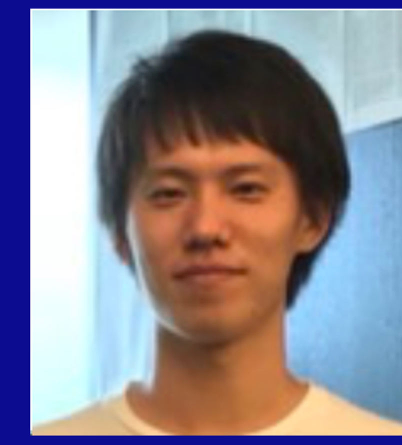
Detection of mass ejection from a superflare on a solar-type star



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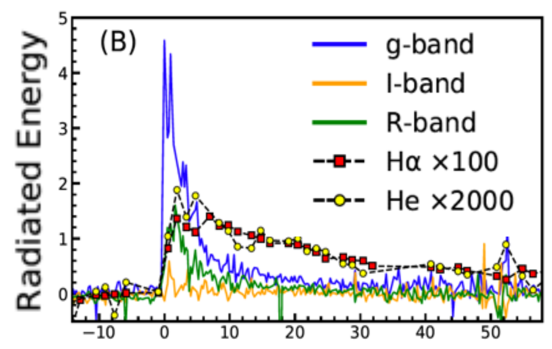
Abstract: In the case of the Sun, mass ejections often occur in association with solar flares and affect the Earth's environment. Active solar-type stars (G-type main-sequence stars) sometimes show large `superflares' (Maehara et al. 2012), but no observational indication of mass ejection has been reported for solar-type stars. We conducted spectroscopic monitoring observations of the active young solar analog EK Dra (a famous zero-age main-sequence G-dwarf) by our 3.8-m Seimei telescope, simultaneously with TESS photometry. Our time-resolved optical spectroscopic observation shows clear evidence for a stellar mass ejection associated with a superflare on the solar-type star (Namekata et al. submitted). After the superflare brightening with the radiated energy of 2.0x10^{33} erg observed by TESS, a blue-shifted Hα absorption component with a velocity of -510$ km s^{-1} appeared. The velocity gradually decayed in 2 hours and the deceleration 0.34 km s^{-2} was consistent with the surface gravity on EK Dra (0.30 ± 0.05 km s^{-2}). The temporal changes in the spectra greatly resemble that of a solar mass ejection observed by the SMART telescope at Hida observatory. Moreover, the ejected mass of 1.1x10^{18} g roughly corresponds to those predicted from solar flare-energy/ejected-mass relation. These discoveries imply that a huge stellar mass ejection occurs possibly in the same way as solar ones.

Introduction: Solar & stellar flares

- Sudden brightening in various wavelength
  ⇒ release of magnetic energy
  - Solar flare ≤ 10^{32} erg
  - Stellar flare ~ 10^{33-38} erg (`superflare')
- Mass ejection (filament eruption/CMEs):
  ⇒ **Can Severely affect the Earth (in stars, can affect exoplanet environment)**



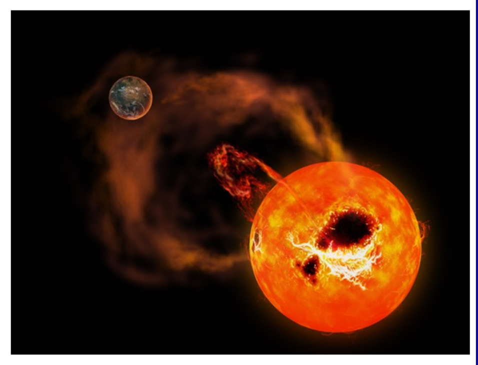


Fig. superflares on AD Leo and imaginary pictures (Namekata et al. 2020b, PASJ; see our press release: https://www.kyoto-u.ac.jp/en/research-news/2020-07-10)

Background: Superflares on solar-type stars

- Superflares are frequent on rapid rotators, binary, M dwarfs
- No superflare on the Sun in this 150-yr modern obs.
- But many superflares on the young/old solar-type star (G-dwarfs) found by the Kepler [Maehara+2012, Nature]
  ⇒ Can superflares occur on the Sun?
  Can (super?) mass ejection happen?

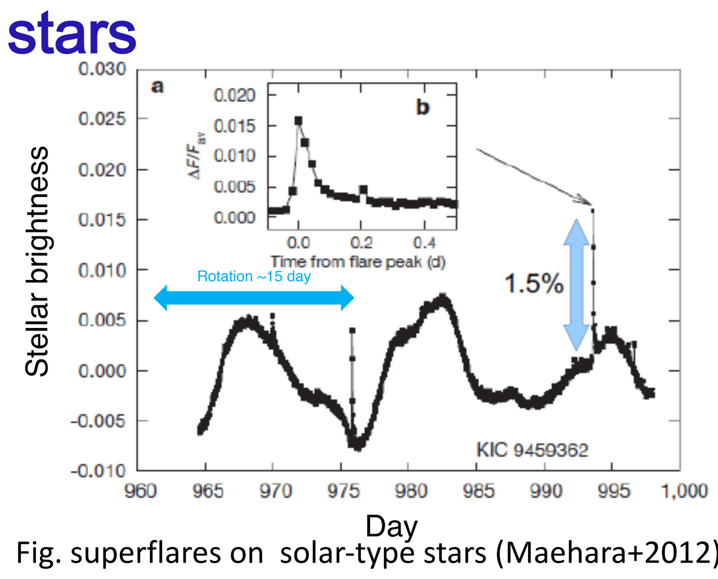


Fig. superflares on solar-type stars (Maehara+2012)

Mass Ejection on solar-type stars?

- Previous works
  - Some signatures in M-dwarfs/evolved stars by spectroscopic obs. [e.g. Honda+18, Argiroffi+19, Moschou+19, more]
  - **No signature on solar-type star.**
- Why no detection on G-dwarfs?
  - Low occurrence frequency
  - Low contrast

⇒ **Long-Monitoring & time-resolved spectroscopic obs. by large telescope is important!!**

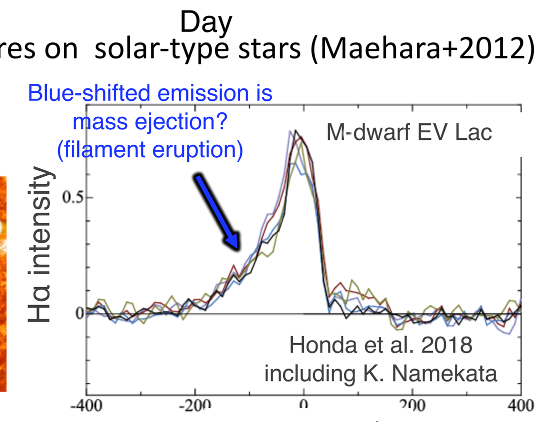


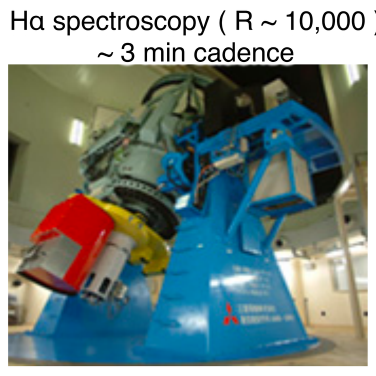
Fig. superflares on EV lac (M-dwarf) with blue asymmetry (Honda et al. 2018 including K. Namekata)

Observations

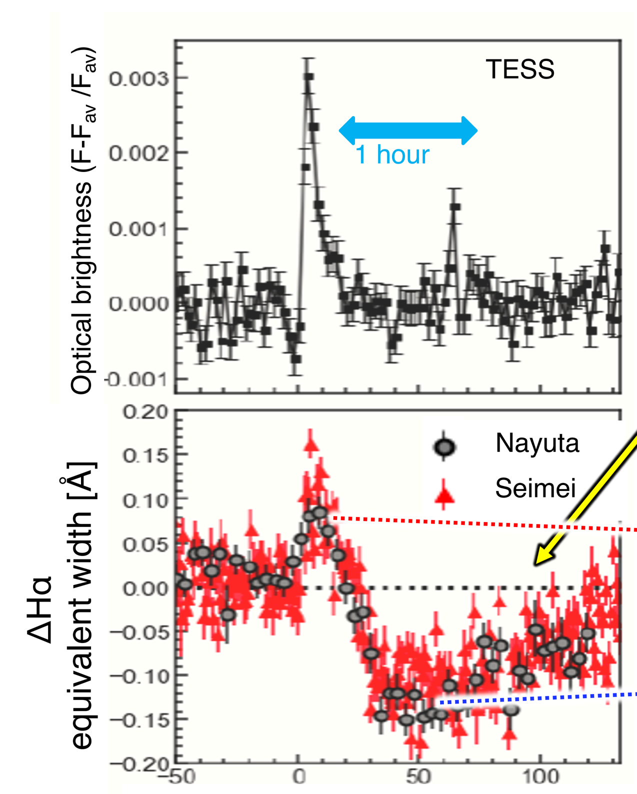
- Target: young solar analog EK Dra (G1.5V, Age~50-120 Myr, Vmag~7.6)
- Observation:
  - Two spectroscopies by two ground telescope. ⇒ Hα line (chromosphere) with 1-3 min cadence
  - Optical photometry (high-precision) by TESS ⇒ 6000-10000 Å continuum with 2-min cadence.

➡ First detection of optical spectra of superflares on solar-type stars (G-dwarfs)!

TESS (Transiting Exoplanet Survey Satellite)	3.8m-Seimei Telescope (at Okayama, Japan)	2m-Nayuta Telescope (at Hyogo, Japan)
Optical photometry (6000-10000 Å) 2 min cadence	Hα spectroscopy (R ~ 2000) ~ 1 min cadence	Hα spectroscopy (R ~ 10,000) ~ 3 min cadence

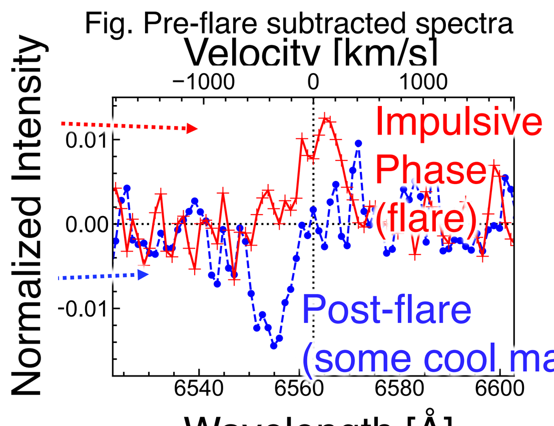


Light curve & Spectra



- Property of the flare
  - Optical flare energy: 2.0x10^{33} erg
    - (20 x the largest solar flares i.e. 'superflare')
  - The associated Hα emission energy: 2 x 10^{31} erg
    ⇒ **First flare spectra on solar-type star**
- **Post-flare Hα dimming**
  - clear absorption in Hα = Blue-shifted absorption
  - ~ 2 hours

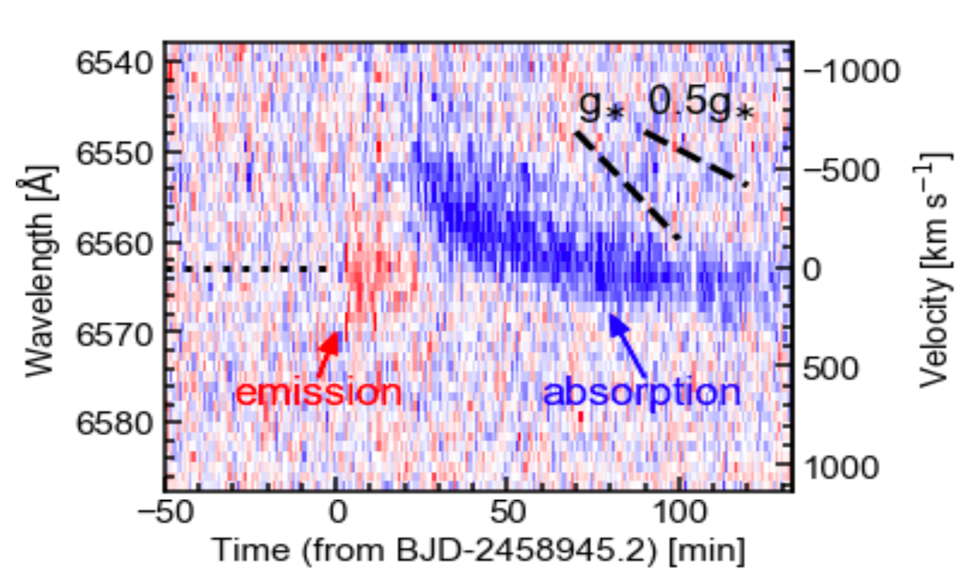
Fig. Pre-flare subtracted spectra



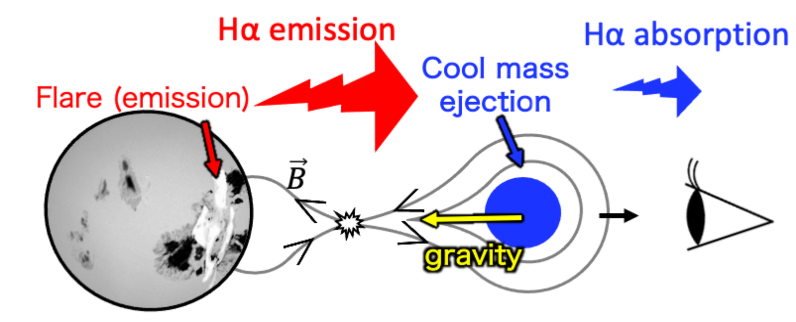
⇒ **Cool materials on the disc is moving toward us with high velocity after superflare (e.g. "filament eruption")**

Time evolution of spectra & velocity

Fig. pre-flare subtracted spectra in time-wavelength



- Maximum velocity: - 500km/s
  ⇒ finally become slow & weak red shift
- Deceleration = 0.34 km/s²
  ~ EK Dra surface gravity 0.3±0.05 km/s2
- Expected picture: mass is erupted from the star being decelerated by gravity

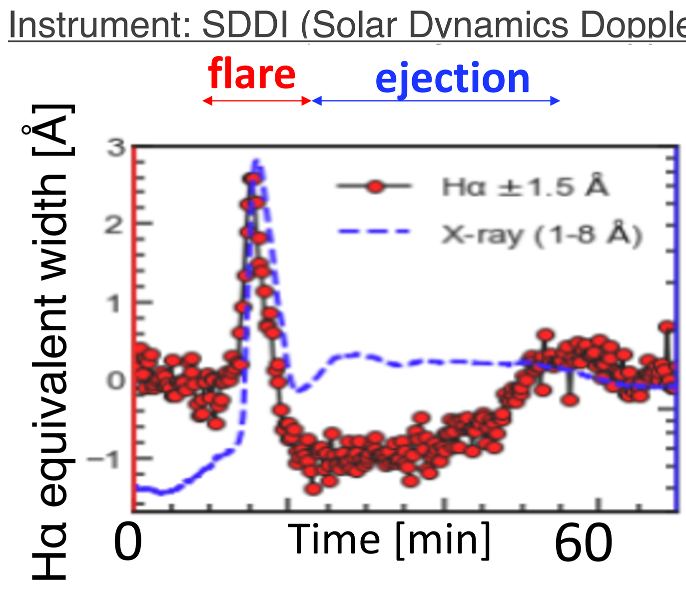


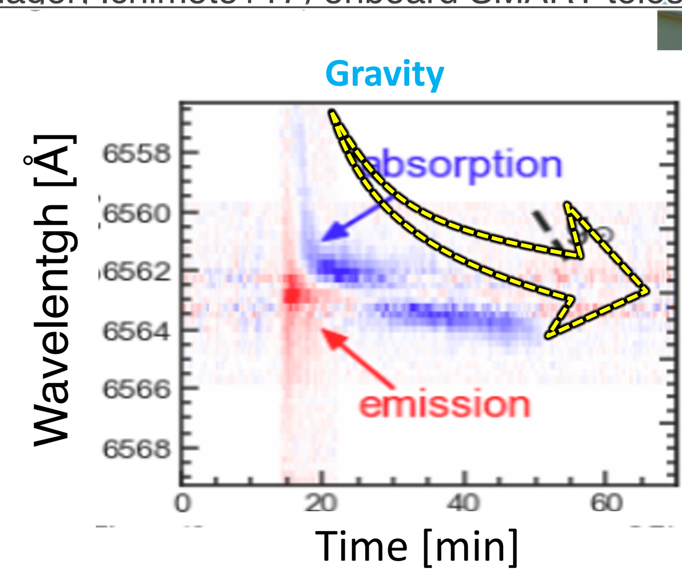
Comparison with the Sun-as-a-star solar filament eruptions

- Q. How the EK Dra eruptions resembles the solar filament eruption
  ⇒ We conducted the-Sun-as-a-star observations of solar filament eruptions as a comparison
- We made the-Sun-as-a-star Hα spectra of solar filament eruption
  ⇒ compare with solar and stellar observations

SMART/SDDI (at Hida Observatory)

✓ Data: solar C8-class flare and cool-mass eruption on 2017/4/2UT
✓ Instrument: SDDI (Solar Dynamics Doppler Imager; Ichimoto+17) onboard SMART telescope, Japan





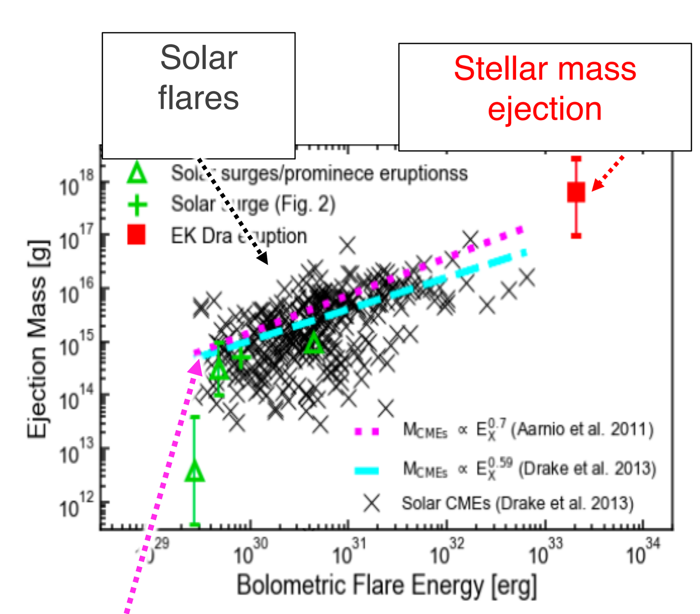
- Results: Temporal changes of blue-shifted spectra is very similar
  ⇒ filament eruption on EK Dra = Large scale ones of solar filament eruption

Filament velocity & mass

Velocity
- The velocity (510 km/s) is less than the escape velocity (670 km/s)
- But, larger than the typical solar filament eruption with CMEs
  ⇒ The outer layers of the EK Dra eruption (i.e. coronal parts) could be ejected with larger velocity to become CMEs

Mass
- EK Dra eruption 10^{17-18} g: greater than the largest solar CMEs.
- The ejected mass corresponds to that expected from solar flare/CME relation. [e.g. Arnio+2011]

Possibly, solar/stellar mass ejection can be explained by the common process? (release of magnetic energy)
(Namekata+submitted)



Solar scaling relations
$M \propto E^{-2/3}$ (Takahashi+16, Aarnio+11)

Conclusion

- We detected first evidence of filament eruption on a solar-type star
- The spectral changes are very similar to those of solar filament eruptions
- The same flare-energy/ejected-mass relation
  ⇒ Possibly the same mechanism of solar/stellar mass eruption? (Namekata et al. submitted)
- Future works
  - How can the filament eruption affect the exoplanet atmosphere? (cf. Airapetian 2016, Nat. Geosci.)
  - How can the mass eruptions contribute to the stellar mass loss? (cf. Osten & Wolk 2015)
    ⇒ Statistical study is important and more observations!!