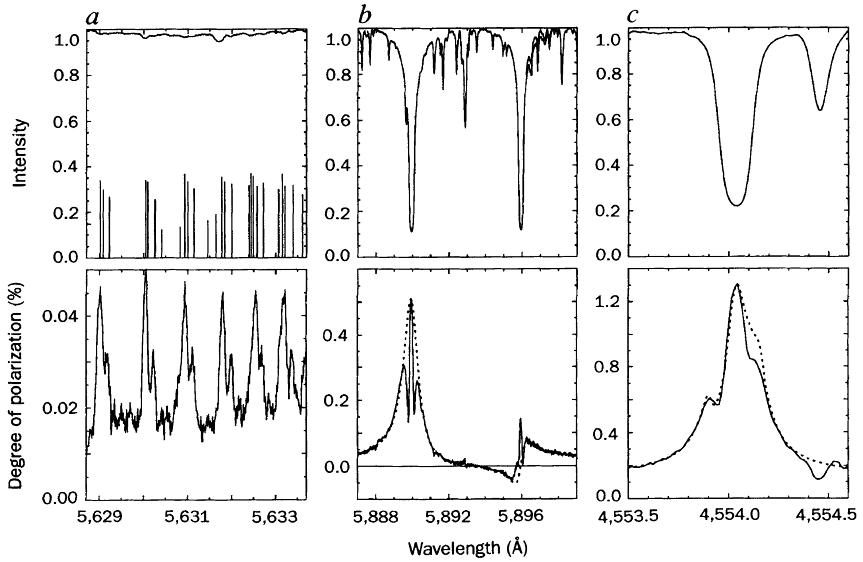
New window for spectroscopy

SIR — We have developed an imaging polarimeter system that can routinely record the Sun's spectrum with a precision of 10^{-5} in the degree of polarization. At this level, the whole solar spectrum is linearly polarized, even in the absence of any magnetic fields, due to coherent scattering processes in the solar atmosphere. The linearly polarized spectrum has a structural richness that is comparable to and often exceeds that of the ordinary, unpolarized spectrum. Not only is its appearance different, but it is shaped by quite different physical processes, as we illustrate below. We call it the "second solar spectrum", because it is as if the Sun has presented us with an entirely new spectrum to explore.

Our CCD (charge-coupled-device)-based polarimeter system, called ZIMPOL, uses piezoelastic modulation at 42- and 84-kHz rates and demodulates the signals within the CCD sensor by shifting the charges back and forth between the illuminated and hidden buffer image planes in synchrony with the fast modulation[1–5]. This procedure eliminates the two main noise sources due to effects of atmospheric seeing and the variable CCD pixel sensitivities. As the polarimetric noise is then limited only by photon statistics, we achieve a polarimetric accuracy of 10^{-5} when ZIMPOL is used in combination with the solar telescope that has the largest photon-collecting area in the world, the McMath-Pierce facility of the National Solar Observatory (Kitt Peak, United States).

The second solar spectrum contains a wealth of unexpected spectral features that are signatures of different physical processes. Here we illustrate a few: molecular scattering, quantum interference, hyperfine structure and isotope effects. These effects are best studied close to the solar limb, where the polarization amplitudes are the largest because of the favourable scattering geometry.



Examples of molecular scattering, quantum interference and hyperfine structure in the second solar spectrum (degree of linear polarization). *a*, C_2 lines; *b*, Na I D_2 and D_1; *c*, Ba II 4,554 Å. Recordings have been made with the spectrograph slit parallel to and 5 arcsec inside the north polar limb of the Sun. Positive polarization means that the electric vector is parallel to the nearest solar limb; negative polarization refers to the perpendicular direction. Bars in the left intensity diagram give the wavelengths and relative intensities of C_2 lines from laboratory data[7]. Theoretical, dotted curves in the middle and right polarization panels have been obtained from quantum-mechanical calculations with superposition of the contributions from the lines and continuum in proportion to their opacities.

Molecular lines like those of the C_2 molecule (*a* in the figure) are prominent in the polarized spectrum although they are almost invisible in the ordinary intensity spectrum. Because their behaviour critically depends on where in the Sun the molecules can form, the polarization amplitudes can be used as a new, sensitive temperature and pressure diagnostic for the solar atmosphere.

Quantum-mechanical interference between states with different J quantum numbers was first discovered in the solar spectrum for the H and K lines of ionized calcium at 3,965 and 3,933 Å (ref. 6). The Na I D_2–D_1 lines illustrated here (*b* in the figure) provide a particularly clean example of this type of interference, while presenting us with new puzzles. Like in the double-slit experiment when each 'photon' has to pass both slits at the same time, each Na I scattering process has to go through both excited $J=3/2$ and 1/2 states 'at the same time'.

The interference between the scattering amplitudes gives rise to sign reversals of the linear polarization around the D_1 line. Although the gross features of the overall polarization curve can be theoretically modelled, it has not yet been possible to explain the narrow polarization peaks at the two resonant frequencies. Although the narrow D_1 peak would require an atomic-physics explanation outside our current theoretical framework, the D_2 peak may have an explanation largely in terms of partial frequency redistribution coupled to polarized radiative transfer, although this needs to be worked out. In any case, the full explanation of the Na I D_1–D_2 system is likely to lead to new insights in both atomic physics and radiative-transfer physics.

The Ba II 4,554-Å line (*c* in the figure) has contributions from various isotopes. The atomic levels of the odd isotopes are subject to hyperfine structure splitting, due to coupling between the electronic angular momentum and the nuclear spin. Our theoretical modelling shows that the polarization components in the blue- and red-line wings come from the hyperfine structure components of the odd isotopes, while the central component is due to the even isotopes. The theoretical fit is sensitive to isotope abundances.

The second solar spectrum will be important in exploring the nature of solar magnetic fields via the Hanle effect. Much of the magnetic flux on the Sun is in a tangled, turbulent state, with mixed polarities within each spatial resolution element. Although such a field is invisible to ordinary Zeeman-effect polarimetry owing to cancellation effects within the resolution elements, such cancellations do not occur for Hanle depolarization effects in the second solar spectrum. The differential Hanle effect in combinations of spectral lines provides us with a new diagnostic window for the exploration of magneto-turbulence.

J. O. Stenflo
Institute of Astronomy ETH Zentrum, CH-8092 Zurich, Switzerland
C. U. Keller
National Solar Observatory, PO Box 26732, Tucson, Arizona 85726-6732, USA

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