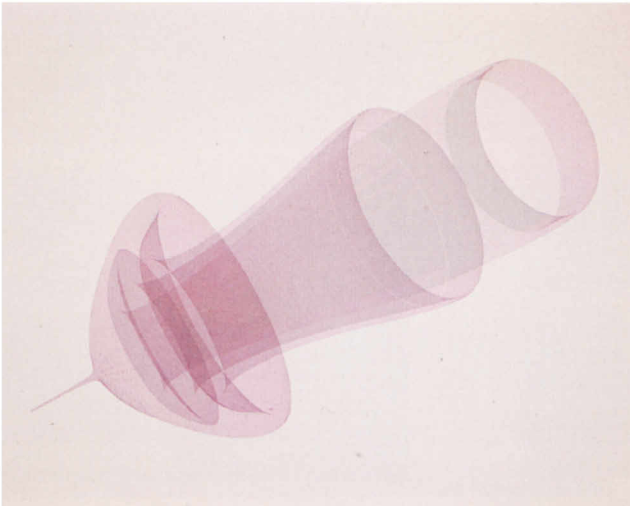

Figure 1

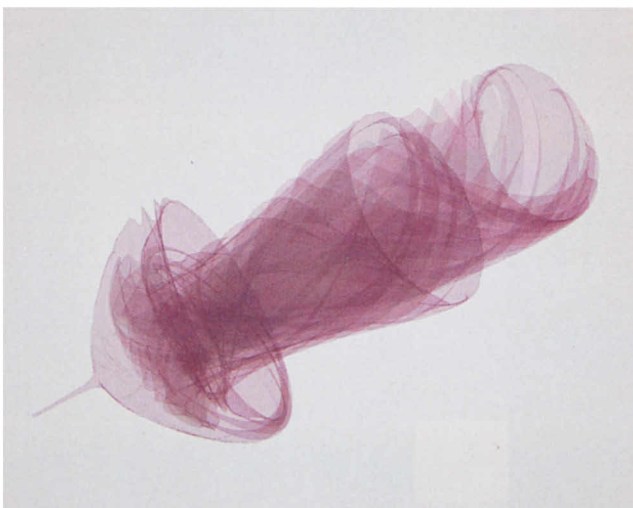

Figure 2

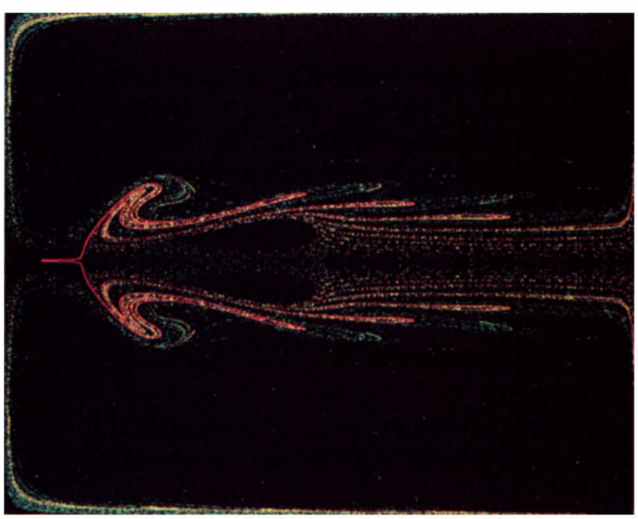

Figure 3

PERIODIC AXISYMMETRIC VORTEX BREAKDOWN IN A CYLINDER WITH A ROTATING END WALL

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When the fluid inside a completely filled cylinder is set in motion by the rotation of the bottom end wall, steady and unsteady axisymmetric vortex breakdown is possible.[1,2] The onset of unsteadiness is via a Hopf bifurcation.

Figure 1 is a perspective view of the flow inside the cylinder where marker particles have been released from an elliptic ring concentric with the axis of symmetry near the top end wall. This periodic flow corresponds to a Reynolds number $\mathrm{Re}=2765$ and cylinder aspect ratio $H/R=2.5$. Neighboring particles have been grouped to define a sheet of marker *fluid* and the local transparency of the sheet has been made proportional to its local stretching. The resultant *dye sheet* takes on an asymmetric shape, even though the flow is axisymmetric, due to the unsteadiness and the asymmetric release of marker particles. When the release is symmetric, as in Fig. 2, the dye sheet is also symmetric. These two figures are *snapshots* of the dye sheet after three periods of the oscillation (a period is approximately 36.3 rotations of the end wall). Figure 3 is a cross section of the dye sheet in Fig. 2 after 26 periods of the oscillation. Here only the marker particles are shown. They are colored according to their time of release, the oldest being blue, through green and yellow, and the most recently released being red. Comparison with Escudier's experiment[3] shows very close agreement.

The particle equations of motion correspond to a Hamiltonian dynamical system and an appropriate Poincaré map may be defined. Streaklines, such as in Fig. 3, can be used to approximate the unstable manifolds of the fixed points of the Poincaré map and these, together with the stable manifolds, can be used to describe in detail the filling and emptying of periodic axisymmetric vortex breakdown bubbles.[4]