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Ages of Young Main and Pre-Main Sequence Stars on the FEPS Spitzer Legacy Program

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1. Introduction

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At present this file includes background material
and a rough-but-improving sketch of what we plan to do.
It is a work in progress and commentary is most welcome.
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The age of the Sun is assumed to be approximately the same as that of the oldest securely dated bodies in the solar system. Such meteoritic ages are known to an impressively high degree of accuracy from analysis of radioactive decay of various elements. The Sun itself, however, as well as all other stars, are age dated through astronomical techniques, not geological, and the uncertainties are far larger. Recent discussions of the various techniques for estimating stellar ages include those by Ayres (1997), Gaidos (1998), and Lachaume et al (1999). For solar-type stars, age indicators fall into five main categories.

First, position on the Hertzsprung-Russell diagram may be related to age through theoretical models. For stars in the pre-main sequence or post-main sequence phases of stellar evolution a unique (though inaccurate due to systematics in the still imperfect input physics) age may be determined. For stars on the main sequence a lower limit to the age is derived for those stars with turn-off ages older than the age of the universe, while for younger main sequence stars both lower and upper limits are found. Second, stellar rotation and its proxies coronal activity and chromospheric activity can provide meaningful constraints on stellar ages. A relationship between rotation and dynamo-driven activity is expected theoretically, based on the conversion of mechanical to magnetic energy, though the calibration to stellar age is derived from empirical correlations of observed quantities. Such observational correlations were first presented in a short (two pages!) paper by Skumanich (1972). Mass is also an important parameter which determines the properties of the convective zone and hence the efficiency of the rotation-activity connection. On the main sequence the calibrations are generally of a two-part form, first relating luminosity or fractional bolometric luminosity in an activity index to rotation, $(F_{index}(v)/F_{index,\odot}) \propto (v/v_\odot)^{\alpha_1}$, and then rotation to age, $(v(\tau)/v_\odot) \propto (\tau/\tau_\odot)^{\alpha_2}$, scaled here to the solar values. The power law index on the activity relationship decreases from the high excitation x-rays through the lower excitation ultraviolet and then optical lines (Ayres et al. 1981; Simon et al. 1985). For very young main sequence and pre-main sequence stars however, the rotational history is more complex and, furthermore, the activity indicators are saturated with more rapid rotation and/or deeper convection producing no additional coronal/chromospheric emission (due to the stellar surface being completely covered with active regions?). Third is the depletion of lithium which is destroyed via nuclear burning at the base of the convection zone; stellar rotation may play a role here as well. Lithium studies are, again, largely empirically based due to the lack of convergence between depletion models and observations. Fourth and fifth are stellar kinematics and metallicity which can be statistially but not quantitatively related to stellar age. We only briefly consider these as age indicators.

In this paper we study a sample of field and cluster stars with astrophysical data sufficient for investigation of age constraints. Our specific targets are members of the Spitzer Legacy program entitled The Formation and Evolution of Solar Systems (FEPS). We employ HR diagrams, rotation, x-ray emission, Ca II H&K emission, Hα emission, and Li I absorption as age diagnostics. Our approach is to calibrate the various age indicators using well-studied nearby young open clusters having well-determined ages, and to then apply these calibrations to our field star sample. Although there are extant calibrations in the literature, the revision of open cluster ages upward over the past decade and the increase in relevant cluster data necessitates a revisitation of these calibrations. Finally, we weight the ages and/or constraints derived from the various indicators and estimate a most probable age or age range for each star.

2. Sample

The source list for FEPS consists of young near-solar analogs, stars ranging in mass from 0.8-1.2 $M_{\odot}$ and spanning ages 3 Myr to 3 Gyr. The stars are drawn from three recently assembled samples.

First, Soderblom (2000) has produced a well-characterized set of ∼5000 solar-type stars spread over the entire sky (see also Henry et al. 1996) having parallaxes that place the stars within 60 pc, (B-V) colors between 0.52 and 0.81 (F8-K0 spectral types), and location in the Hertzsprung-Russell diagram within 1.0 mag of the solar-metallicity Zero-Age Main Sequence. This sample is fully complete out to 50 pc and the R'_{HK} chromospheric activity index has been derived for all members. We have supplemented this sample with stars selected as having (B-V) colors between 0.58 and 1.15 or spectral types G0-K0, strong x-ray emission, kinematics appropriate for the young galactic disk, and high lithium abundance compared to the 120 Myr old Pleiades. Finally, stars in nearby well-studied open clusters [IC 2602 (55 Myr), Alpha Per (90 Myr), Pleiades (125 Myr), Hyades (650 Myr)] serve to "benchmark" our field star results by providing samples nearly identical in age, composition, and birth environment.

From this large parent sample, stars were selected for potential observation with Spitzer if they met various practical criteria including mid-infrared photospheric flux, mid-infrared background, and field crowdedness that make them suitable Spitzer targets. See Meyer et al (2006) for a more detailed description of the FEPS sample and the overall goals of the FEPS Spitzer Legacy Program. In this contribution we focus on age determination for the FEPS sample. In Figure 1 we show the final run of age with distance.

3. Estimators of Stellar Age

We consider a number of age indicators for solar-type stars: HR diagrams, rotation, x-ray emission, Ca II H&K emission, Hα emission, and Li I absorption. These methods involved in these different techniques have varying degrees of reliability, which we assess. We calibrate our indicators to stellar age using stars which are known members of open clusters with widely accepted ages. We also include the Sun; of note is that the Sun is not anomalous in any way in terms of coronal activity (Ayres?), chromospheric activity (Soderblom 1985, Baliunas?), lithium (wait, isn't sun lithium poor?), or rotation (Soderblom 1983). For solar-type stars ($0.52 < B-V < 0.81$) the mean/median and dispersion/interquartile-range values of various stellar age indicators are given in Table 1.

3.1. Hertzsprung-Russell Diagram

3.1.1. Background

The nominal age of the FEPS sample, 3-3000 Myr spans a range of surface gravity for solar-type stars, approximately from 3.0 to 4.5. Solar-type stars less than 20-60 Myr old (depending on mass) are still in the pre-main sequence phase of stellar evolution while older stars are are on the main sequence. For the pre-main sequence stars, position on the Hertzsprung-Russell diagram may be related to age through theoretical models. For stars having already reached the main sequence only a lower limit to age is derived, as the upper limit (the turn-off age) is generally older than the nominal FEPS age range. The major complication to such techniques is in adopting a set of theoretical isochrones, all of which are deficient in some manner.

Table 1. Cluster Rotation and Activity Indicators

Name	log age	av. vsini	med. vsini	av. log R'HK	med. log R'HK	av. W_{Li}	med. W_{Li}	log av. Lx	log med. Lx
NGC 188	9.845			-5.080					
Sun	9.659	2	2	-4.973					27.70±1
M 67	9.602	3.0±0.9	2.7±0.7	-4.860					
NGC 752	9.301			-4.700					
NGC 4651	9.230	5.4± 4.6	3.4± 4.2						
Praesepe	8.954								
Hyades	8.796	5.0± 2.4	4.8±1.2	-4.572					28.80±0.49
Coma Ber	8.690			-4.430					*28.90±0.40*
UMa	8.477	7.6±4.5	6.5±2.4	-4.444					
M34	8.397	15.6±10.8	11±4.5	-4.400					
NGC 6475	8.301								*29.3±0.25*
NGC2516	8.114	17.1±9.5	14.1±7.3						*29.0±0.1*
Pleiades	8.097	14.2±12.6	10.3±4.8	-4.300				29.37±0.11	29.35±0.39
Blanco 1									
Alpha Per	7.954	50.5±55.9	19±33.4					29.74±0.12	29.60±0.24
IC2391/2602	7.740	26.8±20.7	17±10						29.97±0.37
Tuc/Hor	7.477			-4.177				29.97	
NGC 2547	7.431								*29.95±0.05*
LCC	7.204			-4.014					
BPic	7.079			-3.990				30.07	
TWHyae	7.000	17.2±9.6						29.85	
UpperSco	6.699			-4.007					
NGC 2264	6.25								

Note. — NUMBER OF STARS
REFERENCES!!!!!

3.1.2. New Analysis

For the vast majority of FEPS sources distances are known from the Hipparcos catalog (Perryman et al 1997). For stars lacking trignometric parallaxes, proper motions can be used along with a velocity model of known cluster or moving group space motions, which is generally based on analysis of the proper motions and radial velocities of higher mass cluster/group members with trigonometric parallaxes. In this way secular parallaxes can be derived, as described in detail by Mamajek et al (2004).

Given a distance and photometry producing at least one color, FEPS members can be located accurately on a CMD, shown in Figure 1. We consider CMDs rather than the HRD.

3.2. Rotation

3.2.1. Background

As rotating stellar embryos contract they are expected to spin up under angular momentum conservation. This simple picture is mediated in the early pre-main sequence phase of stellar evolution by accretion from a circumstellar disk, by the interaction of stellar magnetic fields with the inner or outer (depending on the model) regions the disk, and by jets/winds. Accretion enhances the spin-up while the latter two mechanisms are expected to retard the spin-up. Following disk dissipation, as they continue to contract towards the main sequence, stars are expected to rotate more rapidly with advancing age. Changes in internal structure and potential core-envelope decoupling may play prominent roles as well. Remembering their earlier history, stars appear to arrive on the main sequence with a wide dispersion in rotation rates at a given mass (Stauffer 1994, Bouvier 1997). On the main sequence, rotation then decreases with age (e.g. Kraft 1965, 1967ab; Smith 1978; Soderblom 1983). Indeed, the famous Skumanich (1972) $t^{-1/2}$ spindown can be understood in a simple theoretical context such as transfer of angular momentum outward from the core to the envelope and then via loss through slow, magnetic stellar winds (e.g. the Weber-Davis wind mechanism), though applicable theoretical models are surely more complex (e.g. Collier-Cameron 1991; MacGregor 1991). Rotation is also a strong function of mass (e.g. XXX Hyades reference XXXXXX; Figure 2)

Rotation, is thus an age indicator if a common main sequence starting point for the ensuing angular momentum loss can be assumed. The slow and rapid rotators arriving at the ZAMS are indeed “equalized” after about 100 Myr according to theory (Kawaler 1989; Keppens, MacGregor, & Charbonneau 1995) and before 600 Myr empirically, based on the narrow range of rotation rates in the Hyades (Stauffer & Hartmann 1987). The initially rapid rotators are thus more efficiently braked than the initially slow rotators, suggesting that rotation is a valuable age indicator beyond ages of several hundred Myr.

A relation of the form $v/v_{\odot} = C \times (t/yr)^{-\alpha}$ or $Prot/day = C \times (t/yr)^{\alpha}$ with $\alpha = 1/2$ was famously derived by Skumanich (1972) for stars older than 100 Myr. Other exponents include 2/3 (Soderblom 1991 or Barry 1987 ??), 1/e (Walter & Barry 1991) and 1.47 (Pace & Pasquini 2004). Catalano (1988) and Kawaler (1989) suggested an additional mass-dependent term, $Prot/day = C \times (t/yr)^{\alpha} \times M/M_{\odot}^{\beta}$. These types of laws are usually calibrated to the solar values (Prot = 25.3 days; t = 4.65 Gyr; M=$M_{\odot}$) via the constant terms.

What is measured is surface rotation, manifest as either vsini or period.

3.2.2. New Analysis

V×sini

V×sin$i$ is measured from the broadening of spectral lines. The technique is dependent on high signal-to-noise spectra and either cross correlation, if rotation dominates the line broadening, or detailed line profile analysis which allows lower values of vsini to be inferred. Because only projected velocity is measured, vsini values are useful as an indicator of rotation in a statistical sense only.

Rotation vs age is extremely mass sensitive, as illustrated in Figure 2 which shows the run of vsini with B-V color for stars in several nearby open clusters. Figure 2 illustrates the resulting mean and median values of vsini for stars with $0.52 < B - V < 0.81$, the colors of our solar-type FEPS targets. For most clusters the median values of vsini are less than the mean values, reflecting the tail of rapid rotators characterizing the diverse angular momentum history of stars younger than 100-200 Myr. Figure 2 illustrates for ages older than 30 Myr a fit to the median vsini data as a function of age. This exercise results in a remarkable match to the historically noted $t^{-0.5}$ spindown law:

$$log\ age/Myr = -1.93 \times log\ vsini/kms^{-1} + 10.24$$

with rms=0.14 and chisq=0.21.

Period

Rotation periods are measured from photometric variations, either broad-band or line flux. Such variations require the star to have surface inhomogeneities that rotate with the star and that are of sufficiently high amplitude to be observable. In deriving a period it is assumed that the chromosphere and photosphere have the same period. Unlike vsini data, the observable is independent of orientation. However, windowing effects must be understood when deriving periods.

What are we going to do here, if anything?

3.3. X-ray Luminosity

3.3.1. Background

Rotation is coupled to the stellar dynamo which generates magnetic fields in or just below the convective zone that eventually heat the stellar corona, thus driving coronal activity with temperatures 10^6-10^7 K. One observational manifestation of this activity is x-ray emission. The level of x-ray activity, either the x-ray luminosity, Lx, or fractional x-ray luminosity, $R_X = L_X/L_{bol} = F_X/F_{bol}$ is thus expected to be related to rotation and the properties of the convective zone; more rapidly rotating stars and those with shallower convective zones should have higher x-ray emission. The relationship with rotation was found by Pallavicini et al (1981) and is often expressed in terms of the Rossby diagram, introduced by Vilhu (1984), of log Lx/Lbol vs log Ro. The Rossby number Ro = Prot/τ_{conv}, allows the presentation of stars of different mass on the same diagram. Initially, stars are saturated with Lx/Lbol$\approx 10^{-3}$ (e.g. Gagne et al 1995), or even super-saturated (e.g. Stauffer et al. 1997; Feigelson et al. 2002), independent of spin rate. More physically, saturation appears to occur for vsini >35-50 kms (Vilhu 1984; Ayres et al 1996, 1999). Both the saturation level, and the rotation rate at which saturation occurs, depend on stellar mass (Pizzolato et al 2003). Before reaching the zero-age main sequence, as they age stars become less luminous and spin faster while the convective envelope decreases in size. On the main sequence, as they age stars become slightly more luminous and spin down with little or no change in convection. The Rossby diagram can thus be thought of as an evolutionary diagram (Randich 2000) with stars moving towards slower rotation and lower activity activity levels as they age.

How to connect x-ray emission to age in a quantitative manner is not clear, however. Over the years controversial claims of power law vs exponential relationships have emerged. Randich (2000) demonstrates for solar type stars in clusters that while there is a general decline in the median Lx with age (Lx $\propto age^{-0.5\mathrm{to}-1}$), the dispersion in Lx for any given cluster is large and overlap in the median Lx between clusters differing substantially in age (factors of 5) is present. Further, for young pre-main sequence stars the rotation-activity connection is not established empirically (e.g. Feigelson et al 2003). Kastner et al. (2002) argue for the softening of x-ray spectra with age based on a distinction in the hardness ratios between young T-Tauri stars (both classical and weak), intermediate-age pre-main sequence stars (TW Hydrae, Tucanae, and Beta Pic associations), and main sequence stars. X-ray activity is thus an ambiguous age indicator at best.

Assuming an age-rotation relation of the form Prot $\propto (t/Gyr)^{\alpha}$ and the empirically derived Lx $\propto Prot^{-2.64}$ from Gudel et al 1997, (Lx $\propto Prot^{-2}$ from Pallavicini et al 1981; Lx $\propto Prot^{-2.9\pm0.3}$ from Ayres et al 1996; Lx $\propto Prot^{-2.6}$ from Pizzolato et al 2003; log-normal advocated by Simon 1990) Gaidos (1998) derive a prediction for the evolution of fractional x-ray luminosity:

$$log(Lx/Lbol) = -6.0 - 2.6 \times \alpha \times log(t/4.6Gyr) + log(1 + 0.4(1 - t/4.6Gyr))$$

which is calibrated to produce the present solar values (Lx = 27.60 erg/s or Rx = -6; t=4.65 Gyr) and thus the saturation value occurs at $30 \times 10^{((\alpha-0.5)/\alpha)}$ Myr or rotation periods of 2-3 days. Indeed, the studies of Feigelson et al 2002 and Flaccomio et al 2003 showed that no x-ray / rotation relationship is present for very young T Tauri-like stars.

X-ray luminosity is notoriously variable, and variability was studied by Marino et al (2002) who found the phenomenon present on all time scales studied with the amplitude independent of both x-ray and stellar luminosity. In the sun, such variability is variously attributed to flares (hours), evolution of active regions (days to months) and magnetic cycles (years) with the later causing 0.5 dex (1σ) range in luminosity (Micela & Marino 2003). Micela & Marino (2003) also argue that stars with $L_x < 10^{28}$ erg/s have variability trends much like those of the sun whereas more active stars do not follow the solar activity paradigm.

3.3.2. New Analysis

For coeval populations of young stars, X-ray luminosity is strongly correlated with stellar mass (Feigelson et al 2002). To most closely mimic the masses relevant for FEPS targets we thus consider x-ray properties of only the solar-type (G and early K) stars discussed in Patten & Simon (1996). Figure XXXX illustrates the resulting median values of Lx For ages older than 30 Myr a fit to the median Lx data as a function of age results in the following relationship

$$log\ age/Myr = -0.88 \times log\ Lx/ergs^{-1} + 33.88$$

with rms=0.16 and chisq=0.20. As found by Patten & Simon this is different from the $t^{-0.5}$ law characteristic of rotational evolution.

For FEPS targets we have converted count rates to flux using Fleming etal 1995 conversion factor though see mamajek notes for modifications to this; also oranje etal 1982?. plot log Lx vs logT or B-V

3.4. UV Continuum Excess and Line Emission

3.4.1. Background

The stellar dynamo and rotation also drive chromospheric and transition region activity with temperatures in the vicinity of 10^4-10^5 K. Many far-ultraviolet through near-ultraviolet emission lines result, in addition to ultraviolet continuum excess. The UV continuum excess shows behavior with stellar rotation similar to that of x-rays, being initially saturated with L_{UV}/Lbol$\approx 10^{-3.5}$ (Christian & Mathioudakis 2002) though de-saturating at higher Rossby numbers (slower rotation rates) compared to coronal emission. As expected, chromospheric saturation requires less magnetic energy than coronal saturation. Ribas et al. (2005), from analysis of a small sample of stars, derived an equation for the average UV continuum falloff with age of the form $F_{1-1200\mathring{A}}[erg/s/cm^2] = 29.7(\tau/Gyr)^{-1.23}$, though also demonstrated an energy trend with shorter wavelength emission decaying more rapidly with time than longer wavelength emission. Emission lines such as Mg II h&k and C IV λ1549 also show saturation with values between 10^{-4} and 10^{-6} for L_{line}/Lbol (e.g. Simon, Herbig, & Boesgaard 1985; Simon 1990), higher excitation lines de-saturating earlier and more rapidly than lower excitation lines. The relationship of UV emission to age was generally noted by Simon (1990) for stars in clusters but explored quantitatively by Simon, Herbig, & Boesgaard (1985); adopting adjusted field star ages based on lithium depletion calculations (Duncan 1981), they found an exponential relationship between log R ($R = F_{line}/\sigma T_{eff}^4$) and log age.

3.4.2. New Analysis

3.5. CaII H&K Emission

3.5.1. Background

Chromospheric emission indicative of stellar activity may be observed in the ultraviolet through spectroscopy on space-based platforms or in the blue optical via the CaII H&K lines (3968 and 3933$\mathring{A}$) at 10^4 K. Vaughan et al. (1978) provides a derivation of the now-standard activity index, S, from observational data while Rutten (1984) details the conversion to line flux, F_{CaII}. A correction for the photospheric (line wings) and basal (line core) components to the flux is made based on color, resulting in F'$_{CaII}$, the excess CaII HK flux arising in the chromosphere. It is the fractional luminosity $R'_{HK} = F'_{CaII\ HK}/F'_{bol}$ which measures chromospheric activity and can be related to rotation properties, either again through the Rossby diagram of log R'_{HK} vs Ro (Noyes et al 1984) or directly (Pasquini et al. 2000). The correlation of chromospheric and coronal activity is well-established (e.g. Ayres et al. 1981; Maggio et al 1987; Rutten et al 1991; Piters et al. 1997).

For solar-type stars the CaII H&K lines were first shown to decrease in strength with increasing age by Wilson (1963). Skumanich (1972) provided the first quantification of the relationship between H&K activity and stellar age, finding the same simple $t^{-1/2}$ power-law that characterized the rotation data, while Barry et al. (1981) found a parabolic decay. Barry, Hege, & Cromwell (1984 also 1988???), Hartmann et al (1984 are these MgII h/K not CaII H/K ???), and Simon, Herbig, & Boesgaard (1985) all argued for an exponential form between R'$_{HK}$ and age, e.g. $e^{-b\ t^{\beta}}$ starting from initially saturated values. Considering only stars older than 1 Gyr Soderblom et al (1991, see also 1985) derived a linear relation:

$$log(t/yr) = -1.50 \times logR'_{HK} + 2.25,$$

Considering a wider age range, Donahue (1993) fit a polynomial:

$$log(t/yr) = 10.725 - 1.334 \times \times R_5 + 0.4085 \times R_5 \times R_5 - 0.0522 \times R_5 \times R_5 \times R_5$$

where $R_5 = 10^5 \times R'_{HK}$. Most of these latter calibrations reflect a knee in the relationship between activity index and age around 1 Gyr with the Donahue et al (1993) formula extending to ages as young as 10 Myr.

The variability of CaII H&K emission is also taken as a stellar age indicator with more rapid, stochastic, and high-amplitude variability indicative of younger more x-ray luminous stars and regularly periodic, long cycle, and low-amplitude variablity characterizing older stars (e.g. Radick et al 1996, 1998; Hempelmann et al 1996; Baliunas et al 1998). Physical mechanisms producing variability include rotation which changes the filling factor of emitting regions, growth and decay of individual emitting regions, and short and long-term activity cycles. For example, the Sun varies by 10% through an 11 year cycle (White & Livingston 1981). In M67 a substantial fraction of the stars exhibit even larger variations (Giampapa et al 2000). At solar maximum R'$_{HK}$ = -4.75 while in the Maunder minimum the value was -5.10. The evidence on variability suggests caution in age derivation for stars for which activity index monitoring has not taken place over a sufficiently long time that mean activity levels can be determined.

Typical measurement error in R'(HK) is 0.05-0.10. Typical error due to variability was discussed by Donahue (1998) who reported on the variation in ages derived from binaries which can be assumed coeval. However, the HK ages differed by 0.5-1 Gyr for stars older than 2 Gyr, i.e. <50%.

3.5.2. New Analysis

Color correction to B-V = 0.60 using Soderblom (1985) slope. Derive new low order polynomial fit.

Peak-to-peak dispersion in measured CaII line fluxes is more than 60% for most clusters (e.g. Pace & Pasquini 2004), which may be either a real dispersion in the activity-age relation (assuming clusters are coeval) or simply indicative of variations in individual stars around the mean activity value, i.e. analogs of the solar cycle.

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###################################################################
# CALCIUM ACTIVITY INDEX CALIBRATION DATA
# q: 1=good 2=not so good (all data corrected to B-V=0.60 using Soderblom 1985 slope)
# CaR'HK logt q  Sample   ref
-5.502 10.100 2  Oldest   least active star in Wright04, for 12.6 Gyr (B-V=cor to 0.60)
-5.080  9.845 1  NGC188   Soderblom91 (conv. Barry87) Sarajedini99 age
-4.973  9.659 1  Sun      median value from below
-4.860  9.602 1  M67      Soderblom91 (conv. Barry87) Sarajedini99 age
-4.700  9.301 1  NGC752   Soderblom91 (conv. Barry87) Dinescu95 age
-4.572  8.796 1  Hyades   Soderblom85 (for B-V=0.60)  Perryman97 age
#                           should add in Radick etal 1987, Paulson etal 2002
-4.444  8.699 1  UMa      King03 (for B-V=0.60)
-4.430  8.690 1  Coma     Soderblom91 (conv. Barry87) WEBDA age (490 Myr)
-4.400  8.301 1  M34      King03 (median of Fig. 1d)
-4.300  8.097 1  Pleiads  Soderblom91 (conv. Barry87) Stauffer age
-4.177  7.477 1  TucHor   Median value from below
-4.014  7.204 2  LCC      Median value from below
-3.990  7.079 2  BetaPic  Median value from below
-4.007  6.699 2  US       Median value from below
#################################################################
# SUN VALUES (median = -4.973)
#-5.123  9.659 1  Sun      Kirkpatrick01 (Maunder minimum; B-V=0.66 cor to 0.60)
#-4.982  9.659 1  Sun      Wright04
#-4.963  9.659 1  Sun      Soderblom93 (cor to 0.60)
#-4.773  9.659 1  Sun      Kirkpatrick01 (Solar maximum ; B-V=0.66 cor to 0.60)
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# TUCANA-HOROLOGIUM
#-4.001  7.477 1  HD222259A Soderblom98 w/ Tuc-Hor age (B-V=0.679 cor to 0.60)
#-4.092  7.477 1  HD202917  Soderblom98 w/ Tuc-Hor age (B-V=0.682 cor to 0.60)
#-4.177  7.477 1  HD222259B Soderblom98 w/ Tuc-Hor age (B-V=1.078 cor to 0.60)
#-4.329  7.477 1  HD1481    Henry96 w/ Tuc-Hor age (B-V=0.52 cor to 0.60)
#-4.385  7.477 1  HD105     FEPS Tuc-Hor grp (B-V)=0.60
# LOWER CEN CRUX
#-4.056  7.204 1  HIP66941  Soderblom98 w/ LCC age (B-V=0.743 cor to 0.60)
#-3.972  7.204 1  HIP59764  Soderblom98 w/LCC age (B-V=0.605 cor to 0.60)
# BETA PICTORIS GROUP
#-4.137  7.079 1  HD35850   FEPS beta Pic grp (B-V=0.54 cor to 0.60)
#-3.842  7.079 1  PZTel     Soderblom98 w/ Zuckerman age (B-V=0.784 cor to 0.60)
# UPPER SCO
#-4.007  6.699 1  HD143006  FEPS Upper Sco grp (B-Vo=0.66 cor to 0.60)
# DISCARDED VALUE
#-4.260  6.477 1  NGC2264  Soderblom91 (conv. Barry87) Sung97 age (*really* doesn't fit,
########################################################################
# COLOR CORRECTION
# all Ca R'HK values were "color corrected" to B-V = 0.60 using the Hyades slope
# from Soderblom+ 1985:
# R'HK(c-c) = R'HK - (B-V - 0.60)*0.391
# This may not be appropriate for other ages, but its the best I've found.
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3.6. Hα Emission

3.6.1. Background

Herbig (1985), Pasquini & Pallavicini (1991), and Lyra & Porto de Mello (2005) have discussed the use of chromospheric Hα emission as an indicator of stellar age. Due to differences in the formation region within the chromosphere, the Hα line has several advantages over the Ca II H&K lines in measuring the level of stellar activity. Among these is the relative insensitivity to high energy events on a star. Lyra & Porto de Mello (2005) derive a relationship of line flux with age of the form log $F'_{H\alpha}$ = 5.79 - 0.39 log age (very close to $t^{-0.5}$) where $F'_{H\alpha} = F_{H\alpha} - F_{phot}$. The relationship is derived for stars older than 100 Myr, and appears to flatten out after 2 Gyr (similar to the results of Pace & Pasquini 2004 for $F'_{CaII\ K}$ and vsini) with Hα emission constant thereafter.

3.6.2. New Analysis

Figure XXX shows the run of W(H_α) vs B-V for FEPS targets compared to the expected trend for dwarfs and sub-giants.

3.7. Lithium 6708Å Absorption

3.7.1. Background

Like the coronal and chromospheric activity indicators, lithium abundance is tied to stellar youth in a manner partly influenced by rotation. As low-mass stars age, lithium is gradually mixed downward in the convective envelope until reaching the temperature at which it burns (2-4$\times10^7$ K), leading to rapid depletion since there is no mechanism for stable lithium production. Rotation can prevent mixing though this point is controversial. Present lithium abundance is therefore an indicator of age assuming for all stars the same primordial lithium abundance (e.g. Herbig 1965; Bodenheimer 1965; Duncan 1981). However, the inability of stellar models to accurately reproduce observed lithium depletion trends (see Piau & Chieze 2002 for a recent discussion) has called into question the reliability of lithium as a chronometer. Observationally, while most lithium-rich main- and pre-main sequence stars are young, and most lithium-poor stars are old, the spread in lithium for stars of similar temperature and age suggests additional influences, such as rotation or metallicity. Nevertheless, some empirical progress is still possible. Boesgaard (1991) derived the linear relationship between lithium abundance and age:

$$logN(Li)/N(Li,\odot) - 12 = -0.30log(t/Gyr) + 5.33$$

(CHECK FORM) log N(Li) = [Li] = log(Li/H) + 12

The resonance doublet at 6707 Å is the strongest LiI line in the optical spectrum, others being located at 6103 and 3232 Å and difficult to resolve from other nearby lines. For typical high dispersion spectra, the 6707 Å feature is a blend of two fine structure components of ^{7}LiI ($\lambda\lambda$6707.76, 6707.91) and ^{6}Li (0.16Å redward of the ^{7}LiI lines). For moderately rapid rotation there is contamination from a weak FeI line (λ6707.44). Some authors correct the total measured equivalent width for this contribution using an empirical relationship between the FeI line equivalent width and color/temperature defined by Soderblom (1990).

Conversion from EW(Li) to N(Li) involves spectrum synthesis and curve of growth analysis. Calibrations by padgett 1996 or 1990 and soderblom et al 1993 AJ 106, 1059 (table 2) For lte/nlte see carlsson etal 1994 and corr_nlte at ftp.astro.uio.no. Claim by de la reze that 6707 line overestimates abundance since formed high up in photosphere or even chromosphere where can be affected by stellar activity. This also explains why young stars often have abundances quoted at higher than ISM value, whereas 6104 is near ISM.

As discussed by Neuhauser & Brandner (1998) and White & Hillenbrand (2005), some solar-type stars with pre-main sequence positions in the HR diagram indicating ages of 3-30 Myr have lithium abundance less than the upper bound of the 120 Myr Pleiades at the same spectral type. Thus although one can be fairly certain that high lithium abundance is correlated with stellar youth, low lithium abundance does not necessarily indicate an aged star. At the other end of the spectrum, there are evolved stars with anomalously high values of lithium, some even close to the the interstellar value (c.f. Charbonnel & Balachandran 2000; Drake et al. 2002). Thus citing the presence of substantial lithium without assessing the surface gravity of a star can be misleading.

check michaud/charbonneau 1991 review for additional data/references

3.7.2. New Analysis

many/most authors have adopted an analysis method which considers the upper envelope in a EW(Li) vs log T plot for stars in a given cluster (e.g. Soderblom et al 1993; Neuhauser et al 1997; Montes et al 2001). instead we consider a method which enables not just a limit but a a best estimate

(Mamajek) The basic premise is this: I have a database of equivalent width measurements for the Li I 6707 line taken from echelle spectroscopy studies of late-type members of 8 clusters and associations. For each group, I assign a "best" age (open to debate). The groups range ages of 2 Myr to 4000 Myr: NGC 2264 + TTS (log(age) = 6.30) IC 2602 (log(age) = 7.72) [assumed same age as IC 2391] Alpha Per (log(age) = 7.95) Pleiades (log(age) = 8.10) M35 (log(age) = 8.24) [Fe/H] -0.21! M34 (log(age) = 8.40) Hyades (log(age) = 8.80) M67 (log(age) = 9.57)

All of the data are high res (usally R 20-100k). For each set of cluster lithium data, I fit a polynomial to the Teff and log10(EW(Li)) data, and characterize the rms scatter. Sometimes the rms is treated in a piecemeal fashion (e.g. Pleiades Li scatter increases as one goes to cooler Teffs). I trust the fit only in the Teff range where (a) there is data, and (b) there are no upper limits. Hence each cluster has a hot and cool Teff limit beyond which the fit is suspect. M67 unfortunately has upper limits everywhere, so the fit is only an approximation over a small Teff range.

For each combination of star (with Teff, EW(Li), unc.EW(Li)), and cluster (polynomial fit + rms), I calculate the deviation of the star from the cluster locus (in "sigmas"). The deviation typically has a large intrinsic scatter (cluster) and small observational scatter (error in EW(Li)). Hence, for a given cluster age, we have a null hypothesis (a star of age XXX should have a given EW(Li) as a function of Teff, within some intrinsic scatter) to test against. The deviation in 'sigma' can be converted to a probability using the erfc function (basically chi^2 probability w/ dof=1), and I assemble a table of (age, probability) with N 8 entries.

The table of (age, probability) has been what I've been playing with trying to derive (age, uncertainty in age). I've been comparing the derived ages to the ages of members of known clusters (e.g. Hyads, Pleiads), with mixed success.

The probabilities are already properly normalized, i.e. *somewhere* in the age range of 2-4000 Myr, one should naively be able to fit a normalized age probability distribution function. I constrain the amplitude (=1), and loop over a wide range of plausible ages (log(age) = [6.2,9.7] and standard deviations [0.1-1.0], and find the best fit through least squares of the deivations between the observed and fit log(probabilities).

I have tried fitting p.d.f.s in (age, probability), (log(age), probability), (age, ln(probability)), and (log(age),ln(probability)). Since negative ages and probabilities are impossibilities, the log units for both appear to be the natural choice. Fitting in (log(age),probability) and (log(age),ln(probability)) gives nearly identical results, and give "Li ages" which better match the existing FEPS database ages (as if these are a good standard :) The fits with linear age were unfortunately very poor.

I suspect that by fitting in log(age) space, there is a bias for the Li ages to be younger than the real ages... if one naively assumes that the space density of disk stars is independent of age (hmmm), then one would expect N=9 10-100 Myr-old stars for every N=1 ¡10 Myr-old star... i.e. the Li code doesn't know a priori that 1 Myr-old stars are rare in the field. It may be worth trying to figure out if this bias can be corrected.

3.8. Kinematics

3.8.1. Background

Stars are born in molecular clouds and can retain the bulk motion of the cloud with respect to the Galaxy for many tens to hundreds of Myr, well after the cloud has dispersed and the spatial coherence of the stars has disappeared. Groups of young stars can thus be separated from the field through their common streaming motions. As the groups disperse individual stars are scattered through interactions with giant molecular clouds and the Galactic plane, increasing their random space motions with time. As stars age they gradually diffuse out of the plane (an effect independent of stellar mass) and hence towards older ages stellar kinematics are indicative of association with the young disk, old disk, or halo and only very crudely trace age. Nevertheless, while old stars can have a range of velocities relative to the local standard of rest, young stars rarely have high velocities.

Method is to combine coordinates, parallax, radial velocity and proper motion information to calculate U, V, W space motions (Johnson & Soderblom 1987). Leggett (1992) define criteria for young disk, old disk, halo. Hopefully all of our stars are young disk.

Interestingly, Manoj & Bhatt (2005) correlate velocity dispersion and IRAS/ISO disks...

3.8.2. New Analysis

3.9. Metallicity

The abundance of heavy elements in the universe has increased with time due to nucleosynthesis in stars. Metallicity may thus trace age, especially for stars older than several Gyr. If present any age-metallicity relationship has very large scatter (Edvardson et al 1993). Some calibration work by Carraro et al 1998 (MNRAS 296, 1045). Probably not very applicable to FEPS though some illustration of the metallicity distribution is probably worthwhile.

4. Application to FEPS Targets

5. Cluster and Solar Calibration of Various Age Estimators

Ages for several nearby open clusters are "well-established" and hence can be used to calibrate the age indicators we wish to apply to our field star sample. Open cluster ages are variously based on the upper main sequence turn-off, pre-main sequence isochrones, and/or the lithium depletion boundary. A portion of the FEPS sample belong well-studied nearby open clusters.

Ages for FEPS Clusters and Moving Groups:

Hyades: 650 +/- 50 Myr

The most recent isochrone-fitting age for the Hyades is 650 Myr (Lebreton et al. 2001). Other isochrone-fitting ages include 660 Myr (Mermilliod 1981) and 625 Myr (Perryman et al. 1998). We adopt 650 Myr +/- 50 Myr.

Pleiades: 100 +/- 25 Myr

There are a large number of published ages for the Pleiades, however with few exceptions the commonly quotes ages fall within a range from about 78 Myr (Mermilliod 1981) to about 125 Myr (Stauffer et al. 1998). The former age is from isochrone fitting using evolutionary tracks incorporating only minimal convective-core overshoot; the latter age is from the lithium depletion boundary method. An age of 100 Myr was obtained by Meynet, Mermilliod and Maeder (1993) using theoretical models incorporating an increased amount of convective core overshoot, as suggested by observations of intermediate mass slightly post-main sequence binaries (e.g. Ribas, Jordi and Gimenez 2000). We adopt an age of 100 +/- 25 Myr.

Alpha Per: 75 +/- 20 Myr

The same set of theoretical isochrones that yields 100 Myr for the Pleiades age (Meynet et al. 1993) gives 52 Myr for the Alpha Per cluster. Similarly, the same methodology for deriving the lithium depletion boundary age of 125 Myr for the Pleiades yields 90 Myr for Alpha Per. We adopt an age of 75 +/- 20 Myr for Alpha Per.

IC2602: 45 +/- 10 Myr

Meynet et al. 1993 do not provide an age estimate for IC2602. An isochrone-fitting age of 35 Myr for IC2602 is given by Mermilliod (1981). There is no lithium depletion boundary age for IC2602. However, a lithium depletion boundary age is available for IC2391, a cluster spatially near to IC2602 that is believed to be coeval with IC2602 (Stauffer et al. 1997). The lithium depletion boundary age for IC2391 is 50 Myr (Barrado et al. 2004). We adopt an age of 45 +/- 10 Myr for IC2602.

Upper Scorpius: 5 +- 2 Myr

Historical age estimates for Upper Sco (US) have ranged from 1-2 Myr (Walter et al. 1994; pre-MS population only) to 6-8 Myr (de Zeeuw & Brand 1985), with 5 Myr as the most-cited value (de Geus 1989, Preibisch & Zinnecker 1999, Preibisch et al. 2002). Preibisch et al. (2002), in their study of a representative sample of the whole stellar mass spectrum of US, find that 5 Myr appears to be an excellent match for the turn-off and pre-MS ages. We adopt 5 +- 2 Myr for US, with 2 Myr being a rather conservative error bar.

Upper Centaurus-Lupus: 17 +- 3 Myr

UCL has a well-defined turn-off sequence of early-B stars, and there is fair agreement between the various turn-off ages for this OB subgroup: 12-13 Myr (de Zeeuw & Brand 1985), 14-15 Myr (de Geus, de Zeeuw, & Lub, 1989), and 17+-1 Myr (Mamajek, Meyer, & Liebert, 2002). Mamajek, Meyer, & Liebert (2002) independently estimate the mean age of the UCL pre-MS stellar population to be 15-22 Myr (depending on choice of evolutionary tracks). We adopt an age of 17 +- 3 Myr for UCL.

Lower Centaurus-Crux: 17 +- 5 Myr

The turn-off sequence for LCC is not well-populated, and the disputed membership status and peculiar characteristics (variability, emission-lines) of some of the turn-off candidates may be the cause of the dispersion in the recent turn-off age estimates of this subgroup: 10-11 Myr (de Zeeuw & Brand 1985), 11-12 Myr (de Geus, de Zeeuw, & Lub, 1989), and 16+-1 Myr (Mamajek, Meyer, & Liebert, 2002). Mamajek, Meyer, & Liebert (2002) estimate the mean age of the pre-MS stellar population to be 17-23 Myr (depending on choice of evolutionary tracks). Alcala et al. (2002) measured Li abundances for a small sample of pre-MS K/M-type LCC stars (whose status as LCC members seems fairly secure through their RVs, Li, X-ray luminosities, and pre-MS HRD positions). Although not explicitly stated in their results, the Li depletions that they measure among the three lowest-mass stars (Cru 1,4,6) are consistent with ages of 23 Myr, 32 Myr, and 13 Myr (through comparing with the Baraffe et al. 1998 tracks). LCC has the least constrained age of the three Sco OB2 subgroups, and requires further study of its lower mass membership to help constrain the age more tightly. We adopt 17 +- 5 Myr for LCC.

Corona Australis: Adopt individual isochronal ages (range: 2-10 Myr)

FEPS has included several stars in the region of the Corona Australis T association in its program. These objects were all discovered in a spectroscopic follow-up of ROSAT All-Sky Survey X-ray sources by Neuhauser et al. (2000). It is unclear how they are related to the CrA cloud, but their radial velocities and proper motions are consistent with the CrA T Tauri stars within the CrA molecular clouds. Individual isochronal ages for these objects should be adopted (with an adopted distance of 130 pc), rather than a mean age. Most of the isochronal ages for these objects are 2-10 Myr (Neuahauser et al. 2002).

FEPS Database Results:

IC 2602 (55 Myr)

```
FEPS Query Results :    Fri Sep 24 06:49:51 2004
N Source Dist (pc) log Age (log yr) SpT Teff (K) [Fe/H] (dex) EW(Li) (mAng) V sini (km/s
 1 R3 150 7.74 null 5249 0.00 null null null
```

```
 2 R45 150 7.74 null 5881 0.00 null null null
 3 W79 150 7.74 null 5375 0.00 null null null
 4 B102 150 7.74 null 5757 0.00 null null null
 5 R83 150 7.74 null 5874 0.00 null null null
```

Alpha Per (90 Myr;)

```
FEPS Query Results :    Fri Sep 24 06:45:22 2004
N Source Dist (pc) log Age (log yr) SpT Teff (K) [Fe/H] (dex) EW(Li) (mAng) V sini (km/s
 1 HE 350 190 7.90 null 5824 0.00 224.2 47.31 null
 2 HE 373 190 7.90 null 5423 0.00 <50 127.01 null
 3 HE 389 190 7.90 null 5979 0.00 155.8 <18 null
 4 AP 93 190 7.90 null 4896 0.00 290.8 71.5 null
 5 HE 622 190 7.90 null 5484 0.00 262.6 60.9 null
 6 HE 696 190 7.90 null 5753 0.00 213.4 15.78 null
 7 HE 699 190 7.90 null 5748 0.00 366.5 89.15 null
 8 HE 750 190 7.5-8 F5 6361 0.00 122.4 30 null
 9 HE 767 190 7.90 null 6209 0.00 118.6 <10 null
 10 HE 848 190 7.90 F9V 6308 0.00 75.8 26.77 null
 11 HE 935 190 7.90 F9.5V 6109 0.00 153.7 64.4 null
 12 HE 1101 190 7.90 null 5691 0.00 209.3 33.84 null
 13 HE 1234 190 7.90 null 5739 0.00 62.6 26.42 null
```

Pleiades (125 Myr; Stauffer et al 1998)

```
FEPS Query Results :    Fri Sep 24 06:48:12 2004
N Source Dist (pc) log Age (log yr) SpT Teff (K) [Fe/H] (dex) EW(Li) (mAng) V sini (km/s
 1 HII 120 130 8.08 null 5687 0.00 195.8 17.62 null
 2 HII 152 130 8,08 null null null 150 11.1 null
 3 HII 174 130 8.08 null 5118 0.00 382.3 92.53 null
 4 HII 173 130 8.08 null 5252 0.00 231.5 <10.5 null
 5 HII 250 130 8.08 null 5771 0.00 227.7 <13 null
 6 HII 314 130 8.08 null 5757 0.00 193.4 40.05 null
 7 HII 514 130 8.08 null 5717 0.00 164.9 16.88 null
 8 HII 1015 130 8.08 null 5906 0.00 161.6 <10 null
 9 HII 1101 130 8,08 null null null 144 20 null
 10 HII 1182 130 8.08 null 5914 0.00 173.6 <20.5 null
 11 HII 1200 130 8.08 null 6208 0.00 64.8 <10 null
```

```
 12 HII 1776 130 8.08 null 5625 0.00 146.3 <16 null
 13 HII 2147 100 <8.08 G7IV 5125 0.00 281.5 38.39 null
 14 HII 2278 130 8.08 null 5221 0.00 221.0 15.44 null
 15 HII 2506 130 8.08 null 6047 0.00 137.8 <10 null
 16 HII 2644 130 8.08 null 5609 0.00 203.2 <11 null
 17 HII 2786 130 8.08 null 6059 0.00 167.3 25.10 null
 18 HII 2881 130 8.08 K2 4860 0.00 231.6 <12 null
 19 HII 3097 130 8.08 null 5569 0.00 209.9 <10 null
 20 HII 3179 130 8.08 null 6122 0.00 124.8 <10 null
```

Hyades (625 +/- 50 Myr)

```
FEPS Query Results :    Fri Sep 24 06:48:59 2004
N Source Dist (pc) log Age (log yr) SpT Teff (K) [Fe/H] (dex) EW(Li) (mAng) V sini (km/s
 1 vB 1 50 9.13 F8 5983 0.13 101.6 <10 -4.60
 2 vB 39 37 8.78 G4V 5643 0.13 32.7 <11 -4.51
 3 vB 49 46 8.78 G0V 5928 0.13 73.1 <10 null
 4 vB 52 48 8.78 G2V 5842 0.13 65.6 <10 -4.36
 5 vB 176 48 8.78 K2V 4942 0.13 <15 <10 -4.40
 6 vB 63 46 8.78 G1V 5703 0.13 66.7 <15.4 -4.39
 7 vB 64 47 8.78 G2+ 5723 0.13 null null -4.43
 8 vB 66 47 8.54 F8 6056 0.13 83.7 19.47 -4.39
 9 vB 73 47 8.78 G2V 5912 0.13 108.6 <14.4 -4.47
 10 vB 79 41 8.78 K0V 5262 0.13 26.2 <10 -4.43
 11 vB 180 40 8.78 K1V 5185 0.13 23.4 <10 -4.46
 12 vB 88 51 9.05 F9V 6101 0.13 104.7 <10 -4.55
 13 vB 91 31 8.78 null 5042 0.13 16.6 <10 null
 14 vB 92 29 8.78 null 5494 0.13 36.9 <14 null
 15 vB 93 46 8.78 null 5106 0.13 <12 <14 null
 16 vB 96 42 8.78 G5 5066 0.13 26.6 <10 -4.53
 17 vB 183 51 8.78 null 5022 0.13 18.4 <10 null
 18 vB 97 43 8.78 F8:V: 5652 0.13 90.5 <10 -4.41
 19 vB 99 67 8.78 null 5161 0.13 <9 <10 null
 20 vB 106 48 8.93 G5 5764 0.13 65.1 <10 -4.50
 21 vB 142 51 8.09 G5 5665 0.13 61.0 <12.9 -4.33
 22 vB 143 58 9.15 F8 6205 0.13 <6 <10 -4.62
```

6. Results

6.1. Ages and Age Errors from Individual Methods

Stauffer assigns a “gold star” to ages in open clusters and a “silver star” to ages from pre-main sequence tracks. All other methods earn only a “bronze star” or less! Further, since rotation is the fundamental variable the various ”other” methods are not physically independent even though the observational techniques are quite independent. We probably want a table like the following that compares the ages from different methods.

Name	t(R’HK)	t(Li)	t(P)	t(vsini)	t(HRD)	t(membership)	t(best)	comment
HD_105	7.0	7.6	7.9	8.0	7.5	7.5	7.5	membership trump
HD_blah	8.5	8.0	8.4	NA	>7.5	NA	8.4	median

6.2. Adopted Ages and Uncertainties

We have discussed both quantitative and qualitative estimators of stellar age for solar-type stars. For the FEPS sample we assign ages, in order of preference, based on:

1) cluster and moving group ages for stars kinematically or otherwise associated with such

2) hrd ages for pre-ms stars (need to be XX mag or XX sigma above main sequence for this method to apply)

3) a combination of the various other indicators for main sequence stars

Errors in cluster ages and dispersion in observed diagnostics for stars of a given age, lead to considerable uncertainties in calibrations.

7. Summary

Have we convinced anybody of ages to a factor of 3 ?????

We thank Jeff Valenti for kibitzing on issues related to stellar ages and the FEPS team for helping assemble the data used in this analysis.

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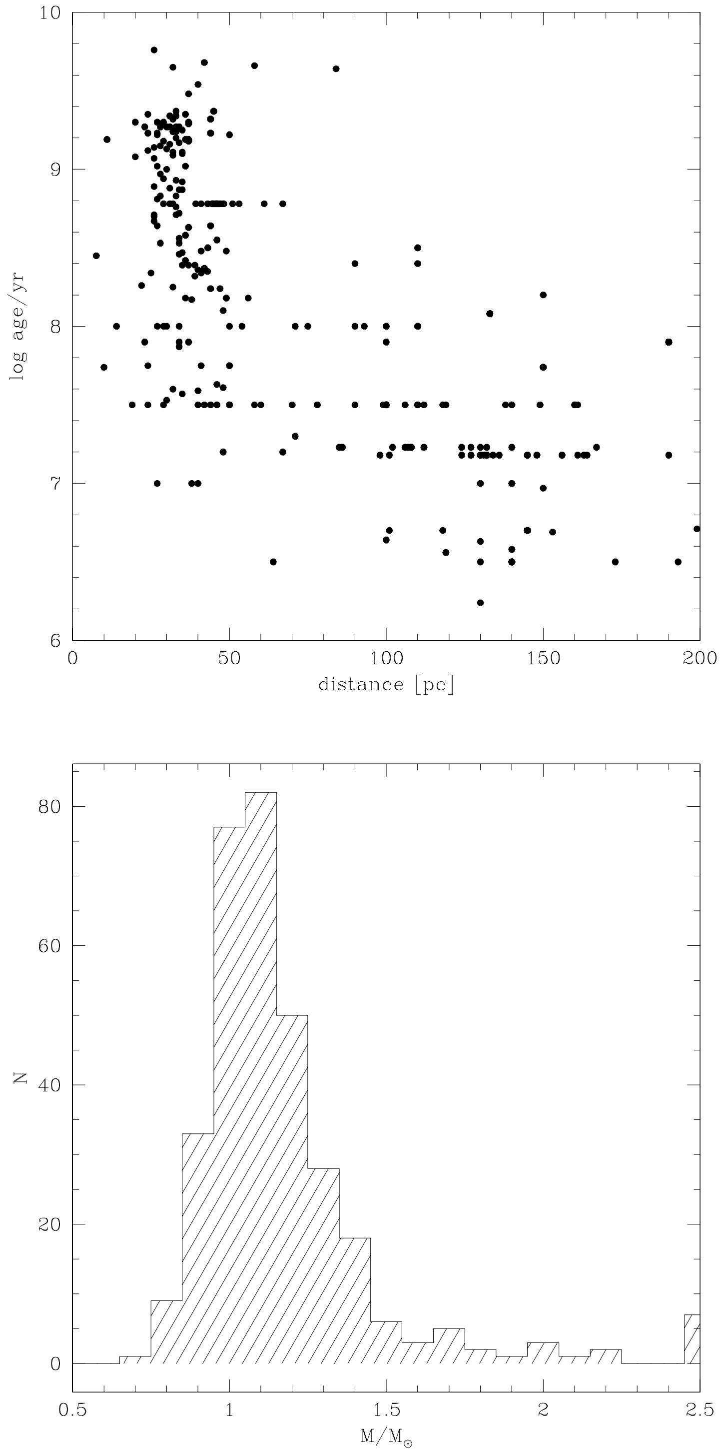


Fig. 1.— Characteristics of the FEPS sample. Upper panel: Age derived herein vs distance. Obviously the ordinate is still under discussion. Lower panel: Mass distribution of FEPS objects derived from the HR diagram and Swenson et al pre-ms/ms evolutionary tracks.

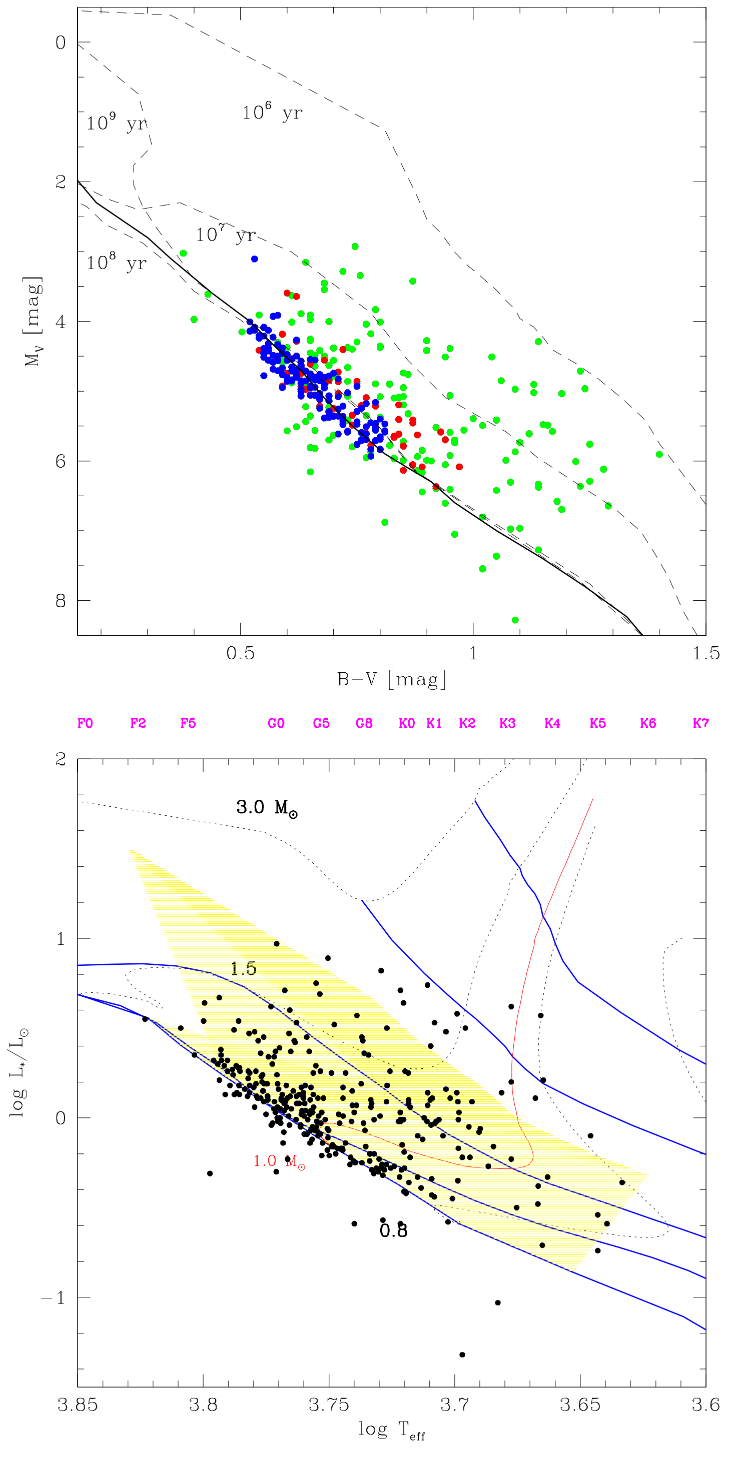
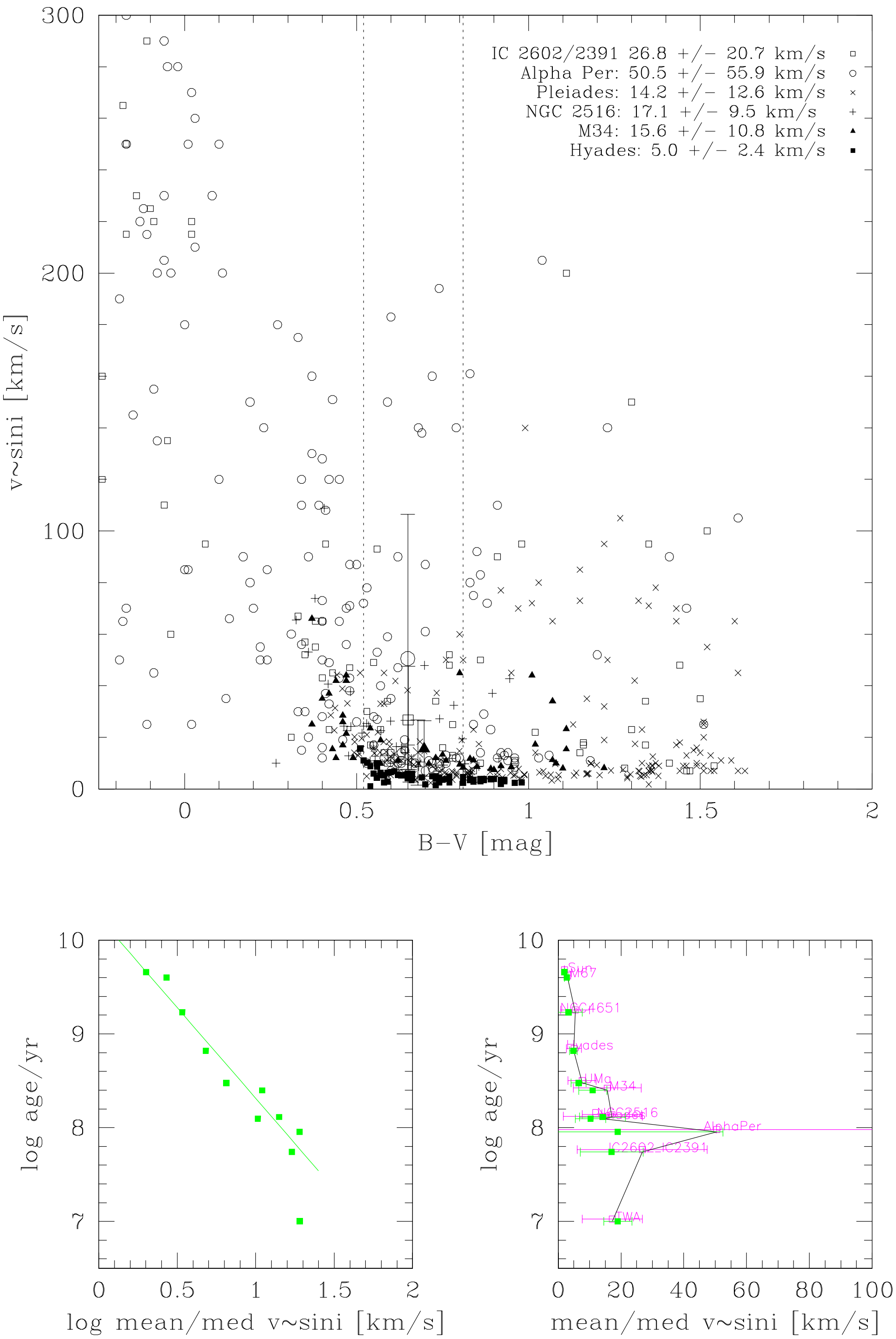


Fig. 2.— Color-magnitude and Hertzsprung-Russell diagrams for FEPS objects. Upper panel: M_V vs B-V. Red represents members of the open clusters IC 2602, Alpha Per, Pleiades, Hyades; blue represents solar neighborhood field stars with Hipparcos parallaxes; green represents more distant field stars selected using x-ray emission as a signature of potential youth. Lower panel: log L/Lsun vs log Teff/K.


IC 2602/2391 26.8 +/− 20.7 km/s
Alpha Per: 50.5 +/− 55.9 km/s
Pleiades: 14.2 +/− 12.6 km/s
NGC 2516: 17.1 +/− 9.5 km/s
M34: 15.6 +/− 10.8 km/s
Hyades: 5.0 +/− 2.4 km/s
v~sini [km/s]
B−V [mag]
log age/yr
log mean/med v~sini [km/s]
log age/yr
mean/med v~sini [km/s]
Sun
M67
NGC4651
Hyades
UMa
M34
NGC2516
AlphaPer
IC2602
IC2391
TWA

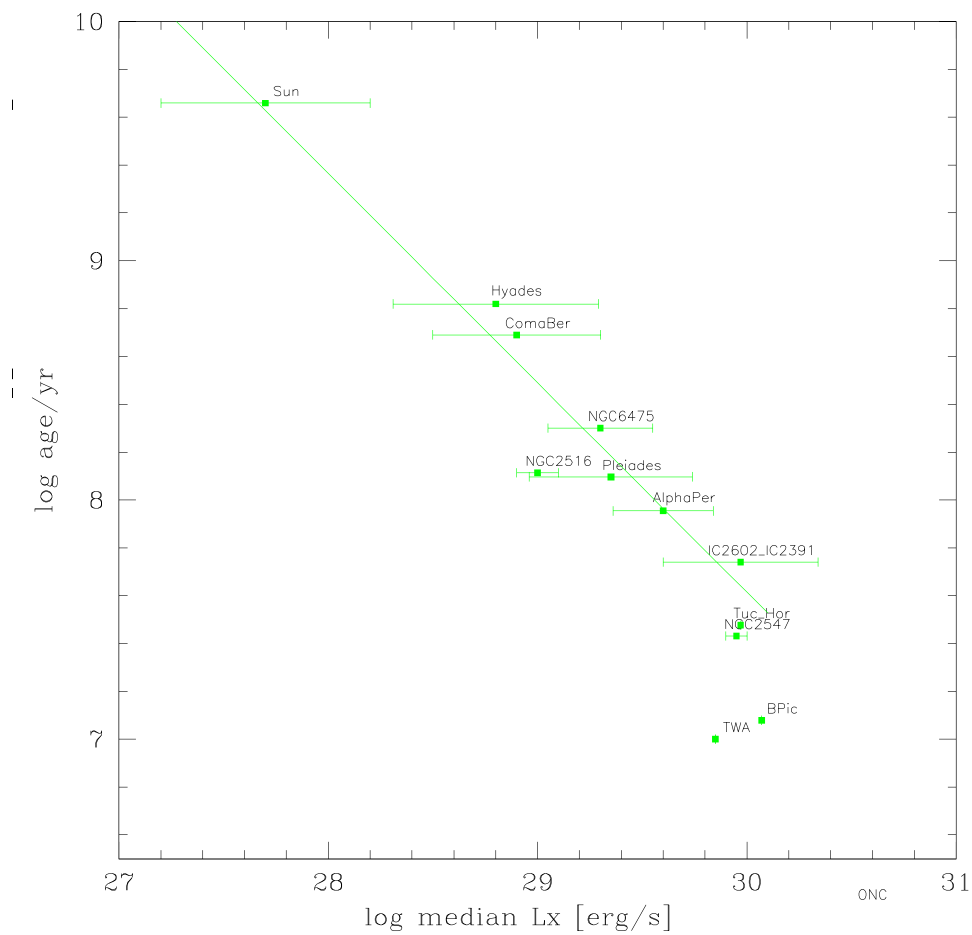


Fig. 4.— Cluster calibration of Lx.

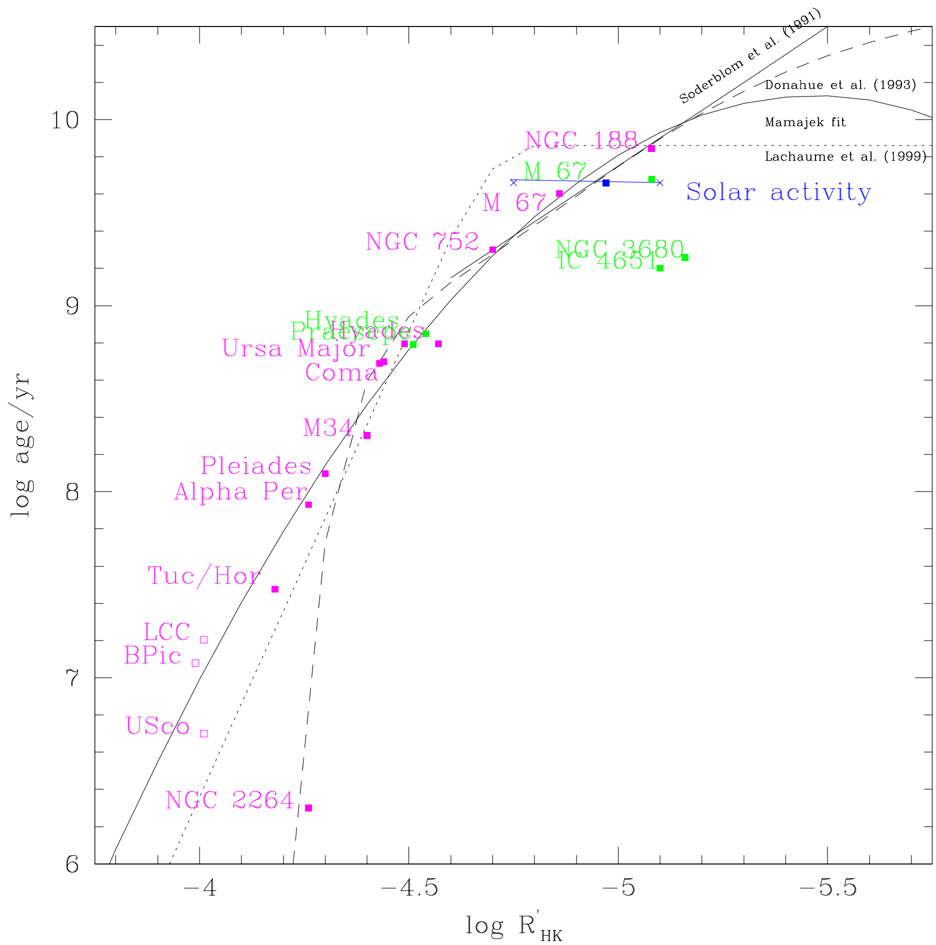


Fig. 5.— Cluster calibration of CaII H&K emission index.

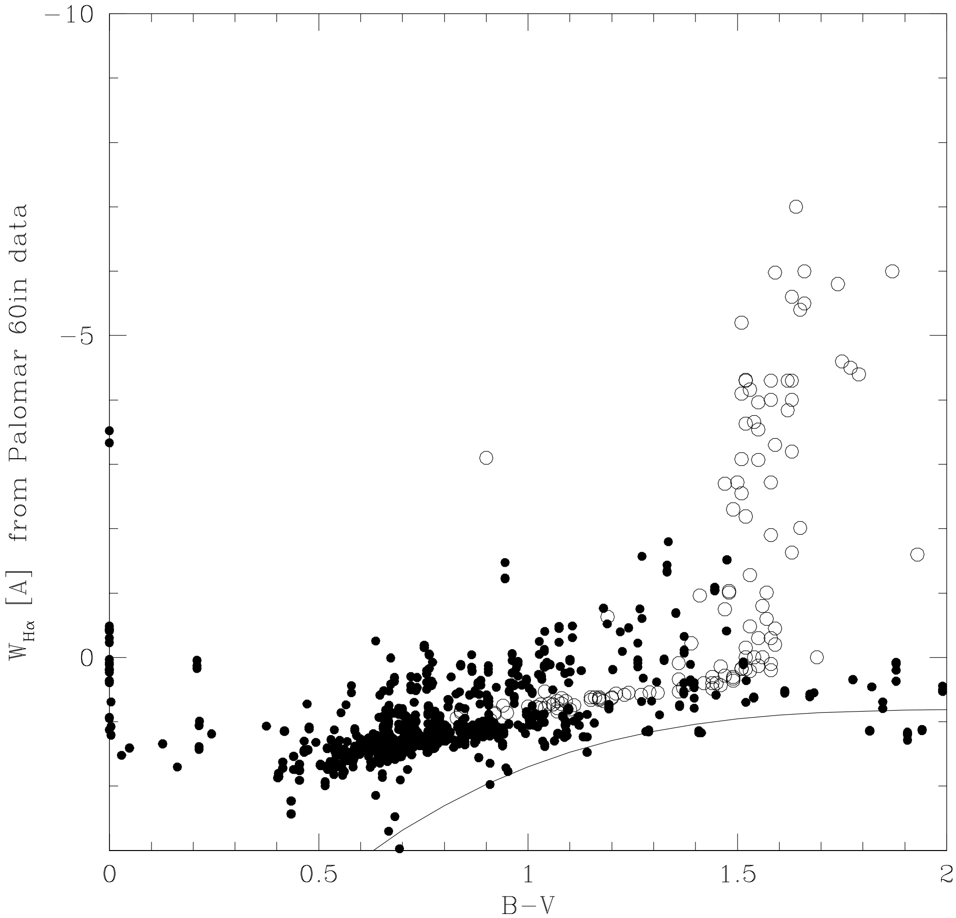


Fig. 6.— Hα equivalent width vs B-V for FEPS objects (filled symbols – currently all P60" observations including standards) compared to the Stauffer et al. (1991) Hyades data (open symbols). Solid lines represent the analytic fit of by Mamajek et al (2002) for field dwarfs and subgiants while dotted lines are the rms in the fit. In the bottom panel only the first-look gas sub-sample from FEPS is shown.

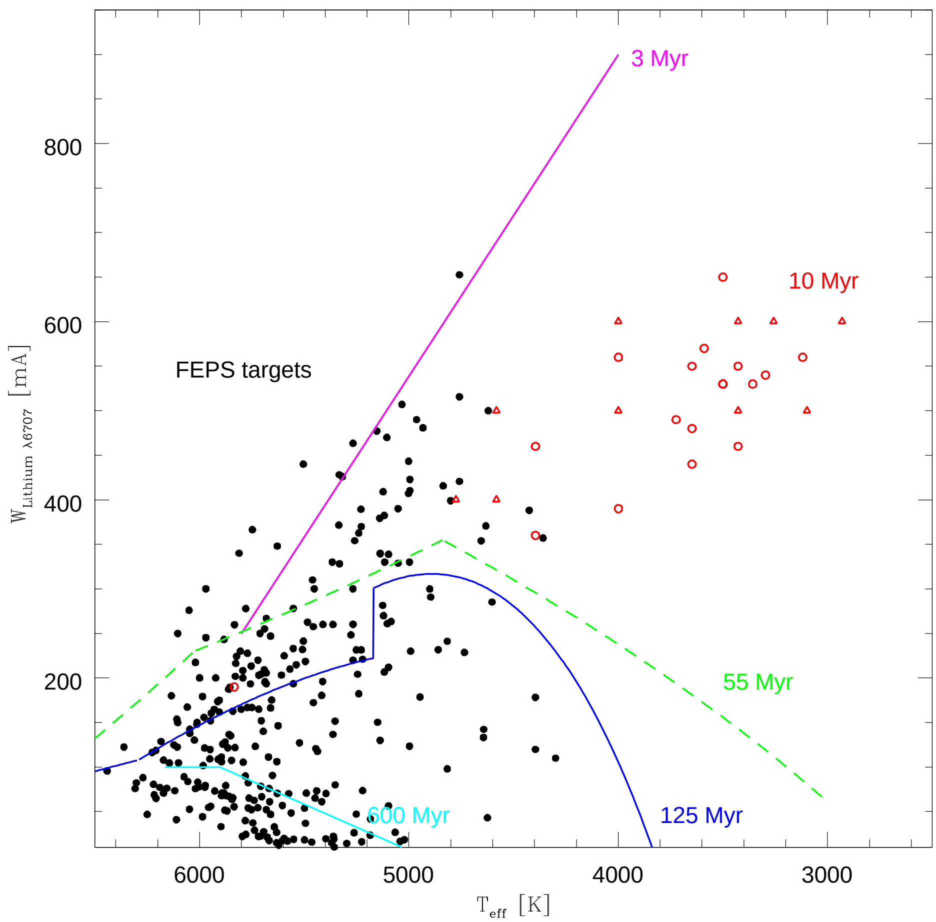


Fig. 7.— LiI 6708 of FEPS stars. "Traditional" lithium minima for clusters shown; Mamajek has different plot showing cluster median and 1σ values.

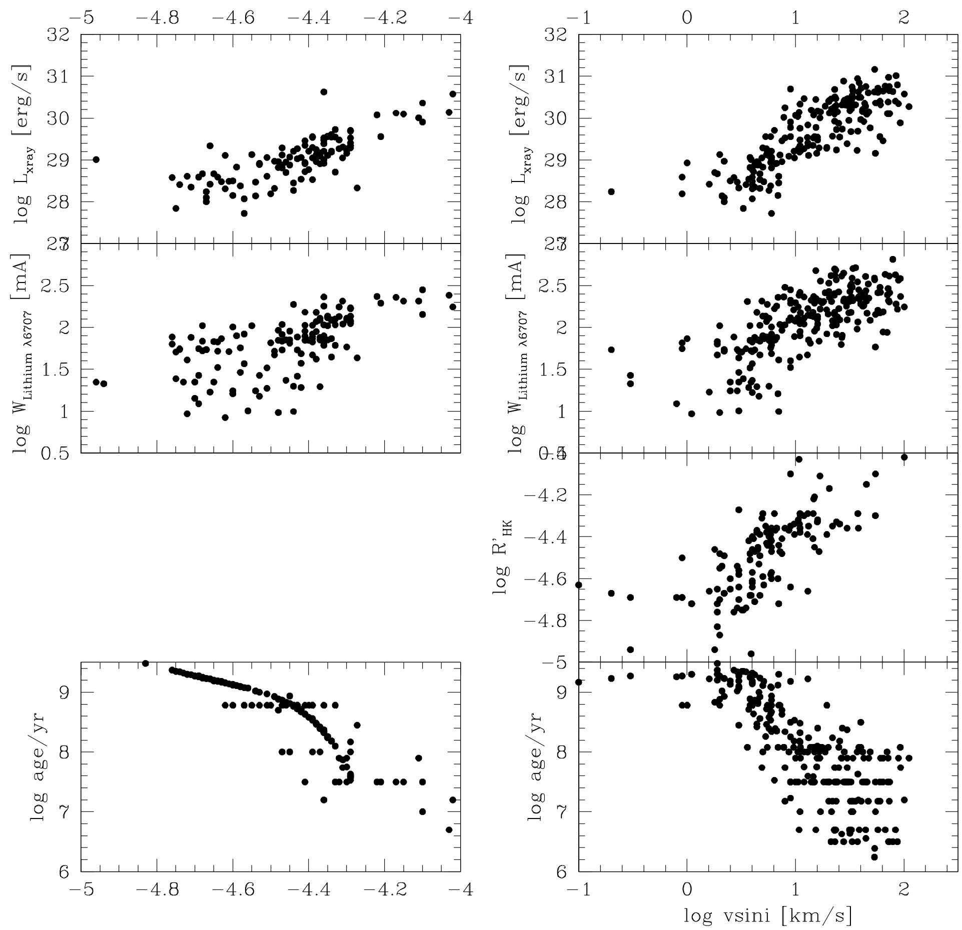


Fig. 8.— Comparison of various empirical age indicators. Note that the lower left panel reflects the Donahue calibration as applied, except for cluster stars which are assigned a single age and some very young stars where the calibration does not apply. Might want to make a separate figure for only FEPS cluster stars?

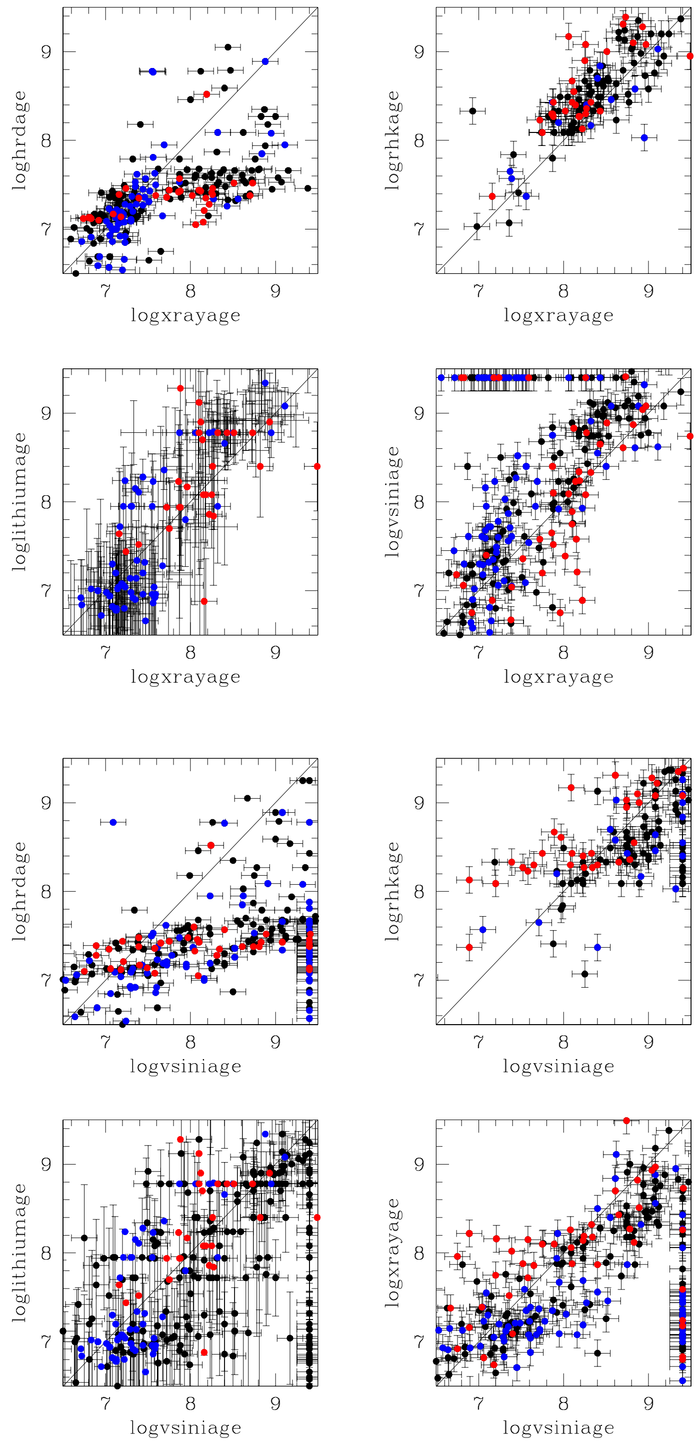


Fig. 9.— Comparison of ages derived from different techniques. Top four panels show x-ray luminosity as the ordinate while bottom four panels show vsini ages as the ordinate.