Determination of Magnetic Fields in the Winds from Hot Stars Using the Hanle Effect

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Abstract. Resonance lines that are sensitive to the Hanle effect are prominent in the UV spectra of early-type stars. To understand the differences from the solar application of the Hanle effect, we focus on the formation of P-Cygni lines both as a scattering process, and as one that allows a spectral isolation of sectors in the wind. Some complications occurring in the solar case are found to be absent for the Hanle effect for hot stars. Rocket observations from the Far Ultraviolet SpectroPolarimeter (FUSP) experiment should allow for a determination of fields in the dynamically interesting range from 1 to 300 Gauss.

1. Introduction

The Hanle effect has never been measured for any star other than the Sun, but it should be observable in the UV spectra of hot-stars such as O stars, OB supergiants, Wolf Rayet Stars and Be stars. These stars have strong stellar winds driven, in part, by the same resonance lines that are sensitive to the Hanle effect. The observed lines are have full widths of about 4000 to 5000 km s$^{-1}$, and are commonly resolved by satellite UV observatories. In the case of the rapidly rotating emission line Be stars, and in some Wolf Rayet stars, observations of the polarization owing to electron scattering have been made from space, but at a lower resolution than is needed for Hanle studies.

2. Hot Star Line Profile Formation

For the Sun, observers can measure the specific intensity, $I_\lambda$, of the light. Other stars are point-like so only the flux, $F_\lambda$, can be measured, and this is an average of the intensity across the face of the star and its envelope. Ignace et al. (1997, 1999, 2001) have addressed this problem of what can be learned from polarized fluxes, and have shown that useful information can be derived about both the field strength and the magnetic geometry in winds from hot stars.

The Hanle diagnostic is possible because the lines are formed by a scattering process, and the lines profiles also allow us to isolate spatial sectors of the envelope of the star. To illustrate the scattering nature of the line formation...
process we use the “spherical shell” explanation of P-Cygni lines. To describe the spatial sectoring, we use the “iso-velocity” or constant line of sight velocity approach.

![Diagram of the shell model for the formation of a P-Cygni line by a purely scattering process.](image)

The left panel of Figure 1, we see that the line is composed of narrow boxes of attenuated light plus broad flat topped emission components. The entire profile is composed of the sum of many components as illustrated in the right panel. The P-Cygni line profile is formed entirely by a scattering process. The emergent scattered light is distributed across the line, even in the so-called absorption side of the line. Using this spherical shell approach to interpret line profiles, modelers regularly derive velocity and ionization structures of hot star winds.

In the iso-velocity approach, first developed by Chandrasekhar (1934) and extended by Sobolev (1947), we consider one wavelength band of the profile at a time. The flux at a Doppler displacement, $\Delta \lambda = \lambda V_z/c$, from line center is formed along one of the constant velocity surfaces shown in figure 2. In the shortward shifted side of the line, there is both a reduction of the light because
of scattering by ions in the area in front of the star’s disk, and an increase by the scattering toward the observer from the entire constant velocity region. The iso-velocity approach shows that we can resolve sectors of the envelope in wavelength space; that is sufficient for applying the Hanle effect. Now, let us include in this picture a magnetic field in the wind. For this discussion, consider a spherically symmetric wind with a superposed stellar dipole field. The spherically distribution for the Rayleigh scatterers would lead to zero net polarization. However, the dipole field introduces an asymmetry needed for the Hanle effect. At every point in our model envelope the Hanle source function can be calculated and then integrated to find the monochromatic polarized line flux.

The fiducial magnetic field for a given line is the Hanle Field, \( B_H(\approx 5 \text{ Gauss} \times 10^8 \text{cm}^2) \), where \( A_{ul} \) is the decay rate for the \( u \) to \( l \) transition. Figure 1 in Nordsieck’s paper (these proceedings) gives polarizability results for the UV features of interest here. Many are closely separated doublets, with each component having a different \( E_1 \) value. Typically, one line of the doublet is sensitive to the magnetic field and the other, an isotropic scattering line, is not. An inter-comparison of the two components is useful for isolating the magnetic effects.
Figure 3 shows a simulation of an observation of ζ Ori A, a supergiant for which there is indirect evidence for the presence of a magnetic field in that the star emits X-rays corresponding to an anomalously hot gas. (Cassinelli and Swank, 1983). In Figure 3 are shown clearly observable changes in the line polarizations of the resonance lines shown as the surface field is increased from 1 to 100 Gauss.

Figure 3. Numerical simulation of the Hanle Effect for the case of a dipole field in a spherically symmetric wind. The top panel shows the Copernicus UV spectrum of ζ Ori (O9.5 Ia). Four lines with the given Hanle fields are noted at the top. The next panel shows the theoretical polarized profiles at surface field strengths of 1, 3, 10, 30, and 100 Gauss. The lower two panels show a simulation of a 300 second FUSP exposure of the star with surface field strengths of 3 and 100 Gauss.

3. Contrasts with the Solar Case

We have heard several other papers at this conference about the Hanle effect as it is applied to the Sun. Let us consider some of the problems raised.

A) Landi Degl’Innocenti stressed the the Hanle effect is a non LTE effect. For the solar application this implies a complicated multilevel atom radiation transfer problem. For our case, we can use the much simpler nebular approximation that all atoms/ions are in their ground states, as we are dealing with resonance scattering starting from the $n = 1$ level.

B) Fineschi stated in his presentation that the presence of velocity fields limits
the applicability of the Hanle effect. This statement would seem to be a major concern for hot stars, as we are always dealing with velocity fields—the winds. However, Fineschi has explained that for the solar case the incident light that is scattered is Chromospheric line emission. Thus the incident flux varies strongly with wavelength across the profile. Transverse motions of the zone being diagnosed produce Doppler shifts relative to opposing limbs of the Sun. This leads to an asymmetry in the the scattered radiation, and to what is called a “false” Hanle Effect. However, for the hot stars this is not a problem because the light that is scattered in the envelope is flat continuum emission from the star, i.e. \( \frac{dF}{d\lambda} \approx 0 \), over the wavelengths where each Hanle diagnostic line forms.

C) Landi Degl’Innocenti also said in his review that Hanle is a useful diagnostic over only a small range in magnetic field, and showed a plot of polarization versus \( B \) to support that statement. However, for the UV one could show several such plots, one for each of the Hanle sensitive lines, and conclude that Hanle will be useful to derive magnetic fields in the range 1 to 300 Gauss. Coincidently, this range corresponds well with the values in surface magnetic fields that can have significant dynamical effects on the wind, (Cassinelli and Miller, 1999). For the Be-stars, the disks could be magnetically spun-up by magnetic fields of about 30 gauss. It is a also range that is difficult to measure with the Zeeman effect owing to the immense line broadening.

4. Conclusions

The Hanle Effect offers a promising way to derive the magnetic fields on early-type stars. The lines needed for the field diagnostics are among the most prominent lines in hot star spectra. With P-Cygni lines, we can derive spatial information about the magnetic field, since each segment of the line profile is formed in a different isovelocity sector of the wind. Three problems affecting the application of the Hanle effect to the Sun are expected to be absent in applications to hot stars.

References

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Discussion

BUENO: I have a question with respect to the UV lines you are proposing for the Hanle effect diagnostics of magnetic fields in the winds of hot stars. Can you really model their Stokes profiles by assuming that they are optically thin in the stellar wind?

CASSINELLI: Although resonance line cross-sections are large, the optical depths in lines can be moderate because of the expansion motions of the wind. The relevant optical depths are those through narrow interaction regions or Sobolev zones, where \( \tau \) depends inversely on the velocity gradient. Also, because of the ionization fractions involved, there are lines in the UV with a range of strengths. The lines of \( \zeta \) Ori (Figure 3) have P-Cygni profiles that are not saturated and indicate optical depths of order unity or less across the lines. It is lines of intermediate strength, i.e. moderate optical depths, that have proven to be of greatest value in nearly all line profile diagnostic studies of hot stars, and the same will hold true for the Hanle effect studies.