Allometric Scaling Laws in the Exploratory Behavior of the *Physarum* Plasmodium

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**ABSTRACT**

The plasmodium of *Physarum polycephalum* is a unicellular and multinuclear giant amoeba. In this paper, the authors investigate four allometric laws in the exploratory behavior of the plasmodium, and integrate them into one schema based on the dynamics of cytoplasmic streaming. This study reveals a novel function of the tubular structure of the plasmodium, shedding new light on the adaptive behavior of the organism.

**Keywords:** Allometry, Cell Motility, Cytoplasmic Streaming, Exploratory Behavior, *Physarum Polycephalum*, True Slime Mold

1. **INTRODUCTION**

Exploration of the environment is one of the most important adaptive behaviors of biological entities, and there have been many studies of exploratory behavior in various species, including mammals, birds, and insects. The foraging behavior of army ants is a well-known example, and the understanding of the mechanisms of exploration by ants has been turned into an application called ant colony optimization (Goss, Aron, Deneubourg, & Pasteels, 1989; Dorigo & Stützle, 2004). Furthermore, recent studies indicated that even a species of bacteria shows exploratory behavior (Ben-Jacob, Shmueli, Shochet, & Tenenbaum, 1992; Ben-Jacob, Becker, Shapira, & Levine, 2004) and the plasmodium of *Physarum polycephalum* in this paper provides an example of unicellular exploration.

The plasmodium of *Physarum polycephalum* is a unicellular and multinuclear giant amoeba that is formed by the fusion of a myriad of uninucleated amoebae at one stage of its life cycle. The plasmodium is in the vegetative and predatory stage; thus if the conditions are suitable for the growth of the organism, the plasmodium increases its size almost indefinitely. On the other hand, the smallest plasmodium consists of a fusogenic body of several amoebae. Therefore the size of the plasmodium varies from the usual unicellular scale (~100 μm) to several meters.

The cell body of the plasmodium consists roughly of two parts: a sheet-like structure at the locomotive front and a tubular structure at the rear (Figure 1). The tubes connect the parts of the cell body to work as a transporta-
tion route for the contents of cytoplasm and maintain the integrity of the unicellular body. The sheets crawl on plane surfaces searching for food sources, and the cytoplasm serves as a resource for this exploration. The plasmodium shows a variety of locomotive and exploratory patterns according to environmental conditions (Takamatsu, Takaba, & Takizawa, 2009).

Recent studies have demonstrated that the plasmodium actually has adaptive capabilities in its exploration. For example, the plasmodium can find a solution to a maze (Nakagaki, Yamada, & Tóth, 2000; Nakagaki, Yamada, & Tóth, 2001; Nakagaki, 2001) and form an optimized network between multiple nodes (Nakagaki, Yamada, & Hara, 2004; Nakagaki, Kobayashi, Nishiura, & Ueda, 2004; Shirakawa & Gunji, 2007). Furthermore, by having such abilities, the plasmodium is also able to solve some graph theoretical problems (Shirakawa, Adamatzky, Gunji, & Miyake, 2009; Shirakawa & Gunji, 2010) and to duplicate the elaborate design of a real railroad network (Tero et al., 2010). The organism is thus attracting a lot of attention, not only from the biological viewpoint, but also in terms of unconventional bio-inspired computing. In fact, some of the researchers in this field insist that the plasmodium can be used as a model of primitive intelligence (Nakagaki, Yamada, & Tóth, 2000).

However, all of the computations using the plasmodium listed above are performed after a full search of the problem space. For example, in the formation of an optimized network between multiple food sources (Nakagaki, Yamada, & Hara, 2004; Nakagaki, Kobayashi, Nishiura, & Ueda, 2004; Shirakawa & Gunji, 2007) the plasmodium first covers the whole space of the experimental system, and then forms a network between food sources. There have already been some model studies of the computational activities of the plasmodium, but they also deal only with the behavior of the plasmodium after a full search (Tero et al., 2010; Tero, Kobayashi, & Nakagaki, 2006, 2007; Tero, Tero, Yumiki, Kobayashi, Saigusa, & Nakagaki, 2008). However, there are not many studies on how the plasmodium makes an exploration in...
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