Observing Application

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A Multi-Scale, Multi-Wavelength Study of Dust in Molecular Cloud Filaments II

Abstract:

We propose to use MUSTANG-2 on the GBT to make 3mm continuum maps of all dense, star-forming filaments within 500 pc which have ALMA Band 3 imaging available. These observations in and of themselves will address a fundamental limitation of ALMA continuum data, which is the unavailability of total power continuum information. We will use these maps, together with large-area maps from the Herschel Gould Belt Survey (500 microns to 160 microns) and the Atacama Cosmology Telescopes (3.3mm to 1.4mm) to study the evolution of dust grain emissivity over three orders of magnitude in spatial scales--- from 5 pc to 0.005 pc--- and over the entire millimeter/sub-millimeter spectral range. These data will determine whether the intriguing enhancement in long-millimeter wave emissivity seen in the OMC-2/3 filament is universal to such environments, and whether it extends beyond the densest molecular cloud filaments to larger spatial scales. The results could have important implications for models of interstellar dust grains and their evolution, which would in turn inform models for the formation and evolution of protostars and protoplanetary systems. We will make our ALMA+GBT maps publicly available as a legacy data product for the community.

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Related Proposals:

Joint:

Not a Joint Proposal.

Observing type(s):

Continuum, OTF Mapping

GBT Resources

Name	Group	Frontend & Backend	Setup
m2 itself (Shared Risk)	MUSTANG-2 instrument	Mustang 2 Mustang 2	Number of Banks: 0

Sources

Name	Position		Velocity		Group
Serpens-S	**Coordinate system**	Equatorial	**Convention**	Radio	Serpens Sources
	Equinox	J2000			
	Right Ascension	18:29:56.5 00:01:30.0	**Ref. frame**	LSRK	
	Declination	+01:58:01.0 00:05:00.0	**Velocity**	0.00	
	Calibrator	No			
Flame Nebula	**Coordinate system**	Equatorial	**Convention**	Radio	Orion B sources
	Equinox	J2000			
	Right Ascension	05:41:46.0 00:01:30.0	**Ref. frame**	LSRK	
	Declination	-1:56:37.0 00:05:00.0	**Velocity**	0.00	
	Calibrator	No			

Name	Position		Velocity		Group
L1641N	Coordinate system	Equatorial	Convention	Radio	Orion A sources
	Equinox	J2000			
	Right Ascension	05:36:27.0	Ref. frame	LSRK	
		00:01:30.0			
	Declination	-6:25:00.0	Velocity	0.00	
		00:05:00.0			
	Calibrator	No			
OMC-4 South	Coordinate system	Equatorial	Convention	Radio	Orion A sources
	Equinox	J2000			
	Right Ascension	05:35:07.5	Ref. frame	LSRK	
		00:01:30.0			
	Declination	-5:55:00.0	Velocity	0.00	
		00:05:00.0			
	Calibrator	No			
OMC-4 North	Coordinate system	Equatorial	Convention	Radio	Orion A sources
	Equinox	J2000			
	Right Ascension	05:35:03.3	Ref. frame	LSRK	
		00:01:30.0			
	Declination	-5:37:00.0	Velocity	0.00	
		00:04:00.0			
	Calibrator	No			

Sessions:

Name	Session time (hours)	Repeat	Separation	LST minimum	LST maximum	Elevation minimum
Serpens Obs	3.5	1	0 day	00:00:00	24:00:00	30
Orion A session	4.25	4	0 day	00:00:00	24:00:00	30
Flame Nebula	1.0	1	0 day	00:00:00	24:00:00	30

Session Constraints:

Name	Scheduling constraints	Comments
Serpens Obs	good weather nighttime	
Orion A session	good weather nighttime	
Flame Nebula	Good weather nighttime.	

Session Source/Resource Pairs:

Session name	Source	Resource	Time
Serpens Obs	Serpens-S	m2 itself (Shared Risk)	3.5 hour
Orion A session	L1641N OMC-4 South OMC-4 North	m2 itself (Shared Risk)	4.25 hour
Flame Nebula	Flame Nebula	m2 itself (Shared Risk)	1.0 hour

Plan of dissertation: no

Technical Justification:

Dates:

n/a

Observing time:

n/a

Mapping:

Time requirements are based on the "canonical" reference -
https://www.gb.nrao.edu/mustang/
and Mason et al. (2020). We note that the map noise quoted in Mason 2020 is dominated by real structures. A jacknife analysis of the Mason 2020 data gives a noise level (140 uJy/bm for 8 minutes integration time in the center of a standard 6' daisy scan) close to what the canonical M-2 noise reference gives (156 uJy/bm for same). We use the canonical reference for time estimates. For OMC-4 targets we aim to go 2x deeper (70 uJy/bm); for all other targets, we aim to go sqrt(2) deeper (100 uJy).

To make solid contact with ACT-90 data we will make slightly wider maps (8' wide instead of 6'). Instead of spacing pointing centers of the daisy scans by 3' we will space them then by 4'. In all cases we will make 8' x 12' (elongated along filament) maps.

To get to 100 uJy in a single D=8' daisy scan requires an integration time of:

1h x (56 uJy / 100 uJy)^2 x (8 arcm/6arcm)^2 = 0.56h

The following table gives integration times for each target region, as well as total observing times (by source group) including overheads, and rounded to the nearest 15m DSS scheduling increment after breaking into sessions. Groups are separated by horizontal lines.

	ALMA map	M2 map	M2 pointings	M2 integ time	M2 obs time by group, with overhead
Serpens-S	3'x4'.5	8' x 12'	1 x 3	1.67h	* 3.5h (group 1)
Flame	2'.5 x 10'	8' x 12'	1 x 1	0.5h	* 1h (group 2 = OMC B)
L1641N	3'.5 x 9'	8' x 12'	1 x 3	1.67h	* 17h (group 3 = OMC A)
OMC-4 S	3'.8x9'	8' x 12'	1 x 3	3.4h	*
OMC-4 N	1'.8x7'	8' x 12'	1 x 3	3.4h	*
					21.5h total

RFI considerations:

n/a at present as far as we can tell, thank goodness

Overhead:

we use the standard MUSTANG-2 factor of 2 overhead for OOF, flux and pointing calibration, etc.

Joint considerations:

n/a

Novel considerations:

standard and demonstrated M-2 OTF

Pulsar considerations:

n/a

LST Range Justification:

n/a

A Multi-scale, Multi-wavelength study of Dust Evolution in Molecular Cloud Filaments

Objectives: *To definitively characterize the properties of thermal dust emission from λ = 3mm to 160 μm, on scales from 5 pc to* 0.005 *pc, in the environs of dense molecular cloud filaments; and to determine whether the elevated long-mm dust emissivity seen in regions of Orion observed by our group is typical of other clouds and environments. This is a resubmission of our partially successful GBT21A-376 program (7 of* 27.5 *requested hours were scheduled on the GBT) which completed most observations of the Orion-B targets from the original proposal.*

Scientific Motivation: Star and planet formation occur in dust-enshrouded regions which are well-suited for study at millimeter, sub-millimeter, and infra-red wavelengths. Thermal emission from the dust grains themselves provides a fundamental and widely used mass tracer to study the structures involved in the sequential stages of the star and planet formation process. Making use of this tracer, however, requires knowledge of the *dust grain emissivity* as a function of wavelength. GBT observations of Orion's "Integral Shaped Filament" (OMC-2/3) at λ = 3.3 mm with MUSTANG (Schnee et al. 2014, Sadavoy et al. 2016) and MUSTANG-2 (Mason et al. 2020, hereafter M20) have shown that thermal dust emission is a factor of $3 - 4$ times brighter than predicted by extrapolating shorter wavelength measurements, calling into question commonly held assumptions about interstellar dust. Additionally, complementary analyses were performed in Lowe et al. 2022, using archival data from *Herschel* and the Atacama Cosmology Telescope[1] (ACT: Fowler et al. 2007), which showed evidence for this phenomenon across all regions targeted in this proposal, as well as those studied in M20, on larger angular scales (120" vs 25'). The primary purpose of this proposal is to see if this enhanced emissivity is common in other, similar structures in the ISM on small scales; and to probe the connections between widely divergent spatial scales and wavelengths by bringing to bear new GBT MUSTANG-2 maps, along with *Herschel*, ACT, and ALMA maps covering complementary wavelengths and three orders of magnitude in spatial scale.

Sub-millimeter observations by the *Herschel* space telescope over the past decade or so revealed that molecular clouds have a universal, filamentary substructure at scales > 0.5 pc; and that these filaments constitute an important stage in the hierarchical process of star formation (André et al. 2010; André et al. 2014). More recent, higher angular resolution millimeter-wave observations with ALMA (Hacar et al. 2018)— as well as single dish spectroscopic measurements (Hacar et al. 2013)— indicate that these filaments comprise individual, dynamically distinct fibers. Molecular cloud cores are still higher density regions which are local maxima in the density field, with characteristic sizes below ~ 0.1 pc (Di Francesco et al. 2007, Sadavoy et al. 2010). These cores, as well as the protostars which represent the next stage of stellar evolution, are highly spatially correlated with molecular cloud filaments (André et al. 2010). It is thought that protoplanetary disks form as a result of the same processes that form protostars (Williams and Cieza, 2011). They have characteristic sizes of 10s to 100s of AU (*i.e.* up to 0.001 pc or even larger in some cases). Understanding star and planet formation requires a clear understanding of processes over a broad range of spatial scales and wavelengths.

The Orion Molecular Cloud (OMC) 2/3 region— also known as the "Integral Shaped Filament"— lies at a distance of 414 pc (Menten et al. 2007; Kim et al. 2008) and is the richest star forming filament within 500 pc. It has been extensively studied at a wide range of wavelengths. Schnee et al. (2014, hereafter S14) mapped the 3mm continuum emission in OMC-2/3 with the original MUSTANG camera and found that the emissivity was a factor of $3 - 4$ higher than expected from extrapolations of shorter-wavelength data using standard dust models. In the context of standard dust grain models,

[1] ACT is a Microwave Background experiment which makes sensitive, large-area maps of most of the sky visible from its location near the ALMA site. We have obtained the ACT 90 GHz, 150 GHz, and 220 GHz data surrounding the regions we propose to observe here. These data have angular resolutions ranging from $2'$ to $\sim 0'.8$ (90-220 GHz).

which model the grain emissivity κ_ν with a single power-law index β ($\kappa_\nu = \kappa_0(\nu/\nu_0)^\beta$), the S14 results between 3mm and 1mm suggested $\beta \sim 1$ in the filament. Sadavoy et al. (2016, hereafter S16) used the MUSTANG 3mm measurements of S14 but greatly extended the wavelength coverage, also bringing to bear GISMO (2 mm), SCUBA-2 (850 μm and 450 μm), *Herschel* (350 μm, 250 μm, and 160 μm) data. These data demonstrated that rather than a uniform decrease in the dust opacity index β in the dense filament, there is a change in the value of β somewhere close to 2mm, with shorter wavelengths being well described by a single emissivity power law and the longer wavelength showing elevated emissivity. Recent measurements of OMC-2/3 with the new MUSTANG-2 camera at 3.3 mm have confirmed the S14 measurement (M20). M20 also presented sensitive 1cm GBT photometry of the OMC-2/3 filament which show that this enhanced emissivity extends out to even longer wavelength and is not consistent with free-free contamination. If this break in the dust emissivity with wavelength is seen in other high-density filaments it could have significant implications for the interpretation of 3 mm core surveys (*e.g.*, Carpenter 2002, Eisner & Carpenter 2006, Kainulainen et al. 2017, van Terwisga et al. 2019) and dust grain models, as well as important implications for the initial conditions for dust evolution in protoplanetary disk formation (Testi et al. 2014).

We propose to use MUSTANG-2 to make 3.3 mm continuum images of *all dense, star-forming filaments within* 500 *pc which also have extant and available ALMA and ACT 3mm data.* The complete set of such regions is shown in **Table 1**. They span a wide range of physical conditions, from low- to high-mass star forming regions. At the mean distance of Orion and Serpens South, these datasets will robustly provide high-fidelity, 3mm continuum imaging of spatial scales from 0.005 pc to 5 pc. **Figure 1** presents the ACT 3mm map of the Orion complex, along with a proof-of-concept map made by combining the MUSTANG-2 map of OMC-2/3 (from M20) with the ALMA 12-meter map of the same region. The enhanced sensitivity of MUSTANG-2 to diffuse, extended emission provides information about emission filtered out of the ALMA map, allowing us to recover for the first time detailed continuum maps of our targets down to ~ 0.005 pc and unlocking the full value of the ALMA data. This is demonstrated in the right-most panel for OMC-2/3.

When completed these observations will be the highest angular resolution single dish maps of star forming filaments currently available, and when combined with ALMA and ACT data they will accurately measure structures continuously from molecular cloud scales to sub-core scales. The primary science questions we aim to address are:

- Are long wavelength variations in dust emissivity a global phenomenon, or are they only seen in the densest filaments? Are they universal in dense filaments? The MUSTANG-2 and *Herschel* data will measure variations in grain emissivity down to the filament scale. Combining *Herschel* and ACT data we will systematically investigate the variations of beta at scales > 0.5 pc along our sample of filaments. These observations will put fundamental constrains on dust grain evolution models determining, among others, the typical β value or the range of variations of this parameter in clouds. Our results could have important implications for dust grain models, such as amorphous grain models (*e.g.* Meny et al. 2007, Coupeaud et al. 2011). These models already have some support (*e.g.* Paradis et al. 2011, *Planck* collaboration 2014), but the data lack sufficient spatial resolution to clearly confirm or rule them out, much less to determine the prevalence of such grains as a function of environment.

- What is the impact of missing larger scale structures and variations in β on determinations of the physical properties of filaments, fibers, and cores from state of the art interferometric data? For each of the regions surveyed in this project, we will obtain individual continuum MUSTANG-2+ALMA maps and assess the masses, radial profiles, and column densities that result in comparison to those derived in the absence of zero spacing information. If these differences are significant, there would be important implications for mass and dynamical stability inferences for cores and disks derived from 3 mm observations. Our results could also have important implications for models of the evolution of dust in protoplanetary disks (*e.g.* Testi et al. 2014).

We will make all of our MUSTANG-2+ALMA maps public on our Harvard Dataverse site. We anticipate that they will become valuable, legacy data products, allowing researchers to select which spatial scales are important to investigate scientifically rather than by instrumental happenstance.

Target	ALMA Map Size	Environment	Noise Goal $\sigma/\sigma_{OMC-2/3}$	ALMA Project Code
Serpens-S	190"x270"	high-mass	$1/\sqrt{2}$	2015.1.00223.S
L1641N	210"x540"	low-mass	$1/\sqrt{2}$	*2016.1.01123.S*
OMC-4 South	230"x540"	low-mass	1/2	*2016.1.01123.S*
OMC-4 North	110"x420"	low-mass	1/2	2017.1.01553.S
Flame Nebula	150"x600"	high-mass	—	*2019.1.00641.S*
OMC-1/2	150"x1200"	high-mass	—	*2015.1.00669.S*
OMC-3	210"x500"	intermediate-mass	—	*2019.1.00641.S*
NGC2023	150"x650"	intermediate-mass	—	*2019.1.00641.S*

Table 1: Bolded targets are those for which we request MUSTANG-2 observations in this proposal; OMC 1, 2, & 3 as well as the Orion-B target NGC2023 have already been imaged by the GBT at 3mm. The Flame Nebula was partially observed during the 21B semester, however the minimum number of scans was not reached and we request time to finish. Noise goals are relative to M20 noise on OMC-2/3 (140 μJy/bm). Italicized ALMA project codes are led by Co-I Alvaro Hacar, others are publicly available. For Orion targets we also have APEX Laboca (870 μm, 19″) & Saboca (350 μm, 8″) data; and for Orion A targets, MAMBO (1.3 mm, 13″).

Proposed Observations & Technical Considerations: We aim to obtain 3mm continuum maps of of six regions in two molecular cloud complexes: one in Aquila/Serpens (Serpens-S), and five new regions in Orion (see Table 1). The Orion targets are visible late in 22B and early in 23A, while Serpens-S has good visibility in late spring. The regions we target are part of the *Herschel Gould Belt Survey* (HGBS), and have extensive sub-mm and far IR data from *Herschel* (André et al. 2010) and the JCMT (Ward-Thompson et al. 2007). Most also have NH_3-derived kinetic temperatures from the Green Bank Ammonia Survey (Friesen et al. 2017). Following the methodology of S16 and M20 we will assemble 3mm to 160 μm SEDs of the dust filaments in these molecular clouds and use them to identify regions that are consistent with, or deviate from, single power law dust emissivities. The ACT and *Herschel* data will allow us to test whether any long wavelength deviations from single-β behavior seen at high angular resolution persist to larger physical scales in the cloud.

MUSTANG-2 observations offer a unique combination of high angular resolution, high surface brightness sensitivity, and accurate reconstruction of relatively large spatial scales. The angular resolution of 9″, is superior to other state-of-the-art instruments (JCMT, LMT, IRAM, *Herschel*). While ALMA offers excellent angular resolution, the largest angular scale it can reconstruct in the continuum at 3mm is limited to $\sim 30''$ for the 12-m array and 1′ for the 7-m array[2]. Furthermore it is notoriously challenging to accurately image extended low-surface brightness emission with interferometers

[2]The ALMA datasets do not have total power continuum information, as that capability has not been offered to the community and there are no clear plans to do so due to fundamental limitations of the receiver architecture.

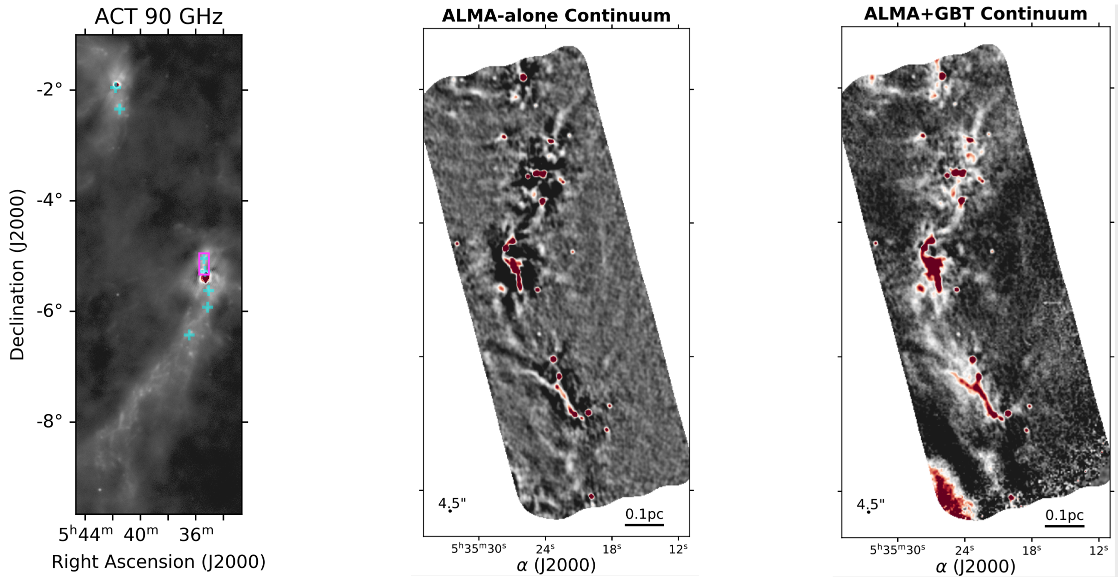

Figure 1: **Left:** ACT 3mm map of the OMC complex ($2'$ resolution, $\sim 1^\circ$ largest accurate angular scale, or LAS); 150 GHz and 220 GHz maps are also available. The centers of regions in OMC we propose to observe with MUSTANG-2 are shown as "+" signs in this map. **Center:** ALMA 12-m 3mm map of OMC-2/3 ($4''.5$ resolution, $30''$ LAS). **Right:** The combined MUSTANG-2 (Mason et al. 2020) and ALMA 3mm map of OMC-2/3 ($4''.5$ resolution, $4'.5$ LAS). The ALMA/GBT maps approximately cover the region enclosed in the magenta box in the ACT (left-most) image.

alone, even when sufficiently short short spacings are measured. The impact of these considerations in aggregate can be seen by comparing ALMA image of OMC-2/3 (*e.g.*, that of Kainulainen et al. 2017, which includes both 12-m and 7-m ALMA data) with the GBT 3mm images of S14 or M20. As suggested by **Figure 1**, the MUSTANG-2 data reliably measures spatial scales up to $4'.5$, and ACT maps extend this by accurately reconstructing from $2'$ to $\sim 1^\circ$ degree scales.

Observing time estimates are based on M20 map of OMC-2/3 ($\sigma_{OMC-2/3} \sim 140\,\mu$Jy/bm), which robustly imaged filament structures at SNR $\sim$ 10 to 70. Four of the six regions we target have comparable column densities to OMC-2/3; for these regions we aim to go $\sqrt{2}$ lower noise so we achieve a robust measurement even if the 3mm dust opacity is not as high as in OMC-2/3. The two OMC-4 targets are fainter, and for these we aim to go two times deeper based on available *Herschel* data. To robustly connect with the ACT 90 GHz data in terms of spatial scales we propose to image slightly larger regions than the ALMA maps. Guided by the ALMA maps, the ACT resolution, and available HGBS data, all M-2 maps will be $8' \times 12'$, elongated along the filament. More details on the time request are in the Technical Justification section of the PST. **Our GBT time request is for** 21.5 **hours of observing, including overheads.**

References: André et al. 2010, A&A 518, L102 • André et al. 2014, PP VI p.27 • Carpenter 2002, Aj 124, 1593 • Coupeaud et al. 2011, A&A 535, A124 • Di Francesco et al. 2007, PP V p.17• Dicker et al. 2009, ApJ 705, 226 • Eisner & Carpenter 2006, ApJ 641, 1162 • Fowler et al. 2007, Apl.Opt. 46, 3444 • Friesen et al. 2017, ApJ 843, 63 • Kainulainen et al. 2017, A&A 600, A141 • Lowe et al. 2022, *review* • Mason et al. 2020, ApJ 893, 1 • Meny et al. 2007, A&A 468, 171 • Paradis et al. 2011, A&A 534, A118 • *Planck* Collaboration 2014, A&A 536, A20 • Sadavoy et al. 2010, ApJ 710, 1247 • Sadavoy et al. 2013, ApJ 767, 125 • Schnee et al. 2014, MNRAS 444, 2303 • Testi et al. 2014, PP VI p. 336 • van Terwisga et al. 2019, A&A 628, A85 • Ward-Thompson et al. 2007, PASP 119, 855 • Williams & Cieza 2011, ARA&A 49, 67