Stellar Age Estimation from ~3 Myr to ~3 Gyr

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Introduction

In contrast to mass, radius, and angular momentum which are -- for a limited set of stars at present -- derivable through fundamental observables such as orbital motion, eclipses, and period measurements, stellar ages have no firm basis or anchor other than in the case of the Sun for which radiometric dating of primitive solar system materials is possible. Yet, stellar ages are critical to establish for investigations such as the time scales for formation and long term evolution of planetary systems. We present recent progress on quantitative estimation of stellar ages using tools such as theoretical evolutionary tracks, rotation, rotation-driven activity diagnostics, and lithium depletion.

Our focus is on roughly solar-mass and solar-metallicity stars younger than the Sun. We attempt to characterize the systematic and random error sources and then derive ``best'' ages along with the age dispersion arising among the age estimation methods.

We also present an application of our techniques to the evolution of debris disks.

Age Dating Methods

- Hertzsprung-Russell diagram. Among stars younger than the Sun, this purely theoretical age estimator is useful only for those <20-30 Myr old, i.e. in the pre-main sequence phase. Track-dependent systematics can be large.

- Chromospheric activity. $R'_{HK} = (L_{HK}/L_{bol})$ ranges over only ~1 dex, from 10^{-4} to 10^{-5} with saturation above -4.35 dex; increasing rotation leads to relatively little increase in CaII H&K line emission activity.

- Coronal activity. $R'_{xray} = (L_{xray}/L_{bol})$ ranges over ~4 dex, from 10^{-3} to 10^{-7} with saturation above -4.0 dex; increasing rotation leads to relatively little increase in soft x-ray activity.

- Rotation. The chromospheric and coronal activity are rotation driven. Periods range from <1 to >40 days; projected velocities range from >150 to <2 km/s. Stellar rotation has maximum spread around the age of Alpha Per (~80 Myr), likely related to dispersion in previous history of disk presence and lifetime, with standard main sequence spin-down thereafter.

- Lithium. Depletion of light elements is a chronometer independent of the others above. Li I λ6707 is required for youth but generally has a factor of two empirical spread at constant age and mass.

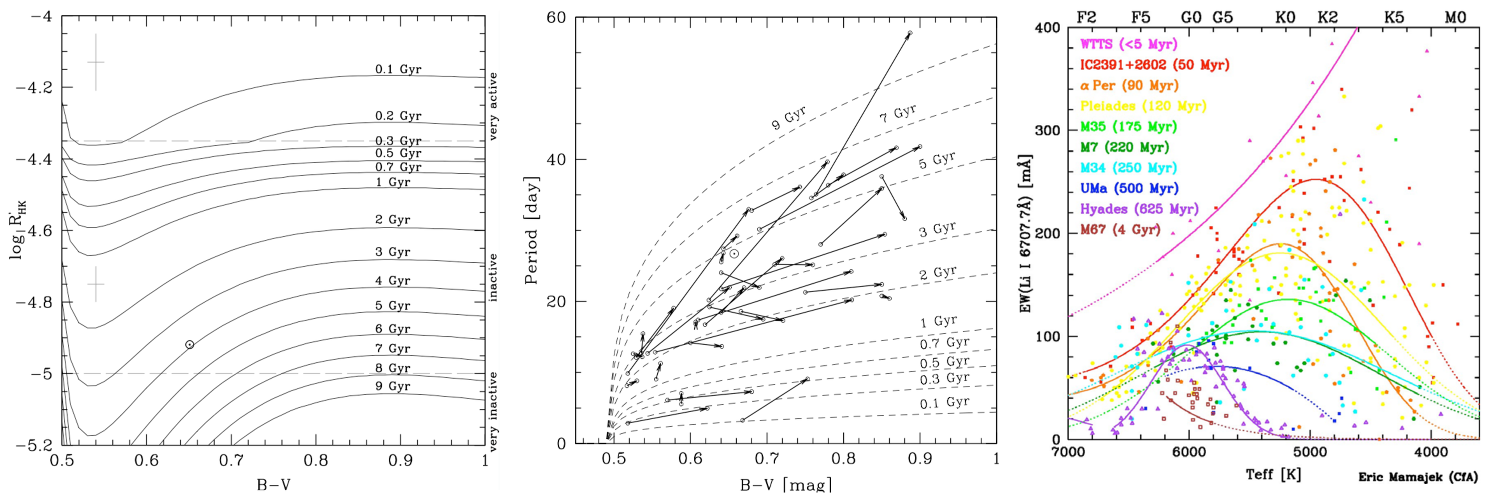
Behavior of each of the above with age is mass dependent!

Calibration Samples

Our calibrations are established using critically scrutinized samples of:
- Open cluster stars
- Visual binaries

See poster by *Eric Mamajek* for equations and demonstration of the 0.2 dex or better accuracy in our new activity-rotation-age calibrations for stars aged between the Hyades (600 Myr) and the Sun (4560 Myr). At younger ages, accuracy is only 0.3-1.0 dex and the Li I and H-R diagram methods may be more accurate.

Activity-Rotation-Lithium with Age



New *color-dependent* activity-age, rotation-age, and lithium-age calibrations from Mamajek & Hillenbrand (2008) and Mamajek et al. (2009) appear above.

- **Left panel**. We have updated the existing Soderblom (1991), Donahue et al. (1993) and Lachaume et al. (1999) chromospheric activity relations, populating the high activity end for the first time and using modern open cluster ages. We have also updated the Sterzik & Schmitt (1997) coronal-chromospheric correlations and tied both activity indicators through the Rossby number to rotation.

- **Middle panel**. We have corrected the Barnes (2007) gyrochronology relations to match the Pleiades, Hyades, and Sun, and show consistency with binary pairs.

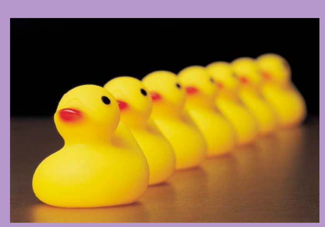
- **Right panel**. We consider the lithium depletion trends in young clusters and devise a probabilistic age estimator that accounts for the observed dispersion.

Recommendations

- Cluster membership most securely establishes a stellar age.
- The H-R diagram can and should be used at <20-30 Myr, with confirmation of youth coming from other activity/lithium diagnostics.
- Lithium buffered by activity/rotation diagnostics can be used ~30-200 Myr.
- Activity/rotation is most useful for slow rotators, age >200 Myr.

- ***Learn to live with 50-150% age ambiguity for field stars younger than the Sun!!***

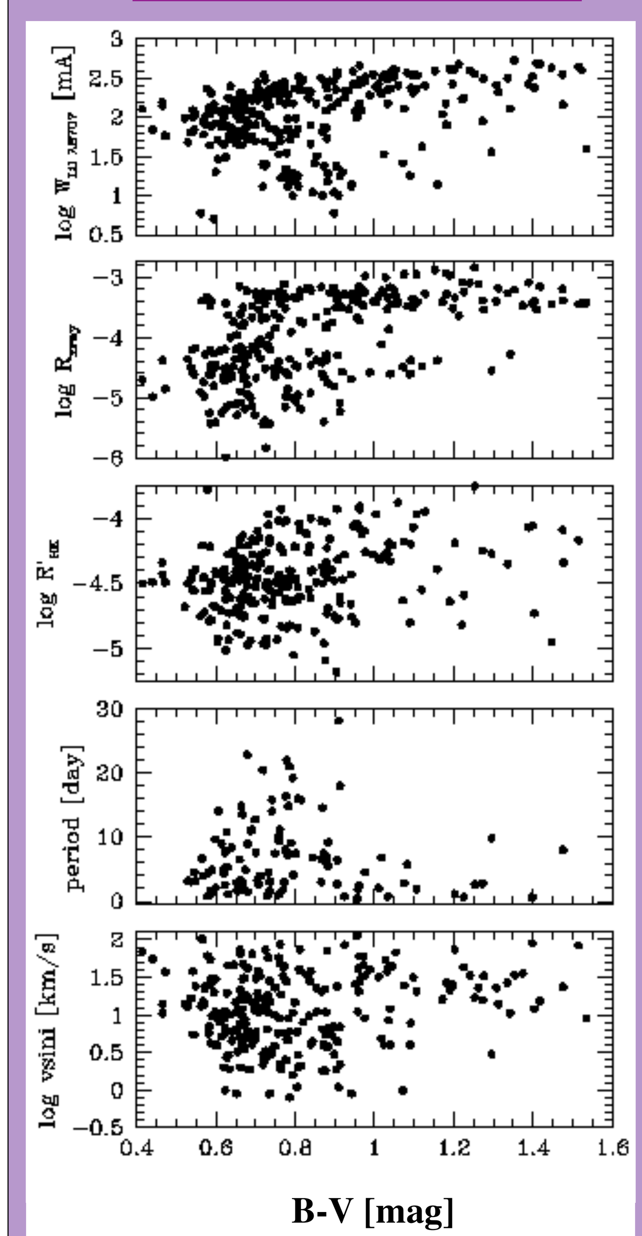
Young Field Star Results

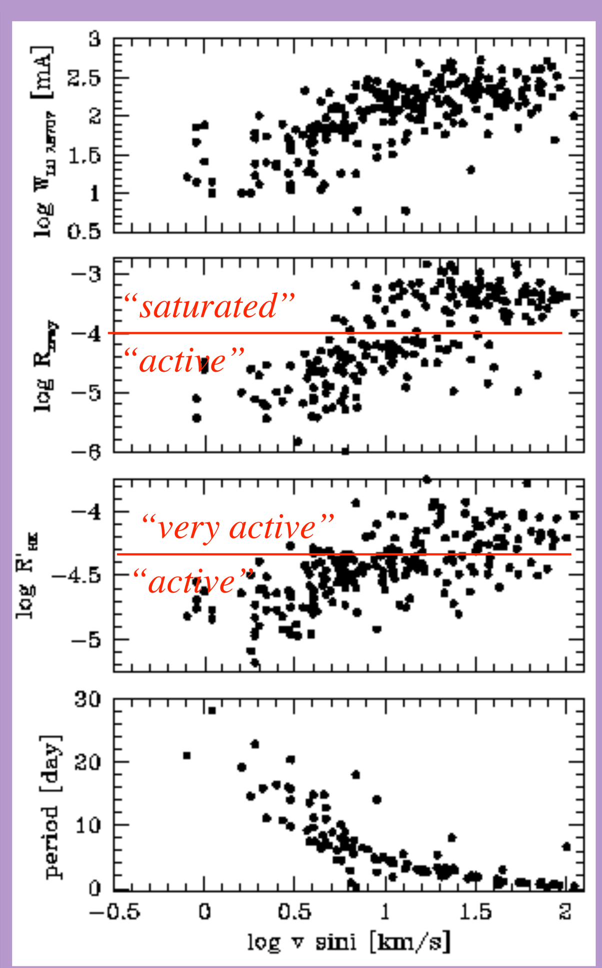


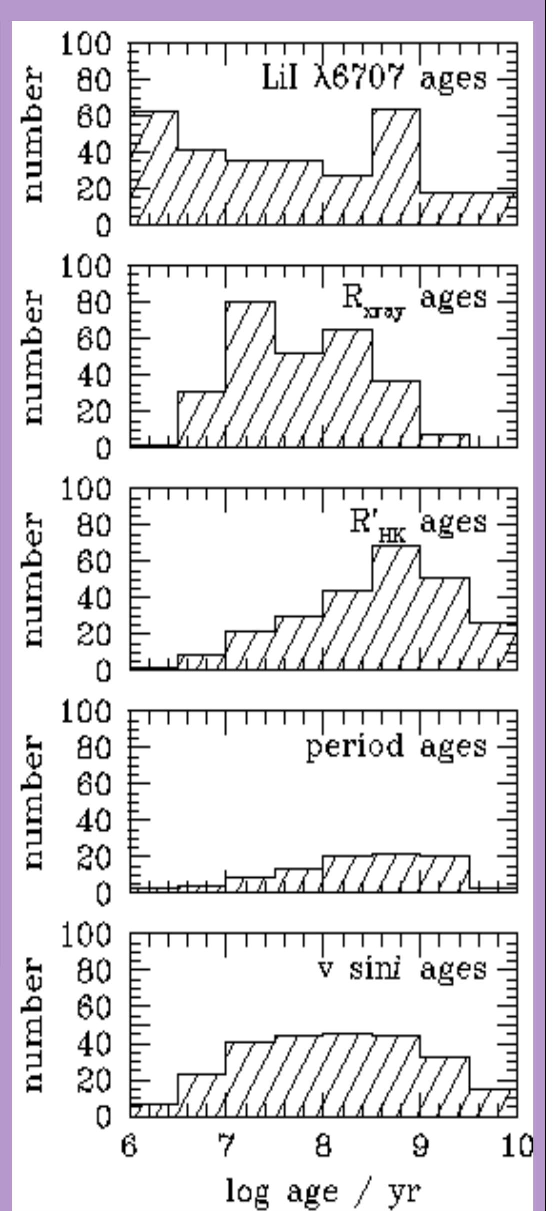
Among our field star sample there is a large spread at any given color in every age diagnostic, reflecting the spread in age as well as astrophysical dispersion.

The empirical age indicators are well correlated with one another and their dispersion highlights the astrophysical spread plus the color effects.

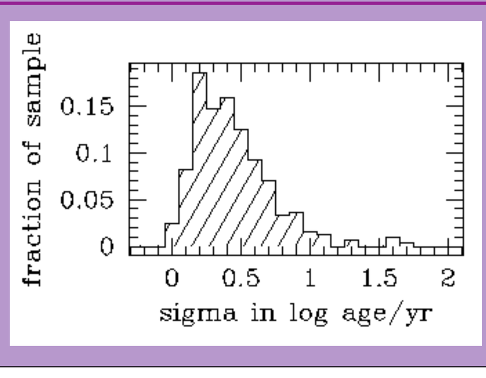
Histogram of ages resulting from each technique. Note that the sub-samples are different in each of the panels since not all stars have all five measurements.

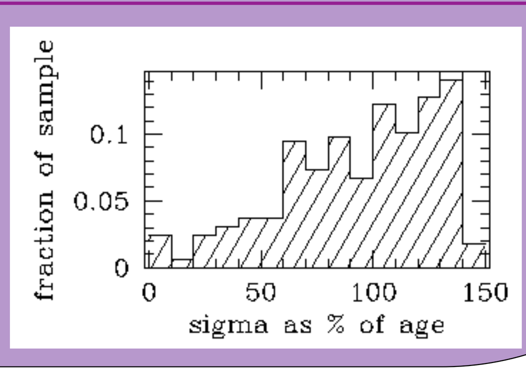




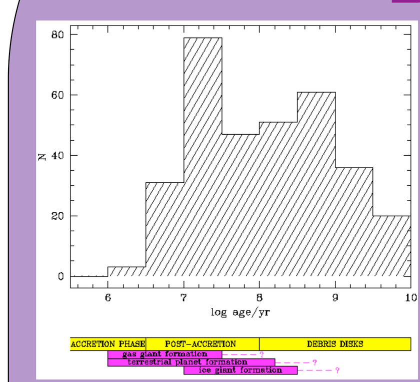


Dispersion in age resulting from application of the ensemble of age estimation techniques to each star. All stars older than 200 Myr have σ(age) = 0.25±0.25 dex while the tail to higher dispersion is populated by younger objects.





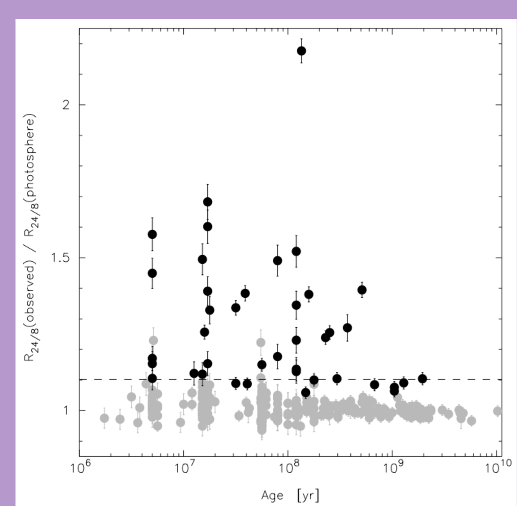
Application to Debris Disk Evolution

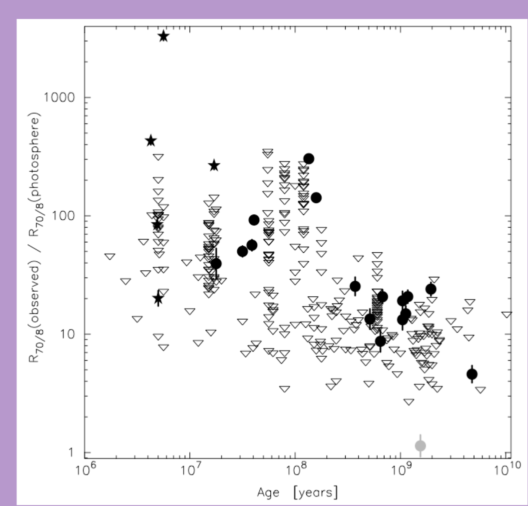


Results from Carpenter et al. (2008) on the evolution of dust signatures from debris disks as studied in the Spitzer/Legacy program FEPS (Meyer et al. 2004) rely on knowledge of stellar ages.

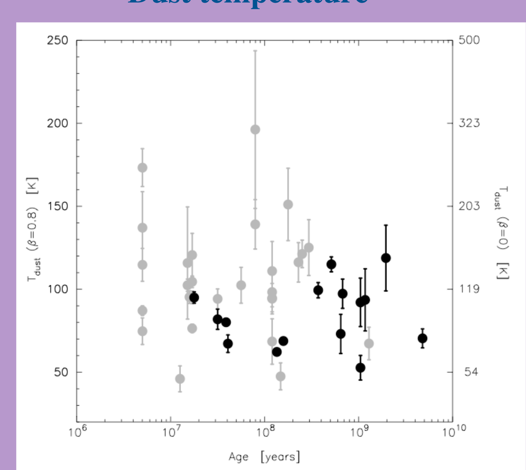
The final FEPS age distribution!

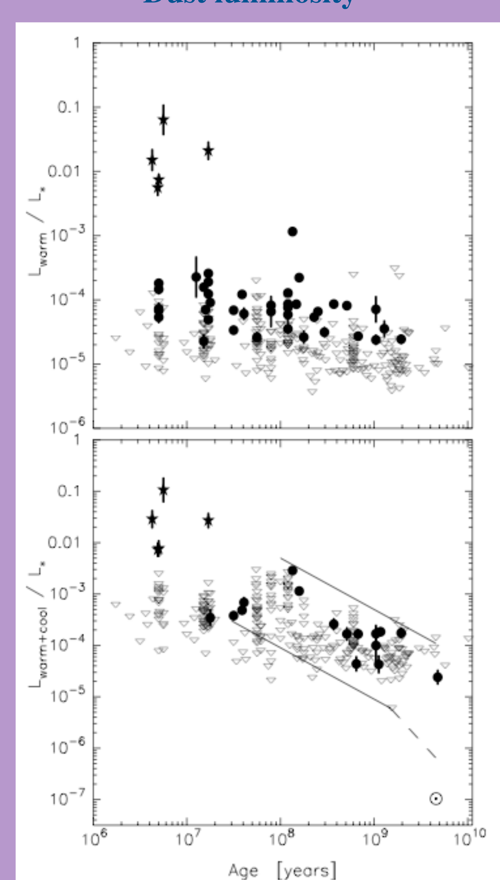
Evolution of empirical quantities.



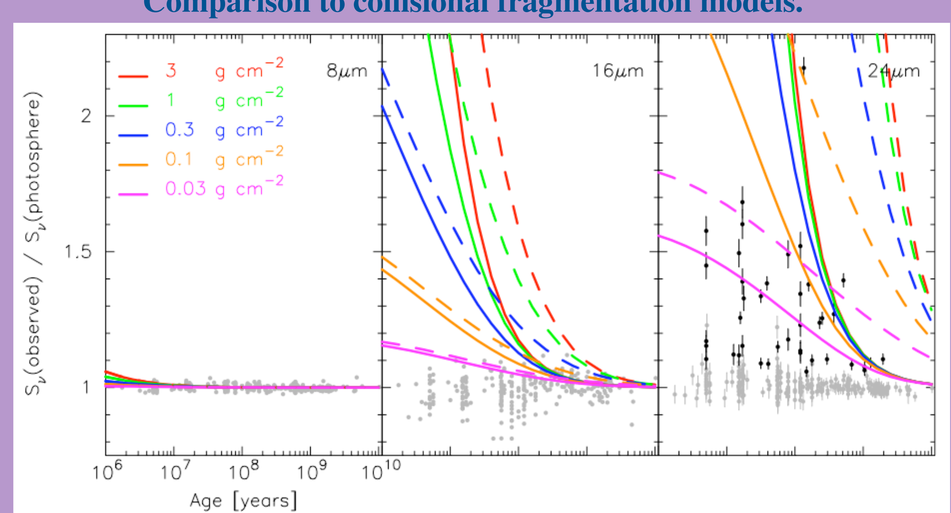


Evolution of derived / physical quantities.





(Dark symbols indicate sources detected at 70 um.)



Debris Disk Science Results: ~300 Myr appears to mark a transitional time in debris disk evolution as evidenced by breaks in dust detection frequency and luminosity. Older stars have weaker disks, roughly consistent with steady state collisional evolution models. At least 15% of solar type stars form debris disks but with inner cleared regions several tens of AU in size and surface densities 3-10 times lower than that inferred for the young Kuiper Belt.