Magnetic Fields in Early (sub)Stellar Evolution

Improving Mass and Age Estimates for Young Objects

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1. Background

Absolute stellar ages are some of the most sought after astrophysical quantities. This is particularly true for identifiably young systems, where absolute ages provide our only constraints on time-dependent features of star/planet formation and evolution. Examples include placing constraints on the lifetime of primordial gas disks (e.g., Haisch et al. 2001; Mamajek 2009), the timescale for giant planet formation (Chabrier et al. 2014), the giant planet migration timescale (), star formation timescales (**?**), and deriving the sub-stellar initial mass function (Chabrier 2003). Unfortunatey, accurate absolute ages for young stars remain elusive (Soderblom et al. 2014) due largely to a necessary reliance on stellar evolution models, which are beset with problems at ages younger than 100 Myr (e.g., Mathieu et al. 2007; Stassun et al. 2014). **This proposal aims to develop stellar models and supporting theoretical tools necessary to establish accurate and precise ages for young stars.**

The textbook picture of early stellar evolution involves the quasi-hydrostatic collapse of a homogeneous gas sphere from an arbitrarily large initial radius down to a star where core hydrogen burning maintains hydrostatic equilibrium (e.g., Henyey et al. 1955; Hayashi 1961; Iben 1965). The four standard equations of stellar structure (mass conservation, hydrostatic equilibrium, energy conservation, energy transport) are assumed to be sufficient to describe the protostar's evolution (Iben 1965; **?**). However, "standard" stellar evolution models constructed within this paradigm appear to provide an incomplete description of early stellar evolution.

Empirical HRDs of young stellar populations exhibit a number of features that challenge this simple evolutionary picture (Naylor 2009; Da Rio et al. 2010; Herczeg & Hillenbrand 2015). Figure 1 illustrates two problems with standard model predictions. First, the observational data (grey points) exhibit a significant spread in luminosity at a given effective temperature; they do not form a tight sequence as is predicted by stellar evolution models (black lines). Luminosity spreads are a common feature among stellar populations with suspected ages $\lesssim 20$ Myr (Hillenbrand 1997; Da Rio et al. 2010). Observational errors are unable to fully explain the observed scatter (e.g., Jeffries 2012; Pecaut et al. 2012). One must therefore conclude that either there are genuine age spreads of several million years resulting from extended star formation processes or our standard picture of early stellar evolution is somehow incomplete (Jeffries 2012; Soderblom et al. 2014).

A second, more concerning, problem is that the median age inferred for a stellar population from its HRD is a sensitive function of stellar effective temperature (Herczeg & Hillenbrand 2015). Figure 1 demonstrates that stars with surface temperatures hotter than 6 000 K are best characterized by a median age between 9 and 14 Myr, whereas cooler stars have a median age around 4 to 5 Myr. This same trend is observed in at least four nearby young moving groups (Herczeg & Hillenbrand 2015). Age estimates for mid- to late-M stars in young moving groups typically appear a factor of two younger than early-M and K stars (Malo et al. 2014; Herczeg & Hillenbrand 2015), which appear a factor of two younger than stars with spectral type G or earlier (**?**). These age gradients align well with results from comparing model predictions to color-magnitude diagrams (Naylor 2009), where redder K- and M-type stars appear a factor of 2 – 5 younger than bluer main-sequence stars in the same population (Naylor 2009; Bell et al. 2012). Critically, age gradients with effective temperature appear largely insensitive to the adopted color-temperature transformation (Herczeg & Hillenbrand 2015). **Stellar evolution models constructed within the standard paradigm seemingly cannot provide a consistent median age for young populations.**

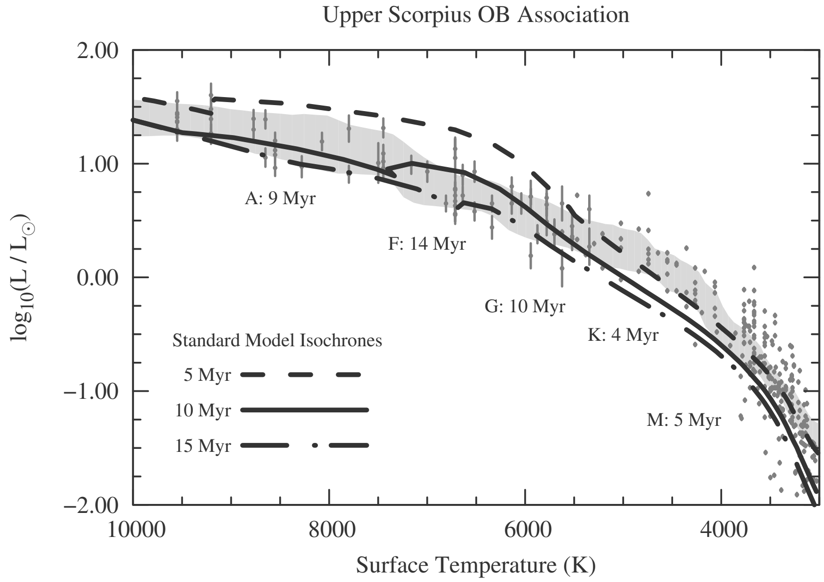

Figure 1: HR diagram for the Upper Scorpius OB Association. Stellar evolution model isochrones are shown in black. Labels show the ages inferred from different sub-populations in the association, highlighting a clear discordance between ages of hot and cool stars.

To further complicate matters, ages for young stellar populations also depend on whether one compares observations to models in the HRD (Figure 1) or in the mass-radius diagram (MRD; Kraus et al. 2015). An observational mass-radius plane can be constructed by measuring masses and radii for stars in detached eclipsing binary systems (EBs; Andersen 1991; Torres et al. 2010). Recent observations of EBs in the young cluster Upper Scorpius (same cluster as in Figure 1) demonstrate that stellar ages inferred from the MRD can be up to a factor of two different than estimates from the HRD (Kraus et al. 2015; Alonso et al. 2015; **?**). Curiously, higher mass stars appear *younger* in the MRD, whereas lower mass stars appear *older* in the MRD (Feiden 2016). **Our simple, standard picture of early stellar evolution is unable to provide a robust age for a *single star*.** This revelation strongly indicates that fundamentally important physics are absent from stellar evolution models.

The difficulty is identifying which physics are missing from the models. Several mechanisms have been proposed to explain the observed luminosity spreads in HRDs of the youngest clusters, including episodic accretion (Baraffe et al. 2009; Baraffe & Chabrier 2010) and starspots (Somers & Pinsonneault 2015). However, until recently, there had not been a convincing demonstration of a physical mechanism to explain the observed age gradients with effective temperature or the mismatch between HRD and MRD age estimates. There has only been speculation, which was focused on uncertainties in descriptions of convection and the absence of magnetic fields and starspots (Stassun et al. 2014; Soderblom et al. 2014; Herczeg & Hillenbrand 2015).

Recently, our group demonstrated that magnetic fields may provide a viable explanation for observed surface-temperature dependent ages in young clusters and the discordance between HRD and MRD age estimates (see Figure 2; Feiden 2016). The hypothesis is that Lorentz forces generated by strong magnetic fields suppresses convective flows in young stars, which acts to cool the stellar surface (e.g., D'Antona et al. 2000; Mullan & MacDonald 2001; Feiden & Chaboyer 2012). As a result, the contraction of young pre-main-sequence stars is delayed, meaning young

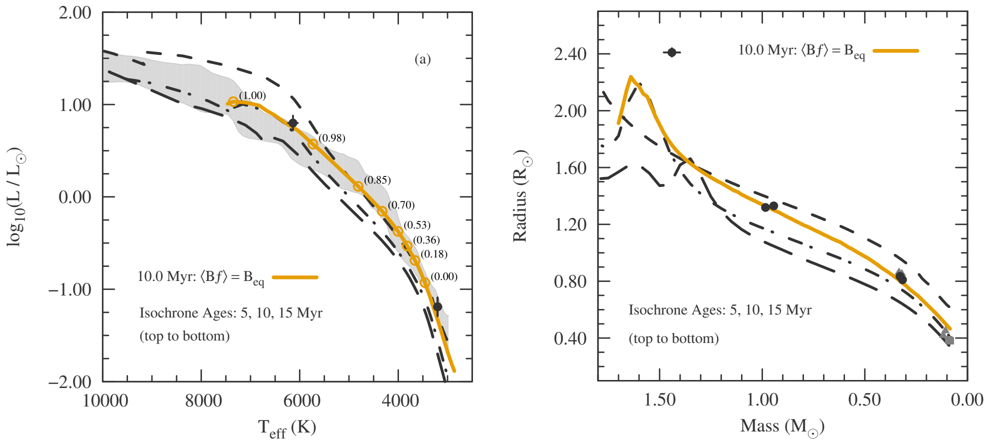

Figure 2: (*left*) HR diagram of Upper Scorpius with components of eclipsing binary systems UScoCTIO5 (Kraus et al. 2015) and HD 144548 (Alonso et al. 2015) observed by *Kepler*/K2 (black points). A 10 Myr magnetic stellar evolution isochrone is shown by the solid blue line. Note that the 10 Myr magnetic isochrone lies on top of the 5 Myr standard isochrone. (*right*) Mass-radius relationship for Upper Scorpius from *Kepler*/K2 eclipsing binary systems. *Unlike standard models, magnetic stellar evolution models naturally reproduce the slope of the low-mass mass-radius relationship at the same age predicted from the HR diagram.*

stars have cooler temperatures and larger radii at a given age when magnetic inhibition of convection is included in model calculations (MacDonald & Mullan 2010; Feiden 2016). The physical mechanism is analogous to formation of sunspots, where strong magnetic fields suppress convection causing the stellar plasma contained within a magnetic region to cool and thus appear darker than its surroundings (Biermann 1941; Deinzer 1965).

Previous investigations showed that magnetic inhibition of convection could relieve age discrepancies for the 25 Myr old β Pictoris moving group (MacDonald & Mullan 2010; Malo et al. 2014). Ages inferred from the HRD of the β Pictoris moving group using standard stellar evolution models indicated the group was 12 Myr old, while the same models provided an age of 20 Myr based on the lithium depletion boundary (**??**). However, by including magnetic inhibition of convection, MacDonald & Mullan (2010) and Malo et al. (2014) showed the two age estimates could be brought into rough agreement with an age between 25 – 30 Myr.

Magnetic models were successful at reconciling the two age estimates, but it was not clear whether the magnetic models were accurate because HRD and lithium depletion boundary studies are mass agnostic. To know whether magnetic models predict accurate properties for real stars, EBs in well-studied young clusters are needed. Masses and radii measured in EBs provide the most stringent tests of stellar models as mass is the primary model input and measured radii are more reliable than $T_{\rm eff}$ and luminosity estimates. In addition, finding EBs in young clusters would provide an opportunity to confirm the MRD age estimate against an age inferred from an HRD.

A source of EBs in a well-studied young cluster became available when *Kepler*/K2 observed the Scorpius-Centaurus OB Association for 80 continuous days. A number of EBs were quickly identified, including two EBs for which precise masses and radii were determined (Kraus et al. 2015; Alonso et al. 2015). Critically, the two EBs occupied two distinct regions of the MRD, as shown in the right panel of Figure 2. Comparing the mass-radius relation formed by these EBs, it is clear that standard models predict an incorrect slope for the mass-radius relationship and that the ages inferred from the MRD did not agree with ages inferred from the HRD.

We showed that including magnetic inhibition of convection in stellar models calculations produces

The recent results of Feiden (2016) are tantalizing, as they offer a path toward reliable young stellar ages, but important questions remain about the validity and accuracy of these "magnetic stellar evolution models." First, properties of the magnetic field are prescribed in a rather ad-hoc fashion (Feiden & Chaboyer 2012, 2013). Simple functions are used to describe the magnetic field strength as a function of radius deep in a star (Feiden & Chaboyer 2013), but the situation in real stars is far more complex and depends intimately on the precise structure and rotational velocity of the star (Browning 2008; Brown et al. 2010). Second, the interaction of Lorentz forces on convection depend strongly on the magnetic field topology throughout the star (Feiden & Chaboyer 2013). At the moment, models use a free parameter to describe an average magnetic field topology, but the parameter is fixed and not allowed to vary as would be expected for a real magnetic field (Feiden & Chaboyer 2012). Finally, the existing magnetic field framework requires the specification of the surface magnetic field strength (Feiden & Chaboyer 2012). This value is either chosen arbitrarily (Feiden & Chaboyer 2012, 2013, 2014a,b), or at best, order of magnitude estimates are used to describe a possible maximum value (Feiden 2016).

The full effect of these modeling choices are felt when stars are allowed to evolve in time. Properties of the magnetic field are a function of the stellar structure and stellar rotation, which both vary over time. Therefore, magnetic fields are expected to also evolve in time. These subtleties cannot be captured with existing magnetic model formulations and it remains unclear what the effect of an evolving magnetic field will have on stellar structure and evolution (Feiden 2016). Ultimately, a complete description of how magnetic fields affect stellar structure would include a physical mechanism that relieves these ad-hoc prescriptions.

Describing how magnetic field generation depends on stellar structure and rotation is within the realm of magnetic dynamo theory. Dynamo theory describes the interaction between predominantly radial convective flows and azimuthal rotation, which are suitable for generating and sustaining magnetic fields. The general picture is that the poloidal component of the magnetic field is stretch into a toroidal configuration by latitudinally differential rotation (Ω effect) while turbulence associated with convection tends to stretch and twist the toroidal magnetic fields back into a poloidal component (α effect; e.g., Parker 1955). The Ω effect are well established, but details of the α effect remain open to debate (Pipin 2012). Nevertheless, simulations that model the formation and time evolution (over decade timescales) of magnetic fields are sufficiently mature to permit reliable estimates of the magnetic field strength and topology for a given star (Brandenburg et al. 2012).

3. Proposed Research: Grids of Magnetic (sub)Stellar Evolution Models

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7. Biographical Sketches

Gregory A. Feiden

Education:

2008 – 2013	Ph.D. (Physics & Astronomy)	Dartmouth College
2004 – 2008	B.S. (Physics)	State University of New York at Oswego

Appointments:

2016 –	Assistant Professor of Astronomy	University of North Georgia
2015 – 2016	Research Scientist	Uppsala University
2013 – 2015	Postdoctoral Fellow	Uppsala University
2012 – 2013	Gordon F. Hull Graduate Fellow	Dartmouth College
2011 – 2012	Neukom Graduate Fellow	Dartmouth College

Awards:

2013 – 2015	Uppsala U. Postdoctoral Fellowship, Physics & Astronomy	840 000 SEK
2012 – 2013	Gordon F. Hull Graduate Fellowship	26 000 USD
2011 – 2012	Neukom Institute for Computational Science Fellowship	26 000 USD

Experience & Expertise:

List everything here.

Relevant Publications:

1. **Feiden, G. A.** *Magnetic Inhibition of Convection and the Fundamental Properties of Low-Mass Stars. III. A Consistent 10 Myr Age for the Upper Scorpius OB Association*, 2016, A&A, in press.
2. Mann, A. W., Newton, E. R., Rizzuto, A. C., Irwin, J., **Feiden, G. A.**, Gaidos, E., Mace, G. N., Kraus, A. L., James, D. J., Ansdell, M., Charbonneau, D., Covey, K. R., Ireland, M. J., Jaffe, D. T., Johnson, M. C., Kidder, B., & Vanderburg, A. *Zodiacal Exoplanets in Time (ZEIT) III: A Neptune-sized planet orbiting a pre-main-sequence star in the Upper Scorpius OB Association*, 2016, ApJ, in press.
3. Stassun, K. G., **Feiden, G. A.**, & Torres, G. *Empirical Tests of Pre–Main–Sequence Stellar Evolution Models with Young Eclipsing Binary Stars*, 2014, New Ast. Rev., 60, 1.
4. Torres, G., Lacy, C. H. S., Pavlovski, K., **Feiden, G. A.**, Sabby, J. A., Bruntt, H., & Viggo Clausen, J. *The G+M Eclipsing Binary V530 Orionis: A Stringent Test of Magnetic Stellar Evolution Models for Low–Mass Stars*, 2014, ApJ, 797, 31.

5. Malo, L., Doyon, R., **Feiden, G. A.**, Albert, L., Lafrenière, D., Artigau, É., Gagné, J., & Riedel, A. *BANYAN. IV. Fundamental Parameters of Low-Mass Star Candidates in Nearby Young Stellar Kinematic Groups—Isochronal Age Determination Using Magnetic Evolutionary Models*, 2014, ApJ, 792, 37.
6. **Feiden, G. A.** & Chaboyer, B. *Magnetic Inhibition of Convection and the Fundamental Properties of Low-Mass Stars. II. Fully Convective Main Sequence Stars*, 2014, ApJ, 787, 53.
7. **Feiden, G. A.** & Chaboyer, B. *Magnetic Inhibition of Convection and the Fundamental Properties of Low-Mass Stars. I. Stars with a Radiative Core*, 2013, ApJ, 779, 183.
8. **Feiden, G. A.** & Dotter, A. *The Interior Structure Constants as an Age Diagnostic for Low-Mass, Pre-Main-Sequence Detached Eclipsing Binary Stars*, 2013, ApJ, 765, 86.
9. **Feiden, G. A.** & Chaboyer, B. *Self-Consistent Magnetic Stellar Evolution Models of the Detached, Solar-Type Eclipsing Binary EF Aquarii*, 2012, ApJ, 761, 30.
10. **Feiden, G. A.** & Chaboyer, B. *Reevaluating the Mass-Radius Relation for Low-Mass, Main Sequence Stars*, 2012, ApJ, 757, 42.

Advisors and Advisees:

Graduate and Postgraduate Advisors: Brian Chaboyer (Dartmouth), Nikolai Piskunov (Uppsala), Susanne Höfner (Uppsala)
Graduate Advisees: Steven Christophe (Paris-Sud / Uppsala)
Undergraduate Advisees: Jaquille Jones (Dartmouth), Jonas Engman (Uppsala)

8. Current and Pending Support

8.1 Gregory A. Feiden

8.1.1 Current

None

8.1.2 Pending

Title: “The Exoplanet Migration Timescale from Young Clusters in K2”
Admin PI: Dr. Adam L. Kraus
Science PI: Dr. Aaron C. Rizzuto
Program Name: ROSES-2016/Astrophysics Data Analysis Program
Sponsoring Agency: NASA
Contact: Douglas M. Hudgins, (202) 358-0988, Douglas.M.Hudgins@nasa.gov
Performance Period: 01/01/2017 – 12/31/2018
Total Budget: $252,385.00
Commitment by PI: < 1 month during the 2017 and 2018 academic years for determining stellar parameters using standard and magnetic models. Supported by the PI’s 9 month salary.

Title: “The Mass-Radius Relation of Young Stars from K2”
Admin PI: Dr. Adam L. Kraus
Science PI: Dr. Adam L. Kraus
Program Name: ROSES-2016/Astrophysics Data Analysis Program
Sponsoring Agency: NASA
Contact: Douglas M. Hudgins, (202) 358-0988, Douglas.M.Hudgins@nasa.gov
Performance Period: 01/01/2017 – 12/31/2018
Total Budget: $234,545.00
Commitment by PI: < 1 month during the 2018 academic year to provide custom models with magnetic fields. Supported by the PI’s 9 month salary.