Time-resolved spectroscopy and photometry of an M dwarf flare star YZ Canis Minoris with OISTER and TESS: Blue asymmetry in Hα line during the non-white light flare

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1. Solar/Stellar flares

- Rapid releases of magnetic energy in the atmosphere caused by the magnetic reconnection
  - electromagnetic radiations at all wavelength
  - prominence eruptions (PEs) and coronal mass ejections (CMEs)
    - Stellar CMEs are thought to affect the exoplanet's atmosphere
      e.g. Airapetian et al. (2020), Yamashiki et al. (2019)
- Stellar PEs/CMEs associated with stellar flares are not well studied
  - Only a few events have been detected
    - PEs: enhancement of blue-shifted components in chromospheric lines (Opt.):
      e.g. Vida et al. (2016, 2019), Honda et al. (2018)
    - CMEs: blue-shifted coronal emission lines (X-ray): e.g. Argiroffi et al. (2019)

➡ More Time-resolved/simultaneous observations are strongly needed.

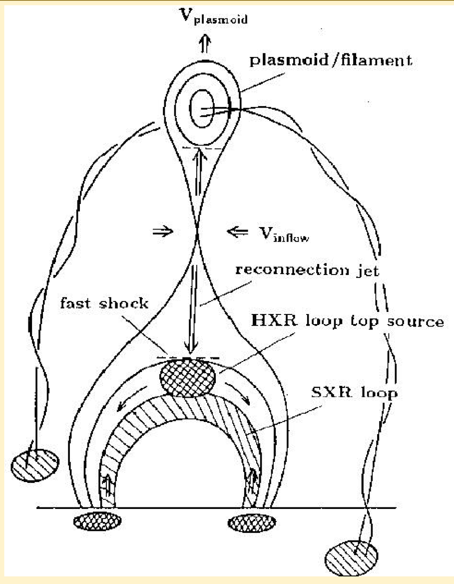


Fig.1 Standard model of flares (Shibata et al. 1995)

2. OISTER

- **O**ptical and **I**nfrared **S**ynergetic **Te**lescopes for **E**ducation and **R**esearch (OISTER) is Japan's nationwide cooperation project by universities on the optical-infrared observational astronomy.
- The aims of OISTER collaboration:
  - Quick/long-term follow-up observations of transient objects
    - GRBs, SNe, electromagnetic counterparts of gravitational wave and neutrino sources
  - Coordinated (simultaneous) multi-band/-mode observations
    - Multi-band: optical and NIR (from U–band to Ks-band)
    - Multi-mode: photometry, spectroscopy and polarimetry

➡ OISTER network is a powerful tool for studying stellar flares.

Fig.2 OISTER Telescope network

3. TESS-OISTER observations of YZ CMi

- TESS: 2019-01-07 — 2019-02-01 (Sector 7)
  - Total observation time: 22.7 days
- OISTER: 2019-01-16 — 2019-01-18

Telescope and obs. mode	Wavelength, resolution	Time-cadence
MITSuME 50-cm (multi-color photometry)	g', Rc, Ic	12-sec
KANATA 1.5-m (low-resolution spectroscopy)	4000-9000Å; λ/Δλ=400	1-min
NAYUTA 2-m (med,-resolution spectroscopy)	6350-6800Å; λ/Δλ=8000	5-min

4. Flares from TESS light curve

- We detected 145 flares from TESS light curve.
  - Flare frequency distribution: $dN/dE \propto E^{-1.75}$

For more details (e.g.. rotational modulations, flare duration statistics, etc.), please refer to Maehara et al., PASJ 73, 44 (2021)

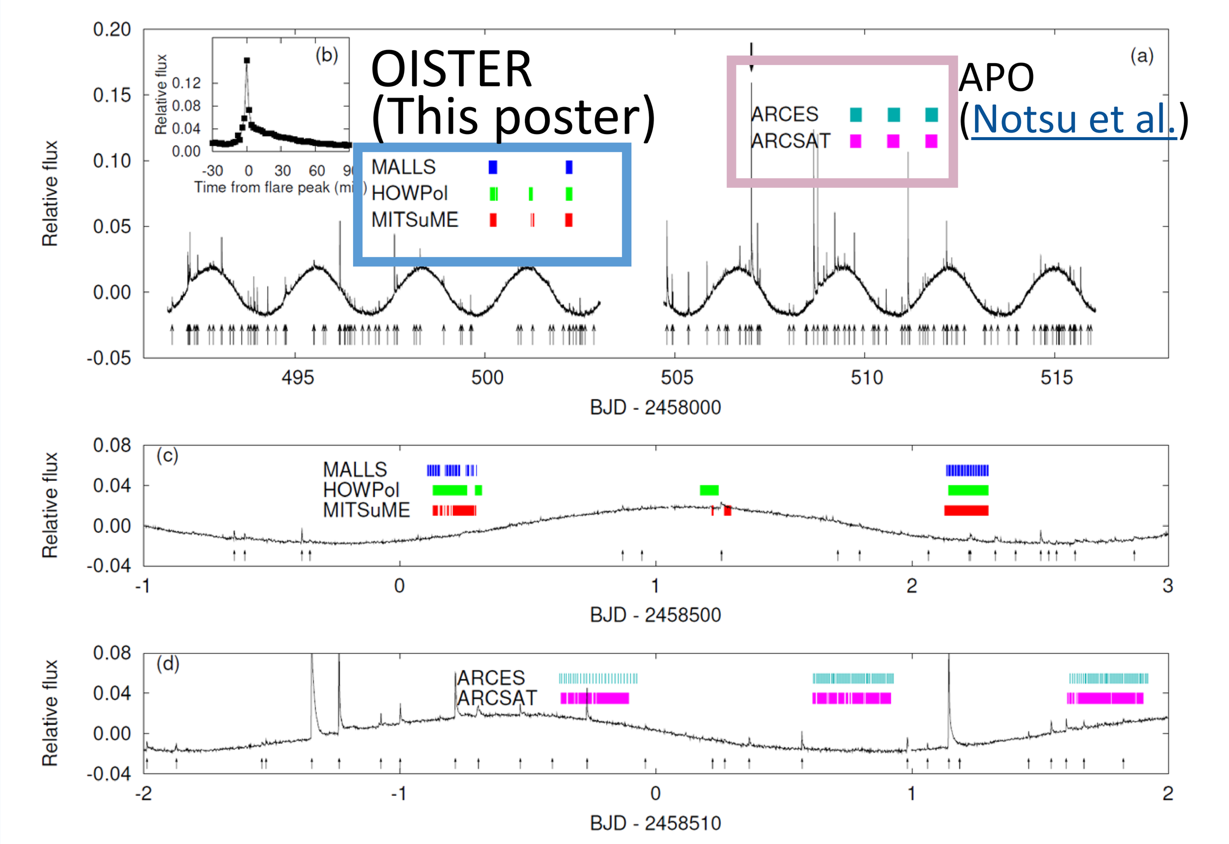


Fig. 3 TESS light curve of YZ CMi.

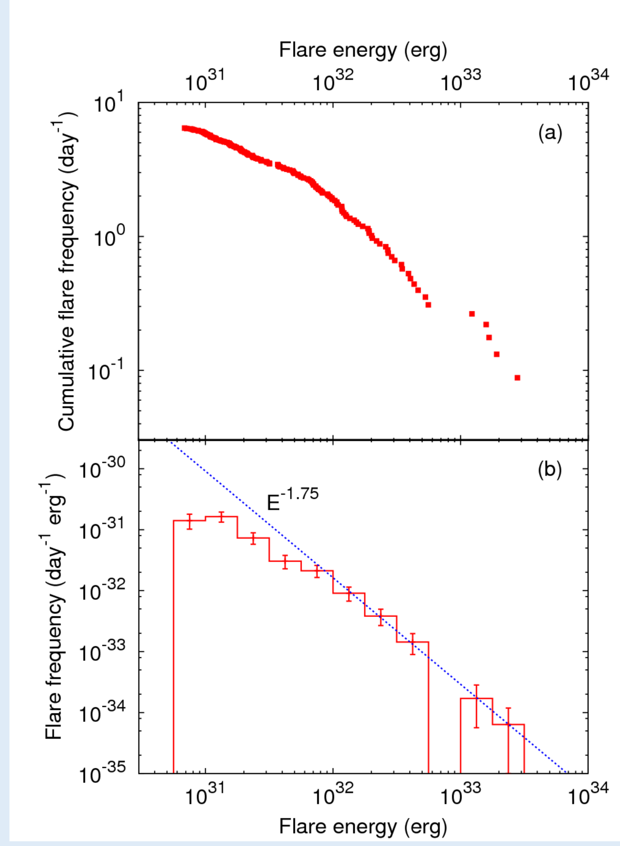
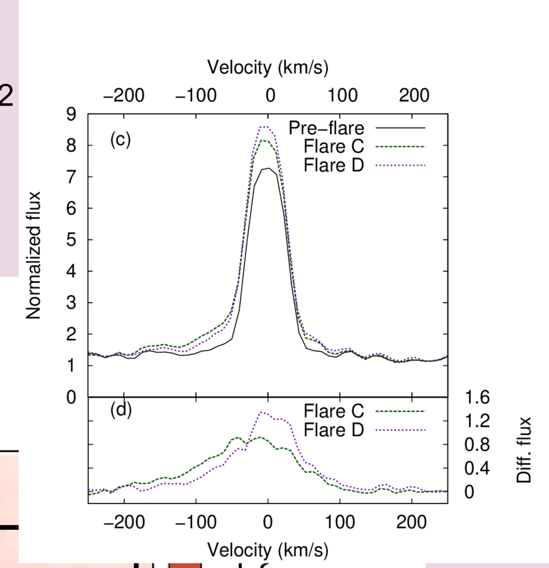


Fig. 4 Flare frequency distribution.

5. Flares observed with OISTER and TESS

- We detected 4 Hα flares during the OISTER observations.
- Two different types of flares on January 18.
  - <u>**Flare C**: slow rise and slow decay; no white-light flare</u>
    - **Hα line profile: blue-asymmetry (velocity: -80 — -100 km/s)**
    - Flare energy: 4.7×10^{30} erg (Hα); $<4\times10^{30}$ erg (TESS-band)
  - <u>**Flare D**: rapid-rise and exponential decay; typical white-light flare</u>
    - **Hα line profile: No red-/blue-asymmetry**
    - Flare energy: 1.8×10^{30} erg (Hα); 1.8×10^{32} erg (TESS-band)



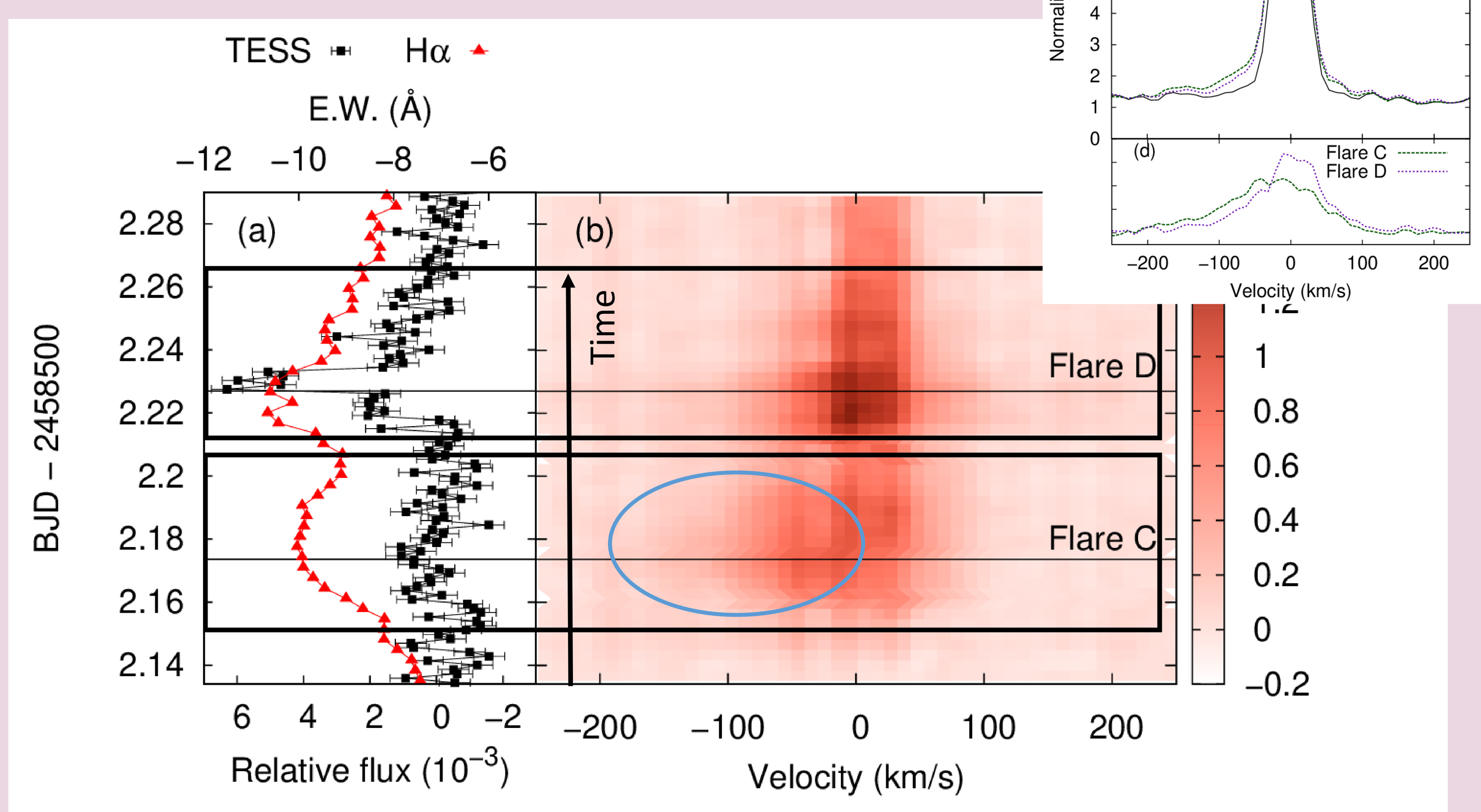
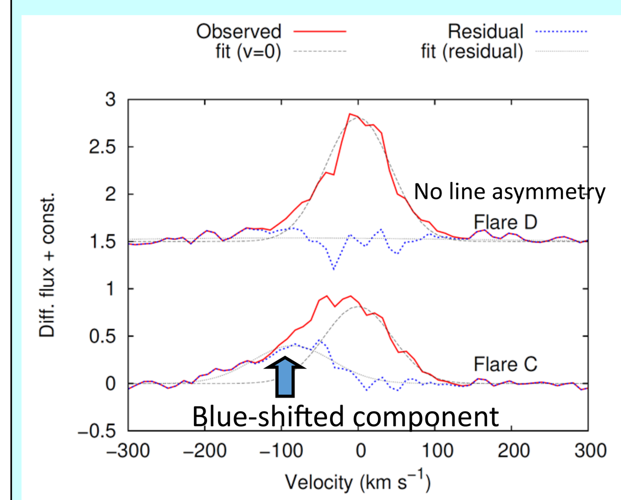


Fig. 5 (a) TESS and Hα light curves of flares on Jan 18. (b) Time evolution of Hα line. (c) Hα line profile. (d) Same as (c) but for the difference from pre-flare line profile.

6. Blue-asymmetry in Hα line

- Duration: ~60 min
- Velocity of blue-shifted component: -80 - -100 km/s
  - roughly constant during the flare C
- Flux of blue-shifted component: 20-30% of total Hα flux of the flare



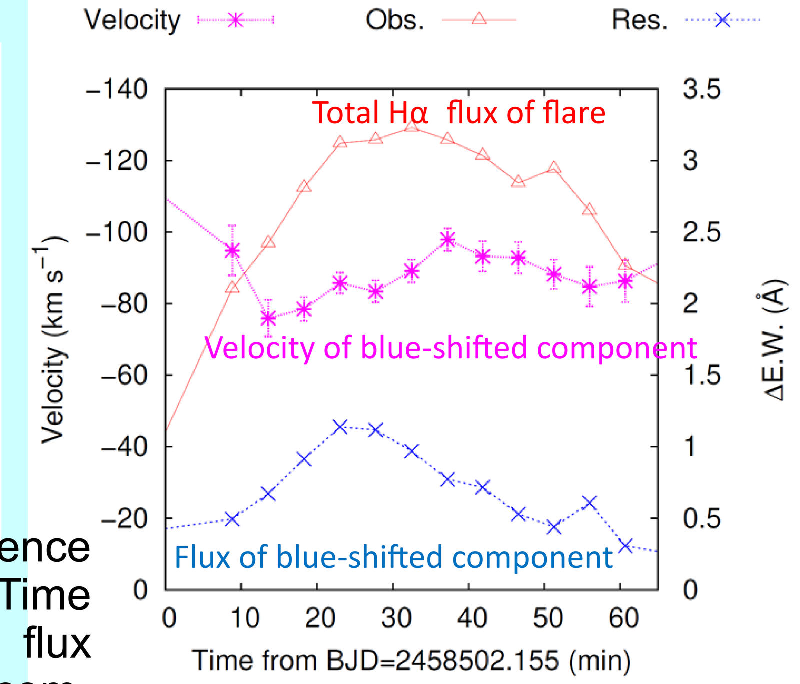
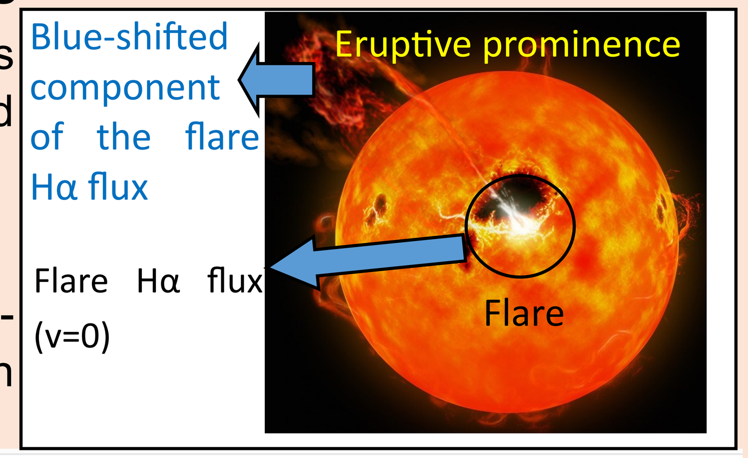


Fig. 6 Left: Line profile difference from pre-flare profile. Right: Time variations of total Hα flare flux (top), velocity of blue shifted component (middle), and flux of blue-shifted component (bottom)

7. Mass and kinetic energy of PEs/CMEs

By assuming that the blue-asymmetry was caused by a prominence eruption, we estimated the mass and kinetic energy.



- Mass: 10^{16}—10^{18} g
  - The estimated mass is comparable to expectations from the empirical relation between the flare X-ray energy and mass of upward-moving material for solar CMEs and other stellar flares.
- Kinetic energy: $10^{29.5}$—$10^{31.5}$ erg
  - The estimated kinetic energy for the non-white-light flare on YZ CMi is ~2 orders of magnitude smaller than that expected from the relation between flare X-ray energy and kinetic energy for solar CMEs.
  - In the case of solar PEs/CMEs, the average velocity of CMEs is 4-8 times faster than that of PEs (Gopalswamy et al. 2003).
    - PEs: ~80km/s
    - CMEs: ~350 km/s (core); ~610 km/s (leading edge)

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  - The discrepancy in kinetic energy could be understood by the difference in velocity between CMEs and PEs

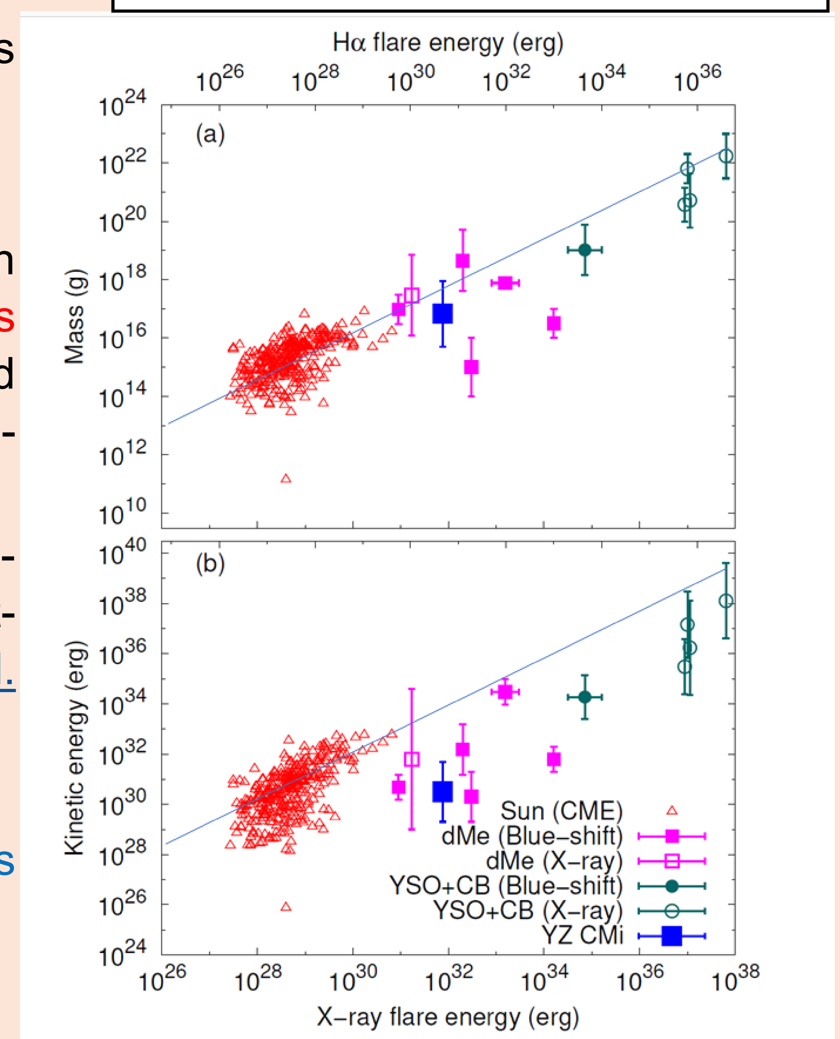

Fig. 7 (a) Mass and (b) kinetic energy of PEs/CMEs vs. flare energy. (Solar CMEs: Yashiro & Gopalswamy 2009; stellar PEs/CMEs: Moschou et al. 2019)