A dynamical view of star-disk interaction processes in young open clusters as seen from space

Laura Venuti

NPP Fellow, NASA Ames Research Center

Collaborators: A.M. Cody, S. Howell (NASA Ames),
L. Rebull (IPAC/Caltech), & CSI2264 team

STARRY Conference, Leeds, June 19, 2019

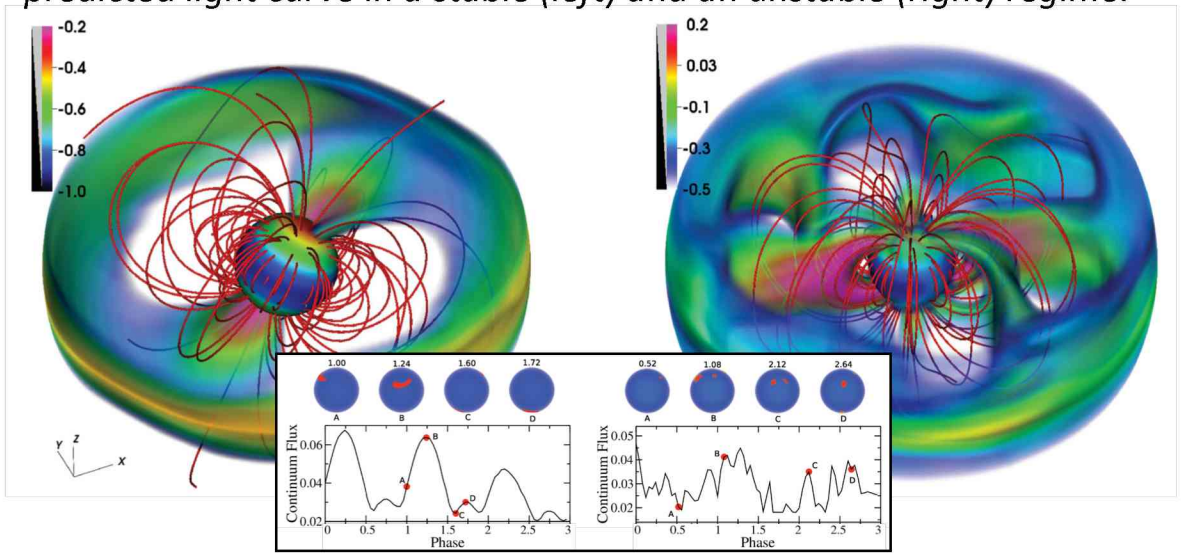
Ames Research Center

NASA POSTDOCTORAL PROGRAM Administered by USRA

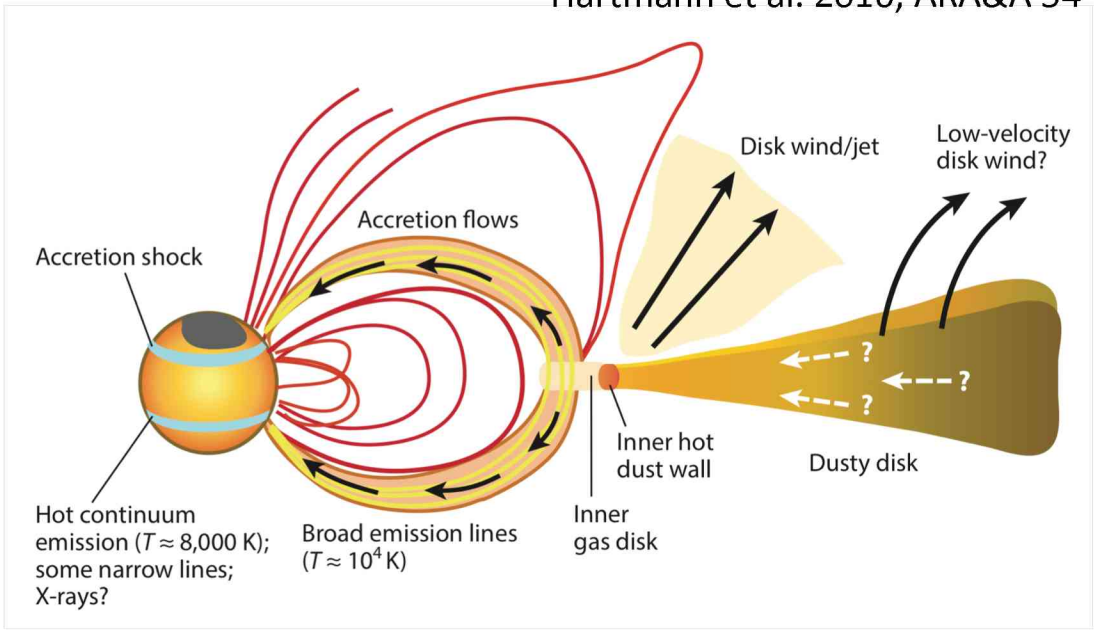
Image credits: ESO/VPHAS+ team

The variable circumstellar environment of young stars

Kurosawa & Romanova 2013, MNRAS 431: *Magnetospheric accretion and predicted light curve in a stable (left) and an unstable (right) regime.*



Hartmann et al. 2016, ARA&A 54

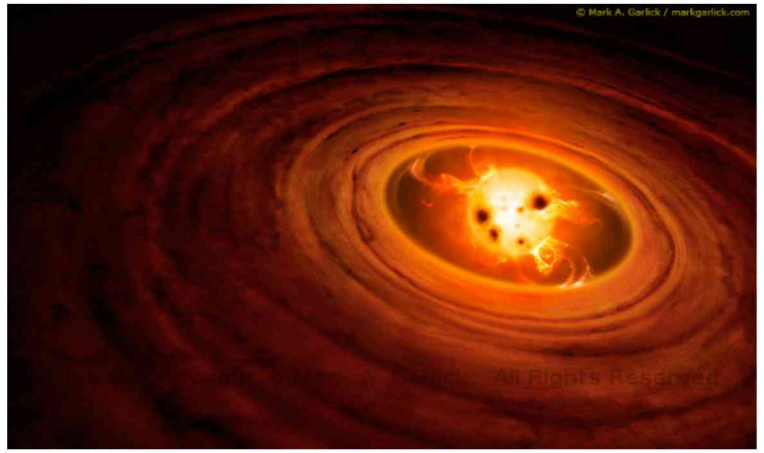


Causes for variability in young (<10 Myr) stars:

- *Magnetic activity* -> flux modulation by starspots
- *Star–disk interaction* -> variable emission from accretion shocks
- *Star–disk geometry* -> varying visibility of different features

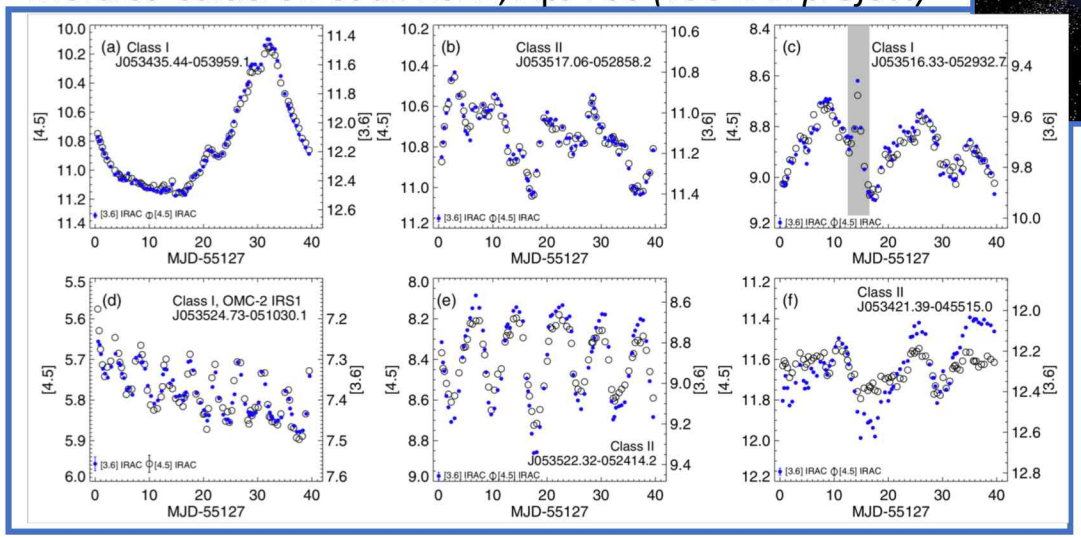
- ➢ Variability of young stellar objects (YSOs) observed at all wavelengths from X-rays to IR, on many timescales including hours to years
- ➢ Key to probing the physics of the inner AU around young stars

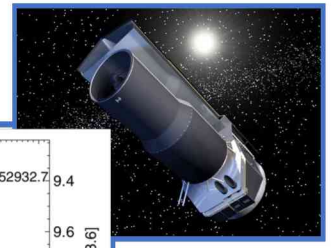
Artist's impression of a young star with disk

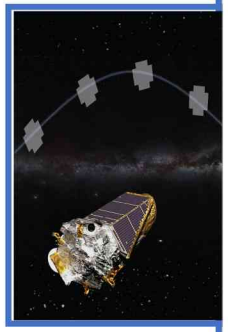


YSOs variability as revealed from space observatories

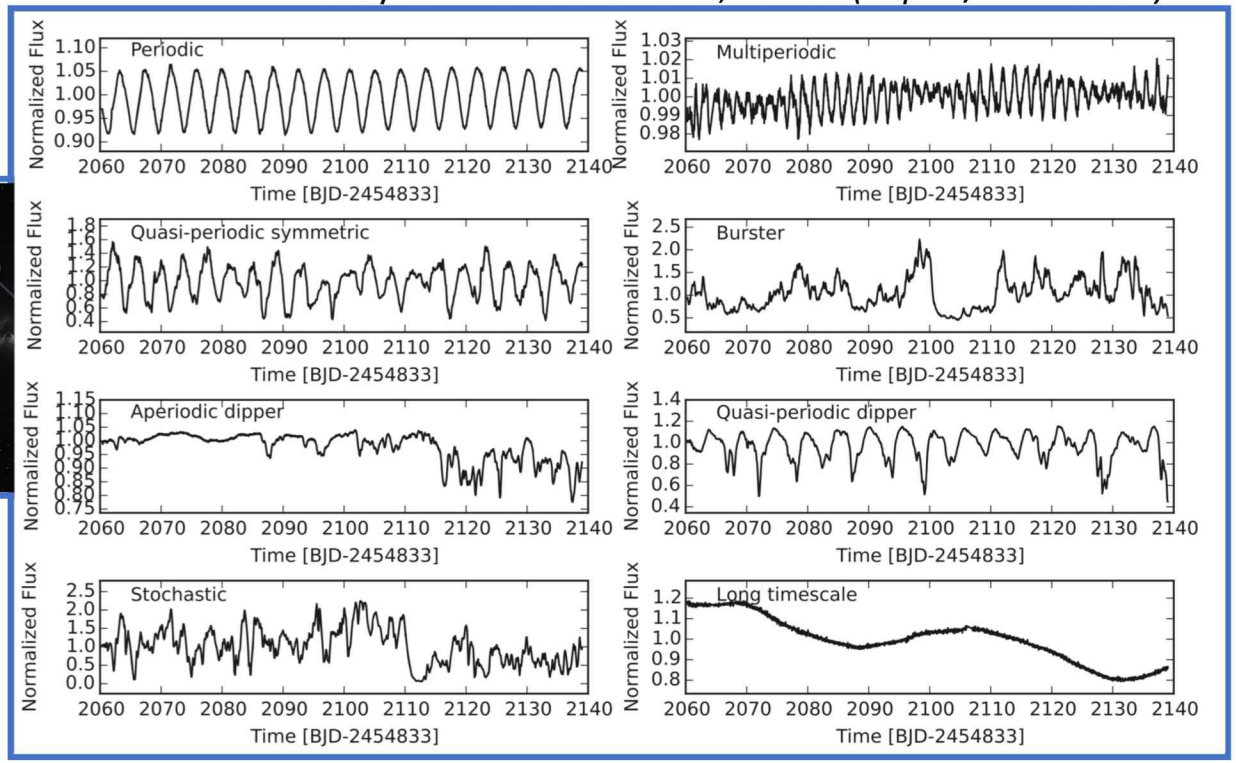
Morales-Calderón et al. 2011, ApJ 733 *(YSOVAR project)*



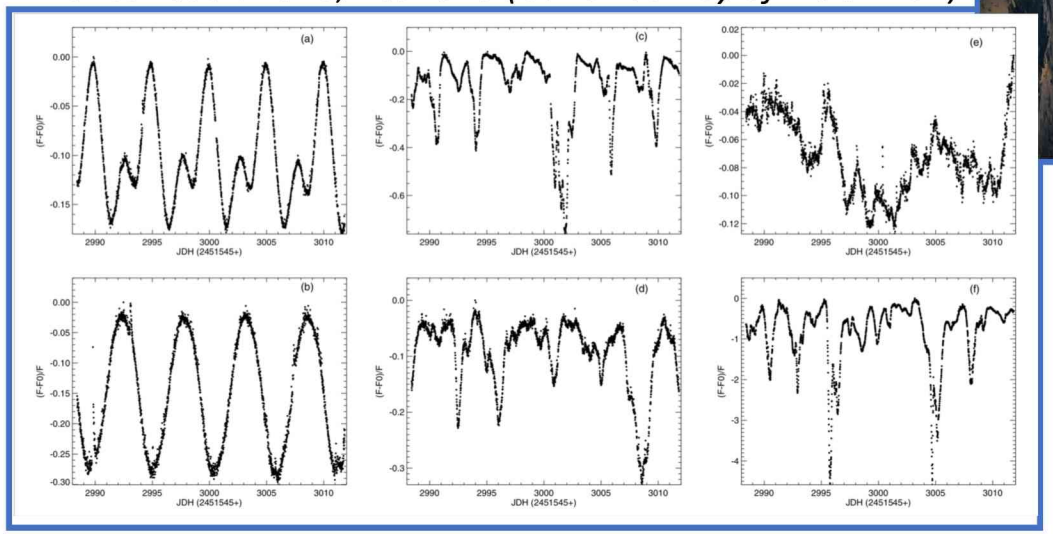




Cody & Hillenbrand 2018, AJ 156 *(Kepler/K2 mission)*



Alencar et al. 2010, A&A 519 *(CoRoT survey of NGC 2264)*



- Nearly continuous monitoring for >20 to 80 days with mmag precision
- *Resolving small-scale light curve structures and timescales associated with different variability signatures*

CSI2264: Classes of variability of young stars with disks

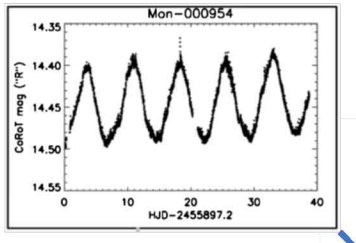
Cody et al. 2014, AJ 147

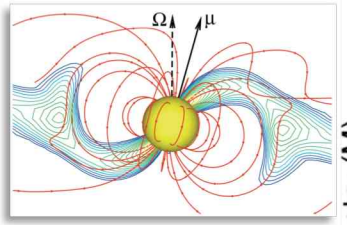
Coordinated Synoptic Investigation of NGC 2264

(PI: J. Stauffer & G. Micela; Dec. 2011- Feb. 2012)

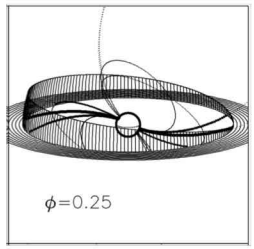
- Hundreds of young stars in NGC 2264 (3-5 Myr) monitored simultaneously from X-rays to mid-IR
- Facilities used include CoRoT (38 days), Spitzer (30 days), CFHT (14 days), VLT (20 epochs)

➢ Statistical selection of eight distinct categories of variability among young stars with disks

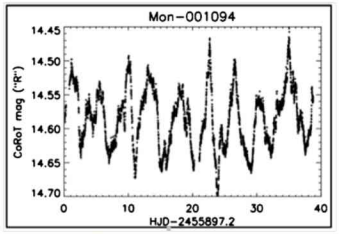


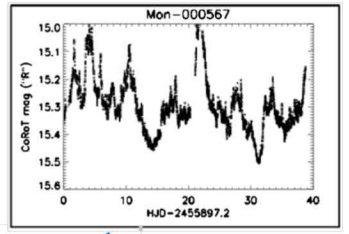


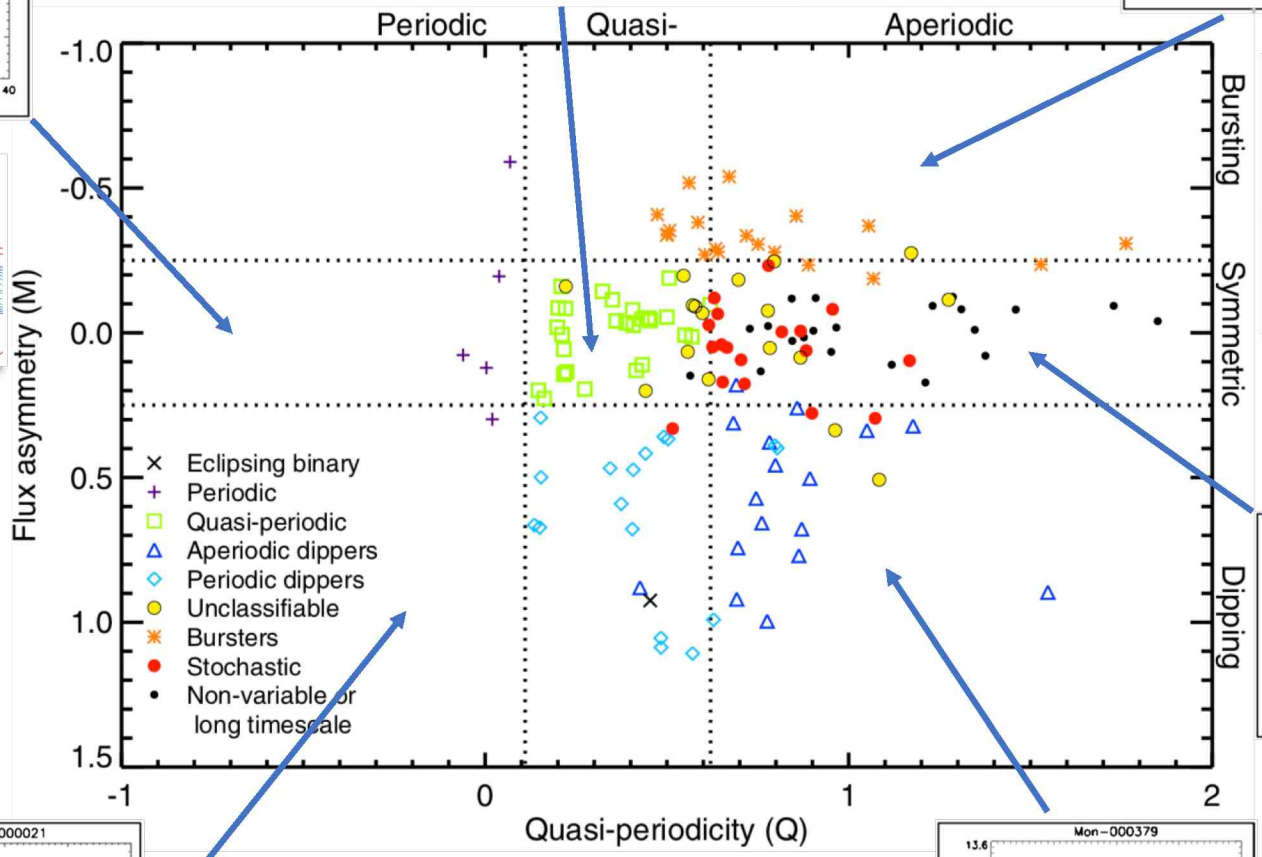
Romanova et al. 2004, ApJ 610, 920

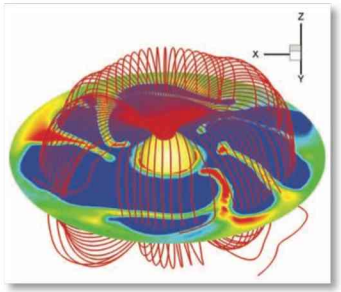


Bouvier et al. 1999, A&A 349, 619

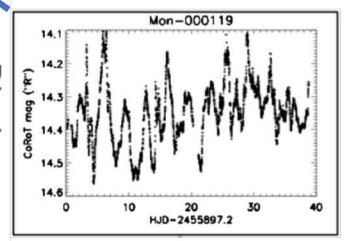


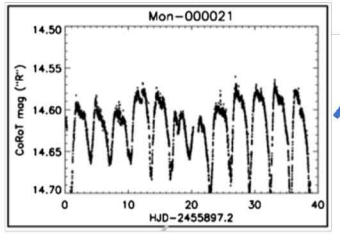


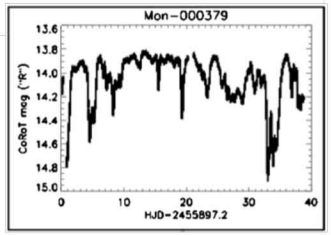




Kulkarni & Romanova 2008, MNRAS 386, 673



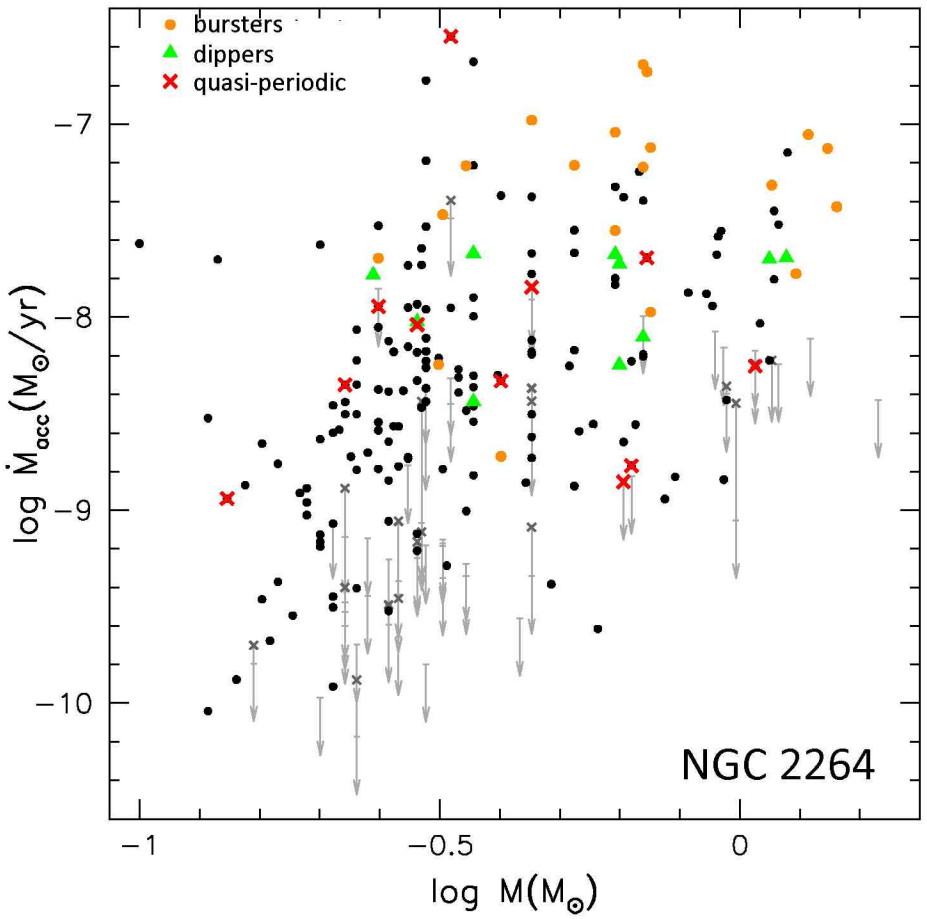




CSI2264: Link between variability and star-disk interaction

Different light curve types match predictions for distinct star-disk interaction modes:

Venuti et al. 2014, A&A 570

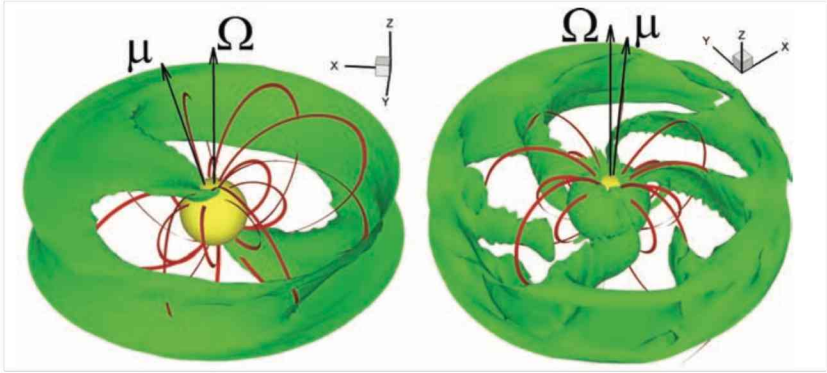


[McGinnis et al. 2015, A&A 577]

- *(quasi-)periodic/dipper* -> stable, funnel-flow accretion combined with geometric effects

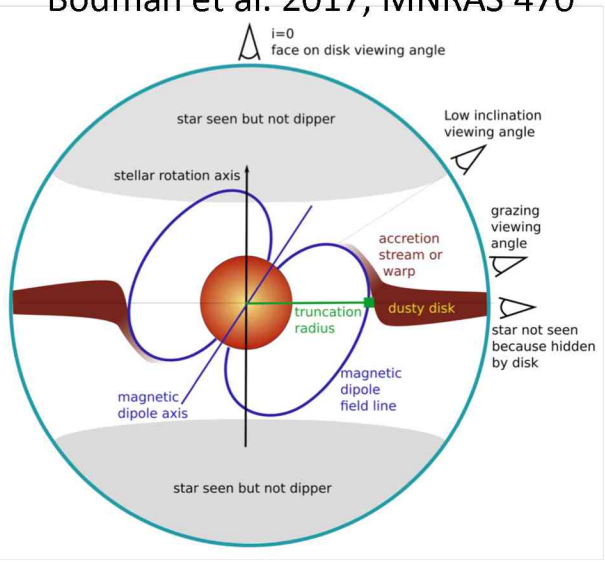
[Stauffer et al. 2014, AJ 147]

- *burster* -> unstable accretion proceeding in intense, short-lived bursts

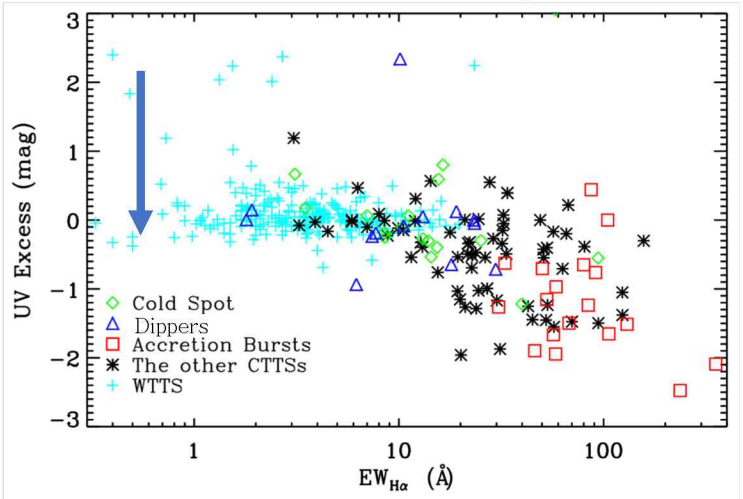


Kulkarni & Romanova 2008, MNRAS 386

Bodman et al. 2017, MNRAS 470

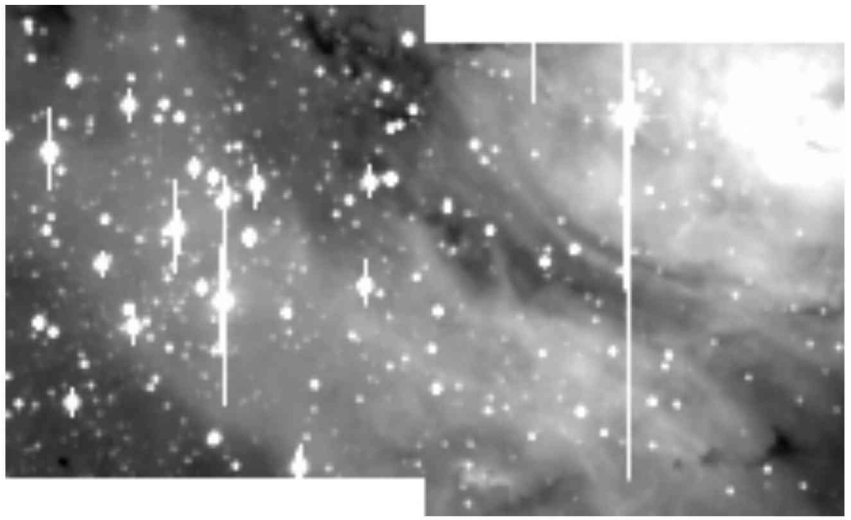


Sousa et al. 2016, A&A 586



The Lagoon Nebula region: probing younger and more massive environments

- Contains the few Myr-old open cluster NGC 6530 (*d = 1325 pc; age ~ 2 Myr*)
- Census from photometric surveys (IR, UV, X-rays), spectroscopy (Hα), astrometry (Gaia)
  (e.g., Sung et al. 2010; Kumar & Anandarao 2010; Getman et al. 2014; Wright et al. 2019)
- Estimated PMS population of 2500 – 3000 stars (Damiani et al. 2019; L. Rebull, priv. comm.)
- Disk fraction ~50% (Prisinzano et al. 2007, 2019)
- Numerous OB population (60-70)



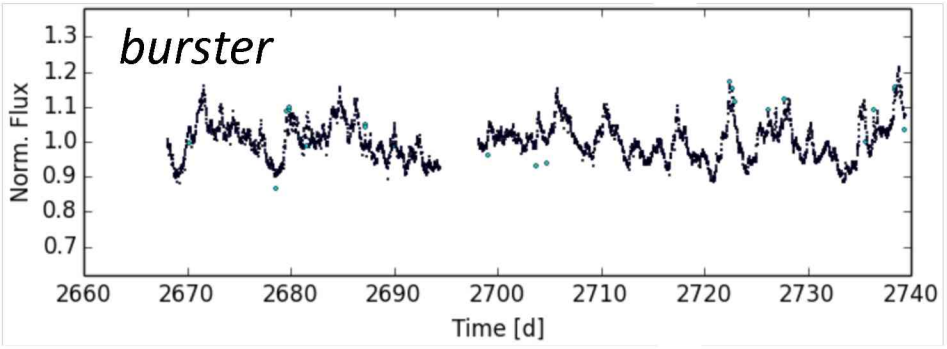
Kepler/K2 Campaign 9:

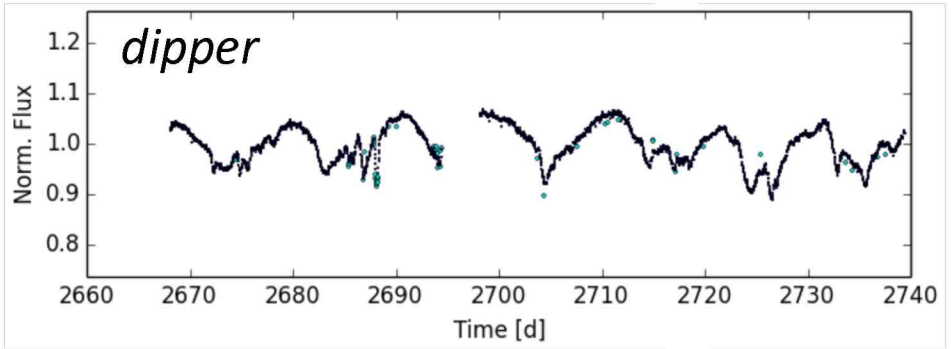
- 80-day monitoring for >500 cluster members
- Light curves already extracted for 323 stars
- Projected completeness limit ~SpT=M0

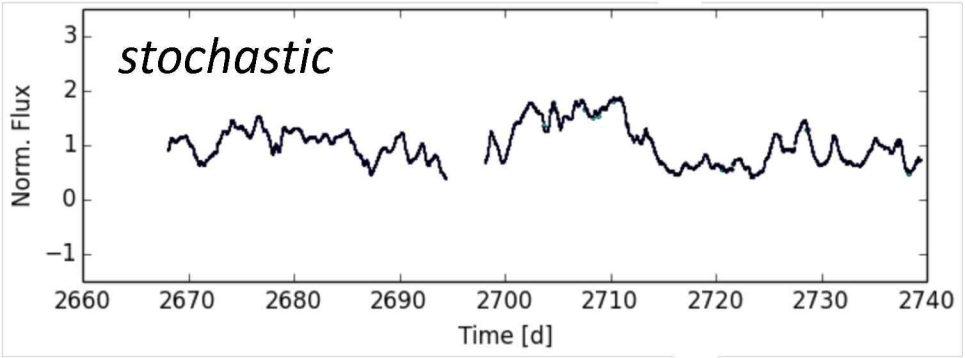
Auxiliary observations:

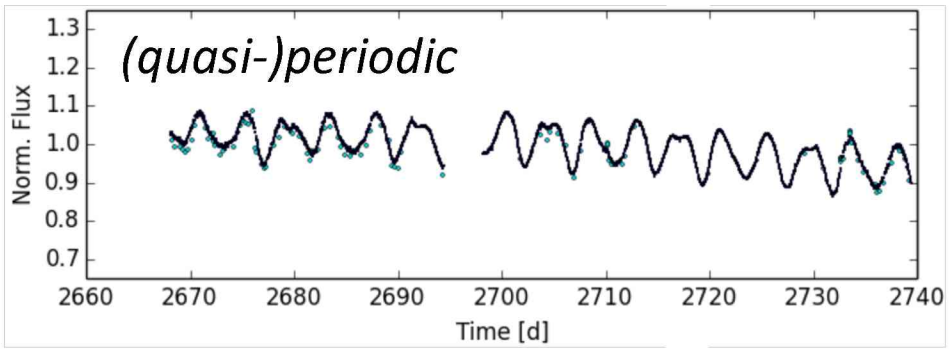
- u,g,r,i,Hα light curves with the VLT Survey Telescope (OmegaCam)
- Hα spectra series with VLT/FLAMES
- Spitzer/IRAC 3.6+4.5 μm monitoring
- Gemini/DSSI+Zorro speckle imaging data to detect companions

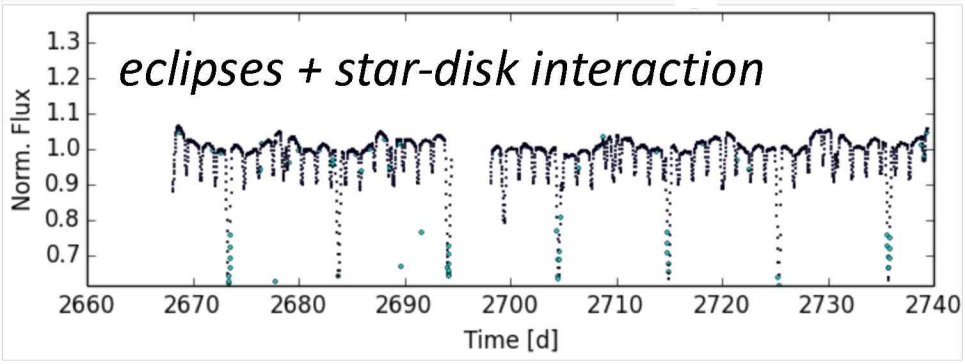
Time behavior of disk-bearing stars in the Lagoon Nebula

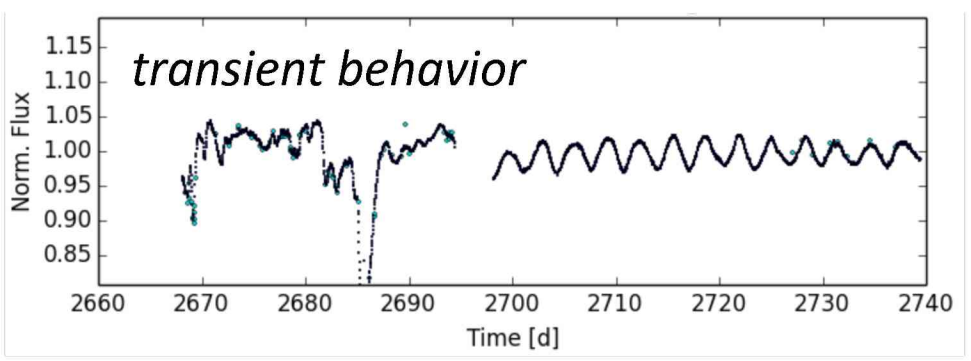












Current sample:

- 118 stars with disk/accretion signatures
- SpT~B1–M0

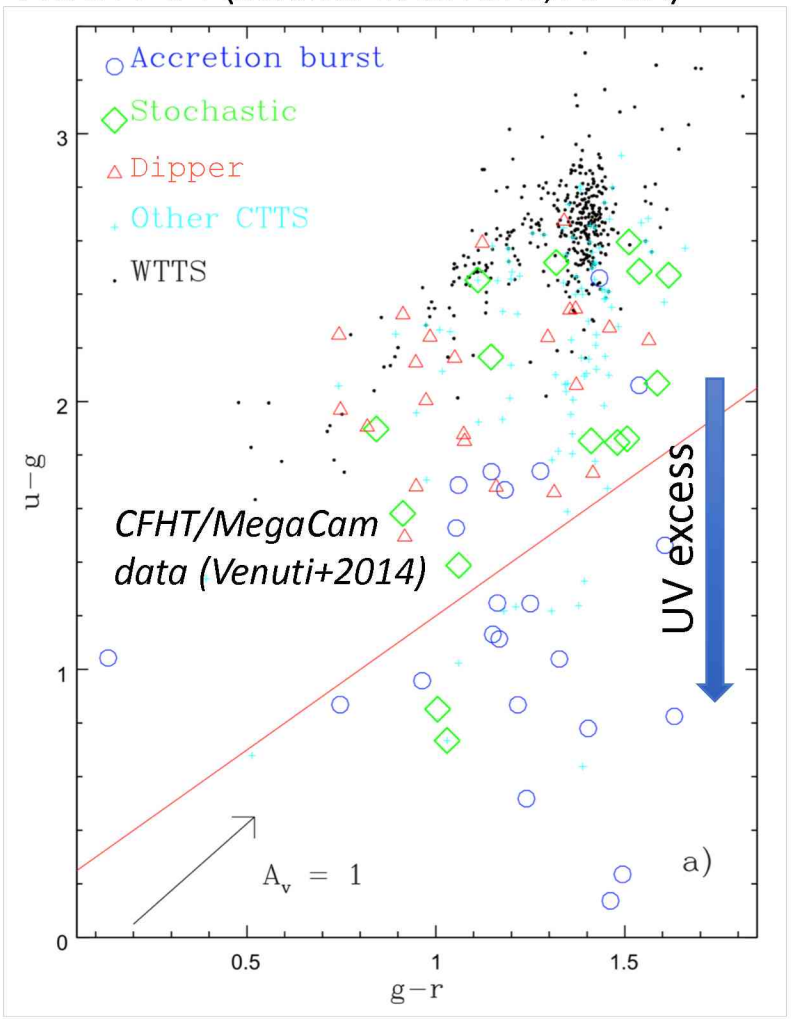
Preliminary occurrence rates of different classes of variability:

- bursters -> 7%
- stochastics -> 11%
- dippers -> 11%
- (multi-)periodic -> 15%
- quasi-periodic -> 27%
- non-classified -> 29%

Variability behavior vs. color properties

Results from previous surveys

NGC 2264 (Stauffer et al. 2016, AJ 151)



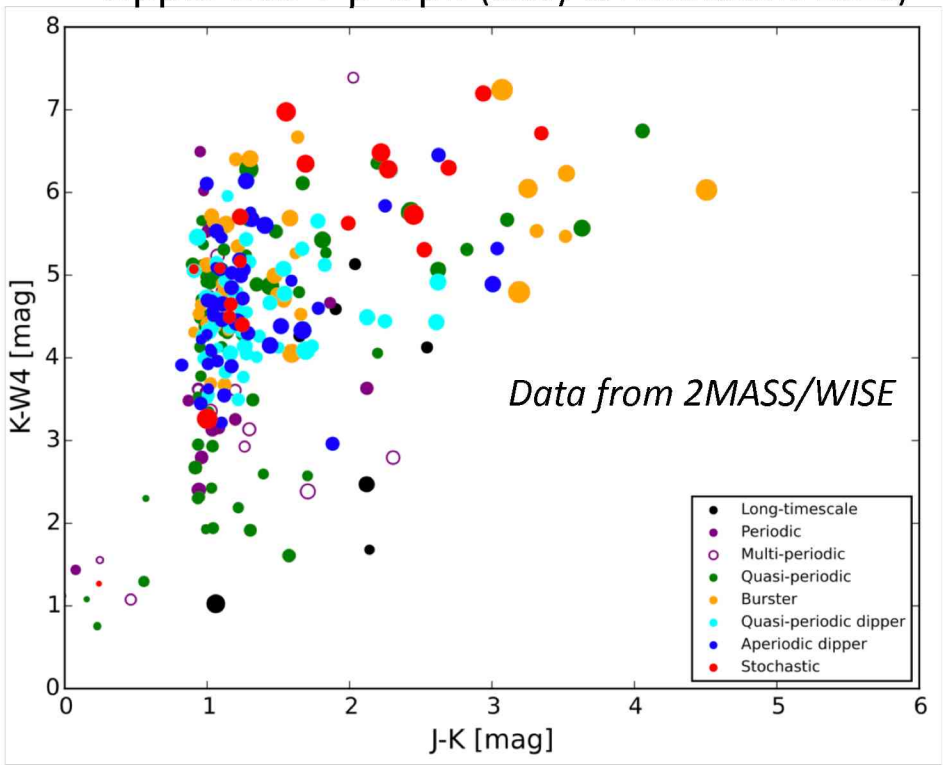
NGC 2264 data from CSI2264

- Light curve class from CoRoT
- Optical colors trace the photospheric emission
- UV excess above photospheric level characteristic of accretors

Upper Sco + ρ Oph data

- Light curves from *Kepler/K2* Campaign 2
- J-K and K-W4 colors trace the emission from different locations within the disk

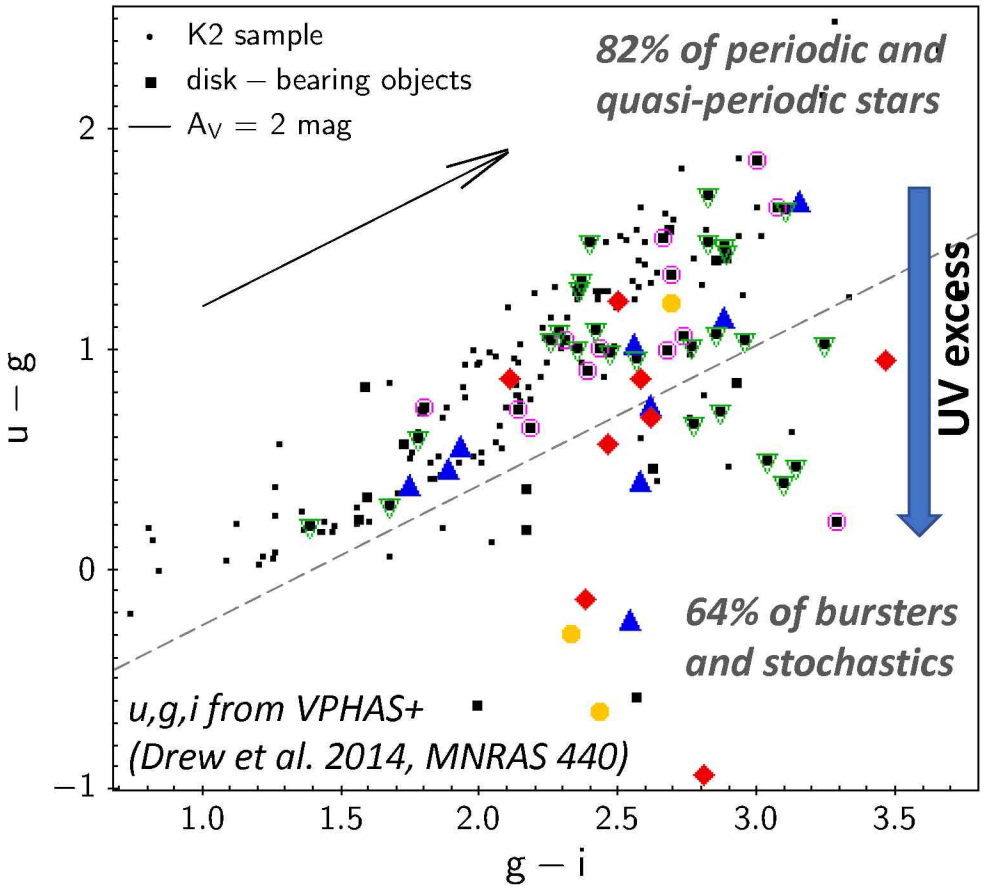
Upper Sco + ρ Oph (Cody & Hillenbrand 2018)

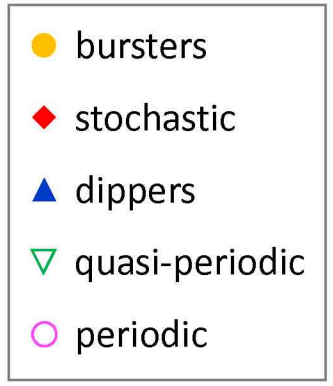


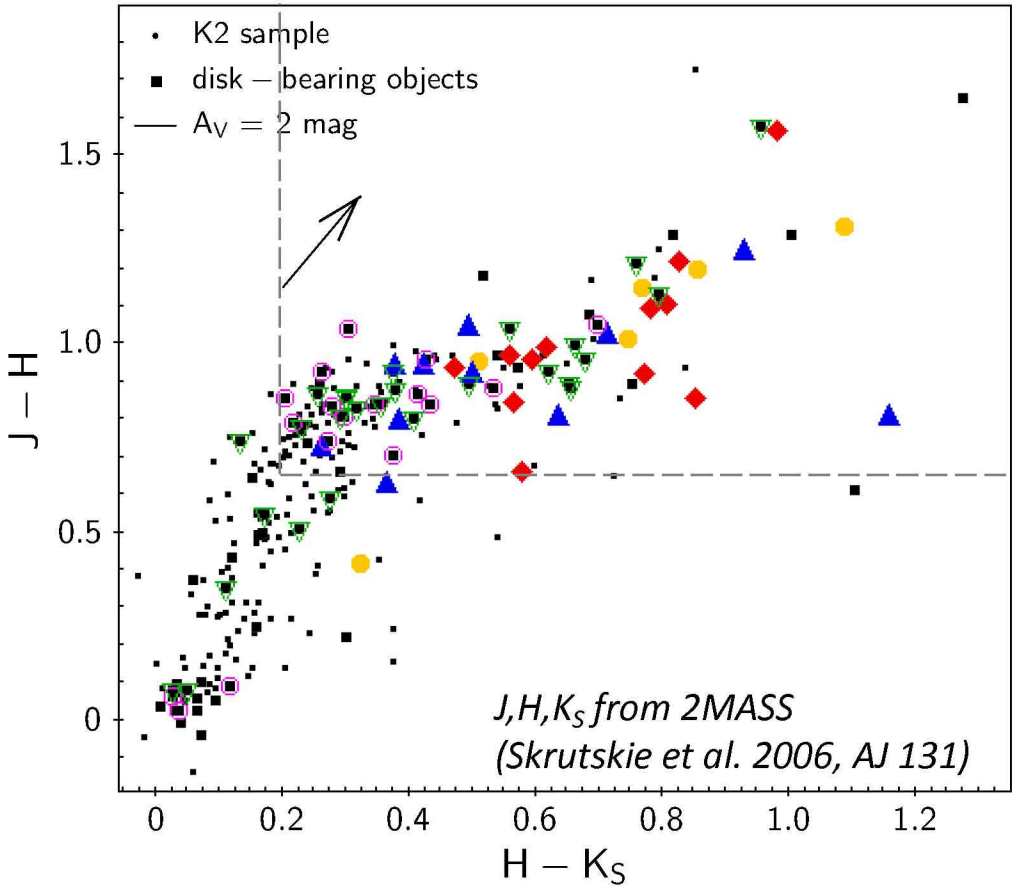
- Bursting behavior associated with strong accretion and disk signatures
- Dipping and stochastic behaviors associated with more moderate UV excess but redder infrared colors than spot-dominated objects

Variability behavior vs. color properties

The Lagoon Nebula case: preliminary results







- Objects with irregular light curves more likely to be found at large UV excesses, and with larger IR excesses than other types of disk-bearing variables
- Periodic variables more likely to be found along the color locus of young stars without disks

Time behavior of young stars with disks: a global view

Cody & Hillenbrand 2018

Morphology class	Oph [1-3 Myr] (%)	Sco [5-10 Myr] (%)	Sco/Oph composite (%)	NGC 2264 [3-5 Myr] (%)	Lagoon Nebula [2 Myr]
Categories based on periodicity and stochasticity					
All Bursters	14^{+5}_{-3}	13^{+3}_{-2}	14^{+2}_{-2}	13^{+3}_{-2}	7%
Aperiodic-symmetric (stochastic)	12^{+4}_{-3}	6^{+2}_{-1}	8^{+2}_{-2}	13^{+3}_{-2}	11%
Quasi-periodic symmetric	20^{+5}_{-4}	29^{+3}_{-3}	26^{+3}_{-2}	17 ± 3	27%
Aperiodic dippers	9^{+5}_{-2}	18^{+3}_{-2}	16^{+2}_{-2}	11^{+3}_{-2}	11%
Quasi-periodic dippers	14^{+5}_{-3}	18^{+3}_{-2}	17^{+2}_{-2}	10.5^{+3}_{-2}	
Periodic symmetric	6^{+4}_{-2}	7^{+2}_{-2}	7^{+1}_{-2}	3^{+2}_{-1}	15%
Other Categories					
Multiperiodic	7^{+4}_{-2}	4^{+2}_{-1}	5^{+2}_{-1}	1^{+2}_{-1}	
Long timescale	8^{+4}_{-2}	0^{+2}_{-0}	3^{+1}_{-1}	1^{+2}_{-1}	
Unclassifiable	2^{+3}_{-0}	0^{+2}_{-0}	1^{+1}_{-1}	11^{+3}_{-2}	29%
Non-variable	6^{+4}_{-2}	3^{+2}_{-1}	4^{+1}_{-1}	19 ± 3	

Frequency of variability classes in:

- ρ Ophiuchi (*K2* Campaign 2)
- Upper Scorpius (*K2* Campaign 2)
- NGC 2264 (*CoRoT* campaign)
- Lagoon Nebula (*K2* Campaign 9; preliminary)

- Around 50% of disk-bearing stars exhibit periodic patterns detected from months-long monitoring campaigns
  - ↳ *dynamic changes in the inner disk region over several rotational cycles*
- Similar fractions of objects found from different clusters in several categories
- Any dependence on:
  - stellar mass?
  - age?
  - environment?
  - stellar multiplicity?

Conclusions

- Space-based monitoring of young stars reveals the structure and characteristic timescales of the inner circumstellar environment, not accessible to direct imaging
- Coordinated campaigns provide key photometric and spectroscopic diagnostics to understand the physical origin of the observed variability features
- Different regimes of disk accretion, stable or unstable, translate to distinct photometric signatures, with a prevalence of repeated modulation features or bursting behavior
- Dipper stars trace dynamic changes in the inner disk dusty structures
- Around 50% of stars with disks exhibit periodic photometric variations over baselines of several months, corresponding to a few tens of rotational cycles
  - Ongoing investigations to probe the impact of stellar mass, age, environmental conditions and stellar companions on the dynamics of star-disk interaction among the young clusters surveyed with *Kepler/K2* (Lagoon Nebula, ρ Oph, Taurus, Upper Sco)

Thank you!