Herschel/PACS variability survey of IC348

Zoltan Balog

MPIA

Collaborators:

James Muzerolle (STScI)
Kevin Flaherty (Univ. of Arizona)
Rob Guthermuth (Umass)
Elise Furlan (IPAC)
Ors Hunor Detre & Jeroen Bouwmann (MPIA)
Gabor Marton (Konkoly Observatory)
Variability of YSOs

- **Variability is a common property of YSOs (Joy, 1945)**
  - optical / near-IR: accretion shocks
  - several surveys at different wavelengths
  - mid-IR: inner disk structure (warped disks, variable scale height)
    - Spitzer/YSOVAR Morales-Calderón et al. 2009
    - Flaherty et al. 2011, 2013 (Spitzer - IC348)
  - far-IR: variable illumination of cold outer disk (class II) or luminosity fluctuations (class 0/I)
    - reason: variable accretion, variation in the scale-height of the inner disk
  - very little pre-*Herschel* data
    - Juhász et. al. (2007), Kóspál et al. (2007) ISOPHOT
    - Harvey et al. (1998), KAO

![Figure 1](image1.png)

**SV Cep**

![Figure 2](image2.png)

**OO Ser**
Variability of YSOs

The situation improved a lot with *Herschel*

- **P27: Ábrahám et al.**
  - Deep 70 μm map of LDN 1688, obtained 2 years after the HGBS
  - Comparison of the two maps revealed 11 variable objects at the >30% level

- **P50: Kóspál et al.**
  - 4-epoch weekly monitoring of 8 selected T Tauris in Cha I
  - 6 sources show 5–11% variability on weekly timescale

- **P32: HYSOVAR Billot et al. 2012**
  - 18-epoch through 4 visibility windows
  - several variable object on the 10%-50% level
  - see also Billot et al. 2012
Observations and Data Reduction

Gutermuth et al. 2009

red: 24 μm; green: 5.8 μm; blue: 3.6 μm

IC348

• relatively nearby ~400pc
• contains all kinds of YSOs class 0 - class II
• well studied at shorter wavelengths

DATA

• 29 epoch in three visibility windows
• covering more than a year in time with different timescales
  • ~1 year, ~2 months, ~2 weeks, ~2 days
• ~15’x15’ area
• most of the Spitzer 70 μm detections
  • trade-off had to be made to keep observing time reasonable

PROCESSING

• The data were uniformly processed with three methods
  • Scanamorphos
  • JScanam
  • High Pass Filtering
• Photometry was performed in HIPE using circular apertures and using the the boloSource() algorithm
• all gave similar results with some systematic differences, however it did not influenced the variability
Photometric stability of the PACS instrument

- absolute flux accuracy ~7%
- repeatability ~2%
  - it is tested only in high-pass filter + photProject
  - other processing methods might introduce a up to 5-10% systematic error see:

  http://herschel.esac.esa.int/2013Mapmaking/Workshop/presentations/PACS_PointSourcePhotometry_ZBalog_MapMaking2013_DPWS.pdf

- for more information on the calibration see Balog et al. 2013 Exp.Astr. in press:
Photometric stability of the PACS instrument

- Tools are in place to improve the repeatability.
- They are being tested
- Final goal: ~0.5% in the blue camera and 2% in the red
Photometric stability of the PACS instrument

- Tools are in place to improve the repeatability.
- They are being tested
- Final goal: ~0.5% in the blue camera and 2% in the red
boloSource() - interpolation in the timeline

Projected L2 map

- Aperture
- L2 mask
- L1 mask of a given bolometer pixel

Nominal scan direction
Orthogonal scan direction

Signal decomposition with Stationary Wavelet Transform:

\[ I(t) = \frac{N_1}{f(t)} + N^D(t) + N^{\text{det}}(t) + I^{\text{S(low freq)}}(t) \]

- Interpolated intensity in masked timeline
- Simulated noise
- Baseline estimate from data

Source-only map with flat, zero level background

Interpolated signal with Monte-Carlo simulated noise spectrum

Estimated baseline

Input mask, extended mask and adaptive mask
boloSource() - interpolation in the timeline

Original images processed with Scanamorphos

Red: 160 µm  Green: 100 µm  Blue: 70 µm
boloSource() - interpolation in the timeline

Interpolated images processed with Scanamorphos

Red: 160 μm Green: 100 μm Blue: 70 μm
Maps and detected sources

Spitzer/MIPS 70 μm image
Maps and detected sources

Herschel/PACS 70 μm image
Maps and detected sources

sources detected with Spitzer at 70 μm 12 in our FOV
Maps and detected sources

sources detected with Herschel at 70 μm
- 46 including all Spitzer detections
- no all suitable for photometry on the individual images
Variability

- 46 sources detected on the combined images
- 37 sources were suitable for photometry on the individual images
  - 30 mJy - 10.5 Jy at 70 μm
- Photometric uncertainty is impossible to estimate on the single epoch maps
- The rms of the background flux within the aperture after interpolation
- Compare it with the rms of the source
  - Variable: source rms > 3 x background rms
  - Source rms > 5%
Variability

- 10 sources show reliable variability at wavelengths of 70 \( \mu m \) and 160 \( \mu m \)
- all brighter than 800 mJy at 70 \( \mu m \) (9 brighter than 1 Jy)
Variability

• some shows variability at shorter timescales ~ 2 months
Variability

- some even shows variability at a 2 weeks timescale
<table>
<thead>
<tr>
<th>Name</th>
<th>Class</th>
<th>70</th>
<th>160</th>
<th>rms: ~1 year</th>
<th>rms ~2 months</th>
<th>rms ~2 weeks</th>
<th>rms ~3 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>LRLL0245</td>
<td>I/II</td>
<td>1.377</td>
<td>1.039</td>
<td>0.201</td>
<td>0.066</td>
<td>0.037</td>
<td>0.031</td>
</tr>
<tr>
<td>LRLL54361</td>
<td>I</td>
<td>7.324</td>
<td>9.668</td>
<td>0.619</td>
<td>0.287</td>
<td>0.257</td>
<td>0.054</td>
</tr>
<tr>
<td>HH211</td>
<td>0</td>
<td>4.565</td>
<td>31.054</td>
<td>0.054</td>
<td>0.053</td>
<td>0.016</td>
<td>0.007</td>
</tr>
<tr>
<td>LRLL57025</td>
<td>0/I</td>
<td>5.864</td>
<td>25.456</td>
<td>0.0618</td>
<td>0.029</td>
<td>0.006</td>
<td>0.009</td>
</tr>
<tr>
<td>SSTc2d_J034357.8+320312</td>
<td>---</td>
<td>1.371</td>
<td>12.392</td>
<td>0.091</td>
<td>0.026</td>
<td>0.026</td>
<td>0.050</td>
</tr>
<tr>
<td>LRLL0051</td>
<td>I/II</td>
<td>8.472</td>
<td>5.952</td>
<td>0.071</td>
<td>0.059</td>
<td>0.064</td>
<td>0.028</td>
</tr>
<tr>
<td>LRLL0031</td>
<td>II</td>
<td>0.869</td>
<td>1.244</td>
<td>0.077</td>
<td>0.071</td>
<td>0.040</td>
<td>0.031</td>
</tr>
<tr>
<td>LRLL1889</td>
<td>I</td>
<td>1.261</td>
<td>1.884</td>
<td>0.081</td>
<td>0.092</td>
<td>0.050</td>
<td>0.026</td>
</tr>
<tr>
<td>LRLL1872</td>
<td>I</td>
<td>5.108</td>
<td>16.114</td>
<td>0.146</td>
<td>0.220</td>
<td>0.018</td>
<td>0.083</td>
</tr>
<tr>
<td>LRLL1898</td>
<td>I</td>
<td>10.450</td>
<td>25.586</td>
<td>0.152</td>
<td>0.200</td>
<td>0.017</td>
<td>0.010</td>
</tr>
</tbody>
</table>
• large variations at all IRAC wavelengths detected in our Spitzer/IRAC survey with a period of 25.34 days
• HST observations reveal a spectacular light echo (Muzerolle et al. 2013)
Explanation: binary induced pulsed accretion
Explanation: binary induced pulsed accretion

Static models of the minimum and maximum reveal the physical properties of the source:

- Envelope infall rate: $3 \times 10^{-6} \, M_\odot \, yr^{-1}$
- Envelope centrifugal radius: $R_c = 30 \, AU$
- Outflow cavity opening angle: $\theta = 30^\circ$
- Angle of the outflow/stellar rotation axis to the line of sight: $i = 70^\circ$
- Total central luminosity (stellar plus accretion): $L = 0.5 \, L_\odot$ and $1.3 \, L_\odot$
- $\eta_{\text{star}} = 0.5$ (min) and 0.19 (max)
- CO$_2$ ice abundance of $10^{-4}$, and an H$_2$O ice abundance of $2 \times 10^{-3}$
- Disk accretion rate: $10^{-6}$
Herschel observations also reveal periodic variations

Huge thanks to the entire Herschel mission planning team
Especially: Mark Kidger and Rosario Lorente
Herschel observations also reveal periodic variations

![Graph showing periodic variations in flux with mean, standard deviation, and peak-to-peak values.]
Two different maxima showed that there is a difference between two periods. It can be modeled entirely with accretion variations.

accretion rate may vary by a factor of 2
LRLL54361 - light echo

Echo 1

Echo 2
LRLL54361 - light echo

HST/WFC3

deconvolved PACS

HST/WFC3

deconvolved PACS
Summary

• multi epoch photometric survey of IC348 with Herschel/PACS at 70 μm and 160 μm
• 46 sources detected including all sources detected with Spitzer/MIPS at 70 μm
  • brightness range ~ 30 mJy - 10.5 Jy
• 10 sources shows reliable variability on the scale of ~1 year
  • majority of the sources show variability on the scale of 2 months
  • some show even reliable weekly or daily variability
  • all brighter than 800 mJy
  • fainter sources show some sign of variability but needs confirmation
• periodic variation of LRLL54361 is confirmed in the far-IR
  • the maximum flux varies from period to period (also in mid-IR)
  • accretion rate at maximum light varies by an order of magnitude
  • tentative detection of the near-IR light echo at 70 μm