200. Chromospheric activity

THE SUN'S chromosphere lies above its photosphere and below the corona. It is seen as a thin (~ 100 km) annulus above the lunar limb during solar eclipse, and its distinctive red colour is dominated by the Hα 656 nm transition. The term was suggested by Lockyer (1868), although the region's boundaries still remain only imprecisely defined (Linsky, 2017, §2). Spicules and prominences, bright features above the limb and dark features on the disk, provide evidence that the chromosphere is out of radiative equilibrium, with a temperature *higher* than at the top of the photosphere (Beckers, 1972).

There is a substantial literature on the complex physics of the solar chromosphere (Carlsson et al., 2019), and its role in coronal heating (Reale, 2014), and in driving the solar wind (Cranmer & Winebarger, 2019), but I will go no deeper into these aspects here.

THE PHENOMENA collectively known as 'solar activity' originate from the cyclic regeneration of the Sun's large-scale magnetic field (Charbonneau, 2010), and it is in this context that solar variations in Ca II and Hα are interpreted (Durney et al., 1981; Zills et al., 2024).

Similarly, strong and variable magnetic fields in cool stars with convective envelopes are driven by analogous stellar dynamos, themselves evidenced by photospheric starspots, chromospheric plages and coronal flares, and by Ca II and Hα emission (Linsky, 1980; Linsky, 2017, §4; Carlsson et al., 2019, §3.2). For solar-type and cooler stars, UV/XUV radiation from their chromospheres and transition regions also drives photochemical processes in exoplanet atmospheres (Linsky, 2017).

Angular momentum loss via the magnetised wind causes the star to spin down, so that phenomena associated with the dynamo and the surface magnetic field decay over time (e.g. Reiners & Basri, 2008). Chromospheric activity, characterised by Hα and Ca II variability, thus contributes to understanding the complexity of stellar magnetic fields, and the resulting variability as a function of stellar type, rotation and age, as well as probing pre-main sequence mass accretion and mass transfer in binary systems (e.g. Gizis et al., 2002; Pace, 2013).

THE VARIOUS SPECTRAL LINES used as chromospheric activity diagnostics probe different physical conditions (Carlsson et al., 2019, §3.2). The Hα line is the 'classical' diagnostic: the lower level of the $(n = 3 \rightarrow 2)$ transition is at an excitation energy of 10.2 eV, meaning that the opacity and line width is temperature dependent, although with large thermal broadening.

The Ca II H and K lines (396.8/393.4 nm) have the ground state as lower level, and trace the dominant ionisation stage for $T \lesssim 13\,000$ K. The parameter $R'_{\rm HK}$, relating line emission to bolometric luminosity (Noyes et al., 1984, § II), facilitates comparison across spectral types.

The Ca infrared triplet (850–860 nm) has metastable lower levels, resulting in temperature-dependent opacities, and with good sensitivity to magnetic field strength.

PAST SPECTROSCOPIC SURVEYS of chromospheric activity include the Palomar/Mount Wilson surveys (Duncan et al., 1991; Gizis et al., 2002), and the HARPS survey of 4454 cool stars (Boro Saikia et al., 2018).

Numbers have been boosted by recent catalogues from the LAMOST survey in these three different lines. A study of 1.1 million solar-like stars using the Ca II HK lines concluded, for example, that the dynamo mechanism of solar-like stars is generally consistent with that of the Sun (Zhang et al., 2024). A survey of 560 000 FGK stars using the Ca triplet at 850–860 nm classified activity as a function of $T_{\rm eff}$, and found that a significant fraction of stars that show a high activity index in both Ca II HK and in the infrared triplet are binaries (Huang et al., 2024). Finally, of more than 2.3 million G-type stars in LAMOST DR10, 220 000 show excess chromospheric activity in Hα (Su et al., 2024).

Other surveys have focussed on specific spectral types, such as the Cepheids (e.g. Hocdé et al., 2020), and BY Draconis variables (e.g. Chahal et al., 2022).

The increasing quantity and quality of such survey data is leading to a resurgence of interest in chromospheric activity, and the prospects of gaining *'a much improved understanding of chromospheric physics and its wide-ranging impact'* (de Grijs & Kamath, 2021).

WITH THE ABOVE by way of context, Gaia's contribution to the measurement of chromospheric activity can be more easily appreciated. Here, it is important to stress that the wavelength interval of Gaia's Radial Velocity Spectrometer (RVS, 845–872 nm) includes, by design, the Ca II infrared triplet lines (850–860 nm).

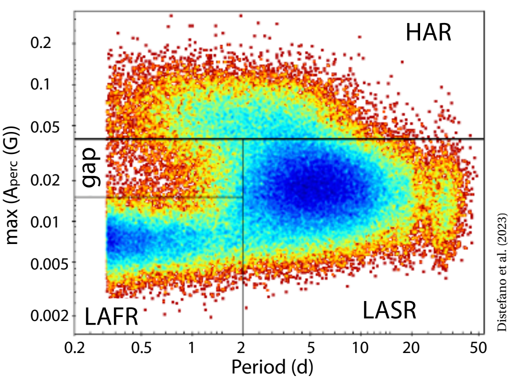
Before detailing the RVS results, some other insights into solar-like variability, including effects of flares and rotating starspots, have also been obtained from Gaia based on the wider photometric variability classification undertaken as part of Data Release 3 (Rimoldini et al., 2023), and specifically focussing on magnetically active stars, initially in the case of DR2 (Lanzafame et al., 2018), and further refined for DR3 (Distefano et al., 2023).

Distefano et al. (2023) analysed a subset of 30 million late-type stars, and derived a catalogue of 474 000 stars with variability induced by magnetic activity, of which 430 000 are newly discovered variables. For each star, their catalogue includes the stellar rotation period P, the photometric amplitude A of the rotational modulation in the Gaia G band (calculated as some maximum over various percentiles), and a correlation coefficient r_0 between magnitude and colour variation.

Their amplitude–period diagram (reproduced below) shows three broad clusterings of rotating stars that they refer to as High-Amplitude-Rotators (HAR), Low-Amplitude-Slow-Rotators (LASR), and a new class of Low-Amplitude-Fast-Rotators (LAFR), the latter not seen, for example, in the Kepler data.

Distefano et al. (2023) conclude that the high-amplitude rotators (HAR) are dominated by long-lived dark spots, while the LAFR stars are dominated by bright faculae and characterised by rapidly variable magnetic fields. The LASR stars are characterised by a moderate correlation between brightness and colour variations, implying that dark spots are still the main cause of their variability, but that faculae spatially or temporally uncorrelated with the spots tend to attenuate the correlation between magnitude and colour variations.

And they interpret the gap between the HAR and LAFR stars as evidence for a rapid transition between their different magnetic configurations.



LET ME TURN NOW to the RVS data, and the insights into chromospheric activity that have been derived from the Ca II infrared triplet lines by Lanzafame et al. (2023).

In Data Release 3, let me recall, the first stage of the RVS processing employs the 'Astrophysical Parameters Inference System' (Apsis, Creevey et al., 2023; Fouesneau et al., 2023), which I summarised in essay 89.

Amongst the 13 Apsis modules, the Extended Stellar Parametrizer for Cool Stars (ESP–CS) computes a chromospheric activity index by comparing the observed RVS spectrum with a purely photospheric (radiative equilibrium) model. For this, $T_{\rm eff}$, $\log g$, and [M/H] are derived from the modules GSP–Spec or GSP–Phot.

Lanzafame et al. (2023) then used the excess equivalent width in the triplet line cores ($\Delta\lambda = \pm 0.15$ nm) as a measure of chromospheric activity (and, in specific cases, of the mass accretion rate in pre-main sequence stars). And, in analogy with the $R'_{\rm HK}$ activity index, they derived a similarly defined $R'_{\rm IRT}$ index, largely independent of the photospheric parameters.

Their derived catalogue contains a stellar activity index, derived from the Ca II infrared triplet, for some 2×10^6 stars. They identified three regimes of chromospheric activity, largely confirming suggestions made in previous work based on much smaller $R'_{\rm HK}$ datasets.

The highest stellar activity regime is populated by pre-main-sequence stars, where the excess flux with respect to radiative equilibrium appears to be dominated by mass accretion, and close binary systems such as RS CVn systems, in which magnetic activity may be significantly enhanced by tidal interaction.

Stars with 3500–5000 K are either very active pre-main-sequence stars, or active main sequence stars with a unimodal activity distribution. A dramatic 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. Some evidence of a bimodal distribution in main sequence stars with $T_{\rm eff} > 5000$ K is also found. Interestingly, their $R'_{\rm IRT}$ index is well correlated with the $R'_{\rm HK}$ values from Boro Saikia et al. (2018) noted above.

These are early days in the scientific interpretation. But the Gaia data are clearly allowing activity to be characterised as a function of stellar parameters with unprecedented detail, outlining different regimes of chromospheric heating, and identifying systems for which emission resulting from mass accretion may dominate.

IN RESEARCHING this essay, I was amused by the opening sentence of the review on 'Solar Spicules' by Jacques Beckers (1968), which resonates with my own experience and interest in writing these essays, and which I thought I would share: *'The author of a review article is undoubtedly the one who benefits most from it.'*