Solar Magnetograph with a Spectroheliograph

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In the following discussion, the writer does not claim to be an expert on the Zeeman effect. The discussion is nonmathematical, so it should elucidate how the Zeeman effect works and how to record it.

A spectrohelioscope is a very versatile solar instrument. In the visible solar spectrum, there are about 4100 spectral lines, more than half of them being faint. On the solar disk in H alpha light, surge filaments and flares can be carefully studied, including surge prominences on the solar limb. The spectrum manifests H alpha zig-zags and flares in bright emissions.

In recent years, the Zeeman splitting of spectral lines in sun spots has been observed first by amateurs Veio and Higgins in 1999 (1), then by Philippe Rousselle of France in 2003 (2), followed by Andre and Sylvain Rondi (father and son) of France in 2005 (2).

Through constant sharing of informations with amateurs over 40 years, Veio has encouraged others into advanced topics of the sun. Now at almost 80 years he can not do it all. To his good luck, Andre and Sylvain Rondi with their compact spectroheliograph and a webcam achieved the first solar magnetogram of a sun spot region in 2006 (2,3). Rondi processed his solar images with the IRIS software by C. Buil of France.

First a bit of history. Around 1880 Secchi and Young had seen a widening and splitting of some photospheric lines in the umbrae of sun spots, not knowing the cause of it (4,5,6). Dr. Pieter Zeeman in 1896 discovered the cause of the Zeeman effect named after him. Before 1906 Mitchell visually observed using a 23 inch refractor with attached spectroscope and compiled a list of 680 Zeeman lines (7). Hale in 1908 with the 60-Foot Solar Tower on Mt. Wilson Observatory was first to prove the splitting of the spectral lines was due to a magnetic field in the sun spot (8).

More history. H. Babcock and H. Babcock (father and son) invented the Babcock solar magnetogram in 1951, employing one photocell on the blue wing and a second photocell on the red wing of a sensitive Zeeman line, designed for weak magnetic fields, about one gauss. In 1952 they installed it in the Hale Solar Laboratory in Pasedena (9). In 1957 they installed another solar magnetogram in the 150-Foot Solar Tower. Leighton in 1967 with the 60-Foot Solar Tower used a special photographic subtraction technique, sensitive to about 100 gauss, to record faint and bright plage surrounding sun spots (10).

In 1964 Veio made a compact spectrohelioscope (11,12). Years later he published a small book on the subject. Again to his good luck, Dr. Harold Leinbach of NOAA wrote for a copy, and he informed Veio that visual Zeeman studies were possible with a professional spectrohelioscope (13). In 1975 Veio wrote an article in ORION, hoping to stimulate a few amateurs into visual polarity observations of sun spots (14).

In a physics laboratory with a powerful magnet, the Zeeman effect is seen with the spectral lines in emission. On the sun the inverse Zeeman effect is shown with the lines in absorption. For an earthly magnet, the north polarity will be a Zeeman doublet of ccw/cw circular polarized light (counterclockwise/clockwise, that is, left/right); for the south polarity a doublet of cw/ccw circular polarized light. On the sun in a sun spot the north polarity of a doublet will be cw/ccw circular polarized light; the south polarity will be ccw/cw circular polarized light (15).

To find a Zeeman sensitive spectral line, one must have a good photographic atlas of the solar spectrum. H. A. Rowland in 1888 with his newly invented concave grating of 21 feet (6.3 meters) made a photographic atlas of the solar spectrum. Examining the photographic plates, he devised a visual scale of intensity (widening and darkness) of the spectral lines. There from he measured the solar wavelengths and had them published in 1895 in the first five volumes of the then new Astrophysical Journal, which was founded by Hale (16).

C. A. St. John is 1928 presented a Preliminary Revision of Rowland's Table of the Solar Spectrum Wavelengths. All errors of wavelengths were corrected and many new lines added. The Rowland intensity scale was still in effect. Just before WW II, M. Minnaert of the Netherlands in 1940 published a Photographic Atlas of the Solar Spectrum. The spectrograms were mounted on a backing of cotton cloth. Meudon Solar Observatory in 1968 offered a low and a high resolution atlas of the solar spectrum, also a catalog of the solar wavelengths and a photospheric profile of the spectral lines.

Pierce in 1966 with the 60 inch (1.5 meters) McMath telescope produced a photographic spectrum with the entrance slit on the edge of the solar limb, similar to a solar eclipse, and from it a catalog of the solar wavelengths in emission (17). Working at Mt. Wilson Observatory, Moore in 1966 published a catalog of the solar wavelengths with the more objective terms of equivalent width and reduced width, instead of the somewhat subjective Rowland intensity scale (18).

Veio visited the Mt. Wilson Observatory in April of 1981. An observatory technician, Larry Webster, gave him a tour of almost all the telescopes. In the observing room at the base of the 150-Foot Solar Tower, Veio was shown how the magnetic field of an umbra was viusally measured with a Zeeman split line. At the time a small sun spot with umbra about 5 arc/sec was near the center of the solar disk. But with the 16.7 inch (418mm) solar image, the doublet of the Fe I line of 6173.3A wavelength was easily viewed. Dark core of the line was 0.03A wide.

A 1/4 wave retardation mica plate converts the circular polarized light to linear polarized light. In the hand one holds a 50x100mm rectangular shape of two Polaroid pieces, each 50x50mm and stuck together, one piece at a 90 degree angle to the other. With the hand one holds it up to the eye and moves the Polaroid sideways. The left linear or right linear polarized components of the Zeeman doublet will alternately appear or disappear. Since 1912 with the 150-Foot solar tower, Dr. G. E.Hale, Tom Cragg and others have used the Fe I line of 6173.3A wavelength for visual observation of sun spots in the spectroscope mode. The wavelength gives a clear visual split of the doublet.

Attachment one: spectroscope visual mode at the exit port

Without the Polaroid, one can estimate visually the width of the split doublet and there from the magnetic field in gauss of the sun spot. **With** the Polaroid one can determine the north or south polarity of the sun spot as the spectral line shifts slightly left to right, or right to left.

The previous discussion was the estimate in gauss of the sun spots in the visual spectroscope mode, also the north and south polarity of the sun spots. Now for the plage and the sun spot polarity of magnetic fields in the spectroheliograph mode.

To make a solar magnetogram, one must take two separate magnetograms, one for the north polarity of the magnetic fields in the sun spot and plage and the second for the south polarity of the magnetic fields of the same. The magnetic flux lines coming out of the sun spot (line-of-siight) and plage are termed the north polarity (+). The magnetic lines going into the sun spot and plage are termed the south polarity (-).

If the mica plate is rotated 90 degrees, the left circular polarized light is changed to right linear polarized light, and vice versa for right circular polarized light to left linear polarized light. With a fixed Polaroid one can take a solar magnetogram of the north polarity of the sun spot and plage, and the second magnetogram with the 1/4 wave mica rotated the south polarity of the sun spot and plage will be captured. The two north and south magnetograms are combined into one solar magnetogram with the north polarity printed in white and the south polarity in black. The background is a faint grey.
A computer can do it more quickly than by the traditional photographic method of the 1960s.

With photoelectric cells Howard states that the exit slit slightly offset on the blue wing of the Zeeman line is best for higher contrast to the strong and weak magnetic fields. The blue wing of the line is steeper than the red wing. Passband about 0.03A. With the exit slit on the red wing of the line, the contrast is acceptable for the strong magnetic fields, not so for the weak nearby fields (19). Solar light from the penumbrae and the umbrae is mostly transverse polarized light that is orientated at right angles to the observer. Solar light from the plage is longitudinal polarized light in the line-of-sight to the observer.

Not too many Zeeman lines split into a simple doublet, which is the desirable method of making a magnetogram. Many sun spot umbrae are about 2400 gauss and the penumbrae 800 gauss. Bright plage will be about 800 gausss, and faint plage about 100 gauss or less. So a solar magnetogram is just within reach for solar amateurs with sufficient solar equipment. For weak magnetic fields, the equipment must be more sophisticated.

Attachment two: spectroheliograph mode for a solar magnetogram

There are two scales for the intensity of the spectral lines. Rowland started with zeros for very faint lines, 000 and so forth. Then changed to -3 and such. If you look at a long list of spectral lines and use the below values, you can acquire an idea of the visual intensity of the line.

Comparison of References of Photospheric Lines

visual dark core, Veio	Rowland intensity scale, 1895	Moore, 1966, equivalent width	comments and examples
very faint	-3 (0000) -2 (000) -1 (00)	less than 6	varying weak intensities
faint photospheric	0 (0)	6 to 12	0.015A core,
less strong 5893A	5 approx.	66	0.03A core; yellow Ni I,
medium strong 5169A	15 approx	114	0.05A core; Fe I b3,
strong and very strong	40 or more	564 or more	Na I, Mg I b1, H alpha, chromospheric

You can make a 1/4 wave mica retardation plate for almost nothing (20). Interference colors are a function of the path differences. An Edmund retardation plate will cost about $350. One must buy high extinction Polaroid.

Mica 1/4 wave Retardation

order of color	path difference	color for crossed Polaroids	color for parallel Polaroids
1	0	black	white
	4500A	brown	light blue
	5000	orange	light blue
	5500	red I	bright green
2	5750	violet	yellow-green
	5900	indigo	yellow
	7000	light blue	orange

The following table is with a 1200 gr/mm grating, assume 50x50mm ruled area in the H alpha region of the solar spectrum. You will gain an appreciation of the Zeeman line split in microns that can be seen.

Zeeman Effect and Linear Disperson versus Focal Length

spectroscope focal length	dispersion first order	Zeeman, 0.2A split	dispersion second order	Zeeman, 0.2A split
4 meters	2.0A/mm	100 microns	0.65A/mm	300 microns
2 meters	4.0A/mm	50	1.3A/mm	153
1 meter	8.0A/mm	25	2.6A/mm	76

Comparison of solar observatories. On Mt. Wilson the 60-Foot Solar Tower has a spectroscope of 30 feet (8.9 meters) focal length, 1.44A/mm inverse linear dispersion in the second order, 300 gr/mm grating. The 150-Foot Solar Tower has a 75 feet focal length, 0.5A/mm dispersion second order, using 600 gr/mm grating prior to 1980. An umbra with 2400 gauss magnetic field will have a Zeeman shift about plus 0.1A in the red wing and minus 0.1A in the blue wing, or a total split of 0.2A. The 6173.3A wavelength, Fe I, was the visual line of choice for clean splitting of the line in the spectroscope mode.

References

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2. Private communications and see their web sites below

3. Rondi A., l'Astronomie, vol. 120, 380 (2006)

4. Secchi P. A., "Le Soleil", 289, 1875

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6. Ingalls A. G., "Amateur Telescope Making", vol. 1, 191, New York, 1957

7. Mitchell W. M., Astrophys. J., vol. 22, 4 (1905)

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16. Rowland H. A., Astrophy. J., vol. 1 to 5 (1895 - 1897)

17. Pierce A. K., Astrophy. J. Suppl., vol. 17, 1 (1968)

18. Moore C. E., "The Solar Spectrum: 2935A to 8770A", Monograph no. 61, 1966

19. Howard R., "Solar Magnetic fields", 292 and 377, 1971

20. Shubnikov A. V., "Principles of Optical Crystallography", 1960

Internet references

The original spectrohelioscope web site was hosted by Fredrick Veio and Dr. J. Christopher Westland of Hong Kong for seven years up to 2007. Since then it was transferred to Michel Rushford's web site, U.S.A. Toshio Ohnishi of Japan has the Veio Zeeman article translated into Japanese.

Spectrohelioscope web site hosted by
Veio: http://groups.yahoo.com/groups/spectrohelioscpes

Christian Buil of France site http://www.astrosurf.com/buil

Leonard Higgins site http://www.spectrohelioscope.org

Meudon Solar Observatory, near Paris, http://mesola.obspm.fr

Andre Rondi site http://www.astrosurf.com/rondi

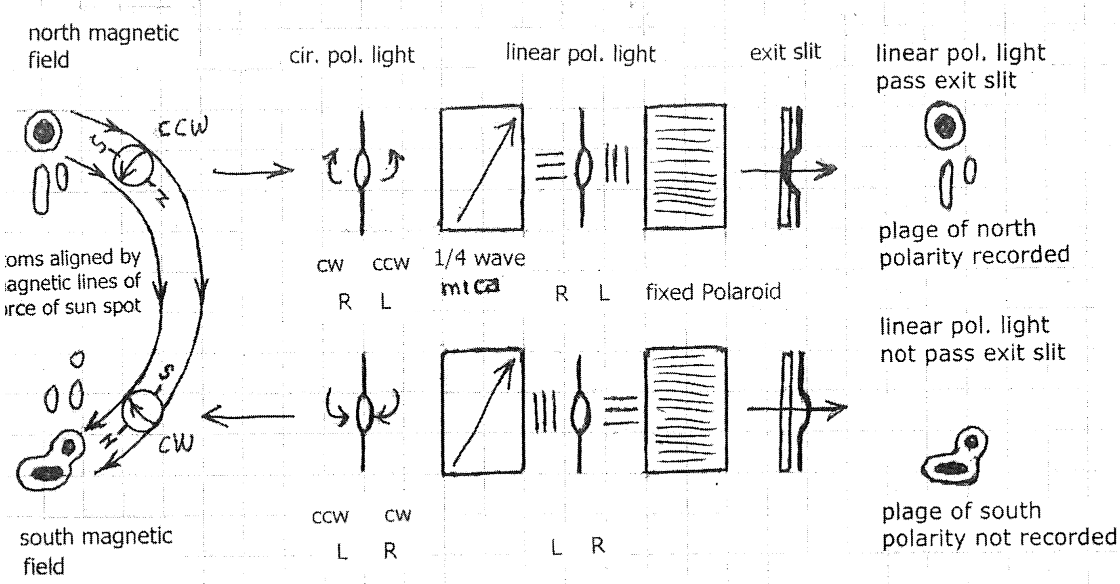
Philippe Rousselle of France site http://www.astrosurf.com/spectrohelio

Michael Rushford site http://www.eyes-on-the-skies.org/shs

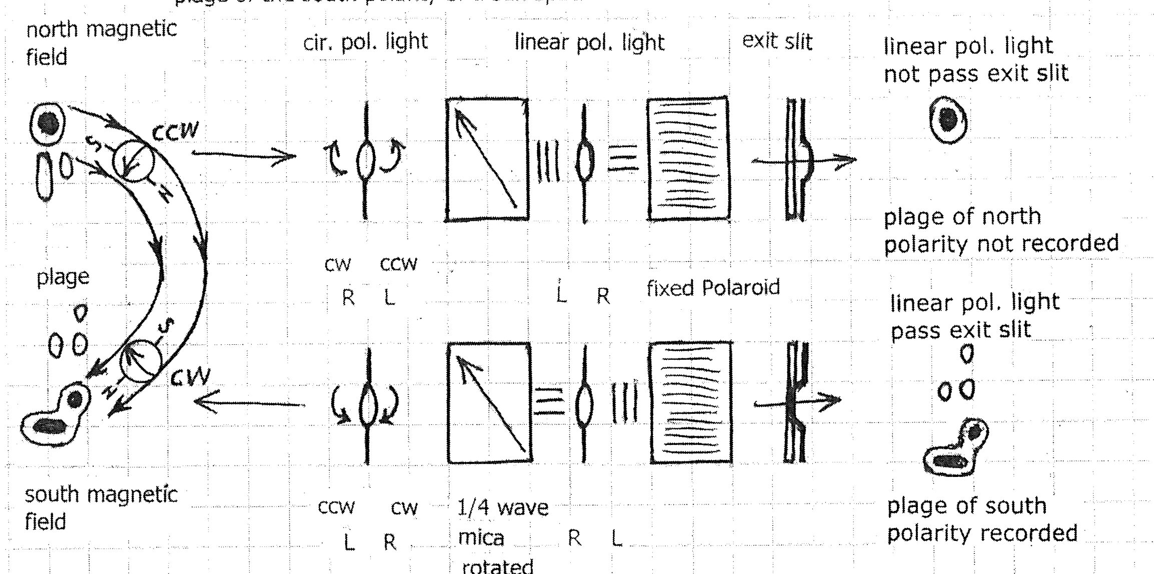
Toshio Ohnishi site http://www2s.biglobe.ne.jp/~t-oni

Attachment two: spectroheliograph mode for solar magnetogram

Let us first record the plage of north polarity of a sun spot. There will be shifts of the line about 0.03A for bright plage of 800 gauss and 0.01A for faint plage of 250 gauss. The plage will be in emission AND into the exit slit. The umbra will shift the line about 0.1A across the exit slit and away from it, not recording any different detail.



The 1/4 wave mica is rotated 90 degrees. Now we record the plage of the south polarity of a sun spot.



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The south polarity is printed dark and the north polarity is white. They are combined to present a complete magnetogram. Instead of a rotating 1/4 wave mica and a fixed Polaroid, one can have a fixed mica and a rotating Polaroid at 90 degrees.

Attachment one: spectroscope visual mode at exit port of 150-Foot Solar Tower

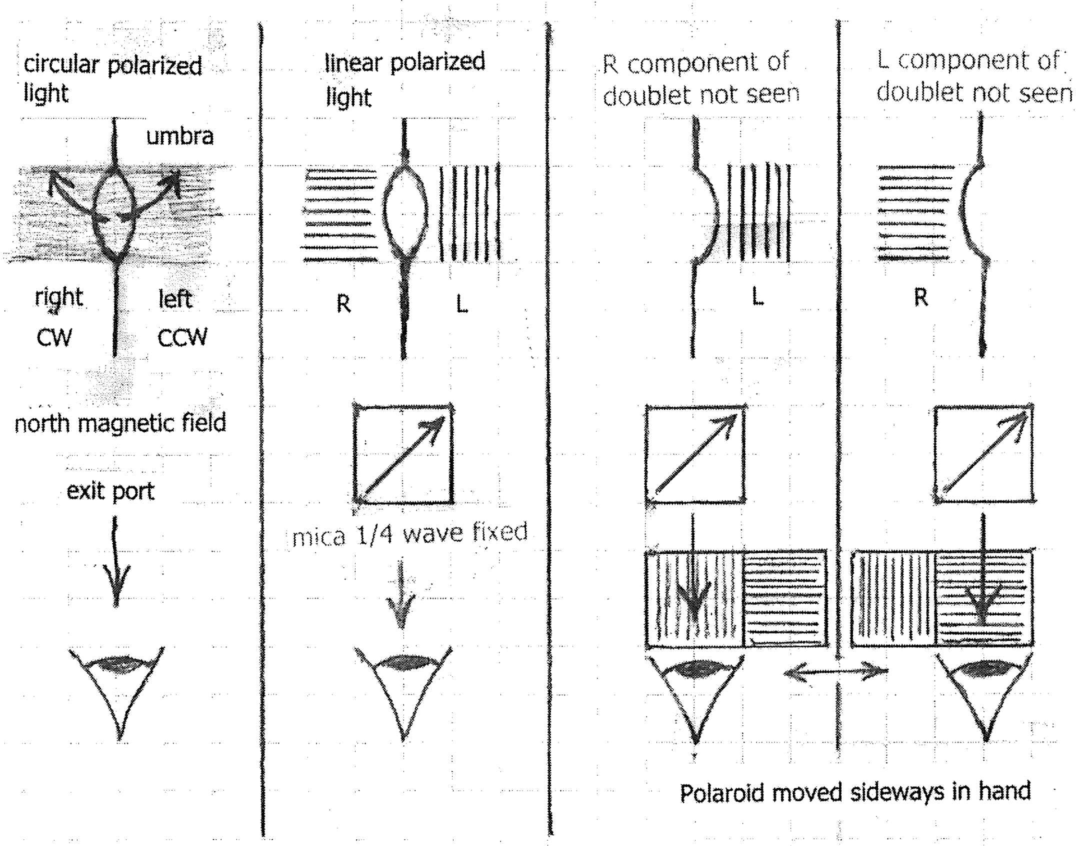
Polaroid with two pieces at 90 degree angle, held in the hand and in front of the eye. The Fe I line of 6173.3A wave length gives a clean doublet split. The optical axis of the 1/4 wave mica is at 45 degree angle to the Polaroid.

There are three methods of observation and detection of the Zeeman line:

1. Polaroid fixed and 1/4 wave mica alternately rotates at 90 degree angle.

2. The 1/4 wave mica fixed and Polaroid alternately rotates at 90 degrees.

3. The 1/4 wave mica fixed, the crossed two-piece Polaroid moves sideways.



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