Stellar Rotation Within the Beta Pictoris Moving Group Using TESS Lightcurves

IMPULS, NITARP Class of 2025

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Abstract

The Beta Pictoris Moving Group (BPMG) is a nearby (~50 pc) association of young (~20 million years old) stars at a critical stage of stellar evolution, when circumstellar disks are dissipating and, as a result, the distribution of angular momentum in the system is actively changing. This project aims to investigate the relationship between infrared excess, stellar rotation, and other youth indicators in BPMG members to better understand disk dispersal timescales and angular momentum evolution in young stars.

The results of this study will contribute to ongoing efforts to characterize young stellar populations and inform models of how stars shed their disks and evolve toward the main sequence, with indirect implications for planet formation.

1.0 Project Introduction and Goals

This project seeks to advance our understanding of stellar rotational evolution during the pre-main sequence phase by studying the Beta Pictoris Moving Group (BPMG). Specifically, our goals are to:

- Compile photometric data from archival photometric surveys to construct spectral energy distributions (SEDs), color-color diagrams (CCDs), and color-magnitude diagrams (CMDs) for known BPMG members.
- Use these diagnostics to identify stars with infrared excesses, indicating the presence of circumstellar disks.
- Extract and analyze light curves from multiple time-domain surveys (and data deliveries) to measure rotation periods and characterize photometric variability.
- Compare BPMG's rotation and disk properties to those in clusters of varying ages to place it within the broader framework of pre-main-sequence stellar evolution.

1.1 Science Introduction and Context

Understanding how stars evolve during their youth reveals more of the broader story of stellar life cycles. Stars change over millions of years, so astronomers cannot observe a single star through all stages of its development. Instead, we study groups (or clusters, or associations) of stars that formed around the same time. By examining many different such groups that are each at different evolutionary stages (each at different ages), we can piece together, for example, how young stars shed their disks, lose angular momentum, and settle into the main sequence. These processes carry clues about how stars interact with their disks (and perhaps form planets) during their formative years.

One key to the formation and evolution of a star and its system is its angular momentum, as manifest in its rotation rate. A star system is born from a nebula, a vast cloud of gas and dust. The nebula likely begins as a roughly spherical cloud of very cold, low-density gas, inheriting a small amount of angular momentum from galactic dynamics and internal turbulence. As the cloud collapses under gravity, angular momentum conservation causes it to rotate more rapidly and flatten into a disk. These accretion disks feed material onto the star and also serve as the birthplace of planets. While a disk is present, the star's magnetic field can lock the rotation of the star to that of the (inner) disk, affecting how fast the star spins. Once the disk dissipates, the star's rotation gradually slows down over millions of years as its magnetized stellar wind carries away its angular momentum. Mapping how stars' spin rates change over time helps us understand the physics and timelines of star and planet formation. Our own Solar System, for example, has most of its remaining angular momentum in the orbital motion of Jupiter orbiting our relatively slowly-rotating central star.

The way to determine the rotation rate of a young star is to use light curves to monitor its variability in brightness over time: as the star rotates, surface features such as starspots rotate into and out of view, causing the star's brightness to vary. When this variability is periodic, it directly corresponds to the star's rotation period and allows us to probe the processes occurring near its surface and at the star-disk interface – regions we cannot directly image with current instrumentation. For young stars, such variation timescales typically range from a few hours to several days. This means that the surface features responsible for brightness variations must be located within a region spanning light-hours to light-days. By comparing these results to other young star clusters of different ages, we can improve our understanding of how stars change as they mature and how their rotation rates are affected by their circumstellar disks.

This study aims to measure the rotation rates of stars within the Beta Pictoris Moving Group (BPMG), a collection of nearby (~50 pc) young stars about 25 million years (Myr) old that move together through space. Studying the BPMG is valuable because it represents a key stage in stellar evolution when most stars have lost their surrounding circumstellar disks and when other factors begin to influence how their rotation rate changes with time. Previous studies of younger groups, such as Upper Scorpius (~8 Myr), and older groups, such as the Pleiades (~125 Myr), have provided important clues about how rotation evolves (e.g., Rebull et al., 2016, 2017, 2018, 2020, 2021, 2022). However, BPMG fills an important gap between these ages, allowing us to better understand how stars transition from disk-influenced rotation to longer-term spin-down mechanisms. Additionally, BPMG's proximity makes observing its members easier, allowing us to probe fainter stars and draw more reliable conclusions from its light curves and vast datasets. This, combined with its intermediate age, makes BPMG a valuable group for studying the evolution of stellar rotation.

1.2 – Stellar Moving Groups and the Beta Pic Moving Group

The formation of stars starts with a large diffuse nebula consisting of dust and gas. Depending on factors such as the mass of the original nebula, clusters of dozens, hundreds, or even thousands of stars can form. Since stars form at the same time from the same nebula "kitchen," it can be assumed that these stars have similar compositions and ages and are moving through space with approximately the same initial motion as the original nebula. These newborn stars interact gravitationally with each other and with the rest of the galaxy and begin to disperse away from one another as they age, even as they continue to move overall with the motion of the original nebula due to conservation of momentum. As these gravitational influences continue to act on the stars over a longer period of time, the stars may eventually disperse into the rest of the Galaxy.

BPMG is one such group of stars that is believed to have been born from a shared nebula. The stars are a group that is moving together through space, hence "moving group." Named after its brightest member, Beta Pictoris, BPMG is a young group of stars relatively close to Earth. It has an estimated average distance of only 51 parsecs, though distances to members range from 10-100 pc (Luhman 2024). Due to this proximity, it appears to occupy a large expanse of the observed night sky with members stretching from the constellations Orion in the north to Mensa in the south (nearly 100^o of declination) , and from Eridanus in the east to Capricornus in the west (about 240^o of right ascension, see Figure 1).

BPMG has been the subject of frequent studies. Beta Pic itself is one of the first stars that we realized had circumstellar dust around it, presumably from the star formation process (e.g., Backman et al. 1986). As a result, Beta Pic is one of the most well-studied stars with circumstellar disks. In addition, the discovery that Beta Pic has nursery mates and that they are so close to us (Zuckerman et al. 2001) launched a scramble to identify more members of BPMG. In the context of our study, we are not attempting to conduct a comprehensive review of the literally hundreds of articles published on Beta Pic and BPMG, but we are focusing on the most recently published papers with members and their characteristics. With BPMG distributed across a large apparent area of the sky, identifying members has been difficult because one has to identify members as distinct from the millions of other stars in the sky. The most recent and comprehensive effort to identify BPMG members comes from Luhman (2024), who used Gaia DR3 data to reconstruct true space motions. He identified 193 confirmed members and rejected 24 previously suggested members. Luhman was then able to estimate the age of BPMG as $24.7^{+0.9}_{-0.6}$ Myr using a measurement of the lithium-depletion boundary (Jeffries et al. 2023) and Gaia CMDs.

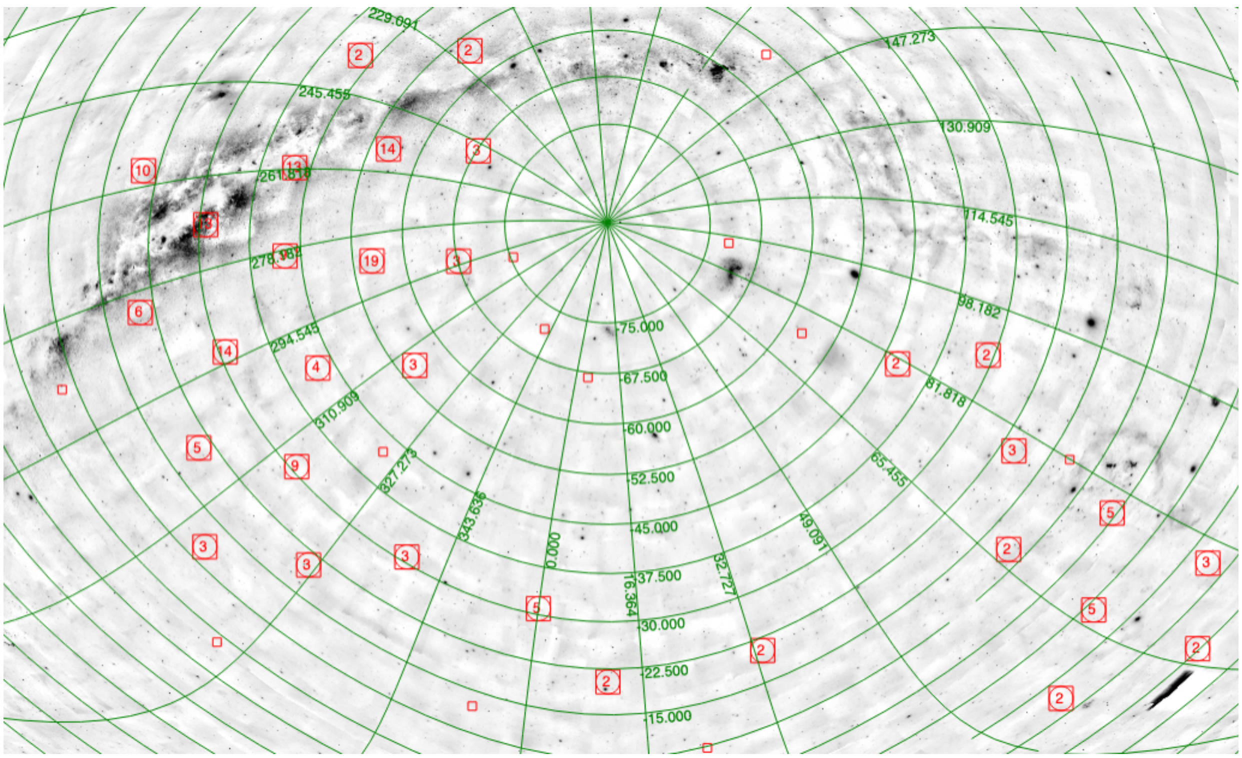

Figure 1: The Beta Pic Moving Group members, as identified by Luhman (2024), plotted on a Palomar Observatory Digitized Sky Survey Red image in reverse grayscale. The larger boxes have >1 target in that region (the enclosed numbers indicate how many targets are in that region); the green coordinates are RA/Dec in decimal degrees.

1.3 – Characteristics of Young Stars

Young stellar objects (YSOs) is a term to encompass still-forming stars at different stages of evolution, from protostars through pre-main-sequence stars approaching the main sequence, and young stars newly on the main sequence. Figure 2 shows a cross-sectional schematic view of a YSO, including the central object and the surrounding circumstellar accretion disk. Depending on their mass and evolutionary state, these stars exhibit a variety of observational signatures. These can be explained by phenomena occurring in different regions of the young stellar object (YSO), including infrared excess from warmed circumstellar dust, H-alpha (Hα) emission from accretion and magnetic activity near the star's surface, and X-rays from flares and enhanced coronal heating. Additional indicators include photometric variability due to surface activity (star spots or accretion), and elevated lithium abundance. Because lithium is easily destroyed in stellar interiors, a high lithium content indicates that the star is still young and has not yet depleted it.

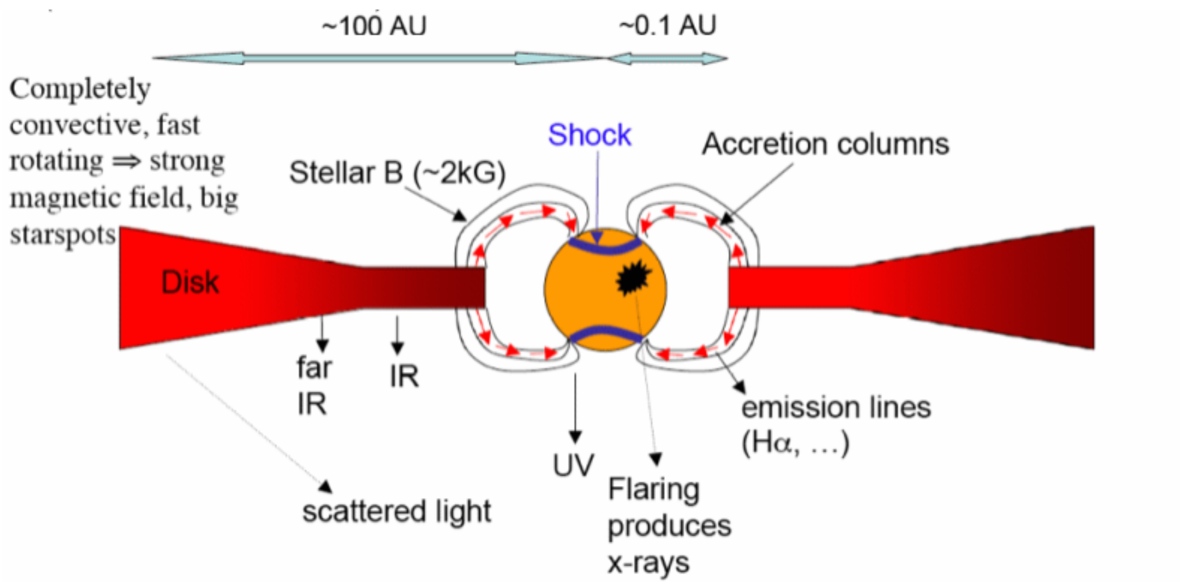

Figure 2. A cross-sectional schematic view of a YSO surrounded by an accretion disk. Infalling matter on the central object creates an H-alpha excess, while an infrared excess is emitted by the warmed dust farther out in the disk. The strong magnetic field from the YSO truncates the disk before it reaches all the way into the star, and funnels accretion onto the YSO.

IR excesses are attributed to the presence of a circumstellar disk, which can be identified with a variety of astronomical tools. SEDs plot emitted energy density as a function of wavelength. Figure 3 shows SEDs for a bare star, a star surrounded by a circumstellar disk and a star with a circumstellar ring (where there is a gap between the disk and the star). The stellar photosphere produces an SED resembling a classical blackbody curve, while a star with a disk shows an excess of infrared emission. This excess arises because dust and gas in the circumstellar disk absorb some of the star's light, become heated, and then emit their own infrared radiation which is detected in addition to that of the star. A dust ring (like a debris disk) makes a bump in the SED as shown in the bottom of Fig. 3.

Hα excesses can also be indicative of youth. Hα refers to an electron transition line of hydrogen at 656 nanometers (0.656 μm); where atoms are shocked and excited, Hα emission occurs. Stars that have a lot of flares can have an excess of Hα, so main sequence stars, particularly M stars, can emit a lot of Hα, but young stars that are rotating quickly and therefore have a lot of stellar activity also have an Hα excess. YSOs that are actively accreting from a circumstellar disk can also have an Hα excess (arising from the accretion stream when it impacts the YSO). Hα excesses can be identified via SEDs, spectra, or CMDs.

CCDs and CMDs are also used to identify IR excesses. A near-IR CCD of the stars in BPMG is shown in Figure 4; stars on the main sequence will cluster along the green line, while stars showing a NIR excess cluster around the blue dashed line (which is from Meyer et al. 1997). Reddening pushes stars up and to the right as shown. Few stars in BPMG show a NIR excess. Indeed, BPMG, at ~25 Myr, is at an age where some stars may still retain their circumstellar accretion disks (Figure 2), but most disks of this age are expected to be optically thin and will have only small Hα and IR excesses. Some stars in more mature systems may instead have debris disks around them. These stars are expected to show only a weak infrared excess from the optically thin disk and little Hα excess from accretion (though they may have an Hα excess from enhanced stellar activity such as flares). Using infrared excess from archival WISE and 2MASS data, Luhman identified 21 members of BPMG as having circumstellar disks – two with significant IR-excess consistent with primordial disks and the rest with (second-generation) debris disks (Luhman 2024).

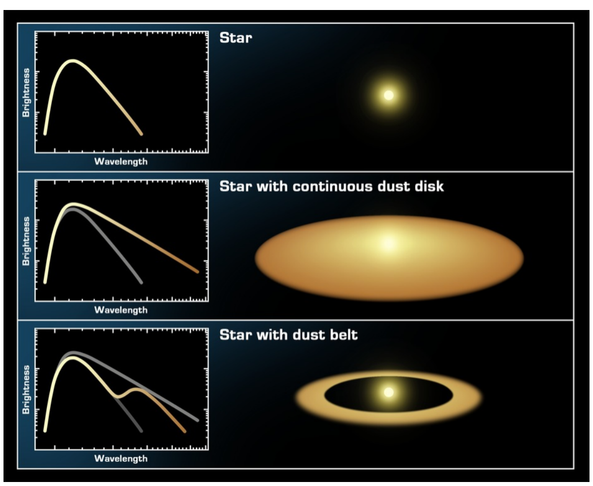

Figure 3. SEDs reveal the presence of circumstellar disks as dust in the disk is heated and radiates its own infrared signature, adding to the infrared from the central object. The top panel shows a diskless star and its near-perfect-blackbody SED. The middle panel shows a contiguous dust disk and an IR excess caused by warm dust in the circumstellar disk. The bottom panel shows an infrared excess bump in the SED caused by a dust ring. (https://www.astropix.org/archive/spitzer/sig05-026/spitzer_sig05-026_1024.jpg)

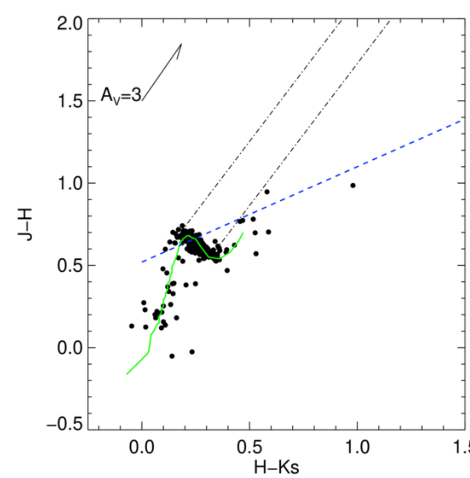

Figure 4. An example of a NIR color-color diagram constructed from 2MASS data for BPMG. The green line is the zero-age main sequence, and the blue dashed line is where stars are with such large IR excesses that the NIR is affected (few stars are like that here). A sample reddening vector is shown; reddened main sequence stars would appear between the dot-dashed lines. Most of the stars in BPMG are consistent with ZAMS colors; a few have large IR excesses and/or reddening.

1.4 Variability

A. Photometric Variability

Photometric variability in young stars arises from processes such as starspots, pulsations, accretion events, and circumstellar interactions (e.g., Li & Wang 2024). Variability has been a defining characteristic of young stars since Joy (1945), with brightness fluctuations occurring across multiple wavelengths and timescales, depending on the physical mechanism and observational sensitivity. Observed variations in brightness may range from small changes to extreme outbursts spanning several magnitudes in optical bands. Variability arises from multiple mechanisms, including but not necessarily limited to: surface flares (e.g., Vievering et al. 2019), rotational modulation from starspots (e.g., Attridge & Herbst 1992; Choi & Herbst 1996), variations in accretion rates (e.g., Kurosawa & Romanova 2013; Stauffer et al. 2014), episodic obscuration by circumstellar material (e.g., Bouvier et al. 2013), dynamical changes within the circumstellar disk (e.g., Meyer, Calvet & Hillenbrand 1997; Rodriguez et al. 2015), and matter entrained in coronal loops corotating with the star (e.g., Bouma et al. 2024), but also more ‘traditional’ origins of variability including eclipsing binaries and pulsations. The amplitude, frequency, and underlying mechanisms of this variability are closely tied to stellar mass and the presence (or absence) of a circumstellar disk. For example, higher-mass stars tend to lose their disks more quickly due to stronger radiation fields and stellar winds, while lower-mass stars retain these youth markers for longer timescales.

Variability can be more random (stochastic) or more periodic, or a mixture of the two. For stars that still have circumstellar disks, accretion-driven variability is often stochastic, arising from the disks’ instabilities, accretion streams, and clumps of material that typically introduce irregular fluctuations in brightness. Depending on the geometry, however, accretion streams between a disk and the star to which it is locked can result in periodic variability (superimposed with stochastic variations) as the streams occult the star once (or twice) per rotation period. Additionally, young stars frequently exhibit energetic flares, further contributing to short-term variability across multiple wavelengths.

For stars with or without disks, rapid stellar rotation results in large, often long-lived starspots, which regularly and periodically modulate brightness as they rotate in and out of view during the life of the starspots. This provides an effective method for determining stellar rotation periods, provided that accretion-driven or magnetically induced stochastic variability does not obscure the periodic signal.

B. Light Curves

Many astronomical surveys and space missions designed to detect variability in astrophysical sources such as transiting exoplanets, pulsating stars, and supernovae incidentally capture young star variability. Especially since transiting exoplanets produce really tiny dips (on the order of a fraction of a percent), using the same telescope and detector to monitor young stars, where the variations can be 10s of percent or more, is trivial by comparison. Extensive work has been dedicated to characterizing the variability of young stars in the modern era of large photometric datasets (e.g., Cody et al. 2014, 2022; Rebull et al. 2014, 2022). While many aspects of young-star variability are well understood, others remain open questions. Figure 5 from Cody & Hillenbrand (2018) illustrates the diversity of light curve morphologies observed in young stars, highlighting this wide range of variability patterns. Though the relative fraction of stars exhibiting each type of variability is still being studied, it appears to evolve as a function of age, disk presence, and environment.

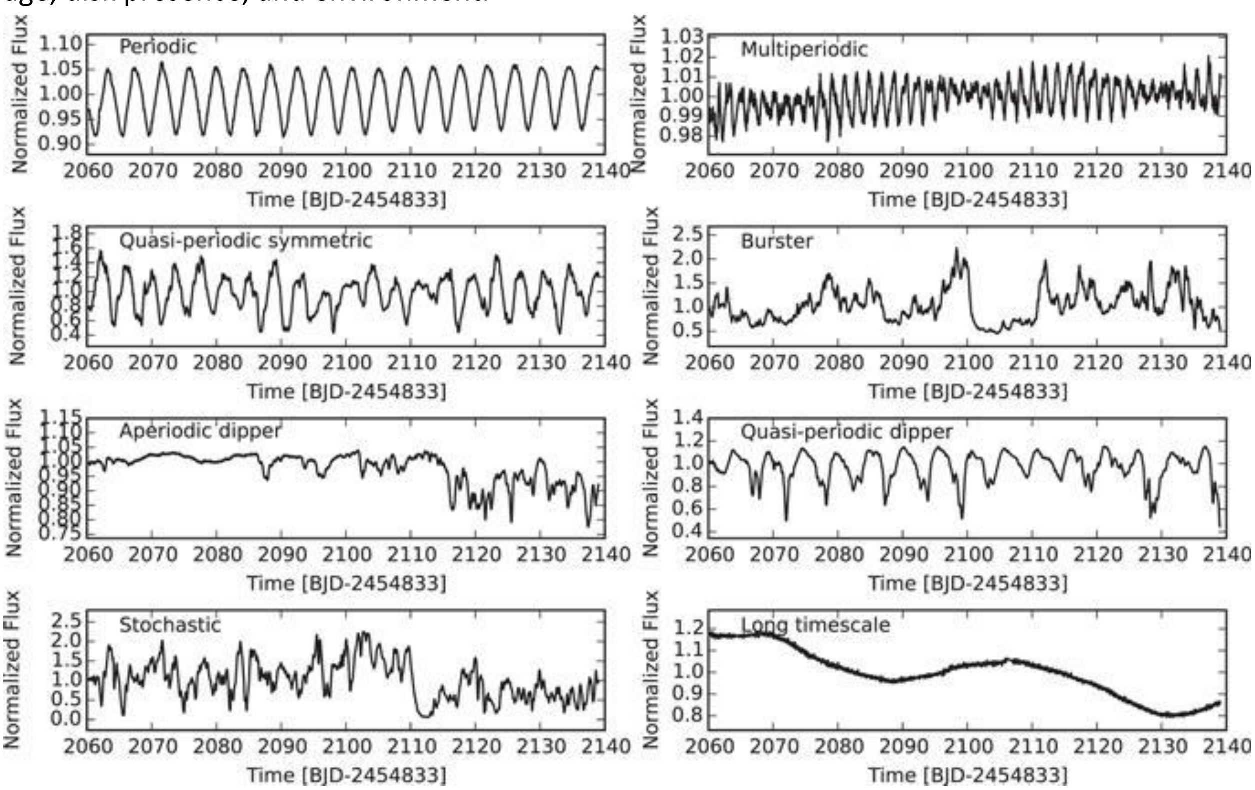

Figure 5 - Light curves characteristic of young stars from K2 observations of Taurus (*from Cody & Hillenbrand 2018*)

For disk-free young stars, the dominant variability pattern is sinusoidal (upper panels of FIgure 5), driven by rotational modulation of surface starspots. These light curves tend to be either singly-periodic, indicating a single dominant starspot or starspot group, or multi-periodic, which can result from multiple active regions or even spots on two different unresolved stars (possibly binary companions). Eclipsing binaries also often manifest in these data, though they are not represented in the Cody & Hillenbrand figure.

In contrast, stars with circumstellar disks and/or ongoing accretion exhibit significantly more complex variability. “Bursters” show rapid increases in brightness due to episodic accretion events, while “dippers” experience flux drops caused by disk material occulting the stellar surface (see, e.g., Cody et al. 2014 and references therein). Additional variability patterns are associated with magnetospheric interactions and remain an active area of study. While these accretion-related variations can obscure the periodic modulation from starspots, quasi-periodic signals are often still recoverable.

Understanding and classifying the variability patterns is far easier when using space-based (as opposed to ground-based) data because the photometric precision is typically high and the cadence is uninterrupted by daytime. The use of Transiting Exoplanets Survey Satellite (TESS; Ricker et al. 2015) data provides observations every ~30 minutes for ~30 day campaigns; K2 (the extended Kepler mission, Howell et al. 2014) had ~70 day campaigns but also observations every ~30 minutes. Ground-based surveys, in contrast, can monitor over much longer timescales; for example, the Zwicky Transient Facility (ZTF; Masci et al. 2019) has monitored the sky visible from Palomar Observatory once every few nights for years.

For BPMG, where the disk fraction (proportion of stars with circumstellar disks) is low but nonzero, we expect that most light curves will fall into the periodic or quasi-periodic categories. This expectation provides a foundation for the analysis section below, where we describe our methodology for extracting rotation periods from these light curves.

1.5 – The Evolution of Rotation Rates and Angular Momentum

Young stars inherit angular momentum from their parent molecular clouds, which themselves retain a residual rotation from the Milky Way’s galactic rotation. As these clouds collapse to form stars, their spin rates increase dramatically. If left unchecked, just due to conservation of angular momentum, this process would result in rotational velocities high enough to break apart young stars. However, observations show that while young stars rotate quickly – typically with periods under 10 days (see, e.g., Rebull et al. 2020 or Rebull et al. 2004 and references therein) – they do not reach these extreme spin rates. This suggests that angular momentum must be shed through some mechanism. Theoretical models suggest two dominant mechanisms for angular momentum loss in pre-main-sequence stars: magnetic braking via disk interactions (“disk locking”) and stellar winds.

In the disk locking paradigm, a star’s magnetic field interacts with ionized material in the inner circumstellar disk; as the star rotates, it drags its magnetic field lines through the disk.

Because the inner disk is ionized, it “sees” the field lines, which effectively slows the star’s rotation rate until it’s coupled (or “locked”) to the Keplerian velocity of the inner disk (Königl 1991; Königl & Pudritz 2000; see Figure 6). The star thus drains angular momentum out to the disk through the magnetic field and is prevented from spinning up even as it contracts in size on its way to the main sequence. Observational signatures of disk locking have been identified (Rebull et al. 2006, 2022), particularly among M-type stars with disks, where a distinct population of stars with rotation periods clustering around P ~2 days is evident in clusters such as Upper Scorpius and Upper Centaurus-Lupus/Lower Centaurus-Crux (UCL/LCC).

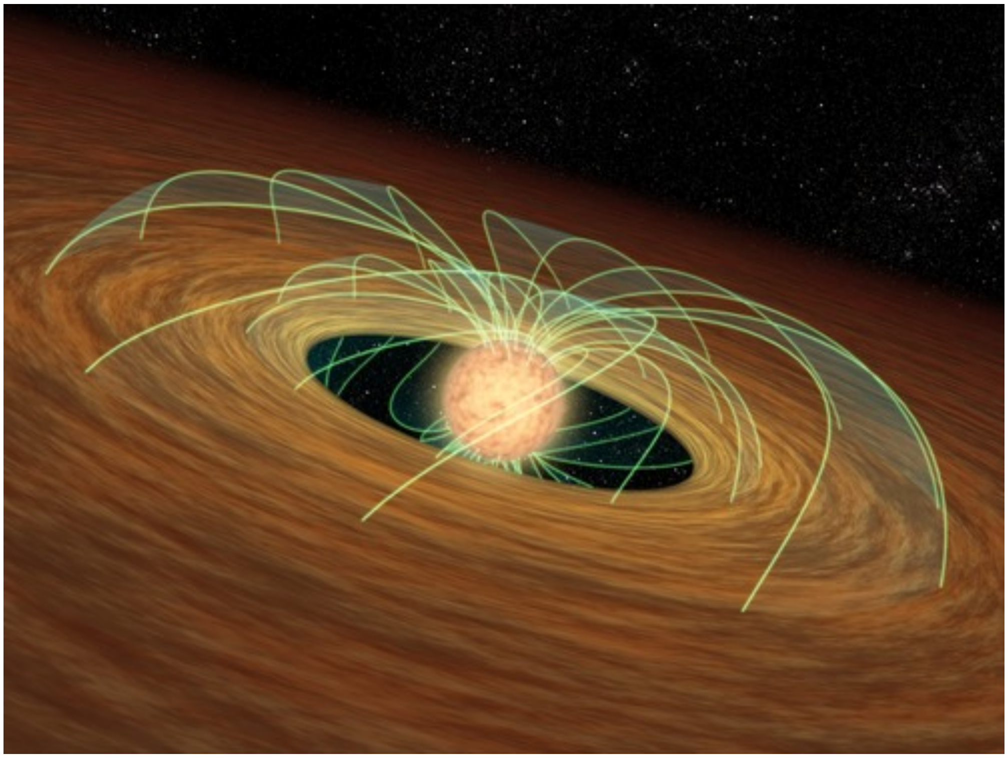

Figure 6 - A rotating star’s magnetic field lines (shown by the green lines) interact with the ionized particles within the star’s inner circumstellar disk, creating a braking force that limits the rotational speed of the star and “locks” it to the rotational speed of the inner disk. (Image: https://www.spitzer.caltech.edu/image/ssc2006-15a-stars-can-t-spin-out-of-control)

Another way to drain a star’s angular momentum is via stellar winds; this mechanism dominates in older (main sequence, disk-free) low mass stars. The magnetized stellar winds produced via the strong internal dynamos carry away angular momentum, gradually spinning them down over time (Skumanich 1972). This wind-driven spin-down occurs on timescales of ~100 million years or more, significantly longer than the typical ~10-50 Myr timescale over which circumstellar disks dissipate. Disk braking must therefore happen over short timescales; wind braking happens over long timescales.

While the overall trend of rotational evolution is broadly understood – where stars start with rapid rotation, experience disk-driven regulation, and undergo wind-driven braking on long timescales – the details of how rotation rates change as a function of both mass and age remain uncertain. This uncertainty is especially pronounced at masses corresponding to K and M spectral types, and the ages where disks are dispersing, such as in the BPMG. Advances in space-based photometric monitoring (e.g., K2 & TESS) have enabled a surge in time-series data availability, allowing for increasingly precise measurements of rotation periods in young clusters (see, e.g., Rebull et al. 2016, 2017, 2018, 2020, 2022, and in prep 2025). These studies have revealed a complex relationship between rotation, mass, and disk presence, reinforcing the importance of studying young clusters like BPMG to bridge gaps in our understanding.

Figure 7 (from Rebull et al. in prep 2025) presents rotational period distributions across nine clusters, using (V-Ks) color as a proxy for mass. The youngest clusters (<5 Myr, e.g., Rho Ophiuchus, Lagoon, Taurus) exhibit a broad distribution of rotation periods, spanning from <1 day to ~10 days, reflecting a mix of stars still experiencing accretion and disk-driven regulation. By ~8 Myr (Upper Scorpius), a distinct pile-up of disked stars at P ~2 days emerges (particularly obvious in the M stars), becoming even more pronounced at 16 Myr (UCL/LCC). This trend suggests that disk locking plays a significant role in regulating early stellar rotation. However, even after disk dispersal, some stars retain this pile-up, as seen in some of the disk-free stars in UCL/LCC, implying a possible lingering effect of disk interactions. By the age of Hyades and Praesepe (~790 Myr), the rotation period distribution settles into a tripartite shape, evidently characteristic of mature main-sequence spin-down.

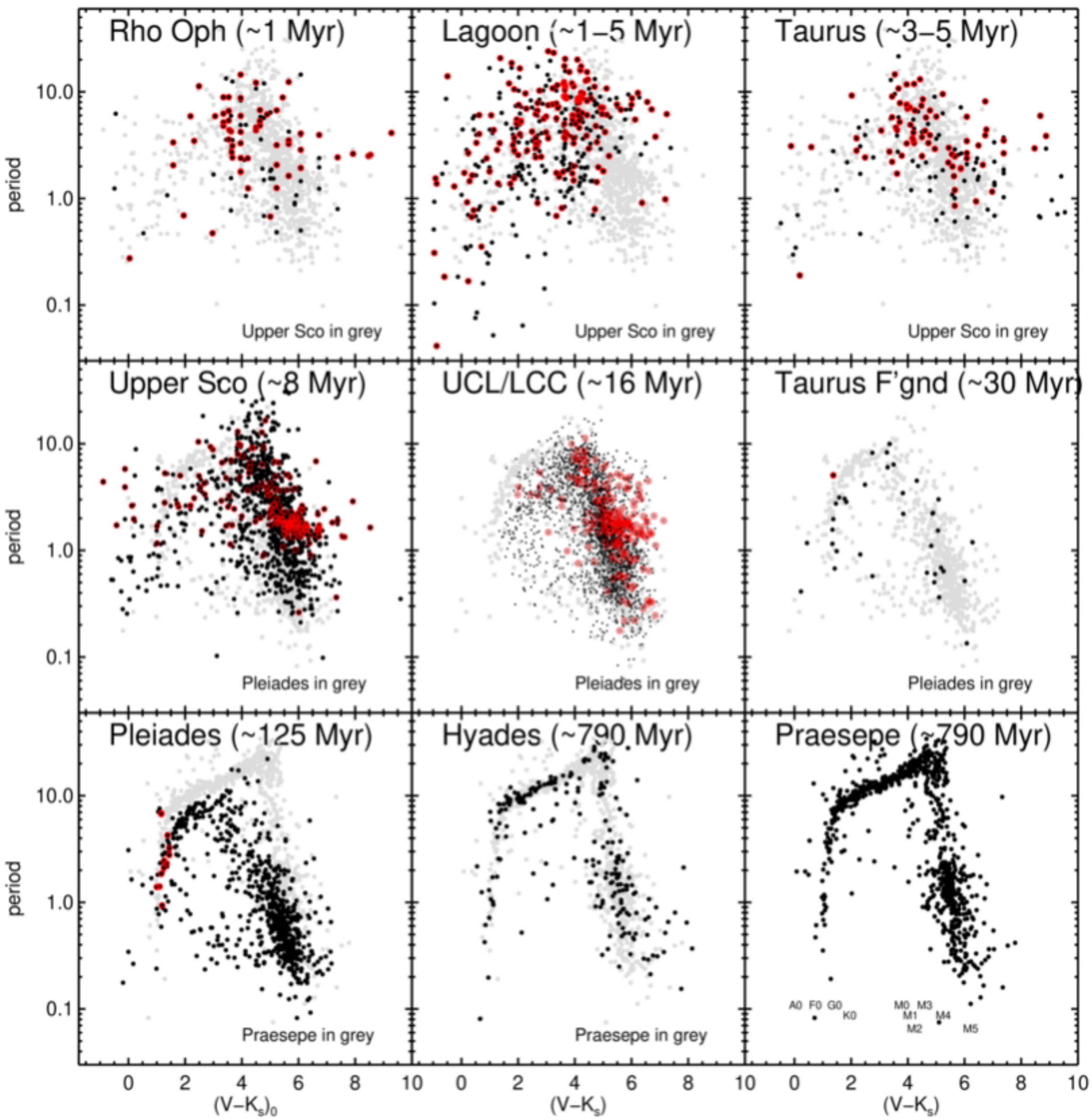

Figure 7. Plots of stellar rotation periods (in days) vs. (V-Ks) for nine clusters. Disked stars have additional red circles; the grey under plotting is the next most populous cluster, provided to guide the eye. (Rebull et al. 2025 in prep.)

BPMG, at ~25 Myr, occupies a key transition stage between UCL/LCC (~16 Myr) and the Pleiades (~125 Myr), making it an ideal test case for studying the persistence of disk-influenced rotational behavior. The small but significant disk fraction in BPMG suggests that some stars may still exhibit rotational patterns influenced by disk-locking, while others have may transitioned to a more disk-independent rotational state. Additionally, given BPMG's proximity, we expect to probe further into the cooler, later-type (K and M) regime, where rotational evolution is less constrained by previous studies. Unlike the well-sampled UCL/LCC, our BPMG dataset is smaller (a few hundred stars), meaning that while we may not produce as statistically robust a distribution, we will nonetheless provide insight into the post-disk, pre-main-sequence spin evolution of young stars.

By investigating BPMG's circumstellar disk properties and photometric variability, we aim through this study to provide new insights into the rotational evolution and stellar activity of young stars. Because Luhman (2024) has already identified 193 high-confidence BPMG members, we will start from that list. Moreover, Luhman (2024) has tabulated Li abundances and X-ray luminosities (L_x), enabling us to investigate correlations between rotation rate, Li abundance, and L_x within BPMG and put it in context with other clusters. Such correlations have been generally known for some time, but, again, the age of BPMG, and its proximity which enables us to reach down through M stars, helps constrain these relationships. For example, in the 125 Myr old Pleiades, Bouvier et al. (2018) finds that faster rotators have more Li than slower rotators, and Stauffer et al. (1994) finds that the L_x is correlated with rotation but only to a point; beyond that, L_x is independent of the rotation rate (referred to as "saturation"). Rebull et al. (2022) and references therein compare the rotation rates in the Pleiades with those from other clusters such as Upper Scorpius (~8 Myr) and UCL/LCC (~16 Myr); see Figure 7 above. With these data in BPMG, we will be able to explore all of these relationships at the BPMG age of ~25 Myr, comparing and contrasting these relationships with those found in older and younger clusters, putting BPMG in context with other clusters.

2.0 – Analysis Plan

The goal of this project is to determine the rotation periods of all BPMG members and explore the relationships between rotation period, color (as a proxy for mass), presence of circumstellar disks, and other characteristics such as L_x and Li abundance, and put these relationships in the BPMG in context with other young clusters. We will adopt Luhman's (2024) catalog of 193 BPMG members as our core sample, but will also include the 24 stars Luhman classified as non-members to explore whether their variability characteristics are consistent with BPMG stars. This yields a total sample of 217 targets for analysis. Analysis will include assembling archival multi-wavelength single-epoch photometry, identifying those with infrared excesses, assembling archival light curves, characterizing variability, and determining rotation periods where possible. We will then provide a comparison with similar young clusters.

2.1 – Assembling Multi-Wavelength Photometry

To support light curve interpretation, we will construct SEDs for all 217 targets using a broad range of archival optical and infrared datasets compiled and processed with a combination of Excel and Python. While Luhman's catalog provides baseline data from 2MASS, WISE, Gaia, and eROSITA (X-rays), we will extend this with additional single-epoch photometry from repositories that are both IRSA-hosted (DENIS, Akari, Spitzer, Herschel) and non-IRSA-hosted (Pan-STARRS, SDSS, VVV). The resulting SEDs will be used to assess potential infrared excesses from circumstellar disks, and explore whether individual targets are affected by source confusion. All sources will also be visually inspected in images across multiple bands where possible to ensure data integrity and rule out spurious sources, source confusion, or instrumental artifacts. Additionally, we will construct color-color diagrams and color-magnitude diagrams in order to place each star in context within the moving group.

2.2 – Extracting and Characterizing Light Curves

A. Investigating Rotation Periods

For time-series photometry, we will retrieve high-level science product (HLSP) light curves available in Mikulski Archive for Space Telescopes (MAST) for all BPMG candidates to avoid processing full-frame images manually. Preliminary queries suggest at least 80% of targets have one or more available light curves from TESS (deliveries from CDIPS, ELEANOR, QLP, SPOC, T16, TASOC, TGLC), K2 (deliveries from EVEREST, K2C, K2SFF, K2VARCAT) and ground-based surveys (ZTF, ASAS-SN).

Given TESS's large pixel scale (21" per pixel), we will cross-check with higher spatial resolution ground-based surveys (ZTF, ASAS-SN) to mitigate source confusion where we identify that it is likely to be a problem in the single-epoch images we assembled for the SED (section 2.1 above). While these ground-based surveys provide less precise photometry and sparser time sampling, they offer independent constraints on rotation periods (and source confusion) and classification of variability.

To determine rotation periods, we will apply Lomb-Scargle periodograms for each light curve, following the approach of Rebull et al. (2022) and references therein. Python, IDL, and Infrared Science Archive (IRSA) web-based tools will be used to perform the analysis, including pre-processing and filtering, validation of sources, and comparisons across the literature.

B. Investigating Variability

Although most BPMG members have lost their disks, some still show infrared excess, suggesting residual circumstellar material. We will investigate whether these disk-bearing stars exhibit variability patterns similar to younger clusters, such as stochastic accretion variability (bursters), periodic or quasi-periodic flux drops (dippers), quasi-periodic variability, and disk-locking signatures indicating magnetic coupling (see figure 5 above and discussion in, e.g., Cody & Hillenbrand 2018).

To assess if these light curve properties are linked to disks, we will compare the light curves of stars with IR excess to those of disk-bearing stars in other clusters. Additionally, we will cross-check light curves that exhibit disk-like features against SEDs to confirm whether they truly originate from stars with disks.

Particularly since these stars likely have relatively recently dispersed their disks, we have an opportunity to investigate whether or not the stars have had enough time to respond to the loss of their disks. For example, there is a clear pile-up of two-day periods in the disked M stars in UCL/LCC and USco. Will we find a pile-up of two-day periods in non-disked M stars in BPMG?

C. Identifying Eclipsing Binaries and Unusual Variability Signatures

BPMG provides an opportunity to identify new or confirm known eclipsing binaries (EBs) among its members. As we analyze light curves we will note any that have sharp periodic dips characteristic of EBs. We will then compare our findings with previously identified EBs to assess consistency and investigate whether any known BPMG binaries provide useful constraints on stellar parameters.

Additionally, we will search for rare and complex light curve morphologies including 'batwings,' which are distinctive light curve shapes associated with occultations of the star by matter entrained in the star's magnetic field that are found more commonly among young stars (see, e.g., Bouma et al. 2024 and references therein).

D. Examining the Non-Members Identified by Luhman

Luhman classified 24 stars as non-members based on kinematic properties, but their variability characteristics have not been explored. We will analyze whether their light curves resemble those of BPMG members or if they exhibit variability consistent with stars of different ages. This could provide additional evidence to confirm or challenge their membership status.

E. Summary

By combining rotation period measurements with variability classification, this project will provide the most comprehensive characterization of BPMG light curves to date. These findings can contribute to the understanding of angular momentum evolution at ~25 Myr and refining BPMG membership classifications. We also anticipate identifying new and unusual variability phenomena within BPMG as well as assessing the role of circumstellar disks in regulating stellar spin-down.

2.3 – Comparing BPMG to Other Young Clusters

Once we derive rotation periods for BPMG stars, we will compare their rotational behavior to find similar trends with other well-studied young clusters by incorporating our results into Figure 7 which plots rotational period vs. (V-Ks) for nine young clusters. This figure, from Rebull et al. (2016, 2017, 2018, 2020, 2022, in prep 2025), shows the evolution of rotation rates across different ages and mass regimes. BPMG (~25 Myr) will be compared to UCL/LCC (~16 Myr) where a pile-up of disked M stars near P ~2 days is evident, as well as Pleiades (~125 Myr) where most stars have lost their disks, and rotation rates exhibit a clearer bimodal or tripartite structure. These comparisons will help show trends in rotation distributions after disk dissipation, identify disk-locking signatures, and assess their impact on stellar rotation.

By placing BPMG in this broader evolutionary framework, we can assess whether its stars follow the expected rotational trend, or display deviations suggesting alternative mechanisms regulating angular momentum. Identifying such patterns helps refine models of stellar rotation evolution. This analysis will clarify the role of BPMG in bridging the gap between younger, disk-bearing clusters and older populations.

Conclusion

This project will provide new insights into the rotational evolution and variability characteristics of the young stars of Beta Pictoris Moving Group. We will leverage space-based photometry to extract rotation periods and disk-related variability. By analyzing light curves across multiple wavelengths, we aim to improve our understanding of angular momentum evolution when a star's disk dispersal nears completion and spin-rates begin to stabilize. The results of this study will contribute to broader efforts to characterize young stellar populations and inform models of pre-main-sequence evolution.

Educational/Outreach Plan

Jeff Benter

I look forward to incorporating our project into my physics and astronomy classes throughout the year. This includes having students work with authentic data as much as possible, including using radio astronomy data to search for pulsars through the Pulsar Science Collaboratory. For students especially interested in our current project, I will host a series of weekend workshops in the spring semester describing in greater detail the science and methods used. High school students who complete the series will be eligible to visit Caltech in Pasadena, California, and attend the American Astronomical Society Conference in January 2026. My students and I will also likely present our experiences to our local school boards. Additionally, as a part-time presenter at the local community college planetarium, I will incorporate information from this project into my presentations there.

Clayton Edwards

I plan to develop a long-term educational outreach initiative centered on building a more coordinated, equitable astronomy education ecosystem in Chicago. Rather than focus solely on one-time events, I seek to establish sustained collaboration among local institutions and educators through the creation of a Chicago Astronomy Education Network (CAEN). This informal alliance will support shared planning, resource exchange, and student engagement across schools and organizations like CIERA, Adler Planetarium, Yerkes Observatory, Chicago Public Schools (CPS), the Chicago Astronomical Society, and others.

In addition to launching this network, the plan includes direct outreach through educator workshops, public talks, and student-facing events such as collaborative Astronomy Nights at CPS high schools, designed to increase access to astronomy and data science for students in under-resourced communities. The ultimate goal is to foster deeper, more sustained student engagement with astronomy by strengthening the infrastructure and partnerships that support it.

Steve Jones

As a result of participation in NITARP, I plan to engage in outreach through not only my current educational institution, but through public engagement opportunities and professional development.

In my current position, I will bring the information and skills I have gained to my students in my research classes and in my astronomy classes. I will give them the tools necessary to practice conducting research on their own, increasing their confidence in their own abilities.

As a NASA/JPL Solar System Ambassador, I have the opportunity to partner with local libraries, museums, and other organizations in outreach. I will conduct public talks on our findings here, and incorporate our work into my monthly star parties.

I also would like to be involved in educator professional development. I hope to show other teachers how they can incorporate astronomy research into their classes through professional development lessons in my district, as well as at national conferences. One such conference is the annual Space Exploration Educators Conference at Space Center Houston. This conference is attended by over 500 educators from around the world every year and is the perfect audience to learn how to incorporate research into their classes.

Eden Pfahler

I plan to conduct the education outreach through developing a comprehensive analysis of the pipelines, catalogues, and tools used in this research with the goal to provide an overview of how to use and understand the materials. I plan to make it more accessible to high school students and teachers, bridging the gap that is commonly required to conduct scientific research. To do that, I'll create a template that walks through the process we used to analyze and categorize the YSOs during this project. I also want to make our pipelines and methodology open and usable by others, even those without a research background. The template will include annotations showing the steps we took, tools and websites we used, and some of the common mistakes we ran into along the way. I'll also build on previous NITARP projects and link them into my analysis to provide more context and resources.

The goal is to create and build upon previous toolkits that other schools can use to carry out similar research. By making everything transparent and easy to follow, we can help more schools contribute to science in meaningful ways. Having this available will allow students and teachers to provide real insight and support research that might otherwise be out of reach, especially for schools that haven't traditionally seen themselves as part of this world.

References

Attridge, J.M. and Herbst, W., 1992, ApJL, 398, 61

Backman, D.E., Gillett, F.C. and Low, F.J., 1986. Advances in Space Research, 6(7), pp.43-46.

Bouma, L.G., Jayaraman, R., Rappaport, S., Rebull, L.M., Hillenbrand, L.A., Winn, J.N., David-Uraz, A. and Bakos, G.Á., 2023. AJ, 167, 38.

Bouvier, J., Grankin, K., Ellerbroek, L.E., Bouy, H. and Barrado, D., 2013, A&A, 557, A77.

Bouvier, J., Barrado, D., Moraux, E., Stauffer, J., Rebull, L., Hillenbrand, L., Bayo, A., Boisse, I., Bouy, H., DiFolco, E. and Lillo-Box, J., 2018, A&A, 613, A63.

Choi, P.I. and Herbst, W., 1996, Astronomical Journal v. 111, p. 283, 111, p.283.

Cody, A.M., Hillenbrand, L.A. and Rebull, L.M., 2022, AJ, 163, 212.

Howell, S., et al., 2014, PASP, 126, 398

Jeffries R. D., Jackson R. J., Wright N. J., et al. 2023, MNRAS, 523, 802

Joy, A.H., 1945, AJ, 102, 168.

Koenigl, A., 1991. ApJL, 370, 39

Königl, A. and Pudritz, R.E., 2000. Protostars and Planets IV ed V. Mannings et al.

Kurosawa, R. and Romanova, M.M., 2013, 431, 2673.

Li, J. and Wang, T., 2024. MRAS, 532, 2683.

Luhman, K.L., 2024. AJ, 168, 159.

Masci, F.J., Laher, R.R., Rusholme, B., Shupe, D.L., Groom, S., Surace, J., Jackson, E., Monkewitz, S., Beck, R., Flynn, D. and Terek, S., 2018. PASP,, 131, 018003.

Meyer, M.R., Calvet, N. and Hillenbrand, L.A., 1997, AJ, 114, 288.

Rebull, L.M., Stauffer, J.R., Megeath, S.T., Hora, J.L. and Hartmann, L., 2006., AJ, 646, 297.

Rebull, L.M., Cody, A.M., Covey, K.R., Günther, H.M., Hillenbrand, L.A., Plavchan, P., Poppenhaeger, K., Stauffer, J.R., Wolk, S.J., Gutermuth, R. and Morales-Calderón, M., 2014, AJ, 148, 92.

Rebull, L.M., Stauffer, J.R., Bouvier, J., Cody, A.M., Hillenbrand, L.A., Soderblom, D.R., Valenti, J., Barrado, D., Bouy, H., Ciardi, D. and Pinsonneault, M., 2016, AJ, 152, 113.

Rebull, L.M., Stauffer, J.R., Hillenbrand, L.A., Cody, A.M., Bouvier, J., Soderblom, D.R., Pinsonneault, M. and Hebb, L., 2017, ApJ, 839, 92.

Rebull, L.M., Stauffer, J.R., Cody, A.M., Hillenbrand, L.A., David, T.J. and Pinsonneault, M., 2018, AJ, 155, 196.

Rebull, L.M., Stauffer, J.R., Cody, A.M., Hillenbrand, L.A., Bouvier, J., Roggero, N. and David, T.J., 2020 AJ, 159, 273.

Rebull, L.M., Stauffer, J.R., Hillenbrand, L.A., Cody, A.M., Kruse, E. and Powell, B.P., 2022 AJ, 164, 80.

Rebull, L. M. 2025. In prep.

Rodriguez, J.E., Pepper, J., Stassun, K.G., Siverd, R.J., Cargile, P., Weintraub, D.A., Beatty, T.G., Gaudi, B.S., Mamajek, E.E. and Sanchez, N.N., 2015 AJ, 150(, 32.

Ricker, G.R., Winn, J.N., Vanderspek, R., Latham, D.W., Bakos, G.Á., Bean, J.L., Berta-Thompson, Z.K., Brown, T.M., Buchhave, L., Butler, N.R. and Butler, R.P., 2015. Journal of Astronomical Telescopes, Instruments, and Systems, 1(1), 014003

Skumanich, A., 1972. ApJ, 171,565,

Stauffer, J.R., Caillault, J.P., Gagne, M., Prosser, C.F. and Hartmann, L.W., 1994. ApJS, 91, 625

Stauffer, J., Cody, A.M., Baglin, A., Alencar, S., Rebull, L., Hillenbrand, L.A., Venuti, L., Turner, N.J., Carpenter, J., Plavchan, P. and Findeisen, K., 2014, AJ, 147, 83.

Vievering, J.T., 2019. Nature of Energy Release and Transfer for Solar and Stellar Flares Using High-Sensitivity Hard X-ray Instrumentation (Doctoral dissertation, University of Minnesota)

Zuckerman, B. and Song, I., 2012, ApJ, 758, 77.