The role of fluid dynamics in the development of left-right asymmetry in vertebrates and in chiral crystallization

Oreste Piro[1*], Julyan H. E. Cartwright[2], Idan Tuval[3]

[1] Instituto Mediterráneo de Estudios Avanzados (IMEDEA), CSIC-UIB, 07122 Palma de Mallorca, Spain

[2] Laboratorio de Estudios Cristalográficos, CSIC, E-18100 Armilla, Granada, Spain

[3] BIO5 Institute, University of Arizona, Tucson AZ 85721, USA

[*] Electronic Address: piro@imedea.uib.es

We will describe two unrelated chiral-symmetry breaking processes where advection by fluid flows plays a fundamental role.

The first is the recent experimental discovery in embryology that a fluid flow within the Hensen's node —a small chamber formed at the early stages of development in the embryo— which is generated by rotating cilia attached to its floor is responsible, in many vertebrates, for fixing of left-right axis of the body plan: the heart on the left, the liver on the right, etc. For normal individuals, this flow is found to run always leftwards. By applying general concepts of physics and fluid dynamics we anticipated that such a leftward flow could only be produced by the rotating cilia if their axis are tilted toward the posterior of the embryo. Moreover, with a simple model for the cilia-fluid interaction we predicted the tilting angle that would reproduce the experimentally observed flow[1]. Remarkably, these predictions were later confirmed by detailed observations of the cilia movement and structure. The question that now remains open is how the leftward nodal flow initiates the development of left–right asymmetry. Consensus seems to be building up around the idea that the mechanism involves the transport of morphogenic substances by the flow. We discuss here several advective scenarios that lead to an asymmetric accumulation of such substances.

In the second example we will demonstrate that the symmetry breaking of the distribution of chiral crystals during crystallization may be an advection mediated nonlinear process. When a chiral chemical compound crystallizes from solution or from its melt, stirring often results in the formation of crystals of just one of the two possible enantiomers, while without fluid advection, both enantiomers are formed. By means of simulations based on agents dynamics in flowing media, we demonstrate that in the presence of chaotic advection, secondary nucleation becomes a nonlinear autocatalytic phenomenon which can explain these observations[2]. Furthermore, we present theoretical arguments and experimental results suggesting that at the microscale the mechanism of secondary nucleation is whisker crystal growth and dispersion in the fluid flow. Finally, our agent-based modelling approach allows us to investigate the effects of other microscopic phenomena included in the picture. In particular, we show that Ostwald ripening is a possible cause of the almost absolute chiral purity resulting from some experiments of crystallization under very intense stirring.

[1] J. H. E. Cartwright, O. Piro, and I. Tuval. Fluid-dynamical basis of the embryonic development of left Vright asymmetry in vertebrates. Proc. Natl. Acad. Sci. USA, 101:7234 V7239, 2004.

[2] J. H. E. Cartwright, J. M. Garca-Ruiz, O. Piro, C. I. Sainz-Daz, and I. Tuval, Chiral Symmetry Breaking during Crystallization: An Advection-Mediated Nonlinear Autocatalytic Process, Phys. Rev. Lett. 93, 035502 (2004).