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Chromospheric Magnetism

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Abstract. Magnetic fields have been measured using chromospheric spectrum lines since Hale's discovery of magnetic fields in sunspots. This is a brief selective review of the history of research on chromospheric magnetism, including some of the key results and future prospects. The topic is challenging both from the observational and analysis perspectives, but major advances on both fronts have recently invigorated this research area. Selected recent results are highlighted with some emphasis on results from NSO. One notable result is that the chromosphere has large areas with predominantly horizontal magnetic field and these areas have structural, dynamical and radiative properties that are different from the quiet Sun, sunspots, plages and filaments and deserve more study. The near term prospects are bright for improved understanding of chromospheric magnetism.

1. Introduction

The chromosphere is an important part of the Sun. It is the place where dominance of the physics passes from hydrodynamic to magnetic forces. Thus, it has long been a goal of solar physics to understand the nature of the chromosperic magnetic field. Indeed, Hale's first published measurements of solar magnetic fields contain not only photospheric but also chromospheric field values (Hale 1908b). Measuring the chromospheric magnetic field is fraught with difficulty. Besides being a region of transition from physical control by hydrodynamic to magnetic forces, the chromosphere consists of strong spatial gradients of density, temperature, and radiative opacity. It is also highly dynamic, containing shocks, wave motions and explosions. There are many traps for the unwary. In spite of these dangers, the literature on the subject is currently growing by more than 100 papers per year as indicated in Fig. 1. The annual production shows roughly exponential growth at a rate of about 20% per year from a very low base in 1960 until the late 1970s. The growth rate from then until 2000 was roughly 3% per year. Since 2000, new interest in the field increased the annual rate to roughly 10%. The first two rates may be compared with 8.6% and 3.8% for the number of papers published in five major astronomical journals over the same periods (Abt 1998). This indicates vigor for this difficult field that exceeds astronomy in general. This shortened version of an oral review is not an attempt to survey all of the literature, but is a highly selected overview of some of the

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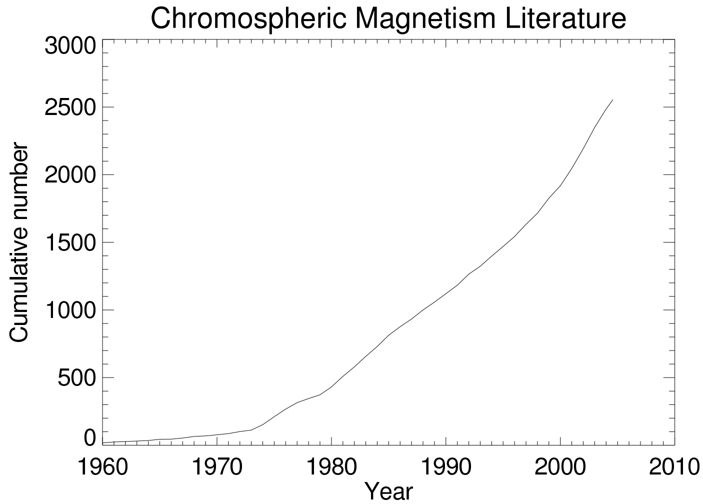

Figure 1. Cumulative number of research papers about chromospheric magnetism. Note recent acceleration. (Source: ADS.)

history, current results and prospects for the future. In this paper, prominences are included as part of the chromosphere. A recent review with emphasis on diagnostic techniques was presented by Trujillo Bueno & Manso Sainz (2002). Relevant reviews have also been given by Raouafi (2005) and Lagg (2005).

2. Historical Overview

2.1. Early Work on the Chromosphere and Solar Magnetic Fields

Research about the chromosphere and magnetic fields were separate topics until the early part of the 20th century. Some key events in the history of the observation of the chromosphere are listed in Table 1. It is cautionary that Flamsteed used Stannyar's report to promote the idea that the features seen at total eclipse were manifestations of a lunar atmosphere rather than solar in origin.

Similarly, significant events in the early history of solar magnetic fields are listed in Table 2. It is interesting that Kepler speculated that the Sun had a magnetic field. He required a force to keep the planets moving in their orbits in pre-Newtonian times and thought that a magnetized Sun could provide the force.

2.2. Chromospheric Magnetic Field Studies

The study of chromospheric magnetism started when Hale (1908a,b) saw vortex-like structure of the chromosphere which stimulated him to look for and discover the Zeeman effect in sunspot spectra. Table 3 provides a selected chronology of studies of chromospheric magnetism up to about 1980.

Around 1980, the state of knowledge about the chromospheric magnetic field was meager. It was widely accepted, but not definitely proven, that chromospheric fine structures were aligned along the magnetic field direction. Measurements in sunspot umbrae indicated that the field strength decreased from

Table 1. Notable events in early studies of the chromosphere

Year	Event	Reference
1706	First clear description at eclipse	Stannyar (Flamsteed 1706)
1842	Named 'sierra'	Airy (1853)
1860	First photographs at eclipse	de la Rue (1860), Secchi (1861)
1868	Named 'chromosphere'	Lockyer (1868)
1869	Start of open slit observations	Huggins (1869)
1889	First spectroheliograph observations	Hale (1892)
1892	Discovery of H & K network	Hale (1892)
1908	First Hα images; vortex hints	Hale (1908a)

Table 2. Notable events in early studies of solar magnetism

Year	Event	Reference
1609	Sun is magnetized	Kepler (1609)
1866	Widened and split lines in sunspot spectra	Lockyer (1866)
1889	Magnetic model of coronal structure	Bigelow (1889)
1896	Zeeman effect discovered	Zeeman (1897)
1908	Hα vortex suggests magnetism	Hale (1908a)
1908	First observation of sunspot fields	Hale (1908b)
1924	Discovery of Hanle effect	Hanle (1924)

Table 3. Some events in early studies of chromospheric magnetism

Year	Event	Reference
1908	Weaker sunspot field in D and b lines	Hale (1908b)
1934	Hα linear polarization in prominences	Lyot (1934)
1956	Theory of line formation in a spectrum line	Unno (1956)
1958	Hα field measured in a sunspot	Severny & Bumba (1958)
1961	Hβ field measured in a prominence	Zirin (1961)
1961	D_1 and H_3 magnetograms in active regions	Stepanov (1961)
1963	Hα filter magnetograms of active regions	Harvey (1963)
1964	Hα Hanle field in a prominence	Hyder (1964)
1966	Zeeman measurements in quiescent prominences	Rust (1966)
1969	Zeeman measurements in active prominences	Harvey (1969)
1970	10830 Å magnetograms of active regions	Harvey & Hall (1971)
1970	First full-disk 5183 Å magnetogram by Livingston	Giovanelli (1980)
1974	Weak CaII magnetic fields mapped	Giovanelli & Jones (1982)
1977	D_3 Hanle fields measured in quiescent prominences	Leroy (1977)
1982	Atomic alignment-orientation transfer described	Landi Degl'Innocenti (1982)

the photosphere to the chromosphere at a rate of 0.2 to 6 G km^{-1}. It was obvious that active region and network magnetic fields were spatially more diffuse and generally weaker than the underlying photospheric fields (see Fig. 2). The canopy effect had been discovered and implied that the field around active regions spread outward surprisingly rapidly with height (see Fig. 3). Fields had been measured in many quiescent prominences and found to be between about 3 and 15 G in strength, horizontally oriented and sheared along the axis of the prominence. Active region prominences had field strengths less than 200 G.

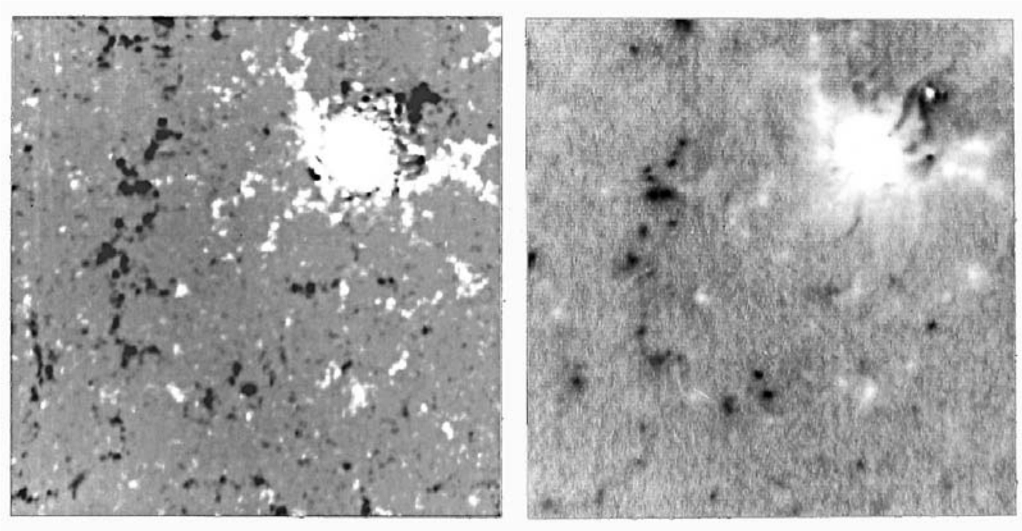

Figure 2. Line-of-sight component magnetograms near disk center on September 9, 1974. *Left:* Photospheric level (8688 Å). *Right:* Chromospheric level (8542 Å). Note weaker and more diffuse fields in the chromosphere. (NSO observation by W. Livingston and J. Harvey.)

3. A Quarter Century of Advances

Since the early to mid-1980s, there have been great advances in observational and analysis techniques that have led to major improvements in our knowledge of chromospheric magnetism.

3.1. Observation and Analysis

Today's high-resolution observing techniques have revolutionized solar research. Observation of the chromosphere is no exception. Figure 4 shows a spectacular pair of images of the chromosphere that leave little doubt that chromospheric fibrils and spicules trace the magnetic field. This was suspected from Hale's day but these observations easily support the case. Note, however, that we still lack definite proof that the features follow the field. Nor do we know the structure of the field where there is no chromospheric material to trace it. Such morphological information is valuable in understanding the organization of the field direction in the chromosphere.

Full Stokes spectro-polarimetry is the main way of measuring chromospheric magnetic fields. Crucial to such measurements are a telescope large enough to collect sufficient photons to get good signal-to-noise ratios and either a low-polarization configuration or an excellent calibration of the polarization modification characteristics of the telescope in order to recover the polarization state of the incoming light. Several telescope systems have been built to do this job; one example is the SOLIS vector spectromagnetograph (VSM; Keller et al. 2003). Equally important to recent observational improvements has been implementation of high efficiency 2D detectors. These have high quantum efficiency, large numbers of pixels, and architectures that permit rapid readout.

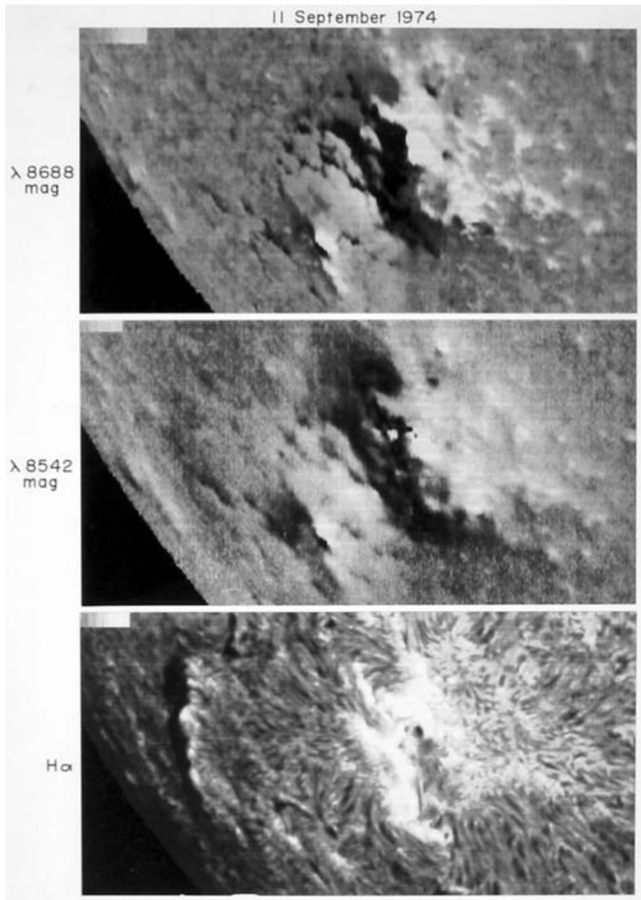

Figure 3. Line-of-sight component magnetograms near the limb on September 11, 1974. *Upper:* Photospheric level (8688 Å). *Middle:* Chromospheric level (8542 Å). *Lower:* Hα intensity image. Note large areas of diffuse fields in the chromosphere surrounding the active regions that correspond with Hα fibrils. (NSO observation by W. Livingston and J. Harvey.)

The astonishing advances in computer capabilities have enabled sophisticated data reduction methods that could only be dreamed of a decade ago. But, perhaps the most important advance in understanding chromospheric magnetism has been better knowledge of radiative transfer in magnetized chromospheric plasma. Excellent introductions to this topic were presented by Trujillo Bueno et al. (2005a,b). A monograph on the subject was published by Landi Degl'Innocenti & Landolfi (2004). It is obvious that the best observations are not very useful without a correct understanding of how the polarized spectra were produced by a magnetic field. For example, early measurements of the Zeeman effect in prominence emission lines neglected important radiative processes (then unknown) that seriously compromised the interpretation of the measurements.

Besides morphology and Stokes polarimetry applied to both absorption and emission lines, microwave radio techniques have been applied to observations of the chromospheric magnetic field based on the birefringence of the chromosphere

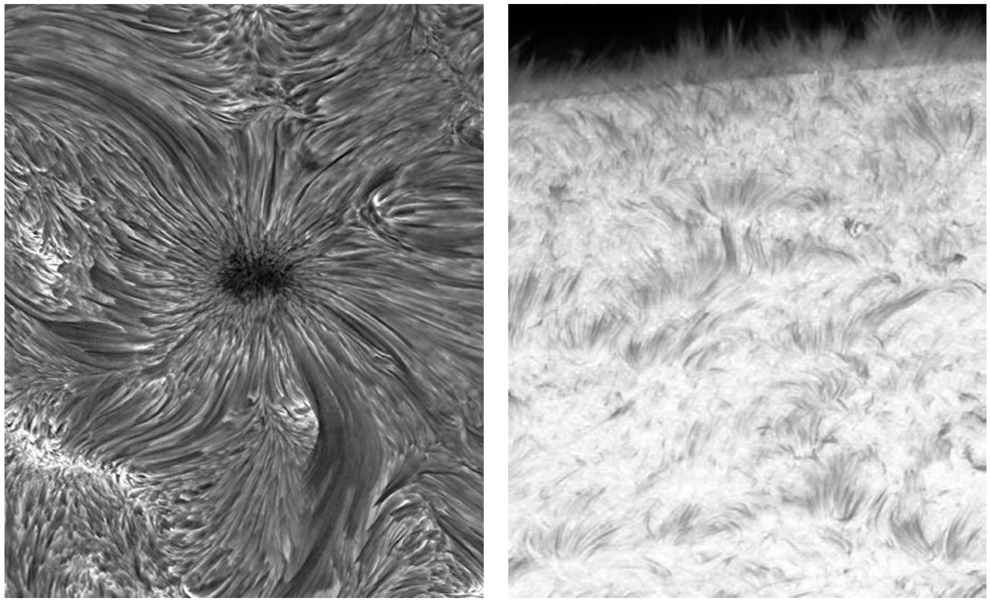

Figure 4. Morphology of the chromospheric magnetic field may be inferred from observations such as these. *Left:* Hα core image near a sunspot showing long fibrils. *Right:* Hα wing image near the limb showing spicules apparently tracing magnetic fields emanating from network magnetic concentrations. (Observations made with the Dutch Open Telescope.)

in a magnetic field at frequencies $> 2\,\mathrm{GHz}$. A detailed description of the method was given by Grebinskij et al. (2000) and it will not be discussed further here.

Another emerging technique is based on the effect of a chromospheric magnetic field on f- and p-mode oscillations. Expected modifications of the frequencies, amplitudes and phases of the oscillations due to a chromospheric field were calculated in the 1980s (e.g., Roberts & Campbell 1988). Recently, oscillation observations were used to map the chromospheric magnetic field (Finsterle et al. 2004).

Today, the chromospheric magnetic field is being regularly observed at several observatories: Huairou, Mt. Wilson, NSO/SOLIS, Mees, Crimea, and Kanzelhöhe. Campaign observation can and are being made at these and most other solar observatories.

3.2. Selected Recent Results

A major task for contemporary solar research is to understand the structure and dynamics of the magnetic field in the corona where space weather is spawned. While this is being tackled observationally using radio and optical spectropolarimetric methods, the faintness of the corona is a major impediment. The tool most commonly used is to extrapolate observations of the photospheric magnetic field outward into the corona and heliosphere. Present methods require that the field be force-free and this is manifestly untrue in the photosphere. It has been argued that the field is much more likely to be force free in the chromosphere and one should use chromospheric measurements as the basis of

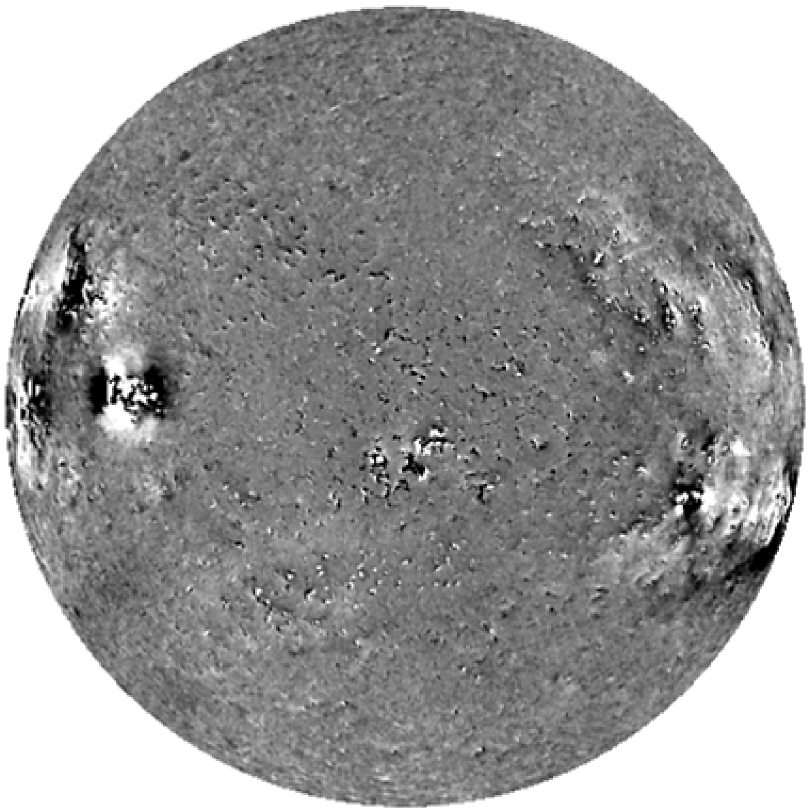

Figure 5. A full-disk NSO SOLIS/VSM image of the difference between the line-of-sight components of the photospheric and chromospheric magnetic fields using the 8542 Å line. Note large areas of diffuse fields in the chromosphere surrounding active regions near the limb.

extrapolations. Metcalf et al. (1995) measured the net Lorentz force in the photosphere and low chromosphere and concluded that the field did not become force free until a height of about 400 km above the photosphere. This is an important result but, we note that in practice, extrapolations based on photospheric and chromospheric measurements do not disagree with each other very much.

The critical importance of proper treatment of radiative transfer in magnetized chromospheric spectrum lines has been demonstrated many times. While important everywhere in the chromosphere, it is particularly significant in the case of prominences (see Brown, López Ariste, & Casini 2003). Polarization of these spectrum lines is caused not only by the Zeeman effect but also by scattering modified by the Hanle effect. While circular polarization may be mainly due to the former, linear polarization is almost always due to the latter (note, however, the existence of zero-field dichroism in some lines (Manso Sainz & Trujillo Bueno 2003). Having two or more mechanisms producing polarization may complicate the analysis of observations but also provides the benefit of additional diagnostic power. For example, López Ariste et al. (2005) report observations of Stokes-V profiles of the Hα line in prominences that are symmetric

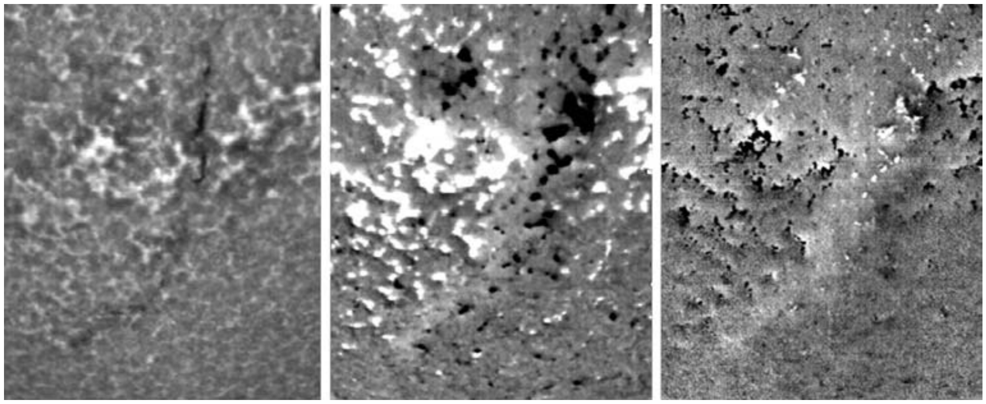

Figure 6. *Left:* A portion of a full disk chromospheric magnetogram showing the core intensity of the 8542 Å line. Note the dark filament channel and some fragments of filaments near the top. *Center:* Longitudinal Zeeman effect around the core of the line showing the chromospheric magnetic field (saturates at ± 15 G). *Right:* Same as center but the photospheric field has been subtracted to emphasize the chromospheric component. Note the diffuse field lying along the filament channel. (NSO SOLIS/VSM observation.)

but with an amplitude stronger than can be explained by the atomic alignment-to-orientation transfer mechanism in a magnetic field. They speculate that an electric field may explain the anomaly. On the other hand, Ramelli et al. (2005) found only one weak example of a Stokes Hα prominence spectrum dominated by a symmetric V profile. Clearly, this is an active research area.

With the strong caveat about the dangers of partial polarimetry and simple interpretations just discussed, many observations of the line-of-sight component of the chromospheric magnetic field exist. These reveal some interesting properties of the field not seen in the underlying photosphere. For example, we use the Ca II 8542 Å line with the SOLIS VSM and an algorithm that simultaneously extracts the longitudinal Zeeman components from the nearly photospheric wing of the line and from the chromospheric line core and also allows for local variations of the line profile shape. In such observations we see near disk center that the network fields are, as expected, stronger in the photosphere. However, beyond about 0.5 radius, the chromospheric background fields become stronger approaching the limb. This is a clear indication that the field spreads rapidly with height and forms small canopies around network elements. The next most prominent difference, illustrated in Fig. 5, is existence of large areas of diffuse, horizontally oriented field in the chromosphere surrounding active regions and sometimes extending many tenths of a solar radius. This is a manifestation of vast canopies associated with active regions. These areas are associated with fibrils and different radiative and dynamic behaviors, and are a part of the solar atmosphere that is unlike the quiet Sun, plages, sunspots, or filaments and deserve more study (Harvey 2005). A time series study of these diffuse fields as the Sun rotates and changes our view of them to different orientations shows that that they are predominantly horizontal, but with azimuthal orientations that often deviate from simple radial projection from the active region and that the basic pattern lasts 2–3 rotations.

Another interesting chromospheric phenomenon is the presence of diffuse, horizontally oriented magnetic fields along some filament channels. One of these is illustrated in Fig. 6. Little is known about these structures but they should help to distinguish among different models of prominences.

4. Outlook and Conclusion

After nearly a century of research on chromospheric magnetism, much has been discovered but much remains to be learned. This is a hard research area that is not for the timid. We know that it is dangerous to draw conclusions from any observations short of complete Stokes spectro-polarimetry analyzed taking into account both the Zeeman effect and scattering polarization including the atomic alignment-orientation transfer mechanism. New observations and analyses are being done with increasing frequency. In September 2006, plans are to launch the Solar-B satellite, which contains focal-plane instrumentation that will allow the chromospheric magnetic field to be measured with a narrowband filter using the Mg I b line at 5173 Å and the Na I D_2 line at 5896 Å with a resolution of about 300 km (Shimizu 2004). There are plans to fly a balloon around Antarctica in 2006/7 (Sunrise) with a grating spectrograph (Sunrise Polarimetric Spectrograph, SUPOS) that is intended to produce Stokes spectro-polarimetry with the chromospheric Mg II k line with a stated resolution of about 35 km! Exciting and rewarding times lie ahead.

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References

Abt, H. A. 1998, PASP, 110, 210
Airy, G. B. 1853, Mem.Roy.Astro.Soc., 21, 2
Bigelow, F. H. 1889, The Solar Corona Discussed by Spherical Harmonics (Washington, D.C.: Smithsonian Inst.)
Brown, A., López Ariste, A., & Casini, R. 2003, Solar Phys., 215, 295
de la Rue, W. 1860, J.Photo.Soc.London, 6, 296
Finsterle, W., Jefferies, S. M., Cacciani, A., Rapex, P., & McIntosh, S. W. 2004, ApJ, 613, L185
Flamsteed, J. 1706, Phil.Trans., 25, 2240
Giovanelli, R. G. 1980, Solar Phys., 68, 49
Giovanelli, R. G., & Jones, H. P. 1982, Solar Phys., 79, 267
Grebinskij, A., Bogod, V., Gelfreikh, G., Urpo, S., Pohjolainen, S., & Shibasaki, K. 2000, A&AS, 144, 169
Hale, G. E. 1892, Astron.Astroph., 11, 407
Hale, G. E. 1908a, ApJ, 28, 100
Hale, G. E. 1908b, ApJ, 28, 315

Hanle, W. 1924, Z.Phys., 30, 93
Harvey, J. W. 1963, S&T, 26, 196
Harvey, J. W. 1969, Ph.D. Thesis, Univ. of Colorado, Boulder, Colorado, U.S.A.
Harvey, J. W. 2005, EOS Trans. AGU, 86(18), 490
Harvey, J., & Hall, D. 1971, IAU Symp. 43, Solar Magnetic Fields, 279
Huggins, W. 1869, Proc.Roy.Soc., 17, 302
Hyder, C. L. 1964, ApJ, 140, 817
Kepler, J. 1609, Astronomia Nova, transl. by W. H. Donahue, 1992, Johannes Kepler New Astronomy (Cambridge: Cambridge Univ.), 385
Keller, C. U., Harvey, J. W., & SOLIS Team 2003, in ASP Conf. Ser. Vol. 307, Solar Polarization 3, ed. J. Trujillo Bueno & J. Sánchez Almeida (San Francisco: ASP), 13
Lagg, A. 2005, in ESA SP-596, Proc.Intl.Sci.Conf. Chromospheric and Coronal Magnetic Fields, ed. D. E. Innes, A. Lagg, S. K. Solanki & D. Danesy (Noordwijk: ESA), CD
Landi Degl'Innocenti, E. 1982, Solar Phys., 79, 291
Landi Degl'Innocenti, E., & Landolfi, M. 2004, Polarization in Spectral Lines (Dordrecht: Kluwer)
Leroy, J. L. 1977, A&A, 60, 79
Lockyer, J. N. 1866, Proc.Roy.Soc., 15, 256
Lockyer, J. N. 1868, Proc.Roy.Soc., 17, 131
López Ariste, A., Casini, R., Paletou, F., Tomczyk, S., Lites, B. W., Semel, M., Landi Degl'Innocenti, E., Trujillo Bueno, J., & Balasubramaniam, K. S. 2005, ApJ, 621, L145
Lyot, B. 1934, Compt.Rend., 198, 250
Manso Sainz, R., & Trujillo Bueno, J. 2003, Phys.Rev.Lett, 91, 111102-1
Metcalf, T. R., Jiao, L., McClymont, A. N., Canfield, R. C., & Uitenbroek, H. 1995, ApJ, 439, 474
Ramelli, R., Bianda, M., Trujillo Bueno, J., Merenda, L., & Stenflo, J. O. 2005, in ESA SP-596, Proc.Intl.Sci.Conf. Chromospheric and Coronal Magnetic Fields, ed. D. E. Innes, A. Lagg, S. K. Solanki & D. Danesy (Noordwijk: ESA), CD
Raouafi, N.-E. 2005, in ESA SP-596, Proc.Intl.Sci.Conf. Chromospheric and Coronal Magnetic Fields, ed. D. E. Innes, A. Lagg, S. K. Solanki & D. Danesy (Noordwijk: ESA), CD
Roberts, B., & Campbell, W. R. 1988, in ESA SP-286, Seismology of the Sun and Sun-like Stars, ed. E. J. Rolfe (Noordwijk: ESA), 311
Rust, D. M. 1966, Ph.D. Thesis, Univ. of Colorado, Boulder, Colorado, U.S.A.
Secchi, A. 1861, AN, 54, 35
Severny, A. B., & Bumba, V. 1958, Observatory, 78, 33
Shimizu, T. 2004, in ASP Conf. Ser. 325, The Solar-B Mission and the Forefront of Solar Physics, ed. T. Sakurai & T. Sekii (San Francisco: ASP), 3
Stepanov, V. E. 1961, Izv.Krim.Astrofiz.Obs., 25, 174
Trujillo Bueno, J. & Manso Sainz, R. 2002, Nuovo Cimento, 25C, 783
Trujillo Bueno, J., Landi Degl'Innocenti, E., Casini, R., & Martínez Pillet, V. 2005a, in ESA SP-588, Trends in Space Science and Cosmic Vision 2020, ed. F. Favata & A. Gimenez (Noordwijk: ESA), CD
Trujillo Bueno, J., Landi Degl'Innocenti, E., Casini, R., & Martínez Pillet, V. 2005b, in ESA SP-596, Proc.Intl.Sci.Conf. Chromospheric and Coronal Magnetic Fields, ed. D. E. Innes, A. Lagg, S. K. Solanki & D. Danesy (Noordwijk: ESA), CD
Unno, W. 1956, PASJ, 8, 108
Zeeman, P. 1897, Phil.Mag., 43, 226
Zirin, H. 1961, AZh, 38, 861