Science Cases for Ultraviolet Polarimetry in the 21st Century

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"Polarimetry is the crucial third leg of the astronomer's light-analysis tripod"

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Introduction

Polarimetry provides unique opportunities for discovery in all areas of astrophysics. Ultraviolet (UV) polarimetry probes high energy sources and small dust grains, but has been only superficially explored to date, mainly limited to the Shuttle-based WUPPE mission and a few instruments on the Hubble Space Telescope. UV polarimetry on large space-based telescopes can probe the radiation and magnetic fields of the diffuse interstellar medium (ISM), reveal structures and processes in hot stars and stellar systems, including the likely precursors of supernovae (SN) and gamma-ray bursts (GRBs), probe solar system objects and planetary rings, characterize exoplanets, and access the hidden engines of active galactic nuclei (AGN). Polarimetry is a crucial capability for a future large space UV/Vis mission.

The uniqueness of UV polarimetry

The UV uniquely traces hot plasmas both in continuum and through atoms, ions and molecules. To study high-mass and degenerate stars, interacting binaries, and the high energy processes in accretion disks and hot gas, the ultraviolet is the natural wavelength range. Astronomical polarization arises from quantum mechanical effects (Zeeman, Hanle), synchrotron and cyclotron processes, scattering by electrons, polarizable molecules and dust grains, and dichroic extinction by asymmetric dust grains. Scattering by polarizable molecules or small grains gives rise to polarization that rises steeply into the blue ($p \sim \lambda^{-4}$), yielding an enhanced contrast to the unpolarized light at shorter wavelengths. Modern radiative grain alignment ("RAT") theory predicts that the ISM polarization curve depends on the size distribution of the grains and the wavelength of the aligning radiation. Hence, UV polarization provides unique access to the alignment of the smallest grains and their mineralogy and structure, as well as the line-of-sight magnetic and UV fields.

The need for large apertures

Because polarimetry requires determining the components of the Stokes vector, it is inherently photon-intensive, requiring high equivalent photometric S/N ratios. However, the intensity (Stokes I) can, if required, be recovered from the Stokes Q, U (and V) components. Many polarization effects, such as scattering and dichroic extinction, are inherently broadband. High spectral resolution and high SNR spectroscopy can therefore naturally be combined with polarimetry. Some bright sources can be observed using smaller missions, such as the European Arago mission. However, to probe magnetic fields, sample stellar polarization over the varying metallicity environments in the Local Group, and to probe the nature of faraway SNe and the details of AGN evolution, large apertures are required.

Selected Science Cases

Tracing the Invisible - Interstellar Medium Magnetic Fields and Grain Characteristics

Dust-induced polarization has long been used to trace the geometry and strength of the interstellar magnetic field. With the development of a quantitative, observationally well tested theory of grain alignment (e.g. Lazarian & Hoang 2007), we can now expand its use to probe the grain characteristics and their local environments (Andersson et al. 2015). Theory predicts that a paramagnetic grain will be radiatively aligned if exposed to an anisotropic radiation field with wavelengths less than the grain diameter. Therefore, the polarization spectrum arises from a convolution of the grain size distribution and the radiation field, and the UV will selectively trace the smallest dust grains. For most diffuse ISM lines of sight (l.o.s.), the polarization yields alignment by a radiation field cut off at the Lyman limit. However, in 2 out of the 30 l.o.s. studied by WUPPE and HST/FOS, the polarization in significantly enhanced in the UV, and shows polarization in the 2175Å extinction bump

(Anderson et al. 1996). This might be due to the presence of hard UV along the l.o.s. - e.g. from sdO or WD stars - and thus measures the interstellar radiation field on small scales. Polarization in the 2175Å "bump" can its carrier, allowing a better understanding of its behavior in different environments.

Recent theoretical work has argued that for the very smallest grains, paramagnetic alignment can be efficient. For such grains the strength of the polarization is predicted to be proportional to the strength of the magnetic field, in contrast to the RAT alignment of large grains (Hoang et al. 2014). Similarly, the radiative pumping of atoms and ions with fine structure are predicted to align the atoms with the magnetic field, giving rise to polarized line emission. A number of prominent UV lines are predicted to show significant polarization and thus provide a means of tracing the magnetic field in the hot gas at small scales (Yan & Lazarian 2008).

Revealing Structure in the Unresolved - Stellar Physics, Explosions, and Exoplanets

Recent advances in the study of explosive transients (SNe and GRBs) have led to renewed interest in the nature of the winds and circumstellar material of their stellar precursors. Co-rotating interaction regions (CIRs) in the winds of WR stars, detected partly via UV spectroscopy, are predicted to show distinctive polarimetric signatures (Ignace et al. 2015). UV polarimetric studies of CIRs will probe WR wind characteristics, with implications for mass loss and SN/GRB production. The temperatures and geometries of hot gaseous circumstellar disks, such as in Be stars, are uniquely probed by UV polarimetry (Bjorkman et al. 2000). Polarimetry can also reveal the structure and origin of stellar magnetic fields and provide 3D images of the magnetodynamics through Zeeman line mapping over the stellar rotation period (Morin et al. 2008).

In addition, although ~75% of all massive stars occur in binary systems (Sana et al. 2012), the role of binaries in producing SNe and GRBs is not well understood. The intrinsically polarized emission lines in these systems trace structures in the winds and wind collision regions at varying distances from the stars (Lomax et al. 2015). Adding UV polarimetry will allow us to probe new regions of the complex circumstellar environment and test theories of mass loss and mass transfer in these systems, helping illuminate the potential binary pathways to SN and GRB explosions.

The technique of "flash spectroscopy" has opened a new window into the study of core-collapse SNe, revealing circumstellar material ejected by the progenitor and then ionized by the SN shock-breakout flash (Gal-Yam et al. 2014). Similar very early-time UV polarimetry will illuminate the geometrical structure of the progenitor's outer winds, constraining progenitor properties and the SN explosion mechanism.

Scattering from extended exoplanet atmospheres is expected to produce strong inherent polarization (Stam et al. 2004) and may provide probes of their structures, chemical characteristics, and orbital plane orientations. Because of the bright host stars, high sensitivity and stable observing conditions are required to detect the resulting signal, but UV polarimetry would provide unique information unavailable in direct light data.

Seeing the Hidden - Probing Obscured Accretion and the Structure and Evolution of AGN

Scattering around obscuring disks and tori allows central sources to be revealed in polarized light and provides enhanced contrasts to the direct light. In AGN, polarization originates as synchrotron emission from relativistic electrons in magnetic fields, seen as jets and blobs at scales of parsec to kpc from the nucleus. The UV provides strong constraints on the high energy distributions and lifetimes of the particles. Polarized light is also observed from scattering by dust or electrons in the vicinity of the AGN.

For optically thin scattering by small particles, the polarization rises sharply toward the UV, enabling the polarized component to be distinguished from other emission components. This allows us to map the 3D structure of scattering regions (Kishimoto 1999). As for imaging polarimetry, the UV scattered light enhances the contrast of broad emission lines such as C IV, N V, and Mg II from visually obscured AGN (Antonucci et al. 1994). In addition, as the continuum emission from accretion AGN disks peaks in the UV, polarimetry at these wavelengths is crucial for characterizing the disks (Antonucci et al. 1996). The shape of the polarized spectrum also elucidates the nature and optical depth of the scatterers (Hines et al. 2001). Combined with infrared direct spectroscopy, this provides multiple views of AGN accretion disks and their broad emission line regions. The Hubble Space Telescope provided the first UV imaging and spectropolarimetry of AGNs, but with results that only scratched the surface of the achievable science. A large aperture UV telescope would enable improvements of at least one or two orders of magnitude in AGN polarimetry and AGN evolution.