Open Access Online Journal on Astronomy and Astrophysics
Acta Astrophysica Taurica
www.astrophysicataurucum.org

Acta Astrophys. Tau. 6(4), 1–23 (2025)

Stars with solar-type activity: studies in recent years*

R.E. Gershberg

Crimean Astrophysical Observatory, Nauchny 298409
e-mail: gershberg@craocrimea.ru

Received 2 February 2024

ABSTRACT

The work systematizes and summarizes the main results of the studies of stars with solar-type activity: from the red and brown dwarfs to solar-like stars. The studies carried out primarily in the 2020s are reviewed, and the results obtained are grouped into the following sections: databases and catalogs, photospheres and starspots, rotation, chromospheres, coronae, flares, magnetic fields, activity cycles, and exoplanets.

Key words: red dwarfs and solar-like stars, databases and catalogs, photospheres and starspots, rotation, chromospheres, coronae, flares, magnetic fields, activity cycles, and exoplanets

1 Introduction

During observations of the Eta Carinae region with a 10-inch telescope in Johannesburg, the Danish astronomer Ejnar Hertzsprung (Hertzsprung, 1924) discovered a new variable star on a plate taken on January 29, 1924: on the third of five photographs taken that night with an exposure time of 30 min, it appeared $1^m.8$ brighter than on the first two photographs, $1^m.1$ brighter on the fourth photograph, and $0^m.75$ brighter on the fifth one. On all 37 plates taken over 19 nights, the star had low brightness. Hertzsprung noted that the discovered variability pattern could not allow for identification of the star with either an RR Lyrae type variable or a nova, and he associated its flare with the fall of a minor planet on the star. As it turned out later, this is how flaring red dwarfs were discovered, and Hertzsprung's variable received the standard designation DH Car. For a hundred years, no other manifestations of activity were detected on this M4 dwarf.

In the subsequent quarter of the century, several more such stars were discovered, but observational difficulties due to their faint brightness did not arise much interest. With the progress in observational techniques and new methods of data processing in the middle of the past century, the situation changed. When electrophotometry prevailed in stellar photometry, it replaced visual observations with objectivity and photographic studies with high accuracy, sensitivity, and temporal resolution. As a result, hundreds of red dwarf stars were discovered; the first catalogs of such variable stars were compiled; the nonperiodicity of their flares was established; the power-law nature of the energy spectrum of flares was detected; and the cyclicity in the activity of such stars was revealed based on photometric series over dozens of years. With the installation of spectrographs with sensitive detectors on large telescopes, flare spectra with high temporal resolution were obtained; the nature of changes in various spectral lines of flares at different phases of their development was detected; and parameters of stellar chromospheres in the quiet and flare states were determined, as well as temperature, density, and velocity of flare matter motion. This ultimately led to the discovery of the physical identity of the flare activity in red dwarfs and solar activity. High-resolution spectra and spectropolarimetric methods led to the detection of stellar magnetic fields. With the advent of large radio telescopes, stellar coronae were discovered, and their thermal emission in the quiet state of stars and nonthermal emission of flares were measured. With the launch of astronomical spacecrafts into space, ultraviolet and X-ray emission from flaring stars became accessible, and their recorded line spectra allowed one to estimate parameters of the upper atmospheres of these stars. For the analysis of these rich experimental data, necessary theoretical studies were simultaneously conducted. The theory of the Balmer decrement for conditions in the atmospheres of such stars was developed; various methods for estimating parameters of cool starspots were proposed; and the theory of magnetic field generation on stars was developed, which made it possible to estimate the structures and strengths of these fields.

The most recent major step in the experimental study of stars with solar-type activity is the launch of space telescopes for panoramic photometry of stellar fields. These telescopes enable simultaneous observations of thousands of objects for a long time periods with high temporal resolution. As a result,

* This review was prepared for the Crimean conference "Stars with Solar-Type Activity: Studies in Recent Years" dedicated to the centenary of Ejnar Hertzsprung's discovery of flaring red dwarfs (CrAO, February 26–27, 2024). In preparing the English version of the review, information was added about the most interesting 33 papers from several dozens of published ones a year and a half after the aforementioned Crimean conference. A.A. Shlyapnikov took an active part in compiling these additions.

very rare stellar flares were detected, which are 2–3 orders of magnitude higher in energy than the most powerful solar flares; and the catalogs of such stars were compiled, the largest of which contain hundreds of thousands of objects.

In 2020, a large monograph by Gershberg, Kleeorin, Pustilnik, and Shlyapnikov "Physics of Mid- and Low-Mass Stars with Solar-Type Activity" was published, which presents in considerable detail the history of studying these objects: from Hertzsprung's discovery to the moment of writing of this book. It is inappropriate here to repeat the results presented in the monograph. However, in the past few years, new important results have been obtained and the number of publications on this topic reached two hundred. It is precisely these studies, along with ongoing investigations and some publications missed in the monograph for various reasons, that are considered in this review.

In the issue of the bulletin "Astronomical News" dated October 27, 2023, a note was published dedicated to the 150th anniversary of Ejnar Hertzsprung's birth, which is briefly presented below.

Ejnar Hertzsprung was born on October 8, 1873, in Frederiksberg near Copenhagen. He studied at the Copenhagen Polytechnic Institute and received a degree in chemical engineering. After graduating from the institute in 1898, he worked for three years in St. Petersburg. Upon returning to his homeland, he began to study astronomy, simultaneously conducting photographic observations at the Copenhagen Observatory, then in Potsdam and Leiden, where he became director in 1935.

Hertzsprung's main scientific works relate to astrophysics and stellar astronomy. In 1905–1907, he discovered the existence of giant and dwarf stars, showing that stars with the same temperature can have significantly different luminosities. He determined the proper motions of many stars in the Pleiades cluster region to identify cluster members. He was the first to note differences in the stellar populations of the Pleiades, Hyades, and Praesepe clusters, which were later explained by differences in the ages of these clusters. Ejnar Hertzsprung performed an enormous number of measurements of double and variable stars from their photographs. He calibrated the relationship between brightness and period obtained by H.S. Leavitt for variable stars in the Small Magellanic Cloud, showing that these variables are Cepheids; using this relationship, he determined the distance to the Small Magellanic Cloud. He established the dependence between the period of Cepheids and the shape of their light curves. In 1911, he showed that Polaris is a Cepheid. Hertzsprung was the first to construct a diagram of the dependence of apparent stellar magnitude on color index for stars in the Pleiades and Hyades clusters; subsequently, when H.N. Russell constructed a similar diagram for all stars with known then distances, it was named the Hertzsprung – Russell diagram. This diagram became a cornerstone in the studies of stellar evolution.

As can be seen, the authors of this note have not considered Hertzsprung's accidental discovery of flaring red dwarfs worthy of mention alongside his fundamental results.

This review focuses primarily on specific experimental results of recent years and consists of the following sections:

1. Databases and catalogs.
2. Photospheres and starspots.
3. Rotation.
4. Chromospheres and prominences.
5. Coronae and stellar wind.
6. Flares and superflares.
7. Magnetic fields.
8. Cyclicity and evolution of activity.
9. Exoplanets.

It is necessary to keep in mind some conditional nature of assigning many studies to one or another of the listed sections, since each work usually concerns more than one of them.

2 Databases and catalogs

Based on the Gaia DR3 data, Distefano et al. (2023) compiled a catalog containing 474 026 stars. From their light curves the authors detected periodic variations, which they attributed to the effects of dark spots or bright faculae, i.e., to manifestations of stellar magnetism. The variability of about 430 000 cataloged objects was detected for the first time. The catalog provides 66 parameters for each star, the most important of which are rotation periods, corresponding brightness amplitudes, and the Pearson correlation coefficient between brightness and color variation. The use of this coefficient allowed the considered objects to be segregated into those where brightness variations are caused by dark spots and those where bright faculae are responsible for these variations.

Chahal et al. (2022) compiled a catalog of BY Dra-type variables containing 84 697 FGKM main-sequence (MS) stars with spots and faculae on the photosphere, including their effective temperatures, radii, luminosities, masses, rotation periods, and photometric magnetic indices $S_{\rm ph}$ in the g and r bands. More than half of this sample are K stars, and 94% of objects have rotation periods less than 10 days and are therefore young stars that have not undergone effective braking. The paper discusses correlations of the listed parameters within the framework of ideas about differences in stellar structures of different temperatures, ages, and magnetism of different degrees of saturation. K stars exhibit a higher magnetically active fraction than M stars.

Engle (2024) made a 15-page review on X-rays, ultraviolet, and the activity – age relationship, including 20 pages of tables with numerous parameters of many M dwarfs.

To determine stellar ages from the empirical relations between rotation period, chromospheric activity, and age, Ye et al. (2024) compiled a catalog including masses and ages of 52 321 FGK dwarfs, 47 469 chromospheric activity indices $\lg R'_{\rm HK}$, 6077 rotation periods $P_{\rm rot}$ and variability amplitudes $S_{\rm ph}$, based on data from LAMOST, Kepler, and Gaia telescopes. Comparison of these data revealed a pronounced correlation between $P_{\rm rot}$, age, and [Fe/H] throughout the MS phase for F dwarfs. For G dwarfs, both $P_{\rm rot}$ and $\lg R'_{\rm HK}$ are reliable age probes in the ranges of ~2–11 and ~2–13 Gyr, respectively. K dwarfs exhibit a prominent decrease in $\lg R'_{\rm HK}$ within the age range of ~3–13 Gyr.

Shlyapnikov (2024a) prepared the third version of the Catalog of Stars with Solar-Type Activity (CSSTA-3). It contains 314 618 objects with the following data: main object designation, its equatorial coordinates, main object type, its variability type according to GCVS, magnitude V from different sources, magnitudes at minimum and maximum, spectral type from different sources, emission lines, chromospheric activity index, presence of spots or their parameters, ultraviolet or flares in ultraviolet, infrared emission, radio emission or radio flares, effective temperature, estimates of radius and luminosity, activity period from different sources, activity cycle duration, presence of exoplanets and their number. A detailed description of CSSTA-3 is given in Gershberg et al. (2024).

Galligan, Lepine (2025) examined 109 276 optical spectra of low-mass stars in the Sloan Digital Sky Survey (SDSS). This is a broad collection of long-lived objects in the solar neighborhood that traces the three major components of our Galaxy: the thin disk, the thick disk, and the halo. These populations have distinct metallicity and kinematics. The authors use a set of 536 improved empirical templates of the spectral classification of K and M dwarfs to more accurately determine spectral subtypes and metallicity. The most metal-rich stars are located primarily in the thin disk. The methodology developed by the authors mitigates the use of the dominant population of local M dwarfs to trace chemodynamics in the solar neighborhood.

3 Photospheres and starspots

Within the framework of the zonal model of stellar spottedness proposed and developed at CrAO, Alekseev, Kozhevnikova (2017, 2018) examined variations of this spottedness for 12 M and 13 G–K dwarfs over decades and found a poleward drift of spots for 11 stars, suspected activity cycles lasting from 25 to 40 years for six stars. The detected spot drift velocities by latitude turned out to be 2–3 times smaller than on the Sun.

Ioannidis, Schmitt (2020) conducted a year-long photometric study of the young fast rotator AB Dor using the Transiting Exoplanet Survey Satellite (TESS) data, covering almost 600 of its rotations. Enhanced stellar activity occurred during 11% of the observation time, and spots were located at the well-defined longitudes from low to high latitudes. The spot positions were determined by both differential rotation of the star and their lifetimes of 10–20 days. On the less spotted hemisphere of the star, the frequency of flares was 60% lower than on the more spotted one, but the fact that their number does not drop to zero is interpreted as the presence of high-latitude spots, which are absent on the Sun.

Johnson et al. (2021) published the first analysis of expected photometric features of magnetically active G–M stars with hot faculae and cool spots. The developed theory is based on light curves in various photometric bands and relies on differences in the visibility of spots and faculae at different distances from the disk center and on the limb darkening effect.

Senavci et al. (2021) performed extensive studies of EK Dra in the optical wavelength range. The authors determined abundances of 23 elements with [Fe/H] = 0.03, with significant overabundance of lithium and barium; s-process elements Sr, Y, and Ce are marginally overabundant, while Ni, Cu, and Zn are marginally deficient compared to solar abundances. The overabundance of barium is most likely due to the assumption of depth-independent microturbulent velocity, and the lithium overabundance is due to the youth of the objects. The authors estimated the star's mass as 1.04 $M_{\odot}$ and age of 27 Myr, which corresponds to the post-T Tauri phase on the pre-main-sequence (PMS). The Doppler analysis of observations over 15 days led to the conclusion on the existence of a circumpolar spot and spots at mid-latitudes with their absence at low latitudes.

By comparing starspot temperatures found by the zonal spottedness method for 26 flaring stars with the photosphere temperatures of these stars, Alekseev, Gershberg (2021) found a good correlation of these values and obtained a simple formula for calculating the former from the latter. The spot temperature estimates obtained in this way do not contradict the results that gave more complex estimates with atmospheric structure calculations and/or MHD considerations.

Bicz et al. (2022) developed a program for modeling the light curves of spotted stars to estimate the number of spots and their parameters. Using TESS observations of M dwarfs, the authors found the presence of two spots on GJ 1243 with a mean temperature of about 2900 K and a spottedness of 3% of the stellar surface, as well as two spots on V374 Peg with a temperature of about 3000 K and a spottedness of about 6% of the stellar surface. For two YZ CMi observations separated by a year and a half, Bicz et al. found a three-spot model with a mean temperature of about 3000 K and a spottedness of about 9% of the stellar surface, as well as a four-spot model with a mean temperature of about 2800 K and a spottedness of about 7% of the stellar surface. Another program developed by them automatically searches for flares from light curves. Dozens of flares with energies of 10^{31-34} erg were detected with rise times from 4 to 77 minutes and decay times from 12 to 273 minutes.

Using high-resolution FUV spectra from the Hubble Space Telescope (HST) during a flare and in the quiet state of the star, Flagg et al. (2022) confirmed the presence of molecular hydrogen in the AU Mic system. The gas temperature is estimated from 1000 to 2000 K. Based on the radial velocities and widths of the H_2 line profile, the line emission is likely produced in the star, rather than in the disk or the planet. Although the indicated temperature is much lower than that of the star.

Katsova et al. (2022a) examined the level of coronal and chromospheric activity for 23 solar twins from the X-ray and ultraviolet data and found a significant scatter in the L_X/L_{bol} ratio and lithium abundance, which may link the surface activity of stars with phenomena at the base of their convective zones. The TESS data allowed them to reveal rotational modulation of stellar brightness associated with starspots. Some sample stars have rotation periods close to six days, which indicates their youth. The most powerful flare had an energy of 8×10^{33} erg and a duration of more than four hours.

Di Mauro et al. (2022) investigated multi-year TESS observations of the planet-hosting magnetically active star GJ 504. The authors made an attempt to isolate oscillatory properties of this MS star but found no pulsations and concluded that the suppression of acoustic modes can be explained by the high level of magnetic activity.

Cao, Pinsonneault (2022) estimated starspot filling fractions for 240 stars in the Pleiades and M67 open star clusters using a modified spectroscopic pipeline that also enables the starspot temperature contrast. In the Pleiades, filling fractions saturate at a level of 0.248 for active stars with a decline at slower rotation, which can be represented by a function of Rossby number. In M67, GK MS stars have mean filling fractions of 0.030 and 10 times less in evolved red giants. Effective temperatures for active stars are offset from inactive ones by −109 K.

The connection between solar flares and spots was ascertained at the very early stage of studying solar activity. It is possible that the pioneer here was the Czech astrophysicist Václav Bumba in the mid-1950s, a graduate student of A.B. Severny at CrAO. Interest in this idea has increased in recent decades when it became clear that the spottedness of active red dwarfs exceeds that of the Sun by 2–3 orders of magnitude, and maximum stellar flares are equally more powerful compared to solar ones. Here we should note the recent interesting result obtained by Katsova et al. (2022a). The authors showed that the frequency of weak flares is practically independent of the degree of solar spottedness, while the frequency of strong flares noticeably increases in large active regions. This circumstance particularly explains the absence of superflares on the Sun.

Yamashita et al. (2022) examined evidence of activity for zero-age main-sequence (ZAMS) stars, where enormous starspots and strong chromospheric emission lines are expected. From TESS data, the authors extracted light curves of 33 stars in IC 2391 and IC 2602, with light curve amplitudes of $0^m.001-0^m.145$ and starspot coverages of 0.1–21%. They recorded 21 flares with energies of 10^{33-35} erg.

Xu et al. (2022) analyzed spots and chromospheric activity on HD 34319 from TESS observations, as well as from spectroscopy at Haute-Provence Observatory and W.M. Keck Observatory telescope in 1995–2013. They applied a two-spot model with a rotation period of 4.4364 days, measured the equivalent widths of CaII and hydrogen lines, and proposed a scheme for spot development. However, referring to Rodonò's two-spot concept (La Fauci, Rodonò, 1983) of forty years ago is surprising.

Martin et al. (2024) drew attention to the important role of the eclipsing system CM Dra in the study of M dwarfs. This is a fairly bright edge-on system consisting of two fully convective dwarfs whose radii and masses were known with accuracy better than 1%, and in this study the accuracies were improved to 0.06% and 0.12%. Furthermore, Martin et al. revealed strong and variable spot modulation, suggesting spot grouping and activity cycles with duration of years. Finally, they detected 125 flares, with the flare frequency not decreasing during eclipses, and suggested that flares are preferentially polar.

Ikuta et al. (2023) analyzed the TESS light curves of AU Mic, YZ CMi, and EV Lac and estimated spot positions on them. It was found that the flare occurrence frequency is not necessarily correlated with rotation phases, which can be explained by the variations of spot size and latitude.

Araújo, Valio (2023) investigated the activity of two K stars observed by the Kepler observatory, similar in every way from mass to rotation periods and planetary systems. Both stars exhibit about a hundred spots found by the transit mapping technique, but Kepler-411 produced 65 superflares, while Kepler-210 presented none. And the spot parameters definitely differ: their average radii are 17 and 58 thousand km, the intensity ratio with respect to the photosphere is 0.35 and 0.64, and the temperature is 3800 and 4180 K, i.e., spots on the star with no superflares are mostly larger, less dark, and warmer than those on the star with superflares. This may indicate either lower magnetic field strength or its simpler structure.

From century-long photometry and 200-day high-resolution spectroscopy in 2018, Kovari et al. (2024) examined the multiple system V815 Her. From numerous photometric cycles from 6.5 to ~26 years, they detected a very complex system: V815 Her Aa is a solar-like spotted ZAMS star with weak differential rotation; the third body, V815 Her B, is an eclipsing close binary with a period of 0.5 days consisting of two M dwarfs; and the object as a whole is a 2+2 young quadruple hierarchical structure.

Di Maio et al. (2024) presented a method that allows modeling of the stellar photosphere with spots for young active and rapidly rotating stars. Within the project on the global architecture of planetary systems, they analyzed more than 300 spectra of the young host star V1298 Tau derived with the high-resolution HARPS-N spectrograph under the assumption that differential rotation increases angular velocity at the equator. The proposed model was confirmed to increase sensitivity and the ability to reproduce information about planets and to model the stellar photosphere.

Monson et al. (2024) explored the influence of flares in stellar atmospheres on the state of subphotospheric matter. Using radiation and hydrodynamic calculations as well as radiative transfer calculations to model the atmospheric response to electron beam heating, the authors synthesized neutral iron lines to obtain Doppler shifts in the intensity profile and showed that blueshifts in the line core depend on the relative contribution of the chromosphere compared to the photosphere. It was concluded that deeply forming lines require multicomponent consideration, with different parts of the spectral line useful for studying individual regions of atmospheric velocity flows.

Smitha et al. (2025) performed the first calculations of starspot spectra based on 3D radiative magnetohydrodynamic simulation. They simulated the starspot spectra on G2V, K0V, and M0V stars in the range from 250 to 6000 nm with a resolution of R = 500 using radiative transfer with the MPS-ATLAS code and found that 1D models do not provide accurate models of the umbra and penumbra on K0V and M0V stars but work well for G2V stars.

Tuomi et al. (2024) simulated the statistics of the dominating spots of two young and active solar-type stars, V889 Her and LQ Hya, to obtain information on the underlying spot distribution, rotation of the star, as well as the orientation of its rotation axis.

Kumbhakar et al. (2025) simulated the light curves of the M dwarfs GJ 182 and 2MASS J05160212+2214528 using the BASSMANN program, selecting the number, positions, sizes, and temperatures of starspots. For GJ 182, the authors obtained a three-spot model with a mean spot temperature of 3279 K and a stellar surface spottedness of 5–8.5%, and for 2MASS J05160212+2214528, a two-spot model with corresponding parameters of 2631 K and 5.4%. On GJ 182, they recorded 48 flares with bolometric energies of 10^{32-35} erg and power-law energy spectrum indices of 1.53 and 1.86 for different samples of flares. Lower estimates of the magnetic field of 12–232 G were obtained.

Carvalho-Silva et al. (2025) considered the relationship between the activity and age of solar-type stars, taking the metallicity factor into account, and found that the chromospheric activity parameter $R'_{\rm HK}(T_{\rm eff})$ strongly depends on this factor. They proposed to consider the age – metallicity – activity relationship for stars in the temperature range from 5370 to 6530 K instead of the age – activity relationship.

4 Rotation

Popinchalk et al. (2021) ascertained the foundations of gyrochronology for M dwarfs. They compiled rotation period data for 713 M0–M8 stars determined from the light curves obtained by the Kepler observatory and also included rotation period data for cluster stars aged from 5 to 700 Myr and objects older than 1 Gyr. Using parallaxes from Gaia 2 and $G - G_{\rm RP}$ photometry, the authors constructed a color – magnitude diagram and analyzed the age distribution of periods on a color – period plot, as well as the distribution of the Hα line equivalent widths and tangential velocities. The transition age from fast to slow rotation in clusters, defined as a break on period – color plots, was found to depend on spectral type, with later spectral types at older ages. The transition from active to inactive Hα line also occurs. Redder and smaller stars remain active at older ages.

Using spectropolarimetry at the Large Binocular Telescope, literature data on Zeeman Doppler images, X-ray emission data, and data from Gaia and asteroseismology, Metcalfe et al. (2022) compared rotation rates of components of pairs of solar-type stars of different ages, estimated their angular momentum loss rate, and found that from 2.6 to 3.7 Gyr, it drops by more than an order of magnitude and then continues to slowly decrease to 7 Gyr.

Using TESS, Gaia data, and own high-resolution spectral observations, Medina et al. (2022) compiled a complete sample of 219 single M dwarfs with masses between 0.1 and 0.3 $M_\odot$ within 15 pc of the Sun and analyzed their kinematic characteristics and activity parameters. They found that the power-law index in the flare frequency distribution by energy is 1.984±0.019 for all stars. Assuming continuous star formation in the Galactic thin disk over the past 8 Gyr, the transition from the saturated to the unsaturated activity regime occurs at 2.4 ± 0.3 Gyr. Stars with rotation periods less than 10 days have ages of 2.0 ± 1.2 Gyr; those with periods from 10 to 90 days, 5.6 ± 2.7 Gyr; and those with periods greater than 90 days, 12.9 ± 3.5 Gyr. Stars with rotation periods less than 10 days and masses between 0.2 and 0.3 $M_\odot$ have average ages of 0.6 ± 0.3 Gyr, while those with masses between 0.1 and 0.2 $M_\odot$ have ages of 2.3 ± 1.3 Gyr.

Lu et al. (2022) compiled a catalog containing rotation periods of 40 553 stars using the automated Zwicky Transient Facility sky survey system.

Kitchatinov (2022) proposed an original idea that the observed cyclicity of stellar activity appears not due to rotational braking but a stronger dependence on effective temperature.

In the PMS stage, the rotation rate of a solar-like star is determined by the interaction of the protostellar disk and stellar compression. At ages above 100 Myr, magnetic braking suppresses the star's initial rotation rate, and rotation determined by gyrochronology is established. The exact transition time between these regimes is determined by stellar mass and requires experimental calibration. To use the open cluster α Per as a calibrator, Boyle, Bouma (2023) performed a joint analysis of data acquired by TESS, Gaia, and LAMOST, compiled an extensive list of stars of the same age, and concluded that the age of the most scattered members of the cluster is close to 50 Myr.

Using TESS observations of AU Mic, Ilin, Poppenhaeger (2022) attempted to verify the hypothesis of whether magnetic activity events on the star occur in phase with the orbit of AU Mic b. During approximately 50 days of observations, the flare distributions with orbital, rotational, and synodic periods are generally consistent with intrinsic stellar flaring. To test this hypothesis, monitoring duration needs to be increased by a factor of 2–3.

As shown by Reinhold et al. (2022), the GPS (Gradient of the Power Spectrum) method can be used to determine rotation periods of stars with aperiodic light curves, based on analyzing not the power spectrum but the gradient of the power spectrum. The authors showed that the GPS method is capable of determining the correct rotation period in 40% of all considered cases and significantly surpasses autocorrelation methods.

To study the rotation – activity connection, Núñez et al. (2022, 2024) obtained optical spectra for 250 stars, X-ray luminosity data for 10 stars, and rotation periods for 28 stars in the Praesepe cluster; similar new data relate to 131, 22, and 137 stars in the Hyades cluster. These data were used to calculate Rossby numbers and $L_{\rm H\alpha}/L_{\rm bol}$ and $L_{\rm X}/L_{\rm bol}$ ratios. At cluster ages of about 700 Myr, almost all M dwarfs exhibit Hα line emission, with binary systems and single stars having the same color and equivalent width distributions of this emission. The authors found that the critical Rossby number value at which activity saturation occurs is smaller for X-rays than for the Hα line. But these emissions are close in intensity, which allows one to suggest that the corona and chromosphere undergo the same magnetic heating.

Monsch et al. (2023) investigated the connection between circumstellar disk lifetimes and rotation evolution of low-mass stars. Employing an internal EUV/X-ray photoevaporation model, they derived a simple algorithm for calculating the impact of disk locking on spin evolution. The authors found that the duration of the disk locking phase affects the subsequent rotational evolution of the young star. This approach leads to agreement between calculations and observed rotation period distributions in open clusters of different ages.

Based on a sample of 44 MS stars with well-known activity cycle periods and rotation periods, Mittag et al. (2023) explored the connection between these parameters. They found linear behavior in the double logarithmic relationship between Rossby number and cycle period. The bifurcation into long-period and short-period branches is clearly real but depends on B–V, i.e., on effective temperature and position on the MS. There is also a correlation between cycle duration and convective turnover time. On this basis, empirical relationships between cycle period and Rossby number were inferred. The Schwabe period on the Sun is about 10.3 years, and the Gleissberg cycle lasts approximately 104 years. Furthermore, the authors suggested that the cycles on the short-period branch are generated in deeper layers of the convection zone, while long-period branch cycles are associated with fewer deep layers in this zone, and that for a wider range of B–V, the Rossby number is a more suitable parameter for universal connection than just the rotation period.

Carmona et al. (2023) investigated the rotation of AD Leo in the near-infrared and optical ranges to determine whether the 2.23-day period results from the star's axial rotation or from the exoplanet's revolution. Observations were conducted in Haute-Provence and Hawaii, achieving radial velocity precision of 3–5 m/s and 2 m/s, respectively. The authors concluded that there is no connection with an exoplanet.

In the first half of MS life, stars rapidly lose angular momentum due to magnetic braking, but when the Rossby number reaches a critical value, braking noticeably weakens. Metcalfe et al. (2023) analyzed new spectropolarimetry of the old G8 dwarf τ Cet and a Zeeman-Doppler image of the younger G8 star 61 UMa and concluded that braking rates over the time from 1.4 to 9 Gyr drop by a factor of 300.

Valio, Araújo (2023) first presented an analysis of differential rotation of stars using starspot transit maps for solar-like stars and M dwarfs. The authors presented differential rotation profiles for 13 slowly rotating stars observed by Kepler and CoRoT with rotation periods greater than 4.5 days and spectral types from M to F. The analysis results showed a significant negative correlation with a coefficient of −0.77 between the rotational shear $\Delta\Omega$ and the star's mean rotation period. On the other hand, a weak correlation was found between differential rotation and stellar effective temperature.

Saunders et al. (2024) discussed to what extent weakened magnetic braking leads to sustained rapid rotation of old stars. They found that a sample of stars with rotation periods and ages measured using asteroseismology is consistent with models that deviate from standard rotation before reaching the Sun's evolutionary stage. A normalized critical Rossby number $Ro_{crit}/Ro_{\odot} = 0.91 \pm 0.03$ was determined as the threshold for deviation from standard rotational evolution, i.e., weakened magnetic braking affects approximately half of the MS lifetime of solar-like stars.

Shan et al. (2024) determined rotation periods for a large sample of M0–M9 dwarfs found photometrically and spectroscopically and compiled a table including 261 periods. They examined the rotation – activity relationship with emission in X-rays, Hα line, and H and K lines of ionized calcium and surface magnetic field strength and showed rotation periods as a function of stellar mass, age, and galactic kinematics. Except for three transiting planetary systems and TZ Ari, all planet-hosting stars in this sample have rotation periods greater than or around 15 days.

Chen et al. (2020) used the ZTF Data Release 2 (DR2) to search for and classify variables down to $r \sim 20^m.6$ and published catalog of 781 602 periodic variables observed with the ZTF. Among all the variable stars, 84 697 BY Draconis stars have rotational modulation due to the presence of starspots.

Using data from the first 26 TESS sectors, Colman et al. (2024) analyzed 432 704 2-minute cadence light curves from individual observation sectors for FGKM dwarfs and detected 16 800 periods for 10 909 individual stars. The authors present a catalog of the median period for each object measured by the Lomb – Scargle periodogram.

Metcalfe et al. (2025) presented observational constraints on the magnetic braking of six early K stars, found that the stellar wind braking torque decreases abruptly at a critical value of the stellar Rossby number, and suggested that weakened magnetic braking may coincide with the operation of a subcritical stellar dynamo.

Stuart, Gregory (2025) examined the evolution of the rotation – activity relation from the saturated regime of PMS stars, where $\log(L_X/L_{bol})$ is approximately constant, to the unsaturated regime of solar-type stars, where this value decreases with increasing Rossby number. Based on observations of about 600 stars from four clusters, the authors simulated the rotation – activity relation up to ages of 100 Myr and found that higher mass stars begin to form the unsaturated regime from around 10 Myr. After 25 Myr, the gradient of the unsaturated regime matches that found for MS stars.

Frasca et al. (2025) presented the results of their analysis of 1581 medium-resolution LAMOST spectra of 283 stars of late-type candidate members of the Pleiades with the aim of determining the stellar parameters, activity level, and lithium abundance.

Yang et al. (2025) detected that the latitudinal distribution of active regions of fast rotating stars is consistent with that on the Sun. These results provide a crucial constraint to the stellar dynamo, indicating that the solar-like dynamo also applies to fast rotating stars and even spans different stages of their evolution.

5 Chromospheres and prominences

In contrast to the classical consideration of the Stark broadening of spectral lines due to plasma particle microfields, Oks (1981, 2006) proposed and developed the concept of Stark broadening due to low-frequency electrostatic plasma turbulence (LEPT). This mechanism may prove to be the dominant factor. First, Koval', Oks (1983) examined hydrogen emission profiles H_5–H_{11} of two strong solar proton flares recorded in Crimea and found that they are broadened by the LEPT mechanism. Recently, Oks, Gershberg (2016) analyzed three spectrograms of two AD Leo flares and an EV Lac flare and found that within the framework of the classical Stark effect, the widths of H_α–H_δ lines give a very high electron density of the emitting plasma, 10^{15} cm^{-3}, while within the LEPT framework, it turns out to be quite close to the electron density obtained by Katsova (1990) from the Balmer decrement of flare spectra.

Leitzinger et al. (2022) examined an event on the young Me dwarf V374 Peg, during which additional emission appeared on the blue side of Balmer lines. Through 1D NLTE calculations, the authors presented the distribution of physical parameters in the structure responsible for this emission and found that, except for temperature and area, all parameters are in the upper range of the typical parameters of solar prominences, whereas temperature and area are higher than those of typical solar prominences. However, models with filament structure turn out to be more numerous than those with prominence geometry.

Using extensive Gaia DR3 data, Lanzafame et al. (2023) conducted a systematic analysis of Ca II infrared triplet emission in stars. They examined the positions of these stars in the color – magnitude diagram and the correlation with the amplitude of the photometric rotational modulation. The authors detected that the highest level of infrared triplet activity is associated with PMS stars and RS CVn binary systems and also found some evidence of bimodal distribution of MS stars at $T_{\rm eff}$ > 5000 K. Stars with temperatures 3500 K < $T_{\rm eff}$ < 5000 K turned out to be either very active PMS stars or active MS stars with a unimodal distribution. A sharp change in the activity distribution is found for $T_{\rm eff}$ < 3500 K, with a dominance of low activity stars close to the transition between partially- and fully convective stars and a rise in activity down into the fully convective regime.

Meunier et al. (2022) examined the relationships between the Hα and Ca II chromospheric emissions in time series for 441 FGK stars and found anticorrelation of these lines for a few percent of the objects, contrary to what is observed on the Sun. The authors concluded that plages alone are unlikely to explain the observed variety of relationships between these lines and suggested that the filaments that have different intensity relations of these lines may be an additional factor explaining the obtained observations. On the other hand, for FGK dwarfs observed with the HARPS spectrograph over 13 years, Gomes da Silva et al. (2022) noted a significant dependence of the correlation of these chromospheric lines on the Hα bandpass width. The correlation is maximum when measuring the hydrogen line with a 0.6 Å band but can even become negative with a very wide bandpass.

From observations with HST, Apache Point, and Gemini South Observatory telescopes, Duvvuri et al. (2023) investigated the nonflare variability in the chromospheres of nine M dwarfs. They explored Balmer lines from Hα to H_{10} and the Ca II H and K lines. These lines were found to vary on the order of 1–20% over the course of an hour, with amplitude of variability being greater for the faster rotating stars. But in ultraviolet lines of N V, Si IV, C IV, C II, and He II, the S/N ratios are too low to detect stochastic changes.

Kumar, Fares (2023) investigated 14-year observations of Ca II H and K, He I_{D3}, Na I, Hα, and Ca II IRT lines in GJ 436 spectra and found positive correlations of Ca II H and K versus Hα variability as well as hydrogen and helium, while infrared Ca II versus Hα lines showed negative correlation. Analysis demonstrated that Ca II H and K lines have a variation period of about 6.8 years; sodium lines, approximately 5.1 years; and the hydrogen line, about 5.9 years; whereas the photometric cycle is approximately 7.4 years. Additionally, Ca II H and K and Hα lines were found to have periods of about 40 days, identified as the stellar rotation period.

Zhang et al. (2022) compiled a database of chromospheric activity of solar-like stars based on low-resolution spectroscopic survey obtained using the LAMOST telescope. From 1 330 654 high-quality spectra, photometric parameters of Ca II H and K lines and the chromospheric activity level S were estimated.

Marvin et al. (2023) performed absolute Ca II H and K and Hα flux measurements for a sample of 110 stars whose spectra were acquired with the HARPS spectrograph and extended $R'_{\rm HK}$ values to M dwarfs, making them available in the temperature range from 2300 to 7200 K.

Strong solar flares are closely associated with coronal mass ejections (CMEs), which are linked to filament/prominence ejections. Using TESS, NICER, and Seimei telescopes, Namekata et al. (2024) conducted a 12-day multiwavelength observational campaign of the solar-like star EK Dra (50–120 Myr age). The star has previously exhibited blueshifted Hα absorptions as evidence for a filament eruption. During simultaneous optical and X-ray observations of EK Dra, the authors identified three superflares with energies from 1.5×10^{33} to 1.2×10^{34} erg and detected two solar-type ejections observed as Hα line emissions blueshifted at speeds of 690 and 430 km/s with masses of 1.1×10^{19} and 3.2×10^{17} g. The faster, massive event shows a candidate of post-flare X-ray dimming with the amplitude of up to ~10%. The energy distribution in the optical and X-ray ranges in the observed superflares is consistent with flares from the Sun, M dwarfs, and close binaries; this may be important for early Venus, Earth, Mars, and young exoplanets.

Bondar', Shlyapnikov (2024) analyzed the results of 30-year brightness observations of the star HD 168443 from ASAS, KWS, and Hipparcos surveys, noted the constancy of its average annual brightness, determined a photometric period of 34.7 days, and associated the detected change in rotational modulation amplitude with the development of active regions.

Ikuta, Shibata (2024) analyzed a large filament eruption associated with one of the EK Dra superflares described above. They found that the Hα absorption, which initially exhibited a blueshift with a velocity of −510 km/s, decelerated in time. The authors performed one-dimensional hydrodynamic simulation of the flow along an expanding magnetic loop emulating a filament eruption under adiabatic and unsteady conditions and found that temporal variations in the Hα line in the EK Dra spectrum can be explained by such a model with longer duration and larger spatial scales than CMEs on the Sun.

Meunier et al. (2024) analyzed the time average and variability of the Ca II H and K, Na D1 and D2, and Hα chromospheric emissions for 177 M stars ranging from subspectral types M0 to M8, paying particular attention to their (anti-)correlations on both short and long timescales as well as slopes between indices. The statistical properties differ from those obtained previously for FGK stars.

Zhang et al. (2024) provided a database of the derived chromospheric activity parameters for 1 122 495 LAMOST LRS spectra of solar-like stars. The calculations demonstrate that $\log(R'_{\rm HK})$ PHOENIX is approximately linearly correlated with $\log(R'_{\rm HK})$ classic. The authors explored the proportions of solar-like stars with different chromospheric activity levels (very active, active, inactive, and very inactive). The investigation indicates that the occurrence rate of high levels of chromospheric activity is lower among the stars with effective temperatures between 5600 and 5900 K.

Su et al. (2025) obtained over 349 000 low-resolution spectra and over 30 000 medium-resolution spectra from LAMOST and used Hα and Ca II H and K lines as indicators of chromospheric activity. The findings confirm the presence of two distinct regions in terms of their relationship between stellar activity and Rossby number (Ro).

6 Coronae and stellar wind

Sakaue, Shibata (2021) constructed a model of nonlinear propagation of Alfvén waves and concluded that these waves can play a crucial role in both heating the stellar corona and driving the stellar wind. Within this scenario, the authors carried out a one-dimensional compressive MHD simulation of the propagation of Alfvén waves for the Sun and M dwarfs, covering the region from the photosphere to the interplanetary medium, including the stellar wind, and concluded that the coronal temperature of M dwarfs should be lower than that of the Sun, the wind speed greater compared to the solar wind, and the mass loss rate much smaller than that of the Sun.

Using VLA in the 2–4 GHz frequency range, Suresh et al. (2020) detected a 29 μJy steady radio source coincident with ϵ Eri at a distance less than 0.2 arcseconds from the star. Combining the obtained results with the previously detected ϵ Eri radio continuum, the authors revealed a spectral turnover at 6 GHz. This emission was ascribed to optically thick, thermal gyroresonance radiation from the stellar corona, as previously assumed for frequencies below 1 GHz. The steep spectral index around 2 strongly disfavors its interpretation as stellar-wind-associated thermal bremsstrahlung. However, attributing the entire observed 2–4 GHz flux density to thermal free-free wind emission, Suresh et al. derived a stringent upper limit $3 \times 10^{-11} M_{\odot}$ per year on the mass-loss rate from the star.

From spectra acquired with HST, Wood et al. (2021) explored Lyα line absorption profiles of nine M dwarfs arising from the interaction of the stellar winds and the interstellar medium. They estimated mass loss rates, constraints on stellar winds, and their dependence on coronal activity. Including previous data, stellar winds for 13 of 15 M dwarfs were found to be weaker than or comparable in strength to that of the Sun, but for YZ CMi and GJ 15AB, mass-loss rates were 30 and 10 times greater than for the Sun, respectively. Wood et al. concluded that not only coronal activity and spectral type determine wind properties but strong stellar winds may be significantly determined by CMEs.

Airapetian et al. (2021) developed a three-dimensional MHD model of the stellar corona – wind system and, using X-ray and extreme ultraviolet (EUV) observations, as well as data from HST and TESS space telescopes, constructed models of the Alfvén wave-heated corona and wind of the young star κ^1 Cet for two epochs separated by 11 months. The authors found that during this time, the global magnetic field structure of the corona had undergone a drastic transition from a simple dipole-like to a tilted and weaker dipole with developed multipole components, with the mass flux in the wind decreasing by 40%.

Kavanagh et al. (2021) put forward an idea of the excitation of radio emission from AU Mic by a planet orbiting it.

Schmitt et al. (2021) performed a comparison of optical photometry and X-ray observations of the young rapidly rotating rotator AB Dor. X-ray data were acquired with the eROSITA telescope aboard the Russian-German Spectrum-Roentgen-Gamma (SGR) mission for almost 20 days. The constant X-ray emission from the star turned out to be very stable for a year and a half with no traces of rotational modulation. During a very powerful optical flare with emission of at least 4×10^{36} erg, the X-ray emission was at least an order of magnitude smaller.

Veronig et al. (2021) noted that sudden dimmings in the extreme ultraviolet and X-ray emission may be associated with stellar CMEs.

Magaudda et al. (2022) compiled a sample of 704 stars of spectral types K5-M7 from the first eROSITA X-ray survey and matched 501 of them with TESS optical results, which allowed for quantitative constraints on the dependence of X-ray luminosity on mass and determination of the change in the activity level with respect to PMS stars. The authors determined rotation periods for 180 M dwarfs that emit in X-rays and estimated the saturation level in the rotation – activity relation. Comparison of hardness ratios and spectra showed that 65% of these X-ray sources have temperatures around 0.5 keV. Comparison with the results obtained 30 years earlier from the ROSAT satellite provides insight into the long-term variability of these sources.

Evensberget et al. (2021) investigated space weather conditions in the solar neighborhood when its age was 0.6 Gyr, which corresponds to the time when life arose on the Earth. For this, the authors calculated three-dimensional stellar wind models for five young solar-like stars in the Hyades cluster aged 0.6 Gyr, using their magnetograms and Alfvén wave-driven wind modeling. Evensberget et al. took the corresponding fundamental parameters of these stars and two absolute magnetic field strength values differing by a factor of 5. The calculated mass and angular momentum loss values generally agree with solar data and differ more than during solar activity minimum and maximum epochs.

Shlyapnikov (2021) identified 67 red dwarfs with X-ray sources in the "first light" field of the eROSITA telescope of the SRG observatory. These stars were found among 2485 X-ray objects.

Pillitteri et al. (2022) conducted 25 observations of HD 189733 over eight years with the XMM-Newton space X-ray telescope. They detected an increase in mean coronal temperature during flares from 0.4 to 0.9 keV with constant fluxes and hardness of the emission outside flares and found a power-law flare energy distribution. Apart from the flares, there are no noticeable changes in the flux and hardness of the coronal emission on a time scale of several months to years, which indicates the absence of detectable activity cycles on such scales.

Toriumi, Airapetian (2022) analyzed 10-year multiwavelength observations of the Sun-as-a-star and young solar-like stars, significantly extending the studies of Pevtsov et al. (2003), who detected a tight power-law relationship between the chromospheric transition region and far coronal ultraviolet, extreme ultraviolet, and X-ray emission fluxes and the total unsigned magnetic flux. The authors found that the power-law exponential coefficient is the smallest at activity maximum and increases during solar maximum and concluded that the atmospheric heating mechanism is universal for the Sun and solar-like stars, despite age and activity level.

Alvarado-Gómez et al. (2022) performed three-dimensional numerical modeling of the stellar wind from AU Mic and examined the evolution of a powerful CME, taking into account the observational constraints on the stellar magnetic field and ejection parameters.

Fuhrmeister et al. (2022) conducted simultaneous observations of Prox Cen in X-rays using the LETGS spectrograph on board the Chandra orbital observatory and in far ultraviolet using the STIS spectrograph on board HST. From 18 optically thin lines in both spectral ranges, they determined the temperature structure and differential emission measure of the transition region and corona during flares. The flare amplitude with regard to its quiet state reaches $A_{\mathrm{X}} = 30$ and $A_{\mathrm{FUV}} = 20$. The emission measure dependence was represented by Chebyshev polynomials in the range $\lg T$ from 4.25

to 8. The constructed synthetic spectra in the 1–1700 Å range can be treated as representative for high-energy irradiation of Prox Cen b during flares.

Chen et al. (2022) investigated variations in emission profiles during several flares from Chandra observations of EV Lac and detected coronal plasma motions with velocities up to 130 km/s from measurements of the O VIII, Fe XVII, Mg XII, and Si XIV lines and their connection to coronal ejections, with upflow velocities typically increasing with temperature. Variable Si XIII triplet line ratios in most flares showed an increase in coronal matter density and temperature. Chen et al. associated these results with explosive chromospheric evaporation in flares. In two consecutive flares, the plasma flow pattern and sharp density increase suggest explosive evaporation at temperatures of at least 10 MK.

In October 2021, Bastian et al. (2022) conducted MeerKAT radio telescope observations of UV Cet in the 886–1686 MHz frequency range. They recorded a flare lasting about two hours with 8-second time resolution and 0.84 MHz frequency resolution, which allowed for examination of the dynamic spectrum demonstrating three peaks and numerous broadband arcs. The arcs are highly right-hand circularly polarized, and at the end of the third peak, short bursts occur that are significantly elliptically polarized. Bastian et al. interpreted this event by a model with a magnetic field dipole and emission mechanism related to cyclotron maser instability, with elliptically polarized emission possibly resulting from reflection from a plasma structure at some distance from the source.

For convenient calculations of upper solar and stellar atmosphere heating, Toriumi et al. (2022) compiled a catalog of spectral indices for ratios of spectral line emissions to surface magnetic flux, which are universal for the Sun and solar-like stars of different ages and activity levels.

Using XMM-Newton, Coffaro et al. (2022) detected coronal cycles in seven solar-like stars; among them ϵ Eri and ι Hor, aged approximately 400 and 600 Myr, showed the shortest X-ray cycles with the smallest amplitudes. The ϵ Eri corona was modeled similarly to solar magnetic structures (active regions, active region cores, and flares) with different filling factors. Studies exhibited that 65%–95% of the coronal surface is covered by magnetic structures, responsible for the small X-ray cycle amplitude. The authors suggested that the main surface coverage by magnetic structures may be higher in the coronae of the youngest stars. To test this hypothesis, Coffaro et al. analyzed X-ray emission from the solar-like star Kepler-63 aged 210 Myr with a 1.27-year photospheric cycle, which is the youngest star observed in X-rays to detect a coronal cycle. From the extended light curve, they found no periodic changes in X-ray luminosity, although a factor of 2 is possible, and attributed this result to 100% surface coverage by active region cores and flares. The authors noted that these young objects have the shortest cycle durations and small amplitudes.

Rigney et al. (2022) conducted low-frequency radio observations with the Australian Square Kilometer Array Pathfinder (ASKAP) telescope totalling 26 h and detected radio emission in Stokes I centered at 888 MHz from four M dwarfs. Two of these sources were also detected with Stokes V circular polarization. However, when examining the detected radio emission characteristics, the authors were not able to distinguish between the models for either electron cyclotron maser or gyrosynchrotron emission.

Analyzing the regions of localization of TeV gamma-ray sources in the X-ray and optical wavelength ranges, Shlyapnikov (2022) determined angular distances from positions of maxima in high-energy flux distributions to probable candidates for identification with red dwarfs.

Gorbachev, Shlyapnikov (2022) searched for periodic variations of brightness and flare activity for 110 red dwarfs, which are candidates for identification with X-ray sources from the eROSITA X-ray telescope aboard SRG mission. Rotation periods were determined for 58 stars, and 233 flares were recorded.

Gorbunov, Shlyapnikov (2022) performed optical identification of stars from the CSSTA catalog that are the X-ray and radio sources. In X-rays, they identified 2507 stars and confirmed 1820 previously identified ones; while in the radio range, 36 and 67 stars, respectively.

Caramazza et al. (2023) compiled a complete list of M0–M4 dwarfs within 10 pc of the Sun and, analyzing this sample, obtained information about general properties of M dwarfs as X-ray sources. Measured X-ray emission values of M dwarfs were compared with various X-ray emitting structures on the Sun: coronal holes, background corona, active regions and their cores. Only star GJ 745 A showed no X-ray emission within the experiment's sensitivity range.

Using HST, Chandra, XMM-Newton, and Swift observatory data, Brown et al. (2023) investigated X-ray and ultraviolet emission from K and M stars, which are exoplanet host objects. X-ray luminosity was measured for 21 of 23 examined stars. Short-term flaring variability was detected for most fully convective stars with $M < 0.35M_{\odot}$ but not for the more massive M dwarfs. The mean X-ray luminosities are $\sim 5 \times 10^{26}$ erg/s and $\sim 2 \times 10^{26}$ erg/s for partially and fully convective stars older than 1 Gyr. Younger, fully convective M dwarfs have luminosities from 3 to 6×10^{27} erg/s.

Evensberget et al. (2023) noted that the initially wide range of rotational periods of solar-like stars contracts and has mostly vanished by a stellar age ~0.6 Gyr, after which solar-type stars spin according to the Skumanich relation. The authors constructed magnetohydrodynamic stellar wind models of 15 young solar-type stars aged from 24 to 130 Myr and, taking into account their previous results, obtained 30 consistent three-dimensional stellar wind models. The models provide good cover of the pre-Skumanich phase of stellar spin-down in terms of rotation, magnetic field, and age. When comparing different magnetic field scalings for each single star, Evensberget et al. found a gradual reduction in the power-law exponent with increasing magnetic field strength.

The magnetic processes associated with the nonthermal broadening of optically thin emission lines with a characteristic velocity of ~23 km/s appear to carry enough energy to heat the corona and accelerate the solar wind. Boro Saikia et al. (2023) investigated whether nonthermal motions in cool stars exhibit the same behavior as on the Sun. For this purpose, excess broadening in optically thin emission lines formed in the chromospheres, transition zones, and coronae was determined from HST spectra. It was found to correlate with stellar rotation rate. The authors concluded that there is solar-like Alfvén wave-driven heating in stellar atmospheres, without excluding heating by flares.

Using the Five-hundred-meter Aperture Spherical radio Telescope (FAST), Zhang et al. (2023) investigated the fine structure of AD Leo radio bursts. Over two days, the authors detected many radio bursts with fine structures in the form of numerous millisecond-scale sub-bursts. Sub-bursts on the first day display stripe-like shapes with nearly uniform frequency drift rates, and on the second day, they reveal a different blob-like shape, which may be caused by electron cyclotron maser instability.

Chebly et al. (2023) performed quantitative estimates of the wind properties of cool MS stars. They simulated the magnetized winds of 21 cool stars of spectral types from F to M using a state-of-the-art 3D MHD code driven by observed large-scale magnetic field distributions. Chebly et al. analyzed dependencies between the spectral type, rotation, and magnetic field strength and Alfvén surface size, mass-loss rate, angular momentum loss rate, and stellar wind speeds, as well as the dependence between the mass-loss rate and the Rossby number. The obtained models encompass the entire Habitable Zones (HZ) of all the stars in their sample, which makes it possible to provide the stellar wind dynamic pressure at both edges of the HZ.

Rodríguez et al. (2023) recorded continuous radio emission from ϵ Eri at frequencies of 10 and 33 GHz whose nature is not clearly established. The authors detected variations of this emission on time scales of days, hours, and minutes. On April 15, 2020, a radio pulse was registered at 10.0 GHz with a total duration of about 20 min and amplitude 4, which Rodríguez et al. simulated as shock wave emission colliding with the stellar wind.

Bloot et al. (2024) conducted radio monitoring of AU Mic for more than 250 hours with the ASKAP telescope in the 1.1–3.1 GHz range and detected a wide variety of radio emission in the time-frequency structure and polarized flux fraction: they identified five distinct types of bursts and broadband quiescent emission. Radio bursts are highly circularly polarized and periodic with the rotation period of the star, i.e., caused by beamed rays and most likely by electron cyclotron maser instability. In the model presented by the authors, the observed emission can be explained by emission from auroral rings on the magnetic poles. The total intensity of the broadband emission is stochastic, but its circular polarization fraction is also periodic with the rotation of the star and may be caused by gyromagnetic emission with magnetic obliquity of at least 20°.

Joseph et al. (2024) compiled a sample of 256 M dwarfs observed simultaneously in X-rays with the German eROSITA instrument aboard the Russian SRG space observatory and in the optical range with the TESS space telescope, which are characterized by relative proximity (up to 100 pc), fast rotation ($P_{\rm rot}$ < 9 days), and high flare frequency. According to the analysis of sample stars, faster rotators showed greater variability, and X-ray flares from these stars often coincide with optical flares.

Freund et al. (2025) investigated the correlation between coronal and chromospheric emissions by combining X-ray data from the stars detected in the eROSITA all-sky surveys with Ca II infrared triplet (IRT) activity indices as published in the third Gaia DR3. The authors studied 24 300 and 43 200 stellar sources with reliable IRT measurement and X-ray detection in eRASS1 and eRASS5, which is by far the largest stellar sample. The ratio between X-ray and IRT fluxes is constant in the saturation regime and decreases for slow rotators.

7 Flares and superflares

Okamoto et al. (2021) refined the results of Notsu et al. (2019) using a large sample of 2341 superflares on 265 solar-type stars: the maximum energy of superflares on solar-like stars is 4×10^{34} erg, and the Sun can cause superflares with energies of 7×10^{33} and 1×10^{34} erg once every ~3000 and ~6000 yr, respectively. Furthermore, Okamoto et al. associated the decrease in maximum flare energy and increase in rotation period with age with reducing total spot area from 10 to several percent and found that superflare frequencies of young stars with rotation periods of 1–3 days are a hundred times higher than those of old slow rotators, but the power-law spectral index of flare energy distribution is approximately the same. No exoplanets were found around the examined stars with superflares, which means they are not necessary for such powerful flares.

Using the Kepler observatory data, Ilin et al. (2021b) investigated flares from 3435 80-day light curves of 2111 members of open clusters Pleiades, Hyades, Praesepe, Ruprecht 147, and M67. In these clusters of very different ages, the authors confirmed 3844 flares on G–M stars, whose energy distributions have power-law form with spectral indices 1.84–2.39. Ilin et al. found that flare activity decreases from mid M stars to G stars and from ZAMS stars to solar-age stars, confirmed the decrease in flare frequencies with age, and that it is greater for more massive stars. The authors found mass and rotation rate values above which flare activity ceases to be saturated.

From the optical Sloan Digital Sky Survey (SDSS) spectra, Koller et al. (2021) performed a search for flares and associated CMEs in F–M MS stars. Flares were detected automatically by detecting significant amplitude changes in the Hα and Hβ lines after a Gaussian profile was fit to the line core. CMEs were searched for by identifying asymmetries in the Balmer lines caused by the Doppler effect of plasma motions in the line of sight. As a result, 281 flares of K3–M9 stars and six CME candidates were identified. Flare energies in Hα are 3×10^{28}–2×10^{33} erg, increasing toward earlier spectral types, whereas the fraction of time in the flaring state increases toward later types. Mass estimates for CMEs range from 6×10^{16}–6×10^{18} g with ejection velocity projections of 300–700 km/s.

During 40-hour monitoring of Prox Cen from radio waves to X-rays in April–July 2019, MacGregor et al. (2021) recorded a short May 1 flare of enormous amplitude from millimeter wavelengths to far ultraviolet: up to 1000 with the Atacama Large Millimeter/submillimeter Array (ALMA) telescope and 14 000 using HST. These bursts, recorded with 1-second cadence, were simultaneous, whereas the optical emission recorded by TESS with 2-minute cadence had amplitude less than 2 and lagged the mentioned bursts by about a minute. The flare began as a 5-second burst in the millimeter and FUV ranges, followed by approximately equally rapid decay, so the flare light curve was represented by a symmetric Gaussian without noticeable exponential decay phase. Millimeter emission at burst maximum reached 2.14 ± 0.15 in units of 10^{14} erg/s Hz, with spectral index changing from

+2, which corresponds to the blackbody emission of the quiet photosphere, to −2.5, which corresponds to synchrotron or gyrosynchrotron, and a substantial change in linear polarization occurred. This may be the third case of synchrotron detection in a stellar flare after observations by Beskin et al. (2017) and the above-mentioned MacGregor et al. (2021).

In 2019, 14-hour monitoring of Prox Cen was conducted with the same equipment, during which ∼50% circular polarization of emission was detected (MacGregor et al., 2021). However, during the above-mentioned May 1 burst recorded in the millimeter and ultraviolet ranges, no events were detected in the microwave range. The next day, microwave observations of this star were supported photometrically and spectroscopically by two optical telescopes, and 42 s before the onset of a strong hour-long optical flare with amplitude greater than 1.5 and energy of 1.6×10^{32} erg, the first fast powerful burst of coherent radio emission was recorded. According to Zic et al. (2020), this emission by polarization and temporal characteristics was analogous to solar decimeter radio emission of type IV caused by accelerated electron flows.

The Prox Cen flare of May 1, 2019, described above, has a bolometric energy of $10^{31.2}$ erg (MacGregor et al., 2021). According to the energy spectrum of this star's flares constructed from TESS observations, such and more powerful flares occur on average once per day in the optical range. Hydrogen, helium, sodium, and calcium emissions with different peak moments were registered in the flare spectrum. 510 s after this flare with a symmetric light curve, a new burst of smaller amplitude occurred, but longer lasting and with a slow decay phase. During both bursts, strong continuum was recorded in the ultraviolet and visible ranges. The obtained multiwavelength flare observations are interpreted by a combination of blackbody and synchrotron emission mechanisms.

Jackman et al. (2021) detected 4430 flares with energies up to 1.5×10^{35} erg on 403 stars using high temporal resolution Kepler data. 515 flares were found near other sources or in binary systems, and frequencies of these flares were systematically higher for faint components.

From the second year TESS observations, Tu et al. (2021) investigated more than 22 500 solar-type stars and detected 1272 superflares on 311 of them. The power-law spectral index of flare energy distribution is -1.76 ± 0.11 with dependence of superflare duration on energy as $E^{0.42\pm0.01}$, which matches the situation in solar flares. Chromospheric activity parameter S was obtained from the LAMOST telescope for 7454 stars and indicates that the Sun is less active than these stars with superflares. Hotter stars in the sample flare less frequently than cooler ones. The superflare energy saturation likely occurs at a level of 10^{36} erg, whereas in a star with the most energetic superflare, TIC93277807, exceeding this limit by more than an order of magnitude, a different mechanism operates.

Recently, using TESS 2-minute cadence data, Ramsay et al. (2021) detected quasiperiodic flare pulsations in seven M dwarfs with periods from 10 to 72 minutes and associated these phenomena with magnetoacoustic waves in flare coronal loops.

In October 2019, three large long-duration flares on the binary system EQ Peg were recorded with the Indian satellite AstroSat in the 0.3–7 keV range (Karmakar et al., 2022). The peak flare luminosity is $(5\text{–}10)\times10^{30}$ erg/s; the rise and decay times are up to 11 and 24 ks; the peak flare temperatures are 26, 16, and 17 MK; the peak emission measures are $(4\text{–}7)\times10^{53}$ cm^{-3}; coronal loop lengths are about 2×10^{11} cm; and their density is units of 10^{10} cm^{-3}, with the magnetic field less than 100 G and total energy up to 10^{34-35} erg.

Using the Dark Energy Camera, Webb et al. (2021) investigated flares from the light curves with 20-s cadence in the g band at a distance up to 500 pc of the Sun in 12 fields with sizes ∼3 square degrees using an original machine-learning program and found 19 914 sources with precise distances from Gaia DR2. The authors identified 96 flares with energies of 10^{31}–10^{37} erg on 80 stars, predominantly M dwarfs, and confirmed a decrease in the fraction of flaring M stars with increasing distance from the Galactic plane. Seventy percent of flares were shorter than eight minutes, and the mean flare density was $(2.9 \pm 0.3) \times 10^{-6}$ flares per pc^{-3}s^{-1}.

Paudel et al. (2021) reported results of simultaneous observations of EV Lac using five observatories. During 25 days of TESS operation, 56 flares were recorded with this instrument. Additionally, during 18 ks of Swift observatory observations, three flares were detected in the X-ray and ultraviolet ranges; and during 98 ks of NICER telescope observations, nine flares in the ultraviolet range. Furthermore, single 3-hour observations were conducted using UH88 and LCOGT telescopes. The energy range of flares recorded by TESS is from $10^{30.5}$ to $10^{33.2}$ erg; flares recorded by Swift, from $10^{29.3}$ to $10^{31.1}$ erg; 14 flares recorded by NICER, from $10^{30.5}$ to $10^{32.3}$ erg. TESS-recorded flares exhibited power-law distribution with index −0.67, but no signs of the FIP effect were found.

Getman, Feigelson (2021) examined X-ray superflares from PMS stars, their energetics and frequencies. Solar-like stars exhibit the highest level of magnetic activity in the early convective PMS phase: peak X-ray luminosity $\lg(L_X) = 30.5 - 34.0$ erg/s and total energetics $\lg(E_X) = 10^{34} - 10^{38}$ erg. From more than 24 thousand X-ray sources detected in previous surveys, the authors selected 1086 young (less than 5 Myr) objects from 40 nearby star-forming regions. Most of these objects demonstrate significantly more powerful optical and X-ray flares compared to those observed on the MS. These events occurred on young stars of all masses at various evolutionary stages: from protostars to diskless stars. A positive correlation was found between flare frequency and stellar mass. Characteristics of flares do not depend on the presence or absence of a disk. The power-law flare energy distribution index is close to 2, i.e., the same as for older stars and the Sun. Megaflares with energy $\lg(E_X) > 36.2$ erg from solar-mass stars have a frequency of about two flares per star per year and constitute 10–20% of all X-ray energetics of PMS stars.

Feinstein et al. (2022) analyzed light curves of 161 836 stars observed by TESS at a 2-minute cadence. The computer program developed by the authors allowed for detection of about a million flares. MS stars with masses greater than 0.3 solar masses showed power-law flare frequency distribution with index around 1.4, which is characteristic of a system with self-organized criticality; this index is somewhat smaller for stars with masses less than 0.3 solar masses and around unity for red giants.

Ilin et al. (2021a) showed that rotation and magnetism disrupt stellar spherical symmetry, which imposes important observational constraints on stellar magnetic fields and on assessing the impact of stellar activity on exoplanet atmospheres. The researchers proposed a new method for estimating flare localization from optical light curves, performed such estimates for a number of flares from TESS data, and suggested that inhomogeneous longitudinal flare distribution needs to be considered when assessing exoplanet habitability.

Fuhrmeister et al. (2022) compared results of the X-ray sky survey conducted by the eROSITA instrument on board SRG and excess emission in the Ca II H and K lines measured by the robotic TIGRE telescope. They detected the expected correlation between $\lg(L_X/L_{bol})$ and $\lg(R'_{HK})$, which improves when selecting quasisimultaneous observations. The authors believe that cyclic variations over long time intervals are more important than correlations of short-term variations in the form of rotational modulations or flares.

Bondar' et al. (2021) reported on the detection of optical flares on the selected G–M dwarfs from observations in 2000–2020: 11 stars exhibited low-amplitude events with $\Delta V < 0.25^m$; BE Cet and two M dwarfs, bursts up to half a magnitude.

Using the ULTRASPEC high-speed spectrograph mounted on the 2.4-meter Thai National Telescope, Doyle et al. (2022) recorded two flares on YZ CMi with a subsecond resolution with a total energy close to 10^{34} erg. A combination of a wavelet analysis, a Fourier transform, and an empirical mode decomposition revealed quasiperiodic pulsations and period doubling. In both events, quasiperiodic oscillations of several minutes were found as well as absence of such oscillations at higher frequencies. These features are interpreted by the authors as dynamics of resonant magnetohydrodynamic waves in coronal loops with lengths of 0.2–0.7 stellar radii, which is consistent with the situation on the Sun.

Pietras et al. (2022) performed statistics of stellar flares from 3-year TESS observations (sectors 1–39) with a 2-minute cadence. Using the developed program for the automatic detection of flares and faculae from light curves, they examined 330 000 stars and detected more than 25 000 stars with flare activity with a total number of flares exceeding 140 000 with energies in the range of 10^{31}–10^{36} erg, i.e., most recorded events are superflares. About 7.7% of the examined objects are flaring stars, but among M dwarfs this fraction reaches 50%. The maximum in flare duration distribution falls at 50 minutes; the mean rise time is less than 10 minutes; and the longest flares lasted several hours. The authors attributed secondary peaks in light curves to photosphere heating by nonthermal electrons. Maxima in flare size distribution by different estimates are 0.2–0.3% of stellar surfaces. The spectral index in flare energy distribution by different estimates is 1.7 and 1.5. From flare energetics and duration, magnetic field strength estimates from 10 to 200 G and flare coronal loop lengths from 10^{10} to 2×10^{11} cm were obtained.

From TESS observations, Yamashita et al. (2022) examined light curves of 33 zero-age stars in young stellar clusters IC 2391 and IC 2602, estimated their brightness amplitudes from $0^m.001$ to $0^m.145$, as for young stars in the Pleiades cluster. The authors found spot filling factors ranging from 0.1 to 21%, as well as strong Ca II emission, characteristic of stars with superflares and exceeding solar emission by two orders of magnitude. On 12 stars of these clusters with saturated chromospheric emissions, Yamashita et al. detected 21 flares with energies 10^{33}–10^{35} erg.

The concept of decisive dependence of solar-type star activity level on its spottedness degree was recently developed in Katsova et al. (2022b). The authors found that the frequency of weak X-ray flares on the Sun practically does not depend on its spottedness degree, whereas the frequency of powerful flares of classes M and X substantially depends on it. Since the spot filling factor of even the most active Sun does not exceed a small fraction of a percent of its surface, while on the most active dwarfs it reaches tens of percent, the absence of superflares on the Sun and their appearance on active stars becomes understandable. Katsova et al. estimated magnetic field strength in starspots, which is about 2 kG, and maximum energy of stellar superflares, which reaches $(1-3) \times 10^{36}$ erg.

Namekata et al. (2022) presented the results of spectroscopic and photometric observations carried out with the Seimei telescope and TESS that recorded a long-duration superflare on the young (50–120 Myr) solar-like star EK Dra: the flare energy was 2.6×10^{34} erg, duration 2.2 hours, which allows for classification of this event as the most powerful superflare on a solar-like star detected by optical spectroscopy. The Hα line profile showed neither noticeable asymmetry observed in previous studies nor line broadening, but the Hα line emission duration turned out to be comparable to white flare duration, which is atypical for M dwarfs.

In April 2020, using a 1-meter and a 0.5-meter telescope, Lin et al. (2022) conducted a 27-hour photometric monitoring of the M6.5 dwarf Wolf 359 close to the Sun and recorded 13 flares with energies from 5×10^{29} to 10^{33} erg. The strongest flare was recorded by both telescopes separated by nearly 300 km and had amplitude 1.6.

Using the Tomo-e Gozen camera mounted on the Kiso Schmidt telescope of Tokyo University, Aizawa et al. (2022) performed a 1-second flare survey for M dwarfs over 40 hours of observations. They detected 22 flares from M3–M5 dwarfs with a rise time from 5 to 100 s and an amplitude from 0.5 to 20. These light curves showed steeper rises and shallower decays than 1-minute light curves obtained by the Kepler observatory, typically a flat peak. Assuming flare emission as blackbody with temperatures 9000–15000 K, Aizawa et al. found peak luminosities 10^{29}–10^{31} erg/s and bolometric energies 10^{31}–10^{34} erg. Ninety percent of host stars exhibited Hα line emission from LAMOST telescope spectra, and the mean flare frequency of these stars was 0.7 events per day. The authors suggested that the observed light curves can be explained by a chromospheric compression model: the rise time is generally consistent with Alfvén transit time of a magnetic loop with scale 10^4 km and field strength 1000 G, while the decay time is likely determined by the radiative cooling of the compressed chromosphere.

From simultaneous X-ray (Chandra) and ultraviolet (HST/STIS) observations, Fuhrmeister et al. (2022) investigated the temperature structure of the corona and transition region of Prox Cen, as well as the effect of this stellar emission on an Earth-type exoplanet located in its habitable zone. Differential emission measure distribution was constructed for flares and quiet state of the star, and flux amplitudes in a flare were 4–20 in ultraviolet and up to 30 in X-rays.

Using HST/COS, Feinstein et al. (2022) conducted more than five hours of observations of AU Mic, aged 22 Myr. Its dust disk contains two exoplanets, making the system ideal for ascertaining the results of irradiation of these bodies by far ultraviolet emanating from the star from the 10^4–10^7 K layer. The authors detected 13 flares with energies in the range of 10^{29}–10^{31} erg with amplitude in continuum $\lambda < 1100$ Å and estimated stellar mass loss of 10^8 g/s.

From archival observations in 2015–2016 with ALMA (12-m) and ACA (1.33-mm) telescopes, Burton et al. (2022) first detected three strong flares on ϵ Eri at millimeter wavelengths. The strongest flare lasted about an hour and had maximum 28 ± 7 mJy, which is 50 times brighter than in the star's quiet state and 10 times brighter than solar flares in the same wavelength range. The spectral index at flare maximum was found to be 1.81, and the lower limit of linear polarization is 0.08 ± 0.12.

Katsova et al. (2022b) showed that with correct accounting for different technologies of observation of solar and stellar flares, differences in maximum energies of these events noticeably decrease, and solar flares and superflares on solar-like stars can be described by a single model of the dependence of activity on spottedness.

Howard et al. (2022) reported on the observation of a unique flare from Prox Cen on May 6, 2019, during a multiwavelength campaign. Observations were conducted in the millimeter, optical, and soft X-ray ranges. This flare turned out to be a weak recorded stellar flare. The X-ray and optical flare energies are 10^{30} erg and 10^{28} erg, respectively; the coronal temperature is 11 MK; and the emission measure is 10^{50} cm^{-3}. Millimeter flare luminosity is more than a hundred times higher than that of an X1 class solar flare and lasts only seconds instead of minutes, as seen for solar flares.

Althukair, Tsiklauri (2023a) proposed and used an automated flare detection Python script to search for superflares on MS stars of types A–M in Kepler observatory data, substantially extending previous studies of only G stars based on only part of Kepler data. The authors studied statistical properties of superflare occurrence frequency and found that on G stars, flares with energy 10^{35} erg occur once every 4360 years. They detected 4637 superflares on 1896 G dwarfs and identified 321, 1125, 4538, and 5445 superflares on 136, 522, 770, and 312 A, F, K, and M dwarfs, respectively. The occurrence rate of superflares has power-law energy dependence with index from 2.0 to 2.1 for all spectral types from F to M, but 1.3 for A stars. The authors then presented cases of superflares on slowly rotating solar-like stars, superflares with large amplitudes on G and K MS stars and concluded that slow flare decay corresponds to small flare energies, while fast decay to large energies (Althukair, Tsiklauri, 2023b). In the next work, they examined F and G stars with rotation periods less than a day and discussed how real are cycles from 5.13 to 8.14 days that should be expected from obtained correlations for such short rotation periods (Althukair, Tsiklauri, 2023c).

Jackman et al. (2023) used optical TESS observations and ultraviolet GALEX observations of M dwarf flares to estimate ultraviolet emission energy emanating from flares recorded in the optical range. As a result, the authors found that the blackbody flare emission model at a temperature of 9000 K, widely used for predicting ultraviolet emission from optical observations, underestimated energy in the GALEX near ultraviolet (NUV) band by a factor of 6.5 and energy in the GALEX far ultraviolet (FUV) band by a factor of 31. They found flare temperature for fully convective M stars equal to 10 700 K and assessed the role of a refined ultraviolet flux in exoplanet biogenesis.

During the same coordinated campaign, Jackman (2022) investigated the M binary Ross 733 in the optical and NUV ranges with GALEX and in the ultraviolet with Swift and obtained light curves of two flares with the latter. By the author's estimate, flares with energy 10^{33} erg occur in the system once every 1.5 d. Jackman estimated a pseudocontinuum temperature of 7340 K during the flare decay.

Brasseur et al. (2023) investigated flares on G stars in the near ultraviolet and optical ranges; observations were carried out with GALEX and Kepler instruments, respectively. The absence of optical flares during such events in the ultraviolet range places an upper limit on the emission ratio in these bands and questions estimates of exoplanet ultraviolet irradiation from optical observations of stellar flares.

Using data from the Indian spacecraft AstroSat, Kuznetsov et al. (2023) carried out X-ray and ultraviolet observations of the binary system AT Mic consisting of two M4.5e dwarfs. During 20 ks of observations, the authors detected the quiet system emission and at least five flares on different components. The X-ray flares were longer and delayed by 5–6 minutes with respect to ultraviolet flares. Analysis of the obtained data led to the conclusion about existence of a multithermal corona with temperatures in the range of 7–15 MK and emission measure of $(2.9 - 4.5) \times 10^{52}$ cm^{-3}. The abundance of heavy elements in the corona of AT Mic is 3–5 times lower than in the solar photosphere and increased during the flares likely due to chromospheric evaporation. The detected flares had the energies of $\sim 10^{31-32}$ erg, and the magnetic fields were stronger than in typical solar flares.

Using the CoRoT space telescope, Rabello Soares et al. (2022) recorded 209 flares on 69 K stars and estimated their blackbody temperatures to be 6400 ± 2800 K and energies from 10^{32} to 10^{37} erg. On the cool M dwarf Trappist-1 with seven exoplanets, Maas et al. (2022) recorded two flares in the g, r, i, and zs bands. Blackbody flare temperatures were 7940 and 6000 K; peak temperatures reached 13 620 and 8290 K.

Stelzer et al. (2022b) described a powerful flare on AD Leo on November 19, 2019, observed in the X-ray and optical ranges. Energy in the 0.2–12 keV range is 1.3×10^{33} erg, whereas bolometric value is 5.6×10^{33} erg. The proton flux is at least 10^5 cm^{-2}s^{-1}ster^{-1}. High temporal resolution spectroscopy revealed the evolution of temperature and emission measure, an increase in electron density and element abundance, and an estimate of the coronal loop length up to 4×10^9 cm.

Vasilyev et al. (2022) proposed a refined method for flare identification based on panoramic photometry materials, which allows for elimination of images distorted by background source emission: in the first stage, the point spread character in the system is determined, and in the second stage, coordinates of the enhanced brightness image are refined. The authors applied this method to 5862 MS stars, and the number of suspected flares decreased from 2274 to 342.

See et al. (2023) found that flares are stronger in more metal-rich stars at fixed mass and rotation period.

Tristan et al. (2023) conducted a 7-day multiwavelength monitoring campaign of the young active M1e star AU Mic with exoplanets and a debris disk. In the wavelength range from X-ray to optical, 73 flares were recorded. NUV (GALEX) and XMM-Newton data were used to study the empirical Neupert effect. Sixty-five percent of flares do not show this effect, and where it exists, four versions are proposed.

Liu et al. (2023) performed a statistical study of 125 flaring stars detected during the first two years of observations starting from 2020, using 1-minute cadence obtained with LAMOST and TMTS telescopes. Most of these objects are late spectral type stars with $G_{BP} > G_{RP} > 2^m.0$, but bluer objects demonstrate higher energy flares with broader profiles. The peak flux of the flare strongly depends on its equivalent duration, which is consistent with results derived from the Kepler and Evryscope samples and resembles the magnetic loop emission. The flares on hotter stars exhibit stronger dependence of the peak flux on the flare equivalent duration. In the spectra of flaring stars obtained with the LAMOST telescope, the Hα line emission is stronger than in inactive stars, but as the authors believe, chromospheric activity may not be the only cause of emission.

Boyd et al. (2023) conducted photometric and spectroscopic observations of EV Lac and in 10 out of 39 observing runs recorded flares with amplitude greater than $0^m.1$. Analysis of the obtained data led them to the following conclusions. The flare energy in the B band ranges from $10^{30.8}$ to $10^{32.6}$ erg; continuum emission maximum is reached earlier than in hydrogen and helium emission lines; and continuum emission decay occurs faster than in lines. On average, 37% of the B band energy comes from lines. Blackbody temperatures of the brightest flares are 10 590 and 19 500 K. A blue shift was detected at brightness maximum.

Tu et al. (2021) proposed and calculated a series of one-dimensional hydrodynamic models of secondary peaks on optical flare light curves of M dwarfs. The authors consider their cause to be free-free and free-bound emission from condensations in coronal plasma loops.

Didel et al. (2024) recorded 21 X-ray flares of AB Dor using XMM-Newton and analyzed 13 of them in detail. The flare amplitudes reached $A_X = 34$; the energy range varied from 10^{34} to 10^{36} erg; and durations were from 0.7 to 5.8 hours. Recorded spectra in the quiet state are represented by three-temperature plasma with mean temperatures 0.29, 0.95, and 1.9 keV. The peak temperature was determined within 31–89 MK, while the peak EM = $10^{52.5}$ – $10^{54.7}$ cm^{-3}. The inverse FIP effect occurred. X-ray light curves exhibited rotational modulation; semi-loop lengths were determined to be within $10^{9.9}$–$10^{10.7}$ cm; and the minimum magnetic field is estimated between 200 and 700 G.

Namizaki et al. (2023) conducted simultaneous spectroscopic and photometric observations of a superflare on YZ CMi with Seimei and TESS telescopes. The bolometric flare energy is 1.3×10^{34} erg, and the Hα energy is 3.0×10^{32} erg. The emission in this line shows red asymmetry throughout the flare, with a duration of 4.6–5.1 hours up to 200–500 km/s.

Using the NICER X-ray observatory in 2019, Hamaguchi et al. (2023) conducted observations of two powerful X-ray flares from the nearby young solar-like star κ^1 Cet, equivalent to superflares. Both flares were recorded from the onset of ignition to the start of decay, which allows for a detailed spectral study of their rise phase. The first flare varies quickly in 800 s, and the second has a few times longer timescale. In both flares in the hard 2–4 keV range, light curves show typical for stellar flares rapid rise and slow decay, while in the soft 0.3–1 keV range, especially in the first flare, prolonged flat peaks occur. The time-resolved flare spectra require two-temperature plasma: both components vary similarly, but the cool component lags by about 200 s and has 4–6 times smaller emission measure compared to the hot one. Comparison with hydrodynamic calculations of coronal loops showed that the cool component originates from X-ray plasma near the magnetic loop footpoints that mainly cools via thermal conduction. The time lag represents the travel time of the evaporated gas through the entire flare loop. The smaller emission measure of the cool component compared to calculations suggests a suppression of thermal conduction by a possible increase in loop cross-sectional area or turbulent fluctuations.

Studies showed that solar and stellar flare duration correlates with event intensity at some wavelengths, such as white light, but not in soft X-rays, and the reasons for this difference remain unknown. In Hamaguchi et al. (2023), a radiative hydrodynamics program was used to determine factors affecting flare emission duration at different wavelengths. The duration turned out to depend on plasma temperature, atmospheric height, relative humidity of radiative cooling, thermal conduction, and enthalpy change. Clear differences were found between emission that forms the lower atmosphere and is directly responsible for heating and emission that forms in the corona and is indirectly responsible for induced heating of chromospheric evaporation. Hamaguchi et al. applied the obtained results to flare energetics.

From TESS data, Kumbhakar et al. (2024) determined a rotation period of 2.224 days for the young brown dwarf MHO 4 (spectral class M7.0) in the Taurus star-forming region and recorded two superflares with bolometric energy of 10^{34}–10^{35} erg.

Using the AstroSat telescope data, Sairam et al. (2023) investigated the outer atmospheres of four rapidly rotating stars AB Dor, BO Mic, DG CVn, and GJ 3331 and recorded flares on the first three of them in the X-ray range and flares on two of them in ultraviolet.

Notsu et al. (2024) conducted simultaneous optical spectroscopic and photometric observations of stars YZ CMi, EV Lac, and AD Leo over 31 nights. Seven of 41 recorded flares showed blue asymmetry in the Hα line profile ranging from −73 to −122 km/s and lasting from 20 minutes to 2.5 hours. One flare showed a transition from blue to red asymmetry. One flare was also observed in soft X-rays, which allows for estimation of magnetic field strength and coronal loop length. Assuming that blue asymmetry is associated with prominence ejection, the authors estimated its mass to be 10^{15}–10^{19} g, which lies between flare mass and a solar CME.

Using Chandra observatory and Gaia DR3 catalog data, Zhao et al. (2024) performed a statistical analysis of flares from solar-like stars in soft X-rays. A sample of 129 flares on 103 stars revealed events with energies from 10^{33} to 10^{37} erg; durations of these events differ from that of optical flares, but the power-law distribution index is the same, i.e., −1.77.

Using capabilities of the AstroSat observatory, Karmakar et al. (2024) recorded five X-ray and ultraviolet flares on CC Eri and AB Dor. The peak X-ray luminosities are within 10^{31}–10^{33} erg/s. Spectral analysis indicated three- and four-temperature coronae for CC Eri and AB Dor, respectively.

The peak temperatures are 51–59 MK for CC Eri and 29–44 MK for AB Dor, with peak emission measures 10^{54} and 10^{55} cm^{-3}, respectively. Global metallic abundances were also found to increase during flares.

Inoue et al. (2024) conducted four-night observations of EV Lac using five different instruments covering the soft X-ray, near ultraviolet, and optical ranges with photometric and spectroscopic equipment and detected a flare with bolometric energy of 3.4×10^{32} erg. About an hour after the flare peak, an excess component appeared in the Hα profile, shifted about 100 km/s to the blue. The authors interpret this as a delayed prominence. The flux ratio in near ultraviolet and white light corresponds to a blackbody temperature of < 9000 K or the maximum energy flux of a nonthermal electron beam that is less than 5×10^{11} erg/cm^{2}s.

It should be noted that blackbody emission of stellar flares was previously considered by MacGregor et al. (2021), Rabello Soares et al. (2022), Maas et al. (2022), Jackman et al. (2023), Boyd et al. (2023), and only the latter authors give a temperature of 19 500 K for one flare, while another flare yields 10 500 K; other researchers provide temperature estimates around 10 000 K. However, using an original colorimetric approach, back in the early 2010s, Lovkaya (2014) confidently showed that stellar flares emit as blackbodies only near brightness maximum and at a temperature close to 20 000 K. Unfortunately, all the author's works were published in Russian and remain unknown to foreign colleagues. Recently, new arguments against wide application of the blackbody model for stellar flare emission were presented by Simões et al. (2024).

Odert et al. (2025) recorded 24 flares over more than 190 hours of observations of AU Mic, which is the highest event rate in the TESS data. The characteristics of eight emission chromospheric lines were determined. At maximum brightness of the most powerful flare, the line intensities increase threefold and the Hα energy is 10^{33} erg.

Zarka et al. (2025) analyzed recently discovered circularly polarized radio bursts from AD Leo and identified them as electron cyclotron maser instability. They constrained the source to a magnetic shell at an altitude of 2–10 stellar radii and estimated the electron energy to be 20–30 keV.

Hakamata et al. (2025) found a nonstationary source in hard X-rays in the 2013 observation archive, the analysis of which in the X-ray, optical, and IR ranges led to the conclusion about its connection with stellar flare activity. Its emission measure of 8×10^{54} cm^{-3} and temperature of 8.21 keV are on average higher than those in previously registered flares; the size of a flare loop is several times larger than the stellar radius. The observed event was suggested to be similar to several simultaneous sympathetic flares as on the Sun.

Aschwanden, Schrijver (2025) found that the distribution of solar and stellar flares over a range of 13 orders of magnitude of their energy – from solar microflares with an energy of 10^{24} erg to stellar superflares with an energy of 10^{37} erg – is described by a fractal-diffusion self-organized criticality model that predicts universal slopes of the power-law spectra.

Burton et al. (2025) carried out about 50 hours of observations of Prox Cen using ALMA and constructed the first energy spectrum of flares in the millimeter wavelength range. They detected 463 flares in the energy range of 10^{24}–10^{27} erg, and the amplitude of the maximum flare reached 1000. The power-law spectrum index is 2.92, i.e. the spectrum in the millimeter range is much steeper than in optics and X-rays.

Tokuno et al. (2025) considered the times between the moments of maximum spot area and the appearance of a flare and found that the distribution of these times on the Sun and on solar-type stars does not depend on either the spot size or flare energy.

Based on spectroscopic and photometric observations of the M dwarf YZ CMi, Kajikiya et al. (2025) found that the blue/red asymmetry of the Hα profile occurs in flares of higher energy than flares without such asymmetry.

Using the spectra of six flares on the young M dwarf AU Mic, previously recorded with the COS spectrograph of the Hubble telescope, Gibson et al. (2025) searched for the Orrall – Zirker (OZ) effect: an enhancement of the red wing of the hydrogen emission line due to nonthermal energy transfer of protons during the impulsive phases of flares. The OZ effect was not detected. However, in one of the flares, an enhancement of the blue wing of several C II and C III emission lines was recorded, which the authors attributed to the ejection of a filament or chromospheric evaporation.

Ram et al. (2025) studied the flare activity of the M4.5 dwarf AD Leo using TESS data, time-series optical spectra, and GMRT 325 MHz radio data. The authors estimated an extremely rare high-energy superflare of 4.9×10^{35} erg and ~400 minute duration with a high magnetic field strength of 1.2 kG and noticed a discrepancy between stellar and solar flares suggesting a difference in coronal magnetic field strength. A 12-minute delay in a spectral flare event was observed between the emission of the Hα and Ca II H and K lines, possibly due to their origination at different spatial locations in the chromosphere. Ram et al. note that radio detection with a flux density of 9.46 ± 1.63 mJy at a frequency of 325 MHz might be coherent emission in the presence of the magnetic field, giving a hint of star–planet interaction.

Tristan et al. (2025) reported on the 7-day observational campaign of the star AU Mic with the JVLA (Ku band – 12–18 GHz) and ATCA (K band – 16–25 GHz) radio data. These frequencies were chosen to observe gyrosynchrotron radiation, which directly correlates with the action of accelerated electrons in stellar flares. High temporal resolution light curves from ~60 hours of observations reveal 19 flares of varying shapes and sizes, from a short (~30 sec) spiky burst to a long (~5 hr) decaying exponential, and some radio flares lack multiwavelength components. Most flares exhibit a polarization of roughly 10–20% that can also evolve over time. Some flares appear unpolarized during peak times, which may be due to temporary optical thickness ($\alpha > 0$) as the spectral peak shifts to higher frequencies. These peak frequencies lie above the common 5–10 GHz range in solar flares, which may imply a division between solar and stellar flares.

8 Magnetic fields

Stellar magnetometry is the most complex area of ground-based experimental astrophysics, and the number of centers where such observations are carried out is limited to a few. However, in recent years, quite numerous magnetometric observations of stars with solar-type activity have been conducted, and important results of such observations and theoretical developments on stellar magnetism have been published.

Kochukhov et al. (2020) conducted magnetometry of solar-type stars by measuring spectral line enhancement by the magnetic field. This method differs from the most common magnetometry by spectropolarimetric observations in that it measures the total magnetic flux by moduli of local field components, whereas spectropolarimetric signals of different signs cancel each other, which with numerous small magnetic structures leads to underestimation of Bf value. To overcome the main difficulty of magnetometry in enhancing spectral lines – separating magnetic and non-magnetic line broadening mechanisms in ordinary spectra – Kochukhov et al. developed a methodology using spectral lines with different Landé factors and performed magnetometry of 14 G dwarfs and one K dwarf of different ages and with different activity levels using three lines of one neutral iron multiplet in the 5500 Å region. As a result, they found that Bf values decrease from 1.3 to 2.0 kG in stars younger than 120 Myr to 0.2–0.8 kG in older stars. They found anticorrelation of the mean field and rotation period or Rossby number and gave calibration Bf(Ro). Kochukhov et al. concluded that all considered stars have fields with strength $B \approx 3.2$ kG, and the increase in Bf value is due to increase in filling factor from 10% to 50% of the stellar surface with increasing activity. The stars they studied showed clear correlation of the mean magnetic field with coronal and chromospheric activity indices L_X/L_{bol} and lg R'_{HK}, respectively. When comparing obtained data with spectropolarimetric magnetometry results, the authors estimated that the latter gives about 1% of total magnetic field energy for the most active stars and about 0.01% for the least active. Note that earlier Johns-Krull, Valenti (1996) conducted magnetometry to broaden the neutral iron spectral line of one of the most active red dwarfs EV Lac.

Reiners et al. (2022) presented measurements of surface-averaged magnetic fields of 292 M dwarfs obtained from more than 15 000 high-resolution spectra. The authors found a connection between mean field strength and Rossby number resembling the rotation – activity relationship and found that among slowly rotating stars, a magnetic flux is proportional to rotation period, while among fast rotators, the mean surface field slightly exceeds the level set by available kinetic energy. Furthermore, Reiners et al. found a close connection between nonthermal coronal X-ray emission, chromospheric emission in hydrogen and calcium lines, and magnetic flux. These relationships, taken together, show that the rotation – activity relationship can be traced to the dependence of the magnetic field on rotation. Calcium emission saturates at a mean field strength of 800 G, while the Hα line and X-ray emission grow with stronger fields in faster rotators.

It is practically widely accepted that flares and CMEs on the Sun and stars draw energy from that stored in coronal magnetic fields, where they are generated by dynamo mechanisms. But the question remains open whether the magnetic field energy supply occurs directly or through transmitting currents. In this regard, Seligman et al. (2022) examined intensity distributions in a sample of about 10^5 MS star flares recorded by TESS that exhibit power-law distribution as on the Sun, though with different indices. The authors investigated mechanisms required for power-law flare distribution through direct current energy, extended the model to include the Coriolis forces, which is essential for faster rotators, and provided preliminary considerations for the predicted rotation – power index correlation.

Brown et al. (2022) presented measurements of stellar chromospheric activity R'_{HK} and/or surface-averaged longitudinal magnetic field Bl for 954 stars from mid-F to mid-M spectral types obtained from spectropolarimetric observations and found positive correlation between logarithms of these values. They combined their results with archival chromospheric activity data and observations of large-scale magnetic field geometry from Zeeman – Doppler imaging. Chromospheric activity, activity variability, and toroidal field strength decrease on the MS as rotation slows. In G stars, disappearance of dominant toroidal fields occurs at the same chromospheric activity level as the change in relationships between chromospheric activity, activity variability, and mean field strength.

Kochukhov et al. (2023) developed a magnetic field diagnostic procedure based on magnetic enhancement of iron atom lines in the optical range, extending it from measuring a single average field strength value to Doppler imaging reconstruction of the two-dimensional maps of temperature and magnetic field strength. They applied this novel method to two spectroscopic data sets of the young solar-like star LQ Hydra. In both epochs, the authors found uniform magnetic field strength distribution, except for a latitudinal trend of increasing strength from 1.5 to 2.0 kG at low latitudes to 3.0–3.5 kG near rotation poles. Such small-scale field distribution shows no clear correlation with temperature spot location or global magnetic field structure.

Lehmann et al. (2024) observed six slowly rotating mid-class M dwarfs with rotation periods from 40 to 190 days with the Canada – France – Hawaii telescope from 2019 to 2022. From numerous circularly polarized spectra of each star, they confirmed period values and investigated the large-scale magnetic field topology by two methods. All studied stars showed large-scale magnetic field changes on a timescale of their rotation periods, magnetic polarity reversal of GJ 1151 and possibly GJ 905. Four fully convective M dwarfs exhibited more temporal variations than two partially convective ones. All six M dwarfs demonstrated large-scale field strength from 20 to 200 G, as in significantly faster rotators.

During the same campaign, Donati et al. (2023a) investigated the large- and small-scale magnetic fields and exoplanets of the young M dwarf AU Mic in the near-IR range. Both field signatures are modulated by stellar rotation with a period of 4.86 days. The small-scale field, estimated from spectral line broadening, reaches 2.51 kG. The large-scale field, inferred from Zeeman – Doppler imaging, is mostly poloidal and axisymmetric, with an average intensity of 550 G. The radial velocity signatures of exoplanets b and c were detected, which allows for estimation of their masses as 10 and 14 Earth masses. The authors obtained a mean magnetic field strength from 0.05 to 1.15 kG and found that including the magnetic field in atmosphere models practically does not affect their parameters. Furthermore, they revealed that small-scale magnetic fields constitute more than 70% of the total mean magnetic field and found no clear evidence that the mean field decreases with increasing Rossby number. The obtained results suggest that dynamo processes may operate in nontraditional regime in these strongly magnetic slowly rotating stars.

Donati et al. (2023b) investigated magnetic fields and rotation of 43 weakly and moderately active M dwarfs from observations with the SPIRou spectropolarimeter mounted on the Canada – France – Hawaii telescope between 2019 and 2022. The authors used 6700 circularly polarized spectra to investigate the longitudinal magnetic field and detected the field in 40 stars and reliable or preliminary rotation periods in 38 stars. The derived periods for early M dwarfs range from 14 to 60 days and more; for most mid and late M dwarfs, from 70 to 200 days. Donati et al. found that detected large-scale field strength does not decrease with increasing period or Rossby number in slowly rotating dwarfs of the sample, as it occurs in more massive and more active stars.

Bellotti et al. (2023) posed a task of tracking variations in the large-scale magnetic field of AD Leo that would show secular evolution from past spectropolarimetric campaigns. They used near-IR observations of the star with SPIRou in 2019–2020 and archival optical data obtained with two specialized spectropolarimeters located in Hawaii and Haute-Provence in 2006–2019, unpolarized Stokes profiles, and other sources. As a result, the authors found evidence of the long-term magnetic field evolution characterized by decreasing axial symmetry, accompanied by weakening of the longitudinal field from 300 to 50 G and corresponding increase in the unsigned magnetic field from 2.8 to 3.6 kG. The large-scale magnetic field of AD Leo exhibited the first hints of polarity reversal at the end of 2020 as a significant increase in dipole inclination, with topology remaining predominantly poloidal and dipolar. This means that low-mass M dwarfs with a predominant dipolar magnetic field can undergo magnetic cycles.

Bai et al. (2023) conducted 146-hour photometric monitoring of AD Leo with the GWAC-F30 telescope and 528 hours of brightness monitoring with TESS; 9 and 70 flares were recorded, respectively. Flare parameters (their durations, amplitudes, and energies found in this study) generally agree with earlier results, indicating substantial activity constancy over decades. A pulsation with a 26-minute period was detected in the decay phase of the most powerful flare.

In a sample of 16 solar-like stars, Hahlin et al. (2023) analyzed Zeeman broadening of six magnetically sensitive and insensitive neutral iron lines in the infrared H band to measure small-scale magnetic fields, using polarized radiation transfer modeling and deviations from nonlocal thermodynamic equilibrium. As a result, the authors found the average magnetic field strength ranging from 0.4 to < 0.1 kG and also revealed correlation between the small-scale and large-scale magnetic fields. When comparing NIR and optical measurements, optical results were found to exceed by a factor of 2 to 3.

Amazo-Gómez et al. (2023) conducted a multiwavelength campaign to probe magnetism of the young solar-like star ι Hor from the photosphere to the corona. They presented results of multiyear spectropolarimetric monitoring using the ultra-stable instrument HARPS mounted on the ESO 3.6-meter telescope, high-precision TESS data, and near and far ultraviolet observations with HST. As a result, the authors reliably determined the star's rotation period. Analyzing the power spectrum gradient of TESS light curves, Amazo-Gómez et al. were able to estimate the faculae-to-spot ratio and concluded that the stellar surface is spot dominated during the time of the observations. The authors compared the photospheric activity properties derived from the GPS method and using Zeeman – Doppler imaging and observed enhanced emission in the HST transition line diagnostics C IV and C III, suggesting a flaring event.

To clarify the interaction of binarity and magnetism in close binary systems, Tsvetkova et al. (2024) examined the binary system FK Aqr consisting of two early M dwarfs and already known as flaring and having components with masses just above the fully convective structure. The authors used spectropolarimetric observations with the Canada – France – Hawaii telescope to extract mean Stokes I and V lines. The longitudinal magnetic fields and chromospheric activity indicators were measured from the least-squares deconvolution (LSD) mean line profiles. The rotational modulation of the Stokes V profiles is used to reconstruct the surface magnetic field structures of both stars.

Bhatia et al. (2024) examined some issues of a small-scale dynamo operating in the convection zone (the so-called magnetic carpet) as an alternative to the average field theory. They investigated the distribution of these fields and their effect on intensity characteristics, velocity, and spatial distribution of kinetic and magnetic energy in the lower photosphere of F3V, G2V, K0V, and M0V spectral type stars using three-dimensional radiative transfer. Field strengths at the $\tau = 1$ surface are quite similar for all cases. The M0V star displays the strongest fields, but relative to the gas pressure, the fields on the F3V star reach the highest values. In all stars, the horizontal field is stronger than the vertical field in the middle photosphere, and this excess becomes increasingly prominent toward later spectral types. These fields result in a decrease in the upflow velocities and a slight decrease in granule size.

Brown et al. (2024) analyzed possible influence of an exoplanet on magnetic field variations of the young solar-like star V889 Her. From magnetic field maps for 14 epochs between 2004 and 2019, the authors found 3–4 yr variations of the magnetic field that evolves from weak and simple during chromospheric activity minima to strong and complex during activity maxima; a persistent polar spot coexists with weaker, short-lived lower-latitude spots. Brown et al. showed that there is certain probability of existence of planets with masses of one and two Jupiter masses around this star and other young solar-like stars with high activity.

Egbo et al. (2025) reported on optically selected stellar candidates of SARAO MeerKAT 1.3 GHz radio continuum survey sources of the Galactic plane. The authors found a significant number of MS red dwarfs with a median radio luminosity of 8.9×10^{15} erg/(s×Hz) and all within a distance of less than 300 pc. Red dwarfs identified in this study likely represent stars with enhanced magnetic activity, either as flare stars or through persistent magnetic phenomena.

9 Cyclicity and evolution of activity

Katsova (2020) published a brief review of observational results contributing to modern ideas on the evolution of stellar activity. The basic laws, derived for both rotation – age and activity – rotation relationships, allowed tracing how the activity of low-mass stars changes with age during their stay on the MS and comparing activity properties of stars and the young Sun. Different tracers of activity, rotation and magnetic fields of solar-like stars of various ages are jointly considered. Katsova identifies rotation periods, when the saturated regime of activity changes to the unsaturated regime, when the solar-type activity is formed: for G- and K-type stars, they are 1.1 and 3.3 days, respectively. This corresponds to an age interval of about 0.2–0.6 Gyr, when regular sunspot cycles began to be established on the early Sun. Properties of the coronal and chromospheric activity in the young Sun are discussed. The estimates of EUV-fluxes show that the far-UV radiation of the early Sun was by a factor of 7 more intense than that of the present-day Sun and twice higher when the regular sunspot cycle was established, while the possible mass loss rate is 10^{-12} $M_\odot$ per year. The estimates of the maximum flare energy 5×10^{34} erg and magnetic field strength are provided. Overall, activity evolution follows stellar angular momentum behavior, and after 100–250 Myr, magnetic fields closely correlate with rotation.

Luhn et al. (2022) investigated the star HD 166620, which is somewhat older and less active than the Sun. Within the HR project for observations of Ca II lines, a 17-year activity cycle was confidently determined for this star, and according to observations conducted in the 2020s at the Keck telescope, no variability was observed, which allows the star to be classified as a candidate for a Maunder minimum-type state.

Bondar, Katsova (2022) investigated cyclic variability of the solar analog BE Cet aged 0.6 Gyr with a rotation period of 7.655 days. From photometric data on the time interval between 1977 and 2019, they detected an activity cycle of 6.76 years with amplitude $0^m.02$. Short-term brightness variations due to rotational modulation occur with increasing amplitude up to $0^m.05$ near cycle minimum.

By extending optical series to exceed 50 years, collecting X-ray and calcium infrared triplet data, Fuhrmeister et al. (2023) confirmed the previously known three-year activity cycle of the young flaring star ϵ Eri, refined the 11-year cycle, and suspected the existence of a 34-year cycle.

According to Metcalfe et al. (2024), the consistently low activity level of the old solar analog 51 Peg leads to the suggestion that the star can be experiencing a magnetic grand minimum. The minimal chromospheric variability may be associated with the onset of weakened magnetic braking, where sufficiently slow rotation disrupts cycling activity and the production of large-scale magnetic fields by the stellar dynamo. The authors evaluated the magnetic evolutionary state of the star by estimating its wind braking torque, which clearly places it in a regime driven by changes in the mass-loss rate.

Bellotti et al. (2025) measured longitudinal magnetic fields using high-resolution spectropolarimetric data on six solar-type stars and inspected their long-term behavior. Two stars with rotation periods of about 20 days exhibited cyclic variability on time scales of 5 and 6 years. A star with a rotation period of 12 days has one polarity reversal in the toroidal component, and a star with a rotation period of 17 days may have short-term evolution of 2.5 years. Two stars with rotation periods of 3–5 days showed no cyclicity of their magnetic fields.

Hahlin et al. (2025) studied the magnetic field of the dwarf star G7 ξ Boo A in the optical and near-IR ranges and, using spectral lines at different wavelengths, radiative transfer accounting for the departures from local thermodynamic equilibrium. Using specialized high-resolution spectrographs, they determined the formation depths of various lines and found that measurements in the H-band yield magnetic field strengths ~0.4 kG, while the optical and K-band is stable at ~0.6 kG for about two decades.

Using the High Resolution Echelle Spectrometer at Keck Observatory, Isaacson et al. (2024) measured stellar flux in the cores of the Ca II H and K lines to determine S-values on the Mount Wilson scale and a metric that is comparable across a wide range of spectral types. From 710 stars, with 52 372 observations, 285 stars were sufficiently sampled to search for stellar activity cycles with periods of 2–25 yr, and 138 stars showed stellar cycles of varying length and amplitude.

Ibañez Bustos et al. (2025) conducted a study of the activity cyclicity for 35 M dwarfs using the Mount Wilson S index measured from 2965 spectra and found 13 potential cycles with durations from 3 to 19 years. For stars with noncyclic activity behavior, they found an average S value from 0.350 to 1.765.

Chahal et al. (2025) searched for activity cycles in young, rapidly rotating MS stars, measured the activity cycles of 138 G–K stars on time series of about 14 years and found that the objects under consideration do not show a strong correlation between cycle length and rotation period, while 34% of the stars fall within the intermediate region between the branches of active and inactive rotators, where our Sun resides.

10 Exoplanets

Analyzing TESS observations of four powerful and long-duration flares on fully convective dwarfs, from brightness modulation of these stars caused by their rapid rotation, Ilin et al. (2021a) estimated flare latitudes ranging from 55° to 81°, which, according to the authors, makes the influence of such stellar activity on exoplanets insignificant.

Stelzer et al. (2022a) identified 112 M dwarfs brighter than $11^m.5$ for which the TESS space telescope can probe the full habitable zone for transits. Having 1276 two-minute cadence light curves, the authors recorded more than 2500 flares and, using the known relationship between flare emission in the optical and X-ray ranges, estimated energy fluxes toward exoplanets in both specified spectral ranges. Stelzer et al. studied the link between rotation and flares, amplitude – duration relation, and flare energy frequency distributions, i.e., their energy spectrum. But rotation periods were found for only 12 stars.

Klein et al. (2022) analyzed a 1-year monitoring campaign of the star AU Mic and its exoplanet using the HARPS spectrograph and determined radial velocity semi-amplitudes of AU Mic b and c, which are 5.8 ± 2.5 m/s and 8.5 ± 2.5 m/s, respectively. For AU Mic c, an independent measurement of the radial velocity semi-amplitude was performed with simultaneous accounting for activity-induced distortions and planet-induced shifts. The resulting semi-amplitude is 13.3 ± 4.1 m/s, which indicates that AU Mic c features a large inner density. Additionally, an increase in the spot filling factor and decrease in the differential rotation level were found, which is indicative of noticeable changes in the star's magnetic activity level over a 1-year time span. The authors also reported a 3σdetection of a modulation at 8.33 ± 0.04 days of the helium doublet, close to the 8.46-day orbital period of AU Mic b.

Loyd et al. (2023) presented a comprehensive analysis of the M2.5 dwarf GJ 436 rotating with a period 44 days that is orbited by a warm Neptune-sized exoplanet with a mass of 25 Earth masses, with a size of 4.1 Earth radii, and the orbital period 2.6 days. Observations at three epochs from 2012 to 2018 span nearly a full activity cycle, sample two rotations of the star and two orbital periods of the planet, and reveal numerous brief flares. The star's 7.75 ± 0.10 yr activity cycle produced the largest observed variations, $38 \pm 3\%$ in the summed flux of the major FUV emission lines. This is a lower value of the flare effect, as the weakest flares are not recorded due to limited instrument sensitivity, while the strongest ones due to their rarity. The maximum amplitude $A_{\mathrm{FUV}} = 25$. A slight increase in the orbit-phased FUV emission corresponds to the planetary magnetic field less than 100 G.

Krolikowski et al. (2024) examined in detail the intensity and variability of activity-sensitive helium triplet λ 10830 Å for estimating exosphere characteristics of young star exoplanets. The study was performed using time series spectra of young stars with transiting exoplanets. The authors concluded that young chromospheres are dense and populate metastable helium via collisions. Flares and changes in stellar surface characteristics lead to changes in the helium triplet emission; variability is largest in the youngest stars and decreases at ages above 300 Myr.

Pillitteri et al. (2023) compared the X-ray emission of active F5 stars KELT-24 and WASH-18 with hot Jupiters. KELT-24 has a two-component corona with temperatures 0.36 and 0.98 keV. A flare with a duration of about 2 ks was recorded on it; during this flare the coronal temperature reached 3.5 keV and its luminosity is well within the range of the typical X-ray luminosity of F stars in Hyades. Small optical flickering similar to flares is recognized in WASP-18. The low activity of this star may be due to WASH-18 b hampering the formation of a corona with powerful X-ray emission, or the star has entered a minimum of activity similar to the solar Maunder minimum.

Pineda, Villadsen (2023) presented 2–4 GHz detections of coherent radio bursts on the slowly rotating M dwarf YZ Ceti, which hosts a compact system of terrestrial planets, the innermost of which orbits with a two-day period. Two coherent bursts occur at similar orbital phases of YZ Ceti b, suggestive of an enhanced probability of exoplanet-induced stellar emission.

Shlyapnikov (2024b) compared rotation periods of 689 lower MS stars and orbital periods of exoplanets around them and found significant period correlation.

From TESS data, Gorbachev (2023) analyzed flare activity of 1518 stars and detected 471 flares with energies between 10^{30} and 10^{36} erg on 60 of them. Analysis of the dependence of activity on the gravitational potential of exoplanets led to the conclusion about possible planetary influence on stellar flares.

Beskin et al. (2023) presented the results of multiwavelength RATAN-600 radio observations of 16 red dwarfs with Earth-like planets in the habitable zones. Upper limits were established for its intensity in flares with a duration of 0.05–10 s at the level of 80–800 mJy and in a steady state with a luminosity of 10^{22}–10^{27} erg/s. During the observation period, 11 anomalous flux outliers at the level of 100 mJy were registered, which apparently have an atmospheric origin.

Using archival photometric and spectroscopic observations, Sairam, Madhusudhan (2025) studied two M-type dwarf stars, K2-18 and TOI-732, the host of exoplanets. Both stars exhibit relatively low activity making them favorable for atmospheric observations of their planets. The analysis of high-precision photometry for K2-18 suggests that the star might have been near an activity minimum during recent JWST observations.

11 Conclusions

The results listed above are so diverse and concern stellar activity from so many different angles that it is impossible to single out the main one among them. But some considerations can be expressed regarding the organization of further research on stars with solar-type activity.

Remarkably, the methodology used by Hertzsprung in discovering flaring red dwarfs about a hundred years ago and the approaches used by modern researchers are essentially the same, and that is panoramic photometry. Despite the fact that Hertzsprung used a 10-inch telescope located in South Africa, while present-day similar studies are carried out using space observatories such as Kepler and TESS, the fundamental principle remains unchanged. The difference lies only in the technical progress achieved over the past century. This means that a novice researcher should not only execute specific assignments from their supervisor but also be interested in the history of the issue.

Simultaneous observations in different wavelength ranges of the spectrum are most promising. It is thus important to participate in campaigns with broad cooperation of observers using qualitatively different equipment.

Researchers of stars with solar-type activity should be well-aware of the phenomena and theories of solar activity events, and the term "stellar and solar physics" should be filled with real content and work in both directions: investigations of the Sun provide source material for understanding processes on stars, while studying stars of different ages is the only possibility for reconstructing the evolution of the Sun.

Compiling this review would not be possible without publications regularly sent by M.M. Katsova from arXiv, for which I am deeply grateful. I am also thankful to A.A. Shlyapnikov, Ya.V. Poklad, Z.A. Taloverova, and M.A. Smirnova for their comprehensive assistance in performing this work.

References

Airapetian V.S., Jin M., Lüftinger T., et al., 2021. Astrophys. J., vol. 916, no. 2, p. 96.

Aizawa M., Kawana K., Kashiyama K., et al., 2022. Publications of the ASJ, vol. 74, no. 5, pp. 1069–1094.

Alekseev I., Gershberg R., 2021. Izv. Krymsk. Astrofiz. Observ., vol. 117, no. 1, p. 44–47.

Alekseev I., Kozhevnikova A., 2017. Astron. zhurn., vol. 94, no. 3, p. 240.

Alekseev I., Kozhevnikova A., 2018. Astron. zhurn., vol. 95, no. 6, p. 421.
Althukair A.K., Tsiklauri D., 2023a. Research in Astronomy and Astrophysics, vol. 23, no. 8, p. 085017.
Althukair A.K., Tsiklauri D., 2023b. Research in Astronomy and Astrophysics, vol. 23, no. 10, p. 105010.
Althukair A.K., Tsiklauri D., 2023c. Research in Astronomy and Astrophysics, vol. 23, no. 11, p. 115015.
Alvarado-Gómez J.D., Cohen O., Drake J.J., et al., 2022. Astrophys. J., vol. 928, no. 2, p. 147.
Amazo-Gómez E.M., Alvarado-Gómez J.D., Poppenhäger K., et al., 2023. Mon. Not. Roy. Astron. Soc., vol. 524, no. 4, pp. 5725–5748.
Araújo A., Valio A., 2023. Mon. Not. Roy. Astron. Soc., vol. 522, no. 1, pp. L16–L20.
Aschwanden M.J., Schrijver C.J., 2025. Astrophys. J., vol. 987, no. 2, 140.
Bai J.Y., Wang J., Li H.L., et al., 2023. Publ. Astron. Soc. Pacific, vol. 135, no. 1048, p. 064201.
Bastian T.S., Cotton W.D., Hallinan G., 2022. Astrophys. J., vol. 935, no. 2, p. 99.
Bellotti S., Morin J., Lehmann L.T., et al., 2023. Astron. Astrophys., vol. 676, p. A56.
Bellotti S., Petit P., Jeffers S.V., et al., 2025. Astron. Astrophys., vol. 693, A269.
Beskin G., Karpov S., Plokhotnichenko V., Stepanov A., Tsap Y., 2017. Publ. Astron. Soc. Australia, vol. 34, p. e010.
Beskin G.M., Chernenkov V.N., Bursov N.N., Panov A.D., Shlyapnikov A.A., 2023. arXiv e-prints, arXiv:2303.01791.
Bhatia T., Cameron R., Peter H., Solanki S., 2024. Astron. Astrophys., vol. 681, p. A32.
Bicz K., Falewicz R., Pietras M., Siarkowski M., Preś P., 2022. Astrophys. J., vol. 935, no. 2, p. 102.
Bloot S., Callingham J.R., Vedantham H.K., et al., 2024. Astron. Astrophys., vol. 682, p. A170.
Bondar N.I., Katsova M.M., 2022. Geomagnetism and Aeronomy, vol. 62, no. 7, pp. 919–923.
Bondar' N.I., Shlyapnikov A.A., 2024. Geomagnetism and Aeronomy, vol. 63, no. 8, pp. 1277–1284.
Bondar' N.I., Katsova M.M., Shlyapnikov A.A., 2021. Geomagnetism and Aeronomy, vol. 61, no. 7, pp. 1069–1074.
Boro Saikia S., Lueftinger T., Airapetian V.S., et al., 2023. Astrophys. J., vol. 950, no. 2, p. 124.
Boyd D., Buchheim R., Curry S., et al., 2023. J. Amer. Assoc. Var. Star Observ., vol. 51, no. 1, p. 14.
Boyle A.W., Bouma L.G., 2023. Astron. J., vol. 166, no. 1, p. 14.
Brasseur C.E., Osten R.A., Tristan I.I., Kowalski A.F., 2023. Astrophys. J., vol. 944, no. 1, p. 5.
Brown E.L., Jeffers S.V., Marsden S.C., et al., 2022. Mon. Not. Roy. Astron. Soc., vol. 514, no. 3, pp. 4300–4319.
Brown A., Schneider P.C., France K., et al., 2023. Astron. J., vol. 165, no. 5, p. 195.
Brown E.L., Marsden S.C., Jeffers S.V., et al., 2024. Mon. Not. Roy. Astron. Soc., vol. 528, no. 3, pp. 4092–4114.
Burton K., MacGregor M.A., Osten R.A., 2022. Astrophys. J. Lett., vol. 939, no. 1, p. L6.
Burton K., MacGregor M.A., Osten R.A., et al., 2025. Astrophys. J., vol. 982, no. 1, 43.
Cao L., Pinsonneault M.H., 2022. Mon. Not. Roy. Astron. Soc., vol. 517, no. 2, pp. 2165–2189.
Caramazza M., Stelzer B., Magaudda E., et al., 2023. Astron. Astrophys., vol. 676, p. A14.
Carmona A., Delfosse X., Bellotti S., et al., 2023. Astron. Astrophys., vol. 674, p. A110.
Carvalho-Silva G., Meléndez J., Rathsam A., et al., 2025. Astrophys. J. Lett., vol. 983, no. 2, L31.
Chahal D., de Grijs R., Kamath D., Chen X., 2022. Mon. Not. Roy. Astron. Soc., vol. 514, no. 4, pp. 4932–4943.
Chahal D., Kamath D., de Grijs R., Montet B.T., Chen X., 2025. Mon. Not. Roy. Astron. Soc., vol. 540, no. 1, pp. 668–687.
Chebly J.J., Alvarado-Gómez J.D., Poppenhäger K., Garraffo C., 2023. Mon. Not. Roy. Astron. Soc., vol. 524, no. 4, pp. 5060–5079.
Chen X., Wang S., Deng L., et al., 2020. Astrophys. J., Suppl. Ser. , vol. 249, no. 1, 18.
Chen H., Tian H., Li H., et al., 2022. Astrophys. J., vol. 933, no. 1, p. 92.
Coffaro M., Stelzer B., Orlando S., 2022. Astron. Astrophys., vol. 661, p. A79.
Colman I.L., Angus R., David T., et al., 2024. Astron. J., vol. 167, no. 5, 189.
Di Maio C., Petralia A., Micela G., et al., 2024. Astron. Astrophys., vol. 683, p. A239.
Di Mauro M.P., Reda R., Mathur S., et al., 2022. Astrophys. J., vol. 940, no. 1, p. 93.
Didel S., Pandey J.C., Srivastava A.K., Singh G., 2024. Mon. Not. Roy. Astron. Soc., vol. 527, no. 2, pp. 1705–1721.
Distefano E., Lanzafame A.C., Brugaletta E., et al., 2023. Astron. Astrophys., vol. 674, p. A20.
Donati J.F., Cristofari P.I., Finociety B., et al., 2023a. Mon. Not. Roy. Astron. Soc., vol. 525, no. 1, pp. 455–475.
Donati J.F., Lehmann L.T., Cristofari P.I., et al., 2023b. Mon. Not. Roy. Astron. Soc., vol. 525, no. 2, pp. 2015–2039.
Doyle J.G., Irawati P., Kolotkov D.Y., et al., 2022. Mon. Not. Roy. Astron. Soc., vol. 514, no. 4, pp. 5178–5182.
Duvvuri G.M., Pineda J.S., Berta-Thompson Z.K., France K., Youngblood A., 2023. Astron. J., vol. 165, no. 1, p. 12.
Egbo O.D., Buckley D.A.H., Groot P.J., et al., 2025. Mon. Not. Roy. Astron. Soc., vol. 540, no. 3, pp. 2685–2702.
Engle S.G., 2024. Astrophys. J., vol. 960, no. 1, p. 62.
Evensberget D., Carter B.D., Marsden S.C., Brookshaw L., Folsom C.P., 2021. Mon. Not. Roy. Astron. Soc., vol. 506, no. 2, pp. 2309–2335.
Evensberget D., Marsden S.C., Carter B.D., et al., 2023. Mon. Not. Roy. Astron. Soc., vol. 524, no. 2, pp. 2042–2063.
Feinstein A.D., Seligman D.Z., Günther M.N., Adams F.C., 2022. Astrophys. J. Lett., vol. 925, no. 1, p. L9.
Flagg L., Johns-Krull C.M., France K., et al., 2022. Astrophys. J., vol. 934, no. 1, p. 8.
Frasca A., Zhang J.Y., Alonso-Santiago J., et al., 2025. Astron. Astrophys., vol. 698, A7.
Freund S., Czesla S., Fuhrmeister B., et al., 2025. Astron. Astrophys., vol. 697, A230.
Fuhrmeister B., Czesla S., Robrade J., et al., 2022. Astron. Astrophys., vol. 661, p. A24.
Fuhrmeister B., Coffaro M., Stelzer B., et al., 2023. Astron.

Astrophys., vol. 672, p. A149.
Galligan E., Lepine S., 2025. In American Astronomical Society Meeting Abstracts #245. American Astronomical Society Meeting Abstracts, vol. 245, p. 339.01D.
Gershberg R., Kleeorin N., Pustil'nik L., Shlyapnikov A., 2020. Physics of mid- and low-mass stars with solar-type activity. M.: Fizmatlit.
Gershberg R., Kleeorin N., Pustilnik L., Airapetian V., Shlyapnikov A., 2024. Physics of mid- and low-mass stars with solar-type activity and their impact on exoplanetary environments. Simferopol': "Forma".
Getman K.V., Feigelson E.D., 2021. Astrophys. J., vol. 916, no. 1, p. 32.
Gibson A., Kowalski A.F., Feinstein A.D., 2025. arXiv e-prints, arXiv:2506.10201.
Gomes da Silva J., Bensabat A., Monteiro T., Santos N.C., 2022. Astron. Astrophys., vol. 668, p. A174.
Gorbachev M., 2023. Proceedings of the conference "Solar and Solar-Terrestrial Physics – 2023", GAO RAN, pp. 67–70.
Gorbachev M., Shlyapnikov A., 2022. Proceedings of the conference "Solar and Solar-Terrestrial Physics – 2022", GAO RAN, pp. 65–68.
Gorbunov M., Shlyapnikov A., 2022. Proceedings of the conference "Solar and Solar-Terrestrial Physics – 2022", GAO RAN, pp. 69–72.
Hahlin A., Kochukhov O., Rains A.D., et al., 2023. Astron. Astrophys., vol. 675, p. A91.
Hahlin A., Kochukhov O., Chaturvedi P., et al., 2025. Astron. Astrophys., vol. 696, A4.
Hakamata T., Matsumoto H., Odaka H., Takasao S., 2025. Publications of the ASJ, vol. 77, no. 2, pp. 356–369.
Hamaguchi K., Reep J.W., Airapetian V., et al., 2023. Astrophys. J., vol. 944, no. 2, p. 163.
Hertzsprung E., 1924. Bull. Astron. Inst. Netherlands, vol. 2, p. 84.
Howard W.S., MacGregor M.A., Osten R., et al., 2022. Astrophys. J., vol. 938, no. 2, p. 103.
Ibañez Bustos R.V., Buccino A.P., Nardetto N., et al., 2025. Astron. Astrophys., vol. 696, A230.
Ikuta K., Shibata K., 2024. Astrophys. J., vol. 963, no. 1, 50.
Ikuta K., Namekata K., Notsu Y., et al., 2023. Astrophys. J., vol. 948, no. 1, p. 64.
Ilin E., Poppenhaeger K., 2022. Mon. Not. Roy. Astron. Soc., vol. 513, no. 3, pp. 4579–4586.
Ilin E., Poppenhaeger K., Schmidt S.J., et al., 2021a. Mon. Not. Roy. Astron. Soc., vol. 507, no. 2, pp. 1723–1745.
Ilin E., Schmidt S.J., Poppenhäger K., et al., 2021b. Astron. Astrophys., vol. 645, p. A42.
Inoue S., Enoto T., Namekata K., et al., 2024. Publications of the ASJ, vol. 76, no. 2, pp. 175–190.
Ioannidis P., Schmitt J.H.M.M., 2020. Astron. Astrophys., vol. 644, p. A26.
Isaacson H., Howard A.W., Fulton B., et al., 2024. Astrophys. J., Suppl. Ser. , vol. 274, no. 2, 35.
Jackman J.A.G., 2022. Mon. Not. Roy. Astron. Soc., vol. 517, no. 3, pp. 3832–3837.
Jackman J.A.G., Shkolnik E., Loyd R.O.P., 2021. Mon. Not. Roy. Astron. Soc., vol. 502, no. 2, pp. 2033–2042.
Jackman J.A.G., Shkolnik E.L., Million C., et al., 2023. Mon. Not. Roy. Astron. Soc., vol. 519, no. 3, pp. 3564–3583.
Johns-Krull C.M., Valenti J.A., 1996. Astrophys. J. Lett., vol. 459, p. L95.
Johnson L.J., Norris C.M., Unruh Y.C., et al., 2021. Mon. Not. Roy. Astron. Soc., vol. 504, no. 4, pp. 4751–4767.
Joseph W.M., Stelzer B., Magaudda E., Vičánek Martínez T., 2024. Astron. Astrophys., vol. 688, A49.
Kajikiya Y., Namekata K., Notsu Y., et al., 2025. Astrophys. J., vol. 985, no. 1, 136.
Karmakar S., Naik S., Pandey J.C., Savanov I.S., 2022. Mon. Not. Roy. Astron. Soc., vol. 509, no. 3, pp. 3247–3257.
Karmakar S., Pandey J.C., Rawat N., Singh G., Shedge R., 2024. Bull. Soc. R. Sci. Liege, vol. 93, no. 2, pp. 333–340.
Katsova M., 1990. Astron. zhurn., vol. 67, p. 1219.
Katsova M.M., 2020. Journal of Atmospheric and Solar-Terrestrial Physics, vol. 211, p. 105456.
Katsova M.M., Nizamov B.A., Shlyapnikov A.A., 2022a. Geomagnetism and Aeronomy, vol. 62, no. 7, pp. 903–910.
Katsova M.M., Obridko V.N., Sokoloff D.D., Livshits I.M., 2022b. Astrophys. J., vol. 936, no. 1, p. 49.
Kavanagh R.D., Vidotto A.A., Klein B., et al., 2021. In S.J. Wolk, A.K. Dupree, H.M. Gunther (Eds.), The 20.5th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun (CS20.5). Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, p. 315. doi:10.5281/zenodo.4728000 (`arXiv:2104.14457`).
Kitchatinov L., 2022. Research in Astronomy and Astrophysics, vol. 22, no. 12, p. 125006.
Klein B., Zicher N., Kavanagh R.D., et al., 2022. Mon. Not. Roy. Astron. Soc., vol. 512, no. 4, pp. 5067–5084.
Kochukhov O., Hackman T., Lehtinen J.J., Wehrhahn A., 2020. Astron. Astrophys., vol. 635, p. A142.
Kochukhov O., Hackman T., Lehtinen J.J., 2023. Astron. Astrophys., vol. 680, p. L17.
Koller F., Leitzinger M., Temmer M., et al., 2021. Astron. Astrophys., vol. 646, p. A34.
Koval' A., Oks E., 1983. Izv. Krymsk. Astrofiz. Observ., vol. 67, p. 90.
Kovari Z., Strassmeier K.G., Kriskovics L., et al., 2024. Astron. Astrophys., vol. 684, p. A94.
Krolikowski D.M., Kraus A.L., Tofflemire B.M., et al., 2024. Astron. J., vol. 167, no. 2, p. 79.
Kumar M., Fares R., 2023. Mon. Not. Roy. Astron. Soc., vol. 518, no. 2, pp. 3147–3163.
Kumbhakar R., Mondal S., Ghosh S., Ram D., Pramanik S., 2024. Bull. Soc. R. Sci. Liege, vol. 93, no. 2, pp. 370–380.
Kumbhakar R., Mondal S., Ghosh S., Ram D., 2025. Astrophys. J., vol. 981, no. 2, 169.
Kuznetsov A.A., Karakotov R.R., Chandrashekhar K., Banerjee D., 2023. Research in Astronomy and Astrophysics, vol. 23, no. 1, p. 015006.
La Fauci G., Rodonò M., 1983. In P.B. Byrne, M. Rodonò (Eds.), IAU Colloq. 71: Activity in Red-Dwarf Stars. Astrophysics and Space Science Library, vol. 102, pp. 185–188. doi:10.1007/978-94-009-7157-8_20.
Lanzafame A.C., Brugaletta E., Frémat Y., et al., 2023. Astron. Astrophys., vol. 674, p. A30.

Lehmann L.T., Donati J.F., Fouqué P., et al., 2024. Mon. Not. Roy. Astron. Soc., vol. 527, no. 2, pp. 4330–4352.
Leitzinger M., Odert P., Heinzel P., 2022. Mon. Not. Roy. Astron. Soc., vol. 513, no. 4, pp. 6058–6073.
Lin H.T., Chen W.P., Liu J., et al., 2022. Astron. J., vol. 163, no. 4, p. 164.
Liu Q., Lin J., Wang X., et al., 2023. Mon. Not. Roy. Astron. Soc., vol. 523, no. 2, pp. 2193–2208.
Lovkaya M., 2014. UBVRI photometry and colorimetry of flares on UV Cet-type stars, PhD thesis. Nauchnyi.
Loyd R.O.P., Schneider P.C., Jackman J.A.G., et al., 2023. Astron. J., vol. 165, no. 4, p. 146.
Lu Y.L., Curtis J.L., Angus R., David T.J., Hattori S., 2022. Astron. J., vol. 164, no. 6, p. 251.
Luhn J.K., Wright J.T., Henry G.W., Saar S.H., Baum A.C., 2022. Astrophys. J. Lett., vol. 936, no. 2, p. L23.
Maas A.J., Ilin E., Oshagh M., et al., 2022. Astron. Astrophys., vol. 668, p. A111.
MacGregor M.A., Weinberger A.J., Loyd R.O.P., et al., 2021. Astrophys. J. Lett., vol. 911, no. 2, p. L25.
Magaudda E., Stelzer B., Raetz S., et al., 2022. Astron. Astrophys., vol. 661, p. A29.
Martin D.V., Sethi R., Armitage T., et al., 2024. Mon. Not. Roy. Astron. Soc., vol. 528, no. 1, pp. 963–975.
Marvin C.J., Reiners A., Anglada-Escudé G., Jeffers S.V., Boro Saikia S., 2023. Astron. Astrophys., vol. 671, p. A162.
Medina A.A., Winters J.G., Irwin J.M., Charbonneau D., 2022. Astrophys. J., vol. 935, no. 2, p. 104.
Metcalfe T.S., Finley A.J., Kochukhov O., et al., 2022. Astrophys. J. Lett., vol. 933, no. 1, p. L17.
Metcalfe T.S., Strassmeier K.G., Ilyin I.V., et al., 2023. Astrophys. J. Lett., vol. 948, no. 1, p. L6.
Metcalfe T.S., Strassmeier K.G., Ilyin I.V., et al., 2024. Astrophys. J. Lett., vol. 960, no. 1, p. L6.
Metcalfe T.S., Petit P., van Saders J.L., et al., 2025. Astrophys. J., vol. 986, no. 2, 120.
Meunier N., Kretzschmar M., Gravet R., Mignon L., Delfosse X., 2022. Astron. Astrophys., vol. 658, p. A57.
Meunier N., Mignon L., Kretzschmar M., Delfosse X., 2024. Astron. Astrophys., vol. 684, A106.
Mittag M., Schmitt J.H.M.M., Schröder K.P., 2023. Astron. Astrophys., vol. 674, p. A116.
Monsch K., Drake J.J., Garraffo C., Picogna G., Ercolano B., 2023. Astrophys. J., vol. 959, no. 2, p. 140.
Monson A.J., Mathioudakis M., Kowalski A.F., 2024. Astrophys. J., vol. 963, no. 1, p. 40.
Namekata K., Maehara H., Honda S., et al., 2022. Astrophys. J. Lett., vol. 926, no. 1, p. L5.
Namekata K., Airapetian V.S., Petit P., et al., 2024. Astrophys. J., vol. 961, no. 1, p. 23.
Namizaki K., Namekata K., Maehara H., et al., 2023. Astrophys. J., vol. 945, no. 1, p. 61.
Notsu Y., Maehara H., Honda S., et al., 2019. Astrophys. J., vol. 876, no. 1, p. 58.
Notsu Y., Kowalski A.F., Maehara H., et al., 2024. Astrophys. J., vol. 961, no. 2, p. 189.
Núñez A., Agüeros M.A., Covey K.R., et al., 2022. Astrophys. J., vol. 931, no. 1, p. 45.
Núñez A., Agüeros M.A., Curtis J.L., et al., 2024. Astrophys. J., vol. 962, no. 1, p. 12.
Odert P., Leitzinger M., Greimel R., et al., 2025. Mon. Not. Roy. Astron. Soc., vol. 537, no. 1, pp. 537–579.
Okamoto S., Notsu Y., Maehara H., et al., 2021. Astrophys. J., vol. 906, no. 2, p. 72.
Oks E., 1981. Proceedings of the international conference "Year of Solar Maximum", vol. 1, p. 200.
Oks E., 2006. Stark Broadening of Hydrogen and Hydrogenlike Spectral Lines in Plasmas. Alpha Science International, Ltd., Oxford, UK.
Oks E., Gershberg R.E., 2016. Astrophys. J., vol. 819, no. 1, p. 16.
Paudel R.R., Barclay T., Schlieder J.E., et al., 2021. Astrophys. J., vol. 922, no. 1, p. 31.
Pevtsov A.A., Fisher G.H., Acton L.W., et al., 2003. Astrophys. J., vol. 598, no. 2, pp. 1387–1391.
Pietras M., Falewicz R., Siarkowski M., Bicz K., Preś P., 2022. Astrophys. J., vol. 935, no. 2, p. 143.
Pillitteri I., Micela G., Maggio A., Sciortino S., Lopez-Santiago J., 2022. Astron. Astrophys., vol. 660, p. A75.
Pillitteri I., Colombo S., Micela G., Wolk S.J., 2023. Astron. Astrophys., vol. 673, p. A61.
Pineda J.S., Villadsen J., 2023. Nature Astronomy, vol. 7, pp. 569–578.
Popinchalk M., Faherty J.K., Kiman R., et al., 2021. Astrophys. J., vol. 916, no. 2, p. 77.
Rabello Soares M.C., de Freitas M.C., Ferreira B.P.L., 2022. Astron. J., vol. 164, no. 5, p. 223.
Ram D., Mondal S., Patra D., Ghosh S., Khumbhakar R., 2025. Astrophys. J., vol. 980, no. 2, 196.
Ramsay G., Kolotkov D., Doyle J.G., Doyle L., 2021. Solar. Phys., vol. 296, no. 11, p. 162.
Reiners A., Shulyak D., Käpylä P.J., et al., 2022. Astron. Astrophys., vol. 662, p. A41.
Reinhold T., Shapiro A.I., Solanki S.K., Basri G., 2022. Astrophys. J. Lett., vol. 938, no. 1, p. L1.
Rigney J., Ramsay G., Carley E.P., et al., 2022. Mon. Not. Roy. Astron. Soc., vol. 516, no. 1, pp. 540–549.
Rodríguez L.F., Lizano S., Cantó J., González R.F., 2023. Astron. Astrophys., vol. 678, p. A185.
Sairam L., Pathak U., Singh K.P., 2023. Journal of Astrophysics and Astronomy, vol. 44, no. 2, p. 90.
Sairam L., Madhusudhan N., 2025. Mon. Not. Roy. Astron. Soc., vol. 539, no. 2, pp. 1299–1316.
Sakaue T., Shibata K., 2021. Astrophys. J. Lett., vol. 906, no. 2, p. L13.
Saunders N., van Saders J.L., Lyttle A.J., et al., 2024. Astrophys. J., vol. 962, no. 2, p. 138.
Schmitt J.H.M.M., Ioannidis P., Robrade J., et al., 2021. Astron. Astrophys., vol. 652, p. A135.
See V., Roquette J., Amard L., Matt S., 2023. Mon. Not. Roy. Astron. Soc., vol. 524, no. 4, pp. 5781–5786.
Seligman D.Z., Rogers L.A., Feinstein A.D., et al., 2022. Astrophys. J., vol. 929, no. 1, p. 54.
Senavci H.V., Kılıçoğlu T., Işık E., et al., 2021. Mon. Not. Roy. Astron. Soc., vol. 502, no. 3, pp. 3343–3356.
Shan Y., Revilla D., Skrzypinski S.L., et al., 2024. Astron. Astrophys., vol. 684, p. A9.
Shlyapnikov A., 2021. Proceedings of the conference "Solar and Solar-Terrestrial Physics – 2022", GAO RAN, pp. 321–324.
Shlyapnikov A., 2022. Izv. Krymsk. Astrofiz. Observ., vol. 118, no. 3, pp. 5–18.

Shlyapnikov A.A., 2024a. Catalog of Stars with Solar-Type Activity – CSSTA (arXiv:2402.15241). Available at: https://arxiv.org/abs/2402.15241.

Shlyapnikov A.A., 2024b. Geomagnetism and Aeronomy, vol. 63, no. 8, pp. 1308–1312.

Simões P.J.A., Araújo A., Válio A., Fletcher L., 2024. Mon. Not. Roy. Astron. Soc., vol. 528, no. 2, pp. 2562–2567.

Smitha H.N., Shapiro A.I., Witzke V., et al., 2025. Astrophys. J. Lett., vol. 978, no. 1, L13.

Stelzer B., Bogner M., Magaudda E., Raetz S., 2022a. Astron. Astrophys., vol. 665, p. A30.

Stelzer B., Caramazza M., Raetz S., Argiroffi C., Coffaro M., 2022b. Astron. Astrophys., vol. 667, p. L9.

Stuart K.A., Gregory S.G., 2025. Mon. Not. Roy. Astron. Soc., vol. 539, no. 3, pp. 1922–1943.

Su T., Zhang L., Han X.L., et al., 2025. Astron. Astrophys., vol. 694, A157.

Suresh A., Chatterjee S., Cordes J.M., Bastian T.S., Hallinan G., 2020. Astrophys. J., vol. 904, no. 2, p. 138.

Tokuno T., Namekata K., Maehara H., Toriumi S., 2025. Astrophys. J., vol. 985, no. 2, 158.

Toriumi S., Airapetian V.S., 2022. Astrophys. J., vol. 927, no. 2, p. 179.

Toriumi S., Airapetian V.S., Namekata K., Notsu Y., 2022. Astrophys. J., Suppl. Ser. , vol. 262, no. 2, p. 46.

Tristan I.I., Notsu Y., Kowalski A.F., et al., 2023. Astrophys. J., vol. 951, no. 1, p. 33.

Tristan I., Osten R., Notsu Y., et al., 2025. In American Astronomical Society Meeting Abstracts #245. American Astronomical Society Meeting Abstracts, vol. 245, p. 418.06D.

Tsvetkova S., Morin J., Folsom C.P., et al., 2024. Astron. Astrophys., vol. 682, p. A77.

Tu Z.L., Yang M., Wang H.F., Wang F.Y., 2021. Astrophys. J., Suppl. Ser. , vol. 253, no. 2, p. 35.

Tuomi M., Lehtinen J.J., Henry G.W., Hackman T., 2024. Astron. Astrophys., vol. 689, A262.

Valio A., Araújo A., 2023. Stellar differential rotation from transit spot mapping. doi:10.5281/zenodo.8144618.

Vasilyev V., Reinhold T., Shapiro A.I., et al., 2022. Astron. Astrophys., vol. 668, p. A167.

Veronig A.M., Odert P., Leitzinger M., et al., 2021. Nature Astronomy, vol. 5, pp. 697–706.

Webb S., Flynn C., Cooke J., et al., 2021. Mon. Not. Roy. Astron. Soc., vol. 506, no. 2, pp. 2089–2103.

Wood B.E., Müller H.R., Redfield S., et al., 2021. Astrophys. J., vol. 915, no. 1, p. 37.

Xu F., Gu S., Ioannidis P., 2022. Mon. Not. Roy. Astron. Soc., vol. 514, no. 2, pp. 2958–2973.

Yamashita M., Itoh Y., Oasa Y., 2022. Publications of the ASJ, vol. 74, no. 6, pp. 1295–1308.

Yang H., Cheng X., Liu J., et al., 2025. Astron. Astrophys., vol. 695, A21.

Ye L., Bi S., Zhang J., et al., 2024. arXiv e-prints, arXiv:2401.15438.

Zarka P., Louis C.K., Zhang J., et al., 2025. Astron. Astrophys., vol. 695, A95.

Zhang W., Zhang J., He H., et al., 2022. Astrophys. J., Suppl. Ser. , vol. 263, no. 1, p. 12.

Zhang J., Tian H., Zarka P., et al., 2023. Astrophys. J., vol. 953, no. 1, p. 65.

Zhang W., Zhang J., He H., Luo A., Zhang H., 2024. Astron. Astrophys., vol. 688, A23.

Zhao Z.H., Hua Z.Q., Cheng X., Li Z.Y., Ding M.D., 2024. Astrophys. J., vol. 961, no. 1, p. 130.

Zic A., Murphy T., Lynch C., et al., 2020. Astrophys. J., vol. 905, no. 1, p. 23.