Massive Stars in Polarized Light

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Abstract: Polarimetry is an important observational technique in the study of hot stars. Practiced across the full range of wavelengths, polarimetry provides a window into a variety of stellar phenomena not accessible by other means. For example, polarimetry constrains the properties of circumstellar disks, unveils details of the magnetic fields in hot stars and their winds, and reveals the complex geometries of binary systems and YSOs.

I focus here on the applications of spectropolarimetry to the study of the atmospheres, winds, and circumstellar material of massive stars and their supernova descendents. When polarized light is produced by electron and dust scattering, spectropolarimetry allows mapping of clumpy and aspherical structures in the atmospheres, winds, and circumstellar surroundings of hot stars and core-collapse supernovae. When polarization arises from magnetic phenomena such as the Zeeman effect, spectropolarimetry probes the complex circumstellar magnetic fields threading the disks and winds of massive stars. I discuss recent results in both these areas and look to the near future, when the combination of polarimetry with interferometric and synoptic observations will open new frontiers in our understanding of massive stellar evolution.

1   Introduction

Astrophysical polarization is most often produced when light scatters in a gaseous or dusty environment. In the case of hot stars, which ionize their surroundings, electron scattering is a particularly important polarizing mechanism. The amount and orientation of polarization encodes information about the geometry and composition of the scattering region. Thus, polarimetric studies can reveal morphological details of stellar atmospheres, winds, and circumstellar material even for faraway, unresolved sources. Although spectral lines are often assumed to be depolarizing, they can acquire their own polarization via mechanisms such as resonance scattering and the Zeeman effect. Polarized lines often trace distinctive paths when plotted in the Stokes Q-U plane (e.g., Vink et al. 2002; Vink, Harries & Drew 2005; Magalhães et al. 2006). Analyzing these effects can lead to more detailed understanding of polarized objects by probing line formation and scattering regions.

Interstellar dust also produces polarization (ISP) via scattering, so stellar polarimetric measurements must be carefully corrected for this effect. An ISP contribution can change not only the amount but also the sense of polarization; for example, it can make polarized emission lines appear to be absorption lines in a polarized spectrum. A variety of methods exist to measure or estimate the ISP contribution to an observed polarization spectrum (e.g., Quirrenbach et al. 1997; Tran et al. 1997). However, the variation of ISP with wavelength is slow, smooth, and constant in time (Serkowski, Mathewson & Ford 1975; Whittet et al. 1992), so any line polarization effects or changes in polarization over time can be safely attributed to the target and not to the ISP.

In the past few years, polarimetric techniques have improved substantially, providing better resolution, better time coverage, longer-term monitoring, larger sample sizes, and more robust interpretation

via detailed modeling than was previously possible. In the rest of this contribution, I highlight some recent polarimetric results in the areas of young massive stars, Oe/Be stars, evolved massive stars, and supernovae and GRBs. The selection is necessarily limited and is meant to be representative, not comprehensive. Finally, I discuss the prospects for future developments in polarimetric techniques and combination of these techniques with others.

2   Young Massive Stars

Imaging polarimetry in the infrared and near-IR allows us to trace the circumstellar structures of massive young stellar objects (YSOs). The disk/outflow morphology seen in low-mass YSOs is relatively common in their high-mass counterparts (e.g., Jiang et al. 2008). However, at least some massive YSOs instead display evidence of episodic mass ejection and asymmetrical outflow structures, perhaps due to binarity (e.g., Simpson et al. 2009).

Imaging polarimetry can also reveal detailed structure within YSO accretion disks; for example, Wisniewski et al. (2008) found indications of self-shadowing and small enhancements in scale height in the disk of HD 163296. However, such data must be carefully interpreted. In the case of AB Aur, polarimetric images in the infrared initially suggested the existence of a gap in the circumstellar disk (Oppenheimer et al. 2008); however, higher-contrast images and detailed radiative transfer modeling subsequently revealed the "gap" to be a region of low polarization intensity likely caused by backscattered light (Perrin et al. 2009).

Line polarization measurements can measure the strength and and probe the detailed morphologies of magnetic fields in young massive stars. Zeeman signatures revealed that the magnetic field in τ Sco is not a simple dipole, but contains a warped torus that may help explain the unusual UV and X-ray properties of the star (Donati et al. 2006). Studies of the Stokes V line profiles in V380 Ori led to estimates of the strength and obliquity of the dipolar magnetic field in this binary system as well as the inclination of the system and the rotation period of the primary star (Alecian et al. 2009).

3   Oe/Be Stars

Polarimetry is especially powerful in combination with other observational and theoretical methods. One of the best recent examples of such combined techniques occurred in the case of the well-studied Be star ζ Tau. A pair of papers by Štefl et al. (2009) and Carciofi et al. (2009) combined quantitative radiative transfer modeling with long time-baseline photometric, spectroscopic, interferometric, and spectropolarimetric data to confirm the presence of a one-armed spiral density wave within the circumstellar disk of this object and to fix its inclination angle for the first time.

Other Oe/Be stars display long-term variations and can best be studied polarimetrically via monitoring on long timescales. Such spectropolarimetric monitoring illuminated the details of the transition between disk and non-disk phases in π Aqr and 60 Cyg (Wisniewski et al. 2010). These authors found that disk loss in these two objects occurs on a viscous timescale and proceeds in an "inside-out" fashion over several to many orbits of the companion. In addition, they detected both small and large outbursts causing disruption of disk symmetry, possibly in the form of disk warps or non-equatorial rings.

Line polarization in Oe/Be stars probes their envelope/wind structure. For example, theoretical modeling of Stokes V line shapes in hot star winds showed that a characteristic "heartbeat" profile can indicate the presence and strength of the winds' magnetic fields (Ignace & Gayley 2003; Gayley & Ignace 2010).

4 Evolved Massive Stars

Like Oe/Be stars, evolved massive stars possess complex circumstellar environments, due in large part to their strong winds and episodic mass loss. Evolved stars with companions may experience Roche lobe overflow, mass transfer, and wind collisions. Polarimetry has been an invaluable tool in disentangling the compound spectral signatures of such objects and enabling us to glimpse their detailed structures. For example, spectropolarimetry of the WR+O binary WR137 constrained the location of dust formation in the system (Harries, Babler & Fox 2000). In the case of another evolved binary, β Lyr, continuum and line polarization analysis revealed the location of the disk "hot spot" (Lomax & Hoffman 2011); similar analysis can be applied to other eclipsing systems (Hoffman et al. 2003).

Polarimetry of evolved massive stars can also probe the details of their evolution (Patel et al. 2008). A spectropolarimetric survey of nearby LBVs (Davies, Oudmaijer & Vink 2005) showed that their winds are aspherical and strongly clumped; depolarization across the Hα line is a signature of asphericity and correlates with strong Hα emission and wind variability.

5 Supernovae and Gamma-Ray Bursts

Complex polarimetric and spectropolarimetric behavior has been observed in more and more supernovae (SNe) in recent years, suggesting that the majority of core-collapse SNe are fundamentally aspherical (Chornock et al. 2010). In addition, SN ejecta can evolve over time from spherical to aspherical morphologies (Leonard et al. 2006) or vice versa (Wang & Wheeler 2008). Many SNe show polarimetric evidence for multiple misaligned axes (e.g., Kawabata et al. 2002; Hoffman et al. 2008) or axial rotation over time (e.g., Maund et al. 2007a, b). This behavior may hold clues to the nature of the pre-explosion mass loss of core-collapse progenitors. Emerging sophisticated line polarization models will help interpret high-resolution spectropolarimetric observations of SNe (e.g., Kasen et al. 2003; Hoffman 2007; Hole, Kasen, & Nordsieck 2010).

Polarimetry of gamma-ray bursts (GRBs) is a developing area of research that promises to reveal important information about the magnetic field structure of the expanding fireballs in these massive explosions (Mundell, Guidorzi & Steele 2010 and references therein). Detection of polarization at the 10% level in GRB 0901012 indicated that the relativistic outflow was threaded by large-scale ordered magnetic fields (Steele et al. 2009). Polarization measurements also probe the nature of GRB progenitor stars; Vink (2007) used line polarization measurements of Wolf-Rayet (WR) stars in the LMC and the Milky Way to investigate their rotational properties. However, he found no difference between the two populations, raising further questions about the identity of GRB progenitors.

6 Future Prospects

In the near future, advances in the study of massive stars using polarimetry will come from improvements in spectral resolution, expansion of the time domain, more sophisticated computational modeling, and a combination of polarimetric with interferometric and other techniques. A more comprehensive overview of upcoming advancements in stellar polarimetry was presented in the Astro2010 white paper *O/IR Polarimetry for the 2010 Decade (SSE)* (Hoffman et al. 2009).

Recent advances in very high-resolution spectropolarimetry promise to refine or even overturn our picture of the physical processes that drive and characterize massive stars. For example, data taken with the HiVIS and ESPaDOnS spectropolarimeters at $R = 13,000$ and $68,000$ showed that Hα line polarization in many Be and Herbig Ae/Be stars is associated not with the emission peak but instead

with the absorptive components of the line, an effect that is not seen in lower-resolution data and is difficult to explain with current scattering theories (Harrington & Kuhn 2009). The MiMeS Project, a CFHT Large Programme using ESPaDOnS, discovered a new magnetic O star whose peculiar emission lines may arise from confined circumstellar material rather than a wind (HD57682; Grunhut et al. 2009). Both results hint at the wealth of new discoveries that such high-resolution spectropolarimetry can enable.

The combination of polarimetric capabilities with the high spatial resolution of interferometric observations promises to shed new light on the complex structures produced at many stages in the lives of massive stars, as well as to calibrate polarimetric signatures that can be observed in extragalactic sources where interferometry is impossible. First steps in this direction have been taken using VEGA/CHARA (Mourard et al. 2009).

New polarimetric instruments are being planned or considered for a variety of upcoming observational facilities. For example, the Robert Stobie Spectrograph (RSS) on the queue-scheduled Southern African Large Telescope will open new vistas in polarimetric studies of variable and transient objects with high time-resolution spectropolarimetric capabilities in the visible and NIR (Brink et al. 2010; Sheinis et al. 2010). RINGO2 (Steele et al. 2010) and GAP (Yonetoku et al. 2010) will expand our ability to detect and track GRB polarization. Meanwhile, advances in computing power will continue to drive new computational models that can predict the polarimetric and spectropolarimetric signatures that will be observed by the next generation of instruments (Hoffman 2007; Hole et al. 2010).

An upcoming topical conference in June 2011 (*Stellar Polarimetry: From Birth to Death*, Madison, WI, http://arwen.etsu.edu/starpol/) will highlight recent results in this field, encourage the formation of new collaborations, and provide opportunities for the community to prepare for new developments in stellar polarimetry. Researchers with interests in all aspects of massive stars are cordially invited to attend.

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Discussion

S. Owocki: Have you looked for linear polarization in any of the magnetic Bp stars, e.g. σ Ori E or some of the similar examples recently discovered by MiMeS. They are inferred to have rotating magnetospheres and so should show rotationally modulated linear polarization.

J. Hoffman: σ Ori E was studied polarimetrically by Kemp and Heman in the 1970's, and they did find linear polarization modulations. I don't know of any more recent polarimetry, so this would certainly be a good target for the revived HPOL. Linear polarimetry of HD108 obtained by Fox & Hines (1998) shows only random variations, not correlated with the rotation period. MiMeS will undoubtedly yield many more interesting targets for linear spectropolarimetry.