What the Variability of Embedded Protostars Tells Us about Accretion

Past, Present, and Future

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• The International JCMT Transient Survey Team
Variable Stars as Probes: Light Curve

1. Measurement of Amplitude, Period, Eigen-frequencies ...
   - Deduce density and/or internal structure – **stellar seismology**

2. Determination of stellar properties
   - Standard Candles (Cepheids, Sne)
   - Probing Physics (mixing length theory)
   - Much, much more
Spitzer: Protostars are Under Luminous

Protostar luminosity comes from accretion. Should only need only formation time to determine brightness. Well known Kenyon et al. (1990) ‘luminosity problem’.

Motivation for the JCMT Transient Survey.

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Why Do We Observe in the Sub-mm?

Optical and Infrared

Cold Dusty Envelope:
Optical -> Obscures, Reddens
Sub-mm -> Glows Bright
The EAO/JCMT Transient Survey

OMC 2/3   NGC 2024   NGC 2071   Ophiuchus

8 Regions < 500 pc (GBS)  3 Year Survey
182 Protostars, 800 Disk sources  One Month Cadence

NGC 1333   IC348   Serpens Main   Serpens South

The First JCMT Protostellar Variable:

**Serpens Main ~ 400pc**

JCMT SCUBA-2 at 850 micron

30’ Pong – viewing central region

13 epochs ~ monthly cadence

2016-February – 2017-April

Careful Investigation by Korean graduate student Hyunju Yoo ...

The First JCMT Protostellar Variable:


- EC 53
- Behind Sun
- % Flux Variation vs. Brightness
  - Noise-dominated uncertainty
  - Serpens Main
  - Mean Family SD: 2.0%
  - Relative Flux calibration ~ 2% limited to high S/N Sources.

Calibrator 1
- Days Since 02/02/2016
- Norm. Cal. Peak Brightness

Calibrator 2
- Days Since 02/02/2016
- Norm. Cal. Peak Brightness

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The First JCMT Protostellar Variable:

Figure 5. Phase diagram of the K-band variations of EC 53. The light curve shows a rapid rise and slower decline from the maximum.
The First JCMT Protostellar Variable:

- **EC 53 (V371 Ser)**
  - Class I source (Hodapp et al. 1999)
  - [possibly Class 0 seen pole on]
  - Observed physical binary 296 mas (92 AU) away – possibly sub-stellar
  - Cometary nebula (One visible lobe of a bipolar structure)
  - Ongoing outflow activity ($H_2$ jet)
  - 18 month *periodic variable* at 2μm (Hodapp et al. 1999, 2012)

- **Postulatation ...**
  - 18 month periodicity suggests disk irregularity at ~ 1 AU
  - Unseen inner companion star (Hodapp et al.) -> ejection of 92AU source?
  - Or perhaps a planet in formation ...
  - We have observed for ~16 months with JCMT – awaiting full period
    - Planned monitoring at 2μm to determine lags and shape variations
Young Disk Observations (IR & mm):

Gaps in disks may be due to sculpting by planets. Accretion periodicity perhaps?

Very likely to be an unstable flow ...

e.g. Munoz & Lai (2015)

Graduate University for Advanced Studies, Japan
Formation of a star in one slide!

Key point for this talk: the material that forms a star is assembled from its prenatal cloud, through an envelope and disk.
Accretion via Inside Out Collapse:
“Shu Model”

• Start with an isothermal sphere
\[ \rho(r) = \left( \frac{a^2}{2\pi G} \right) r^{-2} \]

• Perturb the centre slightly
  – Loss of pressure support yields collapse!

• Rarefaction wave races out at sound speed
\[ \frac{dM}{dt} = 4\pi a \rho r^2 = \frac{2a^3}{G} \]

• Half of this mass flux is accreted onto the central protostar while half is added to the in-falling envelope
  – Steady-state protostellar accretion \( \sim \frac{a^3}{G} \)
Importance of Rotation (or B fields):

- Rotation breaks isotopic symmetry
  - Produce a flattened inner region (a disk)

- Mass flux that would have reached the protostar now *misses* and lands on disk

- No *a priori* reason why mass transport through disk = mass flux onto disk!
  - If disk transports *faster* – no disk build up
  - If disk transport *slower* – significant disk build up

*Note: mass transport through disk may even be radially dependent!*
Mass Accretion – Non-Steady?

- Disk models suggest disk transport often *inefficient*
  - Outer disk fills with mass until gravitationally unstable
  - Next, spiral forms in disk efficiently transporting mass inward
  - Accretion takes place in short energetic bursts and long quiescent intervening periods

- Observations of knots/bullets in jets also suggestive ...

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Young Disk Observations (IR & mm):

- Whether observed in *scattered light* (IR) or *dust emission* (mm) disks around young stars appear *structured*!

Young Disk Observations (IR & mm):

• Interestingly, many disks observed in mm show *rings and gaps* indicating a more quiescent environment, a non-smooth mass transport ... and *suggesting planets in formation*!

• If significant mass from the envelope still falls onto the outer disk, how might this impact the time dependence of accretion?
Accretion Through Disks – Non-Steady?


Caveat: Neither model designed for such short times!

Aside: Variability and Accretion

• Much effort invested in determining how majority of mass accreted
  – Steady-state vs. powerful, rare outbursts
• But, accretion variability may be much more nuanced than this
  – c.f. earthquakes, meteor impacts
  – Timescale(s)/amplitude(s), process(es)?

<table>
<thead>
<tr>
<th>Earthquakes</th>
<th>Meteors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number per Year</td>
<td>Number per Year</td>
</tr>
<tr>
<td>Magnitude</td>
<td>Mass (kg)</td>
</tr>
</tbody>
</table>

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- KASI 2017
Spectral Energy Distribution (SED):

- For a low mass star, the mass accretion onto the protostar releases as much (or more) energy as the protostar itself produces

\[ L_{\text{acc}} \sim \frac{GM_\star}{R_\star} \dot{M}_{\text{acc}} \]

- This energy is absorbed by the envelope and re-radiated in the far IR through mm. Thus, the SED acts as a **calorimeter** for accretion.

- Measurements near the SED peak provide a proxy for accretion. Thus, the **JCMT Transient Survey** or potential **SPICA/OST Variability Surveys** observe accretion variability through brightness variations.
Can We Observe Changes in the SED? Deeply Embedded Protostar Model

- **Density** structure follows inside-out collapse
  - $M_{\text{env}} = 1.5 \, M_{\odot}$
  - $R_{\text{env}} = 2 \times 10^4 \, \text{AU}$
  - $R_x = 6 \times 10^3 \, \text{AU}$ (transition from static to infall)

- Protostar **Mass** $\sim 0.25 \, M_{\odot}$

- Possible **Luminosities**:
  - $L_{\text{PS}} = 1.2 \, L_{\odot}$
  - $L_{\text{acc}} = 5 \, L_{\odot}$ (if steady-state: $c^3/G$)
  - $L_{10} = 12 \, L_{\odot}$
  - $L_{100} = 120 \, L_{\odot}$
Implications of Variable Accretion - I

Temperature Profile of the Envelope responds to accretion luminosity

Implications of Variable Accretion - II

Luminosity of Source gets higher and SED shifts to the blue (Warmer)

- Approximately linear with accretion ratio
- Approximately linear with temperature ratio

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Implications of Variable Accretion - III

Dust must be heated (cooled) to these new temperatures ...

Figure 8.9. The specific heat per gram of dust for silicate (full curve, similar to [Guh89]), graphite (broken curve, after [Cha85]) and PAHs without hydrogen atoms (dotted curve, after [Kru53] using (8.44)).

Implications of Variable Accretion - IV

The light propagation time must be taken into account ...

Crossing time of the effective photosphere, $R_{ph} \sim 50$ AU, is about 5 hrs.
Implications of Variable Accretion - V

The observable timescale for variability can be assessed:

![Graph showing observable timescale for variability]

- 500 hrs
- 5000 hrs
- 0.5 hrs
- 5.0 hrs
- 50 hrs

Don’t Trust

\[ \text{JCMT – SCUBA2} \]
Spitzer/Wise Variability ...

Outbursts seem to be common

- Over 7 years, 3 of 329 protostars began outbursts
- Suggests ~ 800 yrs between outbursts; each protostar has many over its formation period
- But these three luminosity increases are of order ~ 10x (canonical FU Oris are > 100x)
Herschel Variability ...

70 and 160 microns

Orion observed six times over six weeks.

8/17 found to have >10% flux variability (LHS of figure)!

Argue likely due to inner disk variability in mass accretion.

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Figure 2. Sample of reliable PACS light curves drawn from Table 2. The left column presents the light curves of variable protostars, and the right column contains those that show flux variations within the estimated photometric uncertainties (see Section 2.3 for details). The set of graphs in the top row show the light curves at 70 μm and (60) μm when both are deemed reliable, while the other plots give 70 μm fluxes only. The horizontal dashed and dotted lines give the average flux of the sources and the ±5% variations around the mean, respectively, indicating our level of confidence for variability detections. The first epoch was obtained on 2011 February 26, corresponding to the Herschel Operational Day 653 or MJD 55618.
The EAO/JCMT Transient Survey

OMC 2/3  NGC 2024  NGC 2071  Ophiuchus

8 Regions < 500 pc (GBS)  3 Year Survey
182 Protostars, 800 Disk sources  One Month Cadence

NGC 1333  IC348  Serpens Main  Serpens South

Calibration Methodology

Run Source-Finder on all epochs of the field (PhD student- Steve Mairs). Determine which sources are in common between observations. Compare clump centroids and relative brightness between observations.

Six epochs of IC348 observed over half a year. 
Left: Before residual offset calibration; Right: after applying offset.
Calibration Methodology

Image Alignment (to reference map)

By aligning the maps obtained on different dates to a common reference, we can better compare peak brightness changes between dates.

Post-Alignment

Pre-Alignment
Calibration Methodology

Achieve relative alignment calibration of better than one arcsecond.
Achieve relative flux calibration of better than 3%.

JCMT has ~8% Flux Uncertainty

Our relative flux uncertainty is ~2.5%
Calibrated Light Curves and Variance:


Relative Flux calibration ~ 2% limited to high S/N Sources.
Calibrated Light Curves and Variance:

JCMT Variation Over A Few Years ...

Align and apply relative calibration to, 2-4yr prior, GBS Survey images.

**Figure 17.** Same as Figure 10, but showing the Serpens South field with its corresponding archival GBS fields. The red (dashed) circle shows the SerpensS-NW GBS field while the blue (dotted) circle shows the SerpensSouthS-NE GBS field.
JCMT Variation Over A Few Years ...

We perform the same calibration for GBS Data and hunt for variability over several year baselines!

GBS Survey ~4yrs before Transient Survey

Serpens South - Protostar

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JCMT Variation Over A Few Years ...


Figure 7. The distribution of $\delta$ values for all sources. The red points represent a Gaussian fit to the histogram. The vertical dashed lines indicate the threshold for a significant detection of a variable candidate.
JCMT Variation Over A Few Years ...

There are approximately a half dozen sources with a robust detection of flux variation between GBS and Transient epochs.

\[ |\Delta f/f| < 0.20 \quad \rightarrow \quad |\Delta f/f| < 0.05 \text{ per year.} \]

JCMT Ensemble Variability: $\sim \Delta 1.5$ Yrs

1) Create a mean map from all epochs: deepest images
2) Find all the peaks in the map: we use Fellwalker (JSACatalogue)
3) Collate peaks with known protostars and disks: Herschel & Spitzer
4) Determine standard deviation (sigma) for all peaks/all regions
   - With and without sigma-clipping for outliers (small # of epochs)
5) Compare against fiducial model for measurement uncertainty
   - Low flux: *Noise dominates*; High flux: *Calibration dominates*

**Bottom Line:**
So far only EC53 stands out as a clear outlier in measurement uncertainty.
JCMT Ensemble Variability: $\sim \Delta 1.5$ Yrs

6) Fit simple linear brightness profiles to bright sources (> 350 mJy)
   - determine slope and the uncertainty in the slope

7) Randomize order of epochs and repeat fitting process
   - Compare random distribution against ordered distribution

JCMT Ensemble Variability: $\sim \Delta 1.5$ Yrs

6) Fit simple linear brightness profiles to bright sources ($> 350$ mJy)
   • determine slope and the uncertainty in the slope

7) Randomize order of epochs and repeat fitting process
   • Compare random distribution against ordered distribution

Slope measured in units of fractional flux change over one year.
### Table 7. Comparison of Identified Variable Sources

<table>
<thead>
<tr>
<th>Region</th>
<th>Name</th>
<th>Transient Analysis $S/\Delta S^a$</th>
<th>$S$ (yr$^{-1}$)</th>
<th>Transient-GBS Analysis $\delta^b$ S (yr$^{-1}$)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serpens M</td>
<td>EC 53</td>
<td>7.9</td>
<td>0.28</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Serpens S</td>
<td>IRAS 18270-0153</td>
<td>4.1</td>
<td>-0.05</td>
<td>11.81</td>
<td>-0.04</td>
</tr>
<tr>
<td>NGC 2068</td>
<td>HOPS 373</td>
<td>4.3</td>
<td>-0.05</td>
<td>5.34</td>
<td>-0.04</td>
</tr>
<tr>
<td>Serpens M</td>
<td>SMM-1</td>
<td>3.2</td>
<td>0.05</td>
<td>6.85</td>
<td>0.02</td>
</tr>
<tr>
<td>OMC 2/3</td>
<td>HOPS 383</td>
<td>3.0</td>
<td>-0.04</td>
<td>4.17</td>
<td>-0.03</td>
</tr>
<tr>
<td>NGC 1333</td>
<td>Bolo 40</td>
<td>1.5</td>
<td>-0.04</td>
<td>7.99</td>
<td>-0.03</td>
</tr>
<tr>
<td>NGC 1333</td>
<td>IRAS 4A</td>
<td>-</td>
<td>-</td>
<td>7.66</td>
<td>0.02</td>
</tr>
<tr>
<td>NGC 1333</td>
<td>[LAL96] 213</td>
<td>-</td>
<td>-</td>
<td>8.31</td>
<td>-0.09</td>
</tr>
<tr>
<td>Serpens M</td>
<td>SMM 10</td>
<td>5.1</td>
<td>0.07</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

$^a$ Sources with $S/\Delta S > 4$ are robust against false-positives within the entire ensemble (see §4). Those sources with $S/\Delta S \geq 3$ are strong candidates when treated as a special case.

$^b$ Sources with $\delta > 5$ are robust against false-positives within the entire ensemble (see Mairs et al. 2017a). Those sources with $\delta > 4$ are strong candidates when treated as a special case.
Mass Accretion – Non-Steady?


Caveat: Neither model designed for such short times!

Putting It All Together ...

- JCMT Transient Survey finds ~10% of protostars vary ~10% percent per yr
- *Herschel/Wise* suggests ~1% of protostars vary ~500 percent per 10 yrs
- Episodic Accretion implies 100% of protostars vary orders of mag per 1000 yrs

*At end of JCMT Transient Survey we should have much better statistics on the observed secular variability and a cleaner handle on transient phenomena.*
Other Opportunities For Time-Domain

• JCMT Transient – Steve Mairs (PhD), James Lane (Undergrad)
  – Continues for another 1.5 yrs (at least)

• ALMA Follow-up/Monitoring/Serendipity – Logan Francis (MSc)
  – ALMA Cycle 5 proposal to resolve inner part of EC 53 during quiescence and burst
  – Archival comparison of sources over time

• CCAT-P (and other single-dish)
  – Higher sensitivity, larger field of view, higher frequency observations possible
  – For CCAT-P can monitor almost all Orion protostars at 350 microns (S/N > 100) with ~hr per epoch

• Far IR Space Telescopes (SPICA/ORIGINS)
  – Excellent calibration opportunity, limited lifetime
FINAL THOUGHTS

• Initial results from the 3yr (150hr) JCMT Transient Survey suggest a rich future for *Protostellar (Accretion Disk) Seismology*

• Time-domain explorations in the (sub)mm should be carefully considered for existing and planned instruments/telescopes
  – Multi-wavelength (SED) observations advantageous
  – Need Fast-Mapping, Sensitivity (S/N), and Calibration
  – Require observing strategies that control systematics
    • But also provide strong incentive for improvements in calibration techniques (as has taken place at the JCMT)
    – Need to consider physical conditions being probed
  • Determine appropriate observing strategies

Fin