Influence of Turbulence in Dense Cores on the Formation and Evolution of Protostellar Disks

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Summary: The impact of core-scale turbulence on formation and evolution of protostellar disks is still observationally unclear. Our analysis of velocity structures of two protostellar cores using the second-order structure function suggests that the observed velocity structures are consistent with turbulent motion across the dense cores. We found two cases that hint possible influence of the core-scale turbulence on formation and evolution of protostellar disks—a warped disk forming around the Class I protostar, L1489 IRS, and three misaligned outflows around the single Class 0 protostar, IRAS 15398-3359. These would be likely attributed to accretion of material with inhomogeneous angular momentum vectors from the dense cores onto the disks, which could be induced by turbulence. Considering the typical turbulent energy observed in IRAS 15398–3359, such accretion processes could be common in formation and evolution of the disks.

1. Kinematics in Protostellar Cores

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We revealed complex velocity structures on scales of ~1000–10,000 au around the protostars IRAS 15398–3359 (hereafter IRAS 15398) and L1527 IRS (Fig 1), as often observed in dense cores [1,2], suggesting turbulent velocity fields.

To probe whether they originate from core-scale turbulence, we examined correlation between the velocity deviation (δv) and spatial scale (τ) in the velocity fields through the second-order structure function, $S(\tau)$ (Fig 2). The obtained slopes of δv as a function of τ are within the range of those observed in parsec-scale molecular clouds (γ_{2D}~0.2–0.8) [3,4]. They could be also consistent with isotropic turbulence models—Kolmogorov turbulence and Burgers turbulence (γ_{3D}~0.33 and ~0.5, respectively)—when turbulence is being driven [5,6].

Equations:

$$S(\tau) = N(\tau)^{-1} \sum_x \left[v_c(x) - v_c(x+\tau) \right]^2,$$

$$\delta v(\tau) = \sqrt{S(\tau)} \propto \tau^{\gamma_{2D}}, \quad \gamma_{2D} = \gamma_{3D} + 0.5 + \delta\kappa/2$$

γ_{2D} and γ_3 are the spatial dependence measured on the plane of the sky and in 3D space, respectively. $\delta\kappa$ is an empirically derived constant representing degree of density fluctuations. $\delta\kappa$ takes −1.5 to −0.5 and Kolmogorov turbulence and Burgers turbulence expect γ_{2D}~0.08–0.75 when turbulence is being driven.

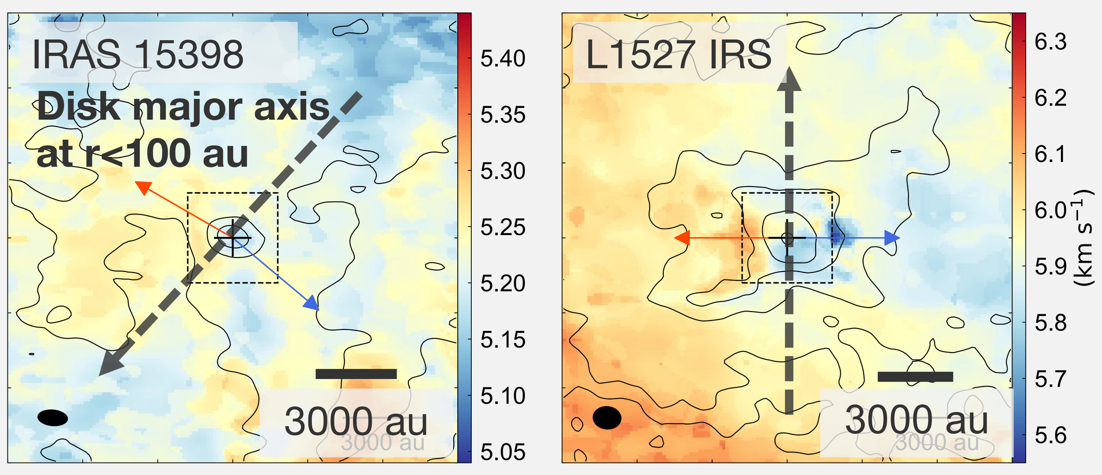

Figure 1. Mean velocity maps of the $C^{18}O$ J=2–1 emission taken with the ACA 7-m array, IRAM 30-m telescope and APEX (60″x60″).

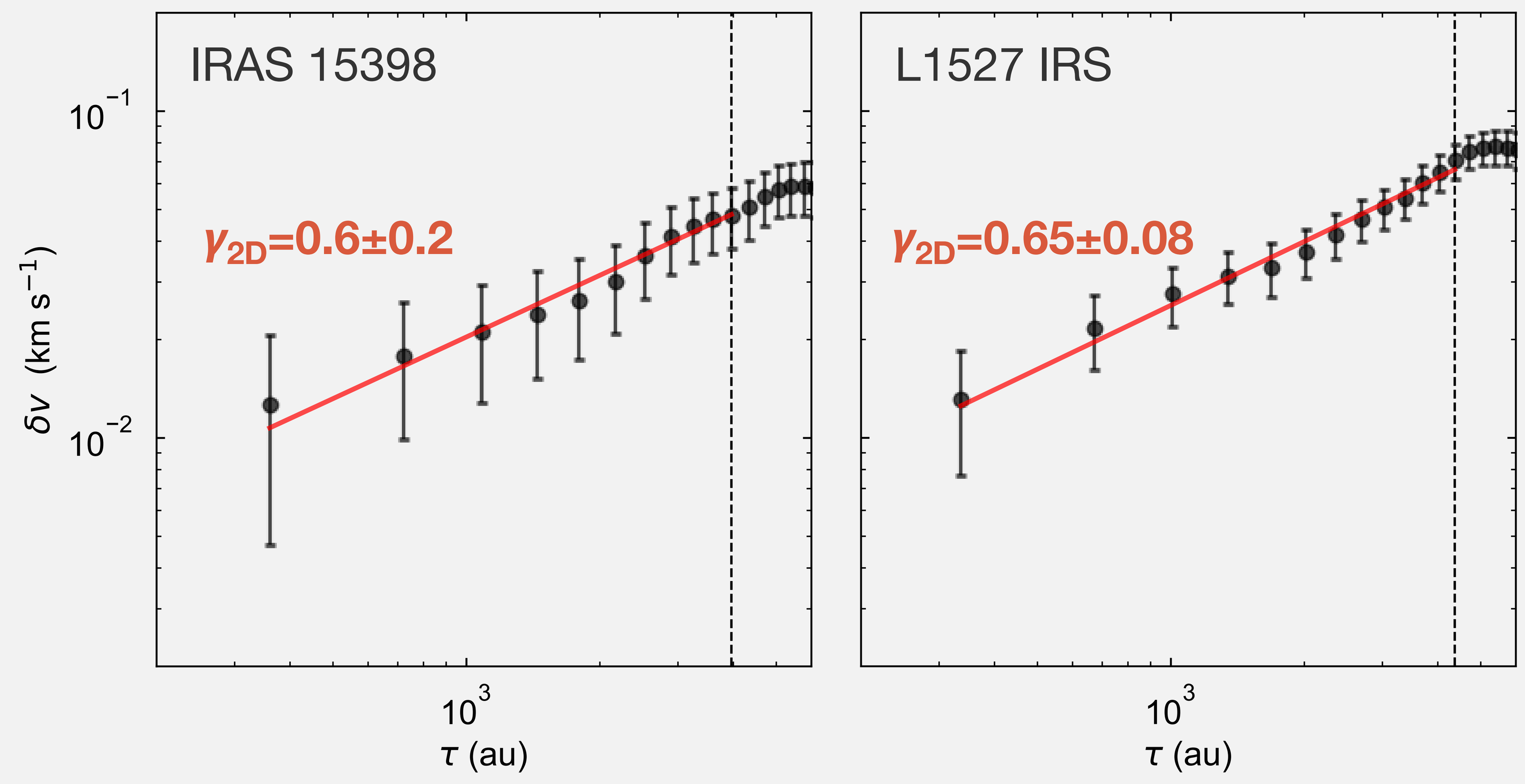

Figure 2. Correlation between the velocity deviation (δv) and spatial scale (τ) measured with one-dimensional cuts of the mean velocity maps along the disk major axis.

2. Warped Disk around L1489 IRS

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A warped structure was observed in a Keplerian disk around the protostar L1489 IRS (Fig 3a). We conducted a simple numerical simulation and confirmed that such a warped disk could form through accretion of material with inhomogeneous angular momentum vectors (Fig 3b). Such an accretion process can indeed occur in turbulent dense cores [7, 8].

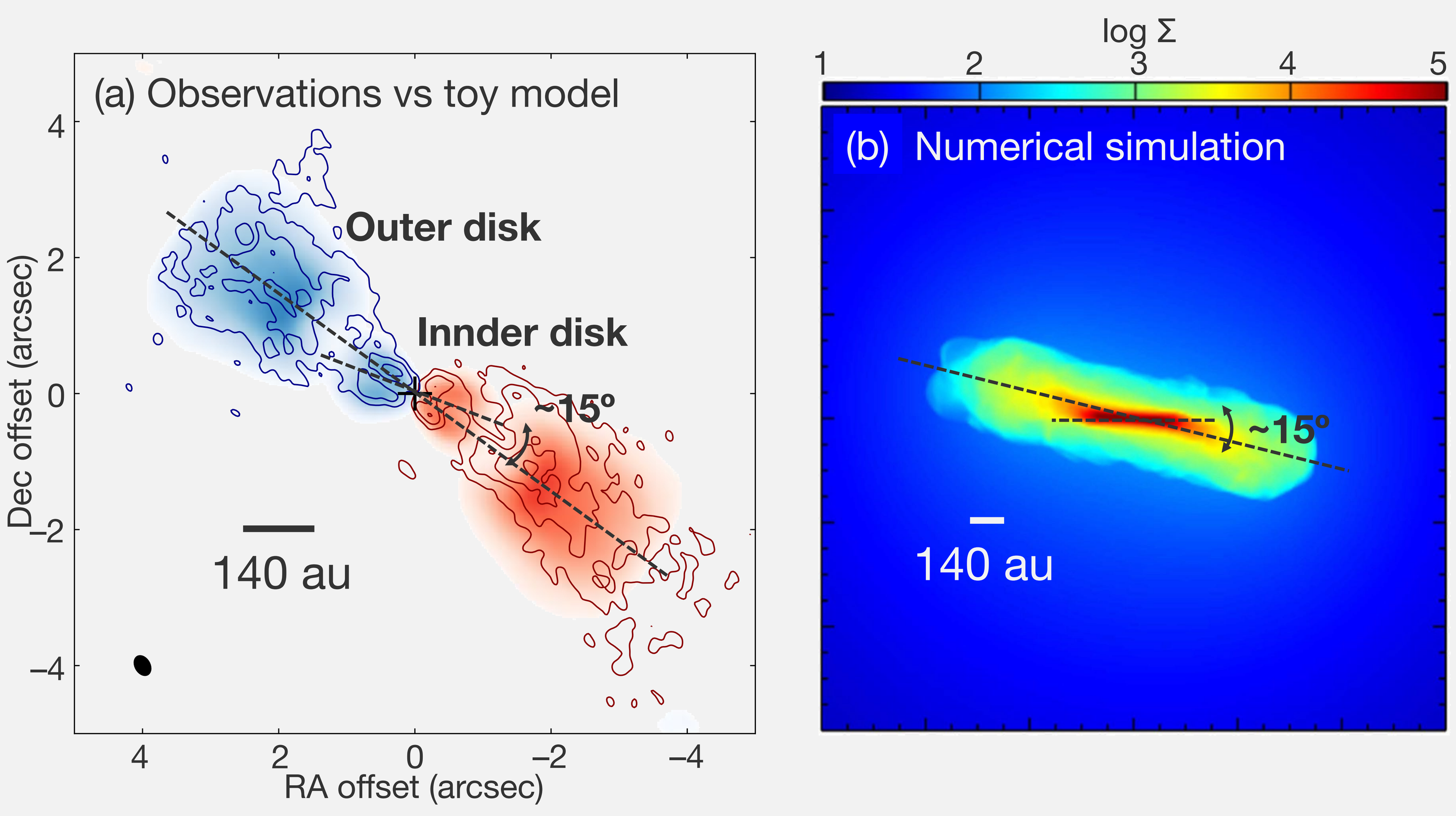

Figure 3. Panel a: the $C^{18}O$ J=2–1 emission observed in L1489 IRS with ALMA (contours) and of a disk model (color). Blue and red contours/colors indicate blueshifted and redshifted components, respectively. Panel b: a warped disk reproduced in the numerical simulation.

3. Three Outflows around a Single Protostar IRAS 15398–3359

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We discovered the third outflow around IRAS 15398, which is highly misaligned with the known primary and secondary outflows (Fig 4) [9]. The protostar appears to be a single source at a resolution of ~6 au [10], indicating that all the three outflows are likely driven by the single protostar. The dynamical timescales of these outflows differ by an order of magnitude at most, suggesting that the orientation(s) of the outflow (and disk) has changed over time.

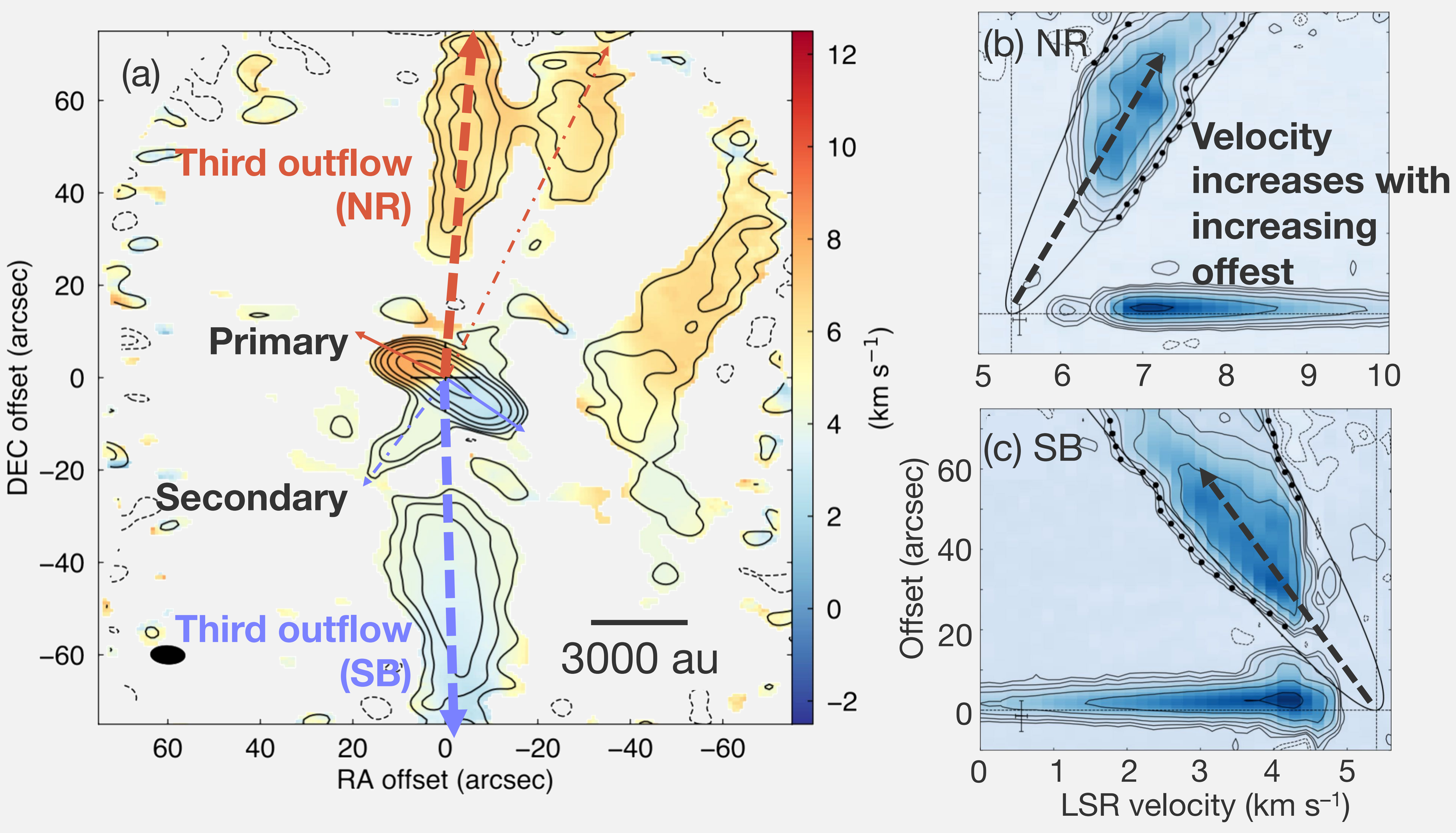

Figure 4. Panel a: integrated intensity (contours) and mean velocity (color) maps of the ^{12}CO J=2–1 emission observed in IRAS 15398–3359 with the ACA 7-m array. Panel b and c: position-velocity diagrams cut toward the northern redshifted (NR) and southern blueshifted (SB) components.

An accretion from a turbulent dense core onto a disk could cause such significant changes in orientations of the disk and outflow, as discussed for L1489 IRS. The ratio of turbulent energy to gravitational energy (β_{turb}) estimated for dense cores including IRAS 15398 is often sufficiently larger than those in numerical simulations reporting time evolution of the disk/outflow directions (Fig 5) [7, 8].

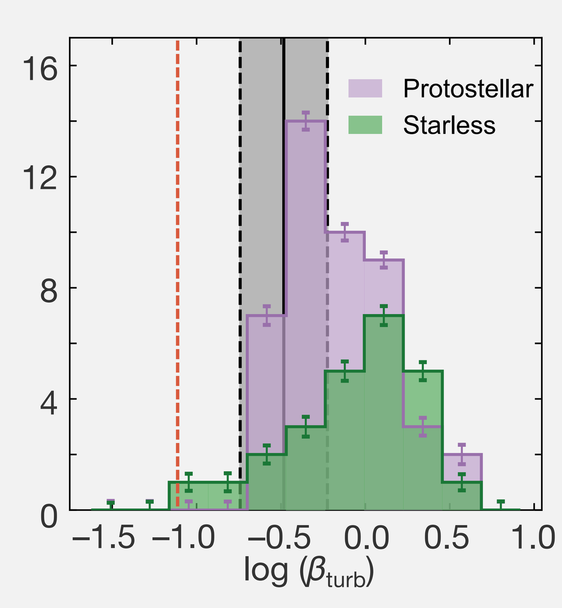

Figure 5. Comparisons of β_{turb} measured in the dense core of IRAS 15398 (vertical solid line), in other dense cores in the Perseus star-forming regions (histogram) [11] and in numerical simulations (red dashed line) [7, 8].

4. Suggested Picture of the Disk Formation and Evolution Process

- **Protostellar disks may form and evolve through accretion of material with inhomogeneous angular momentum vectors induced by turbulence in dense cores.**
- **The orientations of the disks and outflows can significantly change over time, as also predicted by numerical simulations [7, 8].**
- **Such accretion processes could be common in formation and evolution of the disks, considering typical turbulent energy in the dense cores.**

References: [1] Caselli et al. 2002, ApJ, 572, 238; [2] Chen et al. 2019, MNRAS, 490, 527; [3] Miesch & Bally 1994, ApJ, 429, 645; [4] Ossenkopf & Mac Low 2002, A&A, 390, 307; [5] Kolmogorov 1941, DoSSR, 30, 301; [6] Burgers 1974, The Nonlinear Diffusion Equation; [7] Matsumoto et al. 2017, ApJ, 839, 69; [8] Seifried et al. 2013, MNRAS, 432, 3320; [9] Okoda et al. 2021, ApJ, 910, 11; [10] Thieme et al. 2023, ApJ, 958, 60; [11] Kirk et al. 2007, ApJ, 668, 1042.