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Properties of Intermediate-Luminosity Protostars and Circumstellar Disks in OMC-2

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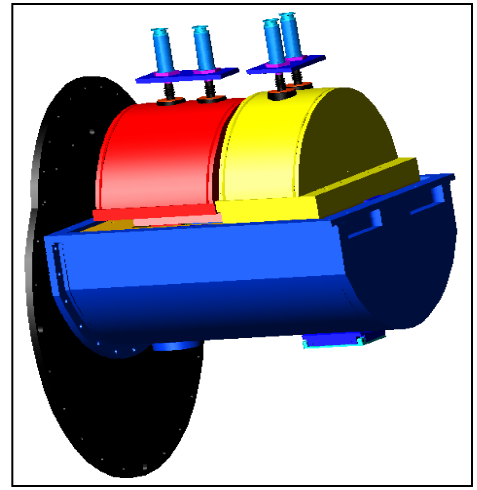
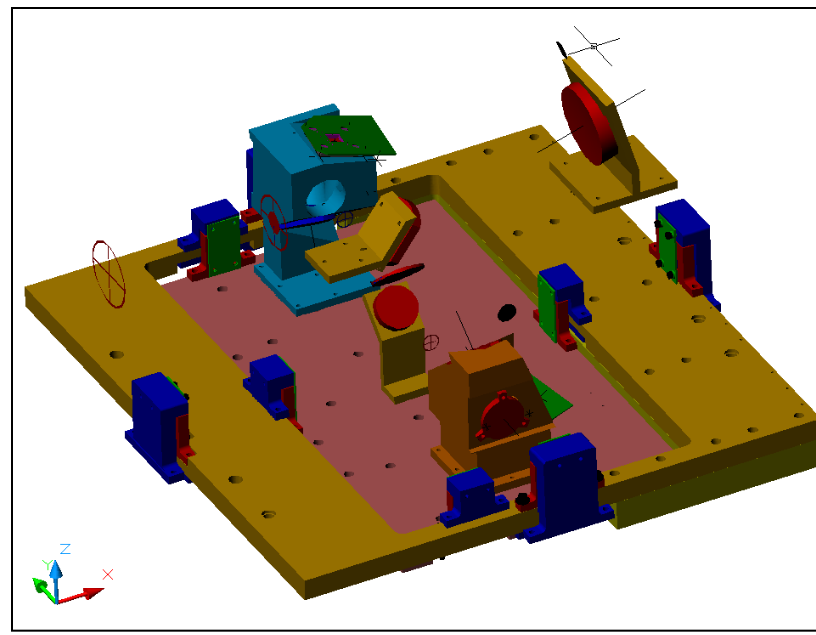
FORCAST Overview

- Facility Instrument for SOFIA
- Dual-Channel 256x256 Camera w/ Si BIB arrays
  - 5-25 μm with Si:As array
  - 25-40 μm with Si:Sb array
- 0.77 arcsec/pixel (rectified) over 3.4×3.2 arcmin FOV
- Diffraction-limited imaging for $\lambda > 15$ μm
- Selectable Filters in 5-40 μm range
- Easily accommodates grisms for spectroscopic capability





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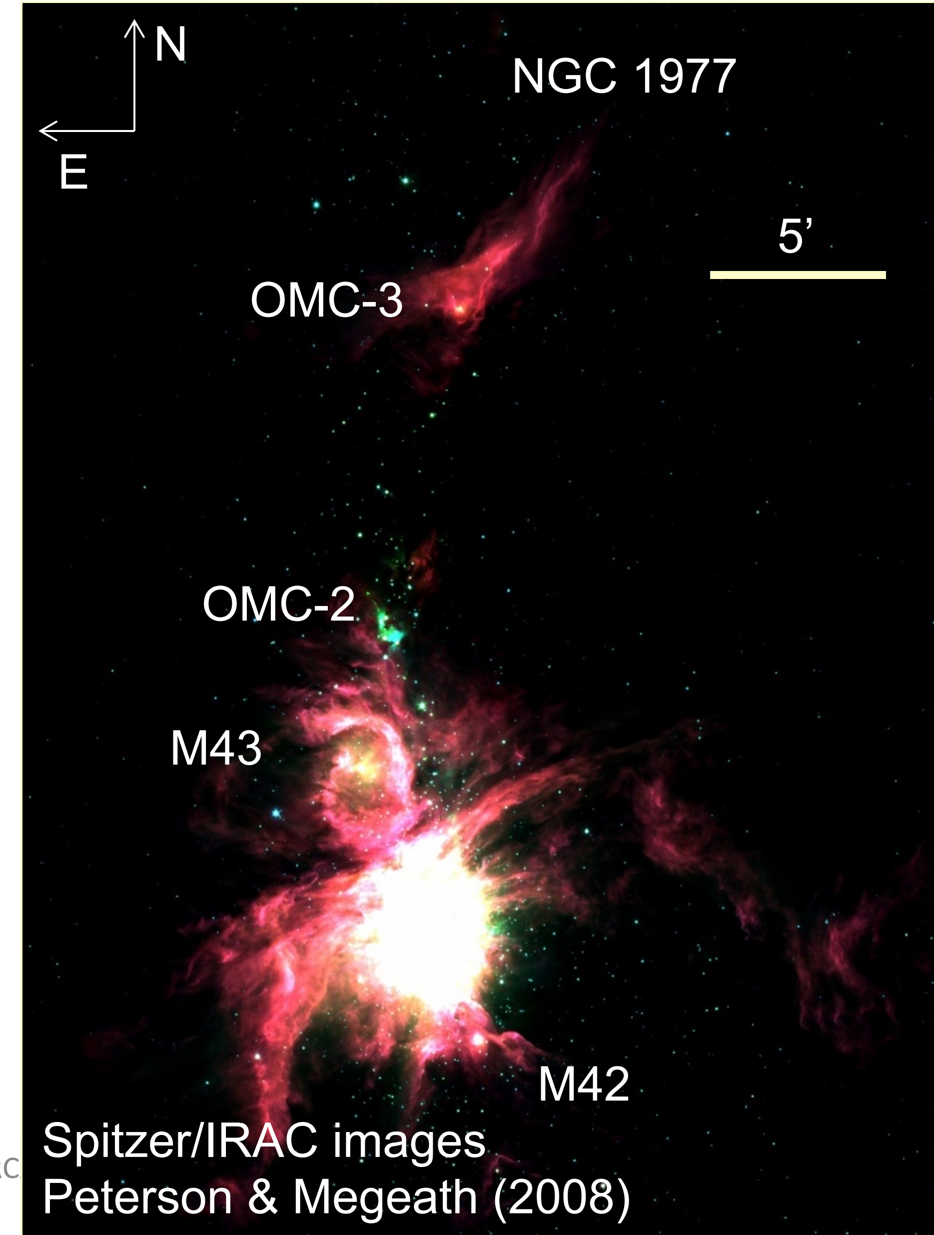
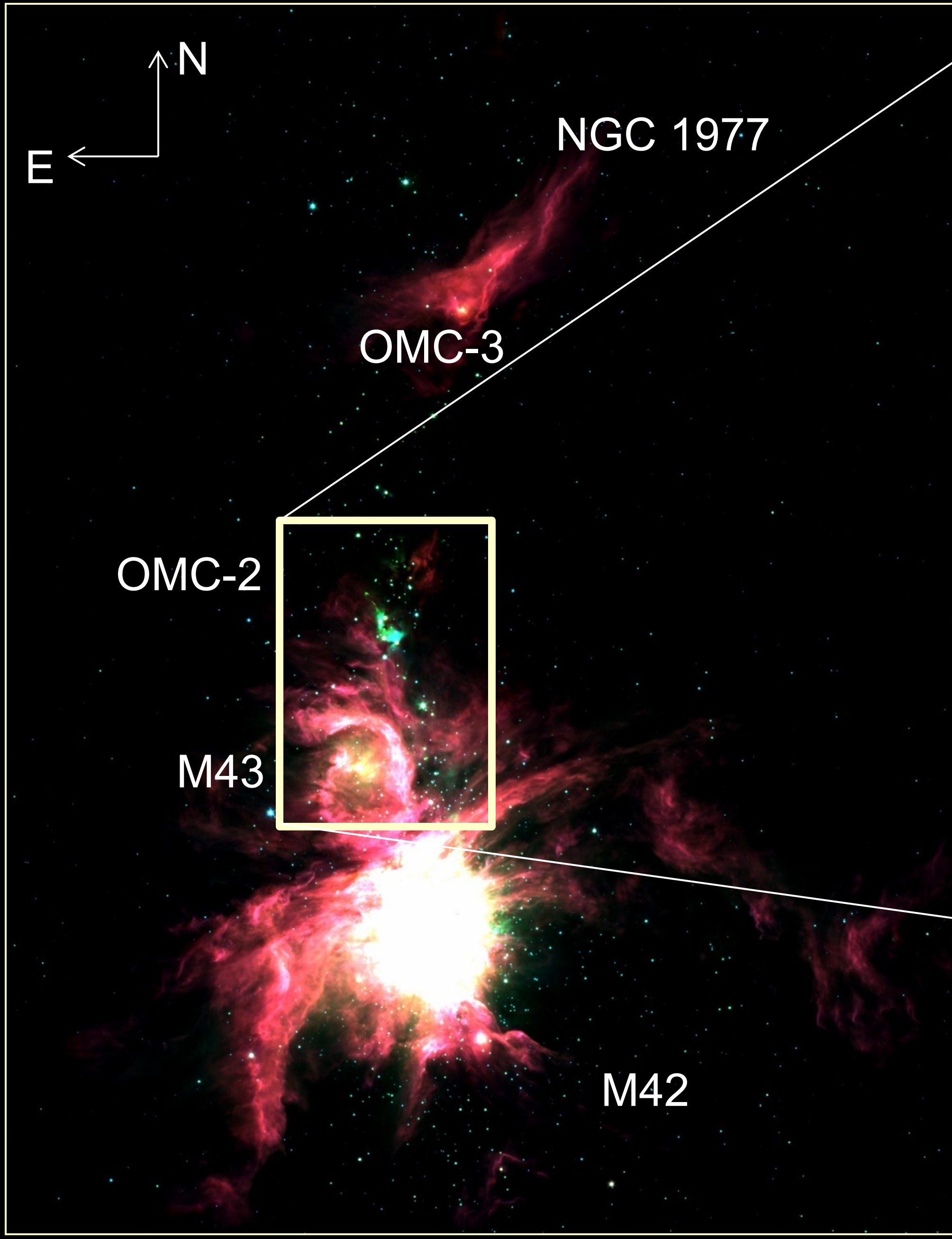
Why Study OMC-2?

- OMC-2 is a nearby, active site of star formation
  - It is one of the most luminous regions in Orion
  - Contains numerous protostars and young stars with circumstellar disks (Nielbock et al. 2003, Peterson & Megeath 2008)
  - Contains cold dusty cores often associated with stellar components and submm emission (Chini et al. 1997, Lis et al. 1998)
  - Shock activity seen in 3.6 cm VLA observations (Reipurth et al. 1999) and 2.12 μm H_2 line emission (Yu et al. 1997)
  - Possible triggered star formation from outflow activity (Shimarjiri et al. 2008)



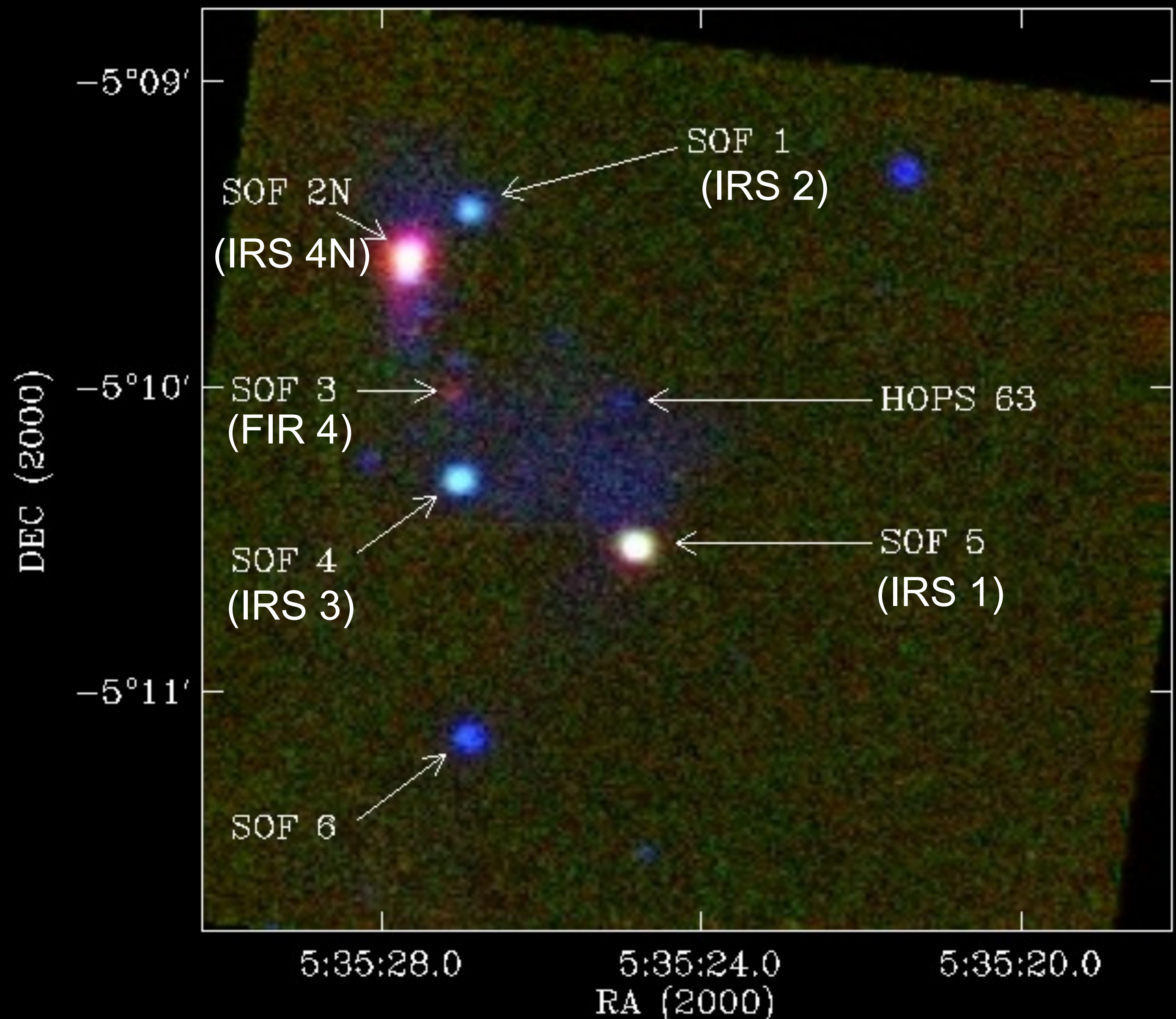
Observations

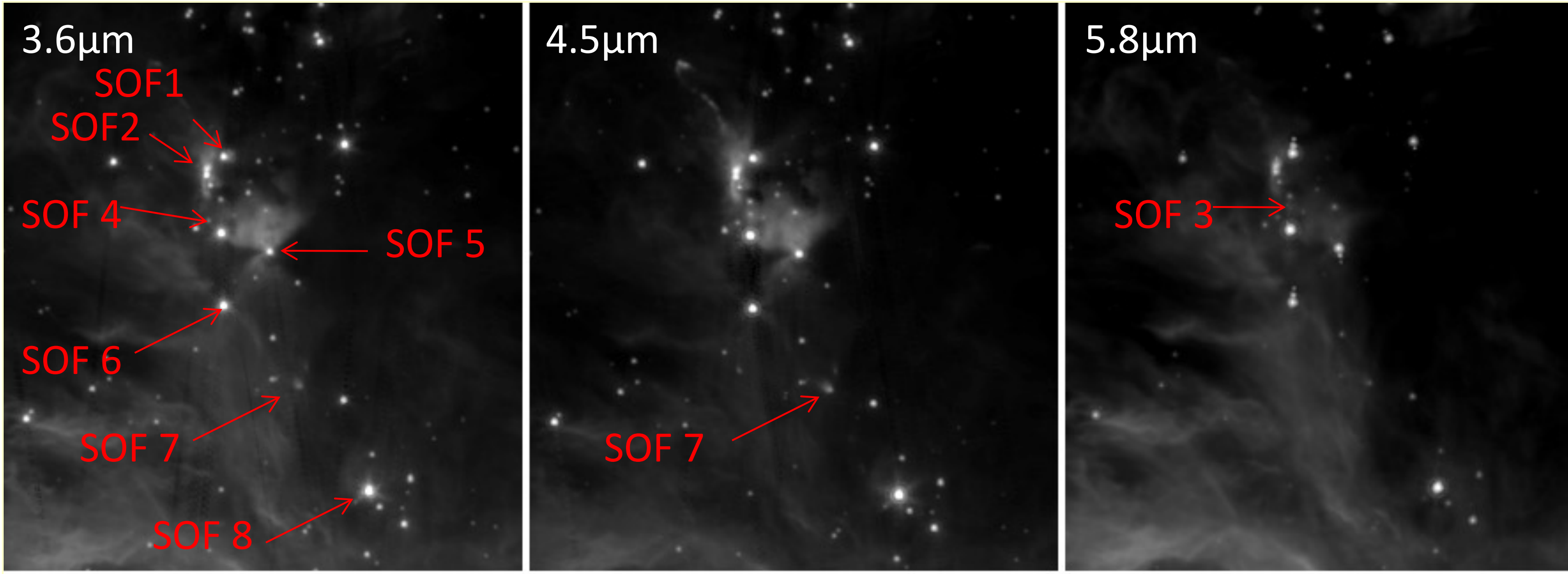
- OMC-2 was observed by SOFIA during Short Science in Nov.-Dec. 2010 during 2 different Orion flight legs
  - 19/37, 19/31, 37 μm
  - 43,000 ft. altitude
- 2 pointing fields covering 3.4’ x 3.2’ FOVs
- 5 x 30 sec integrations in C2N and C2NC2 modes
- Include Spitzer/IRAC/MIPS data at 3.6, 4.5, 5.8, 8.0, 24 μm (Megeath et al. 2005, Peterson & Megeath 2008)
- Include Herschel/PACS photometry at 70 and 160 μm (HOPS; Fischer et al. 2010)
- Include ESO APEX SABOCA and LABOCA photometry at 350 and 850 μm

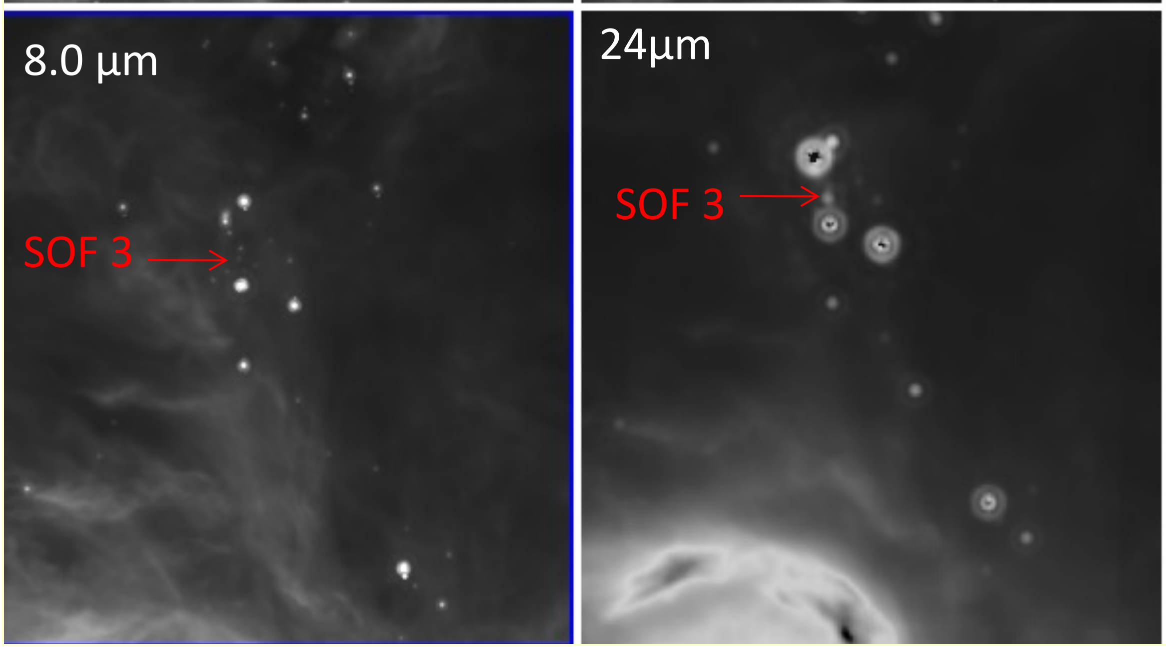


Spitzer/IRAC 3.6, 4.5, 8.0 μm
Megeath et al. (2005),
Peterson & Megeath (2008)
Gately et al. (1974)
Chini et al. (1997)

OMC-2 at 4.5 μm, 19.7 μm, and 37.1 μm





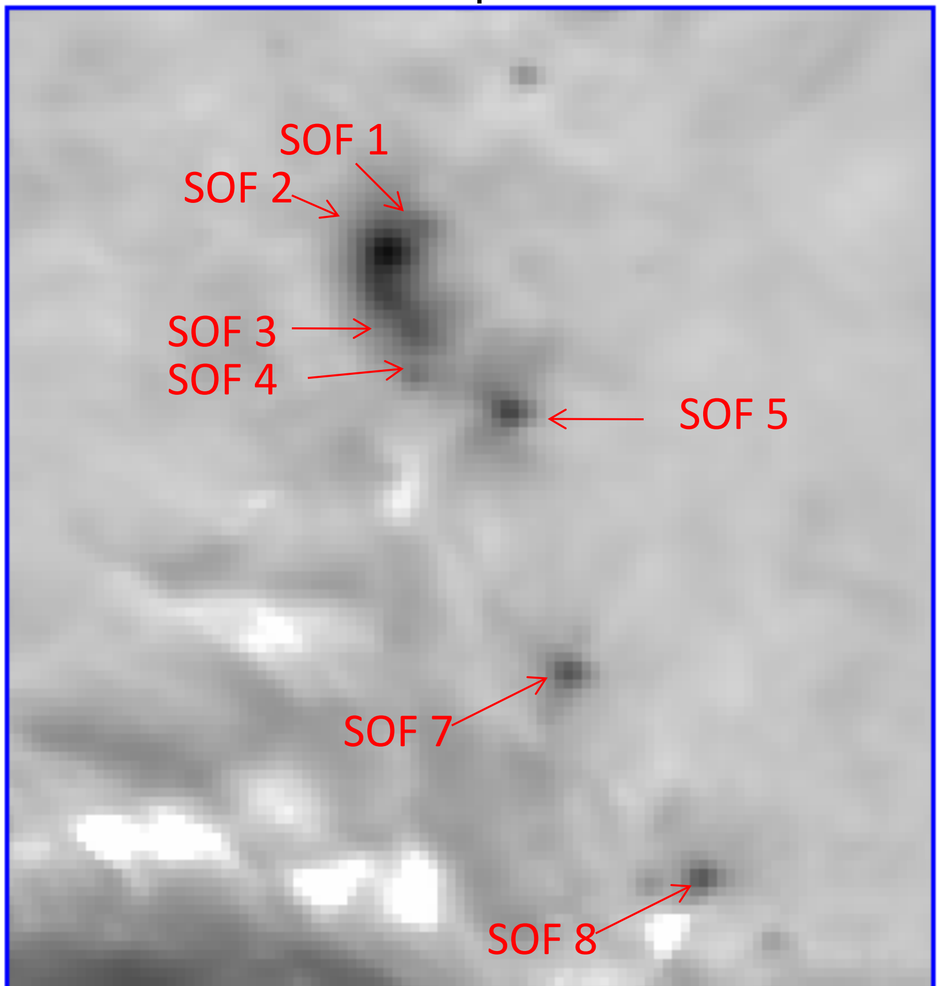


Spitzer Images

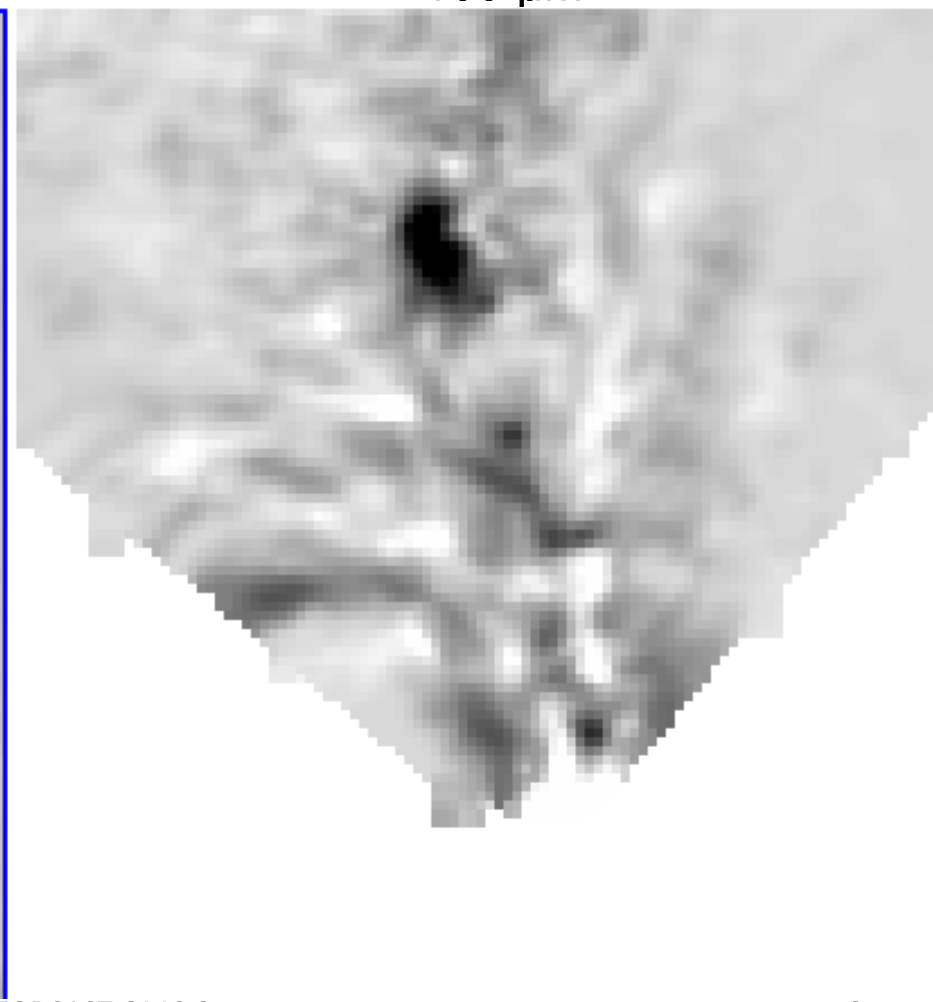
Herschel Observations

* Courtesy HOPS team (Fischer et al. 2010)

70 µm



160 µm



1.3 mm Continuum

Chini et al. (1997)

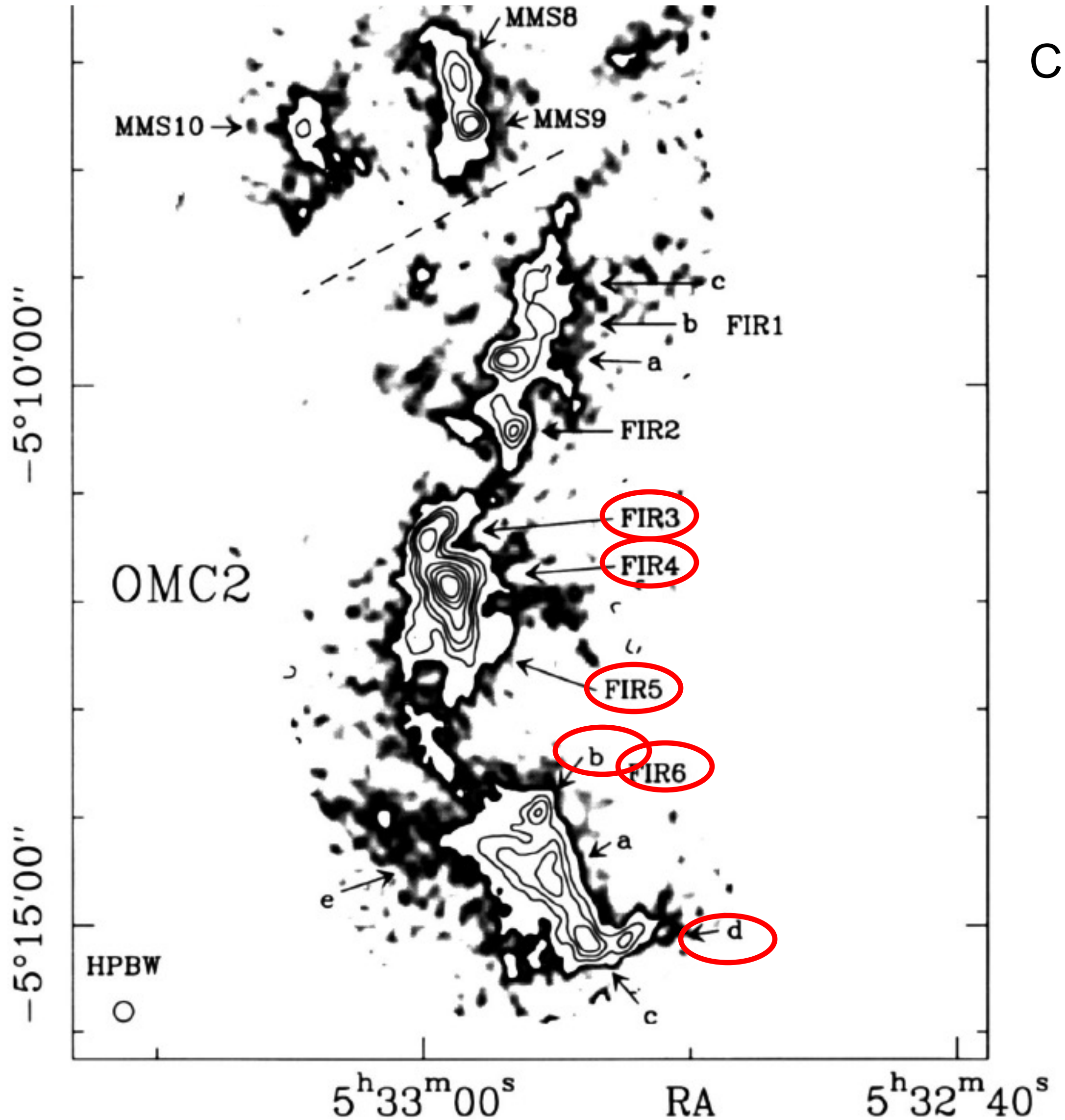


FIG. 1.—A 1300 μm map of a 6′ × 16′ field around the OMC-2 and OMC-3 region in Orion; the abscissa is α(1950) and the ordinate is δ(1950). Cold dust condensations are marked, and their fluxes and positions are listed in Table 1. The faintest emission, between 25 and 100 mJy, is shown in gray scale, followed by contours, which are 100–400 in steps of 100, 600–1200 in steps of 200, and 1600 and 2000 mJy. The rms noise in the map is 25 mJy per 11″ beam. The circle shows one of the 11″ beams of the MPIR 19-channel bolometer array.

VLA Sources (3.6 cm) overlay

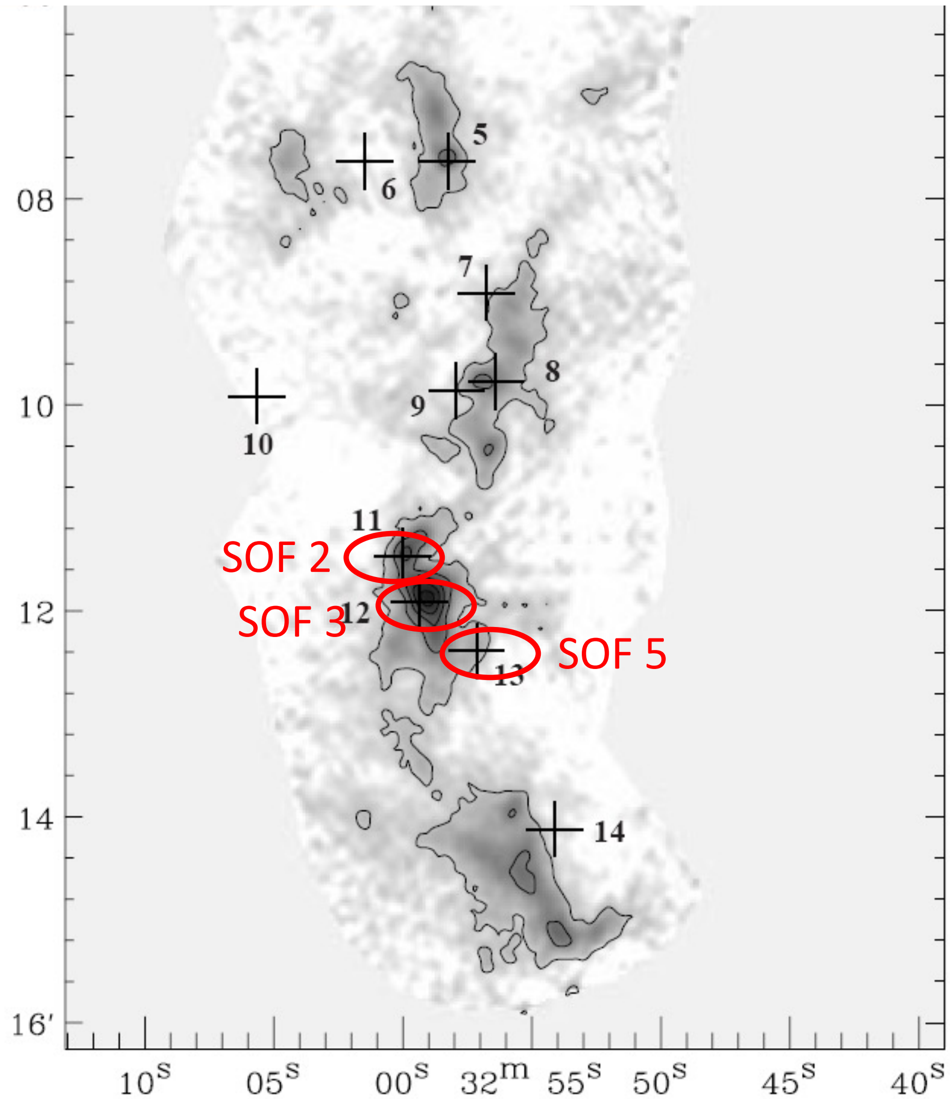


FIG. 1*a*

Reipurth et al. 1999
1.3 mm map from
Chini et al. 1997

FIG. 1.—(*a*) Positions of the VLA sources overlaid on the 1300 μm map of the OMC-2/3 region by Chini et al. (1997). OMC-2 is located at the southern part of the region, while OMC-3 is at the northern part. Sources VLA 2, 6, and 10, which are located away from regions of cold dust, are probably background objects. The ordinate covers the approximate declination range −5°00′ to −5°16′ in 1950 coordinates. The abscissa ranges from $5^h32^m39^s$ to $5^h33^m14^s$ in 1950 coordinates. (*b*) The same map with identifications of the 1300 μm radio continuum sources from Chini et al. (1997).

Multi-wavelength Correlation

Table 1. Positions and identifications for all sources detected by SOFIA/FORCAST (SOF). IRS IDs are given in Gatley et al. (1974), MIR IDs are given in Nielbock et al. (2003), FIR IDs are given in Chini et al. (1997) and Shimajiri et al. (2008), CSO IDs are given in Lis et al. (1998), and VLA IDs are given in Reipurth et al. (1999). Positions are derived from the *Spitzer*/IRAC 3.6 μm image, except SOF 2N (derived at 19 μm) and SOF 3 (derived at 8.0 μm).

SOF	HOPS	RA (2000)	DEC (2000)	IRS	2MASS J	MIR	FIR	CSO	VLA
1	66	05:35:26.84	-05:09:24.7	2	05352683-0509244	20	...	...	...
2N	370	05:35:27.57	-05:09:33.8	4N	05352762-0509337	21	3	22	11
3	108	05:35:27.08	-05:10:00.3	...	...	...	4	23	12
4	369	05:35:26.98	-05:10:17.4	3	05352696-0510173	27	5	24	...
5	368	05:35:24.72	-05:10:29.9	1	05352477-0510296	28	...	...	13
6	...	05:35:26.89	-05:11:07.6	...	05352686-0511076	...	...	...	...
7	60	05:35:23.39	-05:12:02.6	...	05352341-0512023	29	6b	25	...
8	59	05:35:20.14	-05:13:15.7	...	05352014-0513156	31+32	6d	30	...

Adams et al. (2012)

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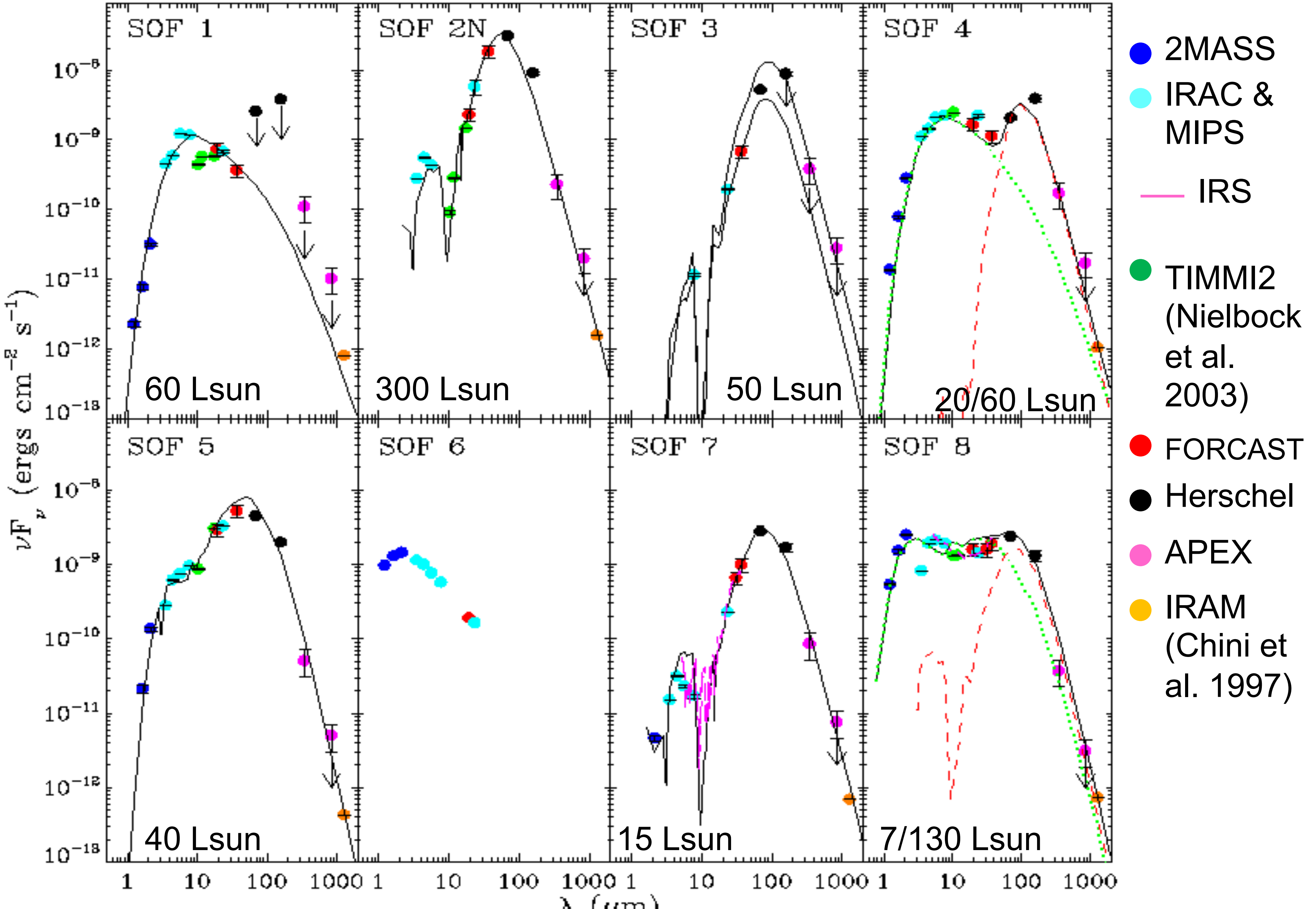
Models

Envelope Models
- Sheet collapse (Hartmann, Calvet & Boss 1994)
- Outflow cavity
- Grain Mixture: Silicates, graphite, troilite, water ice
- 0.005 – 0.3 μm grain sizes
- Dust opacity values based on class I object L1551 (Osorio et al. 2003)
- Temperature and SED profiles are calculated from radiative transfer codes (Kenyon, Calvet, and Hartmann 1993).
- External heating modeled as ~30 K single temperature blackbody

Accretion Disk Models (D'Alessio 1999, 2006)
- Flared geometry
- Temperature distribution is determined by viscous dissipation and stellar irradiation
- Grain growth and grain settling to midplane


SOF 1
60 Lsun
SOF 2N
300 Lsun
SOF 3
50 Lsun
SOF 4
20/60 Lsun
SOF 5
40 Lsun
SOF 6
SOF 7
15 Lsun
SOF 8
7/130 Lsun
νF_ν (ergs cm^{-2} s^{-1})
λ (μm)
2MASS
IRAC & MIPS
IRS
TIMMI2 (Nielbock et al. 2003)
FORCAST
Herschel
APEX
IRAM (Chini et al. 1997)

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Modeling Results

Table 3
Constrained Model Parameters for FORCAST-detected OMC-2 Sources[a]

			Envelope							Disk	
Source	L ($L_\odot$)	i (deg)	η	R_c (AU)	θ (deg)	R_{env} (AU)	$\rho_{1\,AU}$[b] (10^{-13} g cm^{-3})	$\dot{M}_{inf}$[b, c] ($M_\odot$ yr^{-1})	M_{env} ($M_\odot$)	R_{disk} (AU)	M_{disk} ($M_\odot$)
SOF 1	60	40	...	...	...	...	...	...	...	40	1
SOF 2N	300	80	3	300	40	5000	1.5	$\sim 3 \times 10^{-5}$	0.8	280	1.6
SOF 3	50	50	2	380	8	5000	20	$\sim 4 \times 10^{-4}$	10	380	0.6
SOF 3[d]	30	70	2	380	8	5000	5	$\sim 1 \times 10^{-4}$	2.5	380	0.6
SOF 4[e]	20	70	2.5	100	0	5000	9.0	$\sim 2 \times 10^{-4}$	4	...	...
	60	40	...	...	...	...	...	...	...	40	1.5
SOF 5	40	50	2.5	100	5	10000	1.5	$\sim 3 \times 10^{-5}$	2	100	0.2
SOF 7	15	70	2.5	100	30	5000	2.0	$\sim 4 \times 10^{-5}$	1	100	0.8
SOF 8[e]	7	50	2	100	0	5000	6.0	$\sim 1 \times 10^{-4}$	3	...	...
	130	30	...	...	...	...	...	...	...	100	0.1

Notes.

[a] L is the total luminosity of the source, i is the inclination angle of the polar (rotational) axis of the system (that is measured with respect to the line of sight), η is a measure of the degree of flattening of the envelope ($1 \lesssim \eta \lesssim 4$, with $\eta = 4$ corresponding to a very flattened envelope), R_c is the centrifugal radius, θ is the aperture angle of the envelope cavity, R_{env} is the outer radius of the envelope, $\rho_{1\,AU}$ is a reference density (corresponding to the density at a radius of 1 AU of a spherically symmetric free-falling envelope with the same mass infall rate), $\dot{M}_{inf}$ is the mass infall rate (see note c), M_{env} is the envelope mass (obtained by integration of the density distribution), R_{disk} is the outer radius of the disk, and M_{disk} is the disk mass.

[b] Values are likely upper limits because of possible contamination by nearby sources of FIR/submillimeter flux densities.

[c] Estimated from Equation (3) of Kenyon et al. (1993), assuming a nominal value of 1 $M_\odot$ for the stellar mass. $\dot{M}_{inf}$ is proportional to $\rho_{1\,AU}$ and to the square root of the stellar mass, which is not well constrained. Values are accurate within a factor of two for stellar masses in the range 0.25–4 $M_\odot$.

[d] Fit obtained when F_{160} is taken as an upper limit.

[e] Modeled as a double source. In one of the sources the emission is dominated by a star+envelope and in the other source it is dominated by a star+disk.

Adams et al. (2012)

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Conclusions

- SOFIA/FORCAST has detected eight intermediate-luminosity (20 – 300 Lsun) sources in OMC-2
  - Modeling suggests that four are protostars
  - Two sources are likely star+disks
  - Two sources are binary systems containing a protostar and a star+disk system.
- SOFIA's unique wavelength and resolution capabilities are a critical component to multi-wavelength characterization of such objects in nearby, luminous star forming regions