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The discovery of the electron: II. The Zeeman effect

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Abstract. The paper gives an account of the discovery, in the fall of 1896, of the Zeeman effect and of the developments in the months that followed. It is to a large extent based on previously unknown archival material.

Sammenvatting. In dit artikel, dat is voor een groot deel is gebaseerd op onbekend archiefmateriaal, wordt een historisch overzicht gegeven van de ontdekking van het Zeeman effect in het najaar van 1896 en van de ontwikkelingen in de maanden na de ontdekking.

1. Introduction

In the fall of 1896, the Leyden physicist Pieter Zeeman discovered a new phenomenon that would soon be known as the Zeeman effect. He observed a clear widening of the sodium D-lines under the influence of a magnetic field. Not long after the discovery, his colleague Hendrik Antoon Lorentz developed a theory predicting that the observed widening actually was a splitting of the lines in three components when observed in a direction perpendicular to the field. In a direction parallel to the field, two lines, with opposite circular polarizations, would be visible. Both predictions were confirmed by Zeeman: the polarization was observed in Leyden, the splitting in Amsterdam, early in 1897, where, in the meantime, Zeeman had been appointed lecturer.

Lorentz's theory was based on the assumption of the existence of charged vibrating particles inside atoms. Zeeman's discovery, together with Lorentz's theory, were the first indications of the existence of a new charged particle, later known as the electron. In this paper I will give an account of the discovery of the Zeeman effect, supplemented with a short biographical sketch of Zeeman (see the appendix). The paper is to a large extent based on material from the Zeeman archive, which was discovered only a few years ago [1].

2. The Leyden tradition

At the physics laboratory in Leyden, two lines of research were pursued during the last decades of the nineteenth century. One dealt with the equation of state and the behaviour of matter at low temperatures, and would eventually lead to successes such as the liquefaction of helium and the discovery of superconductivity. The other one was the 'Lorentz-series' of magneto-optical experiments. The name Lorentz-series indicates part of the background to this work: it was intimately connected to Lorentz's work in electromagnetism, the work that would ultimately be known as the electron theory. The collaboration between Lorentz and his assistants and the experimenters led by Heike Kamerlingh Onnes was fruitful and provided important support for Lorentz's theoretical work [2].

Pieter Zeeman obtained his doctorate under Kamerlingh Onnes with a dissertation in magneto-optics. It dealt with the Kerr effect, which has to do with the change in degree of polarization of light reflected by a magnetized mirror. This background is important, because it gave Zeeman a feel for the field of magneto-optics and made him aware of the unexplored areas in this field. His search for an influence of a magnetic field on spectral lines must be seen in this light.

3. The discovery

In some later reminiscences [3] Kamerlingh Onnes mentions an early attempt by Zeeman to establish the possible influence of a magnetic field on spectral lines. The thought had occurred to Zeeman when he wondered if a magnetic field would not only modify the way light is propagated and reflected, but also its frequency. Onnes's account is corroborated by a remark by Zeeman in his first paper on the Zeeman effect [4]. He mentions an earlier inconclusive experiment, involving the spectrum of sodium. Of this particular

Figure 1. Pieter Zeeman.

Figure 2. Hendrik Antoon Lorentz.

work no notes are preserved. But there is an intriguing letter to Onnes from 1891, in which Zeeman reports having looked at the spectrum of iron in a magnetic field and having been 'unable to observe a displacement of the lines' [5]. It is possible that this is a reference to the earlier experiment.

The Zeeman archive also provides more background to the motivation behind Zeeman's experiment. In his first paper on the Zeeman effect [4] Zeeman mentions why he had returned to the experiment, in spite of its initial failure. The reason was a passage in an article on Michael Faraday, written by Maxwell, in which Faraday's unsuccessful attempts are mentioned to 'detect any change in the lines of the spectrum of a flame when the flame was acted on by a powerful magnet' [6]. After reading this passage, Zeeman decided to repeat the experiment, because, as he put it: 'If a Faraday thought of the possibility of the above-mentioned relation, perhaps it might be yet worth while to try the experiment again with the excellent auxiliaries of spectroscopy equipment of the present time, as I am not aware that it has been done by others.'

This kind of inspiration fits in with what we can learn from material in the Zeeman archive. In a notebook, started in 1890 as a record of his intellectual development, Zeeman jotted down all kinds of thoughts and ideas, as well as passages from his readings. One of these is Faraday's account of his experiment on the possible influence of a magnetic field on the spectrum of sodium. It is accompanied by Zeeman's observation that 'experiments, with negative outcome, performed by great scientists from the past, using worse instruments than are currently available, are worth being repeated' [7]. To this remark a cautionary observation is added: 'One should not communicate to others ideas that have not been worked out yet, plans that have not been carried out yet, experiments that have not been performed yet.' The notebook contains many such observations and passages copied from the works of great scientists. At least during the early part of his career, Zeeman clearly derived much inspiration from the work of famous predecessors.

One of the items in the Zeeman archive is a laboratory notebook that contains the first recorded observation of the Zeeman effect [8]. The entry is dated 2 September 1896 and is preceded by many pages of notes on totally unrelated experimental work. It opens with the words: 'Influence of magnetization on flame.' The notes that follow describe a very simple experiment: a piece of asbestos, soaked in a solution of kitchen salt, is put in a flame placed between the poles of a magnet. With the help of a grating, a spectrum is created. The yellow sodium D-lines appear as narrow and sharp lines. 'When the magnet is switched on', the description continues, 'the lines become wider until they are two to three times as wide'. This simple sentence describes the discovery

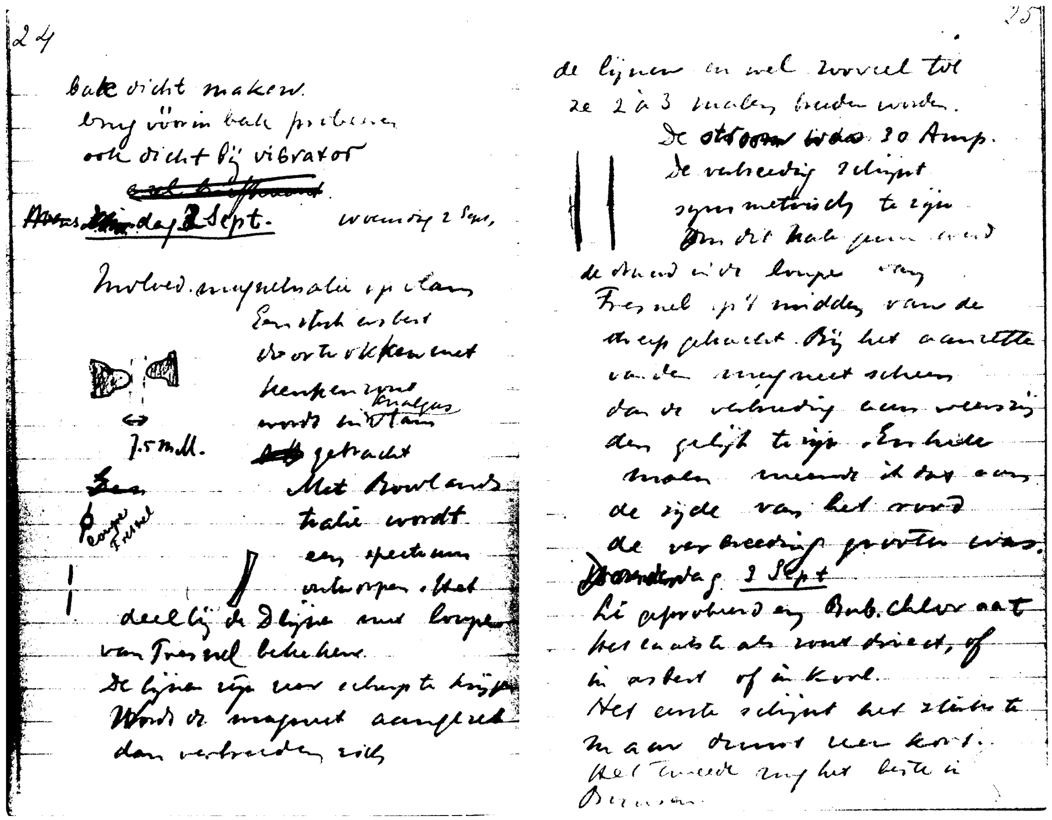

Figure 3. Two pages from Zeeman's notebook with the first recorded observation of the Zeeman effect.

of the Zeeman effect. Everything that follows is just an elaboration of this brief statement.

As we see, no actual splitting of the spectral lines was observed initially, owing to the insufficient strength of the magnet: although Zeeman used an excellent original Rowland grating with a radius of 10 ft and 14 938 lines per inch, the 10 kG produced by the magnet was insufficient to make the splitting visible. It would take several more months before an actual splitting of spectral lines could be established. This event took place in Amsterdam in 1897 and the line in question was the blue cadmium line [9].

Since only a widening of the spectral lines was observed, it was by no means certain that a new effect had been found. No one was more aware of this than Zeeman himself. The two days following the discovery were spent in further observations. Zeeman concluded that quite possibly the broadening was caused by pressure differences owing to temperature or density gradients produced by the magnetic field. The third day after the discovery Zeeman returned to the experiment he had been working on before 2 September.

4. The follow-up

It was not until more than a month later, on 9 October, that Zeeman returned to his magneto-optical work. Now he started a systematic series of experiments, in which the true nature of the discovered effect had to be established. I will not go into much detail here; let me just mention that Zeeman investigated the influence of the form of the flame on the broadening and the effect for absorption lines instead of emission lines, trying to eliminate complicating factors such as temperature and density gradients in his samples. The picture of Zeeman that emerges here is that of a painstakingly careful experimenter, who is his own most severe critic. As J D van der Waals Jr observed much later:

> Whoever reads the publications gets the impression that not the experimenter himself is reporting, but a somewhat unfriendly critic, whose goal is not to evaluate the experiments and investigate their consequences, but to be suspicious of all that he is told. [10]

Towards the end of the month, Zeeman finally became convinced that he had really discovered something new. A publication describing his experiments was presented by Kamerlingh Onnes at the monthly meeting of Saturday 31 October of the Section of Sciences of the Dutch Academy of Sciences. In it Zeeman concluded:

The experiments have made it increasingly probable that absorption and thus also emission lines of a gaseous substance are widened by magnetic forces. [4]

We now know that the experiments had continued until right before the paper was submitted and new experimental results had been added at the last minute. One of these was in response to a remark by Onnes, who had suggested, when he saw the experiment for the first time the day before the Academy meeting, that convection currents might be responsible for the observed phenomena.

According to Zeeman's reminiscences [11], the Monday following the Saturday on which Zeeman's paper was submitted, a theoretical explanation of the effect was proposed by Lorentz, who had been present at the Academy meeting. The explanation is based on the following model. Atoms contain charged particles, harmonically bound to a centre. They are called 'ions'. The frequencies of their vibrations correspond to the frequencies of the spectral lines of the substance in question. When a magnetic field is applied, the vibrating particles will experience a Lorentz force, in addition to the harmonic force. For a field in the z-direction the equations of motion take the following form:

$$m\frac{\mathrm{d}^2x}{\mathrm{d}t^2} = -kx + \frac{eH}{c}\frac{\mathrm{d}y}{\mathrm{d}t} \tag{1}$$

$$m\frac{\mathrm{d}^2y}{\mathrm{d}t^2} = -ky - \frac{eH}{c}\frac{\mathrm{d}x}{\mathrm{d}t} \tag{2}$$

$$m\frac{\mathrm{d}^2z}{\mathrm{d}t^2} = -kz. \tag{3}$$

The general solution of the last equation is:

$$z = a\cos(\omega_0 t + p) \tag{4}$$

with a and p constants and $\omega_0 = 2\pi\sqrt{(k/m)}$. For the x and y motions two sets of solutions are found:

$$x = a_1\cos(\omega_1 t + p_1) \tag{5}$$

$$y = -a_1\sin(\omega_1 t + p_1) \tag{6}$$

and

$$x = a_2\cos(\omega_2 t + p_2) \tag{7}$$

$$y = a_2\sin(\omega_2 t + p_2). \tag{8}$$

The new frequencies ω_1 and ω_2 are found from:

$$\omega_1^2 - \frac{eH}{mc}\omega_1 = \omega_0^2 \tag{9}$$

$$\omega_2^2 + \frac{eH}{mc}\omega_2 = \omega_0^2. \tag{10}$$

Instead of the one frequency ω_0 that occurs in the absence of a magnetic field, three frequencies appear. One of the new frequencies is smaller than ω_0, the other is larger. For the case that the relative frequency change is very small the frequency difference $\Delta\omega$ is found as

$$\Delta\omega = \frac{eH}{2mc}. \tag{11}$$

The 'new' x and y vibrations can be combined to two circular motions in the x–y plane: one with a higher and one with a lower frequency. This implies that, parallel to the magnetic field, the original spectral line is split into two lines (the vibrations in the z-direction are invisible in that case, because no radiation is emitted parallel to the axis of vibration). Moreover, these components are circularly polarized. Perpendicular to the field, three lines appear: one in the original location, one with a higher and one with a lower frequency. All three components are linearly polarized.

These consequences were immediately clear to Lorentz and he discussed them with Zeeman. On 10 November, Zeeman began to investigate the polarization of the edges of the broadened lines. Initially without success, until he discovered why ten days later: he had been looking perpendicular to the field instead of parallel to it. As he wrote: 'The experiment should be done with lines of force in the direction of the grating!' [8]. Observing along the field lines is not a straightforward operation since it involves drilling holes in the poles of the magnet. Finally, on 23 November Lorentz's prediction was confirmed, the edges were circularly polarized. It was a moment of great triumph for Zeeman and Lorentz and Zeeman noted in a diary:

23 November 1896. Finally confirmed that an action of magnetization on light vibrations does indeed exist. With the help of Lorentz shown that the explanation through a modified motion of 'ions' is correct or at least highly probable. Shown Lorentz the experiment in the morning of the 24th. He calls it a 'lucky break' and a direct proof for the existence of ions, together with the Faraday rotation and the Kerr effect. [12]

On 28 November, a second paper by Zeeman was submitted to the Academy of Sciences, in which the confirming results are presented [13].

5. The value of *e/m*

Equation (11) implies that from the magnitude of the splitting of the lines the ratio of the charge and the mass of the intra-atomic 'ions' can be determined. Even though Zeeman had only observed a widening, he succeeded in calculating e/m. He found a value of approximately 10^7 emu g^{-1}. From Zeeman's later reminiscences it appears that Lorentz and Zeeman were surprised and puzzled by this value, which is much larger than would have been expected if Lorentz's 'ions' were the same as electrolytic ions. According to Zeeman, Lorentz even called it 'a bad thing' initially [11]. Curiously, in the paper of 28 November, in which this value is first published, Zeeman does not comment on this anomaly. In a letter to Oliver Lodge, who had

Figure 4. Zeeman's Nobel diploma.

expressed his surprise at the large value in a letter of 28 February 1897 [14], Zeeman even argued that his value was not strange at all because it agreed well with the value derived from the magnetic deflection of cathode rays [15]. Zeeman simply concluded that different kinds of 'ions' existed and that the 'ions' introduced by Lorentz were different from the electrolytic ions.

In addition to determining the value of e/m, Zeeman also succeeded in establishing that the intra-atomic 'ions' were negatively charged (although initially, as reported in his paper of 28 November, an experimental error had led him to the conclusion of a positive charge).

6. Later developments

Soon after Zeeman had moved to Amsterdam it became clear that conditions in the Amsterdam laboratory were unfavourable for further work on the Zeeman effect. The building was plagued so much by disturbing vibrations that only a fraction of the photographic exposures could be used. Thus, Zeeman missed the discovery of the anomalous effect [16] and had to turn to less sensitive experiments. He worked on related problems, such as magnetic double refraction and rotation of the plane of polarization, as well as the occurrence of asymmetries in intensity and position of the shifted lines. Only after 1923, when he had his own laboratory, built especially for precision experiments, did Zeeman return to spectroscopic precision work.

In order to establish the historical importance of the discovery of the Zeeman effect two aspects should be mentioned. First, of course, is its role in the confirmation of the existence of the electron. But secondly, and more importantly in the long run, the fact that the Zeeman effect, in combination with Lorentz's theory, provided a tool to probe the interior of atoms. (Since spectral lines have to do with an atom's interior, a change of frequency reflects a change of this internal structure.)

In the following decades, the importance of the Zeeman effect for theories of atomic structure was made clear time and again. In particular a satisfactory explanation of the anomalous effect was a crucial test for any quantum theory of atomic structure. The importance attached to the Zeeman effect in those years was summarized by Lorentz in 1923, when he said, speaking of the Zeeman effect and its theoretical difficulties:

Still, here too, gradually order was achieved, and as this succeeded it became clear, clearer even than ever before, that the study of the Zeeman effect is one of the most beautiful ways to explore the constitution of matter. [17]

Two years later, and almost thirty years after Zeeman's discovery, all forms of the Zeeman effect were finally explained through the introduction of the electron spin.

Appendix

Pieter Zeeman was born in 1865, in a small village in the Dutch province of Zeeland. He was the son of a protestant minister. After finishing secondary school, he continued his studies at the University of Leyden, where he specialized in physics and served as an assistant to the theoretician Hendrik Antoon Lorentz and to the experimenter Heike Kamerlingh Onnes. Zeeman wrote his dissertation under the guidance of Kamerlingh Onnes; it dealt with the experimental investigation of the Kerr effect. This work marks the start of Zeeman's interest in magneto-optical phenomena and fitted in an already-existing line of research in Leyden.

Not very long after the discovery of the Zeeman effect in the fall of 1896, Zeeman was appointed lecturer at the University of Amsterdam. He remained there until his retirement in 1935, rising from the position of lecturer to that of extraordinary, and later ordinary professor, and subsequently becoming director of the physics laboratory and then head of his own, specially created and designed laboratory. Zeeman received many honors, the most important of which was the Nobel Prize in 1902. He shared the prize with Lorentz for their work in magneto-optics. Zeeman died in 1943, in the middle of the Second World War.

Zeeman was an experimenter par excellence, whose work is in the first place characterized by extraordinary precision. He had a unique talent for designing precision experiments and performing them with great persistence. After his initial work on the Zeeman effect, he had to shift to different fields of research, because of the unfavourable conditions in the Amsterdam laboratory. After having worked on related topics, such as magnetic double refraction and the rotation of the plane of polarization in a magnetic field, he applied his talents to experimental relativity: first he repeated Fizeau's experiment with unprecedented accuracy, confirming the prediction of special relativity for the speed of light in moving media (in particular the occurrence of a dispersion term in the expression for the speed of light). A few years later, he investigated the equality of gravitational and inertial mass for anisotropic and radioactive materials, using a very sensitive torsion-balance. Toward the end of his career, he tried to observe the transverse Doppler effect and became involved in nuclear physics through his investigation of the hyperfine structure of spectral lines.

The Zeeman archive, discovered in 1989, provides much new material on all of Zeeman's work, in correspondence, scientific notes and laboratory notebooks. In addition, it gives much background information on Zeeman's personality. He emerges as a dedicated scientist, who was constantly looking for ways to apply his skills to new problems and kept a lively interest in current developments in physics. The wealth of archival material makes it possible to develop a detailed and balanced view of Zeeman's work and of his personality.

References

[1] The Zeeman Archive is kept in the Rijksarchief in Noord-Holland (Haarlem). Items from the archive are referred to with the abbreviation ZA, followed by a number and, if necessary, a page number. See also the appendix for more information on the archive.

[2] For more details on the research in the Leyden laboratory, see *Het Natuurkundig Laboratorium der Rijks-Universiteit te Leiden in de jaren 1882–1904* (Leiden: IJdo).

[3] Kamerlingh Onnes H 1921 *Physica* **1** 241

[4] Zeeman P 1896 *Versl. Kon. Ak. Wet.* **5** 181
Zeeman P 1897 *Phil. Mag.* **43** 226 (Engl. transl.)

[5] Zeeman P to Kamerlingh Onnes H, 31 July 1891 (ZA 82)

[6] Niven W D (ed) *The Scientific Papers of J Clerk Maxwell* vol 2 (Cambridge: Cambridge Unversity Press) p 786

[7] ZA 313, p 63

[8] ZA 506

[9] Zeeman P 1897 *Versl. Kon. Ak. Wet.* **6** 13
Zeeman P 1897 *Versl. Kon. Ak. Wet.* **6** 99

[10] Van der Waals J D Jr 1935 *Pieter Zeeman 1865–25 Mei–1935* ('s Gravenhage: Nijhoff) p 1

[11] Zeeman P 1928 *De Gids* **22** 105

[12] ZA 313

[13] Zeeman P 1896 *Versl. Kon. Ak. Wet.* **5** 242

[14] Lodge O to Zeeman P 26 February 1897 (ZA 101)

[15] Zeeman P to Lodge O 1 March 1897 (ZA 101)

[16] In the anomalous Zeeman effect, discovered in 1898, a splitting in more than three components is observed.

[17] Lorentz H A 1925 *Physica* **5** 73

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Hale Discovers Strong Magnetic Fields in Sunspots

The discovery of strong magnetic fields in sunspots by George Ellery Hale in the early twentieth century marked a significant advancement in solar research. Building upon observations initiated by Galileo in the seventeenth century, Hale utilized innovative instruments like the spectroheliograph to study sunspots in greater depth. In 1908, he identified the Zeeman effect—splitting of spectral lines caused by magnetic fields—in the spectrum of sunlight, which indicated the presence of intense magnetic fields associated with sunspots. His findings revealed that these magnetic fields were strongest at the center of sunspots and varied in strength across their surface.

Hale's work not only confirmed the existence of extraterrestrial magnetic fields but also provided a framework for applying terrestrial electromagnetic theories to cosmic phenomena. This contributed to a broader understanding of the Sun's overall magnetic properties and the implications for solar activity, including how these magnetic fields could affect Earth's environment. The significance of Hale's discovery extends to modern astronomy, as understanding solar magnetic fields is crucial for predicting solar flares and their potential impact on technology and human life on Earth.

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By: Hrovat, Mary

Hale Discovers Strong Magnetic Fields in Sunspots

Date June 26, 1908

George Ellery Hale discovered that magnetic fields are associated with sunspots, giving astronomers valuable information about the formation of sunspots.

Locale Mount Wilson, California

Key Figures

George Ellery Hale (1868-1938), American astronomer
Pieter Zeeman (1865-1943), Dutch physicist
Henry Augustus Rowland (1848-1901), American physicist

Summary of Event

In the seventeenth century, Galileo first observed dark spots on the surface of the Sun with a small telescope. Since that time, astronomers have invented new ways to observe the Sun and have used these new methods to learn more about what causes the spots and other features of the Sun. In the early twentieth century, George Ellery Hale developed several solar-observing instruments and used them to determine that the dark spots on the Sun exist in an intense magnetic field. This discovery fueled further research and theorizing about the nature and causes of the spots and about the magnetic fields of the Sun in general.

In 1908, Hale observed the solar disk with a special instrument he had developed called the spectroheliograph. This instrument worked essentially by filtering the light of the Sun so that the Sun's various surface features, such as sunspots, could be viewed in the light of one particular wavelength. This was useful for studying the processes going on in the Sun, because each wavelength represents a particular atomic process in a particular type of atom.

When Hale observed the Sun in a wavelength coming from hydrogen atoms, he noted the very interesting fact that there appeared to be huge swirls of hydrogen gas resembling a terrestrial storm or tornado. These "vortices" seemed to be associated with the formation of sunspots. Hale considered what the consequences of this rotating motion might be. Research by the English physicist Joseph John Thomson had shown that hot bodies emit electrons, and, as the Sun is very hot, Hale thought that perhaps the Sun was emitting electrons, which, if caught up in this whirling motion, might create a magnetic field in the sunspots. (Henry Augustus Rowland had proven earlier that a moving electric charge acts magnetically in the same way as an electric current. Hans Christian rsted had discovered earlier that electric currents affect magnets, and electromagnetic theory explains that electric currents produce a magnetic field.)

Hale had a way to check this hypothesis. A star's spectrum (the pattern of bright light and dark lines that results when the star's light is passed through a prism or reflected from a grating) can reveal much about the temperature of the star's constituent gases, the velocity of its rotation, and other information. In 1896, Pieter Zeeman discovered that if a source of light is placed in a magnetic field, the lines in the spectrum of the light source will be split into two or more components. Zeeman discovered this phenomenon (known as the Zeeman effect) in the laboratory, but it proved valuable in deducing even more information from a star's light. When Hale learned of the Zeeman effect, he conducted laboratory work of his own to observe what the effect looked like in certain test cases.

He carried out observations of light from an iron arc (or spark) from other sources and recorded much diversity in the splitting of the spectral lines from the different materials. Some lines split into two parts, some into three, and one even into twenty-one components. Once he had this information, he was ready to compare any observed splitting behavior in solar spectral lines to the laboratory results; if there was a magnetic field associated with sunspots, he could expect a close match between the solar line splitting and the laboratory line splitting. Each dark line in the spectrum represents a particular element undergoing a particular process; therefore, Hale could recognize and identify solar elements by the distinctive wavelengths of light at which their characteristic dark lines appeared in the spectrum.

Because the Sun is much closer and thus much brighter to the earth than other stars, its spectrum can be photographed and examined in greater detail than can be done for other stars. The Sun emits light at many wavelengths, each associated with a different color of light. White light is seen from the Sun because the colors of these many wavelengths are all blended and viewed together; to spread the light back into its separate colored components, one must use a prism or finely spaced grating. With enough care and effort, it is possible to spread the light and observe detail in the dark lines.

Hale expended much care and effort in building a 60-foot (18-meter) tower telescope on Mount Wilson. This tower had mirrors on the top to catch the Sun's light and reflect it through a telescope lens down to a spectrograph about 30 feet (9 meters) underground. At the spectrograph, the light was spread out into a spectrum. Because the mirrors that collected the sunlight were high above the ground and were fairly thick, they were not subjected to as much distortion from the Sun's heat as previous solar telescopes had been, and the height of the mirrors also helped to avoid some of the warm air currents near the ground. The underground room where the final image was obtained had a nearly constant temperature, thus avoiding possible air currents caused by changes and differences in air temperature. Moving air and warped mirrors distort and muddy the images obtained from telescopes, so the net result of all these precautions was to produce an image that was unusually steady and sharp compared with previous images from solar telescopes.

Hale used this tower telescope to observe the Sun's spectrum and its surface and, in particular, to search for the Zeeman effect of splitting of lines in the Sun's spectrum. A doubling of certain lines in the spectrum had been observed previously, but this result had been misinterpreted at the time and no one, until Hale, had been able to observe the lines with sufficient precision to arrive at other ideas about why they appeared split.

Hale, an energetic and active man, spent much of the summer of 1908 running up and down the ladder of the telescope tower in the course of his work. He was fortunate in having a period of clear skies during the second half of June, 1908, which enabled him to spend much of his time observing. On June 26, 1908, Hale observed a doubling of spectral lines that he thought was caused by the Zeeman effect. He was greatly excited and immediately compared his observations of the Sun with his laboratory observations of the effect. He found a correlation between the two sets of observations. For the first time, an extraterrestrial magnetic field had been detected and related to laboratory observations. Hale wanted to be absolutely certain of his discovery, so he continued to make observations for two more weeks. By July 6, he was confident that what he had found was indeed the

Zeeman effect, indicative of magnetic fields in sunspots. Zeeman considered Hale's results and agreed that Hale's hypothesis was the best explanation for the observed phenomena. Astronomers in general were impressed by Hale's results and excited about the possibilities they raised for further study of the Sun's magnetic properties.

Significance

One important effect that Hale's discovery had on astronomers was that it enabled them to extend their application of the relatively new field of electromagnetic theory to the cosmos at large. Astronomers work by understanding processes that can be observed on earth and applying them in the heavens. With Hale's discovery, astronomers realized that they could apply their knowledge of terrestrial magnetic and electric phenomena to the distant stars; this gave them a new tool to use.

Zeeman had found—in addition to the fact that spectral lines split in the presence of a magnetic field—that the distance between the components of the split line is directly proportional to the strength of the magnetic field causing the split. Hale measured the separations in lines split in the laboratory by a magnetic field of known strength, measured the separations in split lines in the spectrum of a sunspot, and derived the strength of the sunspot's magnetic field. He found impressively large magnetic fields. Also, Hale was able to study how the strength of the field varied at different places in a sunspot; he discovered that the magnetic field is strongest at the center and weakest toward the edges. This finding has implications for what the structure of a sunspot might be like.

Hale then turned his attention to the question of whether the Sun has an overall magnetic field in addition to the fields associated with sunspots. Although Hale worked at this question periodically for the rest of his life, he was never able to answer it. Later astronomers not only determined that the Sun has a magnetic field overall but also learned how this field changes over the Sun's twenty-two-year sunspot cycle, how the field is affected by the Sun's rotation, and the role that the field has in sunspot formation and other types of solar activity. Magnetic fields have poles (like the north and south poles of magnets), and astronomers have worked on discovering the polarity of the Sun's magnetic field. Understanding the Sun's magnetic properties has been crucial in understanding the Sun's activity.

Another question Hale considered was whether the magnetic fields associated with sunspots could be strong enough to cause magnetic storms on Earth. Hale was not in a position to answer this question, given that he would have needed records on both solar and terrestrial magnetic events over a period of time. The question, however, indicates why the study of the Sun is important to astronomers. Sunspots are associated often with energetic events on the Sun's surface, which can send charged particles and energetic radiation out into space to interact with the earth's atmosphere. This interaction can cause benign phenomena such as the aurora borealis, or northern lights, and it can also interfere with terrestrial communications systems. In the future, the radiation from solar flares could prove hazardous to inhabitants of long-term space colonies. Astronomers are interested in studying the magnetic processes that drive sunspot and flare formation because of the effects of these phenomena on humans.

Bibliography

Bhatnagar, Arvind, and William Livingston. *Fundamentals of Solar Astronomy*. Hackensack, N.J.: World Scientific Publishing, 2005. Presents a history of solar astronomy and then discusses basic methods and techniques used in the field. Provides information that amateur astronomers can use to build simple solar telescopes. Includes glossary, bibliography, and index.

Kaufmann, William J. *Discovering the Universe*. New York: W. H. Freeman, 1987. Intended as a textbook for an introductory descriptive course on astronomy, this volume discusses Hale's discovery and considers other solar features as well as sunspots and the role that magnetic fields play in these features. Includes photographs and drawings as well as various study aids, such as chapter summaries, review questions, and a glossary.

Mitton, Simon, ed. *The Cambridge Encyclopedia of Astronomy*. New York: Crown, 1977. Includes a section on sunspots that discusses Hale's participation in discovering the role that magnetic fields play in sunspots and other solar disturbances. Discusses current ideas on solar magnetism. Includes many photographs and drawings, as well as a brief physics primer at the end of the book that gives a concise overview of the magnetic and hydrodynamic facts used to explain solar activity.

Noyes, Robert W. *The Sun, Our Star*. Cambridge, Mass.: Harvard University Press, 1982. Describes Hale's discovery of the magnetic field in sunspots as well as his work with the spectroheliograph and discusses the Sun and its magnetic properties. Intended for both scientists and nonscientists. Includes photographs, drawings, and graphs.

Struve, Otto, and Velta Zebergs. *Astronomy of the Twentieth Century*. New York: Macmillan, 1962. Coauthor Struve witnessed some of the astronomical events this book covers. Contains a chapter on the Sun that discusses Hale's work and its implications for theories of solar magnetic fields and their effects. Discusses the growth of the solar observing facilities at Mount Wilson.

Wentzel, Donat G. *The Restless Sun*. Washington, D.C.: Smithsonian Institution Press, 1989. Discusses the Zeeman effect and gives a thorough presentation of current views on the Sun's magnetic field. Includes diagrams, drawings, and black-and-white photographs. Presents a good discussion of solar physics, written for the nonscientist.

Wright, Helen. *Explorer of the Universe: A Biography of George Ellery Hale*. 1966. Reprint. Melville, N.Y.: American Institute of Physics Press, 1994. Drawing heavily on letters and diaries written by the participants in the events described, this engaging book is an excellent source for the story of Hale's discovery of the magnetic field associated with sunspots. Includes drawings and photographs of sunspots and solar spectra as well as bibliographies.

Wright, Helen, Joan N. Warnow, and Charles Weiner, eds. *The Legacy of George Ellery Hale: Evolution of Astronomy and Scientific Institutions, in Pictures and Documents*. Cambridge, Mass.: MIT Press, 1972. Relying heavily on photographs and original documents, this collection of material on Hale's astronomical work

includes the text of an address Hale gave in 1909, "Solar Vortices and Magnetic Fields." Also valuable for the letters, photographs, and newspaper clippings about Hale and his work.

Related Topics

George Ellery Hale   Magnetic field   Physicist   Electric charge   Pieter Zeeman   Radiation

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On the discovery of the zeeman effect on the sun and in the laboratory

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Abstract

The origin of the discoveries, both on the Sun and in the laboratory, of the action of a magnetic field on spectral lines—the so-called Zeeman effect—is studied. The paper embraces the period from 1866, first date of which the author is aware of observed evidences about the widening of spectral lines in sunspots (as compared to those formed in the photosphere), until 1908, year in which the magnetic filed in sunspots is definitely discovered. The interval between 1896–1897, and 1908 is mainly dealt with from an astrophysical standpoint, although there are plenty of important contributions from laboratory experiments. The reason is two-fold: on the one hand, the significant role played by the Zeeman effect on the development of quantum mechanics has suggested major historical studies that have already appeared in the literature and that are mainly concerned with laboratory—but not with astrophysical—spectroscopy; on the other hand, the understanding of the sizeable delay between Zeeman's and Hale's discoveries (12 years) seems to be of concern after accounting for the fact that the findings by the first author were soon brought to the notice of the astrophysical community.

References (58)

J.S. Ames *et al.*
Astrophys. J. (1898)

H. Becquerel *et al.*
Comptes Rendus (1898)

A. Cornu
Comptes Rendus (1897)

A. Cornu
Comptes Rendus (1898)

A.L. Cortie
M. Notices R. Astron. Soc. (1886)

A.L. Cortie
M. Notices R. Astron. Soc. (1898)

A.L. Cortie
M. Notices R. Astron. Soc. (1902)

A.L. Cortie
M. Notices R. Astron. Soc. (1903)

P.A.M. Dirac

M. Faraday

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