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Spectropolarimetry with new generation solar telecopes

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Abstract. Next generation solar telescopes will provide the possibility of performing solar observations at unprecedented levels of spectral, spatial, and tempoarl resolution, combined with very high polarimetric sensitivity. This talk will concentrate on the new diagnostic possibilities that will be opened by these telescopes to the solar scientific community, with particular emphasis on the diagnostics of the magnetic field vector. Also, I will discuss the ultimate limitations due to the pysical complexity of the solar atmosphere and to radiative transfer effects.

Key words. Sun: atmosphere – Sun: sunspots – Sun: turbulence

1. Introduction

In the near future large aperture telescopes will be available to the community of solar physicists. Just in these days (November 15, 2012), the National Solar Observatory has announced the start of construction for the Advanced Technology Solar Telescope (ATST) at the Haleakalā High Altitude Observatory site. ATST has been funded by the National Science Foundation, and, with its 4 m clear aperture, it will be the world's most powerful solar observatory for some years from now. Quoting the same words of the announcement: "ATST is poised to answer fundamental questions about the basic processes which govern variations in solar activity. It will provide a revolutionary new window on the solar magnetic atmosphere and will be the primary scientific tool for understanding the impacts of variations in the solar output on the Earth's climate. Solar astronomers will use ATST to understand what causes solar eruptions and provide the knowledge necessary to develop space weather forecasting, necessary for protecting or mitigating the potentially devastating societal and economic impacts of solar flares and mass ejections on the nation's space assets, the power grid and communication systems".

Another large aperture telescope, the European Solar Telescope (EST) is presently in its Conceptual Design Study, financed by the European Commission. It involves at the moment 29 partners plus 9 collaborating institutions from 15 different countries. The project, promoted by the European Association for Solar Telescopes (EAST), foresees the construction of a 4-meter class solar telescope that will be located in the Canary Islands. It will be optimised for studies of the magnetic coupling between the deep photosphere and the upper chromosphere. This will require diagnostics of the thermal, dynamic and magnetic prop-

Send offprint requests to: E. Landi Degl'Innocenti erties of the plasma over many scale heights, by using multiple wavelength imaging, spectroscopy and spectropolarimetry. To achieve these goals, EST will specialize in high spatial and temporal resolution using instruments that can efficiently produce two-dimensional spectral information.

The approval by the financing agencies of the ATST project, and of the EST conceptual design study, has been an important success of the american and european communities of solar physicists.These achievements have been made possible by the work of several colleagues who have widely investigated the observing strategies of solar phenomena on which the availability of high spatial resolution can bring important contributions. Several documents have been prepared, like e.g. the document "Science goals of the ATST" where one can find a detailed list of possible applications of large aperture telescopes on the main "hot points" of solar physics, namely: 1. Origin and generation of magnetic fields; 2. Magnetic activity and magnetic instabilities; 3. Chromospheric and coronal structuring and heating; 4. Sun and earth climate. However, to prepare solar physicists to the challenges of high spatial resolution, it is also important to stress some basic physical points which will inevitably come into play when large aperture solar telescopes will be available. These are analyzed in the following.

2. Limitations due to photon counting

When speaking about high resolution observations of the solar atmosphere it is always important to recall which are the limitations connected with the size of the telescope and with the transparency of the optical train spanning from the primary mirror to the final point, where photons are detected.

Suppose you want to perform an observation of a detail of the solar atmosphere. The target of your observation is a square "element of surface" of side Δx that is observed for a time interval Δt . Also, you want to perform a spectral analysys of your target at the wavelength λ with resolution $\Delta\lambda$. With a telescope having aperture D and transparency $\mathcal{T}$, the number of photons, $N_{\rm phot}$ collected by the dectector is given by

$$N_{\rm phot} = \frac{\pi D^2}{4} I_\lambda \, \frac{\lambda}{h\,c} \, \Delta\lambda \, \Delta t \left(\frac{\Delta x}{a}\right)^2 \mathcal{T} \quad , \qquad (1)$$

where a is the astronomical unit and I_λ is the radiation field intensity coming from the target. For our purposes, we can suppose that I_λ is the fraction α of the Planck's law relative to the effective temperature of the sun. For an observation in the continuum $\alpha = 1$, but for an observation in the core of a strong spectral line, α can be as small as a few percent. For the number of photons we then have

$$N_{\rm phot} = \frac{\pi D^2}{2} \, \frac{c}{\lambda^4} \left[\exp\left(\frac{h\,c}{\lambda\, k_{\rm B}\, T_\odot}\right) - 1 \right]^{-1} \times \cap$$
$$\times \Delta\lambda \, \Delta t \left(\frac{\Delta x}{a}\right)^2 \alpha \mathcal{T} \;\; . \qquad (2)$$

Substituting the value $T_\odot$ = 5800 K, assuming for a typical observation λ = 5000 Å, $\Delta\lambda$ = 10 mÅ, and expressing Δx in arcsec, Δt in seconds and D in meters, one gets the following expression

$$N_{\rm phot} = 1.25 \times 10^9 \, D^2 \, \Delta x^2 \, \Delta t \, \alpha \, \mathcal{T} \quad . \qquad (3)$$

It is worth noticing that using the telescope at its maximum capabilities of angular resolution, remembering the well known expression for the resolving power of the telescope

$$R = 1.22 \, \frac{\lambda}{D} \quad , \qquad (4)$$

for the same values λ = 5000 Å, $\Delta\lambda$ = 10 mÅ, one finds the following result, independent of the aperture of the telescope

$$N_{\rm phot} = 1.98 \times 10^7 \, \Delta t \, \alpha \, \mathcal{T} \quad . \qquad (5)$$

These equations clearly show that the transparency of the telescope is very important, probably the most important quantity that has to be controlled in the design of the telescope. Needless to say that the transparency has to be kept as high as possible. Indeed, proceeding along this exercise on photon counting, and assuming that the measurement errors are just due to a Poisson distribution of counts, the relative error on a single observation, with the telescope used at its maximum resolving power, is given by

$$\epsilon = \frac{1}{\sqrt{N_{\rm phot}}} = 2.25 \times 10^{-4} \frac{1}{\sqrt{\Delta t\, \alpha\, \mathcal{T}}} \quad . \tag{6}$$

Due to the presence of multiple reflections and of post-focus instrumentation, (including adaptive optics, the spectrograph, and, for instance, polarimetric analysis), the transparency can hardly get larger than a factor 0.05 (1/20). Assuming this value as typical, one gets

$$\epsilon = 10^{-3} \frac{1}{\sqrt{\Delta t\, \alpha}} \quad . \tag{7}$$

For many spectropolarimetric observations, especially for the diagnostics of turbulent magnetic fields, it would be desirable to have observations with relative errors not larger than 10^{-4}. This implies an integration time, Δt, on the order of 100 s (or even more, depending on α), which may be too long to see transient phenomena. Of course this time interval can be decreased by degrading either the spectral or the spatial resolution, but one has always to keep in mind that, even with large aperture telescopes, compromises among the three different aspects of resolution (spatial, spectral, and temporal) can hardly be avoided.

3. Limitations due to radiative transfer

Irrespectively of how strong a line is (how large is its absorption coefficient) its "interval of formation in height", Δh, defined, for instance, as the distance between the points corresponding to τ=0.3 and τ=1.5, respectively, is given by

$$\Delta h \simeq H \quad , \tag{8}$$

where H is the pressure (or density) scale height, given by the usual expression

$$H = \frac{k_{\rm B}\, T}{\mu\, m_{\rm H}\, g_\odot} \quad , \tag{9}$$

$k_{\rm B}$ being the Boltzmann constant, μ the average molecular weight, $m_{\rm H}$ the atomic mass unity and $g_\odot$ the gravity at the solar surface. With the standard values (T = 5000 K, μ = 1.28, $g_\odot$ = 2.4×10^4 cm s^{-2}, one gets $H \simeq 130$ km.

Obviously, stronger lines form higher in the atmosphere while weaker lines, or the continuum, form at lower heights. The important thing to mention is, however, that, irrespectively of the wavelegth at which observations are performed, there is always an uncertainty in establishing the depth at which a spectral detail is formed. This uncertainty is on the order of the scale height H, a quantity that is a kind of "invariant", characteristics of the full photosphere (or chromosphere), something of the order of 100 km. Obviously, the scale height becomes larger (by more than two orders of magnitude) at coronal levels.

These limitations in establishing the depth at which a particular phenomenon is taking place can be partly overcome only by means of stereoscopic observations. The situation is somewhat better for establishing the position of the occurrence of a phenomenon on the plane of the sky, provided scattering effects do not play a major role.

4. Limitations due to the presence of turbulence

According to an apocryphal story, Werner Heisenberg was asked what he would ask God, given the opportunity. His reply was "When I meet God, I am going to ask him two questions: Why relativity? And why turbulence? I really believe that he will have an answer for the first". A similar witticism has been attributed to Horace Lamb (the author of one of the most wonderful books on Hydrodynamics). He is quoted saying, in a speech to the British Association for the Advancement of Science: "I am an old man now and when I die and go to heaven, there are two matters on which I hope for enlightment. One is Quantum Electrodynamics and the other is the turbulent motion of fluids. About the former I am rather optimistic...". Also, Nobel laureate physicist Richard Feynman called turbulence the most important unsolved problem of classical physics. Just to make an example, no one really understands precisely how the flow of a gas, or of a liquid, goes from smooth (or lam-

inar) to turbulent. Indeed, even in a physical situation as simple as the water flowing from a tap, the value of the velocity at which this happens is not yet known. All this is just to remind that our understanding of the physics of turbulence is still in a very preliminary phase. Yet, there is indeed something that we succeded in understanding about turbulence. Almost everything came out from laboratory experiments (Osborne Reynolds, Theodor von Kàrmàn), and, in some cases, by extraordinary intuitions mostly based on dimensional anlyses (Andrej Kolmogorov, Nikolai Obukhov, etc.). The problem with turbulence is that the basic equations that control the motion of fluids are perfectly known. There is no particular reason to think that something is missing, for instance, in the Navier-Stokes equation, or in the continuity equation, or to think that these equations are wrong. But we are capable of solving such equations only in rather schematic situations and, once the solutions are found, it is always very difficult to ascertain their stability against infinitesimal fluctuations. Moreover, when the analysis shows that the motion is unstable, nobody can predict what kind of motion really develops in the physical world.
What we know, in very general terms, is that turbulence develops at high Reynolds numbers. We recall here the definition

$$\mathrm{Re} = L\,V/\nu \ , \tag{10}$$

where L is the typical scale of the motion, V is the characteristic velocity, and ν is the kinematic viscosity coefficient ($\nu = \eta/\rho$). Referring, for instance, to the phenomenon of solar granulation, one can assume $L \simeq 1000$ km, $V \simeq 1$ km/s, $\nu \simeq 1$ m^2/s, thus getting extremely large Reynold numbers on the order of 10^9. Obviously we are falling in a regime where laboratory experiments are difficult, if not impossible, to perform, and even numerical similations cannot reach these high values of Re. Are the laws found by our ancient colleagues still valid? Can we still trust the Kolmogorov spectrum? Needles to say that the situation gets even more involved when we consider MHD turbulence, instead of "normal" turbulence.

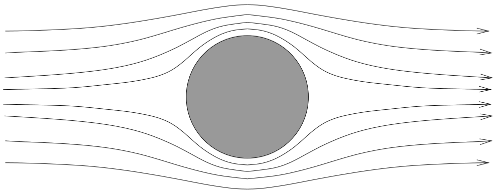

Fig. 1. A schematic view of a wind tunnel experiment. The ball is steady and the fluid flows from left to right with velocity V, For small values of the Reynolds numbers, the motion of the fluid around the ball is laminar.

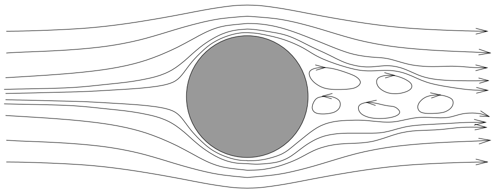

Fig. 2. Same as Fig. 1. For sufficiently high Reynolds numbers (Re > 1000), fully turbulent motions develop in the wake of the ball up to a distance on the order of one or two diameters from the back of the ball.

Even one of the most schematic cases of the development of turbulence, the wind-tunnel experiment on a spherical body (a ball), schematically depicted in Figs. 1 and 2, raises extremely difficult physical problems. Moreover, if one imagines to measure, by remote sensing, what is happening in the wake of the ball for the case of high Reynolds numbers one would derive a longitudinal velocity component (along the direction of the wind) which increases from 0 (just behind the ball) to V (the velocity of the wind in the tunnel), this value being reached at a distance from the ball on the order of one or two diameters. On the other hand, the lateral components (perpendicular to the wind) will be found to average to zero. One would then find, by remote sensing that the equation

$$\mathrm{div}\boldsymbol{V} = 0 \tag{11}$$

is violated. Obviously, however, nobody doubts that mass is conserved.... When studying the solar atmophere we are obliged to stik to remote sensing. We have no other way of discovering what is happening, of measuring the physical quantities that we are interested in (except for the possibilities that are opened by solar probes, like Solar Orbiter, that in any case have to remain sufficiently far away from the solar surface to avoid being destroied). The philosophy is that we have to learn how to use the high resolution observations that will be provided by our big telescopes. For instance, when "measuring" the magnetic field with a polarimeter, we have always to keep in mind that our "measurement" is nothing but a statistical average, over the resolution element, over the photon's free-path, and over the exposure time, of a quantity that, in typical cases, has even a chaotic behavior. It is not just a matter of averaging over space and time, it is also a matter of averaging over something that has an intrinsic chaotic behavior, that is not deterministic even if observed with infinite spatial resolution. As a paradigm case we can consider the measurements of magnetic fields in sunspots. A typical sunspot has lateral dimensions on the order of 10,000 km and, at the photospheric level, shows magnetic fields on the order of 1,000 G. The large value of the magnetic field allows a rather direct measurement by means of standard polarimetric observations, pionered by Hale (1908). Assuming for the magnetic field in the sunspot a kind of "funnel shaped" model, well confirmed by plenty of observations repeated for more than one century, one immediately derives that the order of magnitude of the derivative of the component, B_x, of the magnetic field with respect to the horizontal coordinate, x, is 0.1 G km^{-1}. More recently, many researchers have tried to obtain, by means of several different methods, an estimate of the vertical gradient of the vertical component of the magnetic field vector, B_z. The results obtained are indeed surprising since they show that the vertical gradient of the magnetic field is on the order of 1-4 G km^{-1} (Westendorp Plaza et al. (2001), Balthasar & Scmidt (1993), Pahlke & Wiehr (1990), Collados et al. (1994), Bruls et al. (1995), Mathew et al. (2003), Berlicki et al. (2006), Bommier et al. (2012)). These results have been obtained by different authors using different inversion techniques (SIR inversion, Unno-fit, response functions, contribution functions, forward modeling, etc.) and different spectral lines (including infrared ones). There is here an obvious problem, because the horizontal gradients of the horizontal component of $\boldsymbol{B}$ are systematically lower, by approximately one order of magnitude, with respect to the vertical gradients of the vertical component. In other words, observations show that

$$\left|\frac{\partial B_x}{\partial x}\right| \ll \left|\frac{\partial B_z}{\partial z}\right| \quad , \tag{12}$$

which seems to imply that in the umbrae of sunspots we have

$$\mathrm{div}\boldsymbol{B} \neq 0 \quad . \tag{13}$$

Obviously this does not imply that the umbrae of sunspots are harboring magnetic monopoles. Nobody would believe it. Much more prosaically we can coclude that

$$\mathrm{div}\boldsymbol{B}_{\mathrm{measured}} \neq 0 \quad , \tag{14}$$

and that we still have a long way to go before being capable of having a diagnostics of the magnetic field that we can really trust upon. I am almost sure that the soultion of this further mystery is strictly connected with turbulence and that high resolution observations will help us in solving these enigmas.

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