

Flocking through a sea of rods

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We investigate the collective behavior of motile rods immersed in a monolayer of apolar rods confined between vertically vibrating plates using numerical simulations. We uncover an antidiffusive phenomenon whereby motile rods segregate from the apolar medium and form anisotropic flocks whose size increases with the medium concentration. Remarkably, enhanced segregation leads to a reduction of the global polar order, giving rise to an anomalous dependence of the polar order on the medium concentration and the angular noise of the motile rods. The flock structure is strongly influenced by the anisotropy of the medium rods. For small aspect ratios, the flocks are elongated perpendicular to the mean direction of motion, whereas for larger aspect ratios they elongate along the direction of motility. We rationalize the emergence of segregation-induced disorder using a minimal mean-field model.

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I. INTRODUCTION

Flocking is a central phenomenon of active matter, emerging when motile entities interact through a surrounding medium, direct mechanical contact, or perceptual cues, giving rise to robust collective motion and striking spatiotemporal patterns [1–12]. It displays intrinsically nonequilibrium features absent in passive systems and occurs across an extraordinary range of physical realizations, from living organisms spanning multiple length scales to synthetic motile particles engineered in the laboratory. In this paper, we investigate how a medium composed of elongated particles influences flocking in dry active granular systems using numerical simulations. While most studies focus on flocking in structureless environments [3,13–26], far less is known about how flocking emerges when the surrounding medium is complex [27–54]. Motivated by recent studies of polar swimmers navigating nematic backgrounds in both wet and dry active-matter systems [34,37–43,48], we address how a collection of granular, motile (polar) rods flocks while traversing a monolayer medium of granular, nonmotile (apolar) rods confined between two vertically shaken plates with periodic boundary conditions in the horizontal plane. This medium exhibits a rich variety of phases—including isotropic, nematic, chevron, and defect-melted nematic states—accessible by tuning the rod length and concentration [55]. Such tunability introduces an additional layer of complexity to the emergent dynamics, significantly enriching the system’s behavior.

We summarize our main findings as follows. We find that motile rods exhibit a strong tendency to segregate from the apolar medium and form flocks as the medium concentration increases. Within

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each flock, the constituent rods remain polar aligned and move collectively in the same direction. As the medium concentration increases, the flocks become progressively more elongated, developing a long, tail-like morphology along their collective direction of motion. Here, *flock elongation* refers to the anisotropic shape of the flock rather than the orientation of its constituent rods. Although the rods remain highly aligned within individual flocks, the increasing segregation between flocks reduces the global polar order of the motile rods. In the absence of intrinsic angular noise of the motile rods, this mechanism leads to a phase transition from a homogeneous polar-ordered state to a disordered, segregated regime characterized by elongated flocks that do not sustain global order. Introducing intrinsic angular noise progressively weakens segregation and, counterintuitively, enhances polar order, revealing an anomalous noise-induced ordering effect. At sufficiently large noise strengths, the system ultimately crosses over to a homogeneous disordered phase. At high apolar-rod concentrations, the flock structure is strongly influenced by the anisotropy of the medium rods. For small aspect ratios, the flocks are elongated perpendicular to the mean direction of motion, whereas for larger aspect ratios they align parallel to the direction of motility, consistent with segregation-induced structures observed previously in a bead medium [23]. We rationalize the emergence of segregation-induced disorder using a minimal mean-field model.

II. METHODS

We perform Newtonian dynamics simulations of our system of rigid particles confined between vertically oscillating plates, in which both interparticle and particle-wall collisions are assumed to be inelastic [23,24,55–61]. The vertically oscillating plates are modeled as horizontally extended moving walls with vertical positions $A \cos(\Omega t)$ and $A \cos(\Omega t) + w$, respectively, where A denotes the vibration amplitude, Ω is the angular frequency, and $w = 1.2$ mm is the fixed gap between the plates. The simulations are further simplified by imposing periodic boundary conditions in the xy plane. Collisions are treated using an impulse-based collision framework [62]. Each rod is represented as a linear chain of partially overlapping spheres. The apolar rods are symmetrically tapered at both ends, with a diameter varying from 0.8 mm at the center to 0.4 mm at the ends, and have lengths ℓ_a ranging from 0.8 to 4.5 mm, corresponding to aspect ratios σ varying from 1 to 5.62. Note that $\ell_a = 0.8$ mm corresponds to a spherical bead [see Fig. 1(a)]. The motile rods have a fixed length $\ell_p = 4.5$ mm and a diameter that varies from 1.1 mm at the thick end to 0.7 mm at the thin end [see Fig. 1(b)]. The friction and restitution coefficients are chosen to be the same as the values established in previous studies of motile rods in a bead medium [24]. The dimensionless acceleration parameter $\Gamma = A\Omega^2/g$ is set to 7, with the driving frequency fixed at $\Omega = 400\pi \text{ s}^{-1}$, where g is the gravitational acceleration. We also incorporate angular noise for the motile rods by introducing a random angular velocity in the xy plane upon collisions with the plates, quantified in terms of the single-rod rotational diffusion coefficient D_r . No intrinsic angular noise is applied to the apolar rods.

The simulation box size is set to $L = 56 \ell_p$. The concentrations of motile and apolar rods are measured by their respective area fractions, ϕ_p and ϕ_a , defined as the fraction of the system area

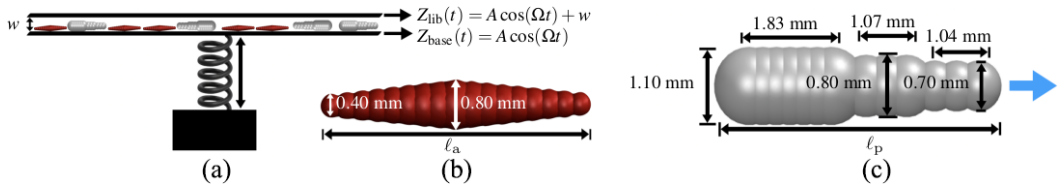


FIG. 1. (a) Schematic of rods confined between vertically vibrated plates. (b) Geometry of an apolar rod (red). (c) Geometry of a motile (polar) rod (silver), with the blue arrow indicating the direction of self-propulsion.

covered by the rods, assuming they lie entirely in the xy plane. Visualization and rendering of simulation trajectories are performed using the VMD software package [63]. Various averaged quantities calculated here are estimated using time averages in the steady state. Additional details—including friction and restitution coefficients, rod numbers, the precise definition of area fraction, and the mechanism of rotational noise—are provided in the Sec. I of the Supplemental Material [59,64]. For each set of parameters, a single long-duration simulation was performed. The system was first evolved until it reached a steady state, identified by the saturation of the corresponding global order parameters of both the motile and apolar rods, which then exhibited only small fluctuations about their mean values with time. After the steady state was reached, the simulation was continued for a sufficiently long time to collect a large number of statistically independent configurations. All reported quantities and their associated error bars were calculated from these steady-state data. The error bars represent one standard deviation of the steady-state measurements. We also verify that the steady-state statistics are independent of the initial configuration, consistent with the ergodic nature of the system.

III. RESULTS

We first investigate the collective behavior of motile rods embedded in an isotropic medium at $\sigma = 3.12$ ($\ell_a = 2.5$ mm) in the absence of intrinsic angular noise, i.e., $D_r = 0 \text{ rad}^2 \text{ s}^{-1}$. The plots of the nematic order parameter for the medium, shown in Fig. S1(a) in Sec. II of the Supplemental Material [64], confirm that the medium is in an isotropic phase. Figure 2(a) shows that at low

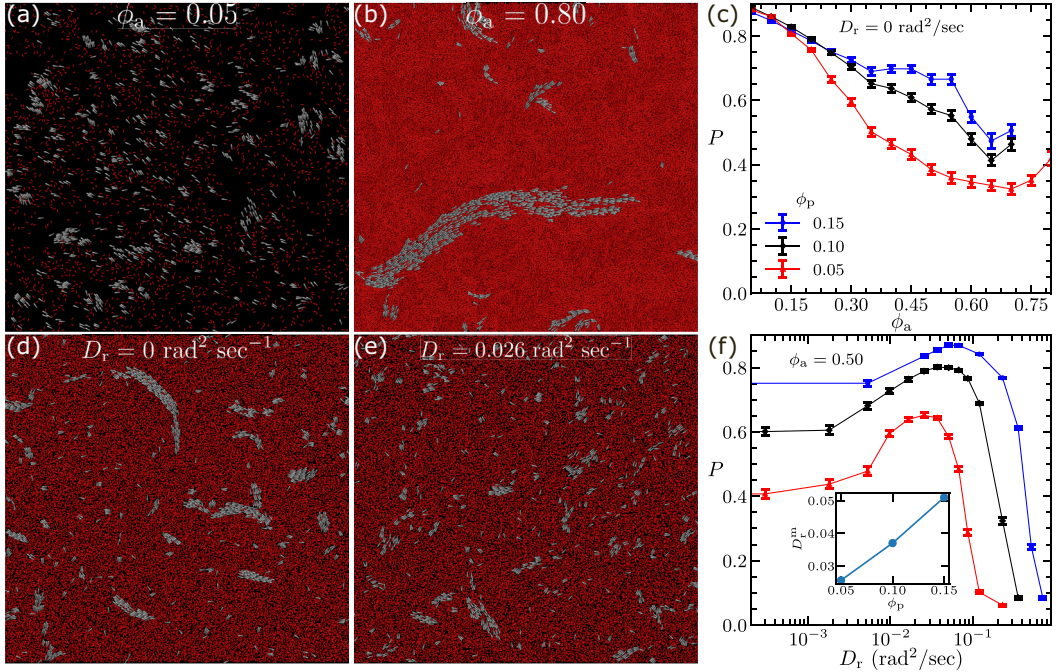


FIG. 2. Effect of ϕ_a at $D_r = 0 \text{ rad}^2 \text{ s}^{-1}$: Steady-state configurations at $\phi_p = 0.05$ for (a) $\phi_a = 0.05$ and (b) $\phi_a = 0.80$. (c) Polar order parameter P of the motile rods vs ϕ_a for different ϕ_p . Effect of D_r at $\phi_a = 0.50$: Steady-state configurations at $\phi_p = 0.05$ for (d) $D_r = 0 \text{ rad}^2 \text{ s}^{-1}$ and (e) $D_r = 0.026 \text{ rad}^2 \text{ s}^{-1}$ [corresponding to the maximum value of P in panel (f)]. (f) P vs D_r for different ϕ_p . Inset: D_r^m (where P is maximal) vs ϕ_p . Here, $\sigma = 3.12$ ($\ell_a = 2.5$ mm). The red rods represent the apolar rods, the silver rods represent the motile rods, and the black background corresponds to the canvas.

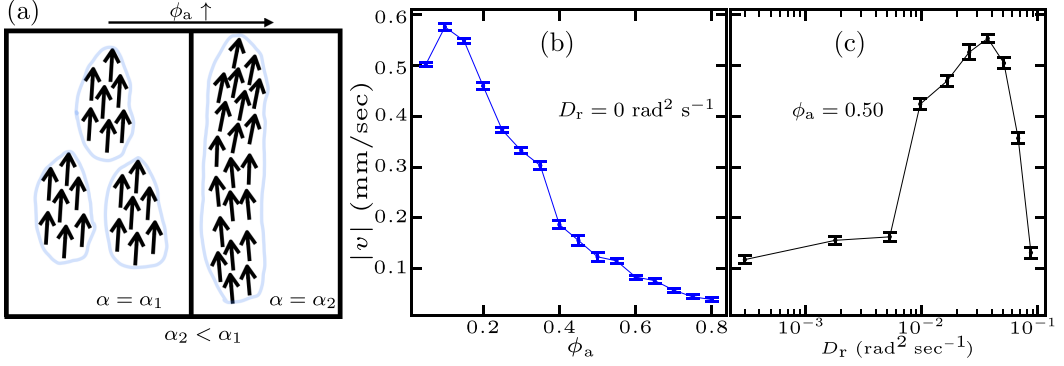


FIG. 3. (a) Schematic illustrating the mechanism of segregation-induced disorder. As segregation between motile and apolar rods increases with ϕ_a , the interfacial length decreases, leading to a reduction of the coupling constant α in Eq. (2). (b) Average speed $|v|$ of the medium rods measured at a distance of 100 mm from a motile rod in its comoving frame, averaged over rods and time, as a function of ϕ_a for $D_r = 0 \text{ rad}^2 \text{ s}^{-1}$. Consistent with the mechanism shown in panel (a), $|v|$ decreases with increasing ϕ_a . (c) $|v|$ as a function of D_r at $\phi_a = 0.50$, showing an increase at small D_r . Here, $\sigma = 3.12$ ($\ell_a = 2.5 \text{ mm}$) and $\phi_p = 0.05$.

ϕ_a , the motile rods form small flocks that move coherently, resulting in an ordered phase. In contrast, at large ϕ_a , larger flocks emerge that move incoherently, leading to a disordered phase [Fig. 2(b) and Movie S1 of the Supplemental Material [64]]. These flocks are highly dynamic, continuously breaking into smaller flocks that subsequently merge again to form larger polar flocks (see Fig. 7 in Appendix A). The instantaneous direction of a flock is strongly influenced by emergent topological defects in the medium (see Movie S1 of the Supplemental Material [64]), and the flocks develop elongated tails along their direction of motion, a structure we term *longitudinal flocking*. A detailed analysis of the flock size and shape is presented later. The transition from an ordered to a disordered phase with increasing ϕ_a is further confirmed in Fig. 2(c), which shows that the polar order parameter P decreases as ϕ_a increases for different values of ϕ_p . Strikingly, this trend contrasts with that observed in a spherical-bead medium, where the medium instead enhances ordering at large ϕ_a (see Fig. S4 in Sec. III of the Supplemental Material [64]) [23,24]. Moreover, rods in a bead medium form a homogeneous ordered phase, in contrast to the randomly moving clustered flocks observed here. A slight upturn in $\langle P \rangle$ is observed at the largest values of ϕ_a explored. This behavior correlates with the increase in the nematic order parameter $\langle S \rangle$ of the apolar-rod medium [Fig. S1(a) in Sec. II of the Supplemental Material [64]]. As ϕ_a increases, the medium develops stronger local nematic alignment, which promotes the alignment of neighboring motile rods and results in a modest increase in $\langle P \rangle$. However, the medium remains globally isotropic over the range of ϕ_a considered here, so this enhancement is limited.

Two mechanisms underlie this anomalous medium-induced behavior. First, as ϕ_a increases, the coupling between the orientations of the motile rods and the local nematic alignment of the medium enhances the effective rotational diffusion of the rods. This effect becomes increasingly pronounced at larger ϕ_a , where topological defects in the medium play a significant role [see Fig. S3(c) in Sec. II of the Supplemental Material [64]].

Second, the motile rods exhibit a strong tendency to segregate and form larger flocks at large ϕ_a , thereby reducing the interfacial length between the motile-rod-rich regions and the surrounding medium [Fig. 3(a)]. The theoretical basis for the role of the interfacial length in determining the medium-induced ordering is presented in Sec. IV. Since the motile rods interact with the medium through their interface, a reduction in interfacial length weakens their ability to push the medium. Therefore, the medium-induced velocity field that drives enhanced ordering is suppressed, leading to a reduction in the degree of polar order [see Fig. 3(b)] [23].

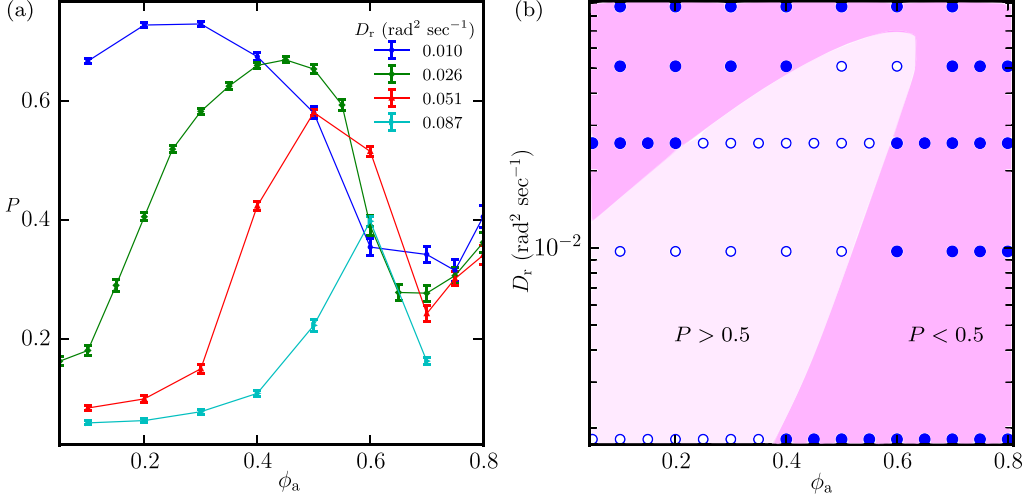


FIG. 4. (a) P vs ϕ_a for different D_r . (b) Phase diagram in the D_r - ϕ_a plane. Hollow and solid circles denote states with $P > 0.5$ and $P < 0.5$, respectively. Here, $\sigma = 3.12$ ($\ell_a = 2.5$ mm) and $\phi_p = 0.05$.

Next, we examine the role of intrinsic angular noise D_r of the motile rods, keeping $\phi_a = 0.50$ fixed, in the same isotropic medium ($\sigma = 3.12$). As discussed above, at $D_r = 0 \text{ rad}^2 \text{ s}^{-1}$, the system is in a disordered phase with large, uncorrelated flocks [see Fig. 2(d) and Movie S2 in the Supplemental Material [64]]. Upon introducing a small amount of angular noise, the large flocks fragment into smaller ones, increasing the interfacial length between the motile-rod-rich regions and the surrounding medium. The increased interfacial length enables the motile rods to drive the medium more effectively, thereby enhancing the medium velocity field [inset of Fig. 3(b)] and increasing polar ordering [see Fig. 2(e) and Movie S2 in the Supplemental Material [64]]. At larger values of D_r , however, angular noise dominates over alignment induced by the velocity field, causing the polar order to decrease and leading to a reentrant homogeneous, disordered phase. Figure 2(f) shows that P initially increases with D_r and then decreases beyond an optimal value D_r^m . This nonmonotonic trend persists across the range of ϕ_p studied, and D_r^m increases with ϕ_p [see the inset of Fig. 2(f)]. For completeness, we plot P as a function of ϕ_a in Fig. 4(a) for different D_r and observe a similar nonmonotonic dependence at finite D_r , consistent with the same underlying mechanism. Figure 4(b) shows the phase diagram in the D_r - ϕ_a plane, where states with $P < 0.5$ are denoted by solid blue circles and those with $P > 0.5$ by hollow blue circles. The light and dark regions correspond to the ordered ($\langle P \rangle > 0.5$) and disordered ($\langle P \rangle < 0.5$) phases, respectively. The phase boundary is obtained by linearly interpolating between neighboring data points on either side of the threshold $\langle P \rangle = 0.5$, assuming that the transition varies continuously over the explored parameter range.

Since the observed segregation constitutes an antidiffusive phenomenon, our system provides a realization of anisotropic antidiffusion [61,65–70]. This, in turn, leads to an anomalous effect of D_r and ϕ_a on the polar order. We now study the shape and size of the flocks and the degree of segregation in the system.

We compute the segregation order parameter $\Sigma \in [0, 1]$, where $\Sigma = 0$ corresponds to the theoretically minimal level of segregation, while $\Sigma = 1$ indicates complete segregation [71,72] (see Appendix B). Figure 5(a) shows that Σ increases with ϕ_a at $D_r = 0 \text{ rad}^2 \text{ s}^{-1}$, indicating that the system becomes increasingly segregated into motile-rod-rich and apolar-rod-rich regions at larger ϕ_a . This observation is consistent with our earlier finding that the flock size increases with ϕ_a [see Figs. 2(a) and 2(b)] and arises from the strong effective attraction between motile rods mediated by the apolar medium. A detailed analysis of this mechanism will be presented elsewhere [73].

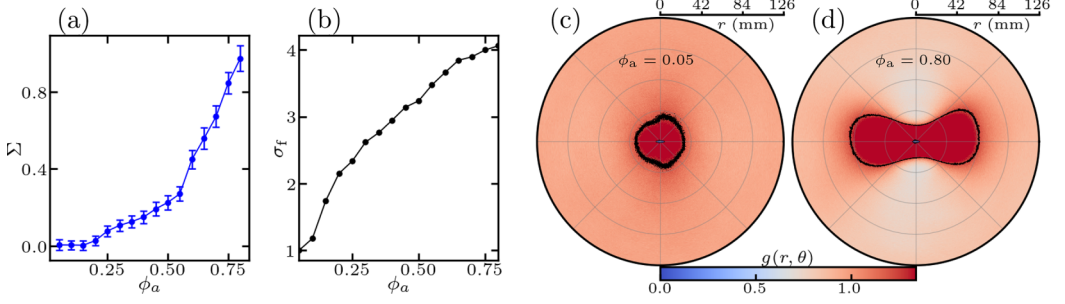


FIG. 5. (a) Segregation order parameter Σ vs ϕ_a . (b) σ_f , quantifying the flock aspect ratio, as a function of ϕ_a . Polar heat maps of $g(r, \theta)$ at (c) $\phi_a = 0.05$ and (d) $\phi_a = 0.80$. Here, $\sigma = 3.12$ ($\ell_a = 2.5$ mm), $D_r = 0 \text{ rad}^2 \text{ s}^{-1}$, and $\phi_p = 0.05$.

To examine the shape of the flocks, we compute the pair distribution function $g(r, \theta)$ in the corotating frame of a reference motile rod, averaged over all motile rods. To this end, each motile rod is treated as a reference particle, and the coordinate system is rotated such that its orientation is aligned with the positive x axis. For every other motile rod, the relative displacement from the reference rod is computed under periodic boundary conditions and subsequently transformed into the reference frame of the tagged rod. The transformed coordinates are then used to determine the radial distance r and polar angle θ , which are accumulated into a two-dimensional histogram over all reference rods and steady-state configurations to obtain $g(r, \theta)$. Figures 5(c) and 5(d) show polar heat maps of $g(r, \theta)$ for $\sigma = 3.12$ and $\phi_p = 0.05$ at $\phi_a = 0.05$ and 0.80 , respectively. At low ϕ_a , the distribution $g(r, \theta)$ is isotropic, indicating that the flocks are somewhat isotropic. In contrast, at large ϕ_a , the flocks become longitudinal, with a strongly anisotropic $g(r, \theta)$ that exhibits an enhanced probability of finding motile rods ahead of and behind a reference rod over large distances, resulting in elongated structures. We further assess this elongation by computing the average aspect ratio σ_f of the flocks, obtained from the closed contour corresponding to 70% of the maximum value of $g(r, \theta)$ [black contours in Figs. 5(c) and 5(d)]. The thicker ends of the contour in Fig. 5(d) arise from transient undulatory flocks with arclike shapes. Since the curvature of these flocks continuously evolves with time, the time-averaged contour captures their overall spatial extent, making σ_f a meaningful measure of flock elongation. As shown in Fig. 5(b), σ_f increases with ϕ_a . Orientational correlations, quantified by the polar order parameter correlation function $G(r, \theta)$, display a similar anisotropic structure at large ϕ_a , with strong alignment along the longitudinal direction and weaker correlations transverse to it (see Fig. S2 in Sec. II of the Supplemental Material [64]).

To elucidate the role of medium-rod anisotropy in the order-disorder phase transition, we set $D_r = 0.23 \text{ rad}^2 \text{ s}^{-1}$, for which motile rods are disordered in the absence of the medium. We then vary σ and ϕ_a , while keeping $\phi_p = 0.05$ fixed. Figure 6(a) presents P versus ϕ_a for different σ . For small σ , P increases with ϕ_a , indicating a transition from a disordered to an ordered phase, consistent with earlier observations for motile rods in a bead medium ($\sigma = 1$) [23]. In contrast, increasing σ within the isotropic phase of the apolar medium suppresses polar ordering at large ϕ_a , thereby inhibiting the phase transition. A phase diagram in the σ - ϕ_a plane is displayed in Fig. 6(b). As in Fig. 4(b), the light and dark regions indicate the ordered ($P > 0.5$) and disordered ($P < 0.5$) phases, respectively. The boundary is obtained by linear interpolation across $P = 0.5$. As displayed in Fig. 6(c), at $\phi_a = 0.80$, P decreases with σ up to $\sigma = 3.12$, for which the medium remains isotropic. Upon increasing σ further to 5.62 , the apolar medium becomes ordered, and the motile rods recover orientational order. Interestingly, at large ϕ_a , the structure of the flocks depends sensitively on σ . For $\sigma = 1$ (the bead-medium case), the motile rods form transverse band, whose extent perpendicular to the mean direction of motion exceeds that along it, consistent with Ref. [24] [see Fig. 6(d) and Movie S3 of the Supplemental Material [64]]. Increasing σ to 1.25 results in a homogeneous spatial distribution despite polar order [see Fig. 6(e) and Movie S3 of the Supplemental Material [64]]. For intermediate

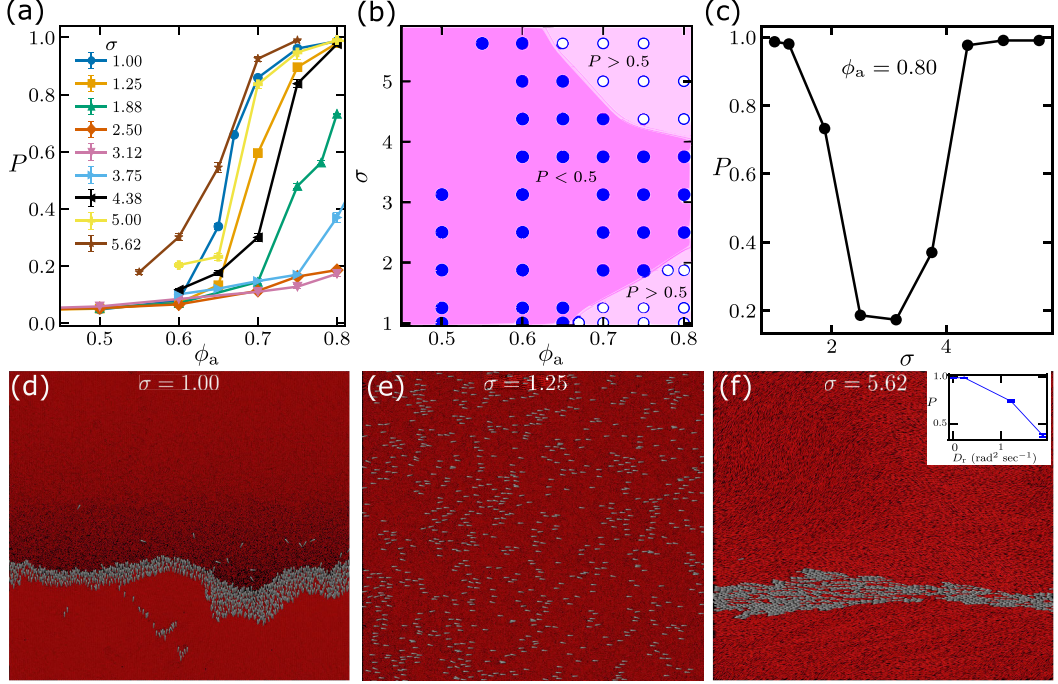


FIG. 6. (a) P vs ϕ_a for different values of σ . (b) The phase diagram in the σ - ϕ_a plane. (c) P vs σ for fixed $\phi_a = 0.80$. Steady-state configurations at fixed $\phi_a = 0.80$ for (d) $\sigma = 1.0$, (e) $\sigma = 1.25$, and (f) $\sigma = 5.62$. Here, $D_r = 0.23 \text{ rad}^2 \text{ s}^{-1}$ and $\phi_p = 0.05$.

values of σ , global order is destroyed, and the system exhibits small, randomly moving longitudinal flocks (Movie S3 of the Supplemental Material [64]). At sufficiently large σ , where the medium itself has nematic ordering, polar order is restored, and the motile rods form a long band oriented along the direction of motion, extending across the simulation box [see Fig. 6(f) and Movie S3 of the Supplemental Material [64]]. The band develops undulations, leading to the creation of topological defects in the medium that, in turn, drive the band through active nematic currents. As a result, the band begins to drift in a direction normal to its orientation (Movie S6 of the Supplemental Material [64]). At sufficiently large D_r , the band progressively dilutes, and at still larger D_r the system becomes disordered, accompanied by a loss of nematic order in the medium [see inset of Fig. 6(f) and Fig. S5 in Sec. IV of the Supplemental Material [64]].

IV. THEORY

In our theoretical description, we do not address the antidiffusive mechanism responsible for the formation of segregated flocks, as this would require a detailed continuum theory involving coupled equations for the polar order parameter field, the nematic order parameter field, the velocity field, and the polar and apolar area-fraction fields. Such a framework, previously developed for bead media [74], would need to be extended to incorporate the nematic order parameter in order to account for the formation of longitudinal bands or flocks. While a complete theory lies beyond the scope of the present work, the essential physical origin can be traced to the effective attraction between motile rods mediated by the apolar medium. Here, we focus solely on the order-disorder phase transition and restrict ourselves to the empirical observation that motile and apolar rods exhibit a strong tendency to segregate. We therefore construct a minimal mean-field description

involving only the spatially averaged polar order parameter $\mathbf{P}$ and the mean velocity $\mathbf{v}$, following Kumar *et al.* [23]. The resulting equations of motion are given by

$$\partial_t \mathbf{P} = -a \mathbf{P} + \lambda \mathbf{v} - b|\mathbf{P}|^2 \mathbf{P}, \quad (1)$$

$$\rho \partial_t \mathbf{v} = -\Gamma \mathbf{v} + \alpha \mathbf{P}. \quad (2)$$

Here, ρ denotes the mass density. The parameter a controls the relaxation of the polar order parameter $\mathbf{P}$ and originates from the angular noise of the motile rods. At large D_r , steric interactions between motile rods can be neglected in the dilute regime, and a is approximately equal to D_r . At small D_r , however, steric-collision-induced alignment cannot be ignored, leading to deviations from this simple relation. In particular, in the limit $D_r \rightarrow 0$, the parameter a would become negative due to interaction-induced ordering. The term $\lambda \mathbf{v}$ represents polar ordering induced by the flow of the medium. The nonlinear term $-b|\mathbf{P}|^2 \mathbf{P}$ ensures saturation of the order parameter, preventing unbounded growth. The term $-\Gamma \mathbf{v}$ denotes the dissipative force density arising from friction with the confining plates, while $\alpha \mathbf{P}$ corresponds to the active forcing due to motile rods that generate the velocity field. Assuming that $\mathbf{v}$ relaxes much faster than $\mathbf{P}$, i.e., $\rho \partial_t \mathbf{v} \ll \Gamma \mathbf{v}$, we obtain $\mathbf{v} \simeq \frac{\alpha}{\Gamma} \mathbf{P}$. Substituting this expression into Eq. (1) yields an effective equation for the polar order parameter,

$$\partial_t \mathbf{P} \simeq \left(\frac{\alpha \lambda}{\Gamma} - a \right) \mathbf{P} - b|\mathbf{P}|^2 \mathbf{P}. \quad (3)$$

In the steady state, when $\alpha \lambda / \Gamma - a > 0$, the magnitude of the polar order parameter is given by $|\mathbf{P}| = [(\alpha \lambda - a \Gamma) / (b \Gamma)]^{1/2}$. For $\alpha \lambda / \Gamma - a < 0$, the system remains in a disordered state with $|\mathbf{P}| = 0$. The parameters a and α depend primarily on ϕ_a and D_r . As the motile rods and the medium rods segregate more strongly, the interfacial length between motile-rod-rich and apolar-rod-rich regions decreases [see Fig. 3(a)]. Since motile rods push the medium microscopically through frictional contact during collisions, a larger interfacial length allows the motile rods to more effectively push the medium rods. Thus, enhanced segregation reduces α , leading to a decrease in the polar order parameter P . This provides the physical origin of the anomalous dependence of P on ϕ_a and D_r . As shown in Fig. 5(a), the segregation order parameter Σ increases sharply beyond $\phi_a \simeq 0.6$. As a result, at large ϕ_a , P decreases with increasing ϕ_a due to the reduced velocity field, in contrast to the behavior observed in a bead medium [see Fig. 3(b)]. A similar mechanism operates when varying D_r . At fixed $\phi_a = 0.50$, Σ decreases with increasing D_r for small D_r (see Fig. 8 in Appendix B), leading to an increase in α and a corresponding enhancement of polar ordering [see Figs. 2(f) and 3(c)]. Likewise, Σ increases with the apolar-rod aspect ratio σ , resulting in a decrease of P with increasing σ [see the inset of Fig. 6(a)], unless σ becomes sufficiently large that the medium itself enters an ordered phase.

The dependence of a on ϕ_a becomes particularly important at large ϕ_a , where nematic currents associated with topological defects enhance the rotational diffusivity of the motile rods [see Fig. S3(c) in Sec. II of the Supplemental Material [64]] [59]. These active currents also disrupt the medium flow generated by the motile rods, further reducing α .

V. DISCUSSION AND SUMMARY

Defect dynamics plays a central role in the behavior observed in this system. The dynamics of elongated flocks is strongly influenced by the presence of topological defects in the medium. In particular, in the nematic medium, defect creation and annihilation events lead to the fragmentation and breakup of bands, resulting in strong temporal fluctuations of the polar order parameter (Movie S4 of the Supplemental Material [64]). A fundamental open problem is to understand the role of nematic defects in this behavior and to study the interfacial instability at the boundary between motile-rich and apolar-rich regions that may drive the breakup of these bands. The flocks also exhibit rich collective dynamics, including coherent reorientation events such as smooth turns reminiscent of biological flocks, as well as occasional millinglike motion (Movie S5 of

the Supplemental Material [64]). Remarkably, the dynamics of each flock is often governed by a leading motile rod at the front of the flock, which acts as an effective leader (Movies S7 and S8 of the Supplemental Material [64]). Reorientation initiated by this leading rod propagates coherently through the entire flock, producing a collective turn of the whole structure (Movies S7 and S8 of the Supplemental Material [64]). At high ϕ_p , such collective turning events are accompanied by the development of density gradients in the apolar medium. In the nematic medium, at large ϕ_a , we further observe the periodic formation of bands associated with a layered phase of the medium [55].

In summary, our simulations demonstrate that motile rods immersed in a medium of apolar rods undergo segregation-driven collective behavior. Increasing the medium concentration promotes the formation of segregated flocks while simultaneously diminishing global polar order. In the absence of intrinsic angular noise, this interplay gives rise to a transition from a homogeneous polar-ordered state to a disordered regime composed of elongated, segregated flocks lacking system-spanning order. Remarkably, angular noise counteracts segregation and enhances polar order over an intermediate range, leading to an anomalous noise-induced ordering effect before the system ultimately becomes homogeneously disordered at large noise strengths. These findings are captured qualitatively by a minimal mean-field framework, which rationalizes the emergence of segregation-induced disorder. We further show that the geometry of the flocks is governed by the anisotropy of the medium rods: Small aspect ratios favor structures elongated transverse to the mean direction of motion, whereas larger aspect ratios produce flocks aligned with the direction of motility [23]. Thus, the medium plays a crucial role in shaping the anisotropic character of the antidiffusive behavior. Our results establish the system as a realization of anisotropic antidiffusion [61,65–70], which gives rise to an anomalous dependence of the polar order on the concentration of surrounding medium and the angular noise of the motile rods.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

APPENDIX A: CLUSTER ANALYSIS

To identify and track individual flocks, we use the density-based spatial clustering of applications with noise (DBSCAN) algorithm with a custom precomputed distance matrix D ($N \times N$) that incorporates both spatial proximity and polar alignment. The pairwise distance is defined as

$$d_{ij} = \begin{cases} 0.0, & \Delta r_{ij} < r_c \quad \text{and} \quad \Delta \theta_{ij} < \theta_c, \\ 1.0, & \text{otherwise,} \end{cases} \quad (\text{A1})$$

TABLE I. DBSCAN parameters used for flock identification.

Parameter	Symbol	Value
Spatial cutoff	r_c	6.0
Angular cutoff	θ_c	0.5 rad (28.6°)
DBSCAN radius	ϵ	0.5
Minimum samples	MinPts	3

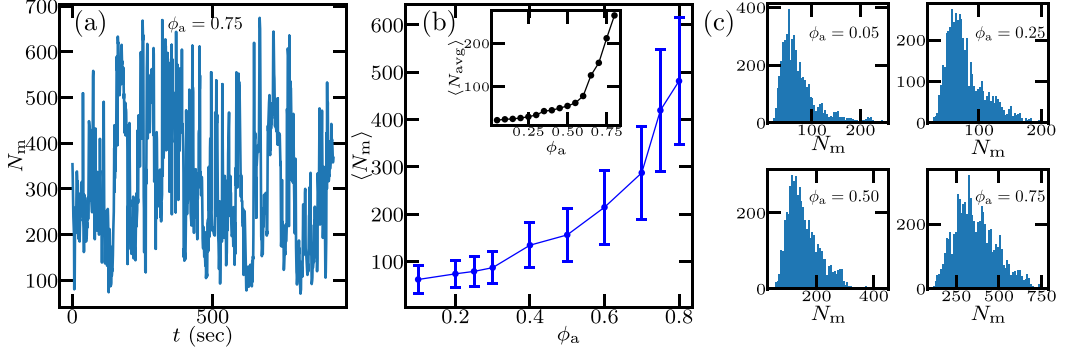


FIG. 7. (a) The largest flock size N_m vs t at $\phi_a = 0.75$. (b) Steady-state averaged largest flock size $\langle N_m \rangle$ vs ϕ_a ; Inset: Average flock size N_{avg} vs ϕ_a . (c) Histogram of N_m for different ϕ_a . Here, $\phi_p = 0.05$ and $D_r = 0 \text{ rad}^2 \text{ sec}^{-1}$.

where Δr_{ij} is the center-to-center distance under periodic boundary conditions and

$$\Delta \theta_{ij} = \min(|\theta_i - \theta_j|, 2\pi - |\theta_i - \theta_j|). \quad (\text{A2})$$

The clustering parameters are summarized in Table I. We use $r_c = 6.0$, $\theta_c = 0.5 \text{ rad}$, $\epsilon = 0.5$, and $\text{MinPts} = 3$. With this binary metric, rods satisfying both spatial and orientational criteria are connected ($d_{ij} = 0 < \epsilon$), while all others are excluded ($d_{ij} = 1 > \epsilon$). A flock is identified when at least three connected rods form a cluster.

Using this method, we extract the largest polar flock in an isotropic medium at $\sigma = 3.125$ ($\ell_a = 2.5 \text{ mm}$), $D_r = 0$, and $\phi_p = 0.05$, as shown in Fig. 7. Figure 7(a) shows that the largest flock size N_m exhibits strong temporal fluctuations due to continuous merging and fragmentation. Figure 7(b) shows that the steady-state average largest flock size $\langle N_m \rangle$ increases monotonically with ϕ_a . The inset shows the average flock size N_{avg} , estimated from the 70% contour of the maximum pair distribution function $g(r, \theta)$, which also increases with ϕ_a , indicating enhanced clustering in denser media. Figure 7(c) shows the distribution of flock sizes for different ϕ_a , exhibiting a systematic shift toward larger N_m with increasing ϕ_a .

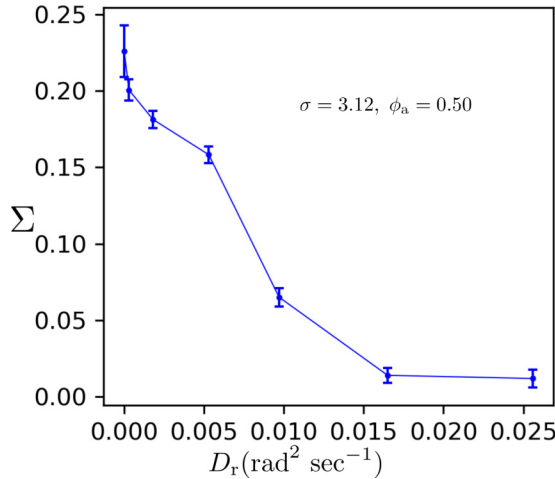


FIG. 8. Σ vs D_r . Here, $\sigma = 3.125$, $\phi_a = 0.50$, and $\phi_p = 0.05$.

APPENDIX B: SEGREGATION ORDER PARAMETER

In order to quantify how well-mixed motile rods are inside the medium, we compute the segregation order parameter Σ defined as [71,72]

$$\Sigma = \frac{1}{2\phi_p[1-\phi_p]} \sum_{i=1}^N \left(\frac{n_i}{n_{\text{tot}}} \right) |\phi_i - \phi_p|, \quad (\text{B1})$$

where simulation box is divided into N number of square cells of side length a , where ϕ_i is fraction of motile rods in the i th cell, n_i is the total number of motile rods in the i th cell, n_{tot} is the total number of motile rods in the simulation box, and ϕ_p is the total fraction of the motile rods in the simulation box. The prefactor normalizes Σ such that $\Sigma \in [0, 1]$, where $\Sigma = 0$ corresponds to the theoretically minimal level of segregation, while $\Sigma = 1$ indicates complete (maximal) segregation. Noting that Σ is nonzero even in the absence of the medium, we subtract this baseline contribution in order to compute the value of Σ in the presence of the medium.

Figure 8 shows the segregation order parameter Σ as a function of the intrinsic rotational diffusion coefficient D_r for $\sigma = 3.125$, $\phi_a = 0.50$, and $\phi_p = 0.05$.

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