SPECTROPOLARIMETRY OF THE Hα LINE IN HERBIG Ae/Be STARS

D. M. HARRINGTON and J. R. KUHN
Institute for Astronomy, University of Hawaii, Honolulu, HI 96822; dnh@ifa.hawaii.edu
Received 2007 June 12; accepted 2007 July 31; published 2007 September 6

ABSTRACT

Using the HiVIS spectropolarimeter built for the Haleakala 3.7 m AEOS telescope, we have obtained a large number of high-precision spectropolarimetric observations (284) of Herbig AeBe stars collected over 53 nights totaling more than 300 hr of observing. Our sample of five HαeBe stars, AB Aurigae, MWC 480, MWC 120, MWC 158, and HD 58647, all show systematic variations in the linear polarization amplitude and direction as a function of time and wavelength near the Hα line. In all our stars, the Hα line profiles show evidence of an intervening disk or outflowing wind, evidenced by strong emission with an absorptive component. The linear polarization varies by 0.2%–1.5% with the change typically centered in the absorptive part of the line profile. These observations are inconsistent with a simple disk-scattering model or a depolarization model that produce polarization changes centered on the emissive core. We speculate that polarized absorption via optical pumping of the intervening gas may be the cause.

Subject headings: circumstellar matter — stars: emission-line, Be — stars: individual (AB Aurigae, MWC 480) — stars: pre–main-sequence — techniques: polarimetric

1. INTRODUCTION

High-resolution linear spectropolarimetry measures the change in linear polarization across a spectral line and is a useful probe of circumstellar environments at small spatial scales. Circumstellar disks, rotationally distorted winds, magnetic fields, asymmetric radiation fields (optical pumping), and in general, any scattering asymmetry can produce a change in linear polarization across a spectral line such as Hα. These signatures can directly constrain the density and geometry of the circumstellar material. Typical spectropolarimetric signals are small, often a few tenths of a percent change in polarization across a spectral line. Measuring these signals requires very high signal-to-noise ratio (S/N) observations and careful control of systematics to measure signals at the 0.1% level.

In this Letter, we present the spectropolarimetric variability, as well as spectroscopic variability, of the Herbig Ae/Be stars AB Aurigae, MWC 480, MWC 158, MWC 120, and HD 58647. To date, only a few detections of spectropolarimetric signals in Herbig AeBe’s have been reported, and the variability of these signatures has not been studied in detail (Vink et al. 2002, 2005; Mottram et al. 2007). We show that variability is significant, and we show how it can provide information about the near-star environment with future modeling.

The Hα line in these stars is very strong, having line/continuum ratios of roughly 3–12, typically with P Cygni profiles or central reversals. Our observations of AB Aurigae, MWC 480, and MWC 120 show P Cygni profiles with strong variability of the blueshifted absorption component, often over 10 minute timescales. This is entirely consistent with other studies (Catala et al. 1999; Beskrovnaya et al. 1995). The Hα lines of MWC 158 and HD 58647 showed strong central reversals and were much more stable, although we had fewer observations.

The amplitude of the change in linear polarization across the Hα line is roughly 1% for AB Aurigae, MWC 480, and MWC 158, while HD 58647 and MWC 120 show smaller, but still significant signatures. These polarization changes are all centered on the absorption component, not on line center, and almost always have a single-loop trajectory in QU space, a so-called QU loop.

Many types of polarization effects are known in optical astronomy, some related to scattering and others relating to atomic and molecular processes. Polarization effects can be seen in broadband continuum polarization, or as changes in polarization resolved across a spectral line. Early analytical studies showed the possibility of spectropolarimetric effects from scattering very close to the central star (McLean 1979; Wood et al. 1993; Wood & Brown 1994). Recent Monte Carlo modeling of scattering by circumstellar materials has shown a wealth of possible polarimetric line effects from disks, winds, and envelopes (Vink et al. 2005; Harries 2000; Ignace et al. 2004). For example, unpolarized line emission that forms over broad stellar envelopes can produce a depolarization in the line core relative to the stellar continuum. Small clumps in a stellar wind that scatter and polarize significant amounts of light can enhance the polarization at that clump’s specific velocity and orientation.

This technique probes small spatial scales, being sensitive to the geometry and density of the material near the central star. Even for the closest young stars (150 pc), these spatial scales are smaller than 0.1 mas across and will not be imaged directly, even by 100 m telescopes. Since the circumstellar material is involved in accretion, outflows, winds, and disks, with many of these phenomena happening simultaneously, spectropolarimetry can put unique constraints on the types of densities and geometries of the material involved in these processes.

A preliminary study of the Hα line at medium spectral resolution (R ∼ 8500, rebinne heavily) in Herbig Ae/Be stars showed many different morphologies and amplitudes (Vink et al. 2002). Some showed polarization changes as high as 2%, while others showed none at all. Since the models predicting polarization across spectral lines are not currently invertible and predict spectropolarimetric effects centered on the emissive core, we wanted to do an in-depth study of a few sources to see if the variability of the spectropolarimetric line profiles could shed some light on the nature of the near-star environment.
Fig. 1.—AB Aurigae Hα line averaged for each night on 29 nights from 2004 to 2007. Each curve is an average of all the data on a given night, typically 8–128 spectra, with continuum S/N of 300–800 for each individual spectrum.

2. TARGETS

Since spectropolarimetry is a photon-hungry technique, we wanted to apply this technique to bright, well-studied stars that had previously detected spectropolarimetric signatures to monitor their variability and the nature of the polarimetric signatures. We chose AB Aurigae and MWC 480 for close study, and MWC 120, MWC 158, and HD 58647 as other bright observable targets.

The Herbig Ae star, AB Aurigae (HD 31293, HIP 229910), is the brightest of the northern hemisphere Herbig Ae stars (V = 7.1) and is one of the best-studied intermediate-mass young stars. It has a near face-on circumstellar disk resolved in many wavelengths (e.g. Grady et al. 2005; Fukagawa et al. 2004). It also has an active stellar wind, with its strong emission lines often showing strong P Cygni profiles. Spectroscopic measurements put AB Aurigae somewhere between late B and early A spectral types (B9 in The et al. 1994; B9 Ve in Beskrovnaya et al. 1995; A0 to A1 Fernandez et al. 1995) with an effective temperature of around 10,000 K. The star has a wind that is not spherically symmetric with a mass-loss rate of order 10^{-8} M_☉ yr^{-1}, and an extended chromosphere reaching T_{max} ~ 17,000 K at 1.5R_☉ (Catala & Kuasz 1987; Catala et al. 1999). A short-term variability study done by Catala et al. (1999) showed that an equatorial wind with a variable opening angle, or a disk-wind originating 1.6R_☉ out with a similar opening angle could explain the variability.

There were only two previous high-resolution spectropolarimetric observations of AB Aurigae. One was a single data set taken in 1999 and published with two different papers (Vink et al. 2002; Pontefract et al. 2000), another was taken in 2004 (Mottram et al. 2007). The polarization varied by roughly 0.4%–0.7% across the line, but to achieve the required signal-to-noise ratio (S/N) in each resolution element, the polarization spectra were rebinned to constant flux with a lower effective resolution of 2700 (25 elements over 60 Å but with varying spectral coverage). We are uncertain why the QU loops changed shape between the Pontefract et al. (2000) and Vink et al. (2002) papers, but there is clearly a shape change between Vink et al. (2002) and Mottram et al. (2007), showing evidence of moderate variability.

MWC 480 and MWC 120 also showed strong blueshifted absorption components. The Hα line and the continuum polarization of MWC 480 had been studied in detail by Beskrovnaia & Pogodin (2004) who concluded that MWC 480 also had an inhomogenous wind that was variable on short timescales. MWC 480 had a large amplitude signature (~1.8%) in Vink et al. (2002) but showed a less significant signature in Mottram et al. (2007), again pointing to variability.

MWC 158 and HD 58647 showed strong absorption near line center. MWC 158 is a mid-B type star and was previously studied for spectroscopic variability as well as low-resolution spectropolarimetry (Bjorkman et al. 1998; Pogodin 1997; Jaschek & Andrillat 1998). HD 58647 is a late B type star (B9 in The et al. 1994). Hα line spectropolarimetry for MWC 120 and MWC 158 was presented by Oudmaijer & Drew (1999) showing line effects. All stars had signatures in Vink et al. (2002). Clearly the signatures are at least mildly variable long timescales, partly motivating this study.

3. OBSERVATIONS

We observed our targets on eight nights during the engineering of the HiVIS spectropolarimeter (with five more lost to weather) in 2004 and on 27 nights over the fall and winter (with 13 more lost to weather) of 2006–2007. We observed AB Aurigae or MWC 480 continuously for several hours on some nights and all five targets intermittently on others with a focus on AB Aurigae and MWC 480. We have a total of 148 polarization measurements for AB Aurigae, 58 for MWC 480, 24 for MWC 120, 39 for MWC 158, 19 for HD 58647, plus 33 unpolarized standard star observations taken over the 40 nights in 2006–2007. We achieved a continuum S/N of typically 500 or better for our observations. The polarization data were subsequently binned by flux to a nearly constant S/N for each resolution element, typically 800–1000, accounting for the 0.1%–0.2% noise seen in the continuum polarization measurements.

The Hα line for all stars showed significant variability in intensity, width, and profile shape that is entirely consistent with other spectroscopic variability studies (Beskrovnaia et al. 1995; Beskrovnaia & Pogodin 2004; Catala et al. 1999). Figure 1 shows the average Hα line for AB Aurigae for each night to illustrate the nightly variations. Figure 2 shows the absorption

Fig. 2.—P Cygni absorption trough on selected nights for the AB Aurigae Hα line. These nights showed very significant changes over a few hours. Each curve is the average intensity for a single polarization measurement, with a roughly 8–16 minute cadence. From bottom to top the nights are 061228, 070117, 061106, 061027, and 061128.
Fig. 3.—Examples of spectropolarimetry for the AB Aurigae Hα line. The polarization is shown before any frame-rotation or flux-dependent binning to illustrate the data quality. The star symbols show the raw Stokes Q spectrum binned 4:1 for clarity. The solid and dashed curves are the smoothed Stokes Q and U spectra. The diamonds show the normalized intensity of the line. Each individual measurement has a raw continuum S/N of 300–800. The polarization signature in the absorptive part of the line is clearly visible and traces the absorptive component of the Hα line.

Fig. 4.—Nightly spectroscopy and spectropolarimetry of all five targets and the unpolarized standard stars. Each star has three boxes: Stokes Q in percent in the top, Stokes U in percent in the middle, and average nightly spectra on the bottom. The left column (top to bottom) is AB Aurigae and MWC 120. The middle column is MWC 480 and HD 58647. The right column is MWC 158 and unpolarized standards. All observations have less than 0.5% noise, with a typical noise around 0.1%–0.3%.
was strongest (~1%) for those stars with the strongest P Cygni absorptions (AB Aurigae and MWC 480). There was also a significant change of about 0.5% in the central reversal of MWC 158. The change was much weaker in MWC 120 and HD 58647, which showed a P Cygni absorption and strong central reversal, respectively.

AB Aurigae exhibits some intrinsic spectropolarimetric variability. Even though we do not have a full model for the telescope’s polarization effects yet, observations at a single pointing over many different nights show changes in the shapes and widths of the polarization spectra. The overall width and structure of the polarization spectra certainly change from night to night, regardless of what telescope calibration we will apply to these data in the future.

4. DISCUSSION

In the analytic studies of McLean (1979) and Wood et al. (1993; Wood & Brown 1994), and in subsequent Monte Carlo models of Vink et al. (2005), the simple “disk-scattering” polarization models predict spectropolarimetric signatures centered on the emissive core. The models use the stellar surface (chromosphere) as the source of a broad unpolarized emission line. This line flux is then scattered by the circumstellar material, which doppler-shifts and polarizes the scattered flux. This scattered light causes the polarimetric effects when added to the original unpolarized line. McLean (1979) also mentions a depolarization effect, where the stellar continuum is polarized, and unpolarized Hα emission depolarizes the starlight across the line. This effect would also be strongest in the emissive core. In our stars, the change in polarization occurred in and around the absorptive component, whether central or blue-shifted, and the polarization near the emission peak was nearly identical to the continuum polarization. McLean (1979) did mention another effect in a P Cygni absorption trough, but only when there is a signature in the emissive component. The lack of models explaining signatures only in the absorptive component led us to explore other explanations that would require the absorbing material to also be the polarizing material.

We are developing a new model in which an anisotropic radiation field causes the absorbing material to polarize the transmitted light. The polarization originates from the anisotropy in the lower level populations of the n = 2–3 Hα transition in the intervening gas. Anisotropic radiation from the star excites the intervening gas and leads to a population anisotropy in the n = 2 substates (called optical pumping). The anisotropy causes the absorbing material to absorb different incident polarizations by different amounts. The main difference between this model and the scattering model is that only the absorbing material, the material occulting the photosphere and chromosphere, is responsible for the changing polarization, whereas the scattering models integrate scattered light from the entire circumstellar region with each part contributing to the polarization change.

In AB Aurigae, the Hα photons are thought to come from an extended chromosphere, out to 1.5R*, with the P Cygni absorption occurring farther out where the incident radiation anisotropy is significant (Catala et al. 1999). The optical pumping model would produce polarization where there is absorption of the underlying Hα emission. The optical pumping model we are developing shows good promise of giving a direct constraint on the density and geometry of the absorbing material, and thus a possible way of determining the circumstellar material’s physical properties (Kuhn et al. 2007). While the depolarization explanation and the electron-disk scattering models of Vink et al. (2005) could explain many of their observations, they do not explain polarization effects isolated in the absorptive component. The optical pumping model can explain these absorption-only polarization effects. We compiled this very large high-precision data set to show the diversity of spectropolarimetric effects and hope that future modeling efforts will allow us to use such data to constrain the density and geometry of circumstellar material.

This work was partially supported by the NSF AST 01-23390 grant. We wish to thank Katie Whitman for help during the engineering observations and for discussions about data reduction. We also wish to thank Don Mickey for many stimulating discussions about telescope polarization.

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