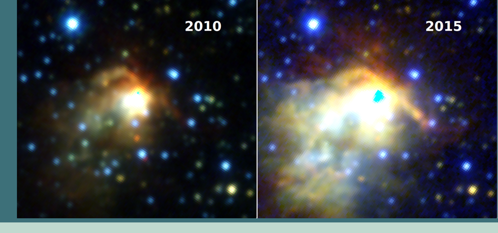


Episodic Accretion in High-Mass Star Formation

The paradigm of high-mass star formation

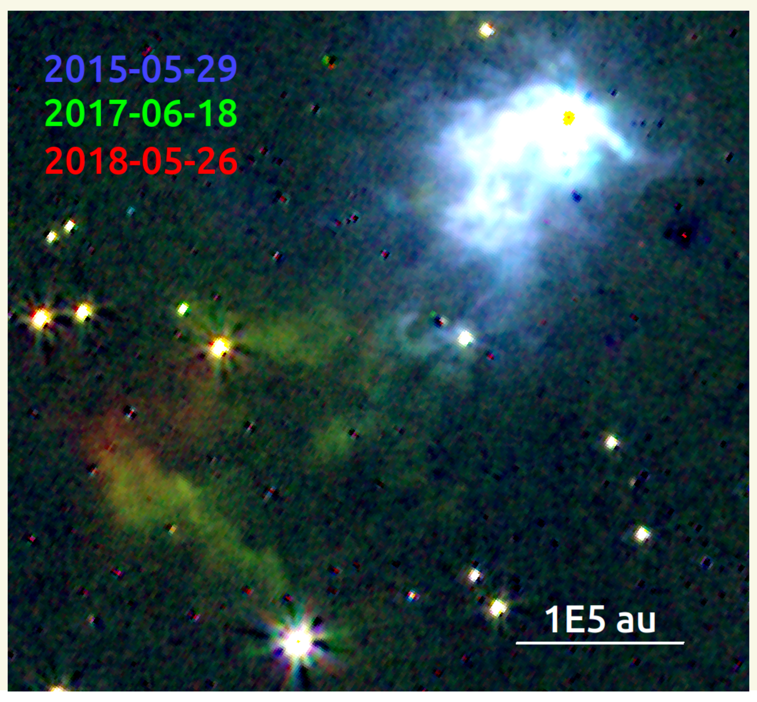
Young high-mass stars are rare, distant, deeply embedded, evolve fast, and have strong radiative feedback. Therefore, their formation has been a puzzle for quite some time. The recent detection of accretion bursts in massive young stellar objects (MYSOs)[2;6;8] strengthens the evidence that they form via disk-mediated accretion, like their low-mass siblings. Most of the stellar mass is probably assembled within short periods of vivid accretion. This causes powerful bursts that impact the protostellar environment in various ways, as illustrated in the following.

A wide range of outburst characteristics

Object	M_* $M_\odot$	L_*^{pre} $10^3 \cdot L_\odot$	ΔL^{burst} $10^3 \cdot L_\odot$	t_{rise} yr	Δt yr	E_{acc} 10^{38} J	M_{acc} M_{Jup}	$\dot{M}_{acc}$ $M_\odot/yr$
S255IR-NIRS3*	20	30	130	0.4	2.5	>12	>2	$5 \cdot 10^{-3}$
G358.93-0.03-MM1*	9.7	5	18	0.14	0.5	2.9	0.6	$1.8 \cdot 10^{-3}$
G323.46-0.08-MM1*	13?	60	60	1.4	8.4	230	23	$2.8 \cdot 10^{-3}$
NGC 6334I-MM1*	6.7	3	44	0.6	>6	>32	>0.3	$2.3 \cdot 10^{-3}$
M17 MIR	5.4	1.4	7.6		9-20			$\approx 2 \cdot 10^{-3}$
V723 Car	10?	≈4		4	≈15			

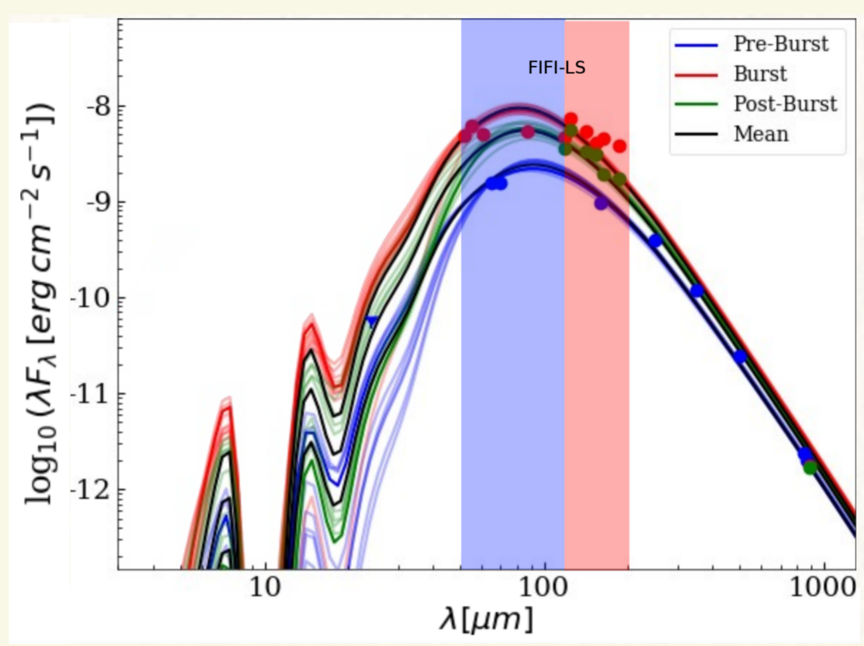
MYSO outbursts observed so far. They last from a few months to more than a decade. Estimates of accreted masses range from >0.3 to more than 20 M_{Jup}. An asterisk marks an accompanying 6.7 GHz Class II methanol maser flare. Our group studies the highlighted events.

Light echos

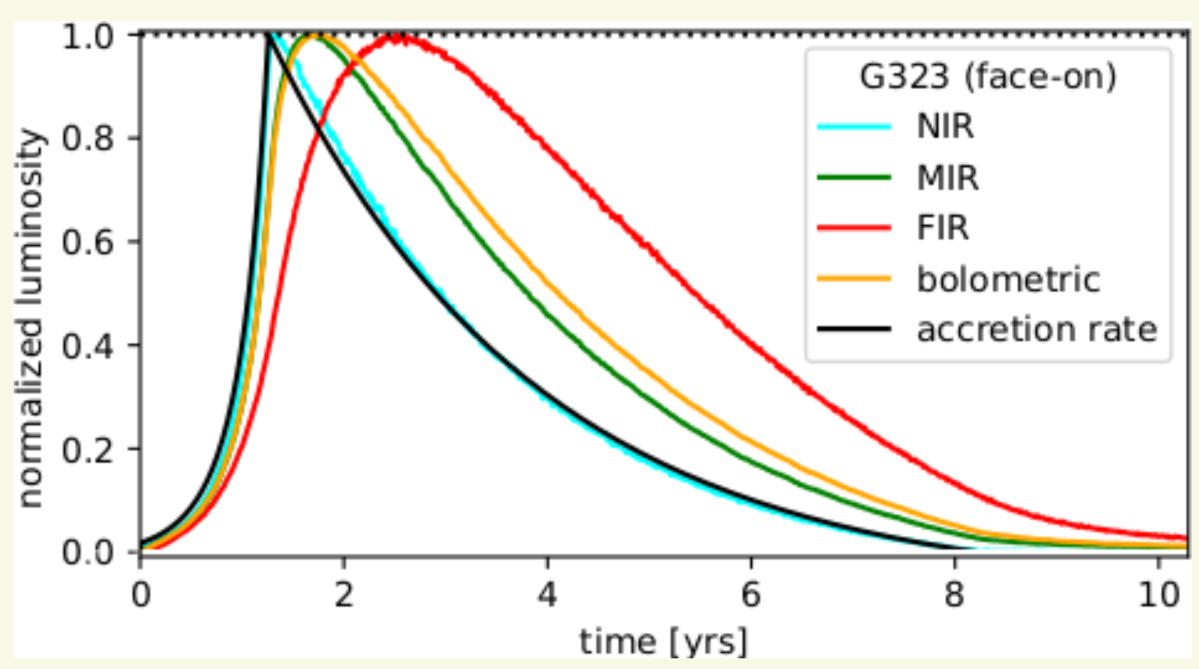


K_s images of G323 at three epochs reveal its light echo. Photons emitted by the burst are scattered off ISM dust grains into the line of sight. The extra path delays their arrival time. These echoes differ from the ring-like ones of supernovae because of the MYSO disk/envelope structure. The burst of NIRS3 led to a biconical light echo.

Afterglows & time-dependent radiative transfer

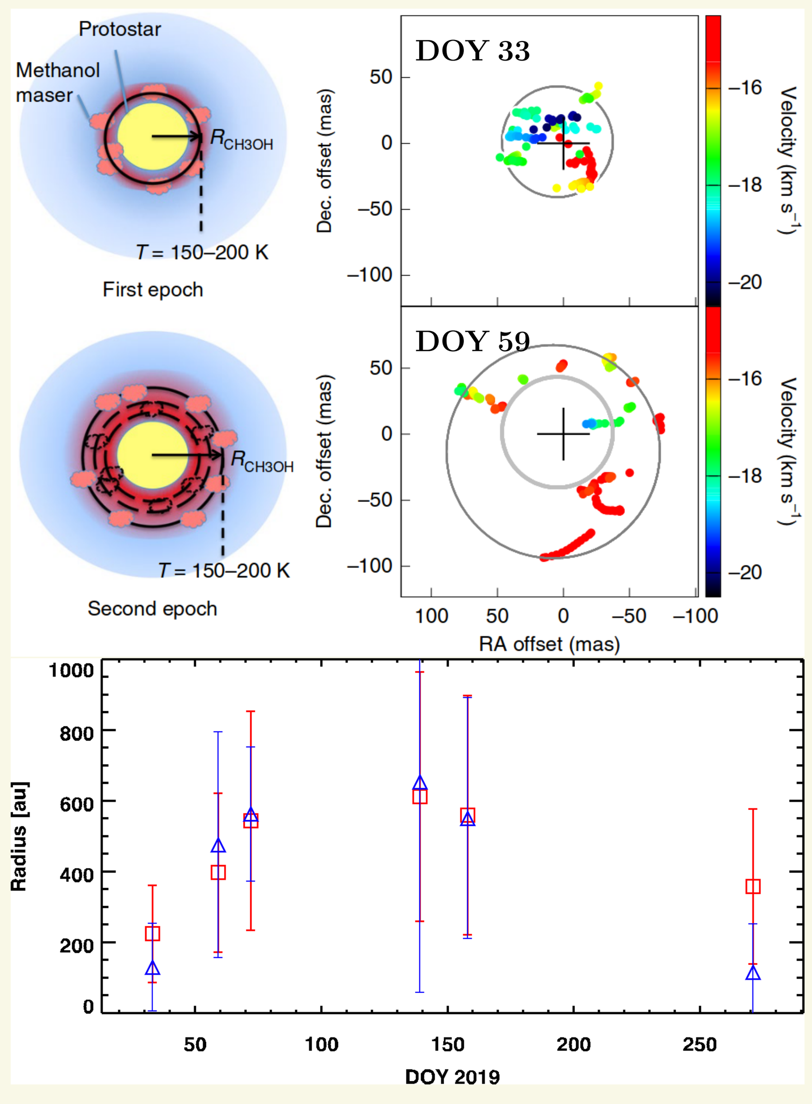


Pre-, mid- and post-burst SEDs of G358 with spectral coverage of the SOFIA FIFI-LS instrument. About 15 months after enhanced accretion stopped, the FIR fluxes still exceeded the preburst level. This thermal afterglow is caused by the subluminal speed of energy transfer at high dust optical depths[8].



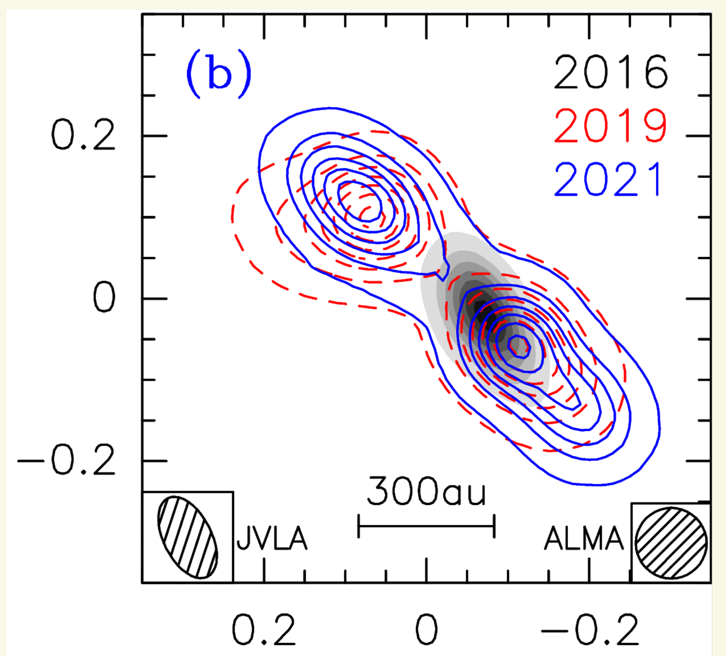
Normalized luminosity light curves of the G323 model for various spectral ranges show that MIR and FIR afterglows exceed the duration of the accretion burst (black). Their length depends on wavelength and inclination. For MYSOs seen face-on, the NIR response is prompt, while strongly delayed for edge-on disks. The model is computed with the time-dependent radiative-transfer code TORUS[4] (Wolf et al., in prep.).

Heat wave and 6.7 GHz methanol maser relocation



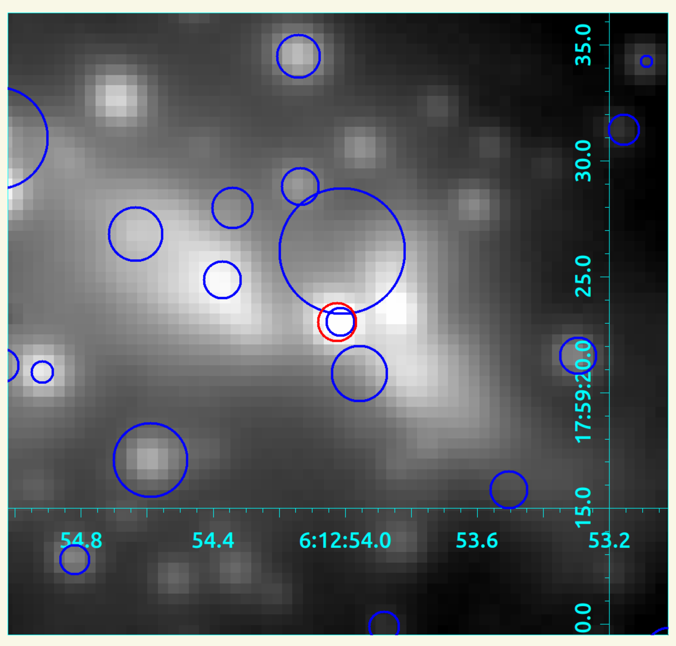
Methanol masers are relocated during the burst due to their radiative excitation[7]. VLBI maps of G358 revealed subluminal expansion of a ring-shaped maser configuration during the burst[1] (top). The plot below compares the observed flux-weighted mean radii to what is predicted by our model (mean radii, where T_{dust} is in the proper range for maser excitation). The bars imply the spatial extent of the emission and the T_{dust} interval, rather than the actual errors. There is a good correspondence during heat wave spread, but a mismatch afterward. This probably results from using the maser light curve as a proxy for the accretion variation, which is not entirely accurate.

Proving the accretion-ejection connection



During star formation, a fraction of the infalling matter is not accreted but ejected at high speed by jets and outflows. For the first time, this connection was observed in the NIRS3 burst. About one year after the burst onset, its radio continuum began to rise, possibly by the launch of an ionized jet[3]. JVLA 7 mm (gray) and ALMA 3 mm observations (contours) confirmed this model by clearly showing the jet expansion (Cesaroni et al., in prep.).

Shocking X-rays from NIRS3 !



High accretion rates can induce bloating of MYSOs, leading to low effective temperatures[5]. Therefore, generation of X-rays in a photosphere similar to that of low-mass stars seems unlikely. However, *Chandra* observations during the burst revealed X-ray emission that was previously absent. Most likely, it is due to wind shocks related to radio jet activity. CSC 2.1 X-ray sources (blue circles) are shown in a K-band image centered on NIRS3 (red circle).

Prospects

- The loss of FIR access due to SOFIA shutdown is a *serious* drawback.
- The reanalysis of SOFIA data using time-dependent radiative-transfer models will refine burst parameters, as well as information on the protostellar environment and viewing geometry.
- JWST studies will focus on the burst impact on the disk/envelope.

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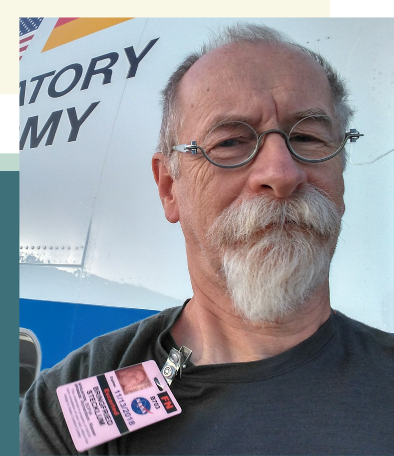

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