On the Importance of Including the Effects of Magnetic Fields in Studies of Young Stellar Objects

Casey P. Deen[1,2] - deen@mpia.de, www.mpia.de/~deen

[1]Max Planck Institut für Astronomie, Heidelberg Deutschland, [2]University of Texas, Department of Astronomy, Austin TX, USA

Abstract: Near-IR spectra are sensitive to Zeeman splitting due to stellar magnetic fields, which for young stars, with mean magnetic fields of several kilo-Gauss, can produce changes in photospheric absorption lines which become significant, even in medium resolution spectra often used for spectral typing young objects. The equivalent width of any line is a function of surface gravity, effective temperature and magnetic field strength. Exploiting the multiplex advantage afforded by the large wavelength ranges of instruments like SpeX and XShooter, it is possible to break the degeneracies by simultaneously examining lines with differing sensitivities. I use MoogStokes to create a three-dimensional grid of synthetic spectra suitable for determining the physical parameters of young stars (Teff, log g, and B) with a Chi-squared minimization routine. As a test case, I examine TW Hydra, a well studied and yet hotly contested young object, and determine its physical parameters using a SpeX NIR spectrum.

Motivation: Studies of the lifetimes of circumstellar disks are based on the exponential decay of disk fraction with cluster age (see Figure 1). However, the age of a single cluster can be difficult to determine (see Figure 2). While the dispersion of young objects in the HR Diagram may be due to initial conditions, accretion physics, and/or an actual age spread (Baraffe 2009, Chabrier & Hennebelle 2011, Baraffe et al. 2012), the typical uncertainty of the placement of a YSO on the HRD makes definite conclusions difficult to draw.

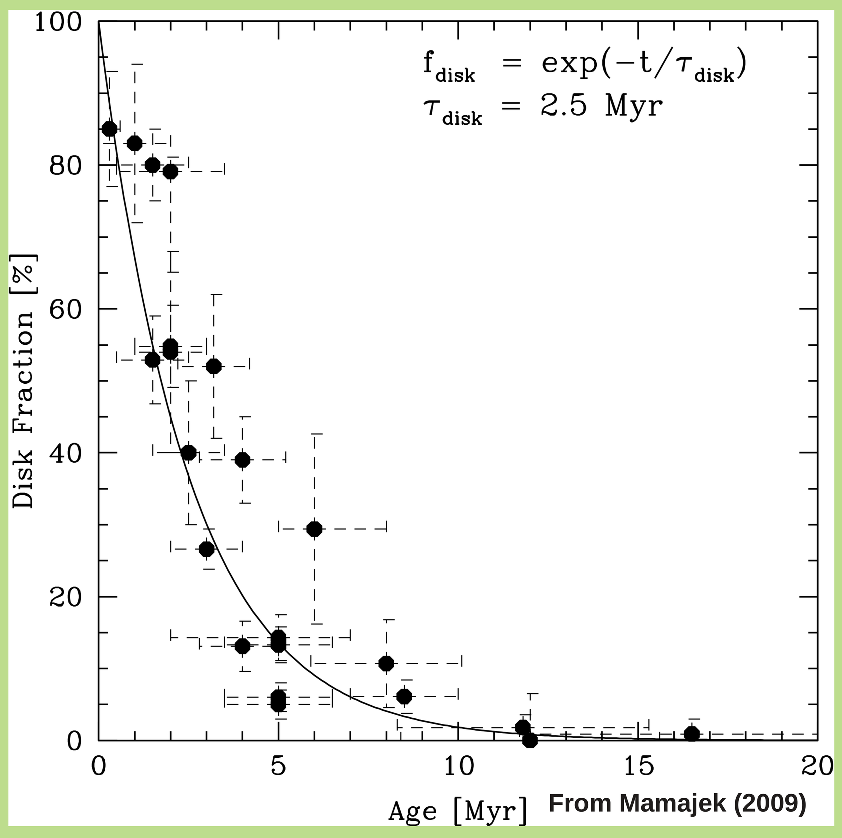


Figure 1) Exponential Decay of Disk Fraction as a function of Cluster Age (from Mamajek 2009)

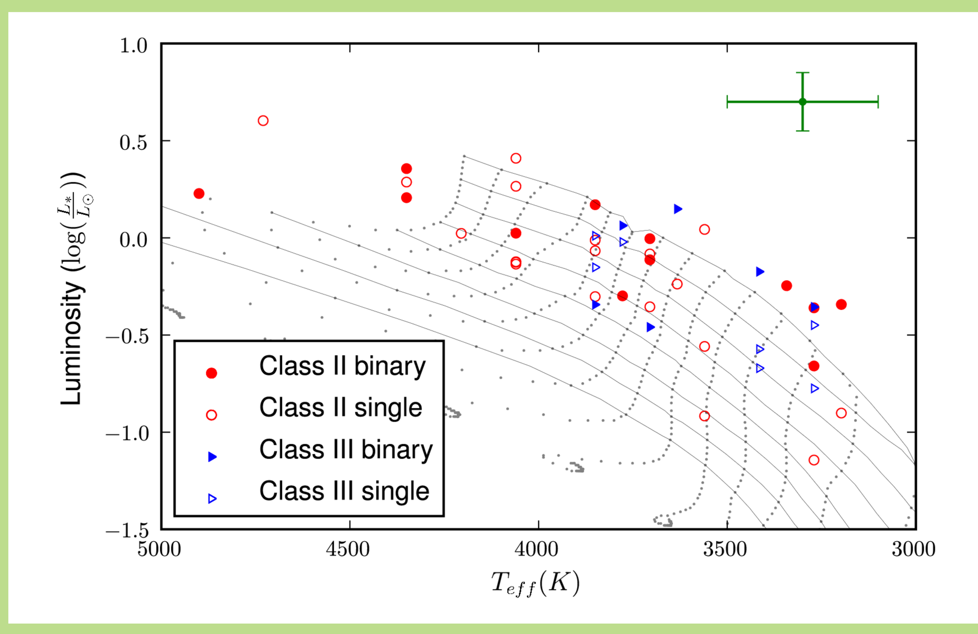
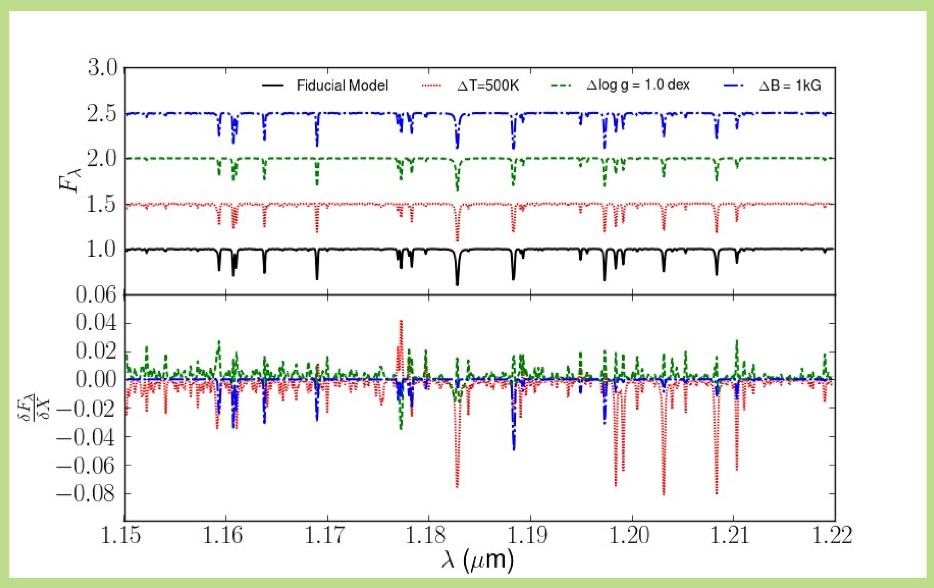


Figure 2) Scatter in the HR Diagram of a magnitude-limited sample of YSOs in Ophiuchus. The model tracks are from Barraffe et al. 1998. The youngest isochrone is 1 Myr, and each subsequent isochrone is older by 0.2 dex

Grid of Model Spectra: Using MoogStokes, I created a grid of synthetic spectra spanning a range in effective temperature (2500K<T<6000K) surface gravity (3.0<log g < 5.5), and magnetic field strength (0.0kG < B < 4.0kG) appropriate for the study of low-mass young stellar objects. Figures 3-6 show the spectral regions selected for the grid computed for a fiducial model (black) and slight differential departures in temperature (500K, red), surface gravity (1.0 dex, green) and magnetic field strength (1.0kG, blue) The bottom of each figure shows the differential sensitivity for each wavelength in the spectrum. These spectra are smoothed to the resolving power of Xshooter (R=9100).



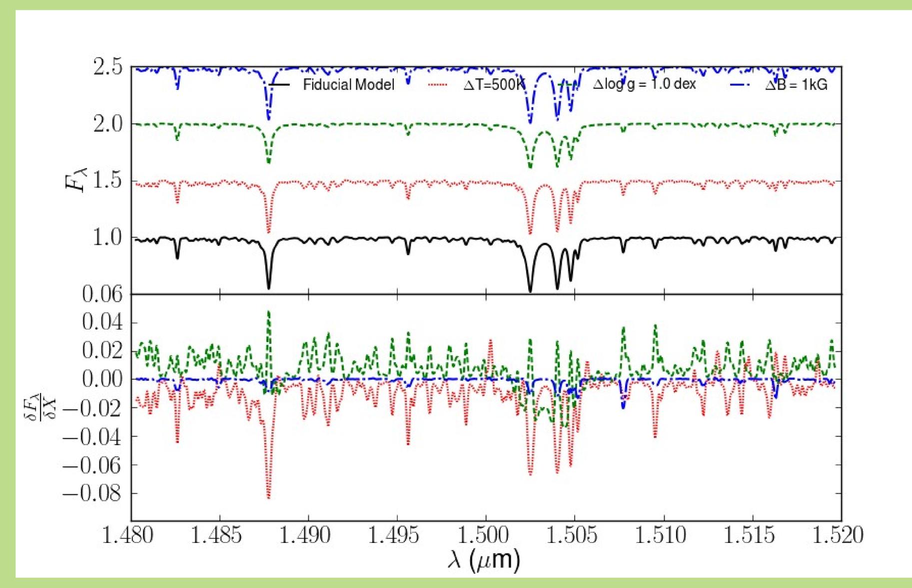
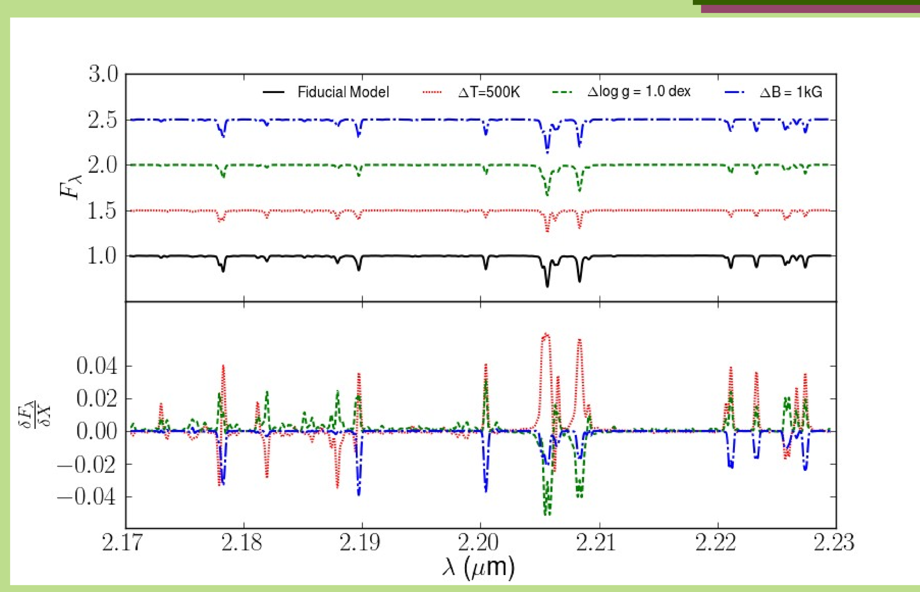
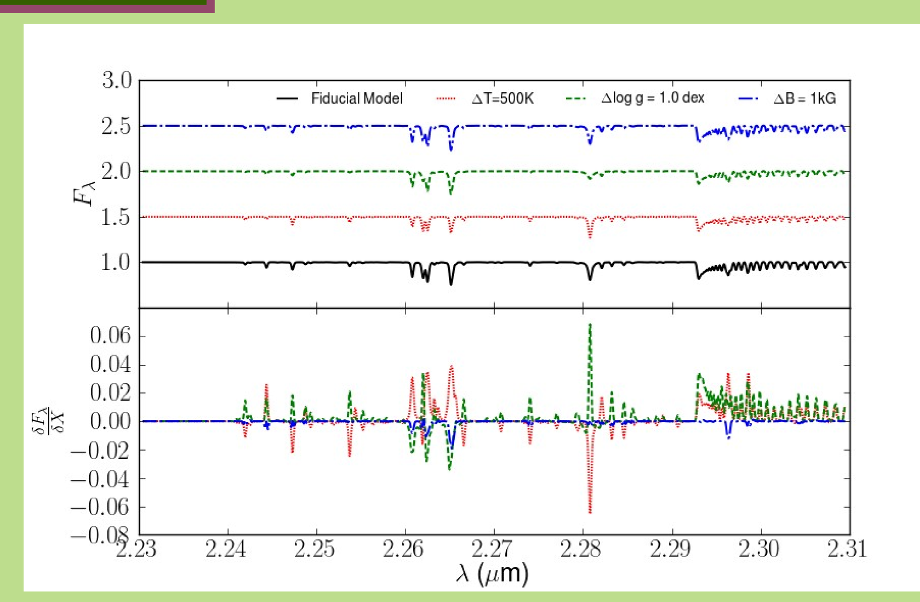


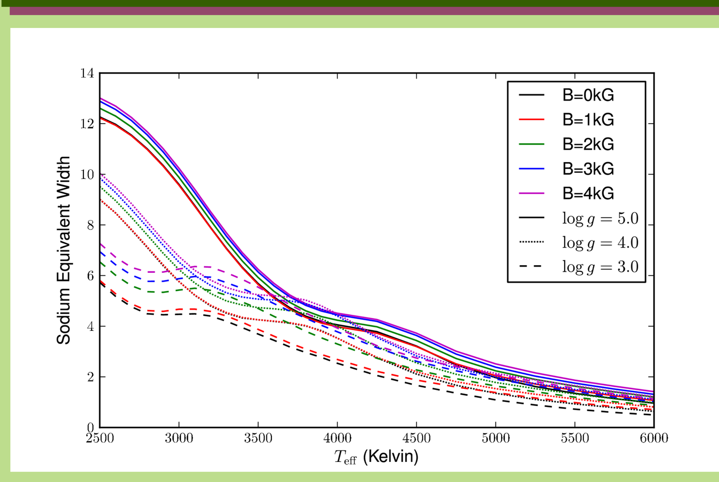
Figure 3) **Figure 4)**
Figure 5) **Figure 6)**





Does it matter?

Figures 7 shows the effect of increasing the magnetic field strength on the equivalent width of the sodium feature at 2.2 microns. The feature is often used to determine spectral types, so assuming the wrong surface gravity or magnetic field strength will result in an erroneous effective temperature determination. Figure 8 shows the effect of this error on the placement on isochrones in the HR Diagram



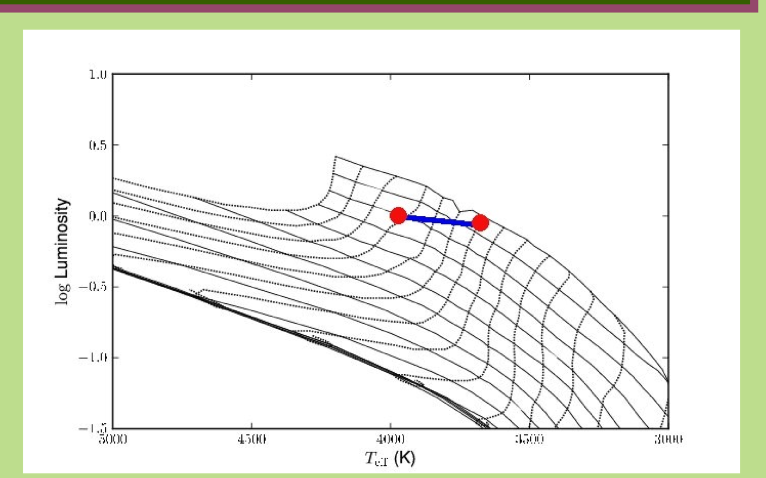


Figure 7) **Figure 8)**

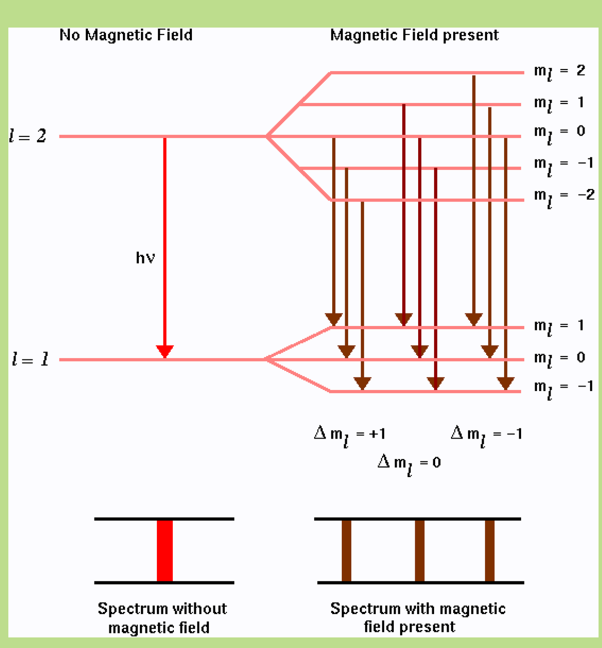
Magnetic Fields in YSOS: Most studies of YSOs (or clusters of YSOs) neglect the presence of a magnetic field, even though strong B fields are predicted/required theoretically (magnetospheric accretion, disk-locking). For the few objects for which a magnetic field has been measured (see Table 1), the global magnetic fields are ~2 kG, much stronger than fields in Main Sequence stars. If the strong B fields affect the spectra of the stars, spectral typing may yield erroneous effective temperature (and by extension stellar age!)

Name	SpT	B Field (kG)
AA Tau	M0	2.78
BP Tau	K7	2.17
CY Tau	M1.5	1.16
DE Tau	M1	1.12
DF Tau	M2	2.90
DG Tau	G0	2.55
DH Tau	M1	2.68
DK Tau	K6	2.64
DN Tau	K6	2.00
GG Tau A	M0	1.24
GI Tau	K5	2.73
GK Tau	K7	2.28
GM Tau	M6.5	2.22
T Tau	G5	2.37
TW Hya	K7	2.61

Table 1) Global magnetic field measured in YSOs via high resolution IR spectroscopy (from Johns-Krull 2007)

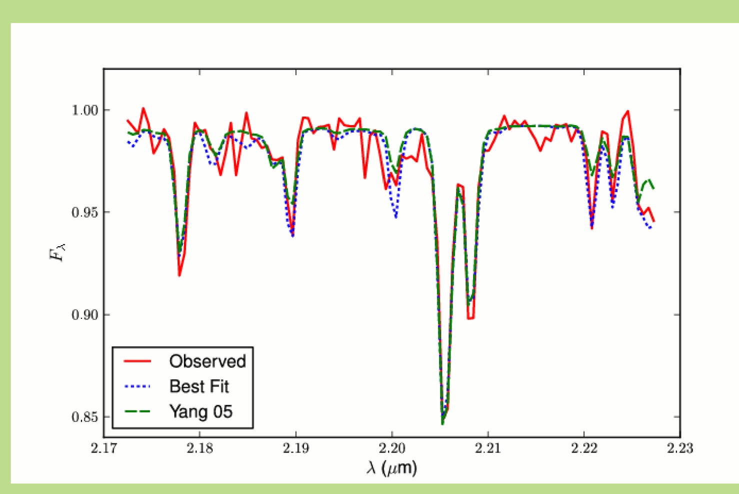
MoogStokes: To properly model the effects of magnetic fields on the near-IR spectra, I modified Moog (Sneden 1973) to accout for the Zeeman effect and polarized radiative transfer of the Stokes Vectors.

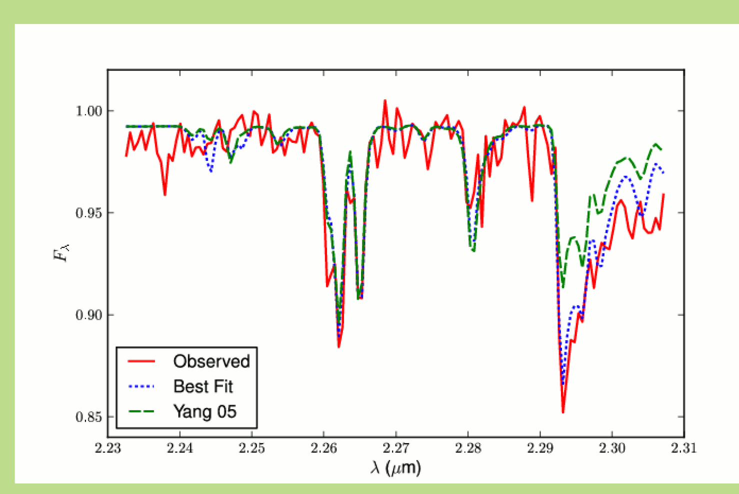
$$\mu\frac{dI}{d\tau} = \eta_0(I - B_T) + \eta_I(I - S) + \eta_Q Q + \eta_U U + \eta_V V$$
$$\mu\frac{dQ}{d\tau} = \eta_Q(I - S) + (\eta_0 + \eta_I)Q + \rho_V U - \rho_U V$$
$$\mu\frac{dU}{d\tau} = \eta_U(I - S) - \rho_V Q + (\eta_0 + \eta_I)U + \rho_Q V$$
$$\mu\frac{dV}{d\tau} = \eta_V(I - S) + \rho_U Q - \rho_Q U + (\eta_0 + \eta_I)V$$



Application to TW Hydra:

I wrote a Chi-squared fitting routine to compare observed SpeX spectra (R=2000) to the synthetic spectra in the model grid, producing best fit parameters for the physical parameters of the star. Shown below are two spectral regions for the best fit to TW Hydra. The best-fit parameters I derive for this star are: T=3540 +\- 40K, log g = 3.33 +\- 1.8 dex, B=1.24 +\- 0.8 kG, and K-band veiling = 0.06 +\- 0.13. Yang et al. (2005) measure physical parameters of T=4125K, log g = 4.84, B = 2.6kG, and r_k = 0.07. The reasons for the discrepancy are most likely due to the different values for the surface gravity, as the lines most sensitive to magnetic fields are also quite sensitive to surface gravity (see Figures 3-6). I plan to repeat my analysis with archival Xshooter data.





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