Accretion Bursts Are Common in Class 0 Protostars

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See Zakri et al. (2022, ApJL, 924, L23)

I. Overview

- Accretion-driven luminosity bursts can address key questions in star formation (see Chapter 10 of the PP VII book, by Fischer et al.):
  - What fraction of a star's mass is accreted during bursts?
  - How do bursts impact outflows and envelope clearing?
  - How do bursts influence planet formation?

  Answers require better statistics for burst rates and amplitudes.
- To investigate the role of protostellar accretion bursts in star and planet formation, we analyzed time-domain photometry of 319 protostars (92 in Class 0) that were characterized by the Herschel Orion Protostar Survey (HOPS) with 2MASS, Spitzer, Herschel, and APEX (Furlan et al. 2016)
- Multi-epoch Spitzer/IRAC maps from 2004 to 2019 revealed three Class 0 bursts of ≥ 2 mag
- WISE and NEOWISE data trace variability during the bursts, while SOFIA, Spitzer/MIPS, and Herschel data allow the measurement of burst amplitudes
- Statistically, each Class 0 protostar is expected to burst every ~ 400 yr. This may be the main mode of mass accretion during the 150,000 yr Class 0 phase.

II. Spitzer Search for Outbursts

Four epochs of Spitzer/IRAC data:

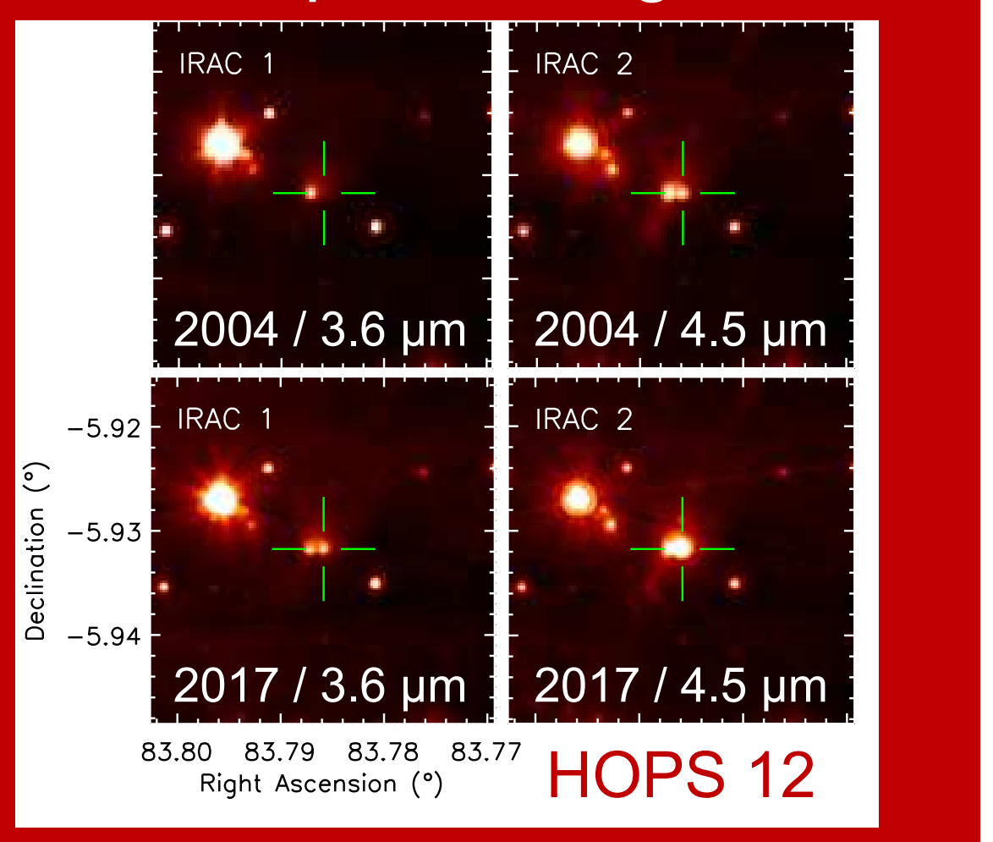
- 2004 (Cryogenic mission; PI Fazio; see Megeath et al. 2012)
- 2009 – 2010 (YSOVAR; PI Stauffer; variability study of the Orion Nebula Cluster; see Morales-Calderón et al. 2011, Rebull et al. 2014)
- 2016 – 2017 (Orion: The Final Epoch; PI Megeath)
- 2019 (Spitzer Beyond; PI Megeath; follow-up of known variables)

Five bursts ≥ 2 mag were detected; all are in young, envelope-dominated protostars:

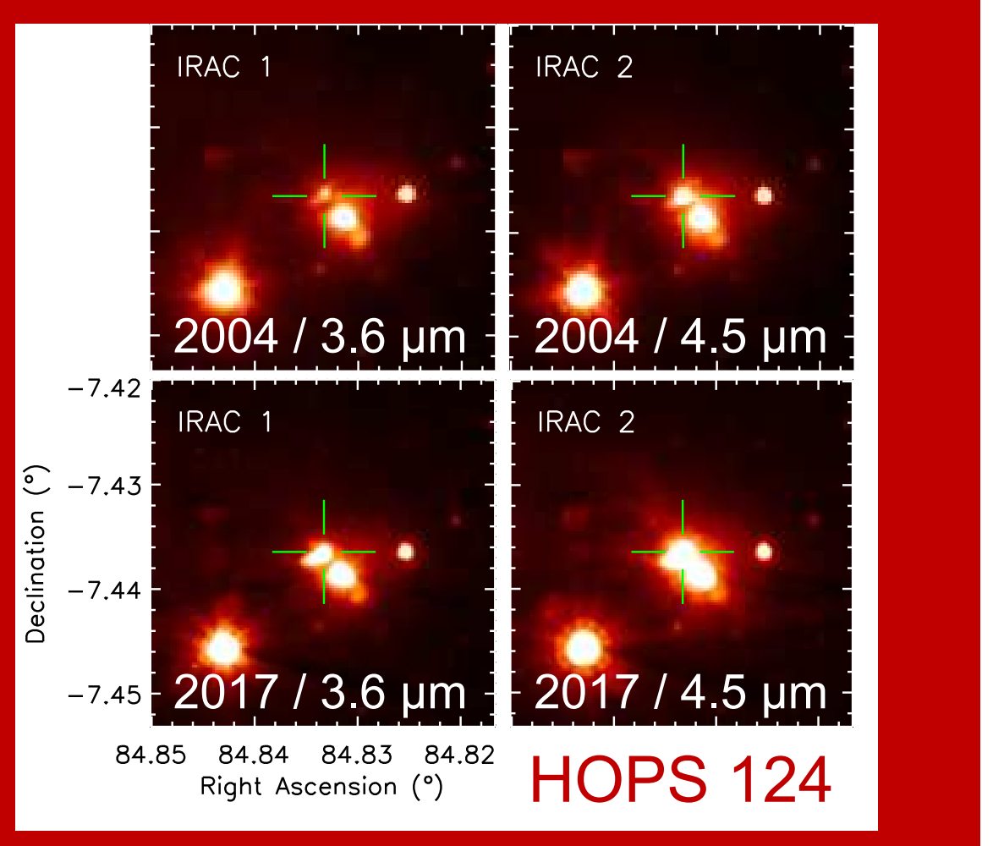
- HOPS 223 (flat-spectrum; see Caratti o Garatti et al. 2011, Fischer et al. 2012)
- HOPS 41 (Class I; in YSOVAR; see Park et al. 2021)
- HOPS 383 (Class 0; in YSOVAR; see Safron et al. 2015)
- HOPS 12 (Class 0; in YSOVAR; not previously reported)
- HOPS 124 (Class 0; not previously reported)

Here we focus on the Class 0 bursts.

Spitzer Images

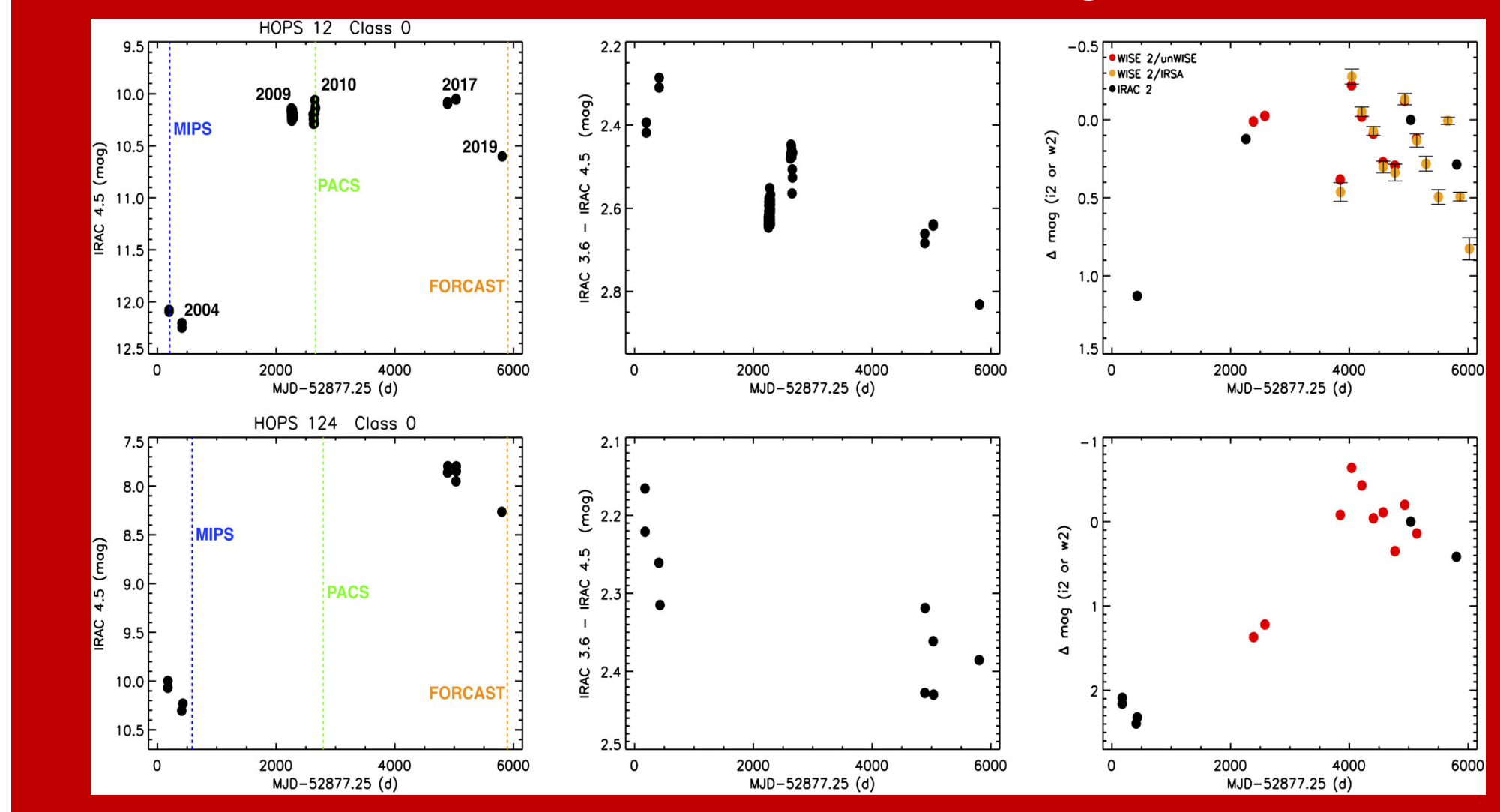


HOPS 12



HOPS 124

Spitzer + WISE / NEOWISE Light Curves



Left: 4.5 µm Spitzer light curves with dates of longer-wavelength observations indicated

Center: 3.6 µm – 4.5 µm colors demonstrate reddening while brightening; this is evidence against brightening due to a drop in extinction

Right: WISE + NEOWISE 4.6 µm data demonstrate variability during bursts

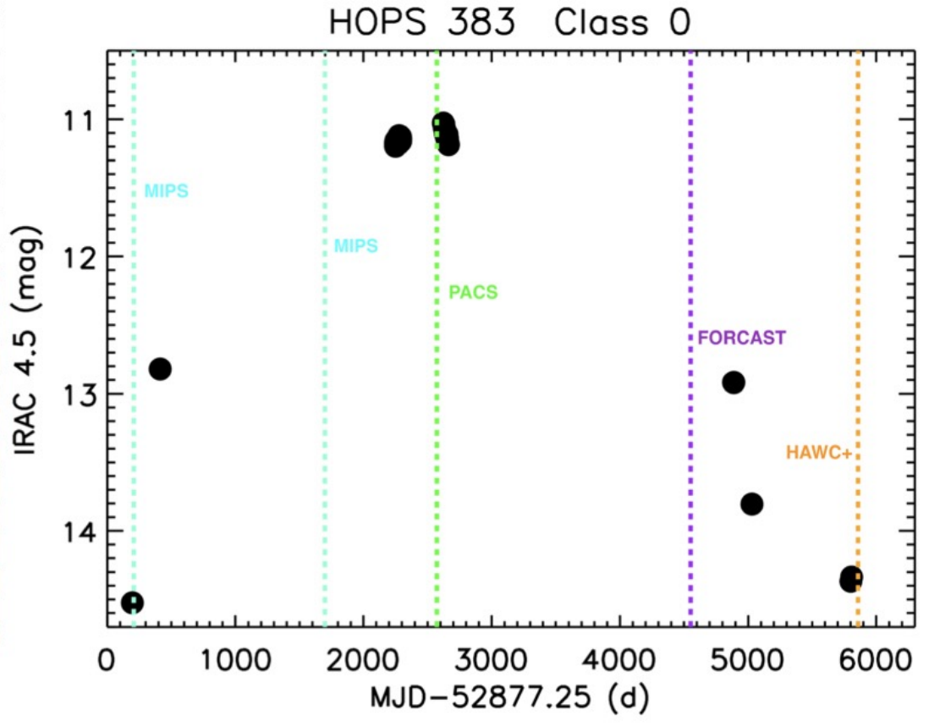
We estimated burst amplitudes with ratios of photometry from different epochs, color-corrected based on the bandpasses and the spectra of protostars. We compared 19.7 µm, 25.3 µm, and 31.7 µm SOFIA/FORCAST data to 24 µm Spitzer/MIPS data; 70 µm MIPS data to 70 µm Herschel/PACS data; and 89 µm SOFIA/HAWC+ data to 70 µm PACS data. Values in red are adopted for mass assembly analysis.

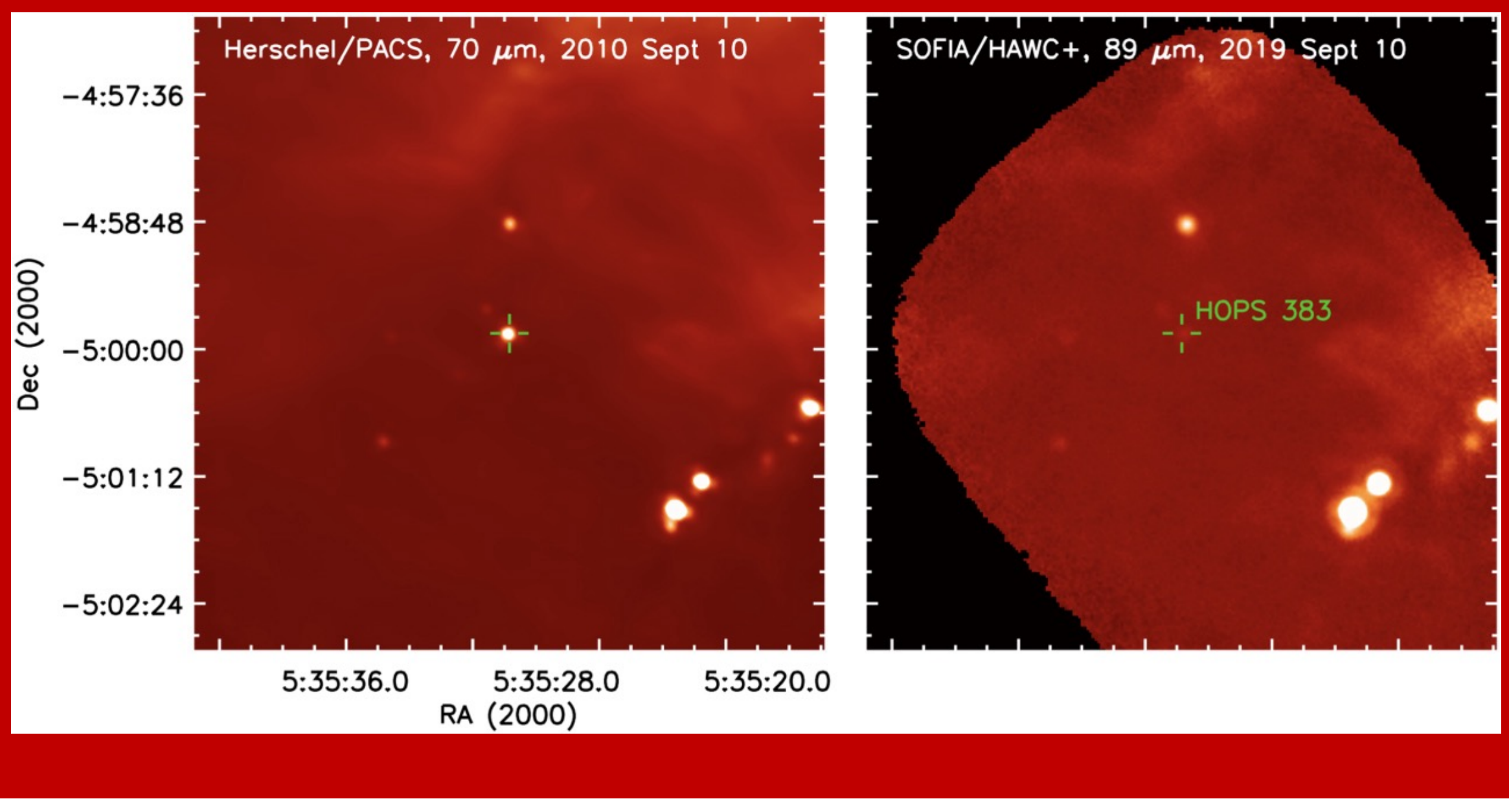
Burst Amplitudes

	HOPS 12	HOPS 124	HOPS 383
19.7 µm	3.8	8.5	
25.3 µm	2.5	5.4	40
31.7 µm	2.5	5.1	
70 µm	3.7		
89 µm			9.7

III. The End of the HOPS 383 Outburst

- HOPS 383 was the first known Class 0 protostar to have an outburst, beginning ~ 2004 – 2006 (Safron et al. 2015)
- Its decline was first reported in an analysis of NEOWISE data (Grosso et al. 2020); this is also seen in the Spitzer 4.5 µm light curve (*right*)
- Comparing Herschel 70 µm and SOFIA 89 µm imaging (*below*) confirmed its decline
- The ~ 10 yr timescale is intermediate between typical EX Lup and FU Ori durations, similar to that of the V1647 Ori burst

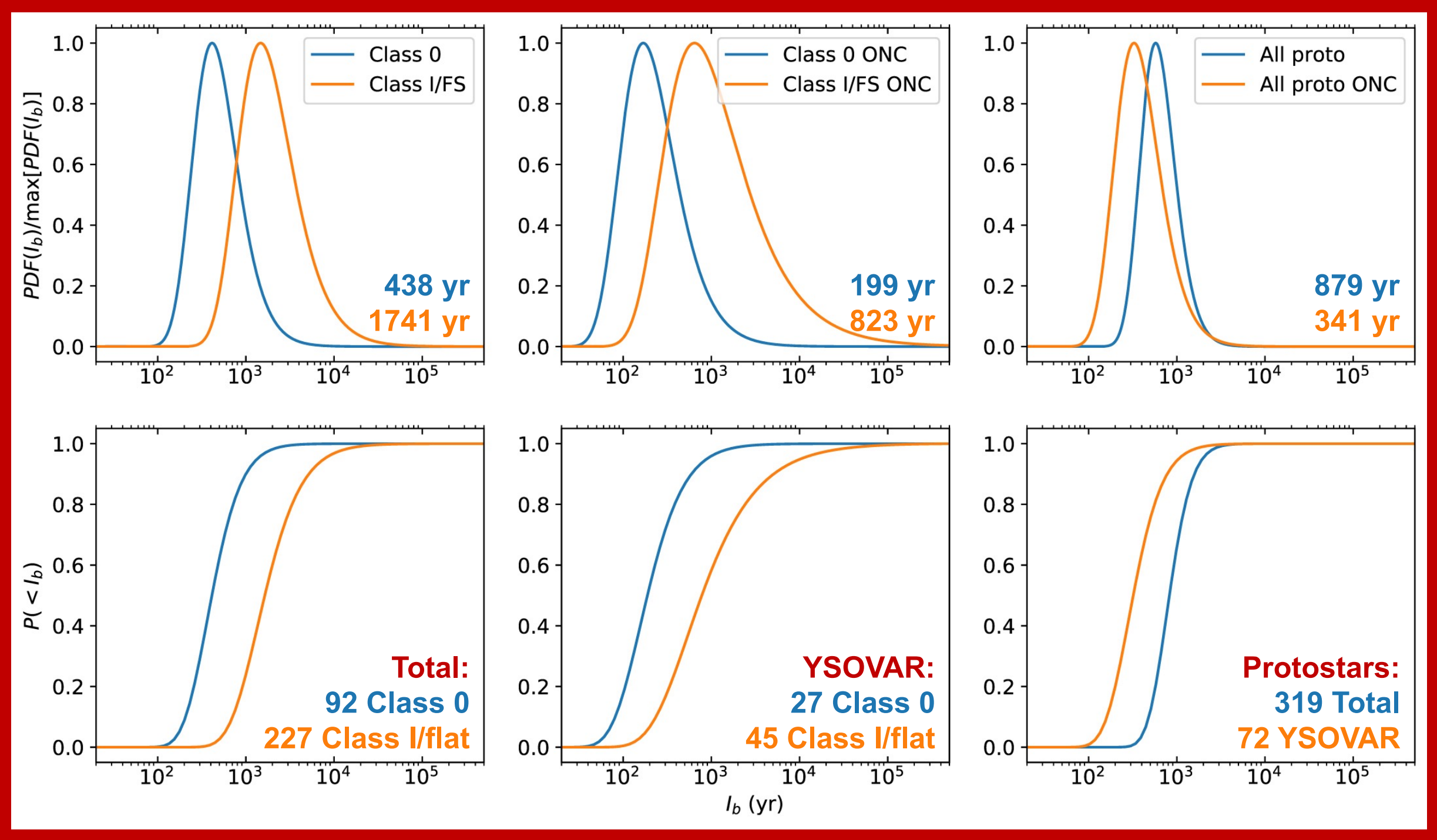




IV. The Burst Interval

We calculate the burst interval for different subsamples, with a 13 yr baseline and logarithmic priors. Key findings include

- The burst interval for all protostars is 880 yr, similar to previous reports of 1000 yr
- The Class 0 interval is ~ half that, and the Class I / flat-spectrum interval is ~ twice that
- The sample size and time coverage are still too small to conclude definitively that the interval is shorter for Class 0
- Derived intervals are shorter in the Orion Nebula Cluster, where we have better time coverage



Above: Probability density functions (*top*) & cumulative probability distributions (*bottom*) for the burst interval. These are calculated for various subsamples as shown.

Subsample	Bursts	Protostars	Interval (yr)	95% CI (yr)
Class 0	3	92	438	161 – 1884
Class I / flat	2	227	1741	527 – 12011
Class 0 (ONC)	2	27	199	60 – 1393
Class I / flat (ONC)	1	45	823	155 – 21694
All protostars	5	319	879	400 – 2515
All protostars (ONC)	3	72	341	126 – 1468

Results for 13 years of monitoring

V. How Much of a Star's Mass Is Due to Bursts?

Fischer et al. (2019) showed that, assuming the protostellar phase can be divided into periods of quiescence and burst, and the accretion rate during bursts is a constant factor *A* greater than the rate during quiescence, then the fraction of a star's mass accumulated in bursts is

$$\frac{M_b}{M} = \frac{A f_b}{(A-1) f_b + 1}$$

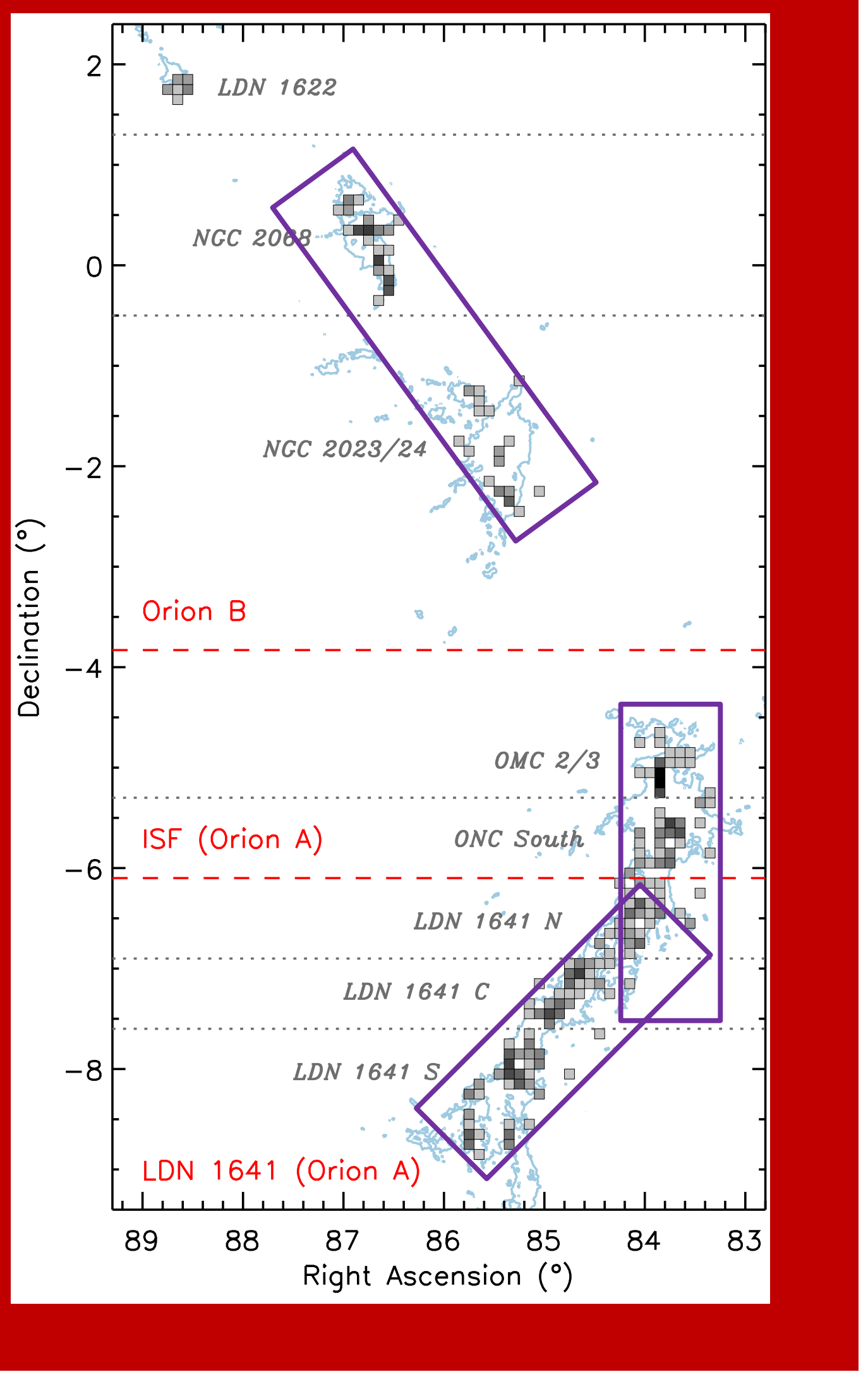
where f_b is the fraction of the time spent in bursts, M is the total mass, and M_b is the mass accumulated in bursts. Estimates of A and f_b are still uncertain and vary from one protostar to the next, but our study suggests that $A = 10$ and $f_b = 15$ yr / 500 yr = 0.03 are typical values. In this case, **bursts are responsible for 24% of a star's mass**.

VI. Far-IR Protostellar Variability with PRIMA

PRIMA

The PRobe far-Infrared Mission for Astrophysics

- PRIMA is a cryogenically cooled, far-IR observatory for the community, being planned for the next decade
- It can conduct far-IR (25 µm – 265 µm) photometric monitoring of 2000 protostars in the nearest 1.5 kpc, with multiple visits per year over a 5 year mission
- Key question to be answered: Do protostars accrete the majority of their masses in >100x bursts?



Right: Example PRIMA mapping strategy for the Orion molecular clouds. Blue contours show the 500 µm Herschel map (Stutz & Kainulainen 2015). Gray boxes indicate the locations of 319 protostars (darker ones contain more; Fischer et al. 2020). Purple boxes show potential boundaries of PRIMA maps.

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References: Caratti o Garatti, A., et al. (2011, A&A, 526, L1); Fischer, W.J., et al. (2012, ApJ, 756, 99); Fischer, W.J., et al. (2019, ApJ, 872, 183); Fischer, W.J., et al. (2020, ApJ, 905, 119); Furlan, E., et al. (2016, ApJS, 224, 5); Grosso, N., et al. (2020, A&A, 638, L4); Megeath, S.T., et al. (2012, AJ, 144, 92); Morales-Calderón, M., et al. (2011, ApJ, 733, 50); Park, W., et al. (2021, ApJ, 920, 132); Rebull, L.M., et al. (2014, AJ, 148, 92); Safron, E.J., et al. (2015, ApJL, 800, L5); Stutz, A.M., & Kainulainen, J. (2015, A&A, 577, L6); Zakri et al. (2022, ApJL, 924, L23)