Stars and their variability observed from space
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DYNAMICS OF STAR-DISK INTERACTION PROCESSES IN YOUNG, LOW-MASS STARS AS SEEN FROM SPACE

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Abstract. High-precision time series photometry provides a unique window into the dynamics of the inner disk regions (< 1 AU) around young stars (< 5-10 Myr), at spatial scales hardly accessible via direct imaging techniques. In this review, we discuss the breakthrough brought in by space-based missions in our understanding of the physics and characteristic timescales of variability of protoplanetary disks in connection with their host stars. Our review is based on several young clusters and star-forming regions monitored with the *CoRoT* (NGC 2264) and *Kepler*/K2 (ρ Ophiuchus, Upper Scorpius) satellites. These regions virtually cover every stage of the disk lifetimes. In each region, hundreds of young, low-mass stars with disks were monitored nearly continuously for 30 to 80 days. The precision and homogeneity of such space-borne data allowed us to identify several distinct classes of young star-disk variables: spotted, quasi-periodic, stochastic, bursters, and dippers. The intrinsic timescales of variability that pertain to each light-curve class are indicative of the characteristic timescales of interaction between the stars and their inner disks, which are in turn related to the dynamical evolution of inner disk structures. The observed photometric behaviors can be associated with at least two distinct paradigms of star-disk interaction: an unstable regime, with erratic flux variations that trace intense and short-lived bursts of mass accretion onto the star, and a stable regime, with ordered accretion streams from the inner disk onto the star. These distinct scenarios may be related to different stages of the inner disk evolution, in an interplay with external and environmental conditions.

Keywords: Accretion, accretion disks – Stars: low-mass – Stars: pre-main sequence – Stars: variables: T Tauri – Open clusters and associations: individual: NGC 2264, ρ Ophiuchus, Upper Scorpius

1 Introduction

Over the last few years, our view of protoplanetary disks around pre–main sequence (PMS; ∼1–10 Myr–old) stars has undergone a dramatic revolution, thanks in particular to the advent of the ALMA telescope, which revealed their varied morphologies (rings, gaps, cavities, shadows) in astounding detail. However, even for the protoplanetary disks closest to us (e.g., TW Hydrae; Andrews et al. 2016), the spatial scales (∼0.1 AU) of the region around the central star, where the magnetospheric star–disk interaction develops, fall well below the limiting resolution that can be achieved in those images. Monitoring the photometric variability of young stars therefore provides the most direct observational approach to unveil the nature and characteristic timescales of the physical processes that govern the inner disk regions. While the variable nature of young stars has been known for decades (Joy 1945; Herbig 1962, and references therein), only in recent years have the exquisite photometric precision, sampling, and time coverage brought in by space–based observatories (MOST, *Spitzer*, *CoRoT*, *Kepler*) enabled appreciating the wide range of distinct photometric behaviors that PMS stars with disks can exhibit. In this contribution, we review the main drivers of variability in young, low–mass stars, and discuss what their light curves reveal on the structure and dynamical evolution of the inner disk environment.

2 The variability of young, low–mass stars

The distinctive variable nature of young solar–type stars (T Tauri stars, TTS; $M_\star \lesssim 1-2\ M_\odot$) can be associated with a variety of mechanisms. At the very basic level, photometric variability on rotational timescales (i.e., days to weeks; see, e.g., Venuti et al. 2017; Roquette et al. 2017) is driven by the presence of unevenly–distributed

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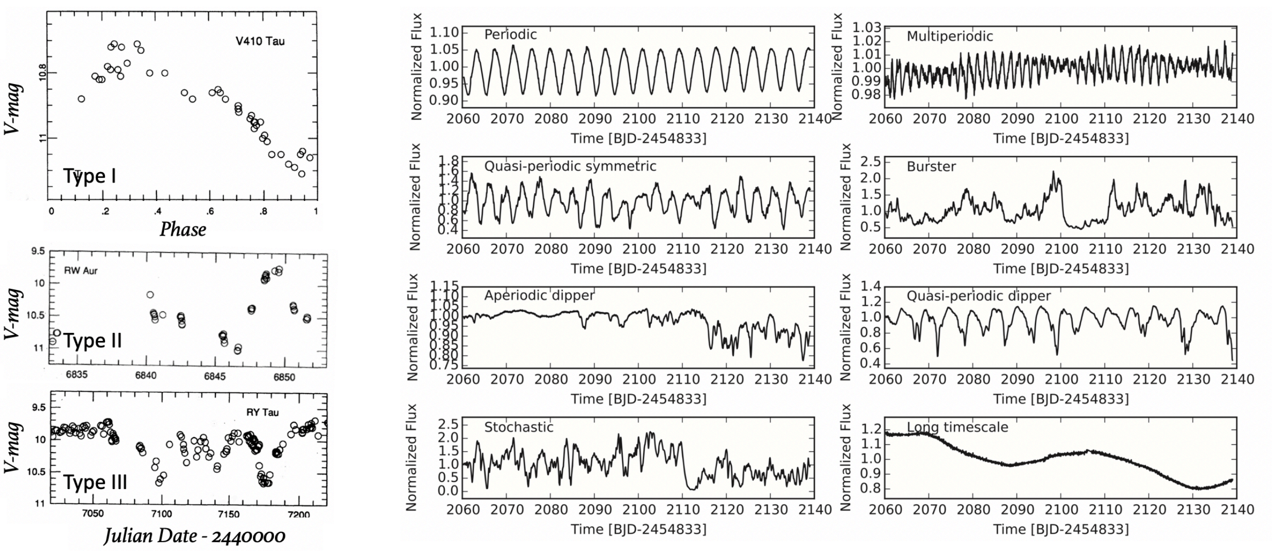

Fig. 1. *Left*: Examples of the three different types of TTS variability identified by Herbst et al. (1994) from ground–based data: cold spot modulation (Type I), mix of cold spots and accretion shocks (Type II), and circumstellar obscuration (Type III). Adapted from Herbst et al. (1994). *Right*: Different classes of variability identified among disk–bearing stars in ρ Ophiuchus and Upper Scorpius from *Kepler*/K2 data. Reproduced from Cody & Hillenbrand (2018).

dark spots at the stellar surface, which are produced by enhanced magnetic activity of the same type observed in our Sun. More intense, and often irregular, variability can be contributed by the process of magnetically–driven interaction between the central star and the inner disk, regulated in particular by accretion of material from the disk onto the star (see Hartmann et al. 2016 for a recent review). The rapidly–evolving accretion shocks that form when the accretion stream impacts the star modulate the luminosity of the star on timescales varying between their intrinsic lifetimes and the stellar rotation timescales. A key role in the observed variability properties is also played by the specific geometry of the star–disk system (from edge–on to face–on) with respect to the observer's line-of–sight, which determines what features of the system come into view.

2.1 TTS variability: a ground–based perspective

A first morphological classification of the different types of variability that TTS can exhibit was presented in the seminal work by Herbst et al. (1994), who identified three distinct variability classes (Fig. 1, *left*). The first type of variability, predominantly associated with TTS with no evidence of ongoing mass accretion (weak–lined T Tauri stars, WTTS), manifested as periodic flux variations that could be explained by rotational modulation by cold surface spots. The second type of variability, characteristic of T Tauri stars actively accreting from their disks (classical T Tauri stars, CTTS), manifested as "generally irregular variations on timescales as short as hours", with larger variability amplitudes than those measured for variables of the first type, and likely driven by a changing mix of magnetic spots and accretion shocks at the stellar surface. The third type of variability, also associated with disk–bearing objects, manifested as irregular and asymmetric flux variations on timescales of days to weeks, with pronounced fading events interspersed with a more slowly–varying luminosity continuum, and was tentatively attributed to variable circumstellar obscuration. However, the sparseness of ground–based observations hampered the identification of the distinct characteristic timescales of variability that pertain to young stars, and the limitedness of the early stellar samples prevented a statistical appreciation of how common different types of variability are among TTS.

2.2 The space–borne revolution in studies of TTS variability

Over the last decade, dedicated space–based monitoring campaigns have dramatically changed our understanding of TTS variability. Thanks to photometric precisions of the order of mmag, and to nearly continuous monitoring with a cadence of minutes over baselines of months, such campaigns enabled a synoptic view of TTS behavior over the time domain on all timescales from several hours (sensitive to short–term variations in accretion) to several rotational cycles (sensitive to dynamic changes in the innermost disk regions, near the co-rotation radius).

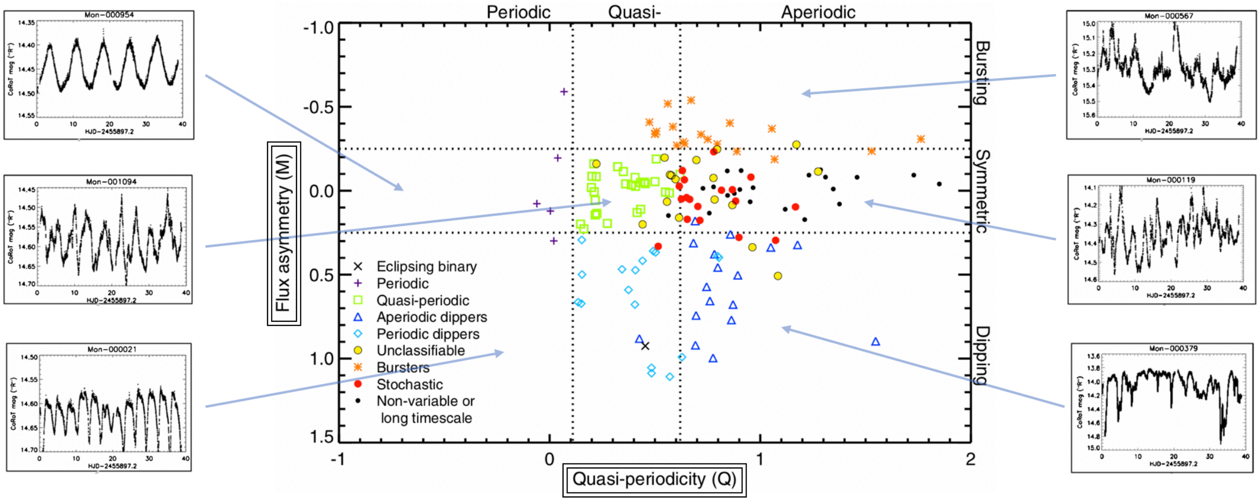

Fig. 2. Metrics defined in Cody et al. (2014) to categorize the variability behaviors of CTTS, applied to NGC 2264 members monitored with *CoRoT*. The side panels show selected examples of light curves for different classes: periodic (left, top), quasi–periodic (left, middle), periodic dipper (left, bottom), burster (right, top), stochastic (right, middle), and aperiodic dipper (right, bottom). Adapted from Cody et al. (2014).

A main revelation brought in by high–precision space photometry is that the actual variety of time behaviors observed among CTTS extends well beyond the broad classes identified from the ground (Fig. 1, *right*). The first large–scale monitoring campaign of thousands of TTS in 12 star–forming regions, the Young Stellar Object VARiability project (YSOVAR; Morales-Calderón et al. 2011; Rebull et al. 2014), was conducted in the early 2010s with *Spitzer*/IRAC at mid-infrared wavelengths, sensitive to the thermal emission from the inner disk. At the end of 2011, the scope of the YSOVAR project was expanded into the Coordinated Synoptic Investigation of NGC 2264 (CSI2264; Cody et al. 2014), a dedicated campaign of variability monitoring across the wavelength and time domains for over 500 TTS in the NGC 2264 region (∼3–5 Myr; Dahm 2008), employing the *CoRoT* (optical), *Spitzer* (mid-infrared), and Chandra (X-rays) satellites, in addition to several other telescopes and instruments (e.g., CFHT/MegaCam, VLT/Flames), from ground and from space.

CSI2264 enabled a first statistical definition of metrics to classify the variability behaviors exhibited by CTTS (Cody et al. 2014), according to how periodic (or aperiodic) the light curve patterns are, and to how symmetric (or asymmetric) the flux variations are with respect to the typical luminosity state of the star (Fig. 2). Based on these parameters, the original classification into three types of variability for TTS could be expanded into eight distinct classes among CTTS alone: *periodic* (with stable light curve patterns over timescales of months), *quasi–periodic symmetric* (with small–scale irregular variability superimposed over an overall periodic light curve pattern), *multiperiodic* (which may exhibit a beating or pulsating pattern, or recurring eclipses added to the "continuum" variability), *bursters* (irregular variability with a preference for brightening events above the light curve continuum), *periodic dippers* (with flux dips regularly spaced over a flatter continuum), *aperiodic dippers* (which exhibit prominent dimming events with no obvious periodicity), *stochastic* (irregular variability with no preference for brightening events over dimming events or vice versa), and *long-timescale* variables (with a light-curve pattern that appears to change across the whole duration of the time series). These distinct behaviors are likely associated with different properties of the circumstellar environment and different modes of star–disk interaction, as discussed in the following section. It is not uncommon for individual CTTS to also switch between different types of photometric behaviors on timescales as short as years, perhaps as a result of more dramatic changes in the inner disk structure on hundreds of rotational timescales (Sousa et al. 2016).

3 Young star variability and star–disk interaction

In the currently accepted paradigm of magnetospheric accretion in CTTS, the stellar magnetosphere connects and drives the interaction between the central star and the inner disk, truncated at a distance of a few stellar radii from the stellar surface. Columns of material are lifted from the disk midplane and channeled along the magnetic field lines until they impact the star in localized regions close to the stellar poles. The hot accretion shocks generated at the stellar surface modulate the observed luminosity of the star, with an overall stable

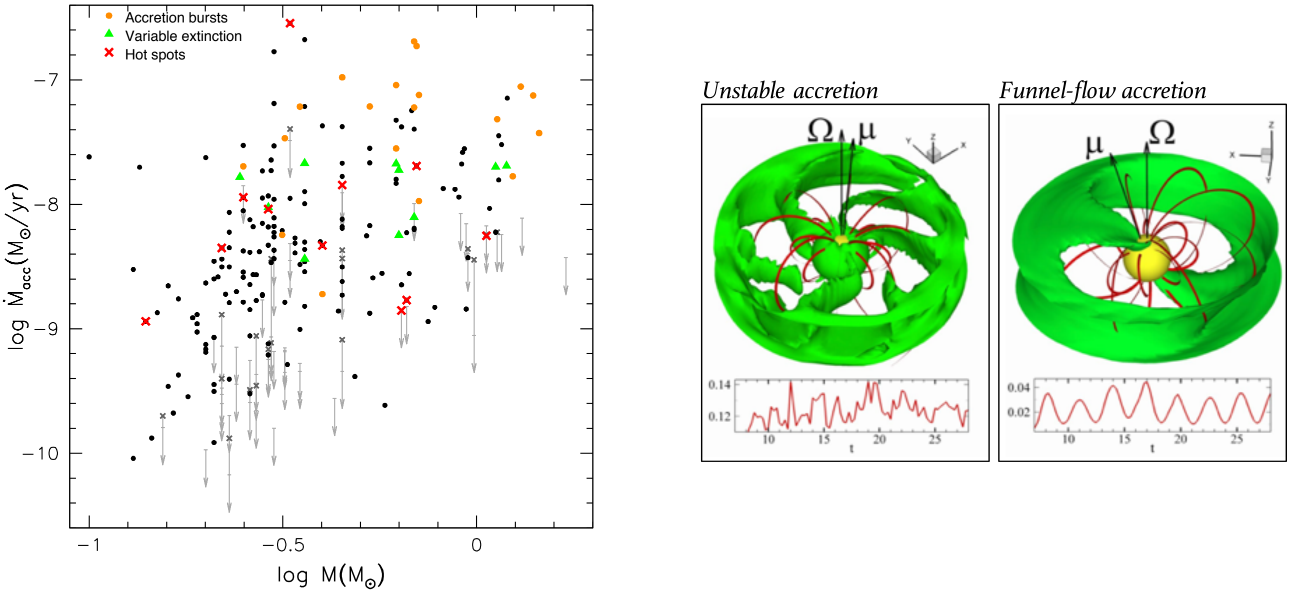

Fig. 3. *Left*: Accretion rates measured, as a function of mass, for CTTS in NGC 2264. Orange circles, green triangles, and red crosses highlight the accretion properties for stars that exhibit a bursting, dipping, or periodic behavior, respectively. Adapted from Venuti et al. (2014). *Right*: Models of CTTS accreting in an unstable or in a stable regime, and corresponding variability predicted for the star on rotation timescales. Adapted from Kulkarni & Romanova (2008).

pattern over several rotational cycles (e.g., Romanova et al. 2004). However, theoretical models also predict different scenarios of star–disk interaction, driven by instabilities at the disk–magnetosphere interface. In these cases, accretion does not proceed in an ordered fashion, but rather in stochastic tongues of material that impact the star surface at random locations, producing intense accretion events and rapidly evolving accretion features (e.g., Kulkarni & Romanova 2008; Fig. 3, *right*). Very different photometric variability signatures are expected in these two scenarios; however, the irregular and short–lived nature of the phenomena associated with an unstable regime of star–disk interaction hampered the identification of such scenarios from the ground.

Thanks to the cadence and duration of space–based data, and to the coordinated exploration of variability across the wavelength domain, CSI2264 was the first campaign to provide observational evidence for the coexistence of distinct modes of star–disk interaction among a given CTTS population. Accretion and disk properties were shown to be the discriminating factor between irregular and regular variability (Venuti et al. 2014; Sousa et al. 2016; Stauffer et al. 2016). Burster stars, in particular, were found to be associated with the strongest accretion rates detected (Fig. 3, *left*), and their light curve patterns were shown to match the theoretical predictions for young stars accreting in an unstable regime (Stauffer et al. 2014). Dipper stars (McGinnis et al. 2015) and periodic or quasi–periodic stars, instead, were found to correspond to more moderate levels of accretion, similar to each other. These photometric behaviors are interpreted to both arise in a scenario of ordered funnel–flow accretion, for different geometries of the star–disk system: in highly inclined systems, the inner disk warp at the base of the accretion columns may periodically occult part of the stellar photosphere, therefore producing the observed flux dips (Bodman et al. 2017); in low–inclination systems, instead, the line–of–sight to the star is not obstructed by inner disk structures, and the observed variability is dominated by accretion hotspot modulation. A bursting behavior is statistically found among CTTS with the thickest inner disks, while less conspicuous infrared excesses are statistically found among dipper stars and quasi–periodic stars.

4 Young star variability and disk evolution

Over the past five years, the *Kepler* repurposed mission, K2 (Howell et al. 2014), has provided an excellent opportunity to extend the census of CTTS photometric behaviors, established during CSI2264, to several other star–forming regions: ρ Ophiuchus and Upper Scorpius (1–3 Myr and 5–10 Myr, respectively; Cody et al. 2017; Cody & Hillenbrand 2018), the Lagoon Nebula ($\sim$2 Myr; Venuti et al., in preparation), and Taurus ($\sim$2 Myr; Rebull et al., in preparation; Cody et al., in preparation). These regions span the entire age range during which

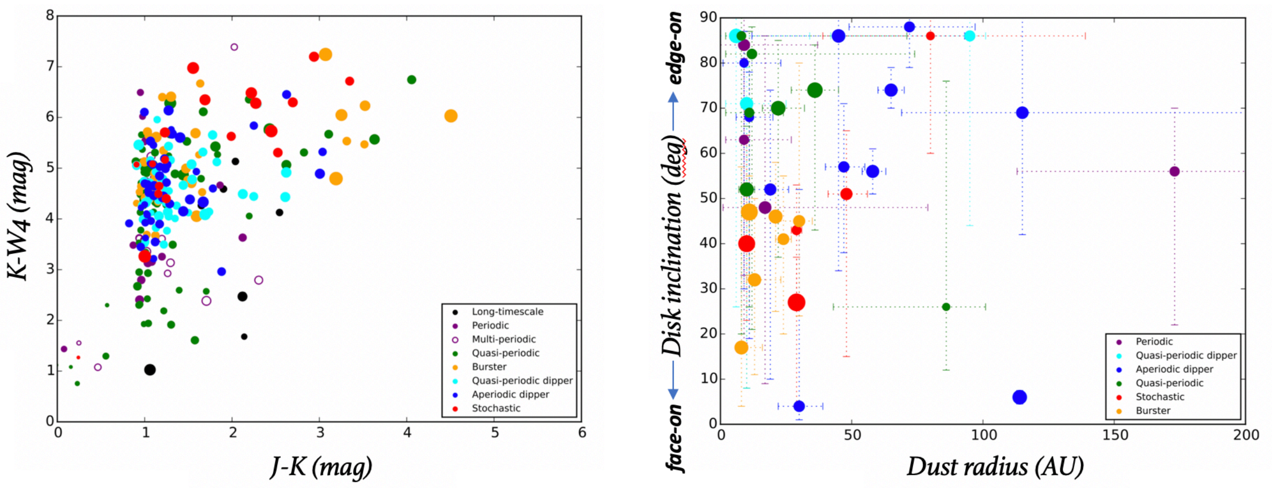

Fig. 4. *Left*: Near- and mid-infrared color properties for CTTS in the ρ Ophiuchus and Upper Scorpius regions, distinguished according to the morphology class of their K2 light curves. Adapted from Cody & Hillenbrand (2018). *Right*: Distribution of CTTS in ρ Ophiuchus and Upper Scorpius, sorted according to their photometric behaviors, as a function of disk inclination and inner disk radius, measured from ALMA data. Adapted from Cody & Hillenbrand (2018).

circumstellar disks are statistically observed to evolve and disperse (e.g., Fedele et al. 2010); therefore, they represent an ideal sample to investigate how the dynamics of interaction between the star and the inner disk regions changes in the course of disk evolution and as a function of the environment.

At the end of the K2 mission, and midway through the analysis of its legacy dataset on young star clusters, the global picture of CTTS variability that is emerging indicates that around 50% of young stars with disks typically exhibit repeated variability patterns, with a periodicity that can be clearly extracted from months–long monitoring data. This suggests that dynamic changes in the inner disk region typically take place over timescales of several rotational cycles. Irregular variability behaviors (bursting, stochastic) appear to be consistently associated with stars that exhibit larger amounts of infrared emission (indicative of more conspicuous inner disks) than dipper stars and quasi–periodic variables (Fig. 4, *left*). Interestingly, the distinction in infrared properties between irregular and regular variables appears to be more marked well into the mid–infrared regime ($\sim$20 μm) than in the near– or early mid–infrared. This indicates that disk instabilities that drive an irregular variability behavior may originate beyond the innermost, and hottest, disk regions (Cody & Hillenbrand 2018).

Preliminary statistics may indicate an overall increase in the occurrence of quasi-periodic and dipping behaviors, and a decrease in the fraction of stochastic behaviors, with cluster age. This would suggest that, as the disks become more evolved, more moderate and stable regimes of star–disk interaction are favored over unstable patterns. However, no obvious trends with the average cluster age are revealed by current data on the fraction of burster stars among CTTS ($\sim$13%). These statistics might be reconciled with the suggestion of a global evolutionary trend by assuming a non–negligible age spread among the population of a given cluster; in each cluster, a bursting behavior may be associated with the youngest, most strongly accreting members (e.g., Venuti et al. 2014, in the NGC 2264 region). However, no clear evidence of such an effect could be deduced for the ρ Opiuchus and Upper Scorpius populations (Cody et al. 2017).

Dipper stars are especially interesting targets to probe the inner disk structure and variability. The large number of dipper stars documented during the K2 mission, combined with the results from ALMA surveys of protoplanetary disks in young star clusters in the solar neighborhood (e.g., Barenfeld et al. 2016), has enabled a direct confirmation of the fact that CTTS with a dipping behavior tend to exhibit highly inclined disks (Fig. 4, *right*), which supports the interpretation of their photometric behavior in terms of inner disk warp occultation. However, this dataset also unveiled several remarkable cases of a dipping behavior found in stars whose outer disks (imaged with ALMA) are observed nearly face–on (e.g., Ansdell et al. 2016). The only scenario where a highly–inclined inner disk and a nearly face–on outer disk can be reconciled is a picture where the initial disk evolves into disconnected and misaligned inner and outer disks, perhaps as a result of dynamical interactions with a stellar companion (Facchini et al. 2018) or a gap–carving protoplanet. More investigations are required to assess how common such scenarios may be during disk evolution, and the potential impact on the host star.

5 Conclusions

Space-based monitoring of young stars has been pivotal in revealing the structure and characteristic timescales of the inner circumstellar environment. Large–scale surveys conducted, among others, with *CoRoT* and *Kepler* have documented a large diversity of photometric behaviors for young stars with disks, from periodic to stochastic and from bursting to dipping. Such photometric behaviors provide the most direct observational signatures of distinct modes of interaction between the stars and their inner disks, ranging from stable and ordered to unstable and chaotic. The typical timescales of variability observed for young stars indicate that structural changes in the inner disk can take place on characteristic timescales of several rotation periods (i.e., weeks). Shorter timescales of variability are instead associated with erratic accretion events, often aperiodic but recurring. The breakthroughs achieved during the past decade have demonstrated the great potential of coordinated efforts which combine multiple diagnostics to unveil the nature and interplay of the different processes that govern the complex star–disk environment. Numerous open questions remain, such as on the connection between stellar, inner disk, and outer disk evolution, and on the link between different timescales of variability, from hours, to weeks, to several years. Current and future missions like TESS, PLATO, and LSST will be key to continuing the exploration of young star variability as a function of stellar mass, age, and external environment, in order to unveil what parameters may drive different patterns of star–disk evolution and planet formation.

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