Scientific Requirements for Extremely Large Telescopes
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Spectropolarimetry with Extremely Large Telescopes

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Abstract. Spectropolarimetry has a broad spectrum of applications, for which there are mostly no substitute observing techniques. They range from the measurement of the strength and structure of magnetic fields via the detection of scattered light from sources obscured by high-density matter or lost in the glare of a nearby bright object to the possibility of individual corrections to the intrinsic luminosities of far-away Type Ia supernovae - and many more. First reconnaissance projects have succeeded with 10m-class telescopes. But the application and extension of the insights gained require substantially larger telescopes. An ELT would in particular enable studies of the formation of structure (AGNs, γ-ray bursts) in early phases of the universe. At the large distances an ELT will reach, the spatial resolution of point sources, even though only at a very low level, will eventually beat any interferometer. Low cost, the possibility to exploit also not perfectly photometric nights, and the D^4 sensitivity of background-limited observations of point sources to telescope diameter are other strong assets.

Keywords. techniques: polarimetric — stars: magnetic fields — supernovae: general

1. Introduction

The vast majority of astronomical instruments only record the following five observables (albeit at very different resolution and over highly disparate ranges): two angular coordinates, time, frequency, and flux. But if electromagnetic radiation is to be characterized completely, the degree and angle of linear polarization and the degree of circular polarization need to be measured as well. While almost everyone complains when one of the 'Big 5' (as one might be tempted to call them in Southern Africa) is missing, polarimetry appears to be much more easily dispensable.

Three circumstances are probably the main culprits: (i) Humans have no sensor for polarization and so became aware of it only by means of technical aids developed since the late 17th century. (ii) In most cases, the net polarized flux is only a small fraction of the total flux. (iii) The information conveyed by polarization forms a large angle w.r.t. the one associated with the other five observables.

These reasons conspire to the illusion that a reasonably self-contained, if not complete, picture can be derived from the five conventional observables. For a large variety of astronomical sources of electromagnetic radiation this is very wrong, and their polarization can be due to one or more of at least the following: (1) cyclotron or synchrotron radiation, (2) scattering by dust particles, (3) absorption by aligned, intrinsically asymmetric particles (e.g., dust), (4) magnetic fields, and (5) scattering by asymmetrically distributed

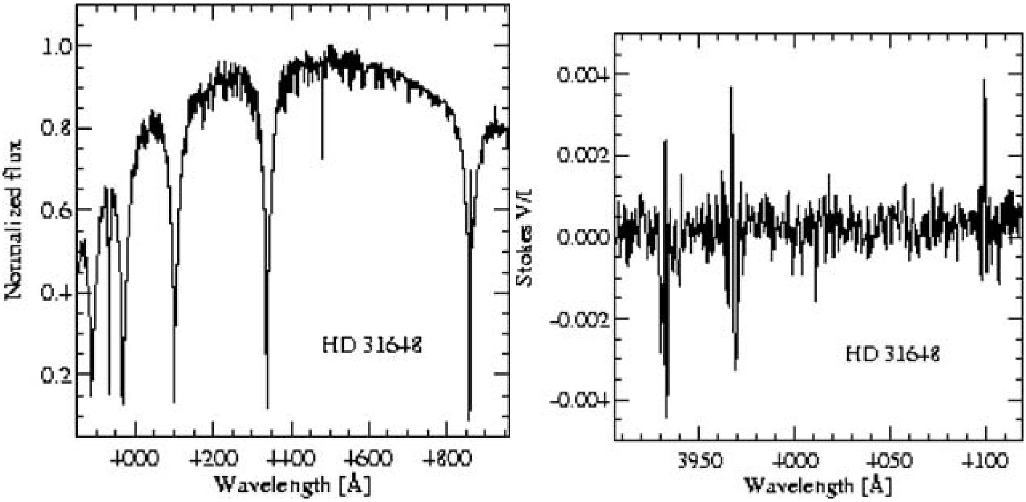

Figure 1. Left panel: Except for the emission component in Hβ, this part of the normal flux spectrum of the Herbig Ae star HD 31648 suggests no anomalies. Right panel: The circularly polarized flux spectrum reveals in all lines (note the reduced wavelength coverage) the typical pattern associated with the longitudinal Zeeman effect (Hubrig *et al.* 2006).

particles (e.g., a disk). In other observables, these processes can mostly only be guessed at whereas polarimetry can infer quantitative details of the underlying physical conditions.

The first three of these mechanisms only have a small wavelength dependence and so can be adequately studied by means of imaging polarimetry. Most of the objects one would like to investigate in this way would not drive a truly extremely large telescope to its absolute limits. But there are also cosmological applications. For instance, the analysis of cosmic shear due to weak gravitational lensing is based on the assumption that the true distribution of the symmetry axes of the lensed galaxies is random. Polarimetry may be the means to verify this hypothesis because gravitational lensing changes the spatial distribution (path) of light but not its polarization properties (Wang *et al.*, in preparation).

Nevertheless, this paper will focus on *spectro*polarimetry as its demand for extremely large telescope apertures is much stronger. The determination of the polarization due to foreground dust will always be part of the analysis. The properties of dust in different environments (cf. Krügel 2003) and over a large range in redshift are a valuable byproduct as they constrain the conditions of dust formation in the universe.

2. Stellar magnetic fields

The primary symptom shown by atoms and ions in a magnetic field is the Zeeman splitting. However, often this is not observable, for instance because the spectral lines are strongly broadened by the Stark effect (pressure) or by rotation, etc. In this case, polarimetry is a very useful alternative because the Zeeman components are polarized. Magnetic field lines in the plane of the sky cause linear polarization (transverse Zeeman effect); the longitudinal Zeeman effect due to a magnetic field component along the line of sight introduces circular polarization (Fig. 1).

There are numerous different types of magnetic stars: helium-variable stars, Ap stars, RS CVn stars, T Tau stars, HAeBe stars, SPB stars, white dwarfs, central stars of

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planetary nebulae, and many candidates are awaiting their confirmation. The associated topics include the effects of magnetic fields on star formation, in early-type stars the relative importance of dynamos and fossil fields, the magnetic braking of rotation, stellar activity, mass loss and outflow, and circumstellar structures (Mathys *et al.* 2001). Almost all of them are critical for the understanding of the Sun.

The proper observational description of stellar magnetic fields poses considerable challenges. As a rule of thumb, a kilo-Gauss field produces a one-percent polarization. This is the order of magnitude of magnetic fields in sun spots, which have a very small filling factor. The average solar surface field is more than a hundred times weaker. Many stars are active, and all stars rotate so that there is time dependency (if rotation dominates, the combination of time series of linear and circular polarimetry can permit the field structure to be modelled in 3-D). The S/N must be high, and the spectral resolution should be at least medium. To lower the detection threshold by the co-addition of lines or to distinguish regions with different physical conditions, the instantaneous wavelength coverage should be as large as possible. Series of observations at different analyzer position angles demand high instrumental stability.

In view of this list it is not surprising that the polarimetric equipment is often less sensitive to magnetic fields than the indirect manifestation of magnetic fields in non-polarimetric observables. This incommensurate polarimetric sensitivity is particularly unsatisfactory if magnetic fields at a level not detectable with current equipment are speculatively postulated to explain other observations. And a quick look at the Sun shows that the mere detection of magnetic fields is still not very useful if nothing can be said about higher-order and tangled field structures. Since 10m-class telescopes have left unanswered many questions concerning magnetic fields even in relatively bright stars, an order-of magnitude increase in sensitivity is needed, requiring a roughly similar increase in light-gathering power.

3. Polarimetry-boosted spatial resolution

Scattering polarizes light. But if the distribution of the scatterers is invariant under rotations through 90 degrees in the plane of the sky, there is no net polarization of the light from an unresolved source. Only if each polarized photon is not compensated for by another photon scattered at a location 90 degrees away in position angle, will there be a net polarization (of typically 1% for a 10% global distortion). Accordingly, the inversion of polarization data yields a very low-order spatial resolution.

Even a 100-m telescope working at the diffraction limit in the optical will not surpass the angular resolution of present-day interferometers. Since it will for quite some years be highly unlikely that an ELT interferometer will be built, high-resolution studies of faint far-away objects will - without polarimetric support - not conquer new horizons. An even more fundamental limiting factor that will eventually wipe out even the largest (realistic) improvements in angular resolution is the nature of the latter: The accomplished spatial resolution, which is the quantity that really matters, drops with distance.

By contrast, the detectability of polarization resulting from an asymmetric distribution of scatterers only depends on the number of available photons, i.e. distance and intrinsic brightness. On bright sources at large distances polarimetry will always win - at a tiny fraction of the cost of an interferometer.

Examples of asymmetric photospheres and other scattering screens include double or multiple stars (ranging from twins to planetary systems), accretion disks, the structure of mass outflows in young, massive or evolved stars, eruptive and cataclysmic variables, nonradial pulsators, and rotationally distorted stars. The facts to be learned cover the orbital inclination angle (thus permitting accurate masses to be derived), detection of planets, formation and dissipation processes of circumstellar disks, the physics of mass loss, pulsation modes, and the fractional critical rotation of stars.

The combination of polarimetry with spectroscopy permits a refinement of the resolution in the plane of the sky and a radial dimension to be added if zones with different physical conditions (temperature, expansion velocity, radius, rotation, etc.) are also polarimetrically distinguishable. This renders spectropolarimetry a high-performance and long-distance tomographic tool, as the two following subsections on supernovae will explain.

3.1. *Core-collapse supernovae*

Core-collapse supernovae have progenitor stars with a mass of at least $8\,M_\odot$ on the main sequence. The degree of the linear polarization increases with time. The maximum value seems the larger, the smaller the hydrogen envelope mass is and can reach 4% (Wang *et al.* 2001). Since the polarization angle is about constant with time and for all spectral lines, there is a global asymmetry that permeates the entire exploding star so that one is driven to conclude that the explosion process itself is asymmetric. One way to let this happen is to invoke jets, which would also offer a possible link to so-called 'long' γ-ray bursts (e.g., Lamb *et al.* 2005).

3.2. *Thermo-nuclear (Type-Ia) supernovae*

Although there is no direct observational proof, Type-Ia supernovae (SNe Ia) are usually thought to correspond with C/O white dwarfs reaching the Chandrasekhar instability limit. Like core-collapse SNe, they show significant linear polarization. However, the degree is substantially smaller (less than 0.5% in the continuum), reaches its maximum at the time of the explosion, and vanishes about a week after visual maximum light (Wang *et al.* 2003). The implied flattening of at most 5% would contribute less than 0.05 mag to the scatter of the absolute-luminosity calibration.

This is probably not in itself particularly relevant to the usage of SNe Ia as standard candles, and the cores of SNe Ia are symmetric anyway. But one should evidently like to understand these important cosmological tools reasonably completely. At a first glance, *spectro*polarimetric data only make things look even more confusing. For instance, in SN 2004dt (Fig. 2; Wang *et al.*, in preparation) several strong lines such as Si II 3859 and 6355, Ca II 3968, Mg II 4481, and O I 7774 all have about the same velocity distribution. Accordingly, all these ions should have about the same radial (line-of-sight) distribution. And yet, the oxygen line is at most marginally polarized while the polarization of all other lines is very high (up to 2%). The polarization angles are roughly the same for all polarized lines and the continuum. Even if oxygen is purely unburnt fuel, it is not easy to understand how its distribution can be much more axisymmetric than the one of all other species.

Conceivably, the resolution of this puzzle is related to some other apparent anomaly: There seem to be very few SNe Ia with no polarization (in the lines). From this one would have to infer some large-scale asymmetries that look about the same from all directions. If the outer layers of SNe Ia were broken up into a number of big bubbles, their polarimetric signatures would match the observations. In fact, model calculations do produce such bubbles (e.g., Reinecke *et al.* 2002) although they still need to be seeded and do not (yet) result from first principles.

There is, therefore, the intriguing possibility that spectropolarimetry can trace details of the explosion physics that can constrain models. If this also helps to better understand individual differences in absolute luminosity, spectropolarimetry not only could improve

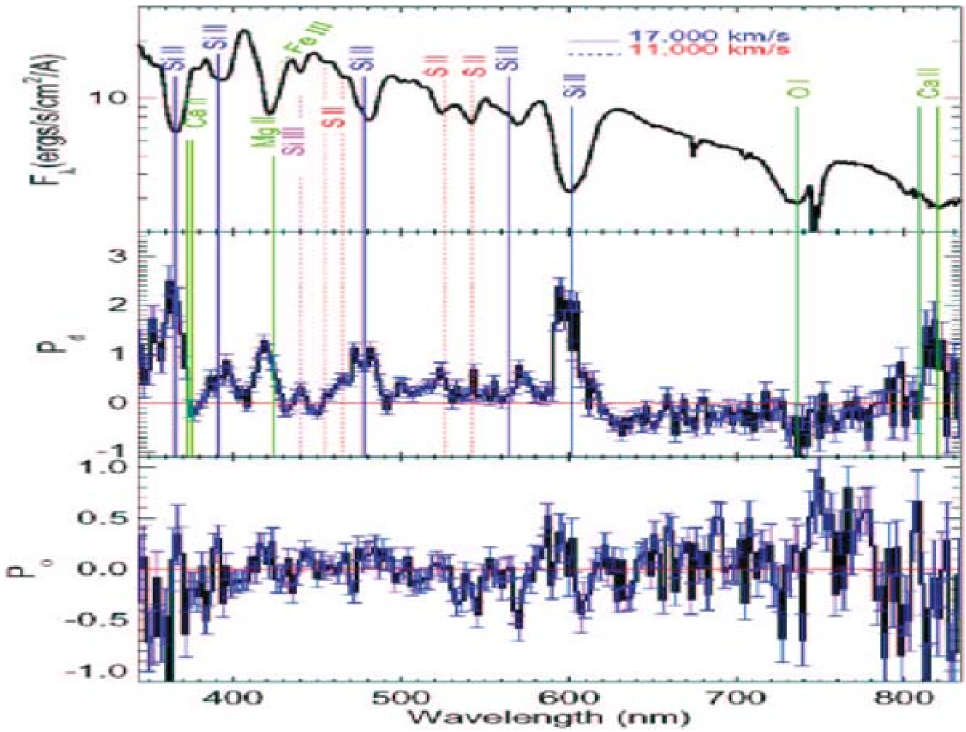

Figure 2. The optical spectrum of the Type Ia supernova 2004dt about one week before maximum light (top panel). The middle and bottom panel show the polarized flux projected onto the axis of the main asymmetry and perpendicular to it, respectively (Wang *et al.*, in preparation). Note the clear polarization of all major spectral features, which is only missing in OI 7774 (Wang *et al.*, in preparation).

the luminosity calibration of local SNe Ia but would also be the tool, with which one could check for any systematic luminosity difference between local and high-z SNe Ia.

4. Spectropolarimetry as a periscopic tool

A particularly interesting application of polarimetry is the separation of scattered light from light that reaches the observer directly. Without polarimetry the corresponding photons would be indistinguishable. But the scattered light is polarized and, if the 'direct' light is not, even relatively small proportions of scattered light can be detected. It may even help to make planets become visible that orbit a vastly much brighter star (e.g., Hough *et al.* 2006).

This strategy is also applicable to light sources that are obscured and not directly visible. For instance, the broad-line regions of AGNs are surrounded by an optically thick torus and become invisible when the latter is viewed edge-on. But polarimetry can identify light that is scattered into the line of sight to the observer. In this way, it was possible to demonstrate that Seyfert 2 galaxies possess a broad-line region very much alike Seyfert 1 galaxies (e.g., Antonucci & Miller 1985), and the unified scheme for AGNs was established.

If the scattering screen is spatially resolved, this method even permits one to observe the hidden source from different directions.

5. Conclusions

Many important astrophysical processes have distinct electromagnetic finger prints that show up in polarization and often only there. Polarimetry is indispensable for the quantitative study of magnetic fields with associated synchrotron/cyclotron radiation, of the size, shape, and composition of dust particles, of stellar magnetic fields, and of weak reflected-light signatures not otherwise recognizable against a very high background.

Polarimetry provides low-order spatial (linear) resolution that is independent of distance. Spectropolarimetry offers a further subdivision by regions with distinct physical conditions. Attached to an ELT, a spectropolarimeter can observe AGNs and GRBs at the earliest epochs and thereby address one of the most fundamental questions, namely the one about the conditions at the beginning of the formation of structure.

Spectropolarimetry is complementary, partly even orthogonal, to other observing techniques and so yields clues not otherwise obtainable. As a strictly differential measurement method it is very accurate and yet operationally lenient as it can exploit mildly non-photometric nights. Because most of the targets will be point sources, spectropolarimetry will benefit from increased telescope diameters at least quadratically (if adaptive optics reaches the diffraction limit). For faint sources at low spectral resolution, the additionally reduced background will extend this advantage up to D^4. On the other hand, the additional cost of including a polarimetric option in the design of a spectrograph only amounts to a few percent.

It is clear that spectropolarimetry requires ELTs. But the inverse is equally true: ELTs require spectropolarimeters.

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Discussion

HOUGH: I agree that polarimetry might be difficult to sell to the public, but it seems increasingly difficult to sell to the telescope instrument designers, e.g. for many of the 8-m telescopes/instruments. I would like to further emphasize the power of velocity-resolved spectropolarimetry in resolving mechanisms and structures on spatial scales that will never be achieved by even interferometers in the foreseeable future.

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FEAST: In many situations there will be more than one source of polarization in operation. How easy is it, in practice, to disentangle them?

BAADE: This is different for each case, e.g. time dependencies often help to separate concurrent effects. Moreover, spectropolarimetry always yields spectra of very high S/N so that the quality of the available information is extremely good.

ARDEBERG: Some of the most attractive science cases are also rather demanding even on ELTs. One example is circum-stellar discs and proto-planetary systems. Here, polarimetry can be exceedingly useful. We have to remember this and take it into account for ELT designs.

GALLAGHER: Since conditions are worse than median half of the time, could you not use these conditions for polarimetry with an ELT? This would be an additional advantage of including spectropolarimetic capabilities on ELTs.

BAADE: Being a strictly differential technique, spectropolarimetry can often be done even under mildly non-photometric conditions.