

Ages of Young Stars and the Early History of Dynamo-Generated Magnetic Fields

Astrophysical phenomena generally occur over time periods inaccessible to even the most patient human. Typical timescales range from thousands to billions of years. Nevertheless, time dependence is a vital component in our understanding astrophysical processes. Instead of monitoring a single system over time, astronomers gain insight into the time dependence of astrophysical phenomena by considering an ensemble of systems at different ages. Individual systems provide snapshots in time and a chronological ordering produces a stop-motion film of various processes across cosmic time. Accurate absolute ages are therefore the most sought after astrophysical quantities. This is particularly true for young systems, where ages provide critical constraints on the formation of stars, planets, and objects in-between. However, despite their importance, accurate ages for young systems remain elusive.

Purpose and Aims

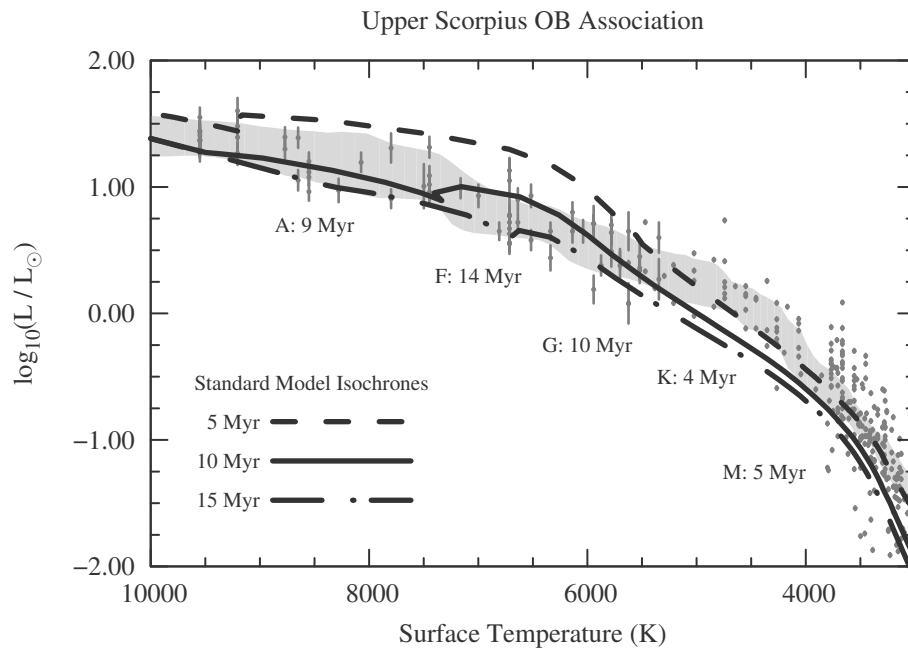


Figure 1: Caption.

Survey of the Field

- Age-dating problems for young stars. (i.e., model inconsistencies)
- Identification / inclusion of magnetic fields in models. (D'Antona, MacDonald, Feiden)
- Magnetic field observations. (e.g., MDI, ZDI)
- Open questions.

Project Description

P1. Dynamo-Generated Magnetic Fields throughout Stellar Evolution

Describe coupling of stellar evolution and mean-field dynamo theory.

SP1. Pre-Main-Sequence Evolution

Magnetic inhibition of convection, magnetic field topology, rotational evolution, activity cycles.

SP2. Main-Sequence Evolution

Rotational evolution, wind breaking, magnetic field topology, activity cycles.

SP3. Post-Main-Sequence Evolution

Depletion of hydrogen in stellar cores eventually reaches a level... Stars begin to traverse across the HR diagram along the sub-giant branch and up the first-ascent red giant branch once hydrogen shell burning ceases. Stars more massive than approximately 1.2 Msun possess a convective core along the hydrogen burning main sequence that is able to sustain a dynamo-generated magnetic field (Featherstone et al 2009; Augustson et al 2016). Upon leaving the main sequence, however, convection in the stellar core rapidly subsides (8 Myr). The fate of the dynamo-generated magnetic fields produced by the convective core during this period of rapid transition off the main-sequence is unexplored.

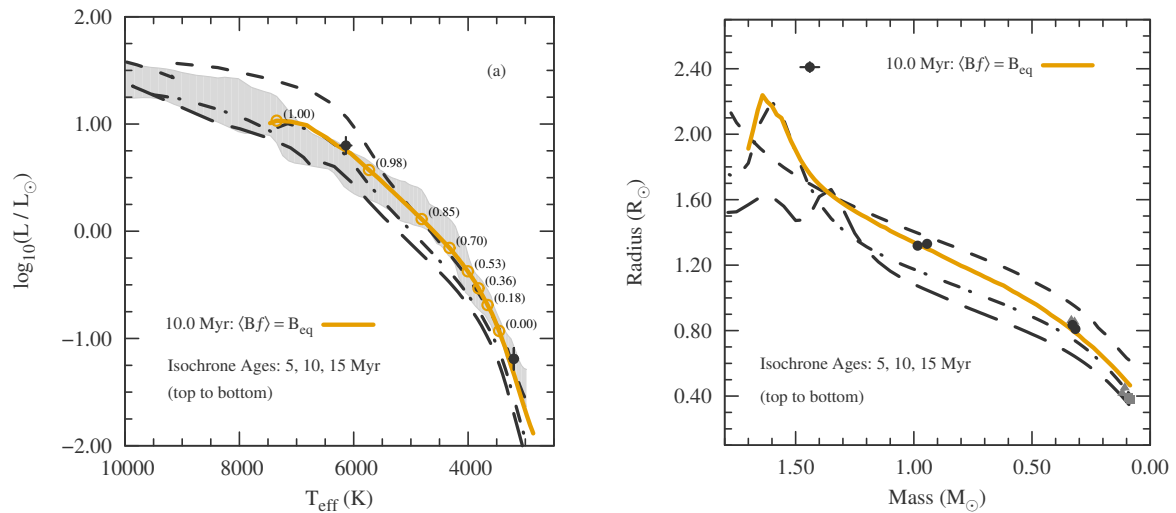


Figure 2: Caption.

There is indirect evidence from asteroseismology that remnant magnetic fields exist in the convectively stable cores of in a fraction of red giant branch stars. Most red giant branch stars observed by Kepler pulsate at specific frequencies that are characteristic of a coupling between wave-modes generated in the radiative stable core and modes created in convectively unstable outer envelope. However, a fraction of stars in the Kepler exhibit a very weak, if not non-existent, coupling between these wave modes (Fuller et al 2015). The current hypothesis is that strong magnetic fields left over from the dynamo-generation process inhibit the propagation of g-modes in the radiative core, ultimately suppressing the coupling of modes between the core and envelope (Fuller et al 2015; Cantiello et al 2016).

We will study how the strength and topology of dynamo-generated magnetic fields evolve in the cores of intermediate-mass stars leading up to, during, and following their transition off the main sequence.

P2. Dynamo-Generated Magnetic Fields in Brown Dwarfs and Giant Planets

P3. Fundamental Properties of Young Single Stars

Confronting model predictions of young star properties as a function of age using a large number of stars characterized with spectro-bolometric techniques (CALYPSO) and young eclipsing binaries observed by Kepler/K2. [Hawaii; UT Austin]

Ages from the HRD rely on using fundamental stellar properties (radius, luminosity, T_{eff}) of a system of stars as comparison quantities. CMDs are incredibly useful tools for deriving ages, but as we've seen, are subject to several uncertainties. Using the HRD removes the uncertainty of converting model properties to colors and magnitudes. One is then interested to know whether stellar evolution models predict accurate fundamental properties for stars, thereby permitting accurate age determinations.

Previous investigations have found that young stellar models are unable to accurately predict effective temperatures and luminosities for stars at a given mass (e.g.,). These studies have focused on astrometric and eclipsing binaries (EBs), making it difficult to rule out whether binarity is playing a role in driving disagreements. Even wide binaries may be subject to subtle interactions that corrupt agreement with models. Recently, Stassun et al. (2014) showed that,

while binarity in and of itself may not be a problem, model errors appear to be correlated with the presence of a tertiary companion. Triplicity among the same of EBs in Stassun et al. (2014) was well above 50%, reducing the sample of potentially reliable comparisons to models and biasing our understanding of whether young models are accurate for predicting properties of single stars.

Therefore, we will create the first collection of single young benchmark stars, whose fundamental properties will be measured with high precision (better than 5% for young stars; Stassun et al. 2014). To derive stellar properties, collaborators Mann and Gaidos are obtaining ground-based, flux-calibrated spectra of bright K- and M-dwarfs in the nearby YMGs, the Pleiades, and Coma Berenices. Flux-calibrated spectra will be used to derive bolometric fluxes and effective temperatures, leading to empirical estimates of stellar radii. This technique was proven to be robust for assessing stellar evolution model reliability for main sequence field K- and M-dwarfs (Mann et al. 2015). Our current target sample contains 130 stars, twelve of which have already been observed and have preliminary properties.

Comparison of properties of benchmark stars to stellar models will be done using Bayesian inference to derive best fit model properties with uncertainties, as was performed in Mann et al. (2015) for main sequence stars. We will then explore how well models reproduce the observed data and whether there are any noticeable correlations with additional observables, such as magnetic activity indicators, inferred age, chemical composition, and the convective mixing length parameter. Since we are targeting stars that are members of known YMGs and clusters, we will also check for internal consistency, ensuring that models are yielding the same ages and distances to stars from a common group. If there are inconsistencies, we will attempt to characterize them in terms of observables and inferred stellar model parameters.

P4. Homogeneous Ages for Young Stellar Associations

Deriving homogeneous ages for young stellar associations using available literature data. Provides constraints on a number of interesting astrophysical phenomena. [partially with UT Austin; Stockholm]

Informed by results obtained in work packages 1 and 2, we will bring together all of the information and try establish ages for young stellar systems that are consistent for different age measures, in both the HRD and CMDs. The age determinations will fold in all necessary ingredients, starting with a base set of standard young stellar models and exploring whether magnetic fields, starspots, or chemical composition are able to provide complete agreement for each system. We'll explore the possibility that the appropriate mix of ingredients from work package 1 and other modified physics from work package 2 lead to consistent ages for all systems or if there are correlations among the mix of ingredients and stellar system parameters like age.

To avoid being entirely dependent on the success of WP01 and WP02, we will begin an initial effort characterizing how magnetic stellar models developed by GAF perform in terms of predicting consistent ages given different age indicators. Notably, consistency between high- and low-mass regions of CMDs and the HRD, as well as the lithium depletion boundary. We have preliminary results using a single eclipsing binary in Upper Sco (Kraus et al. 2015) that indicates magnetic models may provide favorable consistency between different mass regimes and between different age indicators for the binary alone (see Figure 2). We will therefore try to develop a more complete analysis of Upper Sco, including more archival data, and other nearby YMGs to determine the robustness of the solution. We will also provide our magnetic

models to the community to permit additional independent efforts to evaluate the success or failures of these models.

Results of this exercise will be important, whether or not we are able to derive consistent ages or the different stellar systems. If we can derive consistent ages, then that will provide strong support for those derived ages, at least for the moment, which will become a powerful resource for the astronomical community. If we cannot, then we learn that there is yet something missing from models or that our initial hypothesis that low-mass stars are to blame for the systematic age differences observed in young stellar systems is incorrect.

Finally, this sub-project requires production of a grid of pre-main-sequence magnetic stellar models. Since the grid will be produced concurrently with the above studies, no additional time will be required. Local clusters at Uppsala will provide computational resources necessary and the PI is applying for time with SNIC, the Swedish high-performance computing center. All models, data products, and analysis tools will be made publicly available.

Significance

- Ages of Young Stars
 - protoplanetary disk evolution timescales
 - giant planet formation timescales
 - star formation history, including time dependence of IMF
 - properties of directly imaged planets and brown dwarfs (mass distribution → formation)
- Magnetic Field Evolution
 - activity cycles → astrobiology (stretch?)
 - angular momentum transport and stellar rotational evolution
 - accurate stellar properties
 - * ages and masses of single stars
 - * properties of transiting extrasolar planets
- Grid of Stellar Models
 - available to public
 - allows extensive testing of theory
- Relevance for Next-Generation Surveys

Preliminary Results

Feiden (2016, submitted). Identification of magnetic fields as culprit for age discrepancies.

Pilot study for the Sun (and low-mass star?).

Feiden & Christophe (in preparation). Parametrized model of starspots.

Stars characterized for CALYPSO thus far.

Independent Line of Research

- Calibration of Low-Mass Young Stars and their Planetary Systems with Observations (CALYPSO): second avenue of research is characterizing planets around young stars. Feiden (projectledare) provides a comprehensive analysis of host stars using stellar models coupled with Bayesian inference to give stellar mass, age, and distance estimates with realistic uncertainties.
- 4MOST Internal Working Group 7 – Galactic Analysis Pipeline – providing stellar structure and atmosphere code for self-consistent determination of atmospheric parameters, mass, and ages for over 1 million stars.
- Zodiacal Exoplanets in Time (ZEIT).

International and National Collaborations

- Confirmed Star formation group at UT Austin (Kraus, Rizzuto). Fundamental properties of young stars using B- through M-type EBs in young associations with Kepler/K2. Magnetic fields of young stars with IGRINS.
- Confirmed CALYPSO: Calibration of Low-mass Young stars and their Planetary Systems with Observations (Mann [UT Austin], Gaidos [Hawaii], Ansdell [Hawaii]). Fundamental properties of bona fide members of nearby young moving groups using "spectro-bolometric techniques."
- Pending MDI/ZDI research group at ESO (Hussain, Lavail). Magnetic field topologies for young T-Tauri stars that can be compared against predictions from models in P1 with age information from P3.
- Pending MDI/ZDI research group at Uppsala (Kochukhov, Rosén). Magnetic field topologies for young solar analogs in young stellar associations.
- Confirmed Open Cluster collaboration (Silvester, Landstreet). Magnetic field topologies for intermediate mass stars in several young stellar associations.
- Pending Disk group at Stockholm (Janson)? Provide models to compute ages of directly imaged extrasolar planets and systems with circumstellar disks.

Other Grants