Increasing Number Density Induces Rhythmic Behavior in Self-Propelled Camphor Disks

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ABSTRACT

A camphor disk has been known to move spontaneously on water. Recently, it was newly observed that increasing number density induces the mode bifurcation of camphor motion from a continuous to an intermittent oscillatory motion. The mechanism of the mode-switching behavior has been uncovered by theoretical analysis and corroborated experimentally. This behavior is quite similar to quorum sensing observed in biological systems, in which individual behavior bifurcates depending on the population density. Physicochemical systems reproducing characteristic biological behaviors are widely expected to clarify the fundamental mechanisms of these complex biological phenomena.

INTRODUCTION

Collective motion of biological systems shows characteristic behaviors different from that of individual organisms [1]. Examples are schools of birds, sardine balls, and trails of ants. Collective motion realizes some functionalities such as the hydrodynamically efficient array of flying birds, which aids in the birds' ability to successfully escape from natural predators. As a familiar example, the congestion flow of vehicles is a type of collective motion induced by increases in the number density. A part of such complicated behaviors does not require intelligence of individuals but originate from simple interactions between individuals [2]. Therefore, complicated collective motions have been realized by non-living self-propelled objects that have no intelligence or complex interactions [3].

Collective motion of camphor boats

The "camphor boat" system is a typical example of the collective motion of non-living self-propelled objects [4]. A camphor boat is a simple self-propelled object sliding on water spontaneously and is composed of a camphor grain attached to a plastic boat. The surface tension locally decreases around the camphor grain, and thus, the force balance working around the boat is broken, and the resulting net force is generated. Namely, the boat spontaneously moves in the opposite direction of the side where the camphor grain is attached.

Camphor boats floating on an annular narrow channel show a simple repulsive interaction that monotonically decays with increases in the distance between boats. Therefore, the boats arrange homogeneously with a regular gap and move with a constant speed (Fig. 1a-i). This trivial behavior is observed with low number density. On the other hand, the homogeneous distribution of camphor boats becomes unstable with increases in the number of camphor boats, which results in higher and lower density regions spontaneously appearing in the channel (Fig. 1a-ii). In this case, the speed of each camphor boat indicates oscillation. Namely, boats move slowly in the high-density region and quickly in the low-density region [5]. This behavior is similar to congestions in traffic flow [2]. It is noteworthy that the oscillation of speed in congestion flow originates from just the inhomogeneous distribution of boats. Namely, the speed of boats is determined by the local density.

Intermittent oscillatory motion of collective camphor disks

Recently, our research group, which is a joint group composed of researchers from Meiji University and Hiroshima University, found that the mode-switching of camphor disk motion induced with the increase in the number density (Fig. 1b and 1c) [6] and succeeded to uncover the mechanism for such mode-switching [7]. We floated the camphor disks, which are circular disks, on a circular water surface as shown in Fig. 1b. In our experiment, the direction of the movement of the disks was not restricted and thus the disks could leave the high-density region. This situation was radically different as compared to the case in the annular channel, shown in Fig. 1a. The disks can keep their speed constant, which monotonically decreases and finally stops with increases in the number density as shown by Soh et al. [8]. However, intermittent oscillatory motion was newly observed with intermediate number density (Fig. 1-ii) [6].

To clarify the mechanism of intermittent oscillatory motion, the experimental setup was simplified. The number of disks was fixed to one and the number density was varied with changes in the size of the water surface. In the simplified system, the single disk also showed mode-switching similar to that induced by increasing the number of disks. The simplification of the experimental system succeeded in drastically decreasing the number of variables concerning the origin of intermittent oscillatory motion. As a result, the mode-switching of camphor motion has successfully been reproduced by a mathematical model composed of two variable ordinary differential equations, i.e., the speed of a camphor disk and the average concentration of camphor [7].

Conclusion

It is well known in biological systems with "quorum sensing" that bifurcation of individual characteristics is induced by change in the number density. We observed similar behavior in non-living self-propelled objects, and we uncovered the mechanism of mode-switching by using a mathematical model. Such non-living functional systems are expected to be used in sustainable smart materials in the future.

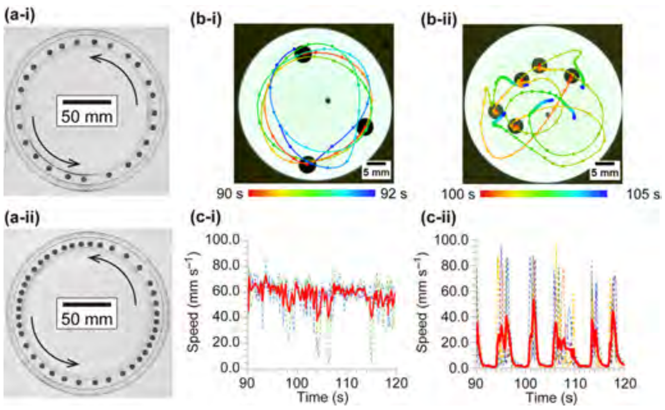

Fig. 1: (a) Collective motion of camphor boats on an annular water channel [5]. **(i)** Free flow with constant speed. **(ii)** Congestion flow with oscillation of speed. **(b)** Trajectories and **(c)** the collective speed profile of camphor disks floating on circular water [7]. **(i)** Continuous motion. **(ii)** Intermittent oscillatory motion.

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