A Dynamical View of Star-disk Interaction Processes in the Lagoon Nebula with Kepler/K2

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Image credits: ESO/VPHAS+ team
The Lagoon Nebula cluster

- Complex HII region and star-forming site (Tothill 2008)
- Contains the few Myr-old open cluster NGC 6530 ($d = 1325 \text{ pc}; \text{age} \sim 2 \text{ Myr}$)
- Census from photometric surveys (IR, UV, X-rays), spectroscopy (H$\alpha$), astrometry (Gaia)
- Estimated PMS population of 2500 – 3000 stars (Damiani et al. 2019)
- Disk fraction $\sim$50% (Prisinzano et al. 2007, 2019)
- Numerous OB population (60 – 70 objects)

Image credits: NASA, ESA, STScI
The Lagoon Nebula cluster: observations

- **K2 Campaign 9 observations:**
  - light curves extracted for 323 confirmed members;
  - hundreds of potential additional members in the “superstamp” region
    (Cody et al. 2018)

- **Auxiliary observations:**
  - u,g,r,i,Hα light curves with the VLT Survey Telescope (VST/OmegaCam)
    [17 epochs distributed over 3.5 weeks, simultaneous with K2]
  - Hα spectral time series with VLT/FLAMES [17 epochs, simultaneous with K2]
  - Spitzer/IRAC 3.6 μm and 4.5 μm monitoring [17 days, simultaneous with K2]
  - Gemini/DSSI speckle imaging acquired so far for 78 members
The K2 sample in the Lagoon

- Current K2 sample of PMS stars in the Lagoon Nebula: 323 (118 with disks, 205 without disks)
- As many additional objects identified in superstamp region (extraction in progress)
- Current spectral type coverage down to M0-M1
- Projected completeness limit ~M0

Gray histogram from data in Damiani et al. (2019)
Time behavior of young stars with disks in the Lagoon Nebula

- **burster**
- **dipper**
- **stochastic**
- **(quasi-)periodic**
- **eclipses + star-disk interaction**
- **transient behavior**
Time behavior of young stars with disks in the Lagoon Nebula

Preliminary rates of occurrence of different variability types:

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

Compared to:
- ρ Ophiuchi (K2 Campaign 2)
- Upper Scorpius (K2 Campaign 2)
- NGC 2264 (CoRoT campaign)

[Codi & Hillenbrand (2018)]

<table>
<thead>
<tr>
<th>Morphology class</th>
<th>Oph [1-3 Myr]</th>
<th>Sco [5-10 Myr]</th>
<th>Sco/Oph composite (%)</th>
<th>NGC 2264 [3-5 Myr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Bursters</td>
<td>$14^{+5}_{-3}$</td>
<td>$13^{+3}_{-2}$</td>
<td>$14^{+2}_{-2}$</td>
<td>$13^{+3}_{-2}$</td>
</tr>
<tr>
<td>Aperiodic-symmetric</td>
<td>$12^{+4}_{-3}$</td>
<td>$6^{+2}_{-1}$</td>
<td>$8^{+2}_{-2}$</td>
<td>$13^{+3}_{-2}$</td>
</tr>
<tr>
<td>(stochastic)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quasi-periodic symmetric</td>
<td>$20^{+3}_{-4}$</td>
<td>$29^{+3}_{-3}$</td>
<td>$26^{+2}_{-2}$</td>
<td>$17 \pm 3$</td>
</tr>
<tr>
<td>Aperiodic dippers</td>
<td>$9^{+5}_{-3}$</td>
<td>$18^{+1}_{-2}$</td>
<td>$16^{+2}_{-2}$</td>
<td>$11^{+3}_{-2}$</td>
</tr>
<tr>
<td>Quasi-periodic dippers</td>
<td>$14^{+5}_{-3}$</td>
<td>$18^{+3}_{-2}$</td>
<td>$17^{+2}_{-2}$</td>
<td>$10.5^{+3}_{-2}$</td>
</tr>
<tr>
<td>Periodic symmetric</td>
<td>$6^{+2}_{-2}$</td>
<td>$7^{+2}_{-2}$</td>
<td>$7^{+1}_{-1}$</td>
<td>$3^{+4}_{-1}$</td>
</tr>
</tbody>
</table>

Other Categories

| Multiperiodic              | $7^{+4}_{-2}$  | $4^{+2}_{-1}$  | $5^{+2}_{-1}$         | $1^{+2}_{-1}$     |
| Long timescale             | $8^{+2}_{-2}$  | $0^{+0}_{-2}$  | $3^{+1}_{-1}$         | $1^{+1}_{-1}$     |
| Unclassifiable             | $2^{+3}_{-0}$  | $0^{+2}_{-0}$  | $1^{+1}_{-1}$         | $11^{+3}_{-2}$    |
| Non-variable               | $6^{+4}_{-2}$  | $3^{+2}_{-1}$  | $4^{+1}_{-1}$         | $19 \pm 3$       |
Link between variability behavior and star-disk interaction

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

[McGinnis et al. 2015]
- (quasi-)periodic/dipper -> stable, funnel-flow accretion combined with geometric effects

[Stauffer et al. 2014, 2016]
- burster/stochastic -> unstable accretion proceeding in intense, short-lived bursts

[see also the cases of ρ Oph and Upper Sco, A.M. Cody’s talk]
Link between variability behavior and star-disk interaction: the Lagoon case

- Optical colors trace the photospheric emission
- Excess emission above the photospheric level, prominent in the UV, is characteristic of accretors

Preliminary indications:
- Objects with irregular light curves more likely to be found at large UV excesses (64% below the dashed threshold)
- Periodic variables more likely to be found along the color locus of young stars without disks (82% above the threshold)

\[ u, g, i \text{ photometry from VPHAS+ (Drew et al. 2014)} \]
Link between variability behavior and star-disk interaction: the Lagoon case

- Near-infrared colors trace the presence of dust in the innermost regions of the circumstellar disk

Preliminary indications:

- Objects with irregular light curves tend to exhibit larger IR excesses than other types of disk-bearing stars
- Periodic variables tend to exhibit IR colors closer to the photospheric emission level traced by disk-free objects

\( J, H, K_S \) photometry from the 2MASS survey (Skrutskie et al. 2006)
Summary and future steps

- The Lagoon Nebula offers a very young, rich population in a crowded environment with tens of massive objects

  *key to probe the impact of stellar mass, multiplicity, and environment on the dynamics of star-disk evolution*

- The K2 light curves reveal a variety of photometric behaviors, possibly connected with distinct scenarios of star-disk interaction and different properties of the circumstellar environment

**Next steps:**
- colors signatures associated with the brightness variations
- variability type as a function of stellar mass/spectral type
- variability type in relation to binarity

Thank you