A THEORY OF SURFACE WATER MOTION DEDUCED FROM THE WIND-INDUCED MOTION OF THE PHYSALIA*

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For many years the author has wondered why the Portuguese Man-of-war (*Physalia pelagica* Bosc.) is so oriented physically that it is consistently driven by the wind about forty-five degrees to the left of the direction in which the wind is blowing[1] (Figure 46, left). Records kept of this leftward tendency showed little variation in distribution or time, within the limits shown in Table I. In the literature concerning this animal no explicit reference to this question of its motion relative to the wind and water has been found.

Physalia is a jellyfish of the order siphonophora which lives in the warm surface waters of the oceans. For the purposes of this discussion, its body may be considered as having two parts: the upper part a balloon-like float called a pneumatophore which is on the surface of the water, and the lower part a mass of tentacles which are attached to the ventral lee side (i. e., side opposite to direction of motion) of the float (Figure 46). Small fish and plankton, upon contact with these tentacles, are stunned by powerful stinging organs after which they are hoisted to the digestive zooids. During calm weather the tentacles may extend many meters below the sea surface, but when driven along by even a moderate wind these tentacles stream out behind the float with only a few centimeters of vertical extension. This means that the Physalia would necessarily "fish" through a relatively shallow layer near the surface while sailing. However, the large volume of water passing its tentacles when it is driven along by the wind should more than compensate for the lack of depth in its "fishing."

In speculating about reasonable explanations for this animal's persistent leftward motion, it was thought probable that the answer

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[1] Hereafter, in all references to directions of motion on or within the surface waters concerned it will be assumed that the observer is facing in the direction toward which the wind is blowing.

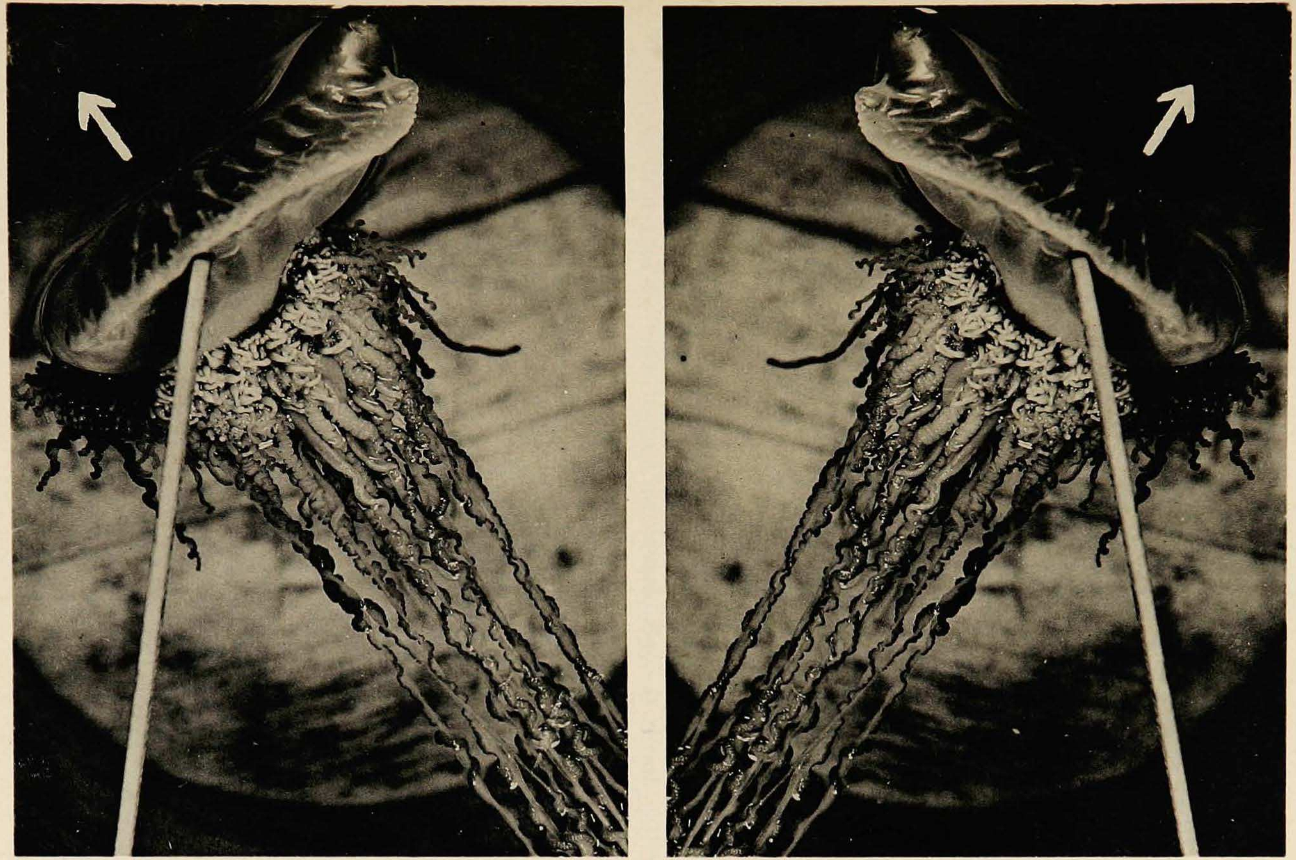

Figure 46. Laboratory photograph showing Physalia in sailing position, with tentacles streaming behind. For convenience, a mirror image of the northern hemisphere animal is used to represent one from the southern hemisphere. The rods indicate wind direction; arrows show resulting direction of motion: (left) in northern hemisphere and (right) in southern hemisphere.

TABLE I—PHYSALIA OBSERVATIONS AT SEA

Number of Physalia seen moving to: Left*	Right*	*Date*	*Wind Force*	*Lat. N.*	*Long. W.*
				North Atlantic	
2	0	Oct. 6, '39	3	39°22′	70°45′
1	0	Aug. 13, '40	–	39 23	72 28
1	0	Aug. 13, '40	–	39 23	72 28
13	0	Apr. 15, '41	4	33 31	74 52
1	0	Apr. 16, '41	3	29 26	74 42
1	0	Apr. 17, '41	3	25 29	72 24
2	0	June 28, '41	4	39 00	46 00
6	0	July 7, '41	4	39 00	46 00
2	0	Aug. 8, '41	2	40 18	67 21
3	0	Aug. 10, '41	5	36 26	64 08
34	0	Mar. 16, '42	3	26 36	80 00
11	0	Mar. 23, '42	5	25 42	80 06
				Gulf of Mexico	
113	0	Mar. 26, '42	5	26 27	84 25
89	0	Mar. 26, '42	4	26 42	84 47
76	0	Mar. 26, '42	4	27 00	85 10
37	8	Apr. 27, '42	4	27 29	86 35
29	1	Apr. 28, '42	5	27 55	89 32
421	9	Totals			

* Left and right of wind as illustrated in Figure 46.

would concern factors of survival such as the catching of food or the avoiding of danger.

In sections of the North Atlantic where the sargasso weed is common, the Portuguese Man-of-war is sometimes seen with tentacles hopelessly and fatally entangled in the weed. Since the weed is most often seen in lines formed parallel with the wind, it was thought possible that some characteristic of the motions of the surface water might cause a leftward-moving animal to avoid more of these lines of weed than a rightward-moving animal.

Langmuir (1938) made a study of formations of lines of drift in fresh water and found that these lines marked zones where surface waters are converging and sinking. "Midway between adjacent streaks" he found subsurface waters rising and diverging laterally (Figure 47A & B), so that under the action of winds the surface water was moving in a series of parallel left and right helical vortex pairs.

From Langmuir's measurements it became clear that the lines of sargasso weed, seen during winds on the sea surface, were collected in the convergent zones of similar vortex circulations. Thus, it was apparent that a Physalia sailing straight downwind would stay within a convergent zone and there encounter a maximum amount of entangling weed or other surface drift. However, this did not help in solving the problem of the animal's persistent leftward motion, for

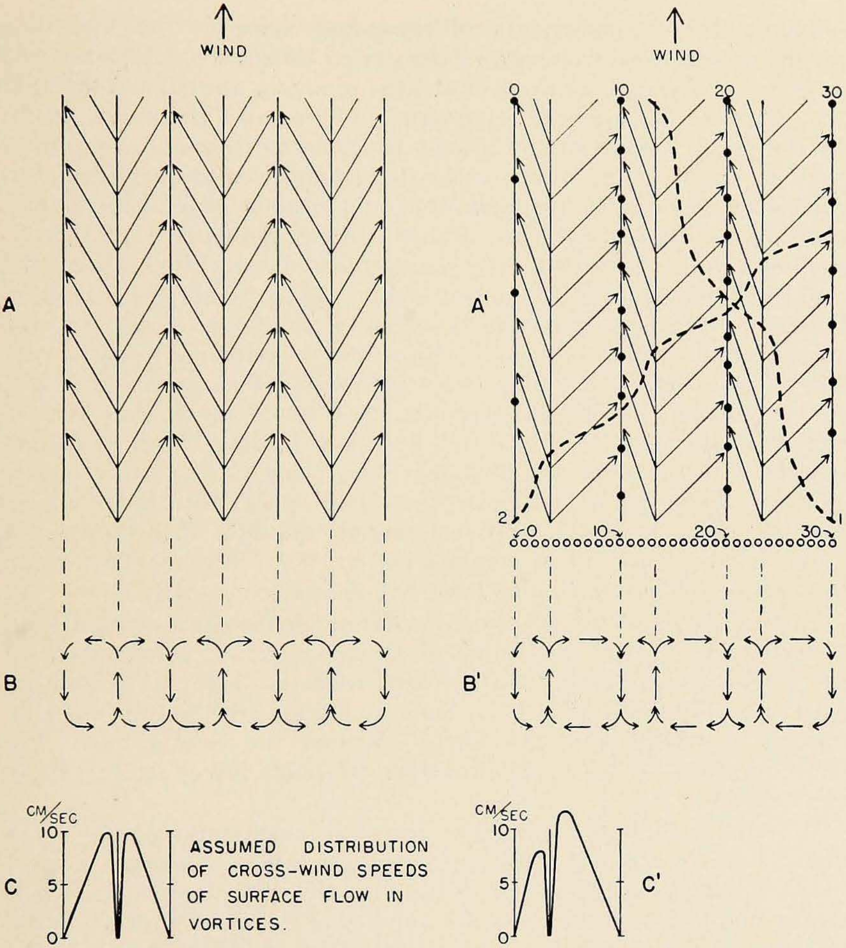

Figure 47. Idealized drawings of wind-induced helical motions in surface waters, with an illustration of the possible effect of asymmetrical vortices upon the drift of bottles and of Physalia. (See text for further explanation.)

a motion either to the left or to the right of the downwind direction, sufficient to oppose the converging currents, would make it possible for a Portuguese Man-of-war to avoid remaining within a convergent zone. There appeared to be no way in which a Physalia moving to the left across a vortex field (Figure 47A) would pass through fewer convergences than an animal moving to the right.

What might be the effect of the vortices upon the feeding of the Physalia, or upon the distribution of its food?

Langmuir's measurements of ascending rates in the upwelling divergences in fresh water give values (1 to 1.5 cm/sec) which are well in excess of the settling rates of at least one very abundant zooplankton, *Calanus finmarchicus* (Gunnerus), (Gross and Raymont, 1942). In the ocean these rates of ascent in divergences would be greater than in fresh water, under otherwise similar conditions, since salt concentrations due to evaporation should cause a general increase in the rates of vertical motion. Hence it seems probable that the upwelling divergent zones at the sea surface contain plankton carried up from the bottom of the mixed layer. When within the regions of lateral surface flow from the divergences to the convergences, the suspended plankton would have ample time to settle many centimeters below the reach of the Physalia's tentacles before descending in a convergent zone. For the Physalia, this would mean that surface waters would be divided into rich and poor feeding bands extending parallel with the wind, the divergent zone being rich and the convergent zone being poor. However, there still appeared to be no reason why a Physalia moving forty-five degrees to the right of the downwind direction across a field of symmetrical vortices (Figure 47A) would not fare as well as one moving forty-five degrees to the left.

A possible indication of greater advantage from leftward motion seemed to lie in the assumption of an asymmetrical arrangement of the wind-induced parallel vortex pairs, with the larger eddy rotating clockwise (Figure 47A′ & B′). Such an asymmetry would imply an unequal distribution of the forces affecting the circulations. The deflecting force of the earth's rotation (Corioli's force) might supply this inequality.

If Corioli's force is assumed to cause an asymmetry of the wind-induced vortices, and if this asymmetry presents an adequate indirect reason for the leftward motion of the Physalia, it then seemed obvious that a simple first check upon the validity of these assumptions could be made from observations of the Portuguese Man-of-war in the southern hemisphere. If the above assumptions were correct, then in southern latitudes one would expect to find most of the Physalia moving to the right of the wind. This expectation proved to be correct concerning specimens available for examination from the southern hemisphere. Of twenty-two south-latitude animals preserved at the Museum of Comparative Zoology, Harvard University and at the U. S. National Museum in Washington, nineteen were left-handed and three were right-handed. That is, eighty-six per cent of them were mirror images of the majority of the animals from the northern hemisphere, and, as a result, would sail to the right of the wind. This partly-confirmed prediction suggested that the assumptions concerning the effect of Corioli's force upon the vortices might have value in fact.

DRIFT BOTTLE EXPERIMENTS

Some recent drift bottle experiments give further evidence that the assumption of asymmetry in the vortices, based upon deductions drawn from the Physalia movements, may be correct.

During April 1942, some special drift bottle tests were made in the surface waters of the Central Sea area of the Gulf of Mexico (Lat. 27° 30′ N., Long. 86° 40′ W.). One hundred numbered bottles (130 cc displacement 12 cm draft) with hard rubber caps were painted a bright orange color and then ballasted with water so that each bottle had a buoyancy of one gram (± 0.1 gram) in the sea water in which they were used. With this small buoyancy the tops of the bottles floated so near the water surface that the surface film swept across the tops continuously. Thus direct wind drag on the bottles was reduced to a minimum.

Before distributing these drift bottles on the sea surface it was necessary to be free of water disturbances caused by the hull of the research vessel ATLANTIS. For this purpose a twelve foot dinghy was used, but this practice necessarily confined these drift studies to winds below Beaufort 5.

Figure 47A′ gives an example of one orientation of the bottles relative to the wind. The open circles show how the bottles were initially distributed from the small boat. Within three to five minutes all of these bottles were always reformed into new lines parallel with the wind direction (shown by the black circles) and at right angles to the initial line of distribution. From Langmuir's measurements (1938, p. 2), and from later tests made by the author, it has been found that the surface water in the convergences moves downwind more rapidly than the water between them. Hence, one would expect that the bottles which happened to be dropped into the water nearest to the convergences would be the lead bottles in the line (i. e., first at the downwind end of the line). With these bottle numbers as references and with the known numerical order and spacing of the preceding and succeeding bottles as initially distributed, one could observe the number of bottles in any particular convergence which came from the right and left of that line, hence the comparative distances to the two adjacent divergences. For example, bottle number twenty in figure 47A′ (open circles) was dropped in a convergence and became lead bottle in that line. If the helical vortex pairs were perfectly symmetrical, then one would expect to find bottles fifteen to twenty-five in the line, with number twenty leading. If the vortices are asymmetrical, with the clockwise eddy larger, then number twenty would be followed by more numbers less than twenty and fewer numbers greater than twenty. In eighteen series of such drift tests (Table II) made in deep water in the Gulf of Mexico, it was found that an average of six bottles came from the left of the line compared to four from the right. Three of these tests showed a small opposite tendency.

No exact method could be devised to make the bottle spacing equidistant initially. However, by tossing them over rhythmically, about two meters apart, the dinghy being rowed steadily at right angles to the wind direction, it was thought that any errors due to spacing would be random. Table II gives the data relative to these drift bottle tests.

TABLE II—Drift Bottle Tests in the Gulf of Mexico (27° N. 86° W.) in 1942

Test No.	*Date*	*Number and Percentage of bottles originating:*				*Temperatures in (°F)*			*Wind*		*Depth of mixed layer in meters*
		*on left**		*on right**		*Air*		*Water*	*Force*	*Dir.*	
	1942	*No.*	*%*	*No.*	*%*	*Wet*	*Dry*			*(true)*	
1	Apr. 21	38	46	44	54	67.7	70.9	71.8	2	63°	7 (tests 1–2)
2	Apr. 21	45	58	33	42	67.0	71.1	72.4	2	85	
3	Apr. 22	46	54	39	46	64.2	73.1	75.5	2	25	11 (tests 3–6)
4	Apr. 22	60	74	21	26	64.4	71.6	73.7	3	15	
5	Apr. 22	46	55	38	45	64.4	71.5	73.7	3	25	
6	Apr. 23	61	69	27	31	67.4	71.4	70.5	3	95	
7	Apr. 23	60	72	23	28	67.8	71.8	70.6	3	100	9 to 15 (tests 7–12)
8	Apr. 23	56	69	25	31	67.8	71.8	70.6	3	100	
9	Apr. 23	48	60	32	40	67.6	71.8	70.8	3	100	
10	Apr. 23	36	47	41	53	66.8	71.9	70.9	3–4	95	
11	Apr. 23	49	61	31	39	66.5	72.1	71.0	3	95	
12	Apr. 23	46	60	32	40	66.5	72.1	71.0	3	90	
13	Apr. 25	40	51	39	49	67.7	71.7	70.1	4	105	27
14	Apr. 26	51	63	30	37	67.3	71.5	70.2	3	115	20
15	Apr. 27	41	56	32	44	68.5	72.4	71.4	2.5	105	4 (tests 15–18)
16	Apr. 27	52	71	21	29	68.2	72.2	71.4	2.5	105	
17	Apr. 27	32	44	40	56	68.3	72.2	71.5	2	105	
18	Apr. 27	50	74	18	26	68.7	72.6	71.8	2.5	110	
Average percent			60.2		39.8						

* Facing downwind.

DISCUSSION

Figure 47A gives an idealized drawing of the surface motions in paired symmetrical helical vortices uninfluenced by the deflectional effects of the earth's rotation. Figure 47A′ shows a hypothetical relative directional change of the surface motions under the influence of the deflection effect. The total deflectional displacement of motion in a given vortex pair is probably affected by their unknown subsurface motions. However, the general effect of the surface deflections should be an extension of the axial component of motion in the counterclockwise vortex and a shortening of the axial component in the clockwise vortex. These changes in the axial component should result in a retarding of the rate of cross-wind flow in the left vortex and an increase in the cross-wind flow in the right (clockwise) vortex (Figure 47C′). Thus the clockwise vortex should be larger and the counterclockwise vortex smaller; of course the total energy of motion of each vortex pair would remain the same.

One important result of such a distortion of the surface vortices, as it might affect the feeding of the Physalia, would be the reduction of the speed of cross-wind flow in the counterclockwise vortex and the increase in the speed of cross-wind flow in the clockwise vortex. A decrease in the rate of this cross-wind flow from a point near the divergence to the zero point in the convergence would be important also (Figure 47C′). The average value of the cross-wind flow in this figure is based upon observed rates of drift-bottle convergence, and the slope of the curves seem reasonable in view of the probable cumulative effect of wind-mixing in retarding the surface water while it is moving from the upwelling to the convergence. In such a system of surface flow a Physalia moving to the left would remain, in a given time, within rich waters longer than one moving to the right (Figure 47A′, dashed lines). Also, the Physalia moving to the left would pass through fewer convergent zones, as a consequence of its more extended course diversions between these zones (Figure 47A′, dashed line 1). Thus in the northern hemisphere the Physalia moving to the left should catch more food at less risk of fatal entanglement than one moving to the right.

Hence, it appears that the circulation of surface waters as outlined above would explain the motions of the drift bottles as well as the proponderance of motion of the Physalia to the left of the downwind direction.[2] Further drift bottle tests should soon give conclusive data concerning the reliability of the results obtained from these first, rather crude, exploratory tests. Plankton net tows in convergent and divergent zones should readily show the effects of the helical vortices upon plankton population distribution in surface waters. Also,

[2] Large numbers of *Vellela* were recently seen in the Gulf of Mexico. Of hundreds of animals observed, all were sailing to the left of the downwind direction. This seems to indicate that the factors which produce the leftward motion under the influence of the wind are not confined to the Physalia alone.

further observations of Physalia north and south of the equator may enlarge upon the biological implications of this apparent reversal of asymmetry with hemisphere.

SUMMARY

Observations are given which show a curious tendency of the pneumatophore of the Portuguese Man-of-war (*Physalia pelagica*) to be so oriented with the wind as to cause the animal to be driven about forty-five degrees to the left of the downwind direction. These observations were made over a large part of the North Atlantic and Gulf of Mexico during a period of about three years.

A hypothesis advanced to explain this leftward tendency required in part that: (a) southern hemisphere *Physalia* be mirror images of those in the northern hemisphere, and that they sail to the right of the downwind direction: (b) wind-induced helical vortex pairs be set up in surface waters at sea, and that these vortices be asymmetrical.

Of twenty-two Physalia from the southern hemisphere available for examination in museum collections, nineteen (86%) were mirror images of those in the northern hemisphere and would sail to the right of the wind.

Drift bottle tests on the open sea have shown that lines of convergence are set up by the wind which are oriented parallel with the wind direction. These lines apparently mark the surface convergences of parallel left and right helical vortex pairs set up by the wind. The tests suggest that these vortices were asymmetrical, the larger vortex of each pair rotating clockwise, the smaller counterclockwise (facing downwind). This asymmetry was shown by the larger number of bottles drifting into the average convergence from the left of that line, the initial distribution of the drift bottles having been approximately equidistant in a line at right angles to the convergence lines.

Such an asymmetry would imply an unequal distribution of the forces driving the circulations. The deflecting force of the earth's rotation may supply this inequality. Hence the following theory is proposed: Corioli's force and frictional forces may produce an asymmetry in the wind-induced helical vortex pairs developed in surface waters on the open sea.

Four facts are apparent: first, the widespread prevalence of the leftward motion (in the given areas) of the animals; second, the reversal of asymmetry among *Physalia* of the southern hemisphere; third, the formation of lines of convergence in the surface water of the open sea parallel with the wind direction; fourth, the six to four average relationship between the number of drift bottles which came

from the left of the surface convergences as compared to those coming from the right of the convergences. While the eighteen drift tests recorded in Table II do not conclusively prove an asymmetry in the helical vortex as developed in the surface waters of the deep sea, they are highly suggestive that such asymmetry exists. Further drift bottle tests and other experiments are planned, but in view of the inherent uncertainties of these times it seems wise to publish these results now.

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