Measurement of starspots and chromospheric emission lines of young solar-type stars

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1. Introduction Starspot and chromosphere
2. Data reduction & Results
3. Discussion Dynamo activity of young solar-type stars

Starspot and chromospheric emission line

The chromospheric emission lines and **the variation of the brightness caused by the starspot** have been observed as the indicator of the activity.

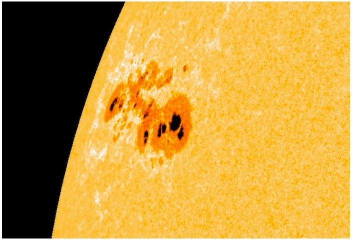


Fig. 1: Solar spots are often surrounded by emission regions, faculae **(NASA/SDO)**

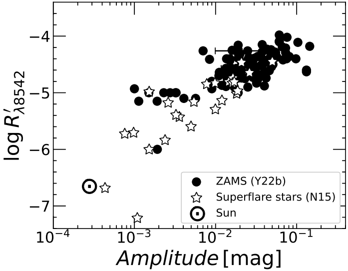


Fig. 2: The strength of Ca II emission line (λ8542 Å) and the amplitude of the lightcurve of the ZAMS stars **(Yamashita et al., 2022b)**

- In 1947, the largest solar spot decresased the solar brightness by $\sim 0.1\%$.
- Some zero-age main-sequence stars (ZAMSs) have larger spot coverage of $4 - 17\%$. **(Allain et al., 1996)**
- Solar-type main-sequence stars with the larger amplitude of the light curve (≒ **larger spot**) also show **the brighter Ca II emission line** **(Fig. 2)**

Dynamo activity of young solar-type stars

■ **Pre-main-sequence stars (PMSs)** and ZAMSs have

- shorter rotation period, P **(Fig. 3)**
- longer convective turnover time **(Fig. 4)**

than main-sequence stars such as the Sun.

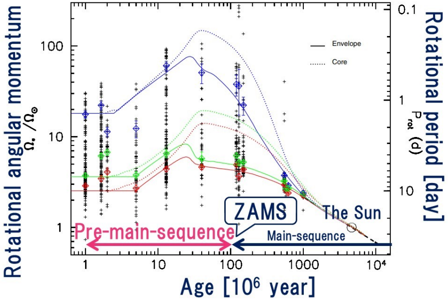


Fig. 3: Rotational distributions of solar-type stars **(Gallet & Bouvier , 2013)**

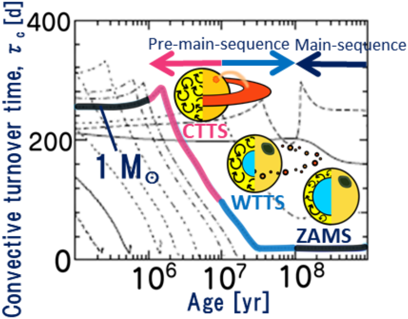


Fig. 4: The models of the convective turnover time, τ_c **(Jung & Kim, 2007)**

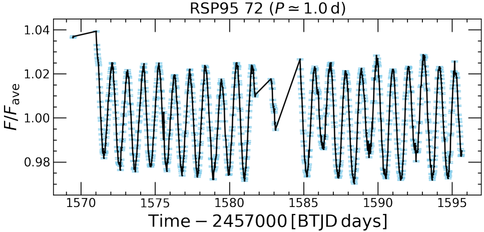
They can have small Rossby numbers $\left(\equiv \frac{\text{rotational period, } P}{\text{convective turnover time, } \tau_c}\right)$.

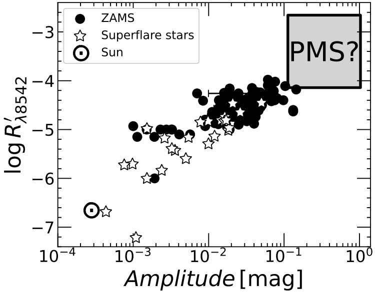
→ It is expected that PMS stars have **active chromosphere**.

Challenges

Q. For PMSs, how is the starspot coverage related with the strength of chromospheric emission lines?

→ Recently the light curves of ZAMS are obtained from *Kepler* and *TESS* **(Yamashita et al., 2022b)**





In addition to the ZAMSs, we analyzed Subaru/HDS spectroscopic data and *TESS* photometric data of **PMSs in 2 molecular clouds and 5 moving groups**. We investigated the relation between its amplitude (≒ starspot coverage) and the Ca II emission lines.

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Our targets

1. **26 PMSs**
2. 134 solar-type ZAMSs
   - IC 2602 ($\sim 30\,\mathrm{Myr}$)
   - IC 2391 ($\sim 50\,\mathrm{Myr}$)
   - Pleiades ($\sim 130\,\mathrm{Myr}$)
3. solar-type superflare stars
4. the Sun

※ The binaries have been removed.

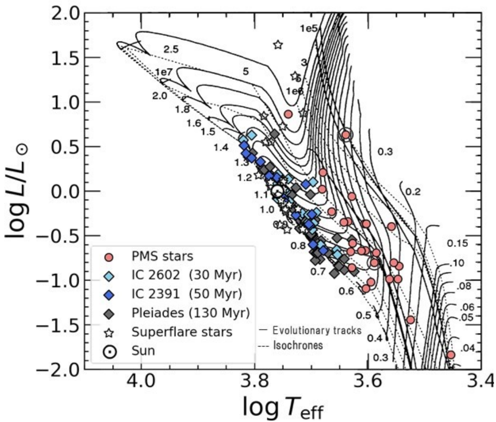
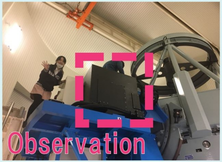


Fig. 5: HR diagram of the young solar-type stars investigated in this study.

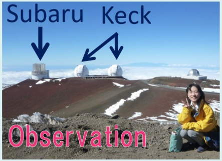
Reference. R' of ZAMS: **Stauffer et al. (1997)**, **Marsden et al. (2009)**, the amplutude of lightcurve of ZAMSs in Pleiades: **Rebull et al. (2015)**, F' and the amplutude of lightcurve of the solar-type stars: **Notsu et al. (2015)**

Observations & Data reduction of spectra

We appreciate **Subaru openuse (S21B, S22A, PI: Yamashita)** & SMOKA !



✓2 m Nayuta/MALLS



✓Subaru/HDS

Archive data

- ✓Keck/HIRES
- ✓VLT/UVES
- ✓VLT/X-shooter
- ✓AAT/UCLES

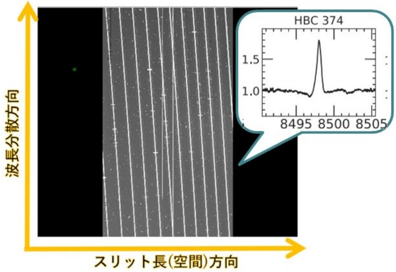


Fig. 6: Example of a spectrum obtained by Subaru/HDS

Data Reduction

1. overscan subtraction
2. bias subtraction
3. flat fielding
4. wavelength calibration
5. removal of scattered light
6. extraction of a spectrum
7. continuum normalization
8. removal of telluric absorption
9. removal of photospheric absorption

Result1: Ca II emission lines of PMSs & ZAMSs

After the subtraction of the photospheric absorption components, all the objects show the emission component of Ca II.

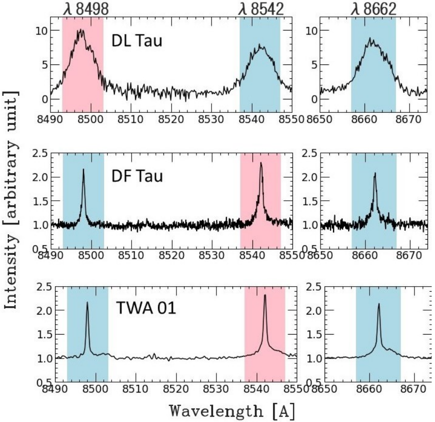


Fig. 7: The Ca II emission lines of 3 PMSs

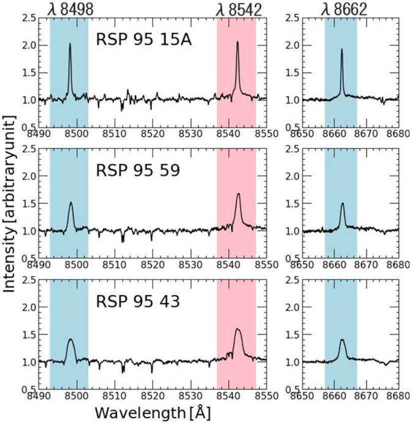


Fig. 8: The Ca II emission lines of 3 ZAMSs

Result2: *TESS* lightcurves

- We analyzed *TESS* photometric data, and obtained **the rotational period, *P*** by conducting Lomb–Scargle periodogram analysis.

→ $P = 0.54 - 14.18\,\mathrm{days}$

- We calculated **the amplitudes of the light curves** (10-90 percentile flux).

→ $\mathrm{Amplitude} = 0.011 - 0.552\,\mathrm{mag}$

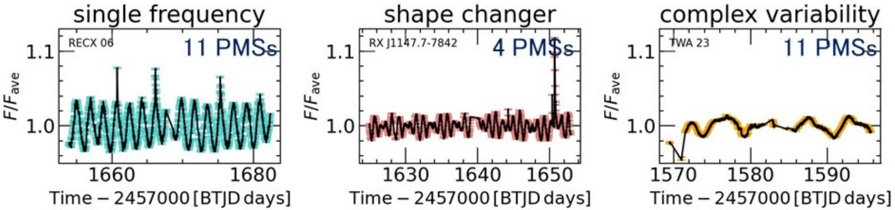


Fig. 9: The examples of *TESS* light curves of the PMSs

Discussion: Young stars have huge spots.

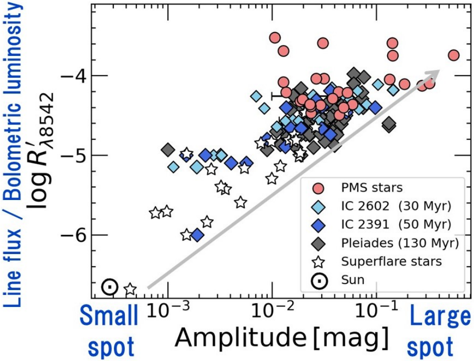


Fig. 10: The strength of the Ca II IRT emission line (λ8542 Å), $R'_{\lambda 8542}$ as a function of **the amplitude of the lightcurve**

- The objects with the larger amplitude of the light curve (≒ larger spot) also show the brighter Ca II emission line
- The PMS stars have about 2-3 orders
  - larger amplitude
  - larger R' (= brighter Ca II emission line)

  than the Sun and the superflare stars.

Dynamo activity of the young solar-type stars

- PMSs could have **enormous spots** on their surface !
- **The large-scale magnetic activity** like the Sun may continue from the PMS stage.

The activities and starspots of the young stars

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Context. Pre-main sequence stars (PMSs) and zero-age main-sequence stars (ZAMSs) are considered to have enormous starspots and strong chromospheric emission lines because of their strong surface magnetic field.

Aims. We discuss the dynamo activities of PMSs and ZAMSs with their periodic light variation caused by a starspot and the strength of the chromospheric emission lines.

Methods. We obtained the amplitudes of the light curves from *TESS* photometric data for 26 PMSs and 39 ZAMSs, and investigated the relation between **the chromospheric Ca II emission line** from HDS.

Results. The ZAMSs and PMSs have about 2-3 orders larger amplitude and brighter Ca II emission line than the Sun.

Conclusions. The ZAMSs and PMSs could have **enormous spots** on their surface and **the large-scale magnetic activity** like the Sun.

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[https://arxiv.org/abs/2202.02065]

Data reduction of spectra 2

1. subtaction of the photospheric absorption component **(Fig. 11)**

   [target object] - [template star]

   * template star: inactive stars with a spectral type similar to that of target stars
   - **veiling** correction
   - **rotational broadening** correction

   → Match the depth and width of the photospheric absroption lines, such as Ni I

2. measuring the equivalent widths and FWHMs of Ca II IRT emission lines
3. We converted the equivalent widths of the emission lines into
   - the surface flux of the emission line, F'
   - R' $(\equiv F'/\sigma T_{\mathrm{eff}}^4)$

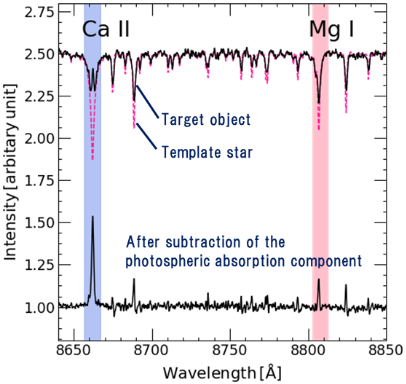

Fig. 11: The procedures of the spectral subtaction of the photospheric component for the PMS star, RECX 11

Activity of ZAMS stars

X axis: Rossby number, $N_{\rm R} \equiv \dfrac{\text{rotational period, } P}{\text{convective turnover time, } \tau_{\rm c}} = \dfrac{2\pi R}{v \sin i}\dfrac{1}{\tau_{\rm c}}$

Y axis: $R' \equiv \dfrac{\text{surface flux of the emission line, } F'}{\text{stellar total bolometric luminosity, } \sigma T_{\rm eff}^4}$

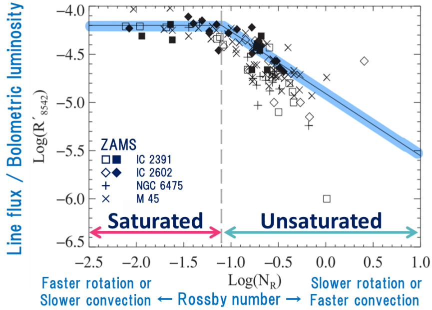

Fig. 12: R' of Ca II IRT emission line (λ8542 Å), versus $N_{\rm R}$ for single ZAMS stars **(Marsden et al., 2009)**

Ca II infrared triplet lines (IRT; λ8498, 8542, 8662 Å)

Unsaturated Regime

The object with small $N_{\rm R}$ shows larger R'.

→ It is expected that the object with small $N_{\rm R}$ has larger emission region.

Saturated Regime

The object shows a constant R' independent of $N_{\rm R}$.

→ It is suggested that the active region fills the chromosphere completely.

Q1. What drives the chromospheric activity for PMSs ?

X axis: Rossby number, $N_R \equiv \dfrac{\text{rotational period, } P}{\text{convective turnover time, } \tau_c} = \dfrac{2\pi R}{v \sin i} \dfrac{1}{\tau_c}$

Y axis: $R' \equiv \dfrac{\text{surface flux of the emission line, } F'}{\text{stellar total bolometric luminosity, } \sigma T_{\text{eff}}^4}$

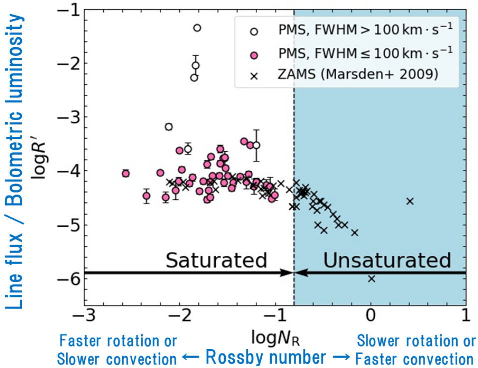

Fig. 13: Rotation-Activity Relation of Ca II IRT emision lines **(Yamashita et al. 2020)**

A. 54 PMS stars (●) are activated by the dynamo process.

- $R' \simeq$ the max of the ZAMSs
- **The chromosphere of PMSs are active.**
- These chromospheres are filled by the emitting region.

A. 6 PMS stars (○) are activated by the accretion.

They show strong and broad emission lines, whose R'_{IRT} are 2 orders of magnitude larger than the ZAMS stars.

Rotation-activity relation and the amplitude

X axis: Rossby number, $N_{\rm R} \equiv \dfrac{\text{rotational period, } P}{\text{convective turnover time, } \tau_{\rm c}}$

Y axis: $R' \equiv \dfrac{\text{surface flux of the emission line, } F'}{\text{stellar total bolometric luminosity, } \sigma T_{\rm eff}^4}$

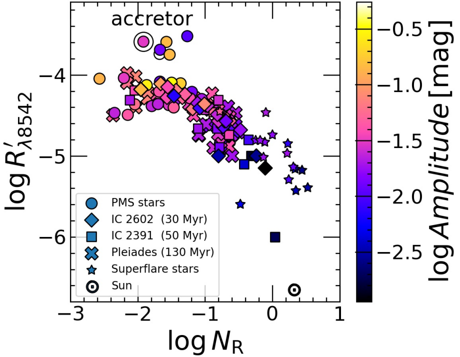

Fig. 14: Rotation-Activity Relation of Ca II IRT emision line (λ8542 Å) and **the amplitude of the lightcurve**

- The objects with smaller $N_{\rm R}$ have
  - larger amplitude
  - larger R' (= brighter Ca II emission line)
- Most of PMSs, ZAMSs, and the solar-type superflare stars **(Notsu et al., 2015)** show similar tendency
- The objects with the larger chromospheric emission lines also have the larger spot / spot group.

ロスビー数 N_R の計算

■ロスビー数 $N_\mathrm{R} \equiv \frac{P}{\tau_\mathrm{c}} = \frac{2\pi R<\sin i>}{v \sin i}\frac{1}{\tau_\mathrm{c}}$

(P: 自転周期, τ_c: 対流の周期, R: 天体の半径, $v \sin i$: 軌道傾斜角を含む自転速度, 軌道傾斜角の平均 $<\sin i>= 0.637$)

- 自転周期 P が既知である天体は，P を用いて N_R を計算した
- P が分からない天体は，自転速度 $v \sin i$ を用いて N_R を計算した
- 天体の半径 R は，シュテファン・ボルツマンの法則 ($L = 4\pi R^2 \sigma T_\mathrm{eff}^4$) に，*Gaia* DR2 より引用した光度 L, 有効温度 T_eff を代入して求めた

■対流の周期 τ_c の経験式 (Noyes et al., 1984)

天体の B 等級と V 等級を用いて，

$$
\begin{aligned}
x &= 1 - (B - V) && (1)\\
\log \tau_\mathrm{c} &= 1.362 - 0.166x + 0.025x^2 - 5.323x^3 (x \geq 0) && (2)\\
\log \tau_\mathrm{c} &= 1.362 - 0.14x (x < 0) && (3)
\end{aligned}
$$

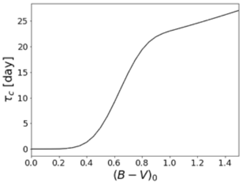

Fig. 15: 天体の色 $B - V$ と対流の周期 τ_c