Accretion outburst from a massive protostar: a sequence of extraordinary observational results

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Observation-based stages of Massive Star Formation

**COMs: Complex Organic Molecules**

- Clumpy molecular cloud
  - $L \sim \text{several pc}$
- Massive prestellar cores (very elusive)
  - $R < 0.1 \text{ pc}$
- Hot molecular core
  - $R < 1000 \text{ au}$
- Hypercompact HII region
  - $R < 10000 \text{ au}$
- Ultracompact HII region
  - $R > 0.1 \text{ pc}$
- HII region / OB association

**Historical context**

- **1980s**: IRAS catalog / VLA-identified ultracompact HII regions (Wood & Churchwell 1989)
- **1990s**: Samples of massive YSOs / HMPOs gathered (Molinari+1996, Sridharan+2002)
- **2000s**: MSX, Spitzer surveys / IRDCs / EGOs = MYSOs with active outflows (Cyganowski+2008)
- **2010s**: Detailed studies of individual fields / protoclusters

Cartoon credits: C. Purcell, F. Motte
Observation-based stages of Massive Star Formation

**COMs: Complex Organic Molecules**

- **Clumpy Molecular Cloud**
  - L ~ several pc

- **Massive prestellar cores (very elusive)**
  - R < 0.1 pc

- **Hot Molecular Core**
  - R < 1000 au

- **Hypercompact HII Region**
  - R < 0.1 pc

- **Ultracompact HII Region**
  - R < 10000 au

- **HII Region / OB association**
  - R > 0.1 pc

- **Not distinct stages; incl. EGOs 4.5um**
  - Accretion outbursts occur here

- **Modest time variability**

- **E.G. G19.30+0.07 Devine+2011**
- **E.G. G11.92-0.61MM2 Cyganowski+2014**
- **E.G. G35.03+0.35, Towner+2018**
- **E.G. G29.96-0.02 Kalcheva+2018**
- **Orion Trapezium Bally+1998**
Evidence for Episodic Accretion in Low Mass YSOs

DIRECT EVIDENCE:

• Classical FUORs (named after FU Ori) (Hartmann+2016):
  • T Tau with >5 mag optical increase for 10-100yr ($\dot{M}$: $10^{-6}$ to $10^{-4}$ $M_\odot$/yr)
  • thought to be disk thermal instability (Bell & Lin 1994)
  • alternative idea: enlarged atmosphere (Herbig+2003, Larson 1980)

• EXORs (named after EX Lup) (E. Janssen, McLaughlin 1946):
  • smaller: 2-4 mag burst for months–years; can repeat (1929, 1995)

• Class 0 Objects: HOPS 383 (Safron+2015, L rose~40x)

INDIRECT EVIDENCE:

• Spitzer c2d Legacy results (Evans+2009):
  • most YSOs underluminous relative to evolutionary models with a constant or decaying accretion rate

• Episodic molecular outflows (Plunkett+2015)

• Chemical evidence
  • snow line further out than expected for $L_{\text{current}}$ (Jorgensen+2020)

Stars gain > 25% of total mass from episodic accretion (Fischer+2019; Offner & McKee 2011)
Episodic accretion in massive protostars (theoretical)

**Meyer+2017:** numerical radiation hydrodynamic simulations, including gas self-gravity & radiative feedback (Kuiper & Klessen 2013)
- Fragmentation of infalling material yields bursts in accretion rate up to $\sim 300 \times$ background rate
- Largest bursts separated by few 1000 yr

**Kuffmeier+2018:** adaptive mesh refinement zoom-in simulations
- Gravitational disk instabilities last 10-100yr
- RADMC3d: SED peak shifts to shorter $\lambda$ at higher $\dot{M}_{\text{acc}}$ (see also Johnstone+2013)

**Outburst mechanisms explored by Elbakayan+2021**
1. Magnetorotational instability activation ($t \sim 1000$ yr, $10^{-4} \, M_\odot/yr$)
2. Thermal instability ($t \sim 100$yr, $10^{-4} \, M_\odot/yr$, FUOR-like)
3. Giant planet ($10R_{\text{jup}}$) disruption: migrates toward star, fills Roche lobe ($t \sim \text{few yr}$, $5 \times 10^{-3} \, M_\odot/yr$)
“A newborn, massive star was formed some 4000 light years from Earth in the Cat’s Paw Nebula (NGC 6334), a region of massive star formation. This exciting conclusion was the result of many hours of observation, sighting, detection, and studying and monitoring readings at the Hartebeesthoek Radio Astronomy Observatory.”

Gordon MacLeod & Derck Smits

Why did they claim this? ...

https://mg.co.za/article/2015-12-11-00-a-star-is-born/
... This is why! An unprecedented maser flare

• HartRAO 26m dish South Africa: 2 decades monitoring H$_2$O, OH, CH$_3$OH masers (Goedhart+2004)
• NGC6334I was their calibrator ($\delta$ = -35° passes near zenith, with strong and stable emission!)
• In Jan. 2015: 10 maser lines in 3 species flared; by 30x in 22 GHz H$_2$O and 6.7 GHz CH$_3$OH

-7.2 km/s Methanol & Water over time

1.8 kJy

16 kJy

Intensity (Jy)

G. MacLeod+ 2018 MNRAS, 478, 1077
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**-7.2 km/s Methanol & Water over time**

<table>
<thead>
<tr>
<th>Intensity (Jy)</th>
<th>Time (MJD)</th>
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<tbody>
<tr>
<td>1.8 kJy</td>
<td>2014</td>
</tr>
<tr>
<td></td>
<td>2015</td>
</tr>
<tr>
<td></td>
<td>2016</td>
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</table>

**G. MacLeod+ 2018 MNRAS, 478, 1077**

**Date of first ALMA observation of this field (in Cycle 2)**
Intro to NGC 6334 “Mini-starburst” (Willis+ 2013; 2283 YSOs)

$D = 1.3 \pm 0.1$ kpc from maser parallax (Reid+2014)

86 compact radio sources (Medina+ 2018)
Intro to NGC 6334 `Mini-starburst`

Orion Trapezium Cluster HST at same scale
*Bally et al. (1998)*

ALMA
1.3 mm
2015.6

First ALMA Image: Cycle 2, 1.3 mm
Resolution: 0.17 (220 au)
Brogan+2016

10,000 AU

NGC 6334 I MM1

MM3
O9-B1
Bik+2005

MM2

MM4

86 compact radio sources (Medina+ 2018)

First CH$_3$OCH$_2$OH detection: McGuire+ 2017

D = 1.3 ± 0.1 kpc from maser parallax (Reid+2014)

25' = 15 pc

25' = 15 pc

Intro to NGC 6334 `Mini-starburst`

Willis+ 2013; 2283 YSOs

Source "I"
NGC6334I mm continuum outburst / maser flare

• Comparison of first ALMA image to SMA image 7 years prior showed a flare in dust emission from MM1 only

ALMA 2015 Band 6  
SMA 2008  
1.3 mm

• Flux density increased by a factor of 4
• No sign of fading after 6 years

(Hunter+2017; 2018, Brogan+2018, MacLeod+2018)

Maser flare means gas was also affected

After 6 years, the methanol maser (and water maser) flares also still going strong
Methanol masers trace a particular stage of massive protostars

- Pumped by mid-IR photons (20-30\,\mu m) and cascading through torsional states
- Requires $T_{\text{dust}} > 100$K and dense gas $10^{4-8}$ cm$^{-3}$
- Seen only in strong radiative environments – massive star forming regions close to protostars

The traditional masers in NGC6334I before the outburst:

**ATCA 1994 & 2011**

after the outburst:

**VLA 2016.9**

**Spot size $\propto \sqrt{\text{flux}}$**

New SOFIA and ALMA Observations (Jan 2018 – July 2019)

Table 1. Observing and imaging parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SOFIA</th>
<th>ALMA</th>
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<tr>
<td></td>
<td>FORCAST</td>
<td>HAWC+</td>
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<tr>
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<td>07.0156.1 GTO 70.0609.13</td>
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<td>J1713–3418 J1717–3342 J1733–3722 J1733–3722</td>
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<td>Wavelength(s) λ₁, λ₂ (μm)</td>
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<td></td>
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<td>2173 1005 758 432</td>
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<td>Projected uw-range (kiloλ)</td>
<td>...</td>
<td>13 – 1218 13 – 1380 16 – 1613 19 – 1746</td>
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</table>

Angular resolution            3.2”, 3.5” 5.6”  all bands are ~ 0.3” x 0.2”
Best pre-outburst infrared images of NGC6334-I   (pre-2015)

Archival (2012) VLT $K_s$ image aligned to Gaia DR2

Strongest mm source / hot core (MM1) was undetected:
 at 18um (CTIO, DeBuizer+2000)
 and 8-20um (IRTF, Kraemer+1999)
 while MM2 was seen faintly (IRS-I-2)

UCHII region (IRS-I-1) = NGC6334-MM3
 dominated the near- and mid-IR:
  central star: kO9-B1 (Bik+2005)
 $L_{\text{bol}} = 7000 - 100000 \, L_\odot$

Old 2-100µm data from UKIRT, IRTF,
 KAO by Harvey & Gatley (1983) yields
 $L_{\text{bol}} (\Sigma \text{ field}) = 90000 \, L_\odot$
 (~1/3 of Orion Trapezium stars)

Hunter+2021
Mid-outburst 25μm image from FORCAST (August 2019)

MM1 is now the dominant object at $\lambda \geq 25$ microns!
Mid-outburst 25um image from FORCAST (August 2019)

MM1 is now the dominant object at $\lambda \geq 25$ microns

Multiple outflows from MM1:
1. extended northeast/southwest flow (known from single-dish)
2. compact north/south flow in ALMA Band 10 CS & HDO (Brogan+2018, McGuire+2018)

water maser locations match edges of thermal gas knots
Photometry (FORCAST, HAWC+, ALMA)

ALMA spectral index image: MM1 and MM2 dominated by dust emission

Not well separated at $\lambda > 25$

Instead, we measure sum of MM1+MM2, by modeling the UCHII MM3 (cyan contours, row 2) then smoothing & removing it (images in row 3)

Model = CTIO 18um image smoothed and scaled to 25, 37, and 53 um

Aperture size increased w/ $\lambda$ in proportion to IR beamsize

Hunter+2021
Modeling of outburst SED (FORCAST, HAWC+, ALMA)

Used Robitaille (2017) radiative transfer models of MYSOs

Non-detection at 2.2um by VVV/VVVX provides additional constraint

Best fit result: MM1+MM2 = 49000 ± 8000 L☉
Modeling of pre-outburst SED (Keck, Herschel, SMA)

Used Robitaille (2017) radiative transfer models of MYSOs

**Best fit result:**

\[ \text{MM1+MM2} = 4300 \pm 900 \, L_\odot \]

**Pre-outburst apportioning:** (based on mm flux)

- MM1: 2900 \, L_\odot
- MM2: 1400 \, L_\odot

**MM1 now** vs. before:

\[ \frac{47600}{2900} = 16.3 \pm 4.4 \]

*Hunter+2017 predicted L>42000 \, L_\odot based on mm \, T_{brightness}
Pre-outburst properties of the progenitor

- MM1B remains point-like to the longest ALMA baselines, solidifying it as the outbursting protostar.
- HCHII region at 1.3cm requires ionizing radiation (ZAMS star?)

\[ L_{\text{protostar}} = \text{photosphere} + \text{accretion luminosity} \]
\[ L = 4\pi R_{\text{proto}}^2 \sigma T_{\text{eff}}^4 + GM_* M_{\text{acc}} / R_{\text{proto}} \]

Simple hypothesis: L split evenly
\[ 2900 \, L_\odot = 1450 \, L_\odot + 1450 \, L_\odot \]

- \( M_* = 6.7 \, M_\odot + 1.8 \times 10^{-5} \, M_\odot/yr \) “background accretion”
- \( R_* = 2.6 \, R_\odot \) (Haemmerle+2013 model for 6M_\odot)
- \( T_{\text{eff}} = 22000 \)

B1.5V – B2V ZAMS (Pecaut & Mamajek 2013)

which can produce enough ionizing photons: \( 2 \times 10^{43} \) ph/s

MM1B 1.3cm flux in 2011 (1.8 mJy) requires: \( 1.7 \times 10^{43} \) ph/s

**Conclusion:** Progenitor consistent with deeply-embedded B2V star accreting at \( 2 \times 10^{-5} \, M_\odot/yr \)
Properties of the outbursting star

\[ L = 4\pi R_{\text{proto}}^2 \sigma T_{\text{eff}}^4 + GM_* \dot{M}_{\text{acc}} / R_{\text{proto}} \]

What is the post-outburst split of luminosity? Consider two limiting cases:

**Case 1) Accretion-dominated**, L increase entirely powered by x32 increase in \( \dot{M}_{\text{acc}} \) to \( 5.7 \times 10^{-4} \text{ M}_\odot / \text{yr} = 0.6 \text{ M}_{\text{Jupiter}} / \text{yr} \)

\[ 47600 \text{ L}_\odot = 1450 \text{ L}_\odot + 46150 \text{ L}_\odot \]

**How to distinguish?**
- Long-term: measure duration and decay profile of outburst
- Short-term: measure drop in ionizing photon flux
- Short-term: look for disk/jet system

**Case 2) Photosphere-dominated**: immediate accretion onto protostar, outer layer of star expands radically

\[ 47600 \text{ L}_\odot = 46150 \text{ L}_\odot + 1450 \text{ L}_\odot \]

e.g. \( R_{\text{proto}} \) increases x20 to 50\( R_\odot \) and \( T_{\text{eff}} \) drops to 12000 K

Contracts on Kelvin-Helmholtz time (see Hosokawa, Yorke, & Omukai 2010)

**Case 3) Somewhere between these extremes:**

Interesting fact: A moderate expansion of \( R_{\text{proto}} \) would enable a higher \( \dot{M}_{\text{acc}} \) for same \( L_\odot \) by accreting into an expanded outer layer: more efficient!
We see a factor of 5 dimming in VLA 1.3 cm emission from MM1B.

Requires lower $T_{\text{eff}}$ and larger $R_{\text{proto}}$

If outburst luminosity remains split equally between accretion

$$L = 4\pi R_{\text{proto}}^2 \sigma T_{\text{eff}}^4 + GM_\ast \dot{M}_{\text{acc}} / R_{\text{proto}}$$

$T_{\text{eff}} \sim 16000$ K (down from 22000)

$R_{\text{proto}} = 20 R_\odot$

$\dot{M}_{\text{acc}} = 2.3 \times 10^{-3} M_\odot/yr$

- How long will $T_{\text{eff}}$ remain low?
- Will the jet flux increase?

Reduction of ionizing photons observed!
Large outbursts cause protostar to make excursions on HR diagram, to lower $T_{\text{eff}}$ and ionizing flux ($S_*$).

The drop in $S_*$ seen in NGC6334I-MM1B confirms the prediction, but is one of the smaller examples.

Prediction: much larger events are expected.

Have we found any other events? Yes, but even smaller ones...
Another outburst in a young MASSIVE protostar

**S255IR-NIRS3**
- Discovered via CH$_3$OH maser flare (Fujisawa+2015)
- Flared in near-IR to submillimeter
- Luminosity rose ~6x (SOFIA)
- Faded after ~2 years
- 6 cm emission flared 60% after ~1yr (interpreted as jet) (Caratti o Garatti+2017, Moscadelli +2017, Liu+2018, Cesaroni+2018)

Outbursts in NGC6334I + S255IR led to the formation of **Maser Monitoring Organization** (M$_2$O) at 2017 IAU conference in Cagliari, Italy

<table>
<thead>
<tr>
<th>Before</th>
<th>After</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Before" /></td>
<td><img src="image2.png" alt="After" /></td>
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</table>

[https://MaserMonitoring.org](https://MaserMonitoring.org)

- 77 members
- 16 papers published
- >400 sources being monitored by single dishes
- 11 active ToO proposals across wavelengths:
  - IR (Subaru/SOFIA) - mm (SMA) - cm VLA & VLBI
  - JWST Cycle 1 ToO approved
  - ALMA Cycle 8 ToO (proposed)
  - Plus continued single dish maser monitoring
The Fruits of M\textsubscript{2}O Labors: A New Massive Protostellar Maser Flare

- **Jan 14, 2019:** Single Dish monitoring at Ibaraki Japan caught 6.7 GHz Class II CH\textsubscript{3}OH masers flaring in the massive star forming region G358.93-0.03 (Sugiyama+ 2019)

- Almost no prior studies of this source: 6.7 GHz Parkes Multibeam maser survey, BOLOCAM (1.1mm), ATLASGAL (0.87mm), Herschel Hi-GAL, WISE

- Distance ~ 6.7 kpc (>5 times NGC 6334)

M\textsubscript{2}O Collaboration began to follow-up...

https://MaserMonitoring.org
G358.93-0.03 Maser flare origin: A Massive Protocluster with a Hot Core

- Protocluster of 8 mm dust cores, total gas mass of 200M☉
- MM1 harbors the CH₃OH maser flare
  - Dust continuum increase < 30%
- Distance uncertain, about 6.75 kpc
  - Protocluster Pre-burst L~ 5700 L☉
- Rich hot core line spectra, like NGC6334I-MM1 & S255IR-NIRS3
  - MM1: Thermal lines well-fit with $T_{\text{exc}} = 172\text{K}$ and $T_{\text{bg}} = 159\text{K}$ model

DDT SMA and ALMA data with 0.5” resolution at +2 and +3 months after the maser flare began

![Maser flare origin](https://example.com/maser-flare-origin.png)
SOFIA was key to measuring burst luminosity in G358.93

- No NIR from MM1, only MM3
- Separated by only 1.5”
- New FIFI-LS plus archival data used to establish MM1 SED at three epochs: pre-burst, burst, and post-burst.
- Hyperion RT code
- Stecklum+2021 (A&A 646, 161)

Pre-burst: $5000 \pm 1000 \, L_\odot$
Burst: $23400 \pm 4000 \, L_\odot$
Luminosity gain: $4.7 \pm 1.8$
Post-burst: $12400 \pm 2000 \, L_\odot$

Time-dependent RT code underway for improved modelling (Stecklum, Harries, Wolf)

For more details, see Bringfried Stecklum’s SOFIA Tele-talk 28-April-2021:
**Where do these events fit into zoo of episodic phenomena?**

**NGC6334I-MM1**
- $x_{16.3}$ increase in $L_{\text{bol}}$ (3mag) is similar to EXORs
- Integrated Energy=$\Delta L \Delta t = (3.2 \pm 0.6) \times 10^{46}$ erg → largest of all 3 events
- A stellar merger would be 30-300x greater (Bally+2005)

**S255IR-NIRS3 and G358.93-0.03**
- in the regimes of diffusive and viscous instabilities
Hydrodynamic simulations of accretion in massive protostars

Meyer+2019a,b, and 2021 parameter study predicts:
- massive stars may gain up to 40–60% of mass during outbursts
- Bursts range from $M_{\text{acc}} \sim 0.01 - 1\ M_\odot$

Events observed so far:
All lie in the lower portion of predicted scatter plot of L vs duration (two 2-mag + one 3-mag)

Need more events to constrain models!

M2O has active trigger proposals:
- IR (SOFIA) - mm (SMA) - cm (VLA & VLBI)
- JWST Cycle 1 ToO approved
- ALMA Cycle 8 ToO (proposed)
Conclusions and Outlook

- In past 5 years, accretion outbursts from massive protostars are established
  - NGC6334I-MM1 is longest in duration and largest in energy
  - All 3 events have arisen from hot cores – repeated outbursts may help form COMs
- More events needed to understand their range and constrain theory
- International collaboration through M$_2$O is key to further progress
- SOFIA along with ALMA/SMA/VLA are essential to understand physical parameters of protostar and its parent protocluster
<table>
<thead>
<tr>
<th>Event Description</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>First ALMA images (odd mm spectral index noted)</td>
<td>Brogan+2016, ApJ 832, 187 (ALMA, VLA)</td>
</tr>
<tr>
<td>Maser light curves</td>
<td>MacLeod+2018, MNRAS 478, 1077 (HartRAO, SMA)</td>
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