Clogging and Jamming of Colloidal Monolayers Driven Across a Disordered Landscape

Ralph L. Stoop\textsuperscript{1} and Pietro Tierno\textsuperscript{1,2,3}

\textsuperscript{1}Departament de Física de la Matèria Condensada, Universitat de Barcelona, Barcelona, Spain.
\textsuperscript{2}Universitat de Barcelona Institute of Complex Systems (UBICS), Universitat de Barcelona, Barcelona, Spain.
\textsuperscript{3}Institut de Nanociència i Nanotecnologia, IN\textsuperscript{2}UB, Universitat de Barcelona, Barcelona, Spain.

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We experimentally investigate the clogging and jamming of interacting paramagnetic colloids driven through a quenched disordered landscape of fixed obstacles. When the particles are forced to cross a single aperture between two obstacles, we find an intermittent dynamics characterized by an exponential distribution of burst size. At the collective level, we observe that quenched disorder decreases the particle flow, but it also greatly enhances the "faster is slower" effect, that occurs when increasing the particle speed. Further, we show that clogging events may be controlled by tuning the pair interactions between the particles during transport, such that the colloidal flow decreases for repulsive interactions, but increases for anisotropic attraction. We provide an experimental test-bed to investigate the crucial role of disorder on clogging and jamming in driven microscale matter.

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Particle transport through heterogeneous media is a fundamental problem across several disciplines as physics, biology and engineering. In condensed matter, the inevitable presence of quenched disorder affects the transport properties of several systems, from vortices in high $T_c$ superconductors \cite{1,2}, to electrons on the surface of liquid helium \cite{3,4}, skyrmions \cite{5}, and active matter \cite{6}. At the macroscopic scale, disorder in form of obstacles, wells or barriers severely alters the flow of bubbles \cite{7,8}, granular media \cite{9,10}, bacteria \cite{11}, sheep or pedestrians \cite{12}. Already a collection of particles that are forced to pass through a small constriction displays a complex dynamics, including flow intermittency, a precursor of blockage via formation of particle bridges and arches. The latter general phenomenon is known as clogging, and is responsible for the flow arrest in different technological systems, from microfluidics, to silo discharge, and gas and oil flow through pipelines. Clogging is also directly related to jamming, which occurs when, above a threshold density, a loose collection of elements reaches a solid-like phase with a finite yield \cite{13}. Jammed systems are associated with the existence of a well defined rigid state and a new type of zero-temperature critical point \cite{14,15}. In contrast, the local and spatially heterogeneous nature of clogging makes this phenomenon more difficult to characterize and to control, despite its technological relevance.

In previous experimental realizations, clogging has received much attention at the level of a single bottleneck \cite{16}, while studies addressing the dynamics of microscale systems driven through heterogeneous landscapes are rather scarce \cite{5}. In contrast, recent theoretical works demonstrated the rich phenomenology of transport and clogging across ordered \cite{17,18} or disordered \cite{19,20} landscapes. The advantage of using colloidal particles as model systems for clogging is their flexibility, since external fields may be used to create driving forces for transport, or to tune in situ the pair interactions.

Here we experimentally investigate the flow properties of a monolayer of paramagnetic colloidal particles that is driven across a heterogeneous landscape composed of disordered obstacles. We find that already the presence of few obstacles significantly alters the collective dynamics by creating regions where clogs, intermittent and free flow coexist. The system mean speed decreases by increasing the density of flowing particles or obstacles. When increasing the particle speed, we find an overall decrease of the mean speed, and this provides an experimental evidence of the "faster is slower" (FIS) effect. Further, we show how to control and reduce the formation of clogs by tuning the pair interactions between the moving colloids. These findings remark the importance of particle speed and interactions on the clogging process.

We transport paramagnetic colloidal particles with diameter $d_m = 2.8 \mu m$ by using a magnetic ratchet effect generated at the surface of a uniaxial ferrite garnet film (FGF). The FGF is characterized by a parallel stripe pattern of ferromagnetic domains with alternating up and down magnetization normal to the substrate, and a spatial periodicity of $\lambda = 2.6 \mu m$ at zero applied field, Fig.1(a). To introduce quenched disorder in the system, we use silica particles with a diameter $d_o = 5 \mu m$, thus larger than the magnetic colloids and distinguishable from them. Previous to the experiments, the particles are let sediment on top of the FGF, and irreversibly attached there by screening the electrostatic interactions via addition of salt. Afterwards, the substrate is dried and refilled with the paramagnetic colloids, see \cite{21} for more details. Using this procedure, we generate a random array of obstacles evenly distributed across the FGF film. The corresponding disorder is spatially uncorrelated and has no detectable features of ordering, as shown by the absence of secondary peaks in the pair correlation functions $g(r)$ of the silica particles, calculated for different samples in Fig.1(b).
The transport mechanism was previously introduced for an obstacle-free substrate [22, 23], and here will be briefly described. Above the FGF, the paramagnetic colloids are driven upon application of a rotating magnetic field. (b) Pair correlation function $g(r)$ of the silica particles for 3 samples with different number of particles $N$. For clarity the $g(r)$ are rescaled along the $y$ axis. (c) Mean particle speed $v_x$ versus driving frequency $\omega$ in the obstacle-free case. Blue [red] fit to the data indicates the synchronous, $v_x = v_m$ [asynchronous, $v_x = v_m(1 - \sqrt{1 - (\omega/\omega_s)^2})$] regime, being $\omega_s = 66.8 \text{rad/s}^{-1}$ the critical frequency. (d) Experimental images of a monolayer of paramagnetic colloids (black circles) driven through a disordered landscape of silica particles (white circles) towards right ($\hat{x} > 0$). The particle trajectories are superimposed in blue on the image at the right ($t = 1.3s$). Scale bar is 20$\mu$m, see also MovieS1 in [21].

We start by analyzing the particle flow at the level of a single aperture, such as a pair of silica particles separated by a surface to surface distance $d \geq 3 \mu$m in a cluster of connected obstacles. The complete trapping of the particles by the obstacles $(\langle v_x \rangle = 0)$ is observed for lower distances. In general, we find an intermittent flow of the magnetic colloids for distance $d \lesssim 4 \mu$m, when the aperture is normal to the driving direction. Larger aperture between the obstacles, as the one shown in the inset of Fig.2, were found to arrest the flow only when the vector joining the obstacle’s centers is not perpendicular to $\hat{x}$. The intermittent flow arises from the simultaneous arrival of the paramagnetic colloids at the aperture, and their accumulation in a close packed state, thus locally jammed. If compared to arches formation in granular systems [9, 25], we find that the combined effect of hydrodynamic lubrication between the particles and the oscillations induced by the magnetic ratchet make these states rather fragile. We analyze different cases, and in all of them we measure the distribution $P(t > t_p)$ of time lapse $t > t_p$ between the particles passing through the aperture, as shown in Fig.2. For all driving frequencies explored, we find that $P$ displays a power law tail, with an exponential distribution of burst size $S$. These observations confirm the universal feature of $P$, as similar results were demonstrated in the past with sheep, granular particles and numerical simulations of sedimenting colloids [16].

Next, we analyze the collective dynamics across the whole landscape by varying the area fractions of magnetic colloids, $\Phi_m$ and obstacles, $\Phi_o$. Here $\Phi_i =$...
FIG. 2. Histograms of burst size $S$ rescaled with respect to $\langle S \rangle$ and measured for different driving frequencies $\omega$. The dashed line is an exponential fit to the data as guide to the eye. The lower temporal limit used to define the bursts is $t_p = 0.4 s$, the average burst sizes are $\langle S \rangle = 2.5$ for $\omega = 18.8\text{rads}^{-1}$, $\langle S \rangle = 1.9$ for $\omega = 37.7\text{rads}^{-1}$ and $\langle S \rangle = 1.7$ for $\omega = 50.3\text{rads}^{-1}$. All data are taken for an applied field with $H_x = 620\text{Am}^{-1}$, $H_z = 950\text{Am}^{-1}$. Top inset: The complementary cumulative distribution function $P$ of time lapses $t > t_p$ for magnetic particles passing through two silica obstacles. The small microscope image at the bottom shows the considered aperture.

$N_j \pi (d_j/2)^2 / A$, being $N_j$ the number of elements $j$ having diameter $d_j$ and located in the area $A$. In Fig.3(a) we show the different dynamic phases in the $(\Phi_m, \Phi_o)$ plane in terms of the normalized mean speed, thus $\langle v_x \rangle / v_m \in [0,1]$. The particle flow is maximal at low obstacle density, $\Phi_o < 0.07$, where few silica particles are unable to arrest the motion of magnetic colloids. However, we find a decrease of the mean speed $\langle v_x \rangle / v_m \sim 0.25$ on the left, lower corner of the diagram ($\Phi_m < 0.1, \Phi_o < 0.07$). In this situation, the magnetic colloids that hit the obstacles at the center are not scattered, but remain trapped there as long as other particles do not release them via collision. A similar feature has been observed recently via numerical simulations of driven disks across a disorder landscape [29]. Increasing $\Phi_o$ reduces the system mean speed, as now flowing regions $\langle v_x \rangle \sim v_m$, coexist with clogged ones $\langle v_x \rangle = 0$. The latter states however, may be easily unclogged by inverting the particle flux, that corresponds to reversing the sense of rotation of the applied field, $H_x \leftrightarrow -H_x$, see Fig.2 and MovieS2 in [21]. This extended region of ”abnormal flow” includes also cases where the system was almost completely arrested $\langle v_x \rangle / v_m \sim 0.3$, but it could be again fluidized by reversing the applied field. At larger obstacle density, $\Phi_o > 0.25$, the silica particles percolate through the system and surround the magnetic colloids, thus impeding any net movement. Here the system forms a solid-like or ”jammed” phase from the very beginning, and cannot be fluidized by the applied drive, see Fig.3 and MovieS4 in [21]. Thus, in our system we never observe fully clogged states, where the mean speed vanishes after a transitory period, and that can be fluidized by inverting the particle current [27]. In contrast, we observe that the presence of few obstacles strongly reduces the jamming threshold where $\langle v_x \rangle = 0$ from the very beginning. In absence of silica particles, the driven colloids will jam near the close packing density, $\Phi_m = \pi/2\sqrt{3} \sim 0.9$. [28]

A small concentration of obstacles $\Phi_o = 0.25$ reduces the jamming threshold to $\Phi_m = 0.3$ or below.

In Fig.3(b) we investigate the effect of varying the driving frequency $\omega$, and thus the particle speed on the sys-

FIG. 3. (a) Diagram in the $(\Phi_m, \Phi_o)$ plane illustrating regions of normal flow ($\langle v_x \rangle / v_m > 0.85$), abnormal flow characterized by coexistence of clogs and flowing particles ($\langle v_x \rangle / v_m \leq 0.85$), and jamming that was found below $\Phi_o \sim 0.25$. The magnetic particles are driven in the synchronous regime with $\omega = 37.7\text{rads}^{-1}$. (b) ”Faster is slower” effect on a disordered landscape: Normalized mean velocity $\langle v_x \rangle / v_m$ versus driving frequency $\omega$ for different disorder densities $\Phi_o$. All data in (a) and (b) where taken for $H_x = 620\text{Am}^{-1}$, and $H_z = 950\text{Am}^{-1}$.
tem dynamics, by keeping constant $\Phi_m = 0.25$. We experimentally observe the "faster is slower" (FIS) effect, where the mean speed of the system decreases as $\omega$ increases, i.e. the single particle velocity in the obstacle free case. The FIS effect was originally observed when simulating the dynamics of pedestrians trying to escape through a narrow exit [29]. A recent surge of interest on FIS [30] resulted from the possibility to observe a similar effect in other systems [31], although its investigation has been limited to a single aperture. On a collective level, the effect of the velocity drop by an increase in the applied driving force has been reported by different theoretical works in condensed matter systems [32,37], although with no experimental evidence. Here, when considering an heterogeneous landscape, we find that FIS is greatly enhanced by disorder. For example a small area fraction of obstacles $\Phi_x = 0.08$, is able to reduce the speed of a $\sim 45\%$ with respect to the free case when increasing the driving frequency from $6.3\text{rads}^{-1}$ to $50.3\text{rads}^{-1}$, as shown in the magenta curve in Fig.3(b).

Our system further allows to tune the pair interactions between the moving colloids by varying the amplitude $H_z$ of the in-plane field. Above the magnetically modulated FGF, the effective interaction potential between two paramagnetic colloids can be calculated via a time average [38]. In polar coordinates $(r, \vartheta)$ this potential can be written as $U_d = \alpha |H_z|^2 (1 + 3 \cos 2\vartheta) - 2H_z^2 |r|^3$, where $\alpha = \chi d_m^3 / (96\lambda^3 M_z^2)$, $\chi = 0.4$ is the effective volume susceptibility of the particles and $M_z = 1.3 \cdot 10^4 \text{Am}^{-1}$ is the saturation magnetization of the FGF. The previous equation shows that, at a fixed value of $H_z$, the sign of the pair interaction is repulsive when $H_x < H_z/\sqrt{3}\cos \vartheta^2 - 1$, while being attractive in the other case. As shown in Fig.4(a), the dipolar interactions between two colloids are strongly anisotropic. We consider two representative cases at fixed frequency, characterized by a complete repulsion for $H_z = 0.4H_z$, and attraction (repulsion), for $H_z = 1.8H_z$ when the relative angle $\vartheta$ between the particles lies in the region $\vartheta \in [n\pi - \vartheta_m, n\pi + \vartheta_m]$ (otherwise). Here $n = 0, 1...$ and $\vartheta_m = 48.7^o$ gives the condition for vanishing magnetic interactions. The corresponding dynamics for these two cases are analyzed in Fig.4(b) in terms of the particle velocities parallel and normal to the direction of motion, $v_x$ and $v_y$ respectively. We find that the attractive interactions, combined with repulsion at large $\vartheta$, facilitate the formation of parallel trains of magnetic colloids that are able to easily move across the disorder landscape. These trains slide plastically through the obstacles and, as a result, the amplitude of fluctuations along the normal direction increases, being the variance $\delta v_y = 1.15\text{um/s}^{-1}$ for the attractive case, the double than in the repulsive case ($\delta v_y = 0.54\text{um/s}^{-1}$). This situation may appear, at a first glance, counter intuitive since one mechanism of clogging in microchannels is the aggre-gation of attractive particles at the entrance [7]. However, here the anisotropy of the pair interactions facilitate the system fluidization, as it induces the formation of elongated structures with a certain flexibility, rather than isotropic compact clusters. When $H_x = 0.4H_z$, the driven monolayer has a larger inter-particle distance that increases $\Phi_m$, reducing the colloidal flow as shown in Fig.3(a). We confirm this general trend by reporting in Fig.4(c) the mean speed for different disorder densities. We finally note that for the field strengths employed here, $H_x \in [0.3, 2]\text{kAm}^{-1}$, the magnetic dipolar interactions between two particles at a distance $d_p$ are of the order $U_d \in [2, 95]k_B T$, thus higher than other interactions as electrostatic or thermal ones.

To conclude, we studied the clogging process in a system composed of an ensemble of interacting paramagnetic colloids driven across a quenched disorder landscape. We have reported a rich phenomenology, including the enhancement of the "faster is slower" effect by quench disorder and the role of the pair interactions on...
system collective transport. The understanding and control of clogging process along the lines of this work may be important in different technological contexts and on different length scales. A further potential avenue of this work may be related to investigating the clogging transition and its connection to jamming in pinned systems, a recent theoretical hot spot [39–41]. We thank Tom H. Johansen for the FGF film, H. Massana-Cid and F. Martinez-Pedrezo for initial experiments, I. Zuriguel, H. Löwen and C. Reichhardt for stimulating/inspiring discussions. R. L. S. acknowledges support from the Swiss National Science Foundation grant No. 172065. P.T. acknowledges support from the ERC starting grant “DynaMO” (335040) and from MINECO (FIS2016-78507-C2) and DURSI (2014SGR878).

* ptierno@ub.edu

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