# SOME VORTEX EXPERIMENTS BEARING ON THE NATURE OF SUN-SPOTS AND FLOCCULI

By George E. Hale and George P. Luckey

MOUNT WILSON SOLAR OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Read before the Academy, April 20, 1915. Received, May 22, 1915

The following working hypothesis of sun-spots was first proposed, in a somewhat different form, in the Annual Report of the Director of the Mount Wilson Solar Observatory for 1912:

As the result of an eruption, or some other cause tending to produce rapid convection, a gaseous column moves upward from within the sun toward the surface of the photosphere. Vortex motion is initiated by differences in velocity of adjoining surfaces or by irregularities of structure and is maintained by convection. The circulation in the vortex is vertically upward and then outward along the photosphere, as in a terrestrial tornado. Expansion produces cooling at the center of the vortex, and a comparatively dark area (the umbra) results. As in Harker's electric furnace experiments, a rapid flow of negative ions sets in toward the cooler gases at the center from the hotter gases without. These ions, whirled in the vortex, produce a magnetic field, plainly indicated by the widened and resolved lines of the sun-spot spectrum.

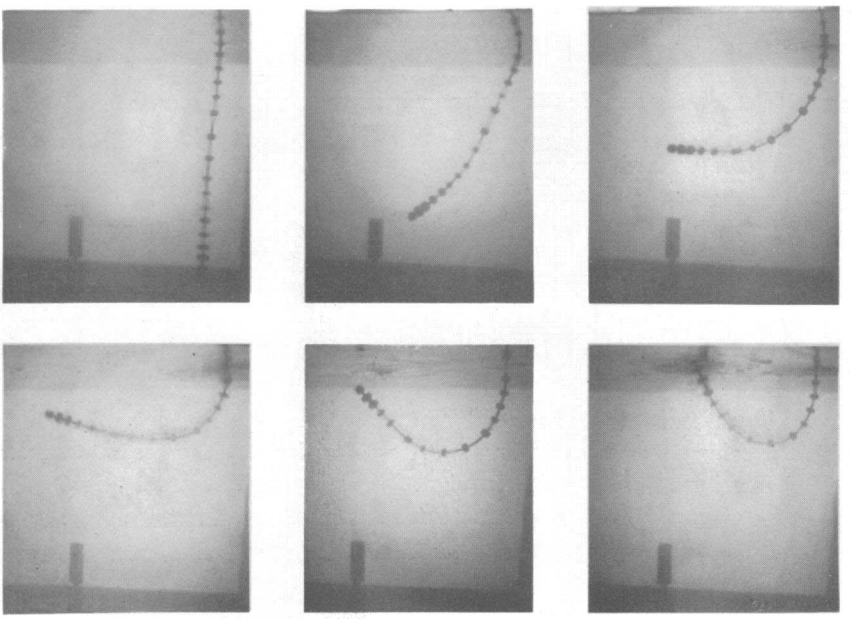
Hitherto we have assumed the spot to be single. The typical sun-spot group is double, though either or both of the principal members may be replaced by several smaller spots. The axis of the group makes a small angle with the solar equator, and the magnetic polarities of the preceding and following members are opposite in sign. Such a group may result from the tendency of any columnar vortex to turn up toward the photosphere, thus forming a semi-circular vortex ring.

A secondary vortex, caused by the influence of the low-lying spot vortex on the gases of the solar atmosphere above it, partially determines the structure of the hydrogen flocculi, which are drawn inward at high levels, then downward and outward at the upper levels of the spot vortex. The hydrodynamic structure thus developed may be more or less modified by the influence of the spot magnetic field on the trajectories of the moving ions within it.

The presence of magnetic fields in all sun-spots and the spectroscopic observations of Evershed and St. John on the revolution of the spot vapors at various levels, seem to prove beyond doubt that sun-spots are vortices. The object of the present paper is to describe some recent experiments bearing on the suggested explanation of double or multiple spots, and the flocculi associated with them.

A closely wound helix of brass wire, with disks of wood threaded on it to increase friction, is hung vertically from the shaft of an electric motor, and spun at moderate velocity in water. A columnar vortex is

thus set up with the helix as a core, which will remain nearly vertical as long as its angular velocity is low. But if the speed of the motor is increased, the lower end of the helix will gradually move toward the surface, giving rise to the successive forms shown[1] in figures 1 to 6. The semi-circular vortex ring finally produced, like an ordinary smoke ring, will have a motion of translation at right angles to its plane, in a direction corresponding to the direction of rotation of its inner edge. It is interesting to observe the depressions and whirls in the water when the end of the helix is approaching the surface. These represent in the hy-



pothesis the incipient spots which often appear and disappear near one extremity of a bipolar group.

An instructive control of this experiment may be readily applied. The water in the tank is set into rotation (by an auxiliary paddle) about the axis of the helix before the motor is started. After the helix is set spinning it will turn up much more rapidly than in quiet water if the direction of the preliminary rotation is opposed to that of spin, i.e., if the water is whirling in the same direction as the second 'spot' of the group. If, however, the whole body of water is rotating in the same direction as the helix, the latter will turn up with difficulty, or remain in the vertical position without turning up at all.

Thus a sun-spot vortex, if produced within a region already rotating

in the same direction, would tend to retain a columnar form, and the second spot of the group would not appear. Other conditions favorable to the production of single spots are low angular velocity of the vortex (similar in effect to the above case), a large ratio of diameter to length, and the presence within the sun of persistent eruptive centers, such as are suggested by the frequent recurrence of spots in the same region of the photosphere. It should be noted that convection may be a factor in prolonging the life of single spots.

If bipolar spots are semi-circular vortices, they should exhibit the proper motion characteristic of vortex rings. This motion, as already remarked, is at right angles to the plane of the ring, and in a direction corresponding with that of its inner edge. In a paper read before the Academy at its last autumn meeting,[2] it was shown that high and low latitude bipolar spot groups rotate in opposite directions. These directions are such that low latitude groups should move toward the equator, while high latitude groups should move toward the poles.

An investigation of the motion of spots in latitude was made many years ago by Carrington, who says:

> In the above table it will be remarked that there is more distinctly a trace of motion in latitude, the signs being on the whole + for latitudes higher N. or S. than 20°, though the daily polar motion between 20° and 40° of latitude on an average does not exceed 2′, a quantity which could only be deduced from the totality of a large number of single results. Between the parallels of 10° to 20° the motion in latitude is evidently very small; but the signs are generally negative and a feeble tendency towards the equator of about 1′ per diem is indicated. Within 10° of the Equator on either side no reliable motion in latitude appears to exist, the signs varying much and the mean results being of less weight.[3]

These results relate to all spots, both single and multiple, whose motions were observed by Carrington. His conclusion as to the reversed directions of motion of high and low latitude spots has recently been confirmed by Dyson and Maunder, who discussed the extensive observational material comprised in the Greenwich sun-spot measures from 1874 to 1912. They remark:

"A slight general tendency is suggested for high-latitude spots in either hemisphere to move away from the equator, but for those in lower latitudes to move toward it."[4]

This apparent confirmation of the hypothesis should not be taken too seriously, as it remains to be seen whether a closer comparison, excluding single spots and grouping the results in strict conformity with the observed polarities of bipolar pairs, would be equally favorable.

The need of caution is emphasized by the fact that the observed daily motions in latitude appear to be considerably smaller than theory would indicate. We have verified Kelvin's approximate expression for the motion of translation of vortex rings[5] by means of a semi-circular vortex ring in water, with paddles which can be driven at angular velocities varying through a wide range. But it does not follow that the same expression can be applied under the very different conditions existing in the sun, and we are seeking further information regarding this point before attempting to complete the quantitative test.

We may now inquire whether experimental methods will not throw some light on the difficult problem of the structure of the hydrogen flocculi. In 1908 we found that sun-spots are centers of vortex phenomena, plainly shown by the spectroheliograph when the sun is photographed with the light of the red line ($H\alpha$) of hydrogen. It was subsequenly proved by Evershed and St. John, however, that these are secondary vortices, extending down through the solar atmosphere from the hydrogen level, where their stream-lines are visible, toward an underlying vortex which constitutes the spot and produces its magnetic field. Are these secondary vortices of hydrodynamic origin, as St. John has maintained, or are they due to the effect of the magnetic field on the trajectories of the electrically charged particles in the solar atmosphere? The latter view, implied in Brester's aurora hypothesis of the flocculi and more clearly stated by Deslandres, has been fully developed mathematically by Störmer. Undoubtedly both hydrodynamic and electromagnetic phenomena must influence the structure of the solar atmosphere, but a satisfactory means of distinguishing between the two has been lacking.

The structure of the hydrogen flocculi shown on spectroheliograph plates can be more or less closely imitated with the aid of smoke in a closed glass box above vortices in water, and photographs of the stream-lines at different levels are easily obtained. The most interesting case we have yet observed is that produced when two paddles, rotating in opposite directions in water, set up a surface circulation similar to that in a bipolar spot group. The stream-lines in the smoke, seen when looking vertically downward toward the water, resemble those of a vortex ring of colored liquid rising through water from the orifice of a tube. When observed from a point in the plane of the ring, the stream-lines in the latter case appear to be closed on the upper or advancing side, while the surplus liquid on the following side moves along lines which are straight and axial opposite the center of the ring and become more and more convex on either side of this axis.[6] In the smoke similar stream-lines appear in horizontal planes, producing the effect of a hood

or arch on one side of the line joining the two 'spots,' with the very different structure just described on the opposite or following side.

Such an appearance of asymmetry would seem to be faithfully reproduced on some of our photographs of the hydrogen flocculi surrounding bipolar spot groups. If this resemblance should prove to be other than superficial, it would apparently indicate that in these cases the hydrodynamic influence of the spot vortices outweighs their electromagnetic effect in determining the structure of the flocculi. It may be added that the inward (nearly horizontal) flow of the smoke at high levels, the downward flow at intermediate levels and the outward flow at low levels is in harmony with solar observations.[7] But no final conclusions can be drawn before the experiments have been multiplied, and the necessary magnetic influence introduced, if possible, by means of magnets within the liquid vortices, acting on the moving smoke particles, ionized by an X-ray discharge, and separated electrostatically. As other photographs of the hydrogen flocculi surrounding bipolar spots seem to show a more nearly symmetrical structure, resembling the lines of force about a bar magnet, it may be true that in such cases the electromagnetic influence predominates, since we have no evidence that one spot may be regarded as a source and the other as a sink. The possible effect of electric fields in and about sun-spots must also be considered.[8]

It has been shown in this paper that some of the phenomena of single and multiple sun-spots can be imitated by simple laboratory experiments, which may also assist in explaining certain characteristic structures and motions of the solar atmosphere. The full details of the investigation will be published in the *Astrophysical Journal*.

[1] The vertical tube shown at the bottom of the tank, used for another experiment, has no effect on this result.

[2] See these PROCEEDINGS, 1, 382 (1915).

[3] *Observations of Solar Spots*, p. 222.

[4] *London, Mon. Not. R. Ast. Soc.*, 73, 687 (1913).

[5] Kelvin, *Mathematical and Physical Papers*, vol. 4, p. 67.

[6] See Mach, *Ann. Physik, Leipzig*, 68, Plate III, fig. 13. A better resemblance is afforded by a photograph of a smoke ring by Wood, reproduced in *Nature*, 63, 418, fig. 1.

[7] The stream-lines in different planes, either vertical or horizontal, are most clearly shown by a narrow beam of sunlight, admitted through the glass wall of the tank by means of a slit, which can be set in any desired position. In this way it is easy to imitate phenomena observed with the spectroheliograph in plan on the sun's disk and in elevation at the limb, where Slocum and others have photographed prominences while being drawn into sun-spots. Radial stream-lines in the horizontal plane, like those often indicated by the hydrogen flocculi about single spots, are well shown by the smoke at high levels.

[8] An error occurs in a paper by Hale and Babcock in a recent number of these PROCEEDINGS (March 1915, p. 125). Having in mind the lines of force between the separated charges in the vortex, the electric lines of force in the spot were described as tangential to the solar surface. This statement is more likely to apply only to the edges of the spot. At its center the lines of force are probably nearly radial.