The Cold Environments of FU Orionis-type Eruptive Stars

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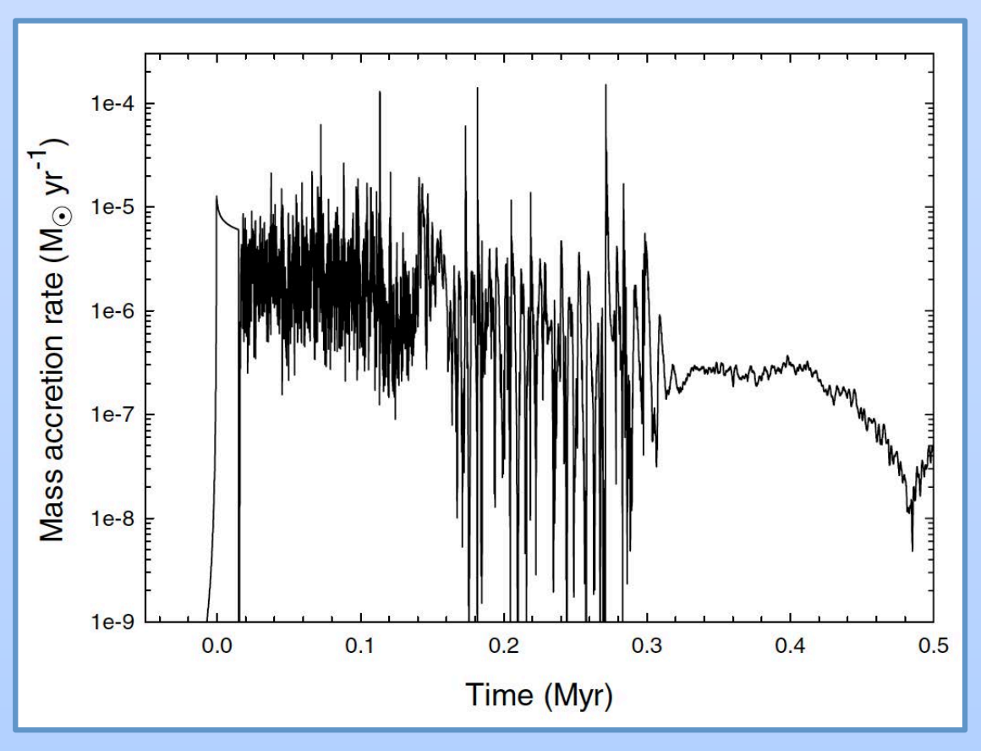
Abstract

FU Orionis-type stars (FUors) are young stellar objects experiencing large optical outbursts due to highly enhanced accretion from the circumstellar disk onto the star. FUors are often surrounded by massive envelopes, which have a significant role in the outburst mechanism. Conversely, the subsequent eruptions might gradually clear up the obscuring envelope material and drive the protostar on its way to become a disk-only T Tauri star. In order to study the dust and gas in the envelope, we obtained continuum and CO line observations with Herschel, IRAM, and CARMA for nine FUors. Here we present preliminary results and discuss the evolution they outline within the FUor group and in the broader context of the formation of low-mass pre-main sequence objects.

Episodic accretion

- According to the general paradigm, Sun-like stars form when dense cores in the interstellar matter gravitationally collapse. Nascent stars are surrounded by circumstellar disks, from which material is accreted onto the growing star. Initially, the system is embedded in an envelope, the remnant of the initial core, which feeds material to the disk.
- A long-standing problem with this paradigm is the luminosity problem: theoretical models for the collapse of cloud cores predict infall rates on the order of 10^{-6} $M_\odot$/yr, which imply luminosities typically 10 – 100 times higher than what is observed for embedded protostars (e.g. Dunham et al. 2013).
- One way to overcome this conundrum is to assume that the accretion rate is not constant in time, but episodic: the protostar normally accretes at a very low rate, and this quiescent accretion is occasionally interspersed by brief episodes of highly enhanced accretion (Kenyon et al. 1990).

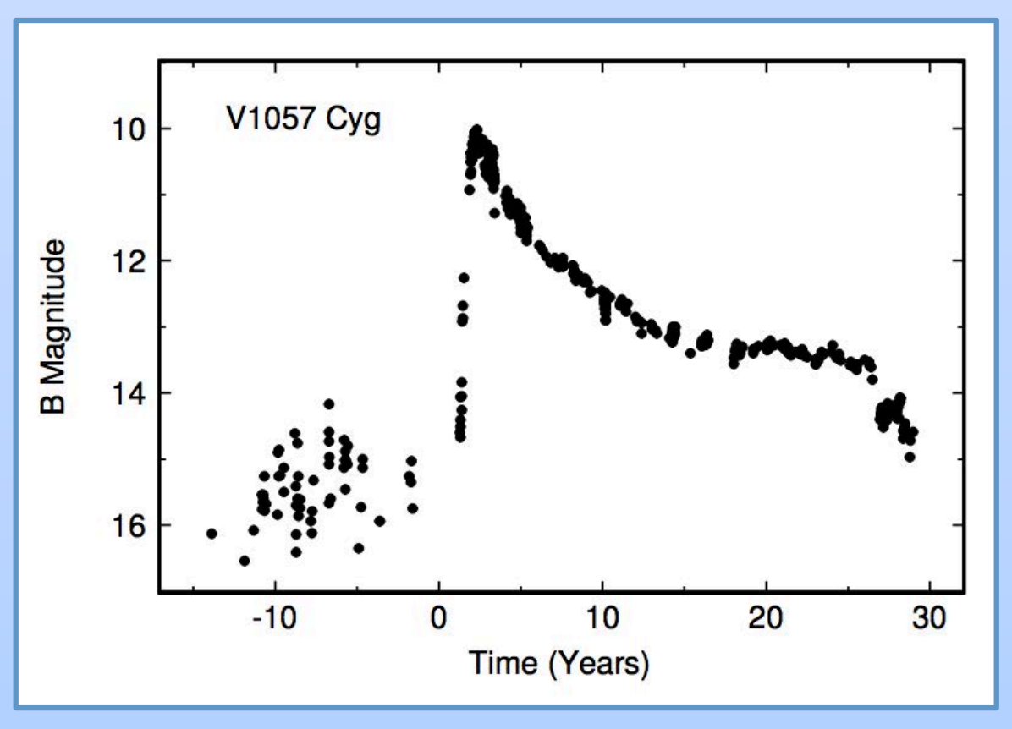
Time evolution of the mass accretion rate onto the star. Example result of our radiative transfer and hydrodynamical simulations that predict short-term variability and episodic bursts (Dunham & Vorobyov 2012).



FU Orionis-type stars

- FU Orionis-type stars (FUors) are the visible examples of episodic accretion.
- They exhibit 5 – 6 mag optical outbursts attributed to enhanced accretion (Hartmann & Kenyon 1996).
- During outburst, the accretion rate from the circumstellar disk onto the star may rise up to 10^{-5} – 10^{-4} $M_\odot$/yr, three orders of magnitude higher than in quiescence.
- Possible physical mechanisms of the outburst:
  - Viscous-thermal instability (Bell & Lin 1994)
  - Gravitational + magneto-rotational instability (Armitage et al. 2001)
  - Perturbation by a close stellar or sub-stellar companion (Lodato & Clarke 2004; Bonnel & Bastien 1992)
  - Accretion of clumps in a gravitationally fragmenting disk (Vorobyov & Basu 2006, 2010)

Optical light curve of V1057 Cyg (Kolotilov & Kenyon 1997). The outburst of V1057 Cyg was the second FUor-type eruption discovered after the prototype FU Ori, and reached peak brightness at B=10 mag in 1972.



What is the envelope infall rate?

- Envelopes play a significant role in the outburst of FUors, partly by replenishing the disk material after each outburst and driving the disk to fragment (Vorobyov & Basu 2010), partly by maintaining disk accretion rates that trigger eruptions (Bell & Lin 1994).
- A fundamental parameter is the mass infall rate from the envelope onto the disk, which regulates all these processes and determines the frequency of the bursts (Vorobyov et al. 2013).
- A general prediction of the inner disk instability models is that the mass infall from the envelope onto the outer disk should exceed a critical value of a few times 10^{-7} $M_\odot$/yr, otherwise the material is accreted steadily onto the star, and no eruptions are produced (Zhu et al. 2009).
- Despite its importance, with one exception, no measured envelope infall rates have been published for FUors. One reason for this is the lack of millimeter interferometric observations: out of the nine FUors listed in the review of Hartmann & Kenyon (1996), millimeter interferometric observations are only published for L1551 IRS 5 (Momose et al. 1998). The other reason is that to determine the infall rate from the observations is a non-trivial task, for which the modeling and computational background has just recently been developed.

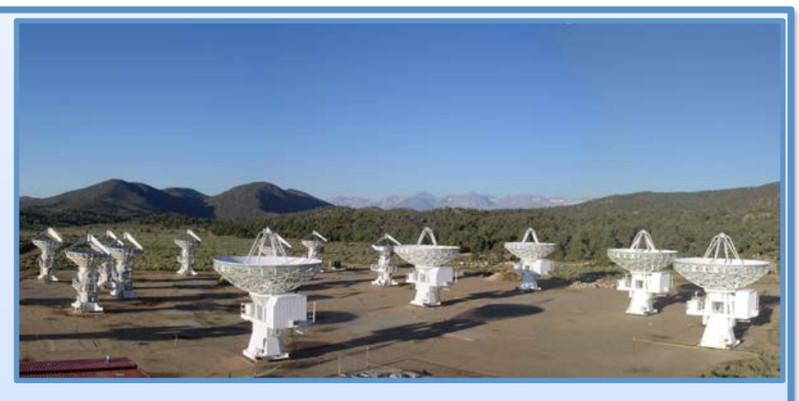
Observations

Herschel

- Observations between 2010–2012
- Six targets: FU Ori, V1057 Cyg, V1515 Cyg, V1331 Cyg, V1735 Cyg, and HBC 722
- PACS 70, 100, and 160 μm images, 50 – 210 μm spectra
- SPIRE 250, 350, and 500 μm images, 190 – 690 μm spectra
- HIFI spectra for the J = 5 – 4 and J = 14 – 13 CO lines

IRAM

- Observations in 2012 and 2014
- Seven targets: V1057 Cyg, V1515 Cyg, V1735 Cyg, HBC 722, V2492 Cyg, RNO 1B/1C, and V733 Cep
- Single dish and interferometric data in the 3 mm band
- J = 1 – 0 line of ^{13}CO and C^{18}O
- Single dish data for several molecular lines in the 3 mm band
- 2.7 mm continuum interferometric data

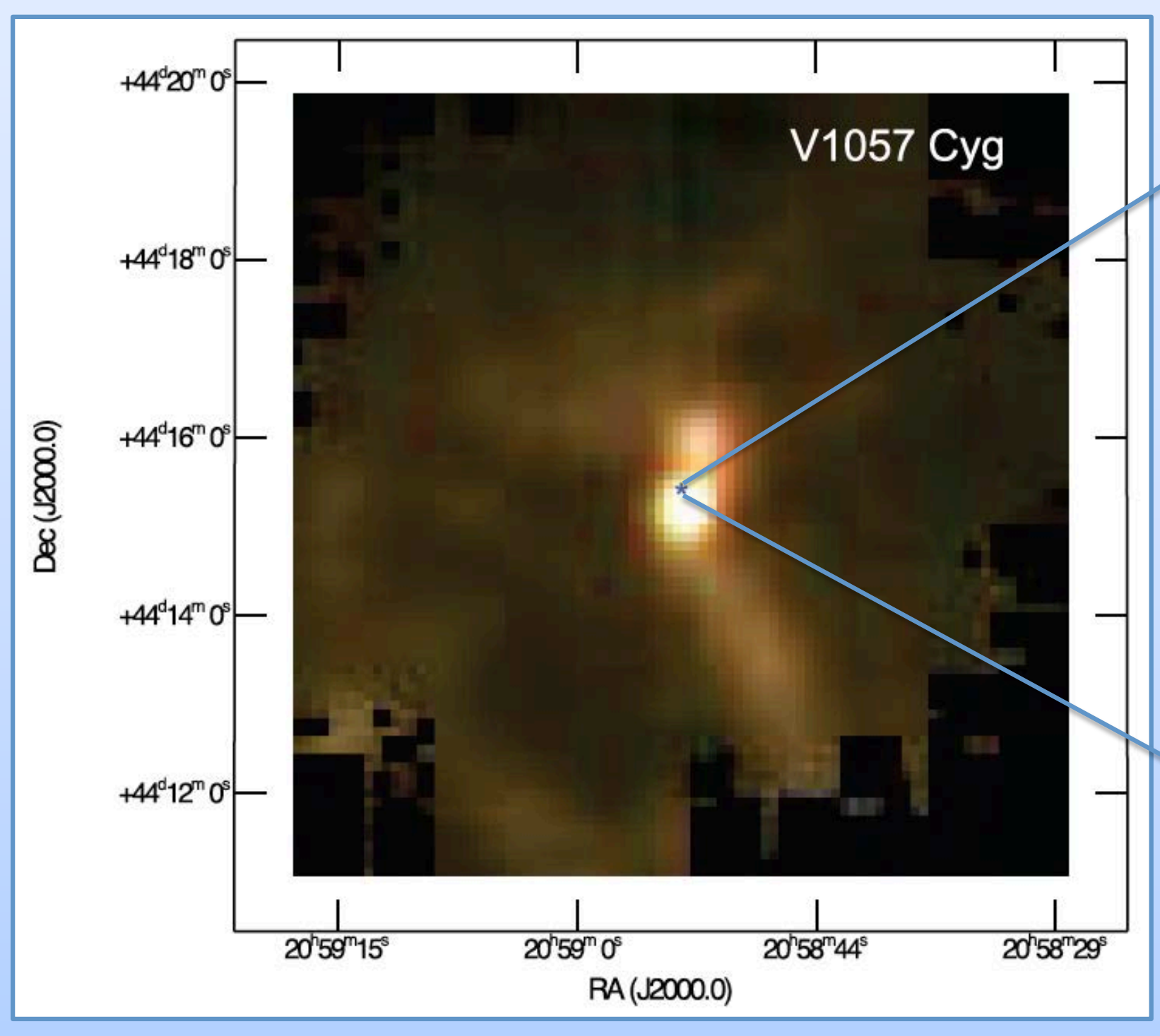


CARMA

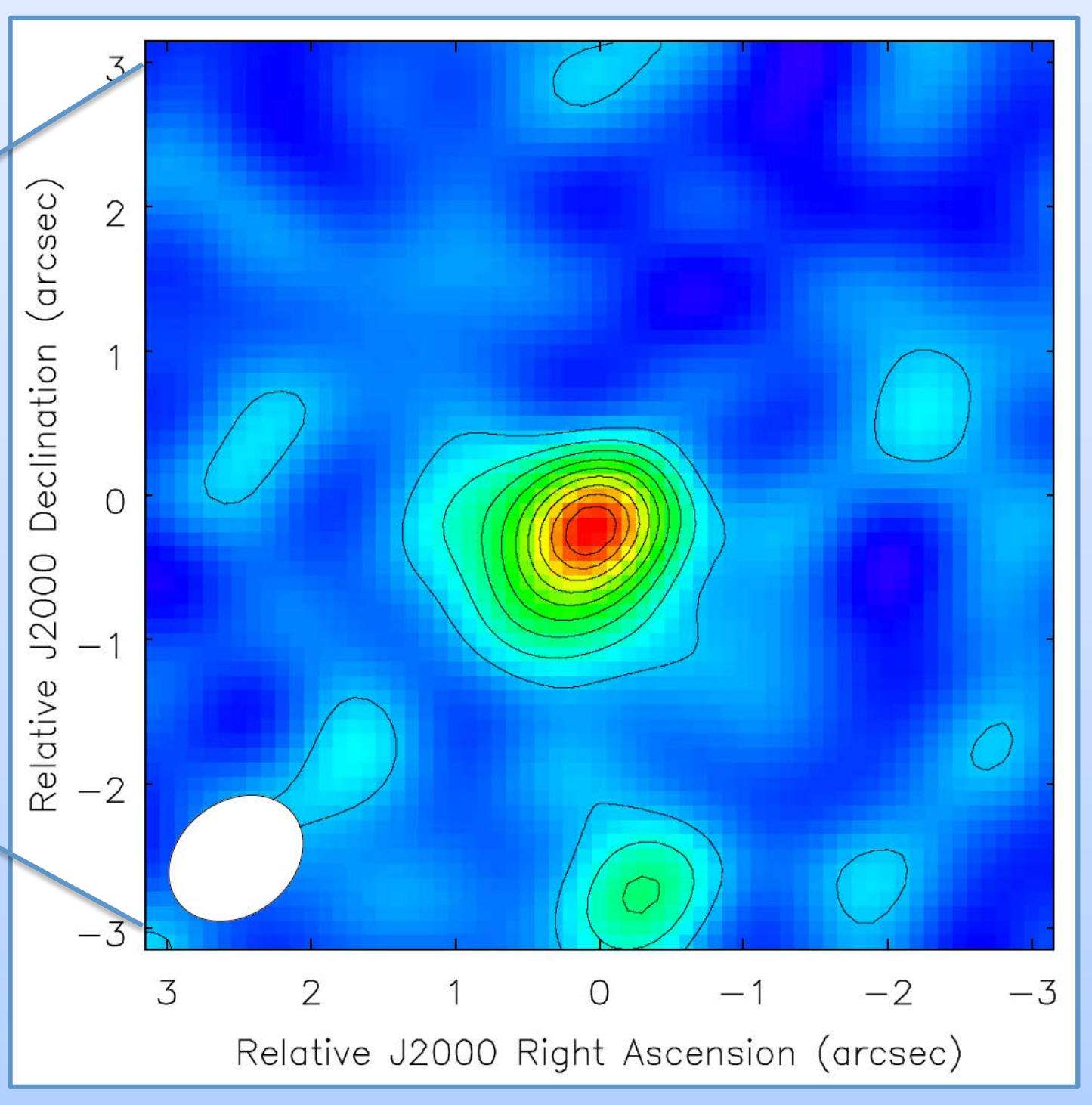
- Observations in 2013
- Four targets: V1057 Cyg, V1331 Cyg, V1515 Cyg, V1735 Cyg
- Interferometric data in the 1.3 mm band
- J=2–1 line of ^{12}CO, ^{13}CO, and C^{18}O
- No single-dish data
- 1.3 mm continuum interferometric data

Case study: V1057 Cyg

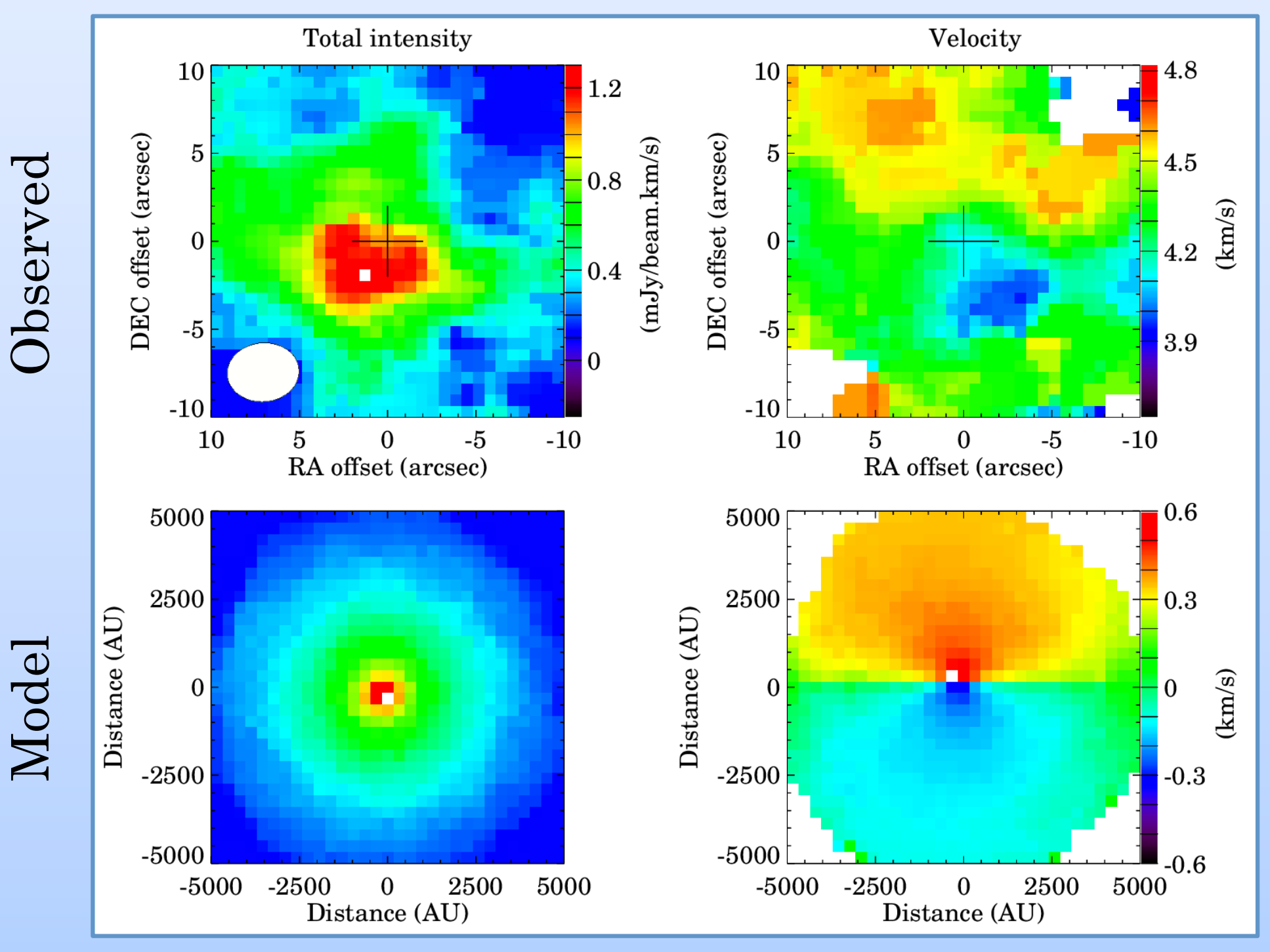
Composite 250, 350, and 500 μm continuum



1.3 mm continuum (CARMA)



^{13}CO J = 1 – 0 line (IRAM 30 m + PdBI)



- A bright and extended envelope around V1057 Cyg is detected with Herschel between 70 μm and 500 μm. The temperature of the envelope is about 40 K, and the total mass is about 0.2 $M_\odot$ (Green et al. 2013).
- The CARMA 1.3 mm and PdBI 2.7 mm interferometric continuum images show a marginally resolved central source which we identify as the disk around the young star. The mass of the disk is about 0.05 $M_\odot$.
- The CO line observations indicate that the fine structure of the gas envelope is clumpy and complex, with a hint for a north-south velocity gradient, possibly due to rotation.

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Acknowledgements

This work was supported by the Momentum grant of the MTA CSFK Lendület Disk Research Group.

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