the available evidence seems to point to the existence and origin of the spot vortex (the vortex which gives rise to the magnetic field) beneath the photosphere. The vortex represented by the hydrogen flocculi, shown by spectroheliograms taken with the Hα line, is apparently a secondary phenomenon lying at a higher level, where it is quite conceivable that its direction of whirl may be independent of that of the spot vortex below it.

Hale's Magnetic Vortices.

By Prof. H. F. Newall, F.R.S., Solar Physics Observatory, Cambridge.

I gladly avail myself of the opportunity, afforded by the courteous invitation of the editor, to add a few words of admiration of the work of Dr. Hale and his associates.

Dr. Hale's discovery, in 1908, of the Zeeman effect in the spectra of sun-spots set a final conclusion to the long conflict of opinion as to the vortical nature of sun-spots. Sir John Herschel's observations led him to suspect that vortical motion must be an invariable condition for sun-spots. Carrington discovered later that the varying daily movements of the spots across the sun's surface indicated the existence of what we may call a certain average régime of rotational motion wherein there is a maximum angular velocity in the equatorial zone about the sun's axis, whilst in the neighbouring zones on either side of the equator the angular velocities gradually diminish as higher latitudes are reached, with very considerable local departures from uniformity of zonal velocities. Faye drew therefrom the conclusion that the relative motions of contiguous zones of latitude must, under certain conditions of local disturbance, lead to vortical motions at the vertical interfaces between zones. But in spite of his weighty arguments, observers found it difficult to believe that either drawings from careful observations (for example, Fig. 4), or photographs of complex groups of spots (Fig. 9), really gave indications of vortical motion. Hence Hale's discovery in 1908 that signs of definite vortical structure could be seen in his spectroheliograms (Fig. 5) came as a convincing proof of vortical motion, at any rate in the lateral surroundings of sun-spots and in the upper atmosphere of the sun. His bold search for evidence of Zeeman's phenomenon was immediately crowned with success. Sun-spots were thus found to be the seats of magnetic fields, strongest in the umbræ, but also extending over the penumbræ and beyond in rapidly diminishing strength.

An important discovery is often followed by a period of apparent stagnation. But, in the case before us, the advance has been rapid and continuous; for the Mount Wilson observers have been assiduously measuring the field strengths and polarities of a vast number (more than 2000) of sun-spot groups during the years 1908–1923, and have thus been able to draw a number of important conclusions as to (1) the relation between the size of the spot umbræ and the strengths of the observed magnetic fields; (2) the rapid diminution of the strength of field above the spots, thus ruling out at the sun's end of the line the possibility of direct magnetic action between sun-spots and earth; (3) the curious association (maintained throughout the 11-year cycle) of opposite polarities with the leading and following members of "bimaculous" groups—if we may use this ugly word to indicate Carrington's associated pairs of spots; and lastly (4) the very remarkable reversal of polarity of "bipolar" groups in successive 11-year cycles. It is scarcely possible to use restrained language in expressing admiration for the superb mass of observational material systematically gathered and discussed by Hale and his associates.

We have become so accustomed to the 11-year cycle that it is a little difficult to readjust ideas to a 22-23-year cycle; and we must be content to look quietly at alternative possible interpretations of the newly discovered phenomenon. The outstanding points for further investigation relate chiefly to determining the seat and extent of the effective vortex in the various levels of the sun's atmosphere, and the source of the energy and the mode of its conversion. The energy relations are somewhat surprising, and it may be of interest to set forth a few instances. It is not very unusual to find a spot showing a "proper motion," relative to the zone of latitude in which it is situated, of as much as 20 minutes of arc per diem—about 4000 km./day or about 40 m./sec. Assuming an average density of 1/200th of the density of air at normal temperature and pressure, corresponding to air at 5460° Abs. ($=20\times273°$) and 1/10 atm. pressure, the kinetic energy of a stream of gas 20,000 km. wide, 100,000 km. long, and 1000 km. deep—dimensions which seem in no way to exaggerate features seen in some of Hale's wonderful Hα spectroheliograms—amounts to 2×10^{29} ergs relative to the contiguous zone travelling with the speed appropriate to the velocity régime.

We may assume that quantities of energy of this sort of amount are available for conversion into the eddies which we call sun-spots, without calling upon sources of energy within the sun's interior, whether of indraught or explosive expulsion of matter.

If we consider the energy of the magnetic field in a fair-sized spot, say of diameter 10,000 km., and assume that a uniform field of 5000 gausses pervades a sphere of this diameter enclosing the spot—an assumption which is based on data available in Hale's papers and in Störmer's calculations—we deduce a value $(\mu H^2/8\pi)\times\text{volume}=0{\cdot}5\times10^{33}$ ergs, taking μ as unity. The energy required to establish the magnetic field is nearly the same as the total output of radiant energy emitted by the whole sun in about one-seventh of a second.

It is perhaps worth pointing out that a local mitigation of the normal régime by either local acceleration or local retardation would not alter the polarity of a vortex, but would only change its latitude with reference to the horizontal stream which, by reason of its accelerated or retarded departure from the régime, would lead to turbulence to the right or to the left of it.

But a sufficiently great local *inversion* of the régime could result in a reversal of polarity at a vertical interface across which the latitude gradient of the velocity is large enough. If such a local inversion occurred intercalated in an otherwise normal régime, conditions might arise in which spots of both polarities are formed. These considerations would seem to provide conditions for the production of either polarity or both, but they leave the correlation of inversion with alternative cycles still to be explained, and would need to be elaborated to explain the maintenance of reversed polarity through a cycle.

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