Submillimeter continuum variability in Planck Galactic cold clumps using the JCMT-SCOPE survey


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Why we are interested in flux variability?

• The variability of the protostellar disk accretion will be important to understand the evolution of the envelope and disk.

• Protostellar luminosity problem (e.g., Kenyon+ 1990; Dunham+ 2010) ← variable protostellar accretion rate (episodic accretion)

• The mass accretion rates are high in the early stages of protostellar evolution (e.g., Whitworth & Ward-Thompson 2001; Schmeja & Klessen 2004). But, direct observations at optical or near-IR variability are very challenging (∵ heavily embedded in optically thick, dense envelopes).

• Fortunately, indirect observations at sub-mm wavelengths are achievable. ∴ Most of emission by the accretion energy appears in far-IR to sub-mm wavelengths by reprocessing through the protostellar envelope (Johnstone+ 2013).
Previous observational results

- The Majority of accretion variability observations have so far been carried out in the evolved stages of pre-main-sequence stars.
  - A large optical brightness increase of a factor of ten or more observed in FU Orionis (e.g., Herbig 1977; Hartmann & Kenyon 1996) or EX Lupi (e.g., Herbig 2008; Aspin+ 2010)
Recently, a few outbursts from deeply embedded protostellar objects have been reported.

- About a-factor-of 1.5 increase at 850 μm toward Class I protostar EC53 (Yoo+ 2017)
- About a-factor-of-2 increase at 350/450 μm toward Class 0 source HOPE 383 (Safron+ 2015)
- Strong, declining light curve over the course of 16 months in HOPS 358 (Mairs+ 2018)
- Also, a factor of 4.2 increase in 870 μm continuum interferometric flux in a high-mass protostellar system NGC 6334I-MM1 (Hunter+ 2017)
The Transient team found that \( \sim 10\% \) of deeply embedded protostars display varying flux at the level of 5\%–10\% per year. However, the nearby regions that they studied are mostly forming low-mass stars.
SCOPE survey: Observations

- “SCUBA-2 Continuum Observations of Pre-protostellar Evolution”
- begun in December 2015 and completed in July 2017

- 850 μm; SCUBA-2 sub-mm bolometer at the 15m JCMT (FWHM = 14.1") cf. Planck: 5'
- CV Daisy mode (Mapping size of diameter ~ 12’)
- Observations under grade 3/4 weather condition with 225 GHz opacities between 0.1–0.15
- First data reduction: filtering out scales larger than 200" on a 4" pixel scale
JCMT-SCOPE Survey: Targets

- **Main aim:** Statistical study the initial conditions occurring during star formation across a wide range of environments

- **Source selection (~1200 PGCCs):**
  - high column density PGCCs (> $1 \times 10^{21}$ cm$^{-2}$ in Planck meas.)
  - randomly selected lower column density clumps at high latitudes (> $5 \times 10^{20}$ cm$^{-2}$ in Planck meas.)

- For about 3/5 of the SCOPE sample (Planck Collaboration+ 2016):
  - About 70% among them are concentrated within 1 kpc while the others are widely distributed at up to $\sim 8$ kpc, with an average angular size of $\sim 8'$.  
  - The mass range is from 0.1 M$_{\odot}$ to $10^5$ M$_{\odot}$. 
The SCOPE survey done three times separate observations for some (< 30) of PGCCs which seem to contain massive clumps (with multiple substructures) in order to obtain deep images of high-mass star forming regions as well as to detect large flux variation events.

See Liu+ 2018 for detailed description of the survey and Eden+ 2019 for information of the first data release and the catalog of compact sources resolved with the JCMT.
In this study, we selected 12 PGCC fields in the first quadrant of the Galactic plane that are moderately bright and contain a relatively large number of clumps. 18 PGCCs are written using the acronym "PGCCs" in the text. These regions span the Galactic longitude range of $14^\circ < l < 36^\circ$ and are located at heliocentric distances from $\sim 1.5$ to 17 kpc (Table 1).

The three observations of each field were not carried out with a regular cadence and, therefore, had intervals spanning three weeks to 13 months. The total exposure time to complete each epoch is 15.4 minutes on average, and the median and maximum of exposure times per pixel are $\sim 55$ and $\sim 200$ s, respectively. Each image was smoothed with a Gaussian kernel of 8″ FWHM (twice the pixel size) to reduce pixel-to-pixel noise. Thus, the final images shown in this paper have an angular resolution of 16 FWHM after smoothing.

3. Data Reduction

The default 850 m absolute flux calibration produced by the data reduction pipeline at the JCMT yields a 5%–10% uncertainty in pointlike calibrator source swath through4 (Dempsey et al. 2013; Mairs et al. 2017b). Therefore, to detect a 3 rms $T$ change in the peak flux of a source, the brightness variation would need to be at least 15%–30%. Simulations (e.g., Bae et al. 2014; Vorobyov & Basu 2015) as well as JCMT Transient Survey observations (Mairs et al. 2017a; Johnston et al. 2018), however, suggest that less dramatic flux variations are more common. In order to increase detection reliability, it is advantageous to calibrate the flux in a relative sense using the method presented by Mairs et al. (2017b). In this way, it is possible to reduce the (relative) flux uncertainty to 2%–3%, which allows for statistically significant measurements of $\sim 6$%–10% flux changes.

In our implementation of the relative flux calibration scheme, we restricted the sources with high $(>25)$ signal-to-noise ratios (S/N; see Section 4.1 for details). However, unlike the Transient Survey procedure, we did not require that the sources are compact. In comparing the source fluxes of different objects, the SCOPE clumps shown in this paper encompass masses from tens of solar masses to thousands of solar masses, spanning the range of cores to clouds. For simplicity, we refer to all these objects as clumps.

Figure 1. Co-added images for the 12 SCOPE survey. Each image is cropped using a circle with a radius of 370″. The field name is displayed at the top left of each image. The color bar is shown in a linear scale, ranging from $-30$ mJy beam$^{-1}$ (black) to the value in parentheses at the top right of each image. White circles are marked to help to locate the outliers described in Section 4, and the number assigned to each circle is from Table 3.

The definition of "clump" is ambiguous. In this paper, SCOPE clumps resolved in the JCMT images are at various distances (see Table 1) and can contain substructures that are visible at higher resolution. The SCOPE clumps shown in this paper encompass masses from tens of solar masses to thousands of solar masses, spanning the range of cores to clouds. For simplicity, we refer to all these objects as clumps.
12 SCOPE fields: Information

Table I

Fields and Epochs

<table>
<thead>
<tr>
<th>Field</th>
<th>Central Positiona</th>
<th>Three Epochs</th>
<th>Time Intervalsb</th>
<th>Distance(s)c</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(h:m:s)</td>
<td>(yyyy mm dd)</td>
<td>(day)</td>
<td>(kpc)</td>
</tr>
<tr>
<td>G14.14−0.55</td>
<td>18:18:11.50</td>
<td>2016 Apr 10</td>
<td>395</td>
<td>1.5</td>
</tr>
<tr>
<td>G14.47−0.20</td>
<td>18:17:31.80</td>
<td>2016 Apr 9</td>
<td>397</td>
<td>3.1 (11.5)</td>
</tr>
<tr>
<td>G14.71−0.19</td>
<td>18:17:59.80</td>
<td>2016 Apr 9</td>
<td>396</td>
<td>3.1</td>
</tr>
<tr>
<td>G15.61−0.48</td>
<td>18:20:48.40</td>
<td>2016 Apr 10</td>
<td>396</td>
<td>1.8 and 16.9</td>
</tr>
<tr>
<td>G23.68 + 0.57</td>
<td>18:32:23.20</td>
<td>2016 Apr 11</td>
<td>394</td>
<td>5.8</td>
</tr>
<tr>
<td>G23.97 + 0.51</td>
<td>18:33:09.20</td>
<td>2016 Apr 11</td>
<td>396</td>
<td>5.8</td>
</tr>
<tr>
<td>G24.04 + 0.26</td>
<td>18:34:10.40</td>
<td>2016 Apr 11</td>
<td>394</td>
<td>7.8</td>
</tr>
<tr>
<td>G24.49−0.52</td>
<td>18:37:48.10</td>
<td>2016 Apr 11</td>
<td>396</td>
<td>11.3</td>
</tr>
<tr>
<td>G25.68−0.14</td>
<td>18:38:39.10</td>
<td>2016 Apr 11</td>
<td>393</td>
<td>10.2 (7.4)</td>
</tr>
<tr>
<td>G26.17 + 0.13</td>
<td>18:38:34.70</td>
<td>2016 Apr 11</td>
<td>141</td>
<td>7.6</td>
</tr>
<tr>
<td>G33.72−0.02</td>
<td>18:52:55.20</td>
<td>2016 Apr 12</td>
<td>101</td>
<td>6.5 (2.2)</td>
</tr>
<tr>
<td>G35.49−0.31</td>
<td>18:57:12.90</td>
<td>2016 Apr 13</td>
<td>55</td>
<td>2.7 (3.2 and 10.3)</td>
</tr>
</tbody>
</table>

Notes.

b Time intervals between the first and second epochs and between the second and third epochs.
c Distances are obtained from (Urquhart et al. 2018, see also references therein). For fields having clumps at various distances, we give the distance of the majority of clumps along with the value(s) of the minority in parenthesis, or, if they are almost equal numbers, two values with the conjunction “and.”
Need for Relative Flux calibration

- Telescope pointing uncertainty: 2-6"
- Default absolute flux calibration uncertainty for SCUBA-2 images: ~ 5-10%
- References: Dempsey+ 2013; Mairs+ 2017b

- To detect a $3 \sigma_{rms}$ change in the peak flux of a source, the brightness variation would need to be at least 15%-30%.
- But, less dramatic flux variations are more common (e.g., Bae+ 2014; Vorobyov & Basu 2015; Mairs+ 2017a; Johnstone+ 2018).
- In order to increase detection reliability, we performed additional relative flux calibration using the method of Mairs+ 2017b.
Data Analysis

- Make data arrays to have same grid coordinates (wcsasalign in STARLINK)

- **Smoothing** using a Gaussian kernel with FWHM = 2 px (gaussmooth in STARLINK) (finally, FWHM = 16.2"")

- Make a co-added image (picard MOSAIC JCMT IMAGES in STARLINK)

- Estimate RMS noise levels as a function of exposure times in areas of no or very little emission for each epoch image

- **Find clumps** using the co-added image (findclump in STARLINK: method=clumpfind) and remove if a clump peak is located beyond 370" from the central position

- **Apply relative flux calibration** and then read peak fluxes from three epochs

- Check clumps showing somewhat higher $\frac{SD_{meas}}{SD_{fid}}$
Clumpfinding & relative flux calibration

- We found clumps in the co-added image. Only sources having a mean peak flux $\geq 250$ mJy/beam ($\sim 25$ S/N in a single epoch; noise $\sim 10$ mJy/beam)

- We used any clumps having $\sigma_{\text{std,meas}}/\sigma_{\text{std,fid}} < 1.7$ for calibration.

\[
\sigma_{\text{std,fid}}(i) = \sqrt{\sigma_{\text{rms}}(i)^2 + \left( u_{\text{cal}} \times F_m(i) \right)^2},
\]

\[
u_{\text{cal}} = \sqrt{\frac{\sum_{c=1}^{n_c} \sigma_{\text{std,meas}}(c)^2 / F_m(c)^2}{n_c - 1}}.
\]

Johnstone+ 2018

- We derived a relative flux calibration factor (RFCF) for each epoch and then each epoch data were divided by RFCF.

- The relative calibration steps were repeated using a clipping process to identify a set of stable calibrators.
Results of Relative flux Calibration

We adopted the methods performed by the Transient Survey team to investigate peak flux changes over time. However, the SCOPE survey was not optimized for this type of work, so the following alterations to the Transient Survey methodology were applied.

First, our smoothing kernel size is slightly larger than that of the Transient Survey team (8″ as opposed to 6″). Second, we used the CLUMPFIND algorithm while the Transient Survey team used GAUSCLUMPS (Stutzki & Guesten 1990). Both these algorithms provide almost the same results overall, but there are some differences in complex areas of a given map. Third, we applied a different set of criteria from the Transient Survey to select clumps from the catalogs obtained by using each algorithm. The Transient Survey team considered only sources which are very bright (50 mJy T) and compact (effective radius assuming a circular projected configuration 10′), and which appear in every epoch. Alternatively, we included less bright (25 mJy T) sources and more extended sources. Fourth, the calibrator selection described above in this section differs from that of the Transient Survey team due to the difference in the number of bright sources. While we considered all the clumps to be potential calibrators at the beginning and then selected the invariable clumps, the Transient Survey team could be more selective as their fields contain many compact, bright clumps for the calibration such that the uncertainty from the noise was less than 5% (Mairs et al. 2017b). In spite of the difference in bright source selection for the relative flux calibration, the procedure presented in this study is sufficient to detect a flux variation of 10%.

4. Results

4.1. Analysis of Peak Flux Measurement

We identified 136 clumps with F250 mJy beam across the 12 fields. Figure 4 shows the std,meas T/std,fid T as a function of the mean peak flux density. Almost all clumps (132/136; marked with filled symbols in the figure) show little flux changes and are used as calibrators. Four outliers (open symbols) in three different SCOPE fields were detected.
4 Outliers

4 outliers of 136 clump peaks in 12 fields

\[ \frac{\sigma_{\text{std,meas}}}{\sigma_{\text{std,fid}}} \]

\[ F_* \text{ (mJy/beam)} \]

\[ T_0 = 0.14 \quad 0.26 \quad 0.55 \]

\[ T = 0.55 \]

\[ \text{cf. EC 53: } \frac{SD}{SD_{\text{fid}}} = 5.6 \] (Johnstone+ 2018)
Large Scale Bias Check

The flux variation indeed originates from the brightness of the localized source.

These are probably caused by artificial large-scale structure. (∵ We do not expect to observe large variations in the brightness of an extended structure in star-forming regions)
One potential Variable Candidate

- Outlier 1: G14.143–0.508 in found in the G14.14–0.55 field
- $\sigma_{\text{std,meas}}/\sigma_{\text{std,fid}} = 2.6$

- matched with ATLASGAL clump AGAL014.142–00.509: $v_{\text{LSR}} = 21.1$ km/s; $d = 1.5$ kpc (Urquhart+ 2015)
- deeply embedded in an IR dark cloud filament, seemingly starless
  - It can’t completely rule out presence of at least one undetected heavily embedded (proto)star(s).
- We suggest that the detected flux change could potentially be caused by accretion variability.
• How to determine whether there is low- or high-mass star formation occurring?

• Relationship between the bolometric luminosity and the envelope mass is useful (e.g., Molinari+ 2008; Urquhart+ 2014; Motte+ 2018).

• Clump of Outlier 1: luminosity ($\approx 37 \, L_\odot$) and the mass ($\approx 23 \, M_\odot$) (Urquhart+ 2018) → likely related to low- or intermediate-mass star formation.
Future Work

- The Transient expansion proposal has been submitted last month. “The JCMT Transient Survey: Fainter Objects, Higher Masses, Longer Timescales” (Herczeg et al.)

- High-mass star forming regions will be studied.
  - M17
  - M17 SWex
  - S255
  - three fields in DR21
Summary

- Among the SCOPE 850 μm survey data, we investigated sub-mm flux-variability of cold Planck sub-clumps (peak flux ≥ 250 mJy/beam) in 12 fields.

- We applied a relative flux calibration and achieved a calibration uncertainty of ∼3.6% on average.

- Total of 136 clumps were identified in all fields. We found four outliers showing peak flux variations.

- One of them is likely to be a potential variable candidate. The variations from the remains appear to be primarily due to large-scale contamination.

- The flux change of the candidate may be associated with low- or intermediate-mass star formation assuming a distance of 1.5 kpc.