SOFIA Proposal 07_0157

Embedded nebula Gy 3-7 - tracing feedback from protostars on cluster scales

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Abstract

During the earliest stages of star formation, protostars are deeply embedded in dense envelopes and drive powerful outflows. Even low-mass protostars may have considerable impact on their star-forming clusters e.g. via regulating the efficiency of star formation (Offner & Arce 2014). The nature and energetics of these interactions are best traced by far-infrared lines of CO, H2O, [OI] and OH, which are efficient gas coolants (Karska et al. 2013). These lines were observed by the PACS instrument on Herschel, but the surveys primarily focused on individual, mostly nearby (< 500 pc) protostars distributed in various clouds (Karska et al. 2014a,b, 2018). Thus, the cummulative effect of feedback from protostars on the entire clusters could not be measured. Here, we aim to use FIFI-LS integral field spectrometer to characterize far-IR line emission from embedded cluster Gy 3-7 located in the Canis Major region in the Outer Galaxy. A combination of molecular and atomic lines will be used to quantify the total mechanical and radiative feedback from protostars and explain exceptional brightness of Gy 3-7 in far-IR. We will take advantage of FIFI-LS unique mapping capabilities and investigate the far-IR emission in CO 14-13 at 186 μm, CO 16-15 at 163 μm, CO 18-17 at 144 μm, [OI] 63 μm and [CII] 158 μm lines. The analysis will rely on our prior experience with a sample of ~100 protostars spanning a broad range of masses obtained as part of the ”Water in star forming regions with Herschel” program (van Dishoeck et al. 2011). We will measure the energy injected into the cluster by protostars. Spatial distribution of emission in various tracers will elucidate the dominant excitation mechanisms in Gy 3-7. Thus, we will quantify cummulative feedback from low- and intermediate-mass protostars in the entire cluster for the first time.

Investigators:

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CoI	Dr. Christian Fischer	DSI, University of Stuttgart	fischer@dsi.uni-stuttgart.de

Number of investigators: 8

DCS account name : barthel@dsi.uni-stuttgart.de
TAC Queue: DE
Regular Observation requested.
Participation in the SOFIA German Ambassador‘s EPO program requested.

Related Proposals

Status of SOFIA Observations in the Last Two Years

Special Instructions

Instruments Requested:

Instrument	Observing Time (hr)
FIFI-LS	4.33

Total observing time requested = 4.33 hours

Objects for FIFI-LS:

1. gy37-o1-63 AOR_ID: 07_0157_1 IRAS 07069-1045 Type: Sidereal Velocity: 16.5 km/s Priority: Medium Order: 1
   Config: DUAL-CHANNEL Spectral Element1: FIF_BLUE Spectral Element2: FIF_RED
   WavelengthBlue: 63.184 WavelengthRed: 157.741
   Blue Spectral Width: 30.0 km/s Red Spectral Width: 30.0 km/s
   Nod Style: SYMMETRIC_CHOP Mode: SYMMETRIC_CHOP
   Requested Time: 2,400 secs Overhead: 4,300 secs Total: 6,700 secs
   RA: 7 09 20.54 DEC: -10 50 25.80 ProperMotion RA: 0.0 DEC: 0.0 arcsecs/year
   Map Area: 900 arcsec^2
   Guide Star message: There are FPI guidestars.
   Requested Water Vapor: Nominal
2. gy37-co-186 AOR_ID: 07_0157_2 IRAS 07069-1045 Type: Sidereal Velocity: 16.5 km/s Priority: Medium Order: 2
   Config: DUAL-CHANNEL Spectral Element1: FIF_BLUE Spectral Element2: FIF_RED
   WavelengthBlue: 118.581 WavelengthRed: 185.999
   Blue Spectral Width: 30.0 km/s Red Spectral Width: 30.0 km/s
   Nod Style: SYMMETRIC_CHOP Mode: SYMMETRIC_CHOP
   Requested Time: 1,020 secs Overhead: 2,000 secs Total: 3,020 secs
   RA: 7 09 20.54 DEC: -10 50 25.80 ProperMotion RA: 0.0 DEC: 0.0 arcsecs/year
   Guide Star message: There are FPI guidestars.
   Requested Water Vapor: Nominal
3. gy37-co-163 AOR_ID: 07_0157_3 IRAS 07069-1045 Type: Sidereal Velocity: 16.5 km/s Priority: Medium Order: 3
   Config: DUAL-CHANNEL Spectral Element1: FIF_BLUE Spectral Element2: FIF_RED
   WavelengthBlue: 87.19 WavelengthRed: 162.812
   Blue Spectral Width: 30.0 km/s Red Spectral Width: 30.0 km/s
   Nod Style: SYMMETRIC_CHOP Mode: SYMMETRIC_CHOP
   Requested Time: 780 secs Overhead: 1,600 secs Total: 2,380 secs
   RA: 7 09 20.54 DEC: -10 50 25.80 ProperMotion RA: 0.0 DEC: 0.0 arcsecs/year

Guide Star message: There are FPI guidestars.
Requested Water Vapor: Nominal

4. gy37-co-153 AOR_ID: 07_0157_4 IRAS 07069-1045 Type: Sidereal Velocity: 16.5 km/s Priority: Medium Order: 4
Config: DUAL-CHANNEL Spectral Element1: FIF_BLUE Spectral Element2: FIF_RED
WavelengthBlue: 84.5 WavelengthRed: 153.267
Blue Spectral Width: 30.0 km/s Red Spectral Width: 30.0 km/s
Nod Style: SYMMETRIC_CHOP Mode: SYMMETRIC_CHOP
Requested Time: 1,200 secs Overhead: 2,300 secs Total: 3,500 secs
RA: 7 09 20.54 DEC: -10 50 25.80 ProperMotion RA: 0.0 DEC: 0.0 arcsecs/year
Guide Star message: There are FPI guidestars.
Requested Water Vapor: Nominal

--- End of Proposal Summary ---

1 Scientific context

Context During the earliest stages of star formation, protostars are deeply embedded in dense envelopes and drive powerful outflows. Even low-mass protostars may have considerable impact on their star-forming clusters e.g. via regulating the efficiency of star formation (Offner & Arce 2014). The nature and energetics of these interactions are best traced by far-infrared lines of CO, H_2O, [OI] and OH, which are efficient gas coolants. However, *Herschel*/PACS surveys focused on individual, mostly nearby (< 500 pc) protostars distributed in various clouds (Karska et al. 2013, 2014a,b, 2018). Thus, the cummulative effect of feedback from protostars on the entire clusters could not be measured.

In Fischer et al. (2016), we explored 100 deg2 of the poorly studied Canis Major region using WISE and identified active star formation sites. The region CMa-l244 contains the largest fraction of young protostars and is the most concentrated source of outflows in the *Spitzer*/GLIMPSE360 survey in the Outer Galaxy (Sewiło et al. subm.). It hosts an embedded cluster Gy 3-7, which is exceptionally bright in the *Herschel*/Hi-Gal images and offers a unique laboratory to study feedback from protostars on cluster scales.

Aims We aim to use FIFI-LS integral field spectrometer to characterize far-IR line emissions from embedded cluster Gy 3-7. A combination of molecular and atomic lines will be used to quantify the total mechanical and radiative feedback from protostars in one of the most exceptional clusters in our Galaxy.

Methods We will take advantage of SOFIA's unique far-infrared integral field spectrometer FIFI-LS to characterize the amount of energy deposited by protostars in Gy 3-7 by mapping CO 14-13 at 186 μm, CO 16-15 at 163 μm, CO 17-16 at 153 μm, [OI] 63 μm and [CII] 158 μm lines.

Synergies Follow-up high-resolution observations with ALMA and VLT/KMOS are proposed for to characterize CO outflows and H_2 jets from individual sources.

Anticipated results We will obtain maps of the far-IR line emission from key gas coolants. By comparison to large samples of protostars observed as part of the WISH program on Herschel, we will measure the total energy injected into the cluster by protostars. Thus, we will quantify cummulative feedback from low- and intermediate-mass protostars in the entire cluster for the first time.

2 Scientific Justification

The formation of low-mass stars is associated with energetic processes that strongly influence the chemistry and physics of the available mass reservoir. The launching of collimated jets and wide-angle winds leads to the formation of outflow cavities, and generates shock waves that compress and heat the envelope material to hundreds or thousands of K. Ultraviolet photons produced by accretion and/or shocks can penetrate to large distances due to the low densities and scattering by dust in the outflow cavities. Far-infrared molecular observations with *Herschel* revealed ubiquitous slow shocks ($v < 50$ km s^{-1}) propagating in partly ionised, magnetised medium (Karska et al. 2014b, 2018). **However, mechanical and radiative feedback from protostars has so far been characterized for nearby sources (≤450 pc) located in various clouds. Thus, the influence of protostars on the entire clusters forming low- and intermediate-mass stars has not been measured.**

We propose to observe a far-IR bright embedded cluster Gy 3-7 located in the Canis Major OB1 association using the FIFI-LS integral field spectrometer to map far-IR emission lines which are the key gas coolants in protostars (CO 14-13, 16-15, 17-16, [OI] 63 μm, [CII] 158 μm lines). These lines will reveal the strength of energy injection into the cluster in outflow shocks, enabling a better understanding on the role of outflow feedback on regulating star formation in this embedded cluster. The angular size of the nebulae matches the field-of-view of the red part of FIFI-LS ($\sim 1'$), which allows to optimize the observations and probe multiple transitions.

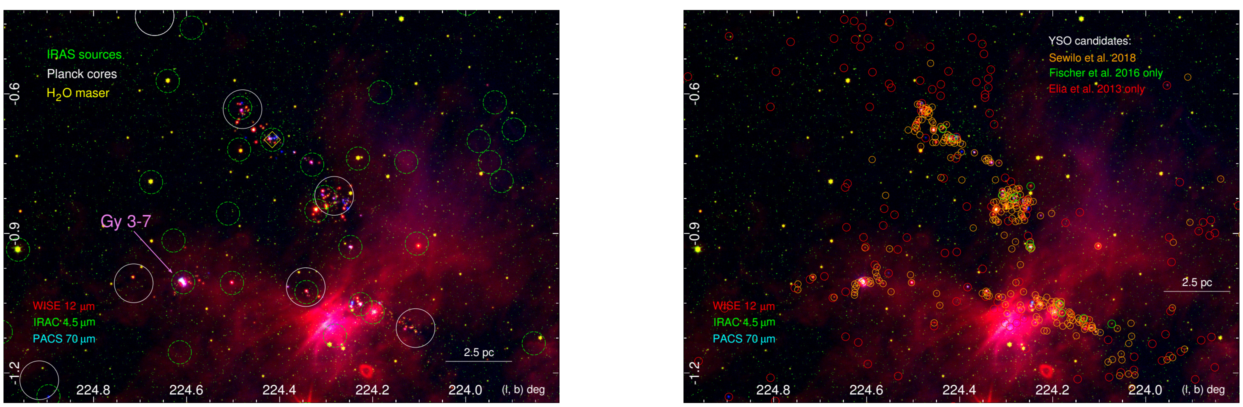

Figure 1: The CMa-l224 region in the Outer Galaxy obtained with the combination of WISE 12 μm (red), GLIMPSE360 4.5 μm (green), and PACS 70 μm (blue). Embedded cluster Gy 3-7 is located at (l,b)∼(224.6,-1.0) and is associated with a strong IRAS source with $L_{\rm bol} \sim 10^3$ L$_\odot$ (Wouterloot & Brand 1989). Several candidate protostars are identified by our team (Sewiło et al. subm.).

Gy 3-7 is a nebulous object cataloged as a "Herbig-Haro-Like" object HHL 49 (Gyulbudagyan et al. 1987) and is known to host the embedded cluster (Tapia et al. 1997, Soares et al. 2003). The object is associated with a far-IR source IRAS 07069-1045 with $L_{\rm bol} \sim 10^3$ L$_\odot$, using a kinematic distance from CO observations of ∼1.4 kpc (Wouterloot & Brand 1989). Our recent study of the Outer Galaxy combining large-scale photometric surveys with *Spitzer* and *Herschel* confirms the embedded nature of Gy 3-7 (Figure 1; Sewiło et al., subm.). **The cluster is exceptionally bright in the far-IR and is associated with extended 4.5 μm tracing H_2 jets** (Figure 2). We identified 9 candidate young stellar objects in the region but their classification is limited by the poor coverage of spectral energy distributions at far-IR and mm wavelengths. Near-IR observations of a few sources suggest a rather evolved stage (Class II), which does not correlate with clearly embedded nature of the source. Since the appearance of Gy 3-7 as a whole resembles an exposive outflow from Orion BN/KL with its famous "H_2 fingers" (Bally et al. 2017, Youngblood et al. 2018), some stellar collisions could have occurred in the cluster and triggered strong feedback.

FIFI-LS spectral maps of Gy 3-7 are necessary to associate far-IR photometry with driving sources and quantify the gas and dust cooling. The source resembles an exposive outflow of Orion BN/KL, but is far enough away to fit in the FIFI-LS field of view.

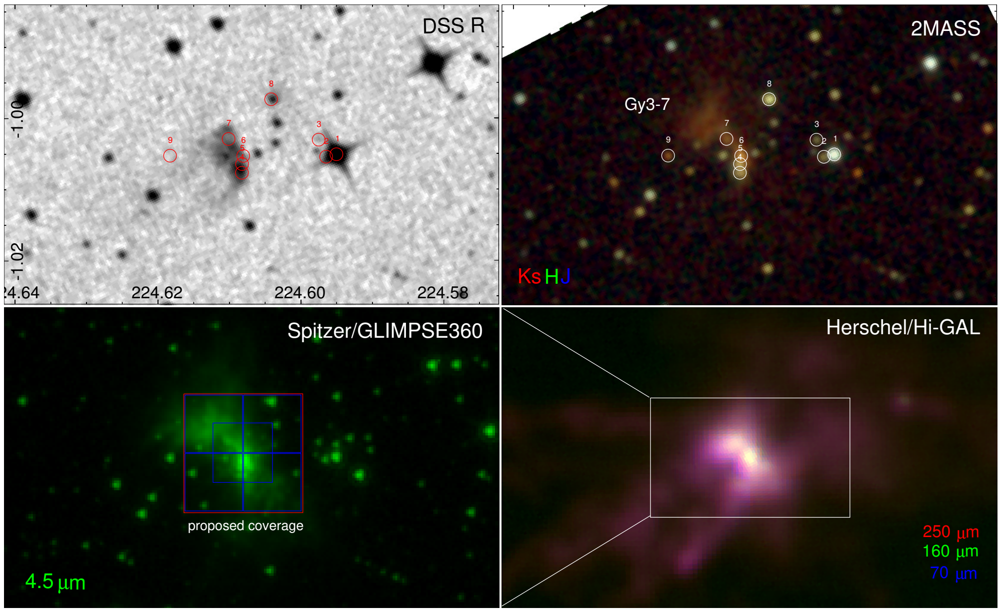

Figure 2: One of the most striking subregions of CMa-l224 in the GLIMPSE360 survey - a reflection nebula Gy 3-7, extended and bright at 4.5 μm. The 1 arc min in size nebula resembles a large outflow and is associated with an embedded cluster of protostars (Tapia et al. 1997).

The mapping capabilities of FIFI-LS and its angular resolution will allow to discriminate between various regions and scenarios responsible for far-IR brightness in the nebula. Hα emission in Gy 3-7 extends $\sim$20$''$ in the east-west direction with the western part being brighter and more compact (associated with sources #4–5) than the eastern part (Tapia et al. 1997). In the near-IR, the nebula extends further to the east and south-east. The *Spitzer* 4.5 μm image reveals a significantly more extended emission than that at optical wavelengths in both east and west directions. **Far-IR spectral maps in the main cooling lines will elucidate stratification of physical conditions and processes in various regions of Gy 3-7.**

The combination of requested far-IR lines will be used to identify dominant excitation processes across Gy 3-7. The high$-J$ CO lines will provide a measure of the gas rotational temperature (Kaźmierczak, et al., 2010, Karska et al., 2013). Guided by our previous surveys with *Herschel*/PACS, we will calculate a total far-IR CO gas cooling, which will inform about the energy injection from the outflows - the mechanical feedback. The ratio of the [CII] and [OI] lines and their absolute intensities will identify any photodissociation regions (PDR). Comparisons to relevant models of PDRs or UV-illuminated shocks will quantify the UV fields and thus radiative feedback. In case of weak [CII], the origin of [OI] will point to shocks along jets and then we will calculate the contribution of [OI] to the total gas cooling by adapting a constant ratio of the [OI] 145/63 μm lines seen in nearby protostars (Karska et al. 2013, Nisini et al. 2015). **The CO, [OI] and [CII] lines uniquely trace physical processes and gas cooling budget, thus allowing us to quantify mechanical and radiative feedback in Gy 3-7. Properties of warm gas will discriminate between various scenarios for exceptional far-IR brightness of the object. In particular, we will be able to assess whether stellar collisions similar to the the ones invoked to explain "H_2 fingers" in Orion BN/KL could have taken place in Gy 3-7.**

3 References

Bally, J., et al. 2017, ApJ 837, 60
van Dishoeck, E., et al. 2011, PASP, 123, 138
Elia, D., et al. 2013, ApJ 772, 45
Fischer, W. J., et al. 2016, ApJ 827, 96
Gyulbudagyan, et al., 1987, RMxAA, 15, 53
Karska, A., et al. 2013, A&A 552, 141
Karska, A., et al. 2014a, A&A 572, 9
Karska, A., et al. 2014b, A&A 562, 45
Karska, A., et al. 2018, ApJS 235, 30
Kaźmierczak, M., et al. 2014, A&A 567, 53
Kaźmierczak, M., et al. 2015, A&A, 574, 71
Kaźmierczak, M., et al. 2010, MNRAS 402, 2548
Matuszak, Karska, et al. (2015), A&A, 578, 7
Nisini, et al. 2015, ApJ 801, 121
Offner, S., & Arce, H., 2014 ApJ, 784, 61O
Sewiło, M., et al. 2018, subm. to ApJS
Soares, et al. 2003, A&A, 404, 217
Tafalla, et al. 2013, A&A, 551,21
Tapia, et al. 1997, AJ 113, 1769
Tobin, J., et al. 2016, ApJ 831, 36
Wouterloot, J.G.A. & Brand, J., 1989, A&AS 80, 149
Youngblood, A., et al. 2018, ApJ 857, 7

4 Feasibility

The proposed program is designed to characterize far-IR emission toward the exceptional far-IR bright young cluster Gy 3-7 in Canis Major (distance 1.4 kpc, angular size 1'). The FIFI-LS observations will enable the energetics of this region to be examined using methods developed by our team for the WISH, WILL, DIGIT, and HOPS teams using *Herschel*-PACS spectroscopy to study large samples of nearby (d< 450 pc) protostars (e.g., Karska et al. 2013, 2014a,b, 2018, Tobin et al. 2016, Fischer et al. 2016).

We will conduct our observations with FIFI-LS using symmetric chop mode, the most efficient observing mode with FIFI-LS. We will use a 300" throw in east-west direction to avoid contaminated off-regions. This chop/nod direction has both off beams below 1% peak emission based on PACS 160 μm continuum data.

The most important lines for our science are CO lines ($J = 14-13$, $J = 16-15$, $J = 17-16$) and the [OI] line at 63 μm, **which are the dominant gas coolants of low- and intermediate-mass protostars (Karska et al. 2013, 2018; Matuszak et al. 2015). The CO lines will be used to calculate rotational temperature of the gas and the role of outflow shocks, whereas the [OI] line will trace the presence of UV radiation in the surroundings of protostars (jets, photodissociation regions).** We will base our integration time estimates on the expected fluxes for those and will map the entire region of the cluster (1'x1') for those lines. For the three CO lines we will only need single point observations, since they are in the red channel of the instrument. A 4 point 30" raster map is needed for the [OI] line.

For flux estimates we scale the fluxes from the similar, intermediate-mass star forming region NGC 2071 from its distance of 422 pc to 1.4 kpc. Also we conservatively assume the flux to be spread equally over the whole 1'x1' mapping area for the three CO lines and over half of it for the [OI] such that we will have a high likelihood of strong detections. We took the CO line fluxes from Matuszak, Karska et al. (2015). We have optimized our choice of lines based on instrument sensitivity and atmospheric transmission. We estimate the time required for each observational setup using the SOFIA FIFI-LS time estimator assuming an aircraft altitude of 41,000 feet, a telescope elevation of 40 degrees and a S/N of 5. Results are summarized in Table 1.

The [CII] line will be observed simultaneously with [OI] and would guide our interpretation: in case of the presence of photodissociation regions (PDRs) within the cluster, the line will be very strong, and its ratio with the [OI] line will be diagnostic of the UV fields. The non-detection will argue against the presence of PDRs. Simultaneous observations of high$-J$ CO ($J = 22-21$; 118.581 μm, $J = 30-29$; 87.190 μm) and the OH dublet at 84.4 μm and 84.6 μm (can be observed in a single spectral setting) could potentially pinpoint regions of high-density, high-temperature gas, but the time estimates are not adjusted to assure their detection. We assume emission from these lines to be localized in the area around the 160 μm continuum peak and have adjusted the array position and orientation to have the blue array centered on that region. If we again scale fluxes from NGC 2071 and assume the emission to be localized in a 3x3 spaxel (9"x9") box we get S/N

Table 1: Estimation of on integration times for the four primary lines. The spaxel size in 12"x12" for the 3 CO lines and 6"x6" for the [OI] line. We conservatively assume that the CO line-flux will be equally distributed in the 1'x1' mapping area and the [OI] line flux in half the mapping area. We use the SOFIA FIFI-LS time estimator with an aircraft altitude of 41,000 feet, a telescope elevation of 40 degrees and a S/N of 5. The total time for each map is calculated with USPOT.

Line	λ [μm]	NGC2071 flux 10^{-15} W m^{-2}	Gy 3-7 flux 10^{-15} W m^{-2}	flux / FIFI-LS spaxel 10^{-17} W m^{-2}	T$_{onsource}$ [min]	T$_{map}$ [min]
CO 14-13	185.999	10.0	0.910	3.64	17	50
CO 16-15	162.812	8.56	0.778	3.11	13	40
CO 17-16	153.267	7.00	0.636	2.54	20	58
OI	63.184	57.0	5.18	10.4	10	112

between 8.5 and 14.5 with the integration times from the priority lines to be observed in parallel. Line detections are quite likely here. Continuum detections at those wavelengths will provide a good coverage of spectral energy distributions (SEDs) and enable estimates of dust temperature.

The CO are not expected to be broad, at most 200 km s^{-1} (Tafalla et al. 2013), which will be spectrally unresolved by FIFI-LS. As such, the lines will fit within the instantaneous spectral coverage and be fully covered during the spectral dithering. We do also not expect the [OI], [CII] or OH lines to be problematically broad.

The total wall clock time required for the observations of all eight lines toward Gy 3-7 is 4.33 hrs. The on-source integration time is 1.5h and 2.83 hr is overhead, as calculated by USPOT.

For data analysis, we plan to use the flux-calibrated data cubes provided by the SOFIA Science Center and we will use our own IDL-based scripts to extract the spectral line emission from the IFU foot prints. We have a large experience with analysing Herschel/PACS data, so only small modifications will be needed.

Interpretation of the obtained data will rely on prior experience with observations in the same wavelengths and spectral resolution of protostars spanning a broad range of masses and luminosities obtained as part of the WISH program on Herschel (Karska et al. 2013, 2014a,b, 2018). Based on a few CO lines and a single [OI] line observed here, we will be able to calculate the total gas cooling using established line ratios and gas fractions, which span a relatively narrow range of values for embedded protostars (Karska et al. 2018). The analysis will benefit from our radiative transfer models for CO lines (Karska et al. 2013) and models of UV-illuminated shocks benchmarked with far-IR line observations by our group (Karska et al. 2018).

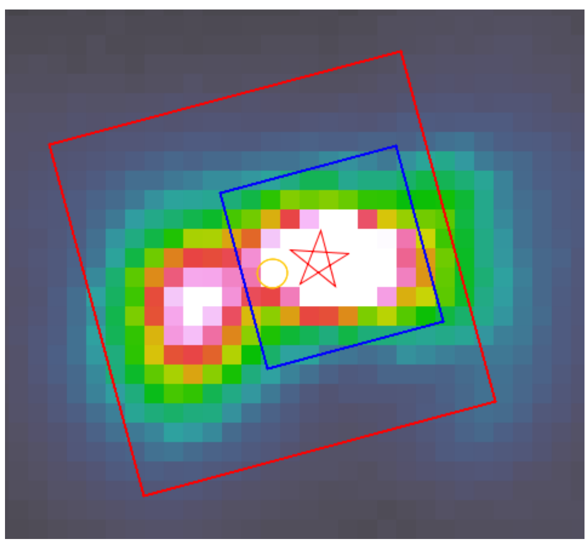

Figure 3: The optimized position of the red and blue field for the CO line observations on the PACS 160 μm.

5 Biographical sketches

PI: Maja Kaźmierczak-Barthel
Maja Kaźmierczak-Barthel is a DSI SOFIA senior scientist. Expert on diffuse/translucent interstellar clouds (Kaźmierczak et. al. 2010) and high mass star forming regions (Kaźmierczak et. al. 2014, 2015). Member of the CHESS and PRISMAS Herschel key programmes. M. Kaźmierczak-Barthel will lead the data analysis and interpretation.

Co-Investigators:
Agata Karska. Assistant profesor at the Nicolaus Copernicus University in Torun (Poland) and a group leader of the Molecular Astrophysics Lab. Member of the WISH, DIGIT, WILL Herschel key programmes. Expert on far-infrared line cooling in low- and high-mass protostars (Karska et al. 2013, 2014a) and protostellar feedback (Karska et al. 2014b, 2018). A. Karska will focus on the data analysis and interpretation.
Marta Sewiło. Associate Research Scientist at the University of Maryland at College Park, residing full time at the NASA Goddard Space Flight Center. Her research is focused on the formation and early evolution of low- and high-mass stars. She will interpret the data in the context of the overall star formation in the CMa-l224 region.
Lars Kristensen. Assistant Professor and group leader at the University of Copenhagen. He has been a member of multiple Herschel spectroscopy projects. His is an expert on shock modeling and will assist in the data analysis.
John Tobin. Assistant Professor in the University of Oklahoma. He led large protostellar surveys at submm, radio and far-IR wavelengths. He will assist in the data analysis and interpretation.
Agnieszka Mirocha. PhD student at the Jagiellonian University in Cracow, Poland, in the group of A. Karska. She has experience in characterizing radiative feedback from low-mass protostars in nearby star forming regions. She will contribute to the data analysis.
William Fischer. Support scientist at Space Telescope Science Institute. Member of the HOPS Herschel key program; previous SOFIA observer. Experienced in the identification and characterization of protostars in mid- to far-infrared maps, including in the CMa star-forming region (Fischer et al. 2016). W. Fischer will assist in the data analysis and interpretation.
Christian Fischer. Project engineer of FIFI-LS instrument at DSI. He will support observation strategy and execution as well as data reduction and calibration.