

Trafficlike Collective Movement of Ants on Trails: Absence of a Jammed Phase

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We report experimental results on unidirectional trafficlike collective movement of ants on trails. Our work is primarily motivated by fundamental questions on the collective spatiotemporal organization in systems of interacting motile constituents driven far from equilibrium. Making use of the analogies with vehicular traffic, we analyze our experimental data for the spatiotemporal organization of ants on a trail. From this analysis, we extract the flow-density relation as well as the distributions of velocities of the ants and distance headways. Some of our observations are consistent with our earlier models of ant traffic, which are appropriate extensions of the asymmetric simple exclusion process. In sharp contrast to highway traffic and most other transport processes, the average velocity of the ants is almost independent of their density on the trail. Consequently, no jammed phase is observed.

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Ants form large trail systems [1] which share many features of vehicular transportation networks. The emergence of a trail pattern has received some attention in the literature [1–3]. Single trails are often stable for hours or days and can be considered the analogs of highways. Therefore, the collective movement of ants on trails (from now onwards, referred to as “ant traffic”) is analogous to vehicular traffic on highway networks [4,5]. The social behavior of ants also indicates the possibility that biological evolution has optimized ant traffic. Surprisingly, despite its striking similarities with vehicular traffic, the *collective* properties of ant traffic have not been studied experimentally until recent years.

The pioneering experiments on ant traffic [6] and all the subsequent related works [7–11] used *bidirectional* trails where the nature of flow is dominated by the head-on encounters of the ants coming from opposite directions [7,8,11]. But, in vehicular traffic, where flows in opposite directions are normally well separated and head-on collisions can occur only accidentally, the spatiotemporal organization of the vehicles in each direction is determined by the interactions of the vehicles moving in the *same* direction. Therefore, in order to investigate the similarities and differences between vehicular traffic and ant traffic, we have collected and analyzed data on *unidirectional* traffic of ants on a natural trail using methods adapted from traffic engineering [12–14] and the theory of stochastic processes [15].

All the experimental data reported here have been collected on a natural trail of monomorphic ant species *Leptogenys processionalis* [3]. This choice ensured that all the ants have the same body size and exhibit identical behavioral responses. Moreover, we maintained the natural

situation so that the true features of ant traffic could be captured by our video recordings. Furthermore, we focused on a particular section of the trail which had neither crossings nor branching which would be the analogs of ramps in vehicular traffic [13,14]. Thus, being far from nest and the food as well as from intersections, this segment mimics an effectively infinite linear trail [4,16]. The shape of the observed section of the trail remained unaltered for several hours and, therefore, we collected each data set continuously for about 13 min. We have verified that during this time the flow can be considered to be stationary and is not disturbed by external factors. Finally, we compared the data recorded at ten different trails of the same type and found that our conclusions drawn from these are generic (at least, for the traffic of the ant species used in our studies) [17].

One of the distinct behavioral characteristics of individual ants in the ant traffic is the absence of overtaking. Although some ants (temporarily) left the trail and were passed by succeeding ones, we never observed any ant speeding up in order to overtake some other ant in front. We exploited this observation to develop a convenient method for our data analysis which we will explain below.

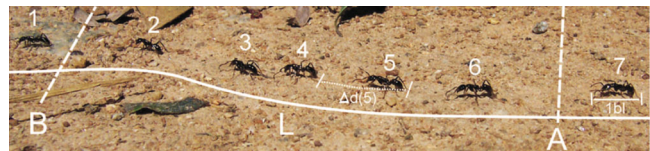


FIG. 1 (color online). A snapshot of the observed trail section. We obtained its length $L = 17$ bl in the units of the body-length (bl) of a single ant. For the observed species one finds $1 \text{ bl} \approx 18 \text{ mm}$.

The actual length L of the observed section of the trail between the two points marked A and B in Fig. 1 has been estimated by averaging over the paths of individual ants which passed through this section. Putting equispaced marks on a transparency mounted on the video screen, we obtained $L = 17$ bl, in the units of the body-length (bl) of a single ant, where $1 \text{ bl} \approx 18 \text{ mm}$ for the ant species *Leptogenys processionalis* used in our study.

Since no overtaking takes place, ants can be uniquely identified by the ordered sequence in which they enter the observed section of the trail; i.e., they follow a FIFO principle (first-in-first-out). Suppose, the n th ant enters the section at A at time $t_+(n)$ and leaves the section at B at time $t_-(n)$. An efficient tool for analyzing such data is the *cumulative plot* (Fig. 2) ([12]); it shows the numbers $n_+(t)$ and $n_-(t)$ of ants which have passed the point A and B , respectively, up to time t . The two resulting curves, which are sometimes called *arrival function* and *departure function* can be obtained by inverting $t_+(n)$ and $t_-(n)$, respectively.

This allows us to extract basic data in a very efficient way [18]. The travel time $\Delta T(n)$ of the n th ant in the section between the points A and B is given by

$$\Delta T(n) = t_-(n) - t_+(n) \quad (1)$$

and the *time-averaged* speed of the n th ant during the period $\Delta T(n)$ is given by

$$v(n) = \frac{L}{\Delta T(n)}. \quad (2)$$

The time headway of two succeeding ants can be obtained easily at the entrance and exit points A and B (Fig. 2, left inset). Since $v(n)$ is, by definition [Eq. (2)], the time-averaged velocity $v(n)$ of the n th ant, the distance headway

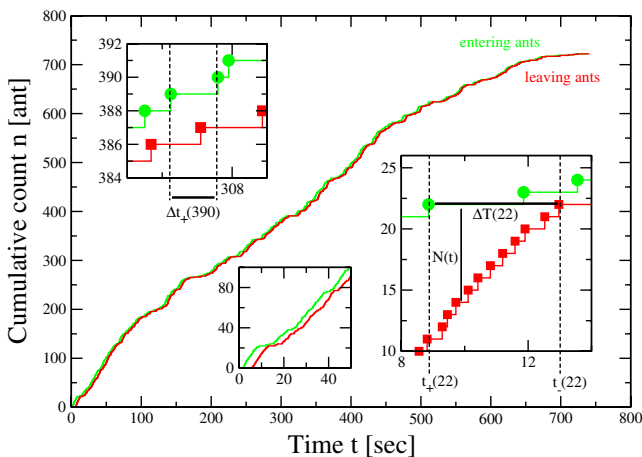


FIG. 2 (color online). Illustrating the technique employed for data extraction. The cumulative count of the ants which have entered $n_+(t)$ (●) and left $n_-(t)$ (■) the trail section between A and B . The right inset shows the travel time ΔT for the 22th ant. On the left inset the time headway Δt_+ of the 390th ant is shown.

between the n th ant and the ant in front of it is given by

$$\Delta d(n) = \Delta t_+(n)v(n-1), \quad \Delta t_+(n) = t_+(n) - t_+(n-1). \quad (3)$$

Entry and exit of each ant changes the instantaneous number $N(t)$ of the ants in the trail section between A and B by one unit (Fig. 2, right inset). Therefore $N(t)$ fluctuates, but stays constant in between two events of entry or exit. Sorting the counts of these events by time one obtains a chronological list $\{t_i\} = \{t_{\pm}(n)\}$ of the changes of the instantaneous particle number

$$N(t) = n_+(t) - n_-(t) = \text{const} \quad \text{while } t \in [t_i, t_{i+1}[. \quad (4)$$

In order to estimate the local density which is experienced by the n th ant during the time interval $\Delta T(n)$ it spends within the observed trail section we first determine the average number of ants in the same section during the time interval $\Delta T(n)$:

$$\langle N \rangle_{t(n)} = \frac{1}{\Delta T(n)} \sum_{t_i=t_+(n)}^{t_i=t_-(n)} N(t_i)(t_{i+1} - t_i). \quad (5)$$

The (dimensionless) density $\rho(n)$ affecting the movement of the n th ant is given by

$$\rho(n) = \frac{\langle N \rangle_{t(n)}}{N_{\max}} = \frac{\tilde{\rho}(n)}{\tilde{\rho}_{\max}} \quad \text{with} \quad \tilde{\rho}(n) = \frac{\langle N \rangle_{t(n)}}{L}, \quad (6)$$

where $N_{\max} = 17 = L/(1 \text{ bl})$ and $\tilde{\rho}_{\max} = N_{\max}/L$. Our empirical data for ρ are in the interval $[0, 0.8]$. The instantaneous particle numbers and the single-ant velocity are averaged over the same time interval $\Delta T(n)$.

The average velocity of the ants is plotted against the corresponding density in Fig. 3; the resulting flow-density

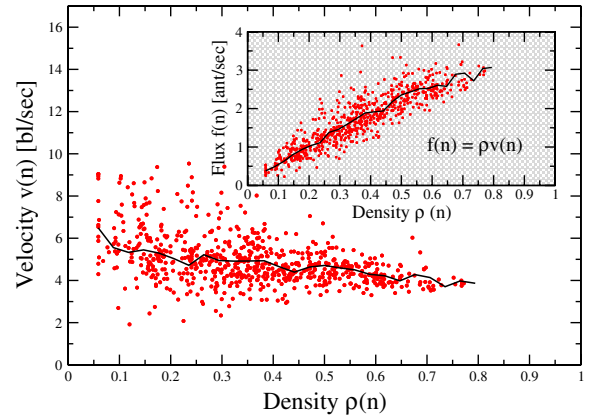


FIG. 3 (color online). Average velocity (solid line) and single-ant velocities (dots) for unidirectional single-lane trail section of length $L = 17$ bl. The corresponding flux-velocity relation, the so-called *fundamental diagram* is plotted in the inset. Mutual blocking is obviously suppressed as the average velocity is almost independent of the density. Consequently, the flux increases almost linearly with the density in the fundamental diagram (see inset).

relation, which is called *fundamental diagram* in traffic engineering [4,13], is plotted in the inset of the Fig. 3. The most unusual feature of the data shown is that, unlike vehicular traffic, there is no significant decrease of the average velocity with increasing density [4,13,14]. Consequently, the flux obtained by the hydrodynamic equation increases approximately linearly over the entire regime of observed density. The jammed branch of the fundamental diagram, which is commonly observed in vehicular traffic and which is characterized by a monotonic decrease of flow with increasing density, is completely missing in Fig. 3. Obviously, effects of mutual blocking, which are normally expected to become dominant at high densities [4,13,14], are strongly suppressed in ant traffic.

From the time-series of the single-ant velocities we have also determined their distributions in different density regimes (Fig. 4). The most striking feature is that the distribution becomes much sharper with increasing global density whereas the most probable velocity decreases only slightly.

Another important quantity that characterizes the spatial distribution of the ants on the trail is the distance headway distribution. The time series (Fig. 5 top left), obtained by using (3), shows clustering of small distance headways whereas larger headways are much more scattered. The distribution of these headways (see Fig. 5) becomes much sharper with increasing density while the maximum shifts only slightly to smaller headways. At low densities, predominantly large distance headways are found; the corresponding distribution for sufficiently long distance headways is well described by a negative-exponential distribution which is characteristic of the so-called random-

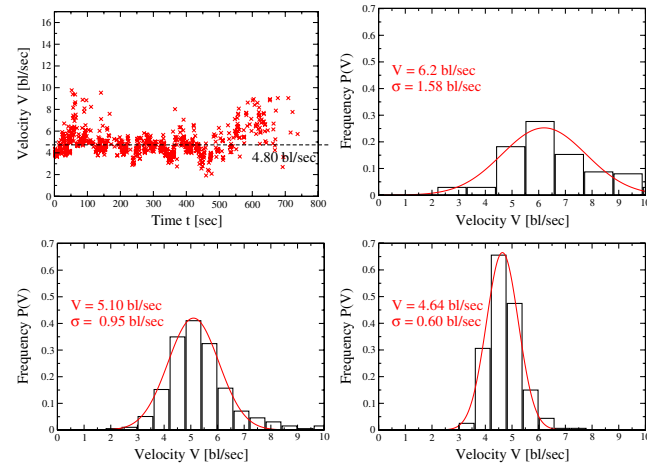


FIG. 4 (color online). The velocities of individual ants are plotted as function of time (top left). Furthermore, the velocity distributions of the ants for small [$\rho(n) \in [0, 0.2]$, top right], intermediate [$\rho(n) \in [0.2, 0.4]$, bottom left] and large [$\rho(n) \in [0.4, 0.8]$, bottom right] densities are shown. For all regimes the corresponding Gaussian fit $P(v) = \frac{1}{\sigma\sqrt{2\pi}} \exp(-(V-v)^2/(2\sigma^2))$ is also shown (solid line).

headway state [13]. In contrast, at very high densities mostly very short distance headways are found; in this regime, the log-normal distribution appears to provide the best fit to our empirical data.

The absence of a jammed phase in the fundamental diagram is closely related to the characteristic features of the distributions of the distance headways of the ants along the observed section of the trail. The dominant, and directly observable, feature of this spatial distribution is the platoons formed by the ants. Ants inside a platoon move with almost identical velocities maintaining small distance headways. These intraplatoon distance headways are responsible for the clustering of data observed in the corresponding time series Fig. 5. In contrast, larger distance headways are interplatoon distances. The full distribution of distance headways has an average of $D = 2.59$ bl which is quite close to the value $D = 1.66$ bl found for very high densities. This indicates the existence of a density-independent distance headway for the ants moving inside platoons. Formation of these platoons has been demonstrated by our earlier simple models of ant traffic [19–23] which are appropriate extensions of the totally asymmetric simple exclusion process [16].

The interpretations of the observed trends of variations of the flux, average velocity and distance headway distribution with increasing density is consistent with the corresponding variation of the distribution of the velocities of the ants (Fig. 4). Ants within a platoon move at a slower average velocity whereas solitary ants can move faster if

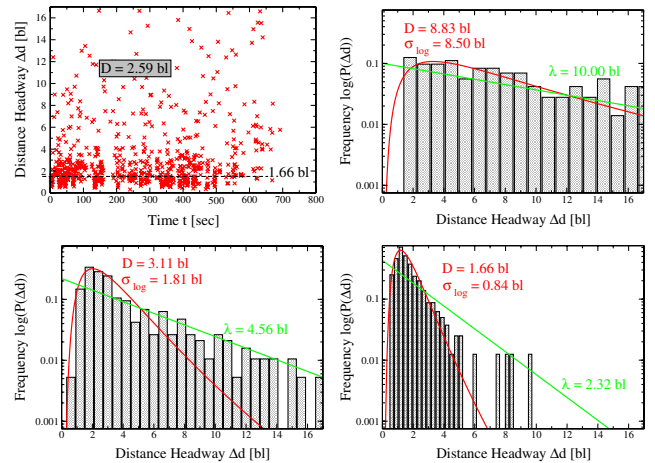


FIG. 5 (color online). Distance headways vs time shows (top left) clustering of short distances which indicates the existence of a density independent intraplatoon separation between the ants. The remaining three figures show the distance headway distributions for small [$\rho(n) \in [0, 0.2]$, top right], intermediate [$\rho(n) \in [0.2, 0.4]$, bottom left] and large [$\rho(n) \in [0.4, 0.8]$, bottom right] densities. Depending on the density regime a log-normal $P(\Delta d) = \frac{1}{\sqrt{2\pi}\sigma_{\log}\Delta d} \exp(2 - [D - \log(\Delta d)]^2 / (2\sigma_{\log}^2))$ or negative exponential $P(\Delta d) = \exp(-\Delta d/\lambda)$ distribution applies.

they detect a strong pheromone trace created by a preceding platoon. Moreover, since fluctuations of velocities of different platoons are larger than the intraplatoon fluctuations, the distribution becomes sharper at higher densities because the platoons merge thereby reducing their number and increasing the length of the longest one. As can be seen in Fig. 4 the maximum of the velocity distribution is almost independent of the density. Its position at sufficiently large densities can be interpreted as platoon velocity, $v_p \approx 4.6$ bl/s.

In this Letter, we have reported results of our empirical studies of *unidirectional* ant traffic on a natural ant trail. Remarkably, we have not observed any event of overtaking of one ant by another. Instead, we found formation of platoons which has been predicted by simple models of ant traffic under various conditions [19–23]. In contrast to what has been previously observed in various transport systems, especially vehicular traffic, in ant traffic (at least for the ant species and the trail systems used in our studies), flow always increases monotonically with the density of the ants. In other words, no jammed branch is exhibited by the flow-density relation for ant traffic.

In highway traffic, the average velocity of the vehicles is constant only for low densities, but the physical origin of this regime is very different from the constant velocity of ants in ant traffic. In low-density limit of vehicular traffic the vehicles are well separated from each other and, therefore, can move practically unhindered in the so-called free-flow state. On the other hand, in ant traffic, this constant velocity regime is a reflection of the fact that ants march together collectively forming platoons which reduce the effective density. We have also not found any evidence for phenomena like hysteresis, synchronised flow, etc., which have been reported for vehicular traffic [4,14]. Although platoon formation is considered to be relevant also for synchronized flow [14], there is no characteristic velocity of these platoons, in contrast to the case of ant traffic.

Thus, in spite of some superficial similarities, the characteristic features of ant traffic seems to be very different from those of vehicular traffic and other typical transport systems. Perhaps, ant traffic is analogous to human pedestrian traffic [10,11,24], as was conjectured beautifully by Hölldobler and Wilson in their classic book [1]; in a future work, we intend to explore this analogy empirically and by quantitative modeling. Our results may have important implications for swarm intelligence [25] and ant-based computer algorithms [26].

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