Spectropolarimetry of the Next Decade

Lifan Wang[1], Dietrich Baade[2], Alejandro Clocchiatti[3], Jennifer Hoffman[4], Peter Höflich[5], Justyn Maund[6], Fernando Patat[2], and Bev Wills[7]

[1] Texas A&M University
[2] European Southern Observatory
[3] Pontificia Universida Catolica de Chile
[4] Denver University
[5] Florida State University
[6] University of Copenhagen
[7] University of Texas, Austin

Summary Spectropolarimetry has a broad spectrum of applications and few rival techniques for the information content provided. They range from the measurement of the strength and structure of magnetic fields, to the composition-dependent structure of supernovae, to the structure and evolution of active galactic nuclei to the structure and evolution of protoplanetary stellar disks. Progress based on the power of specropolarimetry has been made with current ground-based facilities, but there is little effort from space. With the light collecting power of 30 meter class telescopes in the coming decade, spectroplarimetry at 0.01% level is possible for many varieties of astronomical objects. This will open new research front in geometric studies of astronomical objects and their chemical compositions. Spectropolarimetric capability should be considered a high priority for a whole range of facilities.

1. Introduction

The vast majority of astronomical instruments only record two angular coordinates, time, frequency, and flux. Even for images, but certainly for point sources, valuable information about the shape of the source is lost. 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. When designing instruments, polarimetry often is judged dispensable. As an example, an appeal such as this was made during the early design phase of JWST. It was ignored for perceived reasons of cost, but the cost ballooned anyway. With little addition to the current estimated cost, a powerful capability could have been added.

For a large variety of astronomical sources, polarization can be due to, for example: cyclotron or synchrotron radiation, scattering by dust particles, absorption by aligned, intrinsically asymmetric particles (e.g., dust), magnetic fields, and scattering by asymmetrically distributed material.

1.1. Dust

The determination of the polarization due to foreground dust will always be part of the analysis of any distant astronomical object. The properties of dust in different environments and over a large range in redshift are a valuable byproduct of spectropolarization studies as they constrain the conditions of dust formation in the universe.

1.2. Stellar Magnetic Fields

The primary magnetic effect shown by atoms and ions in a magnetic field is Zeeman splitting. Zeeman splitting is often not observable, for instance because the spectral lines are strongly broadened by the Stark effect (pressure) or by rotation. 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. 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 planetary nebulae, and many other candidate types await 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. Theories of stellar evolution are just now beginning to make progress in incorporating the associated effects of rotation and magnetic fields and this theory is still rather unmoored from direct observational constraint. Understanding the role of magnetic fields in a wide variety of stellar contexts is necessary to root the theory in fact.

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, instilling time dependence . 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. Observations of the Sun show 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.

1.3. Resolving Spatial Structure with Polarimetry

Scattering polarizes light. If each polarized photon is uncompensated by another photon scattered at a location 90 degrees away in position angle, there will be a net polarization (of typically 1% for a 10% global distortion). The inversion of polarization data thus yields a very low-order, frequency- and hence composition-dependent, spatial resolution, but one that often cannot be obtained in any other manner. The spatial resolution of an interferometer decreases 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 include 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.

A topic where spectropolarimetry has had a large impact over the last decade is in the study of supernovae (Wang & Wheeler 2008, ARAA, 46, 433, and the references therein). Virtually every supernova that has been properly observed has displayed significant polarization, and hence some significant degree of asymmetry. This has provided new challenges to theory and has shaped the conceptual development of the field. Data has been obtained to crudely sample most of the known types of supernovae, but obtaining sufficient data to provide a proper statistical base is a project for the next decade.

For a variety of core-collapse supernovae – Type IIP, Type IIn, Type IIb, Type Ib, Type Ic and the broad-lined Type Ic associated with long-soft gamma-ray bursts – the degree of the linear polarization increases with time and decreasing outer hydrogen envelope mass. This shows that the inner machine of the explosion is the cause of the asymmetry. This understanding has provided a new impetus to understand the asymmetry, whether in terms of neutrino transport, standing shock instabilities, or magnetic fields. The continuum tends to show a fixed polarization angle indicating a preferred orientation, but there is growing substantial evidence for non-axial symmetry that begs to be more deeply understood. There is a growing effort to use Type IIP supernovae as cosmological distance indicators. Their asymmetries in shape and hence flux, must be understood in this context.

Type Ia supernovae are virtually certain to correspond to C/O white dwarfs that have nearly reached the Chandrasekhar instability limit, given the constraints of UVOIR photometric and spectral evolution. Type Ia supernovae also show significant linear polarization. The polarization decreases with time, vanishing about a week after maximum light, indicating that it is a feature of the outer layers. The polarization in Type Ia is especially strong in certain lines, Si II, Ca II and Fe II. The continuum and line polarization are almost surely clues to the thermonuclear combustion processes that explode the star.

The degree of continuum polarization in Type Ia, less than 0.5% in the continuum, implies flattening of at most 5%. This 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 there are surely effects of asymmetry that are relevant as the field struggles to more tightly understand and control systematic effects. Spectropolarimetry could also be a tool by which onc checks for any systematic luminosity difference between local and high-z SNe Ia.

2. 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. Since the scattered light is polarized and and the direct light is often not, even relatively small proportions of scattered light can be detected. This process has been used to great effect to determine the torus structure of AGNs and may even help to make planets become visible that orbit a vastly much brighter star (e.g., Hough et al. 2006).

The broad-line regions of AGNs are surrounded by an optically-thick torus and become invisible when the latter is viewed edge-on. 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 like Seyfert 1 galaxies (e.g., Antonucci & Miller 1985), and enabling the establishment of the unified scheme for AGNs. If the scattering screen is spatially resolved, this method even permits one to observe the hidden source from different directions.

3. Spectropolarimetry of the Next Decade

Imaging polarimetry is normally subjected to uncertainties in instrumental polarization and the polarization due to interstellar dust. It is usually very difficult to quantify precisely the degree of instrumental polarization, thus introducing an extra source of uncertainties. But this source of uncertainty is expected to be smooth in wavelength space. Spectropolarimetry carries so much information that in many circumstances, the instrumental polarization can be considered a DC component that does not affect the spectral profiles of the Stokes Parameters. Likewise, the interstellar polarization can also be considered as a DC component that does not alter most conclusions drawn from spectropolarmetry. For example, spectral features of supernovae usually show polarization at around 1% level, by decomposing the feature into dominant and secondary axes, one can deduce constraints on the chemical structures of SNe without knowing the interstellar contribution. The method is illustrated in Figure 1.

Right now, the studies of chemical structure of supernovae using spectropolarimetry is limited not by instrumental polarization, or uncertainties in interstellar polarization. Photon statistics is still the dominating error term even with the largest telescopes of today. The future should see tremendous progresses with even larger telescopes on the horizon. When polarization can be measured to 0.01% level, we expect the following areas to benefit the most:

1 Supernova polarimetry: The chemical structures of SNe can be revealed layer by layer as the supernova evolves as becomes transparent. Spectropolarimetry will reveal the clumpiness or details of the asymmetry from inside out, through different chemical species. Supernovae can be observed well after maximum with future telescopes, thus revealing their central cores which are important in constraining the explosion mechanisms. Our experience with ESO VLT in the past ten years has never allowed us to observe a normal SNIa more than 6 months past optical maximum.

2 Exoplanet: High sensitivity will enable scattered light from planetary disks. It will enable direct measurement of Jupiter sized planet through polarization. This will make it possible to analyze chemical compositions of these planets if the resolution high enough.

3 AGN and QSOs: The spectral lines and continuum polarize differently in QSOs/AGNs. High sensitivity will allow detailed map down to the most interior of the central black hole.

4. Conclusions

Many important astrophysical processes have distinct electromagnetic finger prints that show up in polarization and often only in polarization measurements. 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 a new generation 20, 30, or 40 meter telescope, a spectropolarimeter can observe AGNs and GRBs at the earliest cosmological epochs and thereby address one of the most fundamental questions, namely the conditions at the beginning of the formation of structure. Spectropolarimetry is complementary, partly even orthogonal, to other observing techniques and thus yields clues not otherwise obtainable. As a strictly differential measurement method it is very accurate and yet operationally lenient as it can exploit mildly nonphotometric 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. On the other hand, the additional cost of including a polarimetric option in the design of a spectrograph only amounts to a few percent of the cost of the instrument. It is clear that spectropolarimetry requires telescopes of large aperture, but the inverse is equally true: large aperture telescopes require spectropolarimeters.

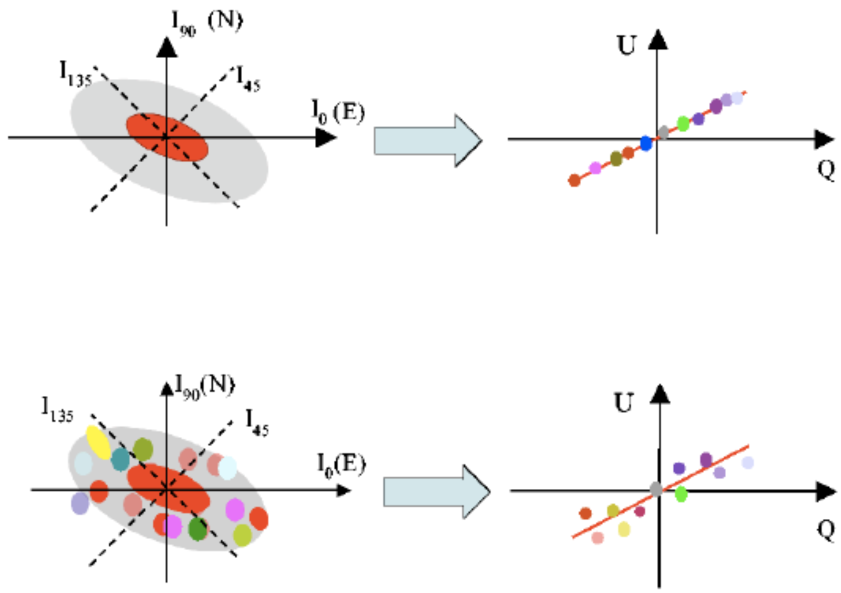

Fig. 1.— The top left illustrates a smooth, axisymmetric structure with the axis tilted at an arbitrary position angle on the sky. The directions denoted by I represent the measurement of the flux at the angles needed to construct the Q and U polarization components. The resulting wavelength-dependent polarization amplitude plotted in the Q/U plane will follow a straight line, the dominant axis, as illustrated in the top right. Dots represent the polarization measured at different wavelengths. The lower left illustrates a case for which the axisymmetry is broken into clumps of different composition and optical depth. Clumps of high-opacity, absorbing material will block parts of the underlying, photosphere. This will induce wavelength-dependent geometry. The polarization distribution in the Q/U plane will in general no longer be along a straight line, as illustrated in the lower right. The basic axisymmetric geometry may still be evident, as illustrated, but the departure from axial symmetry caused by the clumping will yield a finite, and physically significant, distribution along the orthogonal axis.