THE MAGNETIC EFFECT IN SUNSPOT SPECTRA.

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IN *Monthly Notices*, **99**, 217 (1939), I recorded a striking example of a Zeeman doublet in sunspot spectra. This is an iron line in the green at λ 5250·218, a line probably representing a low level in the Sun, and one of those strongly affected in the magnetic field in laboratory spectra. Dr. H. N. Russell informs me that "it is $a^5D_0 - z^7D_1^0$. This should appear as a clear Zeeman triplet with a separation 3·00 times the normal."

I have since secured a good number of spot spectra in the autumn of 1941, and these are in the green and the red regions of the spectrum, including the line λ 6173, also of iron and classed by Hale as a triplet in spots. I have now found that the green line is also a triplet in the umbra of sunspots but a doublet in the penumbra.

As there will be few, if any, opportunities to continue the observational work during the minimum of solar activity, I may now record such features of the magnetic effect which appear in my plates, but which have not apparently been noticed hitherto.

All the large symmetrical sunspots with well-defined umbra and penumbra that have been photographed show much the same Zeeman pattern in the line 5250, and it is now quite certain that the line is a triplet over the umbra, usually with a very narrow and strong central component, but with relatively faint side components. In the penumbra, on the other hand, the line is a well-defined doublet, usually without a trace of a central component.

When the slit of the spectrograph is radial to the Sun's image, and the spot is some distance from the centre of the disk, the entire Zeeman pattern is inclined to the unaffected line outside the spot spectrum; this is due to the Doppler effect, and it proves that the central component is really a part of the Zeeman pattern and is not due to scattered light from the whole Sun superposing the unaffected line on the umbral spectrum.

The normal unaffected line outside the spot spectrum splits into two at the outer edge of the penumbra, the two branches diverging towards the umbra, where the separation may be 0·2 angstroms or more; and it is at this point that the central component usually appears. The magnetic field, therefore, begins at the point where the radial motion is greatest, and reaches a maximum where the radial motion is zero at the centre of the umbra. This applies to spots when near the centre of the disk, these details being then most clearly defined. When they are far from the centre, however, although perhaps less clearly seen, no change has so far been recorded in the magnetic pattern, that is, triple over the umbra and double over the penumbra. In some spots the doublet is very distinct on the penumbra on one side of the spot, but much less distinct on the opposite side, where a higher resolution might reveal a central component. In yet other spots the central component of the umbra extends a short distance into the penumbra.

In the *Astrophysical Journal*, **24**, 86 (1906), this same line, λ 5250, is referred to as "frequently reversed outside the spot umbra" (that is, a doublet in the penumbra), as observed by W. M. Mitchell before anything was known about the magnetic effect, and later in *Astrophysical Journal*, **30**, 82 (1909), it was described by the same author as a wide triplet on a bridge over a sunspot.

This describes the Zeeman effect as photographed by me, and observed by Mitchell, in the green line 5250. But I find that the same pattern is seen in the red line λ 6173, described by Hale simply as a triplet. I find that the triplet character occurs in my spectra only in the umbra: in the penumbra it appears as a doublet, but only under good conditions of seeing, when umbra and penumbra are clearly distinguished in the spectral image. Yet it seems that in the laboratory this red line is stated to be a triplet when observed both along and across the lines of force. Hale also stated that "a few triplets occur in all our spot spectra" (including 6173), but these he regarded as exceptional lines observed in the laboratory as triplets along the lines of force.*

In a Communication from the Mt. Wilson Observatory to the National Academy of Sciences (no. 10, 1915) Hale says that "When a *normal* Zeeman triplet is observed along the lines of force of a magnetic field, the central component is absent, and the two side components are circularly polarized in opposite directions." As both red and green lines appear in my spectra as triplets in the umbra when the spot is near the centre of the disk and we observe along the lines of force, it seems that they are both "exceptional lines"; but as they are doublets in the penumbra, where the light presumably comes across the lines of force, it appears that the red line (and perhaps also the green line) does not behave in the Sun as it is said to do in the magnetic field in the laboratory. It is not understood why the doublet character of the red line in penumbræ has not been recorded by the Mt. Wilson observers, who have examined a large number of spots in great detail, measuring field strengths in both umbræ and penumbræ.

In my spectra the side components in these red and green triplets I have found to be circularly or elliptically polarized in opposite directions, as expected, both in the umbræ and penumbræ. Also the opposite polarity of leader and follower spots in a bipolar group is beautifully shown in a plate taken on 1941 October 28, where the slit of the spectrograph bisected both spots. Owing to the multiple transmission of the light through the prisms, they acquire the property of polarizing the light and acting as analyser in a polariscope: it follows that in this case the red component was suppressed in the leader spot and the blue component in the follower. This happens without any subsidiary apparatus other than three silvered mirrors, used for rotating the Sun's image on the slit-plate. These mirrors convert the elliptically polarized light of the side components into plane polarized light, which is then analysed by the prisms. If the mirrors had been rotated 90° the blue component would have been suppressed in the leader spot and the red component in the follower. This reversal was found with other spots, and it proves that the side components are oppositely polarized.

Most of the lines observed by Hale are described as doublets in spot spectra, but these I have found more difficult to observe, as many of

* *Astrophysical Journal*, **28**, 324 (1908)

them are very faint, and higher resolution is required to obtain a clear separation of the components. Presumably they should be triplets in penumbræ, yet a few lines which seem on my plates to be doublets in the umbræ appear to be doublets also in the penumbræ. The line 5275·761 Cr is an example; it is, however, not certain whether higher resolving power would not reveal a central component in the umbræ. There are also the lines 5247·060 Fe, 5247·576 Cr, 6137·009 Fe, and 6151·630 Fe, classed as triplets, which appear in my plates to follow the pattern of the lines 5250 and 6173.

If the magnetic field is due to a rotation of ionized gases in the spot umbra, it is difficult to understand what is happening in the penumbra, where there is obvious accelerating motion revealed by the Doppler effect; but it is radial to the spot and parallel with the Sun's surface. Moreover, the iron vapour cannot be said to be ionized, since the spectrum lines in the spot are characteristic of the arc rather than the spark spectrum, indicating a lower temperature and less ionization than in the general solar surface. The radial motion cannot be the cause of the magnetic field in the penumbræ, which decreases as the motion increases. The sudden change from triplet to doublet seems to imply a bending over of an electric whirl from a direction perpendicular to the Sun's surface to a horizontal direction, where the light would be observed across the lines of force. It may be remarked that there is usually no spectroscopic or other evidence of a rotation of the umbra in a sunspot, although it is sometimes found that there is a component at right angles to the radial motion, suggesting but not proving a relatively slow rotation of the spot as a whole.

It would, perhaps, be easier to picture what is taking place if the umbra were supposed to consist of a very large number of relatively small vortices and that these bend over in all directions horizontally in the penumbra, the whirling motion decreasing as the radial motion increases. It appears that the magnetic lines of force do bend over in this way, as shown by Hale and his colleagues,* but that the whirling gases do actually produce these strong magnetic fields is, perhaps, difficult to believe. One would imagine that magnetic fields of the order of 3000 gauss could not be supposed to exist many hundreds of kilometres above the exciting cause, so that it seems that this exciting cause must be in the internal motions of the highly tenuous gases in the umbræ and penumbræ. A pair of bipolar sunspots on this view of numerous small electric vortices might be thought of as analogous on a macroscopic scale to a U-shaped permanent magnet consisting of countless elementary atomic magnets or spinning electrons. As the theory of these terrestrial magnets is not completely understood, it is not surprising that the solar magnets are difficult to explain.

The theory of vortex motion of ionized gases was considered by Hale and Lukey in 1915. They suggested that bipolar spots are produced by semi-circular underlying vortex rings, the two ends of the vortex projecting above the photosphere and forming the leader and follower spots rotating in opposite directions. This theory was later developed with

* *Astrophysical Journal*, **49**, plate V, opposite p. 158 (1919).

considerable success by Bjerknes *, but the question how these solar tornadoes of extremely tenuous gases could produce such strong magnetic fields remains unsolved.

As is well known, the extraordinary discoveries of Hale include tho reversal of polarity between the northern and southern hemispheres. In other words, the sign of the magnetic field in a leader spot of the northern hemisphere is opposite to that in a southern leader, and both change places, so to speak, every $11\frac{1}{2}$ years, thus returning to the original order every 23 years.

Apart from the magnetic effects, there are to be explained the movements disclosed by the Doppler effects which I discovered in 1909, namely, the outward accelerating motion of the low-level gases and the inward decelerating motion of the calcium and hydrogen of the higher chromosphere, both movements parallel with the Sun's surface. St. John confirmed and extended these two opposing movements to other elements at intermediate levels, and was able to determine approximately the height above the photospheric level at which this strange inversion occurs.† Surely these movements must in some way be connected with the magnetic effects.

In a normal symmetrical spot not subject to violent change there is no distinct evidence either of a rising or a falling motion in the umbra. There may, nevertheless, be such movements of anything under 100 metres per second. Indeed, a rising movement must occur to supply the outgoing radial movement. It has to be remembered also that there appears to be a general rising movement revealed by the low-level iron lines all over the solar surface, and a descending movement of the high-level calcium which I have found amounts to over 1 km./sec. when allowance is made for the Einstein effect. The gases over spots may, and probably do, partake in these general movements, but further research is necessary to settle this point.

It seems that sunspots, with all their very widespread subsidiary phenomena, which at times are highly spectacular, must indicate something fundamental in the constitution of the Sun. So much has been discovered about these strange markings, and yet so little success has been achieved in co-ordinating all the facts, and forming a consistent picture of what is actually taking place, or is causing these remarkable phenomena. Perhaps we may never know why there should be these periodical outbursts of solar magnets. Terrestrial physics may fail us. One would have thought that by this time, that is to say after two or three thousand million years, a great mass of gas like the Sun would have settled down to a state of calm uniformity without spots or prominences or other strange happenings.

* *Astrophysical Journal*, **64**, 93 (1926).

† *Astrophysical Journal*, **37**, 322 (1913). The discovery of the inflow of calcium and hydrogen has been attributed to St. John in recent books, although he acknowledged my discovery in the opening remarks of this paper. See also *Monthly Notices R.A.S.* **70**, 220 (1910).