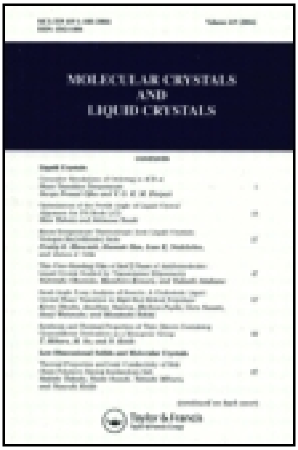

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Experiments On Ring-Shaped Solitons In Nematic Liquid Crystals

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Experiments On Ring-Shaped Solitons In Nematic Liquid Crystals†

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Experiments on ring-shaped propagating single solitons in nematic liquid crystals are reported. These solitons with constant velocities and widths are generated by pressure gradients in the radial direction in homeotropic nematic disc cells. The pressure at the rim of the cell is maintained at atmospheric pressure while that at the center is varied. In suitable pressure gradient regimes these solitons appear as dark rings under transmitted parallel white light passing vertically through two crossed polarizers sandwiching the liquid crystal cell. These results are contrasted with those observed when the pressure at the rim is varied (in which both dark and white rings propagating towards the center are generated).

Keywords: liquid crystals, solitons, nematics, two-dimensional, solitary wave, pressure gradients

†Presented at the 11th International Liquid Crystal Conference, Berkeley, June 30–July 4, 1986.

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I. INTRODUCTION

Solitons are special localized solutions of some nonlinear partial differential equations. They may be considered as nonliner excitations and have been found in many physical systems.[1-3] Initially the word "soliton" was used to mean solitary waves that kept their identities after pairwise collisions. However, in almost all real systems (e.g. $\emptyset^4$ solitons in structural phase transitions and those in polyacetylenes as well as those in our experiments reported here) no such solitary waves exist. These days, in the physics literature,[2,3] the word "soliton" is synonymous to "solitary wave."

In spite of their obvious importance the study of two-dimensional solitons is limited in both theory[4] and experiment,[5-8] in contrast to the one-dimensional case.[1,2] In liquid crystals, elliptical solitons (called "walls") were observed by Leger[6] (above the Fredericks transition) and ring-shaped ones by our group.[7,8] In the latter case, the generation (by pressure gradients) and movement of the solitons can be easily controlled.

In this paper, the experimental setup used in Refs. 7 and 8 is described (in Sec. II). Instead of varying the pressure at the rim of the liquid crystal disc cell (resulting in solitons propagating towards the center) as in Refs. 7 and 8, in the experiments reported here the pressure at the center is varied (with that at the rim fixed at 1 atm) leading to outwardly moving solitons. The observed results are different from those in Refs. 7 and 8 and are given in Sec. III. Sec. IV concludes with discussions.

II. EXPERIMENTAL

A. Liquid crystal cell

The liquid crystal cell is sketched in Figure 1. Two polished glass plats (A and A′) of dimension $12 \times 12 \times 0.5$ cm^3 are used. In the inner surface of the upper glass plate (A) a circular groove with inner radius 5 cm, width 5 mm and depth 2 mm is cut. Five holes, one at the center and four situated symmetrically in the middle of the groove, are drilled in this plate. Radius of each hole is 0.5 mm. Five glass tubes with ballast volume are attached to the holes on the outside surface of the upper plate [Figure 1(b)]. The inner surfaces of the two plates are then treated with lecithin. Carborundum of size 20 μm in diameter is mixed with epoxy resin which is then spread in the

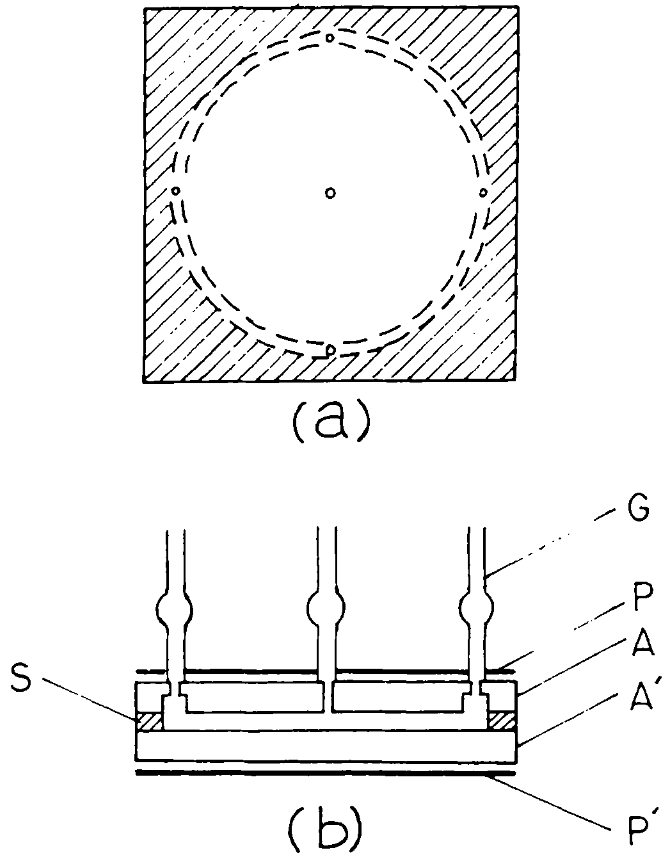

FIGURE 1 (a) Inner surface of the upper glass plate. (b) The liquid crystal cell. *G*—glass tube, *P*—analyser, *A*—upper glass plate, A′—lower glass plate, *P′*—polarizer, *S*—spacer (mixture of carborundum and epoxy resin.

area outside of the groove [the shaded area in Figure 1 (a)] on the inner surface of the upper plate. The two plates are then pressed tightly together for two days. In this way a circular cavity of thickness 20 μm is formed which is then filled with MBBA in vacuum, resulting in a homeotropic disc cell.

B. Pressure controls

In our experiments, the pressure at the rim of the cell (p_r) is maintained at 1 atm (by letting the four glass tubes at the rim open to air). The pressure at the center (p_c) varies with time t according to Figure 2. $t_2 - t_1$ and $t_3 - t_2$ are both equal to 60 s which is chosen

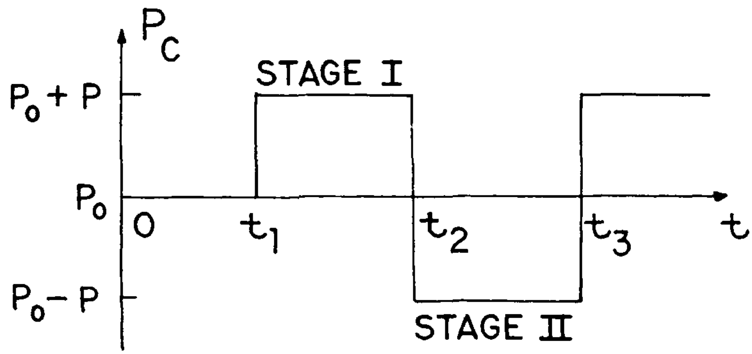

FIGURE 2 Time dependence of pressure at the center, p_c. p_0 = 1 atm.

so that the flow is steady when t approaches t_2 or t_3 from below. The region $t_1 \leqslant t < t_2$ ($t_2 \leqslant t < t_3$) is denoted as stage I (II). In stage I, the nematic flows outward; in stage II, it flows towards the center.

To achieve such a variation of p_c the central glass tube in the liquid crystal cell is connected to a pressure-control device as shown in Figure 3. During the whole experiment the electromagnetic valve E_2 is shut.

In the beginning, the electromagnetic valve E_1 is shut. The valves S_1 and S_2 are set at conditions $S_1^{(1)}$ and $S_2^{(1)}$, respectively (see Figure 4). Air is pumped in by B_1 to obtain high pressure in G_1, and air is pumped by B_2 so that G_2 is at low pressure. The pumps B_1 and B_2

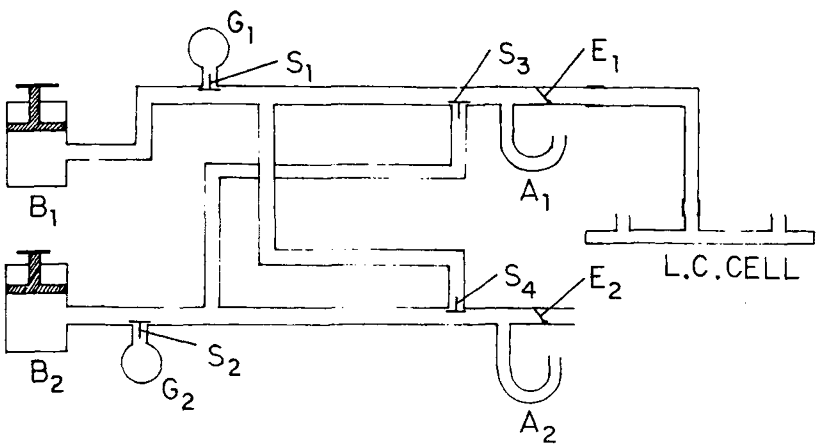

FIGURE 3 Pressure-control devise. B_1,B_2—air pumps, G_1,G_2—air storage bottles, S_1–S_4—valves, E_1,E_2—electromagnetic valves. A_1,A_2—barometers.

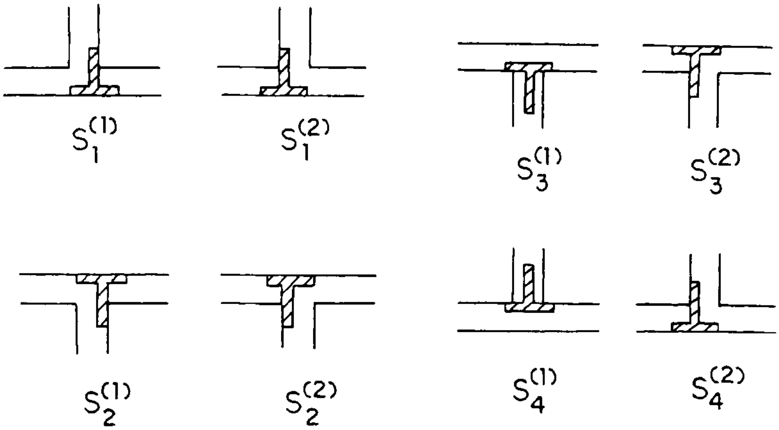

FIGURE 4 Two different conditions of each of the four valves, S_1–S_4.

are then closed. Valves S_1 and S_2 are then set at conditions $S_1^{(2)}$ and $S_2^{(2)}$, respectively (so that B_1 and B_2 are cut off from the rest of the system). We now set S_3 and S_4 at conditions $S_3^{(1)}$ and $S_4^{(1)}$, respectively, and record the pressure at G_1 (G_2) by the barometer A_1 (A_2). The above procedure is repeated until A_1 (A_2) gives a reading of $p_0 + p$ ($p_0 - p$).

For $t < t_1$ we simply disconnect the central glass tube of the cell from the pressure-control device and let it open to air. At $t = t_1$ we connect the central tube to the pressure-control device and then open E_1 resulting in $p_c = p_0 + p$. At $t = t_2$ we set S_3 and S_4 at $S_3^{(2)}$ and $S_4^{(2)}$, respectively, resulting in $p_c = p_0 - p$, which is maintained until $t = t_3$. At $t > t_3$ we use the conditions $S_3^{(1)}$ and $S_4^{(1)}$ again. (If stage II is desired at any time later one only has to use the conditions $S_3^{(2)}$ and $S_4^{(2)}$ again.) For all the time $t > t_1$,E_1 remains open.

[In the experiments in Refs. 7 and 8 the procedures are similar to above except that now it is the four tubes at the rim which are connected to each other and then to the end after E_2. The central tube is open to air. E_1 is shut all the time. E_2 plays the role of E_1 above. A_2 (A_1) should be set to read $p_0 + p$ ($p_0 - p$).]

Inaccuracies in our pressure readings come from two sources. One is due to the reduction of the pressure in G_1 and G_2 each time the valves S_3 and S_4 are shifted in conditions. But this error is minimal and can be neglected since the volume of G_1 or G_2 (60 liter) is much larger than those in the glass tubes (of diameter 3 mm) of the pressure-control device. The other is due to the reading of the height of the mercury columns (used in A_1 and A_2). The error is ± 0.5 mm Hg.

C. Experimental setup

The liquid crystal cell is sandwiched between two crossed polarizers (P and P' in Figure 1 (b)) and illuminated by parallel white light from below (Figure 5). Optical interference patterns can be observed by the eye and are photographed at regular time interval of Δt (with the use of a light chopper, LC in Figure 5). The experiment was carried out at room temperature (25 ± 0.1 °C).

III. RESULTS

For $t < t_1$ the cell is dark corresponding to the molecules being vertical. The observed results in *stage I* depend on the magnitude of p and may be divided into three different regimes.

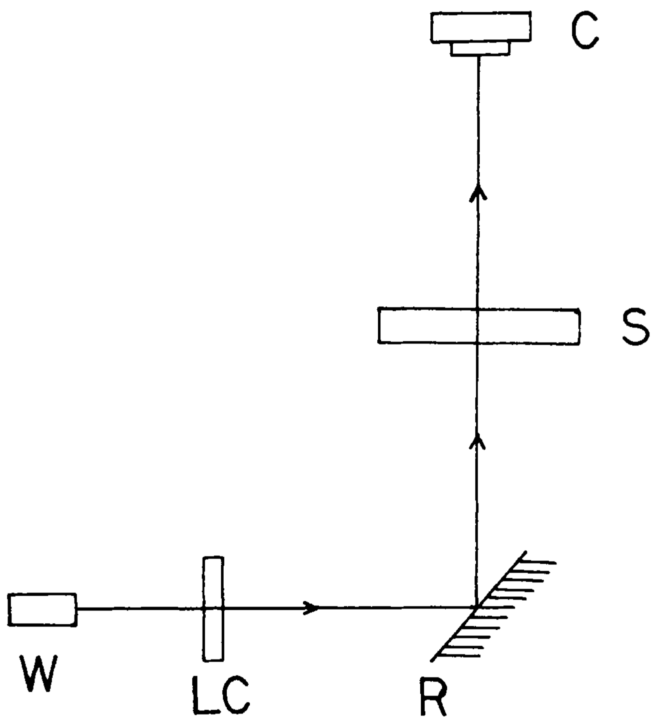

FIGURE 5 Experimental setup. W—white light source, LC—light chopper, R—reflector, S—liquid crystal cell, C—camera.

1. $p<p_1$ (=*2.7 cm Hg*). A round white spot appears at the center (against the all dark background) and enlarges in size to radius $\overline{R}$. $\overline{R}$ increases with p. For p = 2.7 cm Hg, $\overline{R}$ = 2.25 cm. In this regime no dark ring exists (in contrast to the two regimes below). See Figure 6.

2. $p_1 < p < p_2$ (=*34 cm Hg*). Against the all dark background a white circular region is formed at the center. At the same time a grey ring-shaped region appears at the rim. In between the central white region and this grey ring at the rim there is a dark ring. As time increases the central white region increases in size and the outer grey region increases in brightness. The dark ring in between turns into one with constant width and propagates outward with decreasing velocity. It finally stops at a radial distance of R_{max} and becomes a static soliton. See Figure 7.

In Figure 8 the location of the dark ring R (defined as the radial distance of the middle point in the width of the ring) is shown as a function of time t. p is a parameter of each curve. The saturation value of R, i.e., R_{max}, is plotted in Figure 9 as a function of p. It is seen that the larger p the further the dark ring can go. In Figure 10, the constant final width of each dark ring as a function of p is plotted. The width of the dark ring decreases with time (similar to those shown in Refs. 7 and 8) until it reaches a constant minimum δ_m (the quantity plotted in Figure 10). As shown here δ_m decreases with p.

3. $p > p_2$. The result is similar to that in the regime $p_1 < p < p_2$ except that the dark ring, once formed, moves with almost constant velocity towards the rim and vanishes there.

The results in *stage II* can be divided into two regimes.

1. $p < p'$ (=*35 cm Hg*). Against the grey background of the cell there suddenly appears a dark ring from the center. The dark ring moves outward with decreasing velocity and stops before reaching the rim. During this process the width of the dark ring remains constant. Note that the initial stage of this process differs from that in the $p_1 < p < p_2$ regime of stage I above. See Figure 11.

2. $p > p'$. The result is similar to the case $p < p'$ above except that the dark ring reaches the rim and vanishes there.

IV. DISCUSSIONS

1. Compared with the results in Refs. 7 and 8 ($p_c = p_0, p_r$ varying) in which inwardly moving dark and white rings are observed, in the

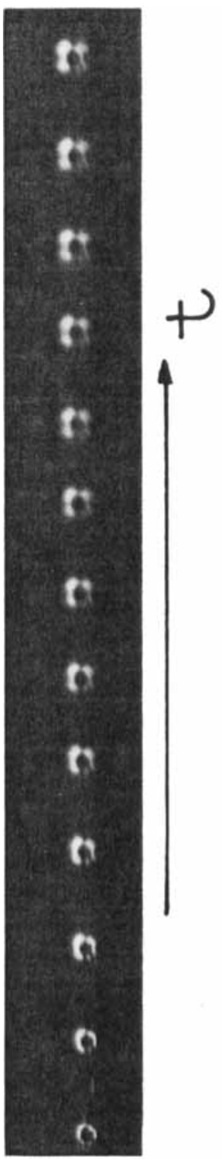

FIGURE 6 Observed optical pattern in Case 1 of stage I. p = 1.5 cm Hg. Δt = 0.025 s.

FIGURE 7 Observed optical pattern in Case 2 of stage I. p = 6 cm Hg, Δt = 0.025 s.
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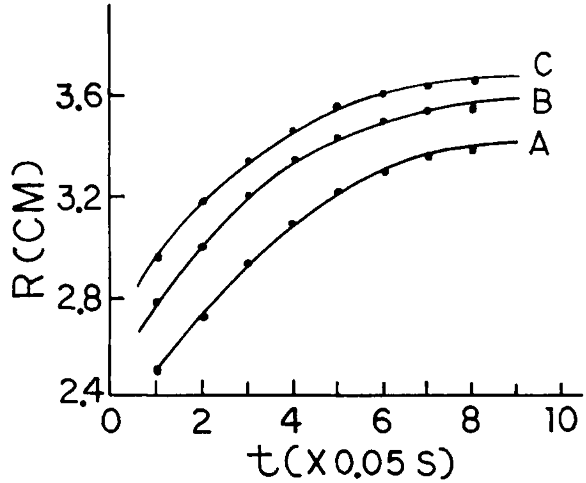

FIGURE 8 Location R of dark ring as a function of time t. The curves A, B and C correspond to $p = 6, 7$, and 8 cm Hg, respectively. The origin of each curve is arbitrary. The dots represent the experimental points. The smooth curve here (and in Figures 9 and 10) is drawn to guide the eye. The results are for Case 2 of stage I.

case reported in this paper, (for p as high as 35 cm Hg or more) we do not observe any grey or white region entering the dark brushes (corresponding to the directions of the crossed polarizers) and there are definitely no white rings generated. Moreover, the static solitons (with constant widths) observed in Case 2 of stage I and Case 1 of

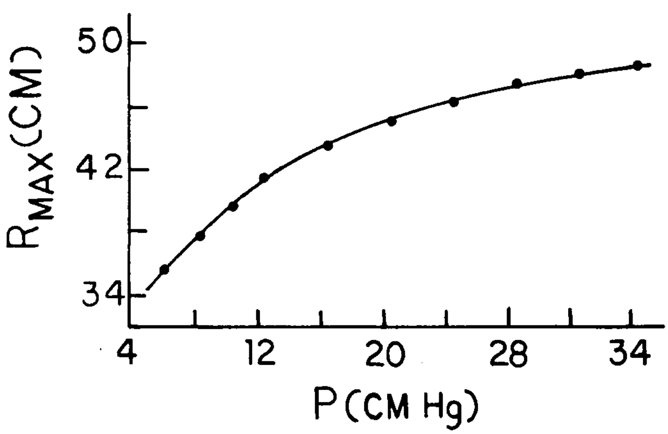

FIGURE 9 The saturation value of R in Figure 8, R_{max} (corresponding to the maximum distance of the dark ring in Case 2 of stage I), as a function of p.

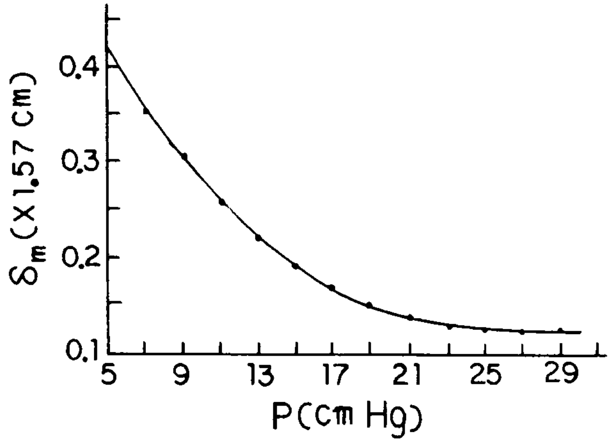

FIGURE 10 The steady constant width of the dark ring, δ_m, as a function of p (in Case 2 of stage I).

stage II here are not found in Refs. 7 and 8. The different results quoted above may be attributed to the asymmetry of the center and rim of a disc cell. One is intrinsic due to the geometry of a disc. The other is extrinsic due to the design of the cell in which the central hole is much smaller than the circular groove at the rim (see Sec. II). Because the central hole is so small if the pressure gradient (proportional to p) is not large enough there is not enough "force" to push the dark ring all the way to the rim resulting in a static ring stopping somewhere before the rim. This interpretation is consistent with the fact that only in high p regimes (Case 3 of stage I and Case 2 of stage II) that the dark ring does propagate all the way and reach the rim.

A third and important difference between the experiments in Refs. 7 and 8 and here is that in the former[7,8] dark rings are generated in stage II only while in here they appear in stage I (Case 3) as well as in stage II (Case 2). This is due to the "free" space offered by the groove at which molecules can move easily.

2. The results reported here are repeatable. Note that in Figure 2 the region $t > t_3$ is not equivalent to stage I. However, if p_c is alternated between the high and low values in Figure 2 repeatedly at equal time intervals the results in the equivalent regions are the same. There is no hysteresis effects.

3. In this paper our aim is to show the existence of ring-shaped (static and dynamic) solitons. The details near t_i ($i = 1,2,3$) are not presented. As is well known in the soliton literature the evolution of

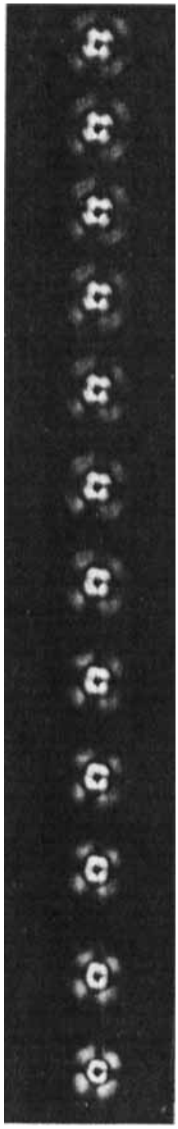

FIGURE 11 Observed optical pattern of dark ring in Case 1 of stage II. $p' = 5$ cm Hg, $\Delta t = 0.03$ s.

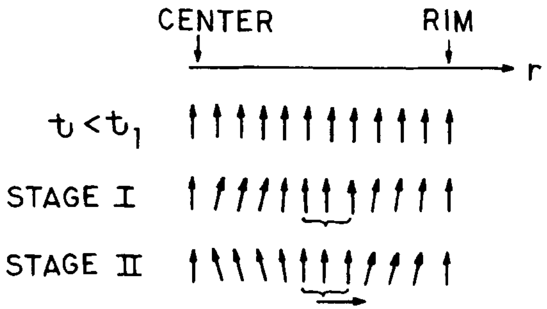

FIGURE 12 Sketch of molecular orientations during different periods of time. That part near the rim in stage I or II is not at all certain (due to the "free" boundary offered by the groove at the rim).

solitons from an initial profile do not depend that much on the details of the profile itself (as long as some general conditions are satisfied).[9,10]

4. While the complete theory of ring-shaped solitons in nematics is not yet available (see Ref. 11 for some preliminary discussions) from the experimental results reported here and borrowing from our experience in the corresponding long-cell case,[12] the mechanism of soliton generation may be something like this. For $t < t_1$ the molecules are vertical (see Figure 12). In the beginning of stage I (when pressure is increased at the center), apart from two thin layers near the surfaces of the glass plates, the molecules near the groove (at the rim) are easily disturbed (because there is no surface treatment of the groove and the molecules there are pretty free to reorient) while those near the center are pushed to fall in the outward direction; a region of vertical molecules in between is formed. As time increases this region (appeared as dark under white light) moves outward (since the pressure at center is kept on). It may or may not reach the rim depending on whether p_c is large enough or not. In the former case we have the dynamic soliton; in the latter, the static soliton. In state II the center is at low pressure and there is a tendency for the molecules at both the center and the rim (at which they are more free to move) to fall inward. Because of the asymmetry of these two places the molecules there do not fall at the same rate and a region of vertical molecules in between is formed (Figure 12) which moves inward. Obviously further checking on these ideas is needed.

5. The negatives of the photographs of our experimental results have been checked with optical microscope and we do not detect any anisotropy in the dark rings. Even though we have used only four

holes at the rim but because the diameters of the holes are smaller than the width of the groove the circular groove effectively makes the pressure at the rim to be isotropic. Any apparent anisotropy appearing on the photographs are due to the brushes (coming from the crossed polarizers). This is checked by using different orientation of the polarizers (relative to the location of the four holes at the rim).

6. The dark rings (solitons) are two-dimensional in shape. By convention in the soliton literature,[3,4] they are called two-dimensional solitons. [Mathematically, they are represented by $\theta = \theta(r - ct)$ which is one-dimensional in the space coordinate.)

7. The system described in this paper may be suitable for the study of coexistence of order and chaos.[13]

Acknowledgments

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