou et al 2019)
- convincing evidence of stellar CMEs are very rare yet. (e.g., Houdebine et al. 1990; Vida et al. 2016; Argiroffi et al. 2019; Veronig et al. 2021; Namekata et al. 2021)

Stellar flares on EV Lac

Here, we report the detection of noticeable flare-induced plasma flows during stellar flares on a nearby M dwarf EV Lac.





Their velocities in the range of 40-130 km/s and only appear as flares occur.
>> The spinning velocity of EV Lac is 4.5 km/s
>> The accuracy of velocity measurements of The Chandra/HEGS : 10-20 km /s
(see Ishibashi et al. 2006; Argiroffi et al. 2017)

Our analysis of the time-resolved Chandra/HEGS spectra

MEG Composite X-Ray Spectra

over different time periods (~ tens of ks)

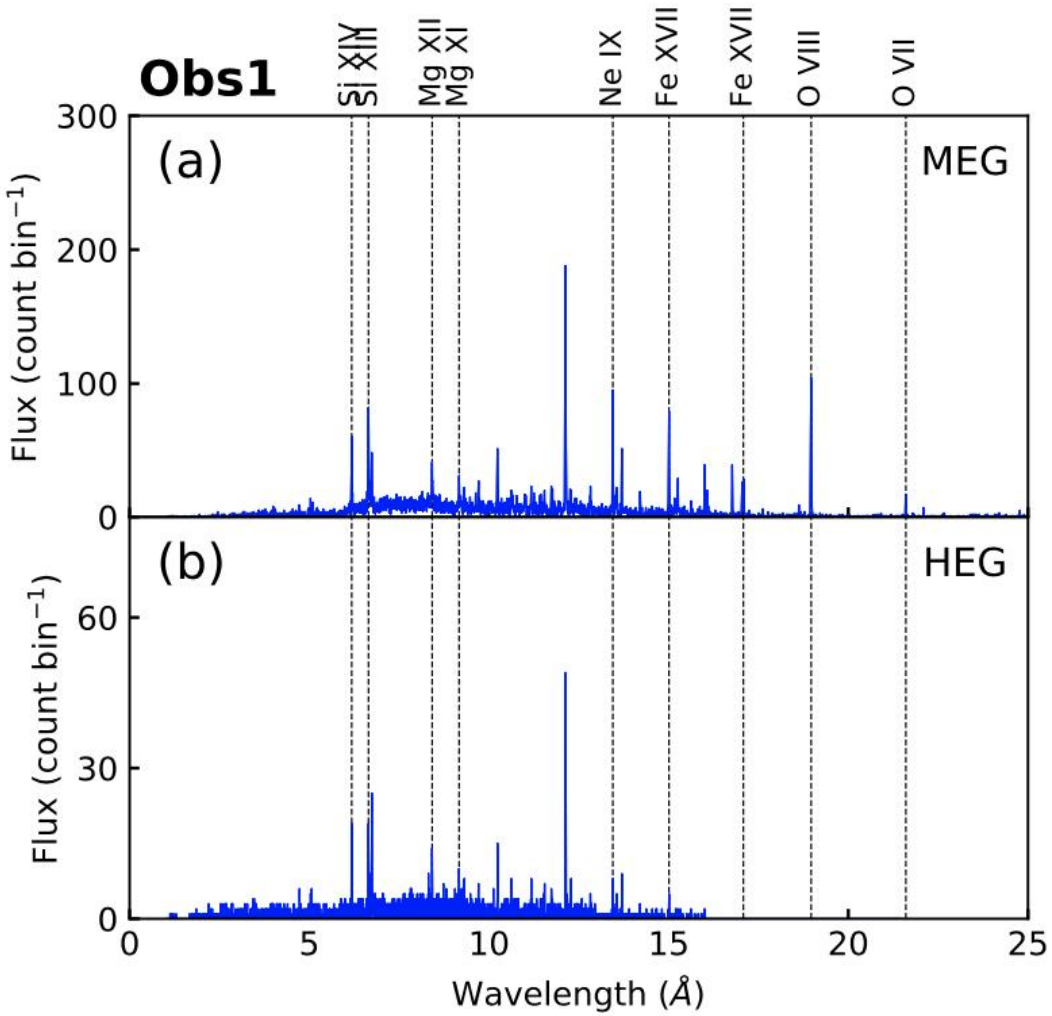
Doppler Shift Measurements

with strong coronal emission lines:

- **OVIII doublet** (18.97 Å, 3 MK)
- **Mg XII doublet** (8.42 Å, 10 MK)
- **Si XIV doublet** (6.18 Å, 16 MK)
- **Fe XVII lines** (15.01 Å, 5-6 MK)

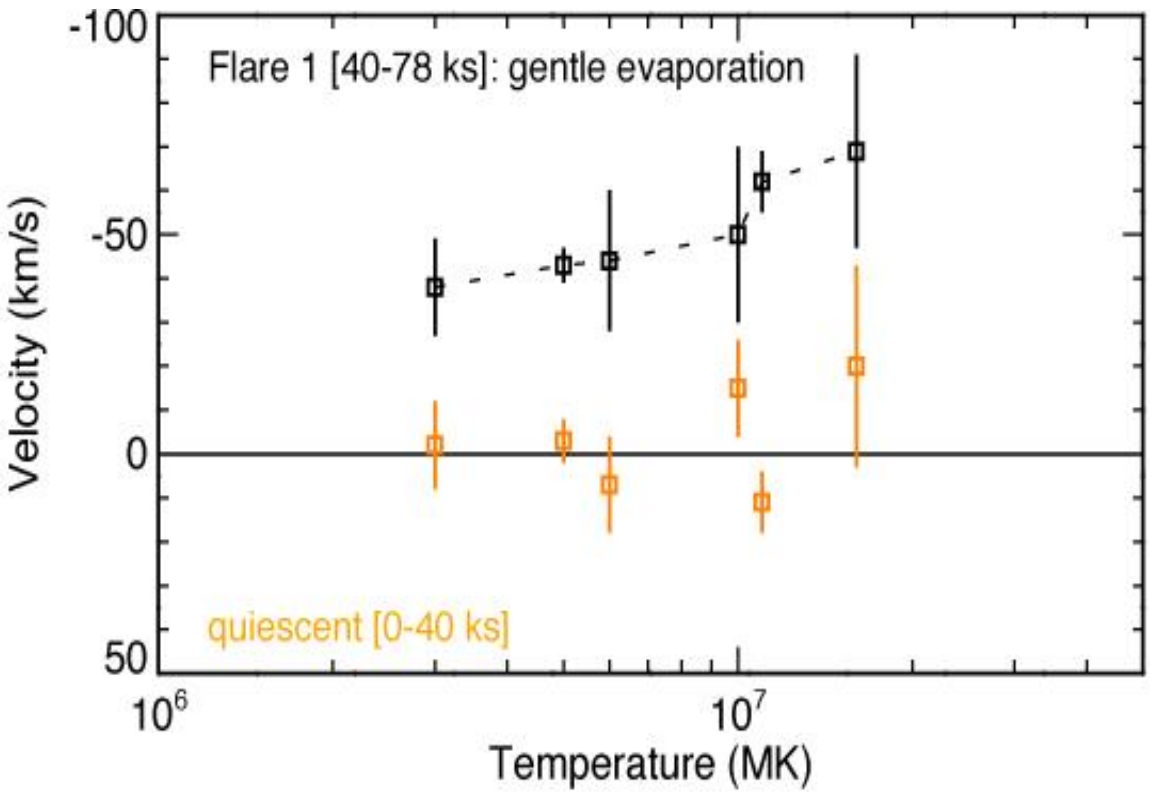
Density/Temperature Diagnostics

with the Si XIII triplets (6.7 Å, 10 MK) and the CHIANTI atomic database v9.0.1

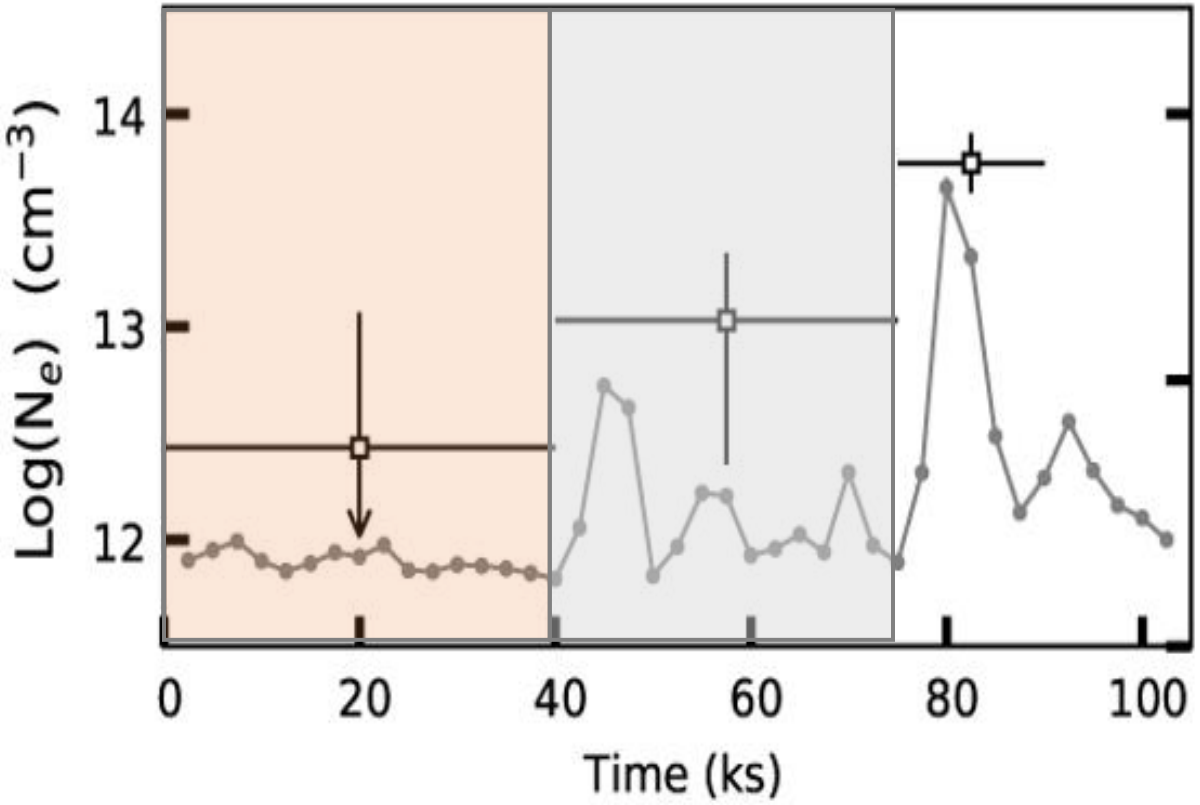


X-ray spectra integrated over the first Chandra observation (Obs1) of the MEG and HEG, respectively.

Our Results: Chromospheric Evaporation of stellar flares on EV Lac

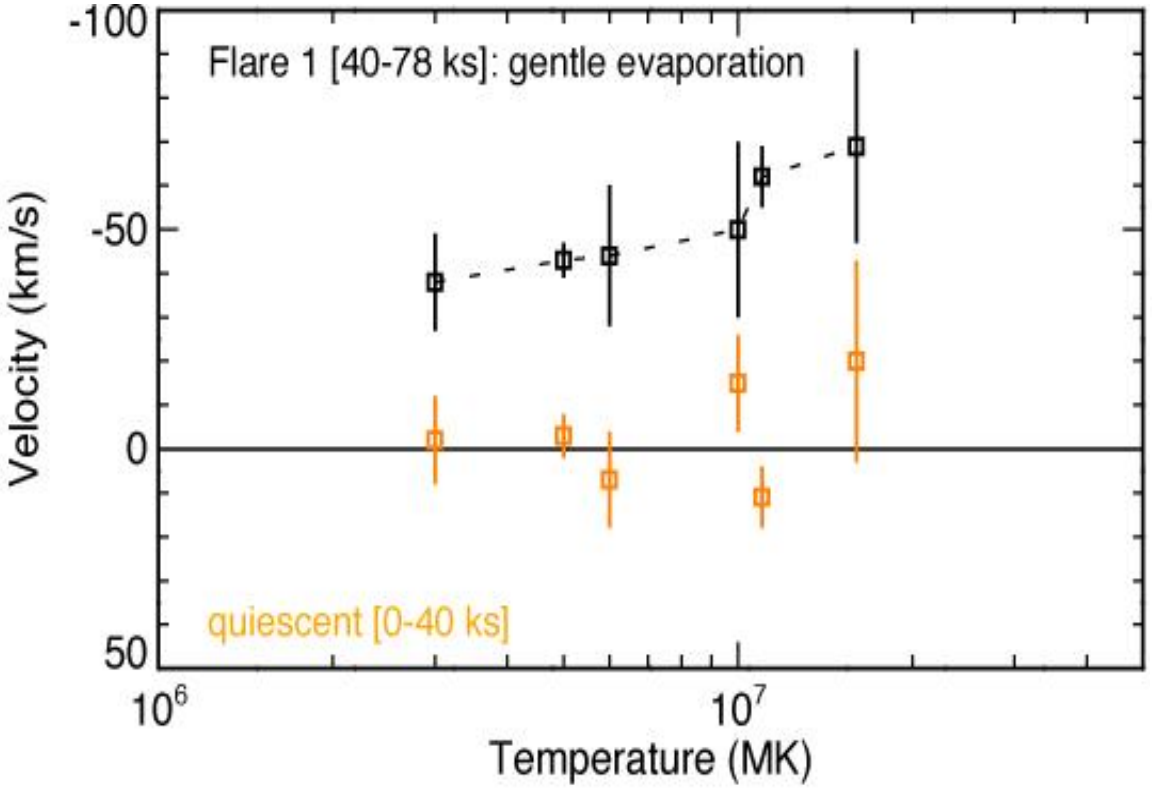


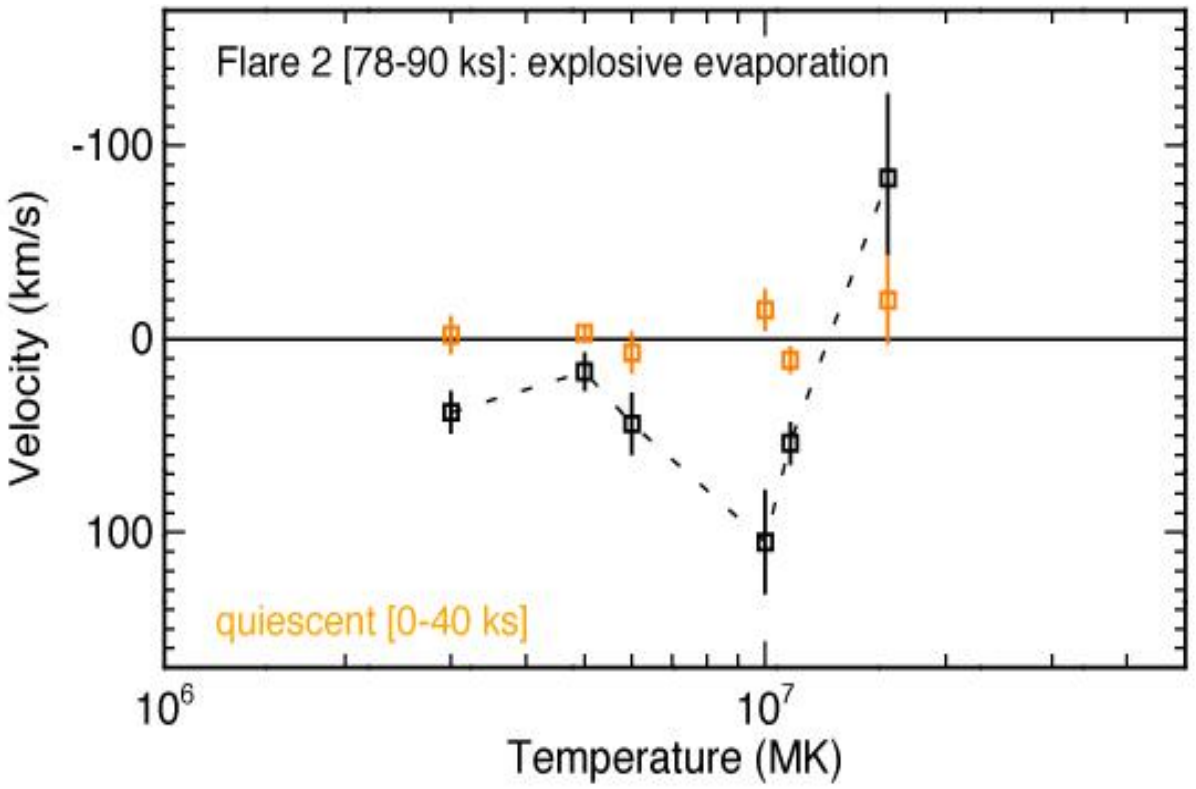
Hot evaporation flows
during one stellar flare on EV Lac



Coronal electron density
measured from the Si XIII triplet

Our Results: Two evaporation patterns of stellar flares on EV Lac



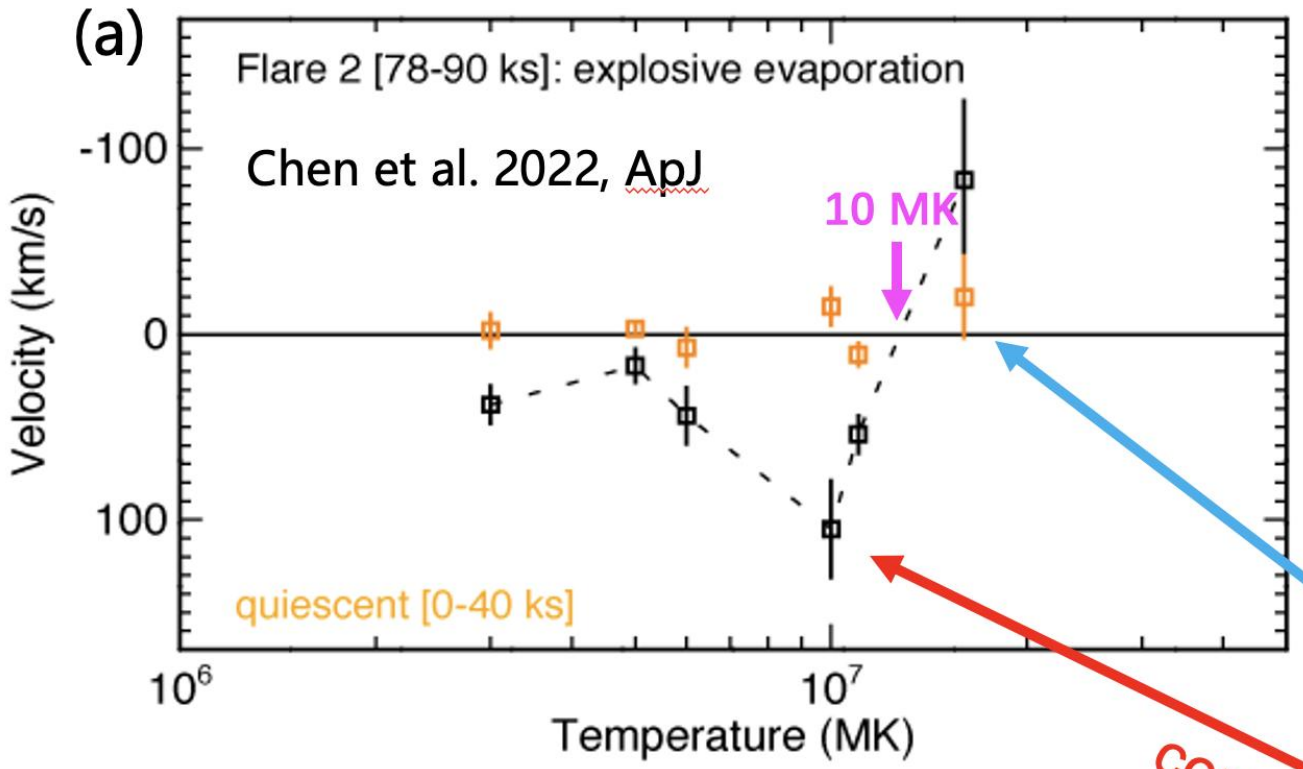


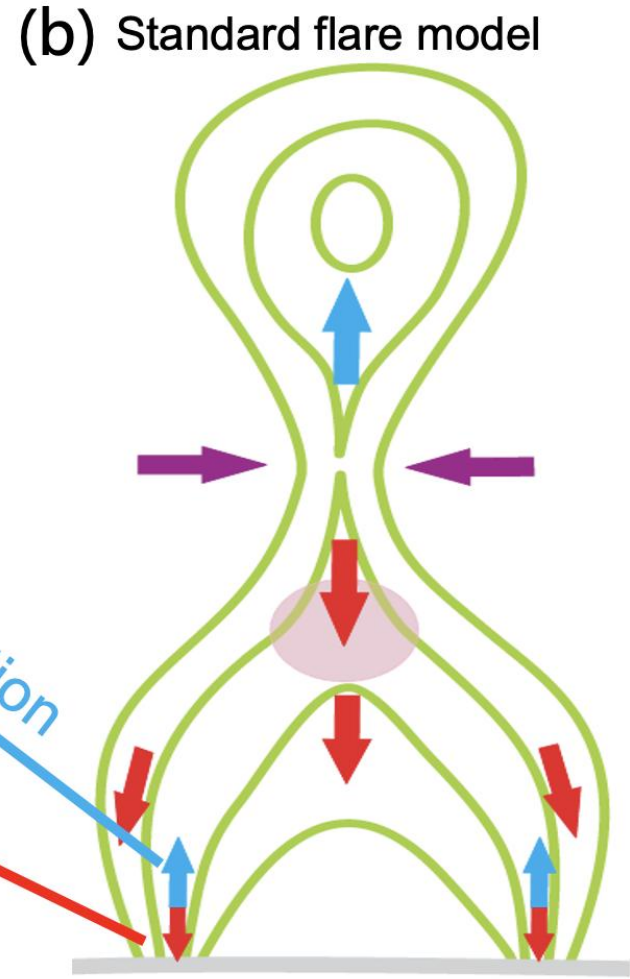
Gentle evaporation
during one stellar flare

Explosive evaporation
during one stellar flare

Similar to the evaporation patterns that observed in solar flares

Our Results: Chromospheric Evaporation of stellar flares on EV Lac

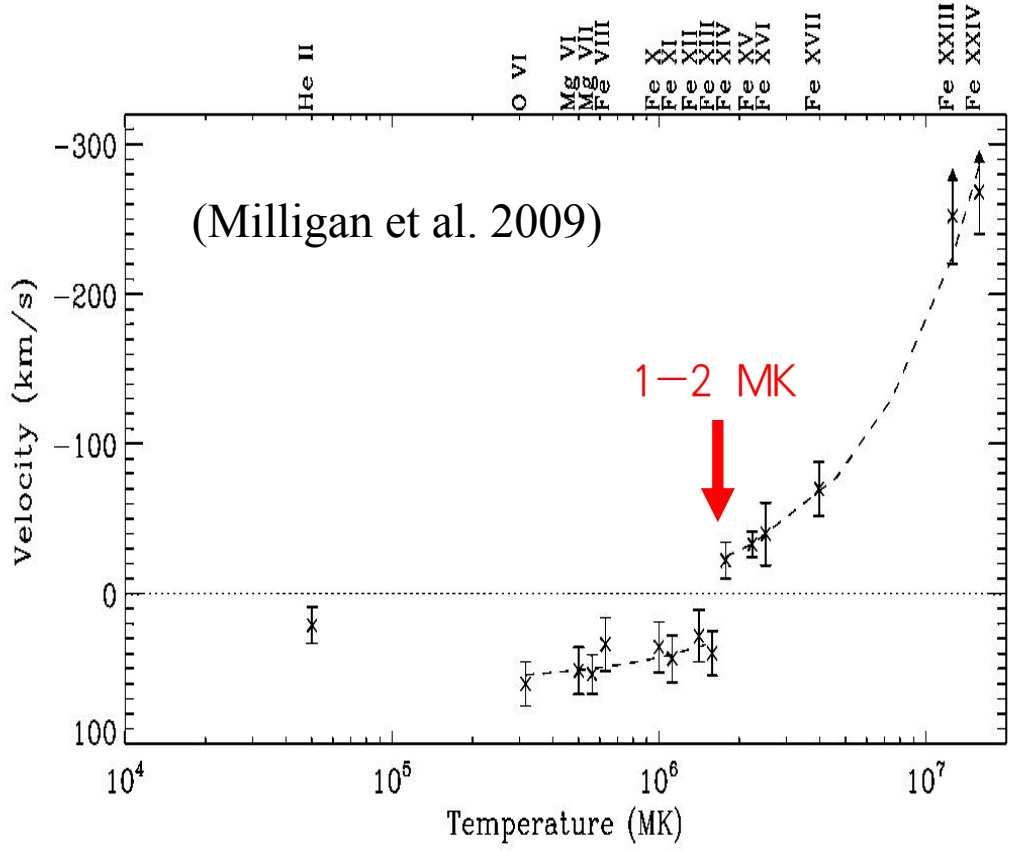




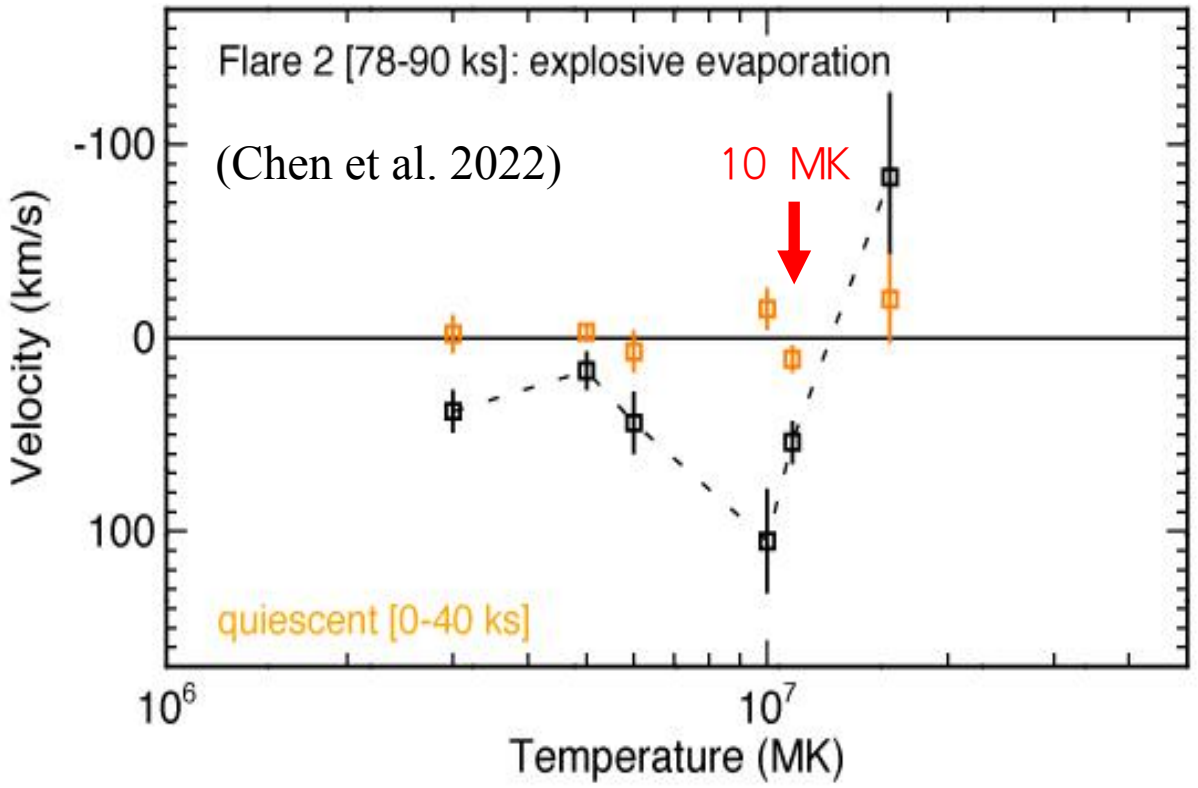
- Flows of flaring plasma rarely observed on stars
- Gentle vs explosive evaporation: different heating mechanisms
- The transition from redshifts to blueshifts occurs at a temperature ~ 10 MK

Tian et al. 2014, ApJL

Our Results: red/blue-shift transient during stellar flares on EV Lac



Solar explosive evaporation reported in (Milligan et al. 2009)

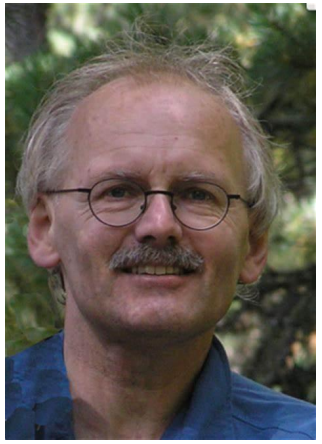


Stellar Explosive evaporation on EV Lac

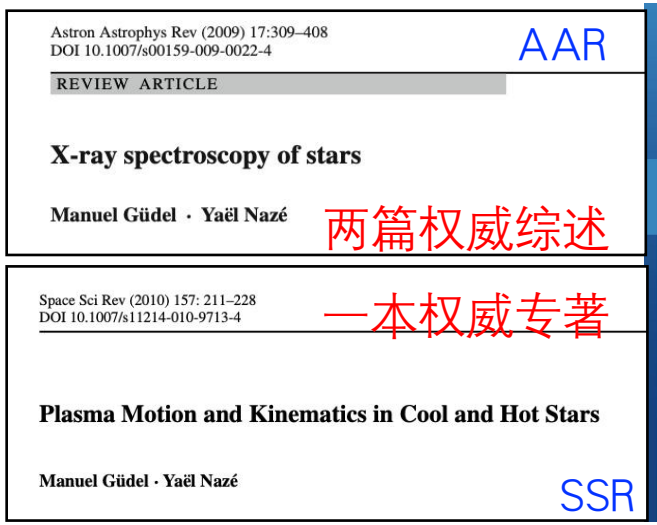
Our Results: The implication

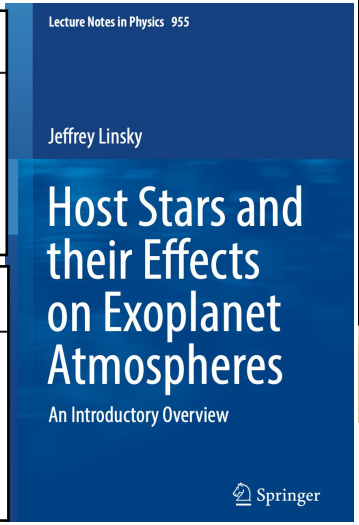
Before our results: (Güdel 2009, 2010, Linsky 2019)

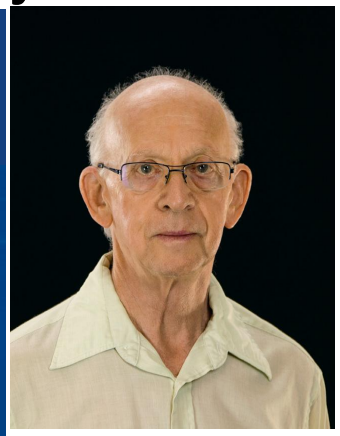
"Upflows of coronal gas during stellar flares have not yet been detected."



Manuel Güdel





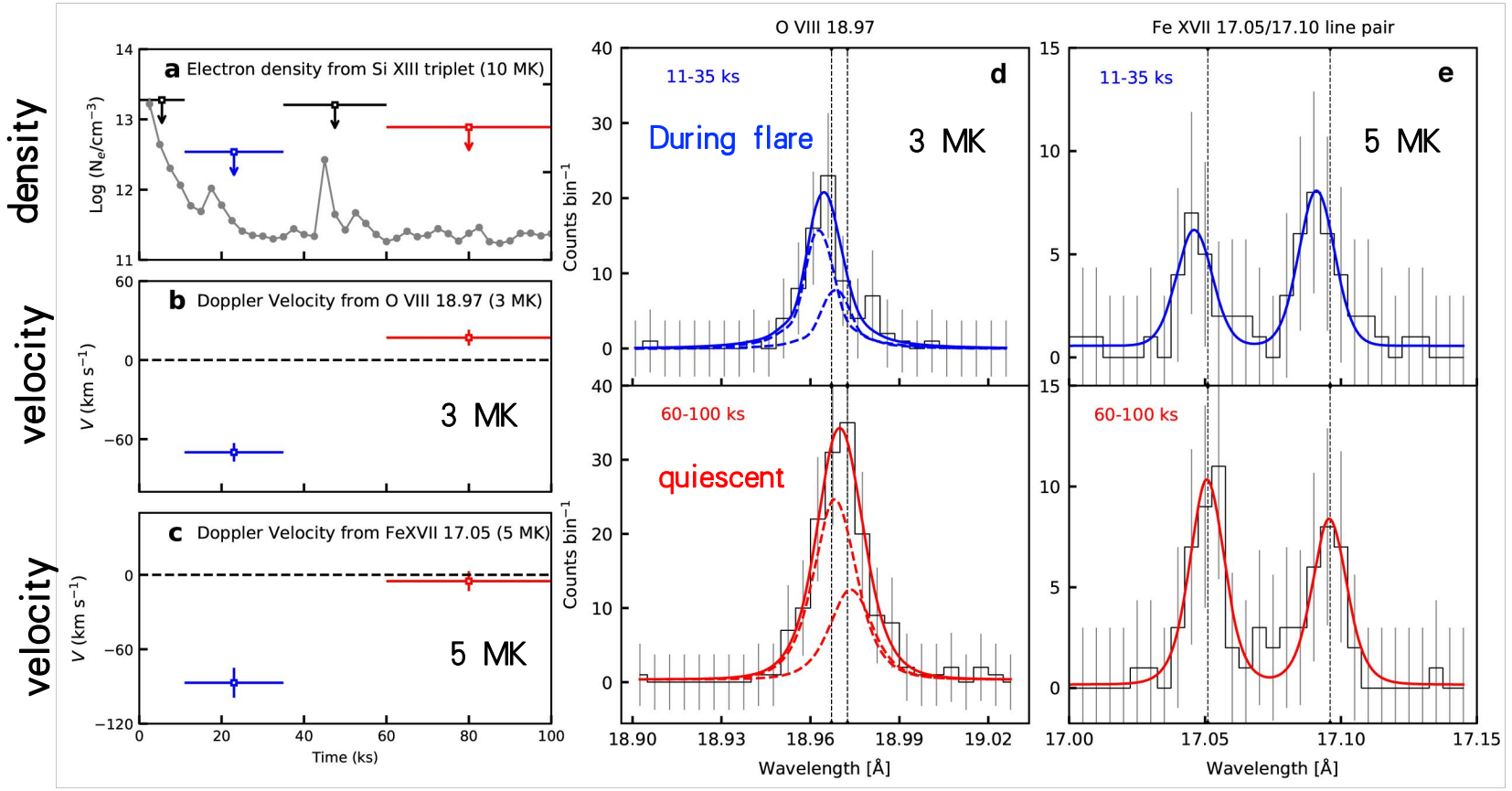


Jeffrey Linsky

Our results: The first direct detection of hot evaporative flows during stellar flares on M dwarfs.

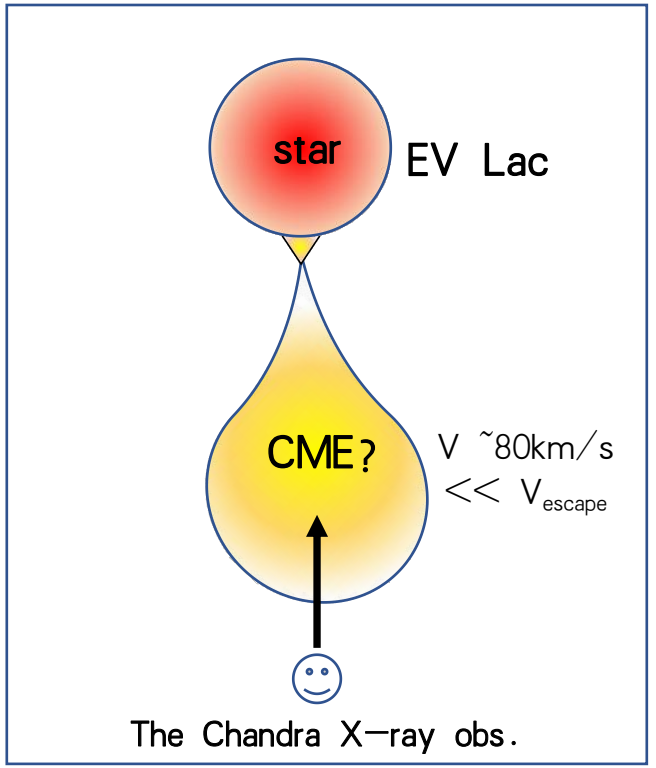
(Chen, Tian et al. 2022)

Our Results: X-ray spectral signals of a possible CME-flare event



Spectral signals of a CME candidate on EV Lac

- persistent blueshift of ~80 km/s at 3-5 MK
- simultaneous density decrease at 10 MK



A possible scenario

(**Chen, Tian et al. 2022**)

A X-ray blueshift signal (90 km/s) has been reported on a giant star by Argiroff et al. (2019)

Summary

SCAN ME

With time-resolved spectroscopic observations, we find that:

The first direct detection of hot evaporative flows during flares on an M dwarf

- gentle and explosive evaporation patterns on M dwarfs

The first X-ray spectral signals of of a possible flare-CME event on an M dwarf

- persistent blueshift of ~80 km/s at 3-5 MK
- simultaneous density decrease at 10 MK

These results provide important and new clues to understanding the plasma dynamics during stellar flares on M dwarfs.

Chen H.-C., Tian, H., Li, H.; et al.; *Detection of Flare-induced Plasma Flows in the Corona of EV Lac with X-Ray Spectroscopy*, 2022, ApJ, et al. 2022. 933. 92

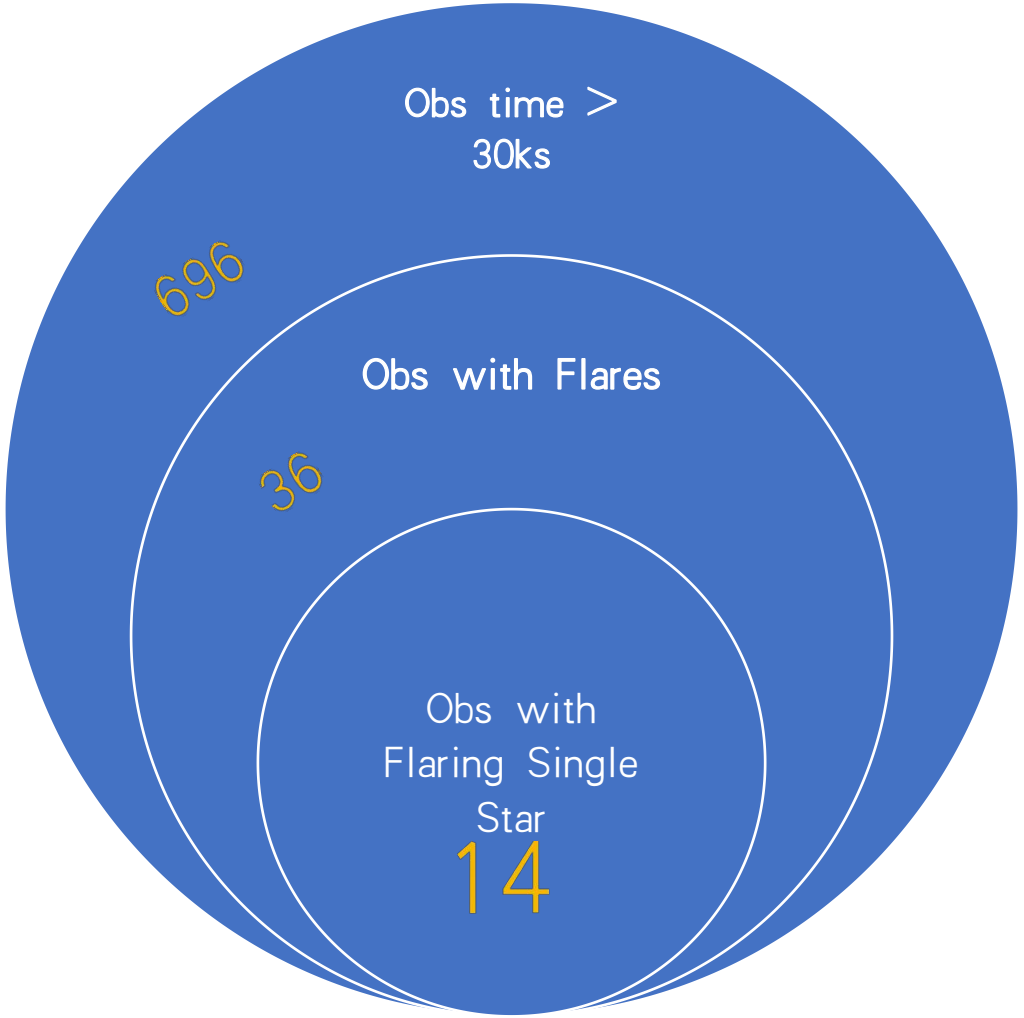
Future work

A Spectroscopic statistical study of Chandra stellar flares is underway……

- Long-time duration (> 30 Ks)
  - ✓ *capture long-duration flares*
- With obvious stellar flares
  - ✓ *Flare-CME relationship*
- Single stars
  - ✓ *for easier physical interpretation*

☐ *Stellar datasets in total: 3273*

(**Chen & Tian. 2025 in paperation**)



Future work

Joint Observations： Einstein Probe and Ground-based Telescopes

Einstein Probe

- **WXT (Wide-field X-ray Telescope)**
- **FXT (Follow-up X-ray Telescope)**

- SXR photometry + spectroscopy
- Observation modes
  - ✓ WXT sky survey + FXT follow-up
  - ✓ FXT ToO
  - ✓ Coord. obs. at other wavelengths
- Scientific objectives
  - Coronal dynamics of stellar flares
  - Stellar CME detection
  - Survey of stellar SXR emission

Late-type stars

- **Spectral type: F、G、K、M**
- **Host stars of exoplanets preferred**

Thanks for your time!

[1] Chen H.-C., Tian, H., Li, H.; et al.; *Detection of Flare-induced Plasma Flows in the Corona of EV Lac with X-Ray Spectroscopy*, 2022, ApJ, et al. 2022. 933. 92