Selective absorption processes as the origin of puzzling spectral line polarization from the Sun

J. Trujillo Bueno*§, E. Landi Degl'Innocenti†, M. Collados*, L. Merenda*‡ & R. Manso Sainz†*

** Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain*
† Dipartimento di Astronomia e Scienza dello Spazio, Università di Firenze, Largo E. Fermi 2, I-50125 Firenze, Italy
‡ Dipartimento di Fisica, Università di Trento, Via Sommarive 14, I-38050 Povo, Italy
§ Consejo Superior de Investigaciones Científicas, E-28006 Madrid, Spain

Magnetic fields play a key role in most astrophysical systems, from the Sun to active galactic nuclei[1–3]. They can be studied through their effects on atomic energy levels, which produce polarized spectral lines[4,5]. In particular, anisotropic radiation 'pumping' processes[6,7] (which send electrons to higher atomic levels) induce population imbalances that are modified by weak magnetic fields[8,9]. Here we report peculiarly polarized light in the He I 10,830-Å multiplet observed in a coronal filament located at the centre of the solar disk. We show that the polarized light arises from selective absorption from the ground level of the triplet system of helium, and that it implies the presence of magnetic fields of the order of a few gauss that are highly inclined with respect to the solar radius vector. This disproves the common belief[4,10,11] that population imbalances in long-lived atomic levels are insignificant in the presence of inclined fields of the order of a few gauss, and opens up a new diagnostic window for the investigation of solar magnetic fields.

The Zeeman effect and optical pumping are two mechanisms capable of inducing polarization signals in the spectral lines that originate in the outer layers of stellar atmospheres.

The Zeeman effect[12] requires the presence of a magnetic field, which causes the atomic energy levels to split into different magnetic sublevels. This splitting produces local sources and sinks of light polarization because of the ensuing wavelength shifts of transitions between levels. The Zeeman effect is most sensitive in circular polarization, with a magnitude that scales with the ratio between the Zeeman splitting and the width of the spectral line (which is very much larger than the natural width of the atomic levels). This so-called longitudinal Zeeman effect responds to the line-of-sight component of the magnetic field. In contrast, the transverse Zeeman effect responds to the component of the magnetic field perpendicular to the line of sight, but produces linear polarization signals that are normally negligible for magnetic strengths $B < 100$ G.

Anisotropic radiation pumping[6,7] produces atomic level polarization—that is, population imbalances and quantum interferences between the sublevels of degenerate atomic levels (Fig. 1). The presence of a magnetic field is not necessary for the operation of such optical pumping processes, which can be particularly efficient in creating atomic polarization if the depolarizing rates from elastic collisions are sufficiently low. As clarified below, the mere presence of atomic polarization of the type illustrated in Fig. 1 implies local sources and sinks of linear polarization. The Hanle effect[8,9] (Fig. 1) modifies the atomic polarization of the unmagnetized reference case, and gives rise to a complicated magnetic field dependence of the linear polarization of the scattered light, which is being increasingly applied as a diagnostic tool for weak magnetic fields in astrophysics.

It is often assumed that the observable effects of atomic polarization of long-lived atomic levels are strongly suppressed by Hanle depolarization in the presence of solar magnetic fields that are highly inclined with respect to the solar radius and have strengths in the gauss range[4,10,11]. As some of the many 'enigmatic' signals of scattering polarization that have been observed within the edge of the solar disk[13–15] have been shown to be due to ground state atomic polarization[9,16,17], and because milligauss (or weaker) magnetic fields are believed to be very rare in the highly conductive solar plasma, it has been concluded that the field must be oriented fairly close to the radial direction wherever the signatures of lower-level atomic polarization are observed[11]. Although this conclusion is probably valid for the observations of scattering polarization in the Na I D_1 line[16], it should not be generalized to all cases in which the signatures of lower-level atomic polarization are observed. Moreover, the observable effects of lower-level atomic polarization, whether the Hanle effect destroys or creates linear polarization signals in spectral lines, depend on the scattering geometry. To clarify the situation, it is necessary to investigate carefully to what extent observable effects of the atomic polarization of long-lived

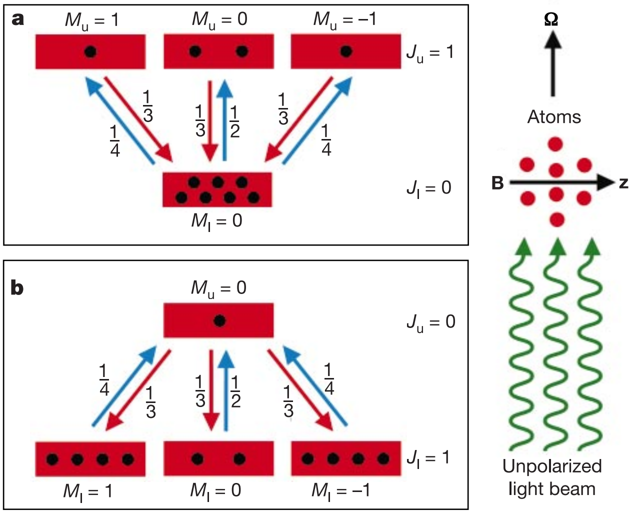

Figure 1 Anisotropic radiation pumping and the Hanle effect. An unpolarized radiation field can induce population imbalances and quantum interferences (or coherences) between the sublevels of degenerate atomic levels (that is, atomic polarization) if the illumination of the atomic system is anisotropic. For example, upper-level population pumping occurs when some upper-state sublevels have more chance of being populated than others (**a**). On the contrary, lower-level depopulation pumping occurs when some lower-state sublevels absorb light more strongly than others (**b**). We note that line transitions between levels having other total angular momentum values (for example, $J_l = J_u = 1$ or with $J_l = 1$ and $J_u = 2$) permit the transfer of atomic polarization between both levels via repopulation pumping (for example, lower-level atomic polarization can result simply from the spontaneous decay of a polarized upper level). The Hanle effect is the modification of the atomic polarization of degenerate atomic levels caused by the action of a magnetic field such that its corresponding Zeeman splitting is comparable to the inverse lifetime (or natural width) of the degenerate atomic level under consideration. For the Hanle effect to operate, the magnetic field vector (**B**) has to be significantly inclined with respect to the symmetry axis (**Ω**) of the pumping radiation field. The formula used to estimate the maximum magnetic field intensity B (in G) to which the Hanle effect can be sensitive is $10^6 B g \approx 1/t_{\rm life}$, where g and $t_{\rm life}$ are, respectively, the Landé factor and the lifetime (in seconds) of the given atomic level. In a reference frame whose z-axis (that is, the quantization axis of total angular momentum) is parallel to the direction of **B**, the population imbalances turn out to be insensitive to the magnetic field, while the coherences are reduced and dephased as the magnetic strength is increased. This so-called magnetic field reference frame is the one we have chosen here while visualizing the induced population imbalances for the 'strong field' case (that is, the case for which the coherences are negligible). We note that the atomic polarization of a given atomic level depends sensitively on the complexity of the assumed atomic model.

atomic levels can not only survive partial Hanle destruction but also even be enhanced by horizontal magnetic fields in the gauss range.

Such investigations can be performed in magnetized astrophysical plasmas, such as those in solar prominences and filaments. These features are relatively cool and dense ribbons of plasma embedded in the 10^6 K solar corona. The ribbons are thought to be confined by the action of highly inclined magnetic fields with strengths in the gauss range[18]. Prominences and filaments are in fact the same phenomenon but observed in different circumstances. Both prominences and filaments absorb the photons from the underlying solar photosphere, and re-emit them in all directions. But prominences are observed outside the visible outer edge of the Sun (that is, against the dark background of the sky), while filaments are the same types of structures observed against the bright background of the solar disk. Therefore, we see emission lines in prominences, but absorption lines in filaments.

Figure 2 contrasts prominences and filaments, and illustrates our theoretical prediction concerning the expected linear polarization of a line transition with $J_\mathrm{l} = 1$ and $J_\mathrm{u} = 0$, where J_l and J_u are the angular momentum quantum numbers of the lower and upper level, respectively. In fact, there are two mechanisms by means of which atomic level polarization can generate linear polarization signals in spectral lines: the first is due to the emission process (that is, to the atomic polarization of the upper level), while the second is subtly related to the absorption process (that is, to the atomic polarization of the lower level). In general, the first mechanism (caused exclusively by the spontaneous emission events that follow the anisotropic radiative excitation) is the only one that is taken into account[4,10,11,14,19]. The role played by the atomic polarization of the lower level in producing linear polarization via the absorption process[20] has never been considered seriously.

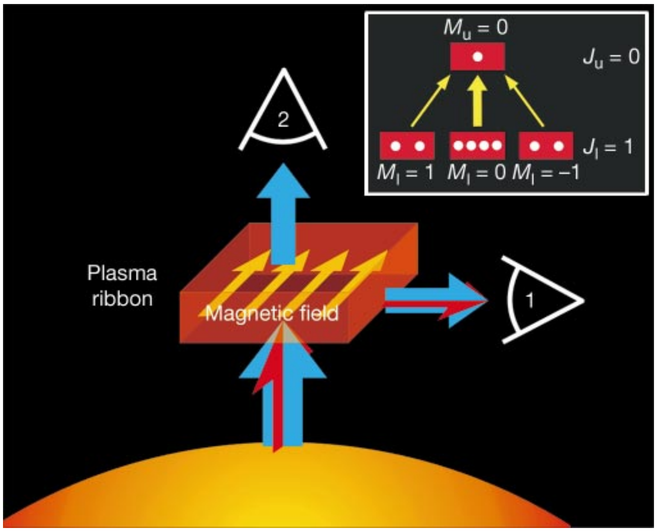

Figure 2 The solar prominence case versus the solar filament case. In a prominence located in the plane of the sky at a given distance above the visible outer edge of the Sun we see the result of 90° scattering events, whereas in a filament situated exactly at the centre of the solar disk we see the result of forward-scattering events. This figure illustrates these two cases by considering observations of a magnetized plasma ribbon using polarimeters at positions 1 (the prominence case) and 2 (the filament case). The figure refers exclusively to the 'blue' line of the He I 10,830-Å multiplet, which is a line transition with $J_\mathrm{l} = 1$ and $J_\mathrm{u} = 0$. As the upper level cannot carry any atomic polarization, the spontaneously emitted radiation which follows the anisotropic radiative excitation is virtually unpolarized. For this reason, the observer at position 1 sees that the fluorescently scattered beam is unpolarized. However, if the lower level is polarized as indicated in the inset, then the transmitted beam seen by the observer at position 2 will have an excess of linear polarization perpendicular to the direction of the horizontal magnetic field, simply because the $\Delta M = 0$, or π transitions, absorb more efficiently than the $\Delta M = \pm 1$, or σ transitions. This selective absorption mechanism[20] is called dichroism because the plasma is behaving as a dichroic medium (that is, the absorption coefficient in the line transition depends on the polarization of the radiation). We note that repopulation pumping is important in polarizing the ground level of the triplet system of He I, as our calculations are based on a realistic multiterm atomic model and not on the two-level model atom considered in Fig. 1. This is why the lower-level polarization shown in the inset is different from Fig. 1b. So for $1 \rightarrow 0 \rightarrow 1$ scattering processes we expect to observe virtually zero linear polarization in optically thin prominences, but a sizeable linear polarization signal in filaments if a significant amount of lower-level atomic polarization is present.

We have observed the intensity and polarization of the He I 10,830-Å multiplet in a variety of solar prominences and filaments using the Tenerife Infrared Polarimeter[21] attached to the Vacuum Tower Telescope[22]. This multiplet originates between a lower term (2^3S_1) and an upper term $(2^3P_{2,1,0})$. Therefore, it has three spectral lines[23]: a 'blue' line at 10,829.09 Å (with $J_\mathrm{l} = 1$ and $J_\mathrm{u} = 0$), and two 'red' lines at 10,830.25 Å (with $J_\mathrm{u} = 1$) and at 10,830.34 Å (with $J_\mathrm{u} = 2$) which appear blended at the plasma temperatures of prominences and filaments. As explained in Fig. 2 legend, detection of a significant linear polarization signal in the 'blue' line ($J_\mathrm{l} = 1$ and $J_\mathrm{u} = 0$) would be due to the atomic polarization of the lower level with $J_\mathrm{l} = 1$. We note that this lower level is metastable—that is, it is a relatively long-lived atomic level whose atomic polarization is vulnerable (via the ground level Hanle effect[24,9]) to magnetic fields of very low intensity ($\sim 10^{-3}$ G).

We first consider prominences. The data points in Fig. 3 show the four Stokes parameters observed in a prominence. As expected from the theoretical prediction of Fig. 2, the 'blue' line of the He I 10,830-Å multiplet does not show any significant linear polarization, which implies that this particular prominence has a very small optical thickness along the line of sight. However, there are very significant Stokes *Q* and *U* signals around the wavelengths of the blended 'red' components. These linear polarization signals are the observational signature of the atomic polarization of the upper levels with $J_\mathrm{u} = 2$ and $J_\mathrm{u} = 1$. Note that there are sizeable circular polarization signals in both the 'blue' and 'red' components. They are the result of the longitudinal Zeeman effect. Their detection is essential for the determination of the intensity of the magnetic field because for fields larger than only a few gauss the He I 10,830-Å multiplet enters into the saturated Hanle effect regime for the upper level, where the linear polarization signals are sensitive only to the orientation of the magnetic field vector.

The solid lines in Fig. 3 show the results of our theoretical modelling, taking into account the influence of ground-level polarization. From the fit to the observation we infer a magnetic field of about 40 G, inclined at 31° to the radial direction through the observed point. The dotted lines in Fig. 3 show what happens if we carry out the calculation with this magnetic field vector, but assuming a completely unpolarized ground level. In the present prominence case, the significant difference with respect to the solid-line calculation is solely the result of the feedback that the existing ground-level polarization is producing on the atomic polarization of the upper levels with $J_\mathrm{u} = 2$ and $J_\mathrm{u} = 1$. We note that a magnetic field diagnostic of solar prominences that neglects the influence of ground-level polarization would imply a significant error ($\sim 10°$) in the field orientation and in the magnetic strength (of a few gauss).

We now turn our attention to filaments. The data points in Fig. 4 show the observed Stokes parameters in a solar filament that was situated exactly at the centre of the solar disk on 2 June 2001. We selected this coronal filament to demonstrate that linear polarization signals can be produced even at the very centre of the solar disk where we meet the forward scattering case. As seen in the figure, the 'blue' line now shows a very significant linear polarization signal with a negative Stokes *Q* amplitude, which is of the same order of magnitude as the positive Stokes *Q* amplitude observed in the 'red' blended component. The observed linear polarization signals are

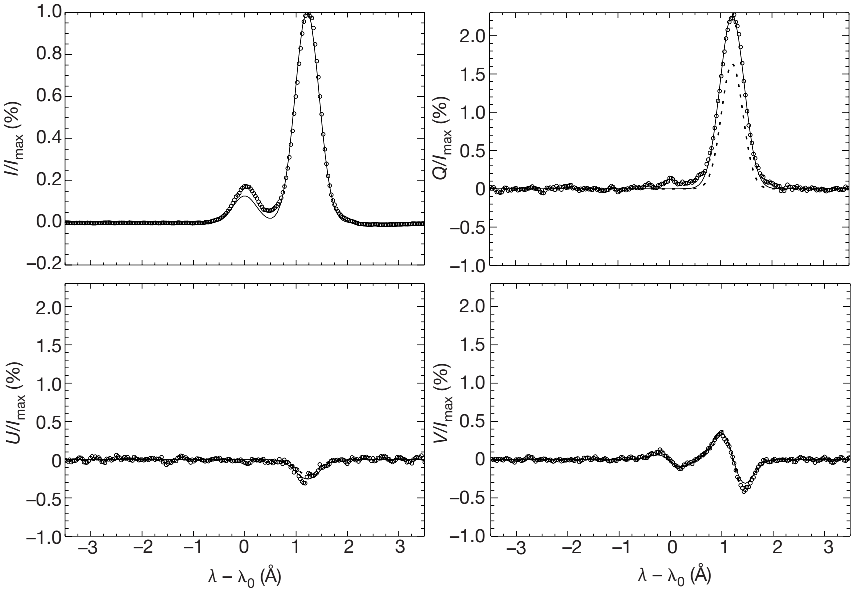

Figure 3 Prominence case: observation versus theory. Spectropolarimetric observation of a solar prominence (circles) versus theoretical modelling taking into account the influence of ground-level atomic polarization (solid line) or neglecting it (dotted line). Our modelling assumes that the He I atoms, lying at a given height (*h*) above the solar photosphere, are illuminated by an unpolarized and spectrally flat radiation field. It is based on the quantum theory of the generation and transfer of polarized radiation[25,26], which we have applied describing the He I atoms in the incomplete Paschen-Back effect regime[27]. The Stokes *I*-parameter quantifies the total intensity of the observed light, the Stokes *Q* and *U* parameters represent the degree of linear polarization along two reference axes that form an angle of 45° between them, while Stokes *V* quantifies the degree of circular polarization[28]. The observed prominence region had a projected height on the plane of the sky of 20″ over the visible edge of the solar disk (that is, $h \approx 15{,}000$ km). The fit to the observations was done assuming a magnetic field vector with intensity $B = 40$ G, inclination $\theta_B = 31°$, and azimuth $\chi_B = 176°$. Note that $\lambda_0 = 10{,}829.09$ Å is the line centre wavelength of the 'blue' component of the He I 10,830-Å multiplet. The positive reference direction for Stokes *Q* is perpendicular to the solar radius vector through the observed point. The Stokes profiles are normalized to the maximum line-core intensity of the 'red' emission line. For this particular geometry of scattering, the determination of the magnetic field is ambiguous. The alternative determination $B = 40$ G, $\theta'_B = 180° - \theta_B = 149°$, $\chi'_B = -\chi_B = -176°$, gives the same theoretical curve.

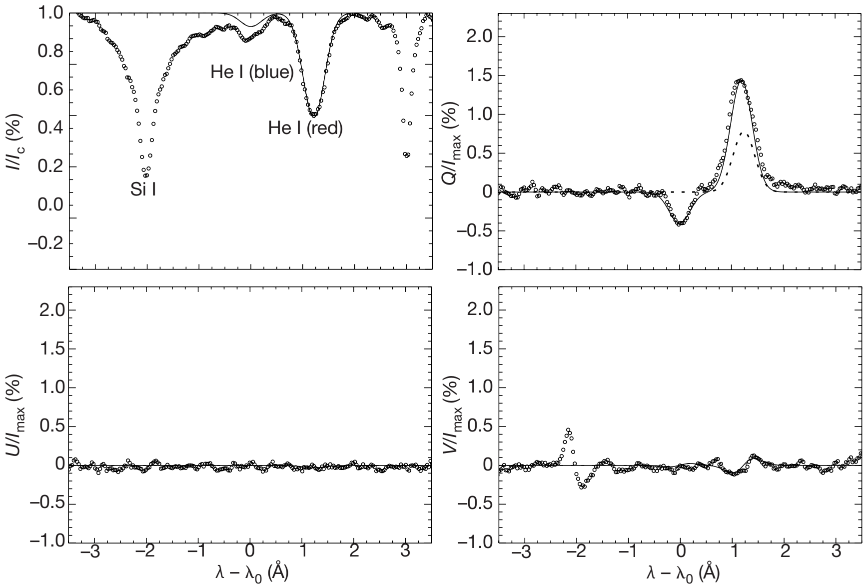

Figure 4 Filament case: observation versus theory. Spectropolarimetric observation of a solar filament located at the disk centre (circles) versus theoretical modelling taking into account the influence of ground-level atomic polarization (solid line) or neglecting it (dotted line). Our choice for the positive reference direction of the observed Stokes *Q* parameter is the one which minimizes Stokes *U*. The solid-line fit has been achieved assuming $B = 20$ G, $\theta_B = 105°$ and a height $h = 40''$ (that is, about 30,000 km) above the solar surface. The positive reference direction for the theoretical Stokes *Q* profile is parallel to the projection of the magnetic field vector on the solar surface. Therefore, negative Stokes *Q* values indicate that the linear polarization of the observed beam is perpendicular to the magnetic field of the filament plasma, as illustrated in Fig. 2. The dotted line neglects the influence of ground-level polarization, but takes into account the (negligible) contribution of the transverse Zeeman effect. The Stokes *I* profile is normalized to the local continuum intensity, while Stokes *Q*, *U* and *V* are normalized to the maximum line-core depression (from the continuum level) of the Stokes *I* profile of the 'red' absorption line. The weakness of the Stokes *V* signal, which is caused by the longitudinal Zeeman effect, arises because the magnetic field vector is almost parallel to the solar surface. We note that, for the particular geometry of this observation, an ambiguity of 180° is present in the determination of the azimuth of the magnetic field vector.

entirely due to the Hanle effect operating at disk centre. This can be possible only if there exists a magnetic field with a significant inclination to the radial direction through the observed point, otherwise the polarization at disk centre would be zero for reasons of symmetry. The very existence of a sizeable Stokes Q signal in the 'blue' line demonstrates that the $^3S_1$ ground level is significantly polarized.

The solid line in Fig. 4 shows the result of our theoretical modelling of the Hanle effect at disk centre taking into account the influence of ground level polarization. From the fit to the observation we infer a magnetic field of 20 G, inclined by about 105° to the radial direction through the observed point and with a horizontal component at an angle of about 10° in the clockwise direction with respect to the axis of the filament. The agreement with the spectropolarimetric observation is notable. It demonstrates that the ground-level Hanle effect is operating in the outer solar atmosphere, producing very significant linear polarization signals by selective absorption from the unevenly populated magnetic sublevels of a long-lived atomic level.

Our results show that the atomic polarization of long-lived levels, which is induced by optical pumping processes, generates observable polarization signatures due to the highly inclined magnetic fields with strengths in the gauss range that are characteristic of solar prominences. Instead of destroying the atomic polarization, the magnetic fields produce (via the Hanle effect) linear polarization signals that are of the same order of magnitude as those caused by the atomic polarization of the short-lived excited states. Moreover, our results provide observational evidence of the operation of an atomic effect that may have diagnostic use in several astrophysical contexts. It concerns the creation of linear polarization signals in spectral lines induced by magnetic fields in forward scattering and by dichroism. These phenomena reveal unfamiliar aspects of the Hanle effect, and open up a new diagnostic window on the investigation of the magnetism of the outer solar atmosphere (chromosphere, transition region and corona). ☐

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Correspondence and requests for materials should be addressed to J.T.B.
(e-mail: jtb@ll.iac.es).

A laboratory analogue of the event horizon using slow light in an atomic medium

Ulf Leonhardt

School of Physics and Astronomy, University of St Andrews, North Haugh,
St Andrews, Fife KY16 9SS, UK

Singularities underlie many optical phenomena[1]. The rainbow, for example, involves a particular type of singularity—a ray catastrophe—in which light rays become infinitely intense. In practice, the wave nature of light resolves these infinities, producing interference patterns. At the event horizon of a black hole[2], time stands still and waves oscillate with infinitely small wavelengths. However, the quantum nature of light results in evasion of the catastrophe and the emission of Hawking radiation[3]. Here I report a theoretical laboratory analogue of an event horizon: a parabolic profile of the group velocity[7] of light brought to a standstill in an atomic medium[4–6] can cause a wave singularity similar to that associated with black holes. In turn, the quantum vacuum is forced to create photon pairs with a characteristic spectrum, a phenomenon related to Hawking radiation[3]. The idea may initiate a theory of 'quantum' catastrophes, extending classical catastrophe theory[8,9].

Optical media govern the propagation of light. Media are usually transparent substances such as glass or water, but empty yet curved space is a medium as well[10]. Certain material media can be manipulated to give them extraordinary optical properties. Inside such media light may propagate with a negative[11] or very low[12] group velocity[7], or may be brought to a standstill[4–6]. In a medium with electromagnetically induced transparency[13] (EIT), an external control beam dictates the group velocity v_g of a second and weaker probe beam, in order to slow down the probe light[4–6,12]. Once the first beam has gained control, the group velocity of the second beam is essentially proportional to the control intensity I_c, even in the limit when I_c vanishes[14].

Imagine that the control beam illuminates the EIT medium from above, see Fig. 1. Initially, the control intensity is uniform, but then