Solar-type stars and their evolution

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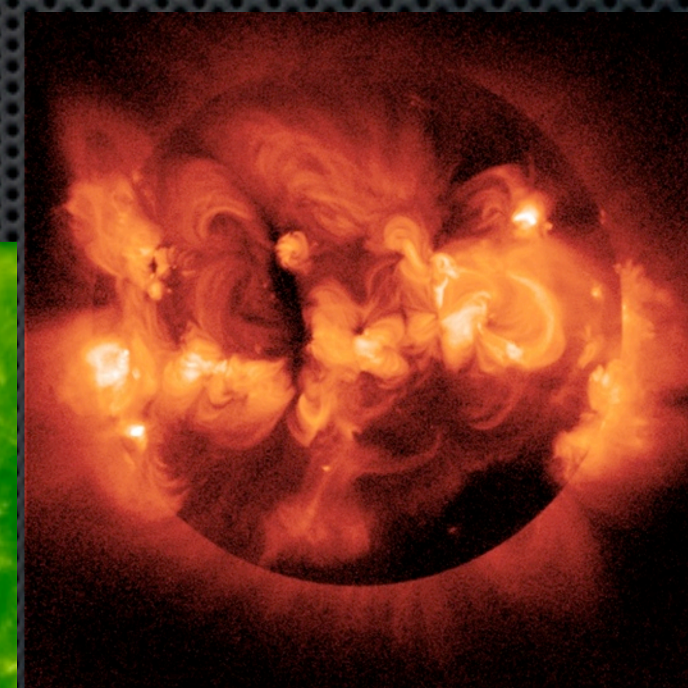
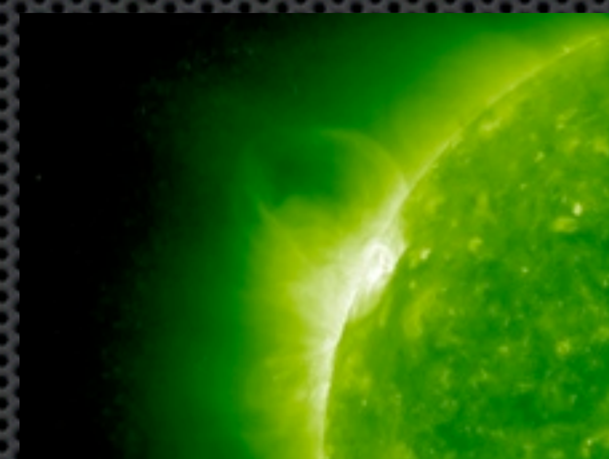
“Are we alone?”

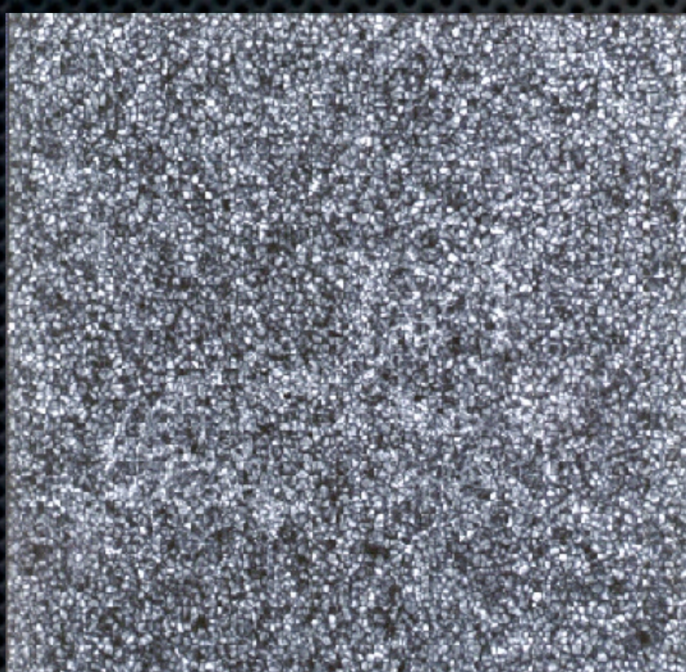
- Are there planets around other stars?
- Are there other planetary systems?
- Are there other Earth-sized planets?
- Are there Earth-like planets with life? With intelligent life?
- Is the Sun typical?
- Why not? What does it mean to be typical?
- What can other stars tell us about the Sun and its behavior?

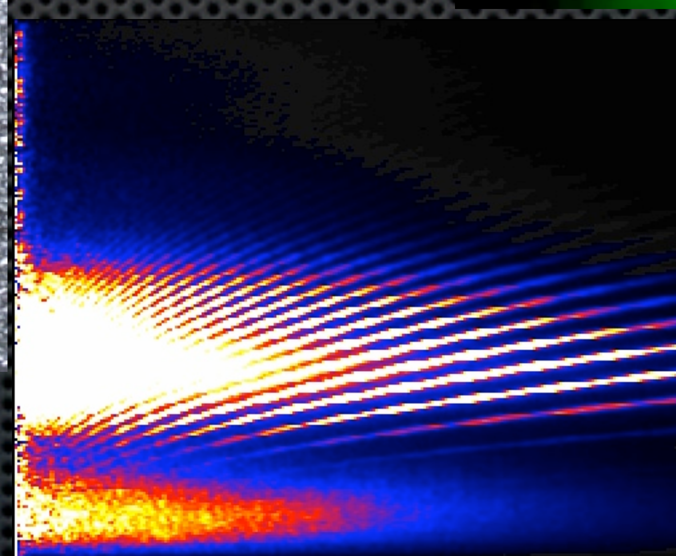
Everything we know about exoplanets comes from observing stars, and everything we know about the stars starts with the Sun. But the Sun itself is a story half told.

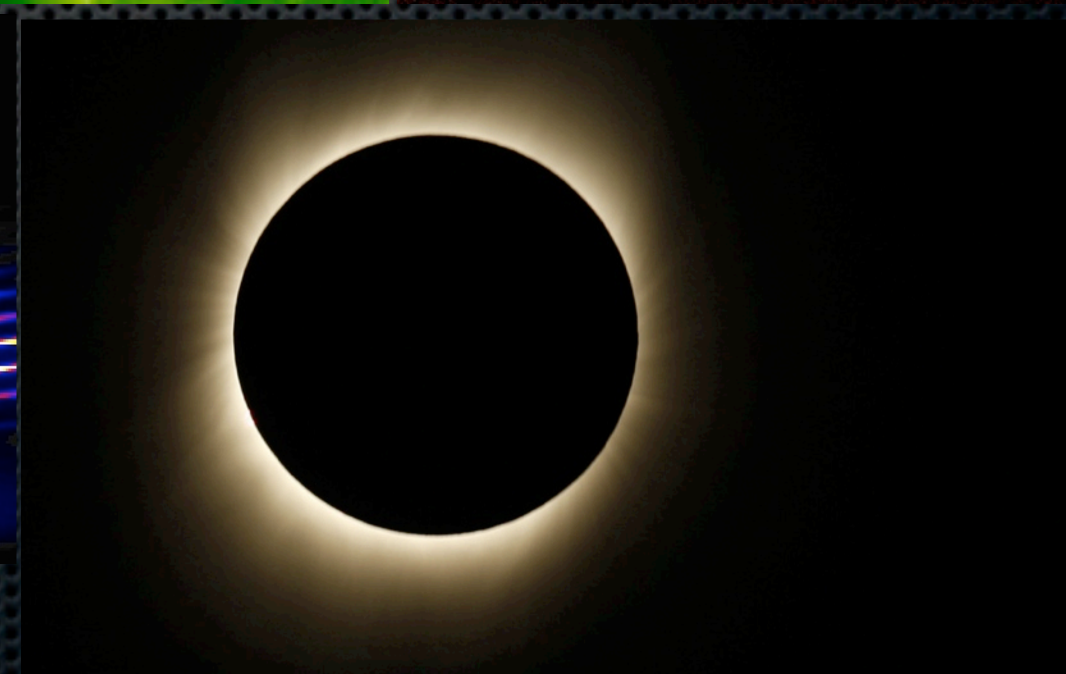
We study the Sun in glorious detail, better than we can for any star, yet to fully know the Sun we must go to the stars.











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Today’s program

- What do we know about stars like the Sun?
- What are the determinant (independent) properties and which are dependent?
- The problem of stellar ages.
- The promise of the next decade.

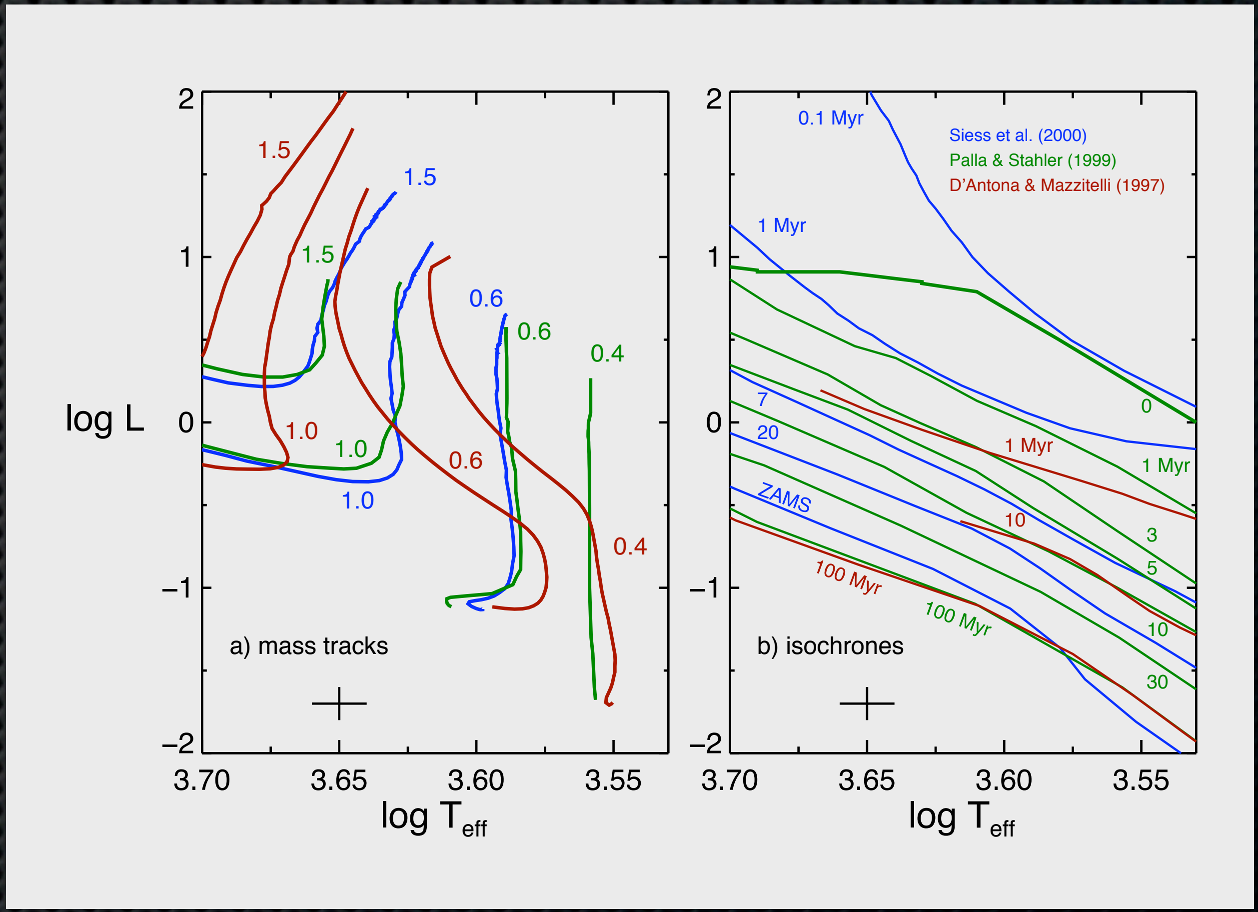
Essential properties

What determines what we observe

- Mass (Torres)
- Temperature (Torres, Giampapa)
- Gross composition (i.e., opacities) and its distribution
- Fine composition (detailed abundance differences) in 3-D
- Rotation (Ω, and its dependence on R and λ)
- Companionship, complete and in detail (Torres)
- Magnetic field properties (3-D and in time) (Ribas, Giampapa)
- Activity, in various forms (Ribas, Giampapa, Fischer)

Mass

- Number one determinant of a star's state, but on evolutionary time-scales (Gyr).
- Not now directly measurable for single stars but inferred to within ~10% from spectral type or color for main sequence stars.
- Modest number of measured masses better than 1% (well-separated nearby binaries).
- Absolutely critical for verifying models.
- We need accurate and precise masses for PMS and ZAMS stars. The available models are consistent, but do we really know the color (temperature) of 1.00 $M_\odot$ on the ZAMS?



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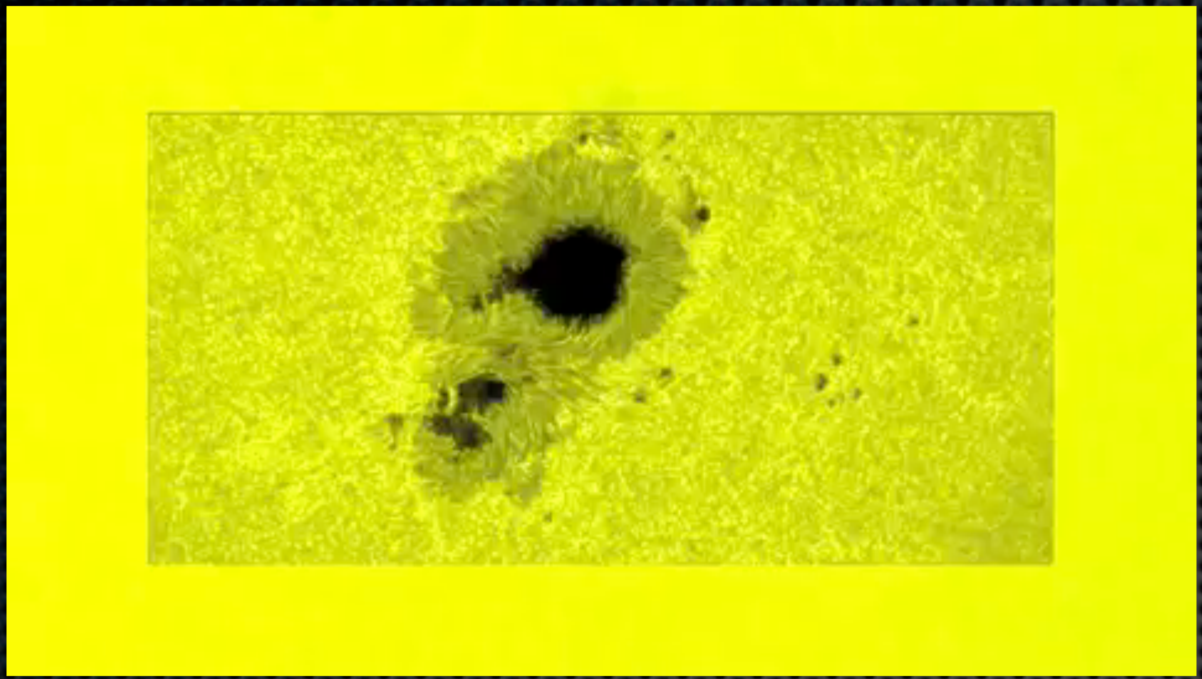
An opportunity (and need)

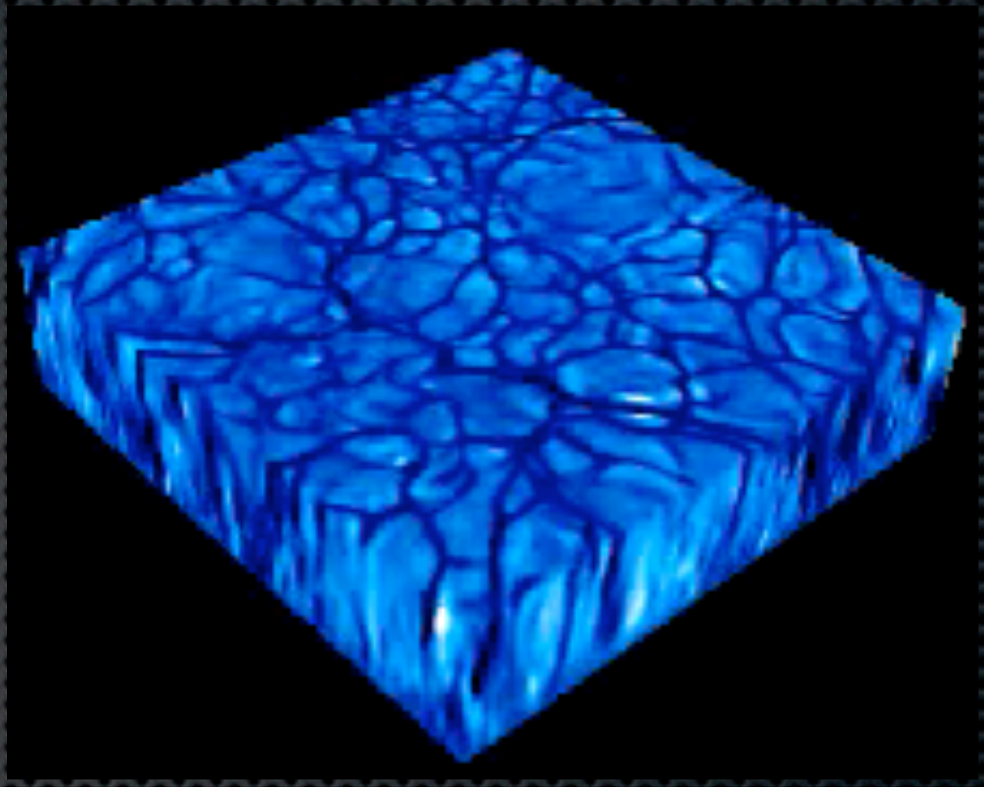
- Measure masses for PMS and ZAMS stars.
  Surprises are probably in store.
  Difficult job: identify binaries, then follow orbits for years.

Temperature

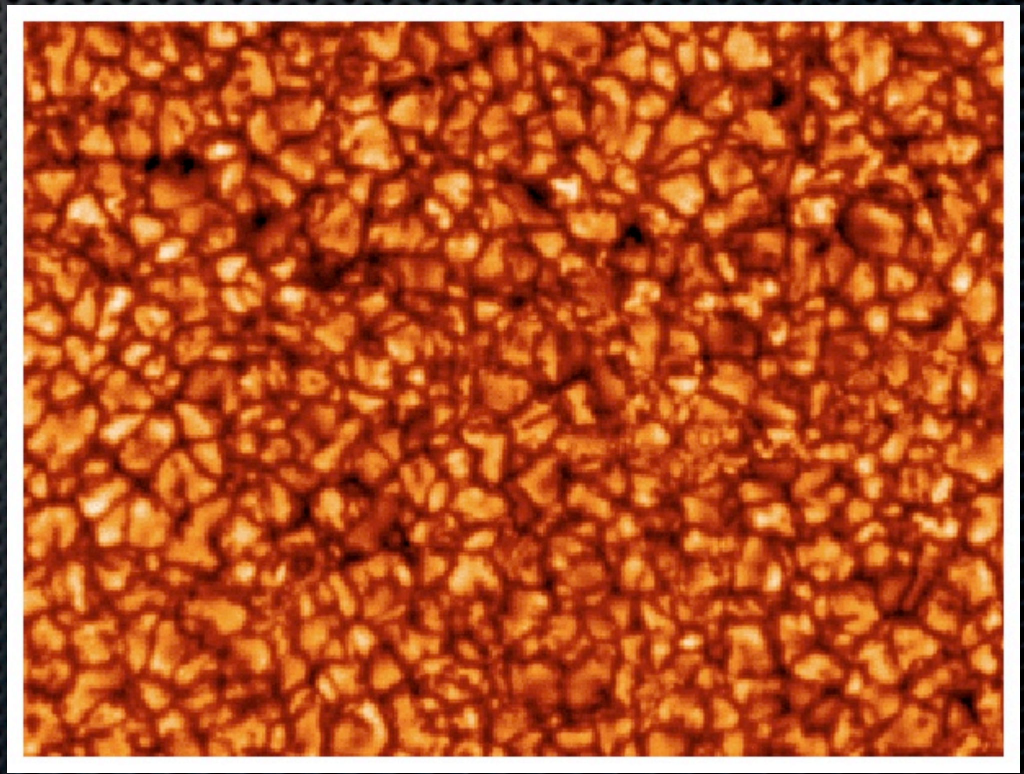
- Two paths: photometric or spectroscopic; both present problems.
- Photometry measures the broad-band SED.
- Spectroscopic values reflect line formation conditions through a complex atmosphere, as well as ionization and excitation balances.
- Spectroscopic methods can be precise, esp. differentially: ~10 K.
- Relating the two still leaves scatter of 80–100 K, taken as the true uncertainty.
- Effective temperature is a measure of total energy output, not the surface.
- A single temperature can only approximate the stellar atmosphere, esp. for younger, heavily-spotted stars, and the photometry shows this, with systematic discrepancies between indices.

The Sun's surface (what's wrong with T_{eff})





$$L = 4\pi R^2 \sigma T^4$$



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Another opportunity

- Create a means for determining a characteristic temperature that takes into account atmospheric physics and all the observational data while respecting uncertainty.

Composition

Gross composition:

- He, C, N, O, Ne, and iron peak especially important for opacities and CZ depth.
- He largely invisible to us. CNO for Sun are controversial (Asplund).
- We determine [M/H] and [X/H] to about 0.03 dex for the nearer stars (Valenti & Fischer 2005). Requires high S/N and high resolution, so it's mostly one star at a time.
- Abundances are measured relative to the Sun. For solar-type stars various effects should be second-order (temperature effects, effects of a star's atmospheric structure, etc.).

Fine composition:

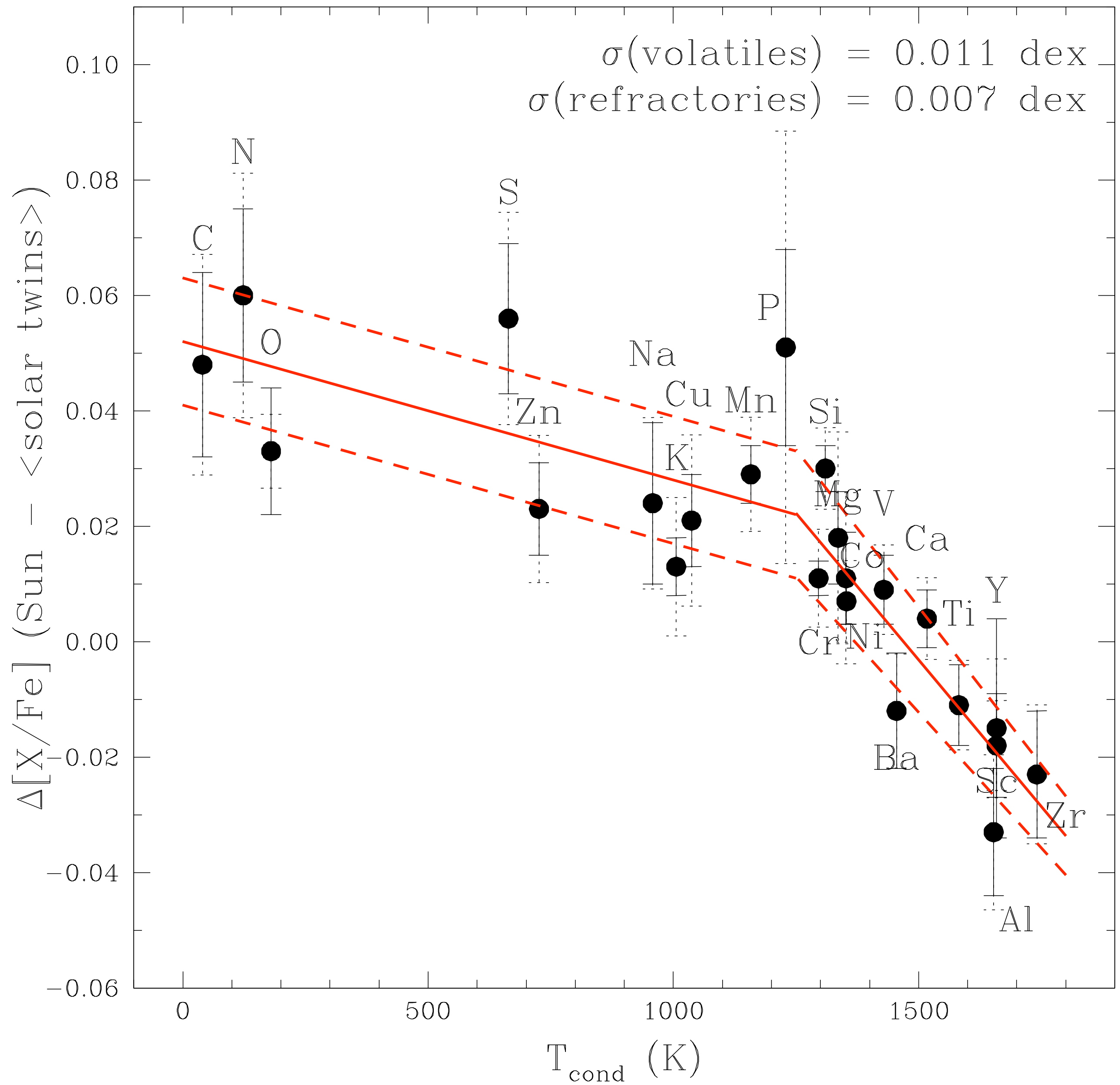
- This includes Li as a tracer of convective processes or diffusion effects, also rarer elements.
- Patterns may reveal enrichment history of pre-stellar material and/or surface enrichment (such as after planet formation).
- Meléndez et al. (2009) claim accuracy of 0.01 dex for [X/Fe] for solar twins ($\Delta T_{\mathrm{eff}} < 75$ K, $\Delta \log g < 0.1$, Δ[Fe/H] < 0.07) and discuss patterns, particularly for refractory elements.

Is the solar composition peculiar?

Melendez et al. (2009):
10 analogs and 11 twins

Mean differences vs. condensation temp.

Does this trend arise from formation of the terrestrial planets?



Opportunity #3

- Can a sufficiently precise and detailed study of elemental abundances reveal familial traits among nearby stars that could point to a common origin (stellar cognates)?

Companionship

A variation on "Are we alone?"

- Close companions can influence the star itself, but let's ignore those cases. We want to know if our family is especially weird, or just another interesting case.
- For other stars, we are now only sampling a very limited portion of the parameter space, where a close-in, single, massive planet dominates the situation.
- Also, stellar and planetary systems are surely dynamic, and change with time. Stellar companions can come and go. Companionship has a history.

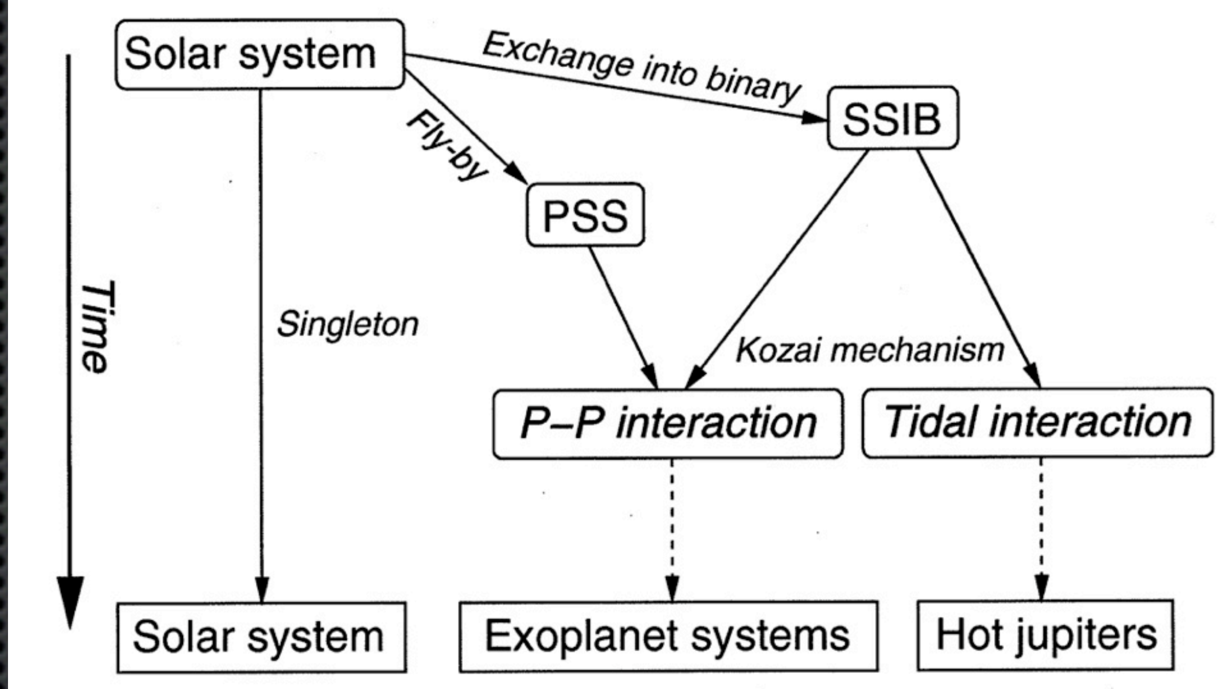


Figure 6. A schematic flow-diagram for planetary systems within stellar clusters. Fly-by interactions lead to *perturbed planetary systems* (labeled PSS) while exchanges into binaries leave *solar systems in binaries* (labeled SSIB).

From M. B. Davies et al., 2008, Nobel Symp. 135; "Is the Sun a singleton?"

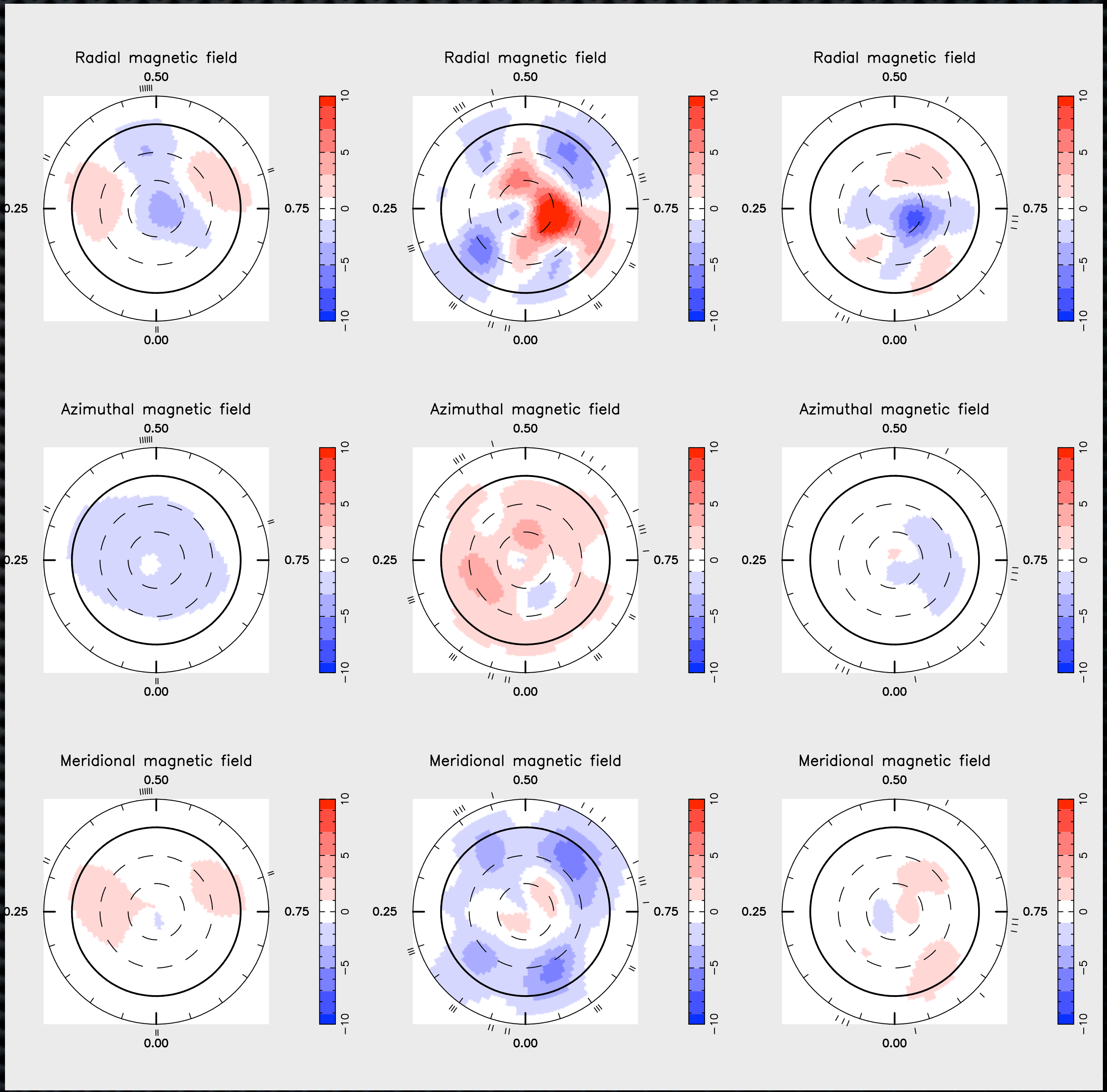
Rotation and convection

Bulk motions

- Full, three-dimensional knowledge of the distribution of angular momentum, convective motions, meridional flows, core convection, etc. is needed to understand fully the stellar physics. The Sun is <u>not</u> a solid-body rotator!
- Other motions classified as "*turbulence*" can be added.
- Note that these effects, fully accounted for, may significantly influence other measurements (cf. Asplund). Or not.
- What we can measure are globally-averaged quantities: $v \sin i$, $\Omega(t)$, "microturbulence," "macroturbulence," convective blueshifts.
- A full three-dimensional treatment of the stellar atmosphere may obviate "turbulence."

Magnetic fields and activity

- A full three-dimensional description of magnetic fields is desired, including their variation with time.
- What is available is much, much less, but improving (spectropolarimetry of τ Boo ➜➜➜).
- We'll add here information on the outer atmospheres of stars; everything above the photosphere:
  - Chromospheric emission
  - Transition region emission
  - Coronal emission
  - Winds



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Essential properties II

Independent variables:

- Mass
- Gross composition (i.e., opacities) and its distribution
- Age
- Other initial conditions:
  - angular momentum
  - companionship

Plus assumptions:

- $dM/dt \approx 0$
- Accretion history of PMS Sun

Dependent variables:

- Rotation (Ω, and its dependence on R and λ)
- Convection
- Magnetic field properties (3-D and in time)
- Activity, in various forms

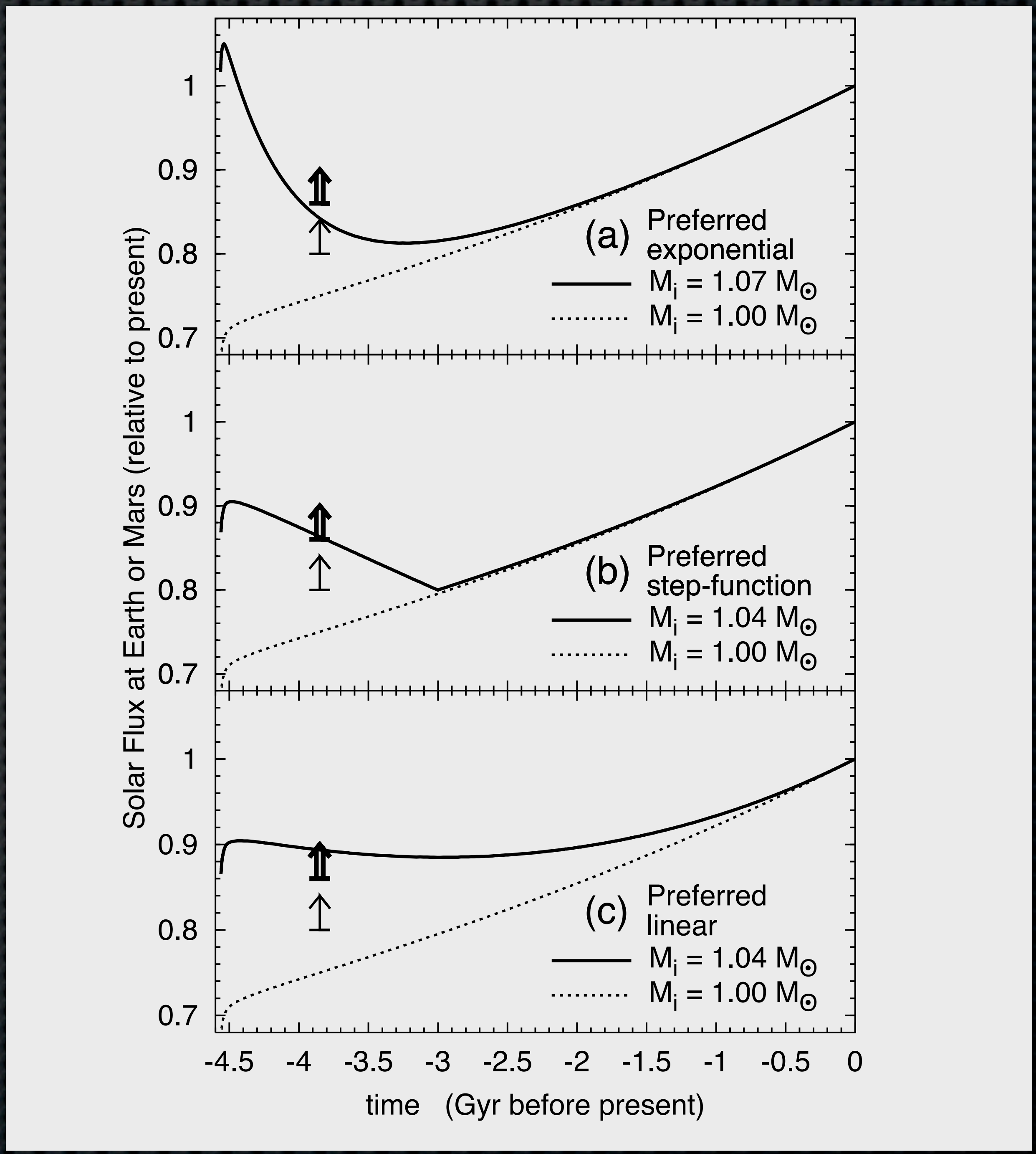
Other properties:

- Temperature
- Fine composition (detailed abundance differences)
- Companionship, complete and in detail

Evolutionary assumptions

High early mass loss?

- Sackmann & Boothroyd (2003) have suggested the Sun reached the ZAMS with up to ~5% more mass.
- This solves the faint-early-Sun problem w.r.t liquid water on the early Earth (and Mars).
- This relatively high mass is consistent with the Wood et al. mass loss rates.
- Possibly testable via helioseismology (Pinsonneault).



Evolutionary assumptions

Early accretion history: does it matter?

- Standard models (e.g., D'Antona & Mazzitelli) predict a fully convective – or at least highly convective – Sun in the PMS phase.
- Other models take into account accretion histories and claim early Sun was more similar to today's (Wuchterl & Klessen 2001; Wuchterl & Tscharnuter 2003). This matters only for first ~1 Myr.
- Nordlund (2009 preprint) claims lock-up of heavy elements into solar CZ helps explain the Asplund discrepancy and also Jupiter's low H.

Opportunities

- #4: Can we infer the early accretion history of stars observationally?
- #5: Can we determine the early (ZAMS) rate of mass loss observationally?

The problem of age

Time is of the essence in stellar evolution:

- star = $f(M, Z, t)$ (Vogt-Russell theorem)
- (and there's rotation, companionship, etc.)

- Or is it? Time is not a direct agent of change, and age cannot be measured, not like mass and composition.

- A challenge: WMAP got an age of the Universe of 13.7±0.13 Gyr; i.e., to within 1%!
- We cannot do as well as 10% for stars.

But one day we will hear of evidence for signs of life – a biomarker – on an Earth-like planet around another star, and the critical question will be: *How old is that star?*

- This star of interest will most likely be nearby and by itself in the field, not part of a cluster. It will probably be fairly old. How well can we estimate its age?

- What information can we use to estimate the age of a low-mass star (i.e., one that is convective, from birth through the main sequence) and how can we use it?
- How precisely and accurately can we determine an age? How does that depend on mass and composition?
- How can we do better?

Some problems looking for ages

- Galactic processes such as chemical enrichment, star formation, and “disk heating.”
- Planet formation and the evolution of proto-planetary disks around young stars (time-scale ~ 10 Myr).
- The dynamical evolution of gas giant planets around solar-type stars (~1 Gyr?).
- The physics of brown dwarfs (find them as companions to FGK stars so you can get an age; ~100 Myr).
- Creating a bona fide comparison sample for the Sun based on mass and age. What is the future of our Sun?
- Almost anything having to do with stellar evolution.

Age indicators

The ideal (Barnes 2007):

- Measurable for single stars
- Sensitive to age and insensitive otherwise
- Variation with age exceeds inherent scatter or noise
- Can be calibrated with quantifiable errors
- Underlying physics understood (or at least rationalized)
- Establishing the calibration involves a minimum of assumptions

We'd settle for:

- Limiting the age by setting bounds.
- Classifying or grouping stars properly (e.g., strong Li in T Tauris)
- Sorting stars to get the order of age correct, even if the scale is uncertain
- Quantifying an age for a single star or a group

Fundamental ages

- An age is fundamental if the measurements and analysis are completely understood, with no real ambiguities.
- There is one fundamental age, that for the Sun:

  4,567±1±5 Myr, with the systematic uncertainty having to do with the sequence of events in the early solar system.
- This situation for the Sun underscores why the problem for stars is so difficult.
- This independent age determination for the Sun is fundamental to all of stellar astrophysics.

  N.B. Radionuclide age-dating has its start in a paper by Ernest Rutherford in *Nature*, 1929: (*Origin of Actinium and Age of the Earth*). "If we suppose that production of uranium in the earth ceased as soon as the earth separated from the sun, it follows that the earth cannot be older than 3.4 (Gyr)..." He goes on to compare this to the Jeans age for the Sun (7000 Gyr!) and notes that U must have been forming in the Sun only 4 Gyr ago.

Semi-fundamental ages

1. Nucleocosmochronology

- Ages from radionuclide decay are almost fundamental: the physics of the process is completely understood (and it is simple). Species used is ^{232}Th ($\tau_{½} \approx 14$ Gyr) with a feature at 4019 Å.
- An assumption must be made about the starting abundance, generally based on scaling other *r*-process abundances.
- Radionuclide ages offer a means to get ages for some very old stars in the Galaxy, but these stars are very faint and spectra of very high quality are needed.
- This works only for low-metal stars, due to line blending.

Semi-fundamental ages

Nucleocosmochronology

A case study: CS 22892–052, with [Fe/H] ≈ –3.1 (Sneden et al. 1996, 2003):

- Comprehensive look at heavy elements, many exotic (Mo, Lu, Au, Pt, Pb, etc.).
- Measured Th II feature at 4019Å, compared to stable elements. Ages derived:

  Th/Eu = 12.8

  Th/Ir = 19.2

  Th/Pt = 10.5

  Th/U > 10.4 Gyr

  Average is 14±3 Gyr.
- Note that Fowler & Hoyle (1960) got a Galaxy age of 15±4 Gyr using this method.

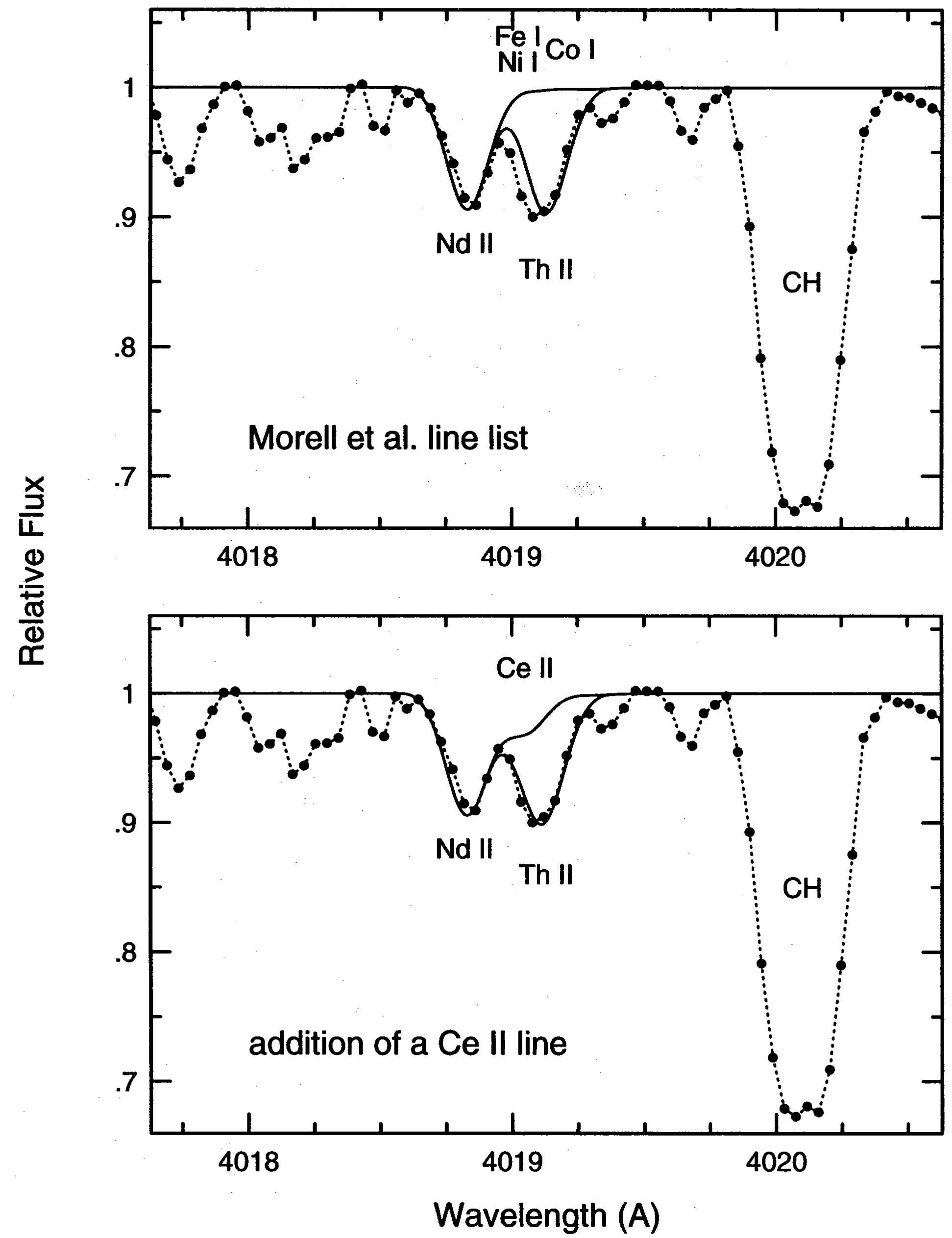


FIG. 8.—Observed and synthetic spectra of the Th II resonance line. For the syntheses displayed in the top panel, the line list of Morell et al. (1992) was employed with and without the Th II feature. In the syntheses of the bottom panel, a Ce II line was added to try to match the blueward asymmetry of the Th feature.

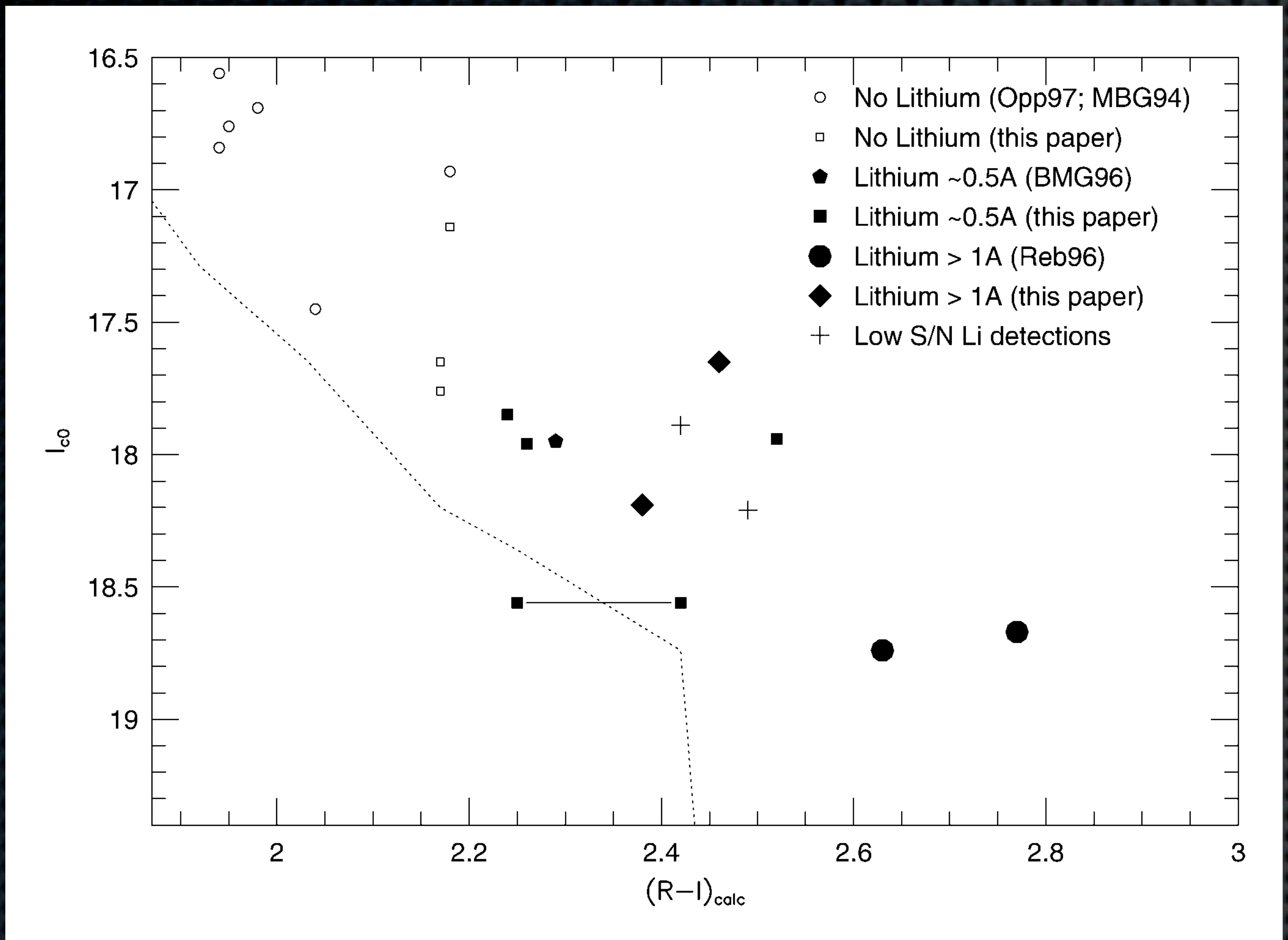
Semi-fundamental ages

2. Kinematic traceback (dynamical ages)

- Over time stars in the Galaxy experience gravitational interactions with massive objects, leading to "disk heating." Time scale is ~200 Myr.
- For very young ensembles (age < 20 Myr) a dynamical age can be determined by tracing space motions back in time to a minimum size.
  - Depends on the quality of kinematic data (π, proper motions, RV).
  - Model dependence comes from the Galactic potential used.
  - Independent of other techniques and is essentially astrometric.
- Works only for groups, not individual stars.
- Used in concert with empirical indicators such as activity.

Model-dependent ages

1. Lithium depletion boundary (LDB)



LDB in α Persei

- Relatively new: first suggested by Rebolo et al. (1992) to tell very-low-mass stars from brown dwarfs. Both are fully convective, but BDs do not reach a core temperature high enough (~3 MK) to destroy Li.
- Effect first seen in Pleiades (Basri et l. 1996): implied age of >125 Myr, versus ~80 Myr from MSTO.
- The HRD region where the LDB is seen is <u>very</u> faint.

Model-dependent ages

Lithium depletion boundary (LDB)

- There are now LDB ages for 5 clusters, and systematically τ (LDB) ≈ 1.5 τ (MSTO).
- Physics of LDB is simple because stars are fully convective, whereas MSTO may be affected by various processes.
- LDB only works for clusters or groups; it is an ensemble property.
- Or is it simple? Jensen has argued that radii of young stars are larger than assumed, retarding Li depletion and so leading to mis-estimated ages.

Opportunity #6

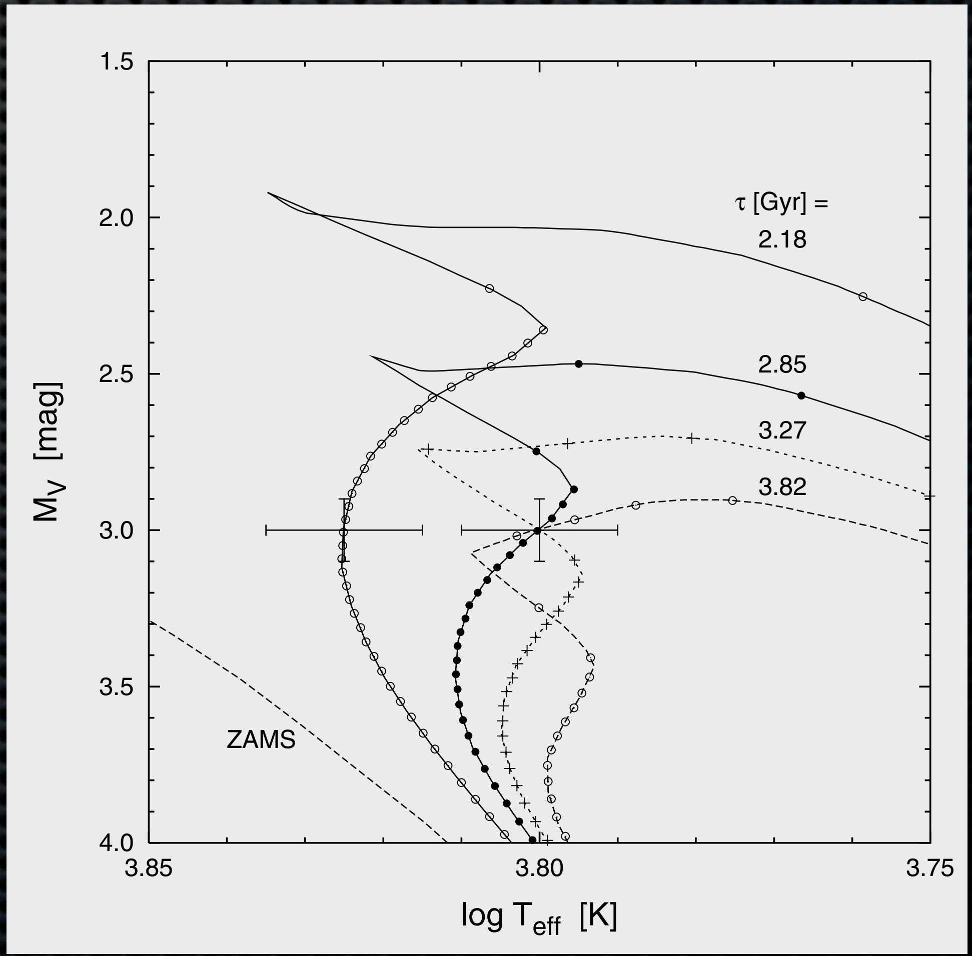
- Model the LDB more fully. Understand cluster ages.

Model-dependent ages

2. Isochrone placement

- Deriving T_{eff}, M_V, and [M/H] (and uncertainties), then placing a star on calculated evolutionary tracks.
- Very different from isochrone fitting to a cluster, where one has not just more stars, but a distribution.
- Isochrones are not invertible, their distribution in the HRD is non-uniform, so results and errors can be biased.
- There is degeneracy; note three curves through one point.
- Bayesian analysis with PDFs attempts to overcome this and move away from the usual direct placement (nearest isochrone).

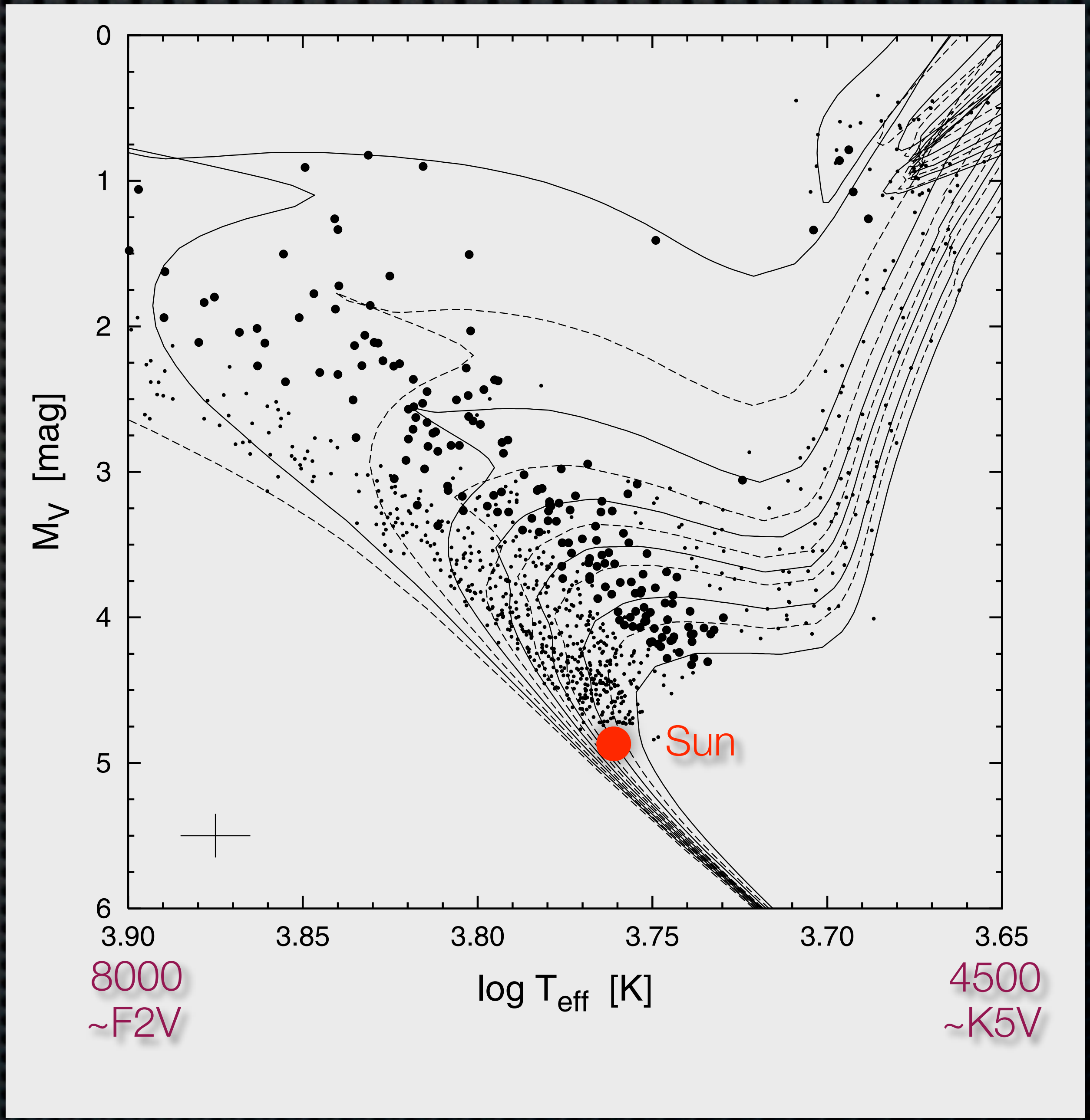
Pont & Eyer (2004)
Jørgensen & Lindegren (2005)
Takeda et al. (2007)



Jørgensen & Lindegren 2005

Jørgensen & Lindeman (2005)

- Large sample of synthetic stars, applied several methods to recover ages.
- Bayesian was consistently most accurate and with smallest errors, <u>but</u>:
  - Errors were 0.20 dex (50%).
  - Sample was relatively massive and old; i.e., evolved.
  - Stars shown have “well-defined” ages (no limits); large dots have σ < 20%. They avoid ZAMS region and solar mass.



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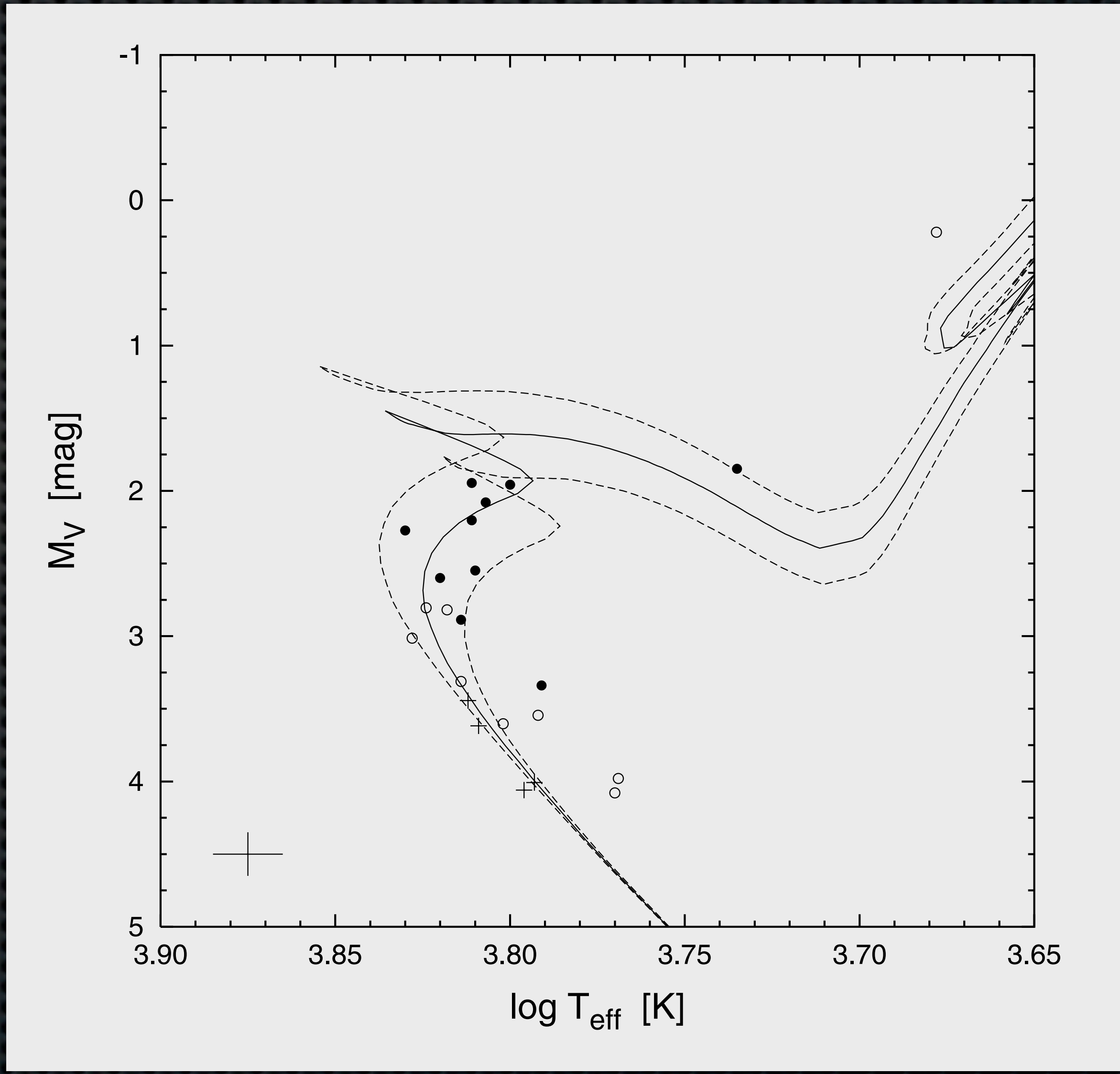
Isochrone placement (cont.)

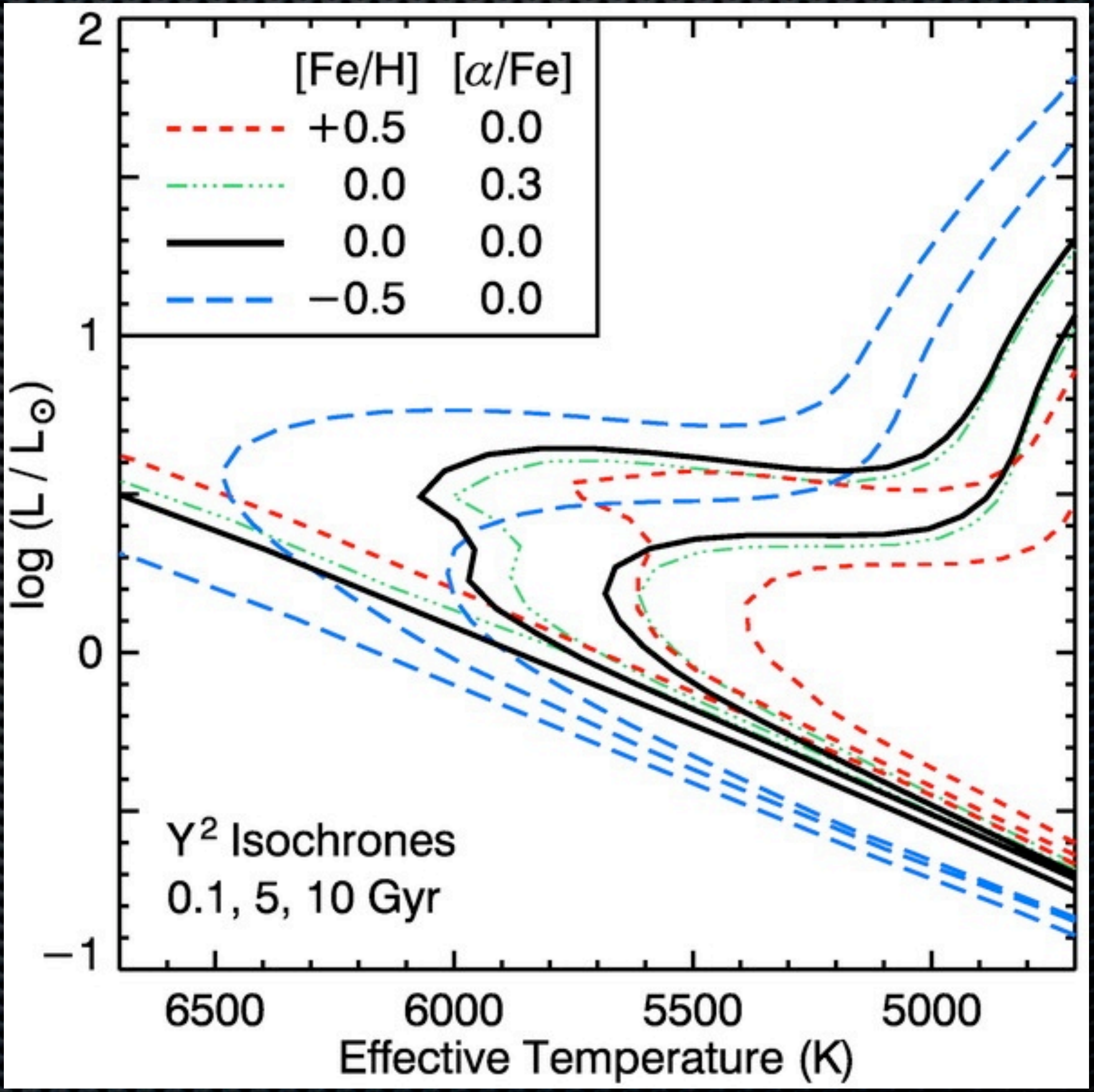
- Bayesian methods may offer advantages for more objective isochrone fitting in sparse clusters, such as IC 4651.
- Solid line is best fit at 1.56±0.03 Gyr.
- Determine 4.05±0.05 Gyr for M67.
- Quoted uncertainties are precisions, not accuracies. Unknown binaries at turn-off can be a problem.



Isochrones: Why metals matter

Valenti & Fischer (2005)

- Note shift to blue as metals go down.
- Note shift to red as alpha elements increase.



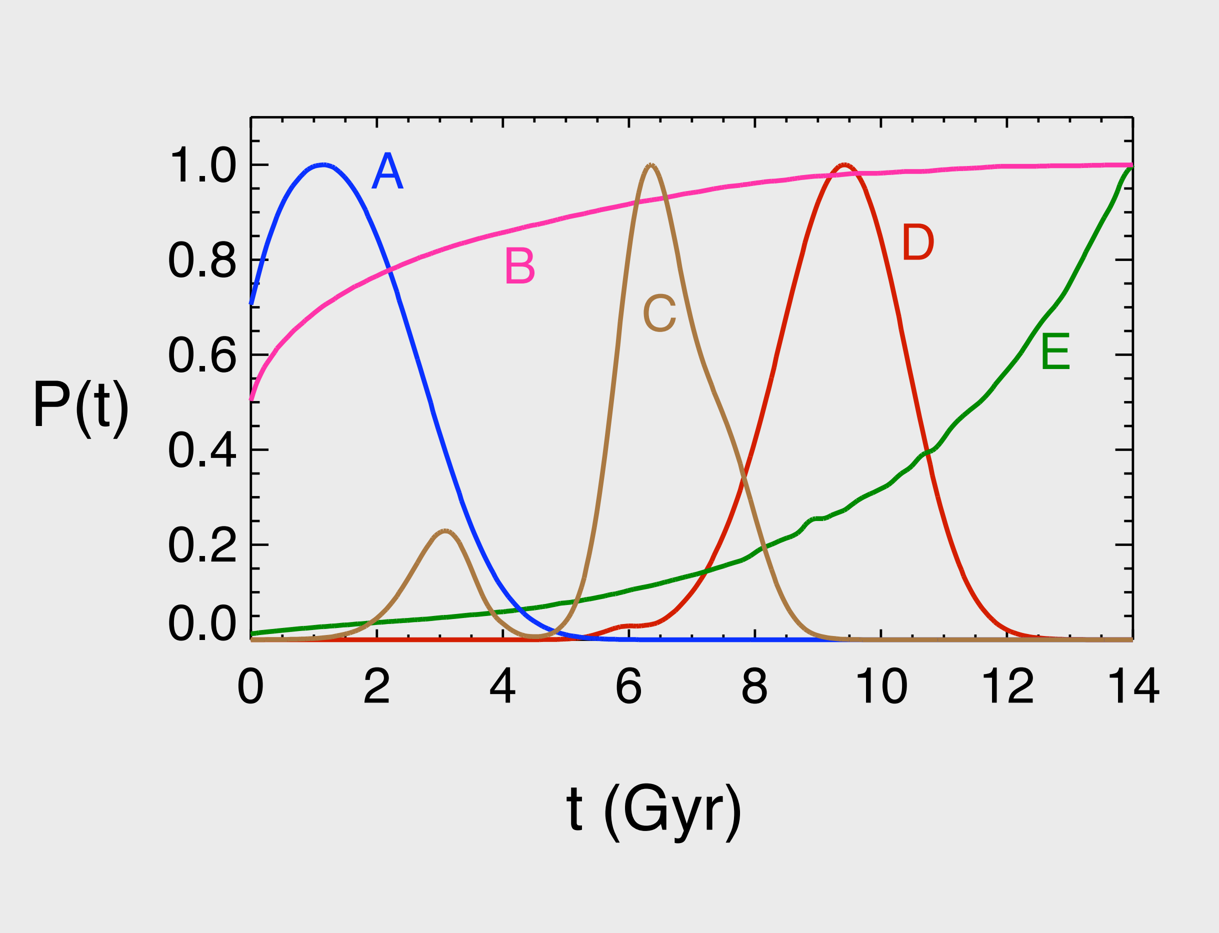
Model-dependent ages

Isochrone ages for single stars

Each curve is for a different star. Some are well-behaved, some double-peaked, some indeterminate. (from Takeda et al. 2007)

There is a bias in that certain age ranges are more likely to produce indeterminate PDFs.

- Obvious requirement: highly-accurate parallax, magnitude, and color to get luminosity and temperature.
- Even with that, significant uncertainty remains in:
  - Bolometric correction
  - Color-temperature relation
- Even with that, composition is crucial.
- Even with that, the derived ages are at best probabilistic, not deterministic (uneven spacing of isochrones and complex interplay of errors).



Model-dependent ages

3. Asteroseismology: see Kurtz and Chaplin

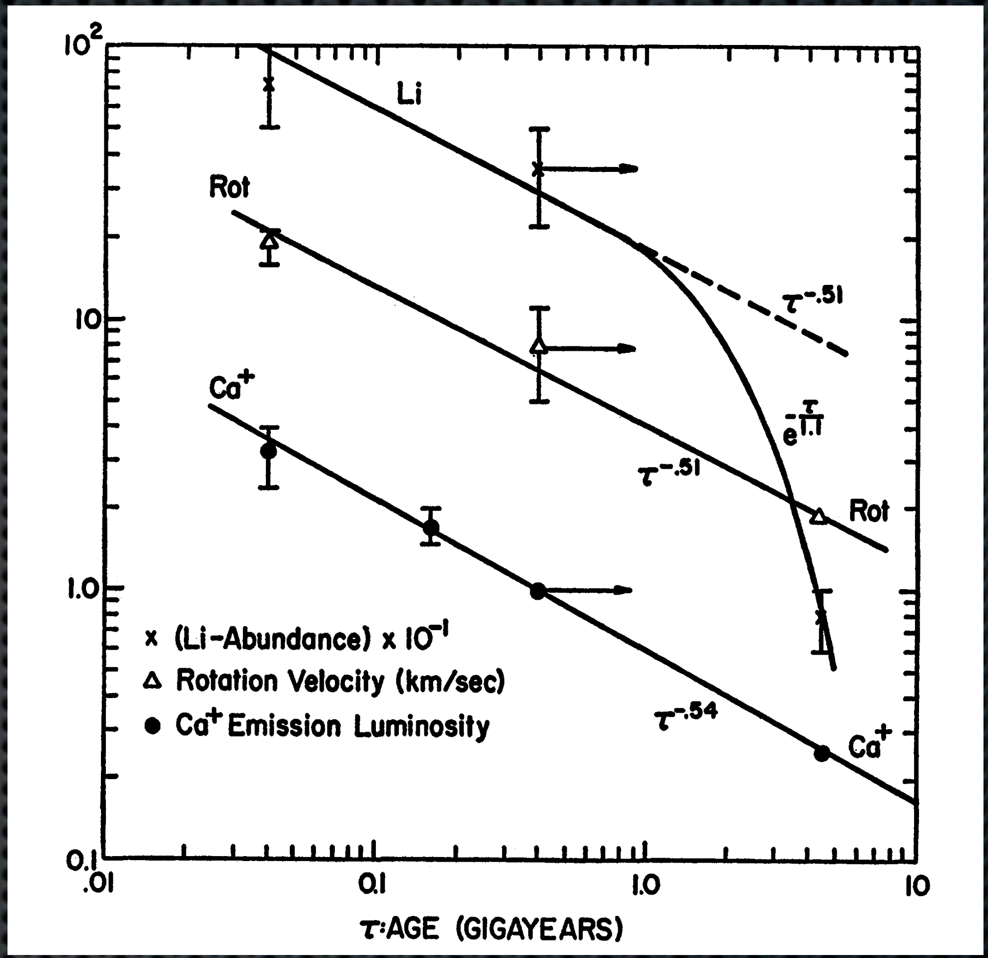
- Detect equivalent of solar 5-minute oscillations in stars.
- Detected modes are the low-order ones. These travel nearly straight through the star and so penetrate the core.
  oscillation frequencies ⇒ sound speed ⇒ core density ⇒ He fraction ⇒ age
- In practice, detecting oscillations even harder than detecting planets. CoRoT and Kepler are leading to breakthroughs.
  With RVs, need ~ 1 m/s; with photometry need ~1 ppm.
  Need ~1 week or more of continuous observations.
- Getting age means detailed models calculated for each star, needing temperature, luminosity, and composition. Labor intensive.
- Models same as for isochrone ages, and isochrone placement is used in concert with seismology. Seismology not really different, but more precise.

Asteroseismology (cont.)
Recent successes

Star	Osc. age	Other age	Reference
ν Ind	>9 Gyr		Bedding et al. 2006
ι Hor	625±5 Myr (Hyades)	0.4 – 6.7 Gyr	Vauclair et al. 2009
μ Ara	6-8 Gyr	1.5 – 6.4 Gyr	Bouchy et al. (2005)
β Vir	4.0±0.3 Gyr	3.5 Gyr	Eggenberger & Carrier (2006)
70 Oph AB	6.2±1.0 Gyr		Eggenberger et al. (2008)

Empirical age estimators

Skumanich (1972)



- Rotation, both $P_{\rm rot}$ and $v \sin i$
- Activity, mainly Ca II HK but also x-rays and Hα
- Lithium abundances
- Errors may be dominated by systematics because we do not understand the physics. There are reasonable scenarios for all these, but no predictive power.
- Any one indicator may work in some age/mass ranges and not others.

Observing age-related properties

- Li easy if strong: EW > 100 mÅ. Solar EW = 2 mÅ.
- Rotation easy for v sin i > 10 km/s; period also shows up readily for such (young) stars.
- Rotation hard below 10 km/s: v sin i values imprecise and very high resolution needed; period not always seen (low contrast).
- Activity easy: low resolving power (~ 2,000) adequate.

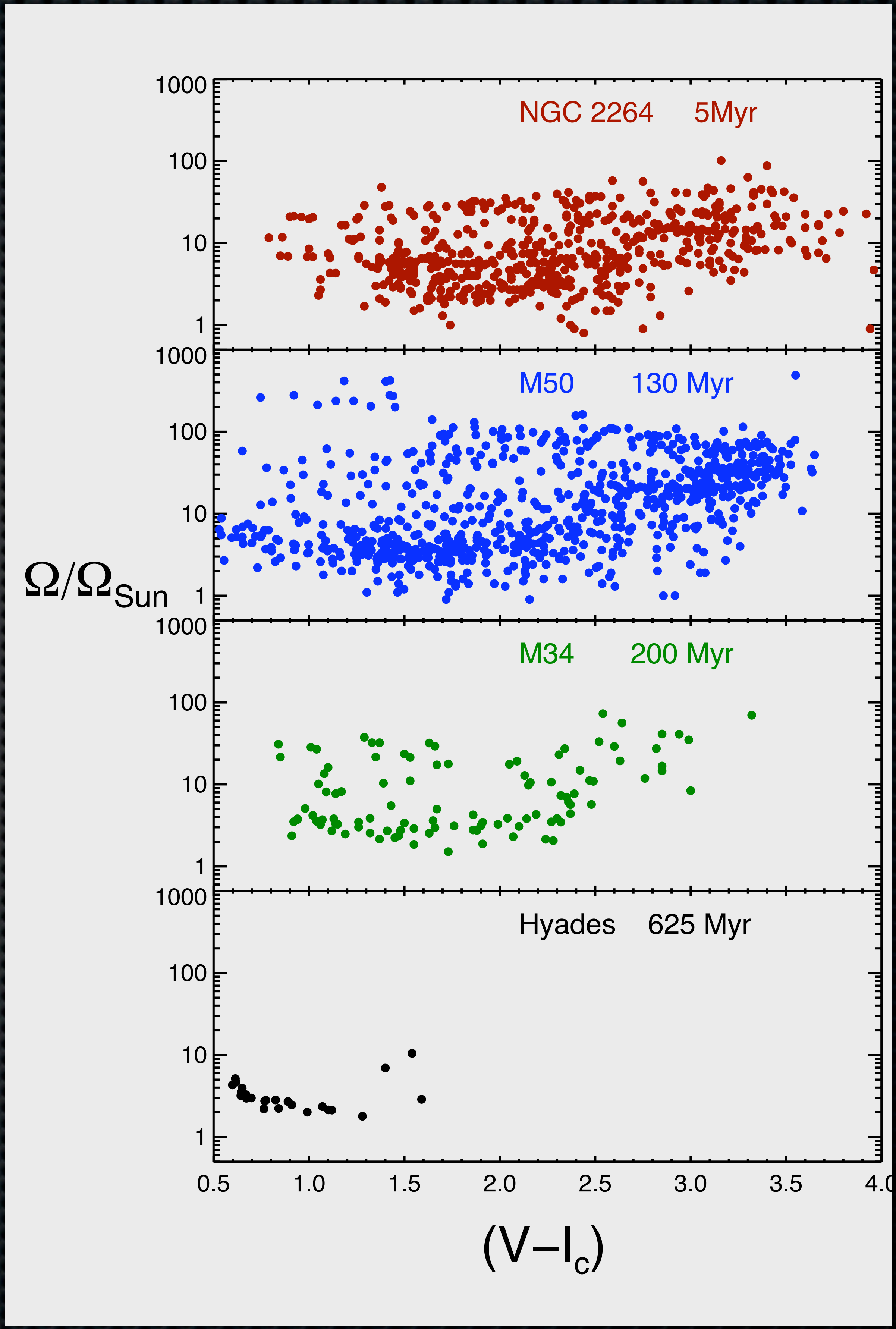
AM loss and decline of activity

- Solar-type stars undergo several observable changes as they age. These all appear to be related to convection in some way, either directly (Li depletion), or through the dynamo mechanism.
- The scenario:
  - Rotation (esp. differential rotation) + convection ⇨ dynamo (B fields)
  - Magnetic field + ionized wind ⇨ angular momentum loss (spindown)
  - Magnetic fields manifested as activity (Ca II HK, Hα, x-rays)
- This scenario is based on what we see on the Sun.
- This mechanism provides feedback, so rotation rates converge over time.
- Relation appears to be $\Omega \propto t^{-1/2}$.

"Gyrochronology"

Using rotation to determine age

- Overall decline of rotation with age for solar-type stars studied for 40+ years (Kraft 1967).
- Note ~100x scatter in M50 but almost none in Hyades; the convergence takes place in ~100 Myr, but then AM loss slows down.
- Recent work by Barnes (2007) and Mamajek & Hillenbrand (2008).



Gyrochronology calibration

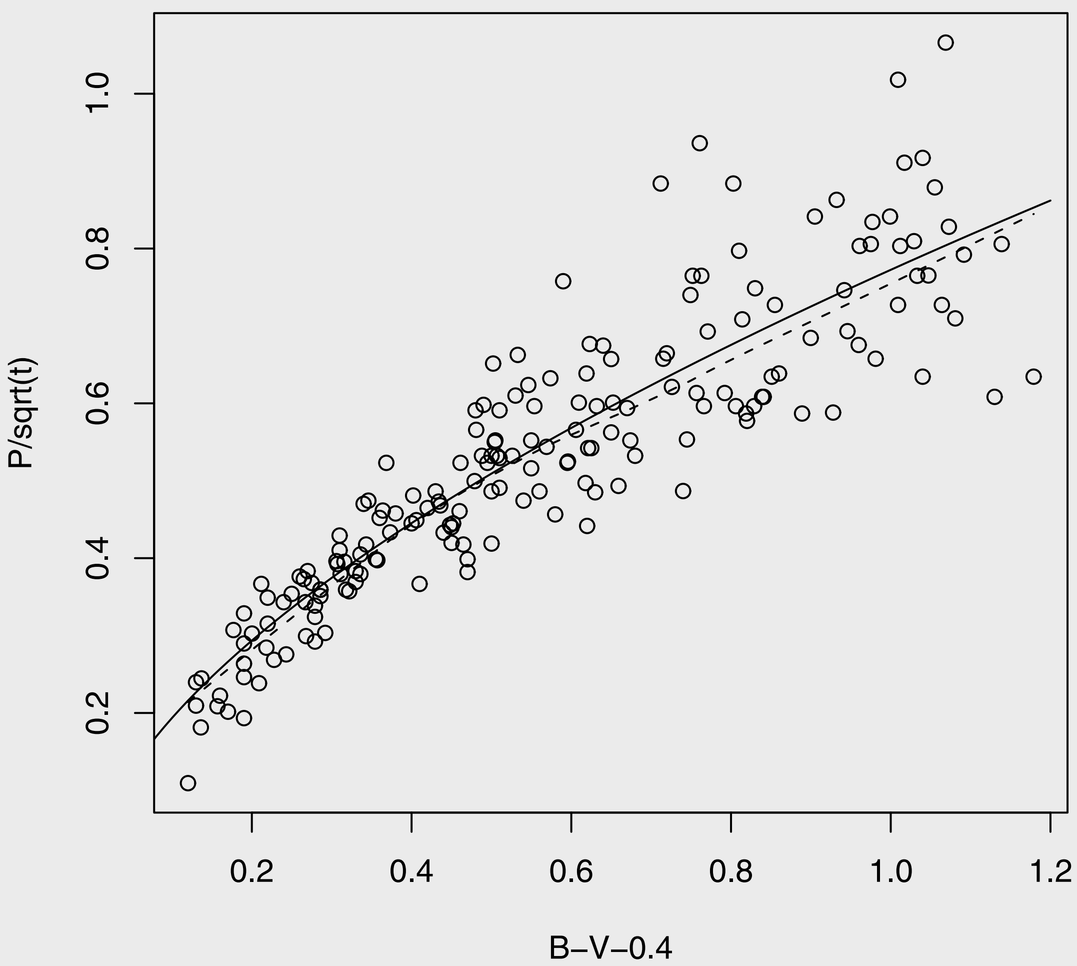
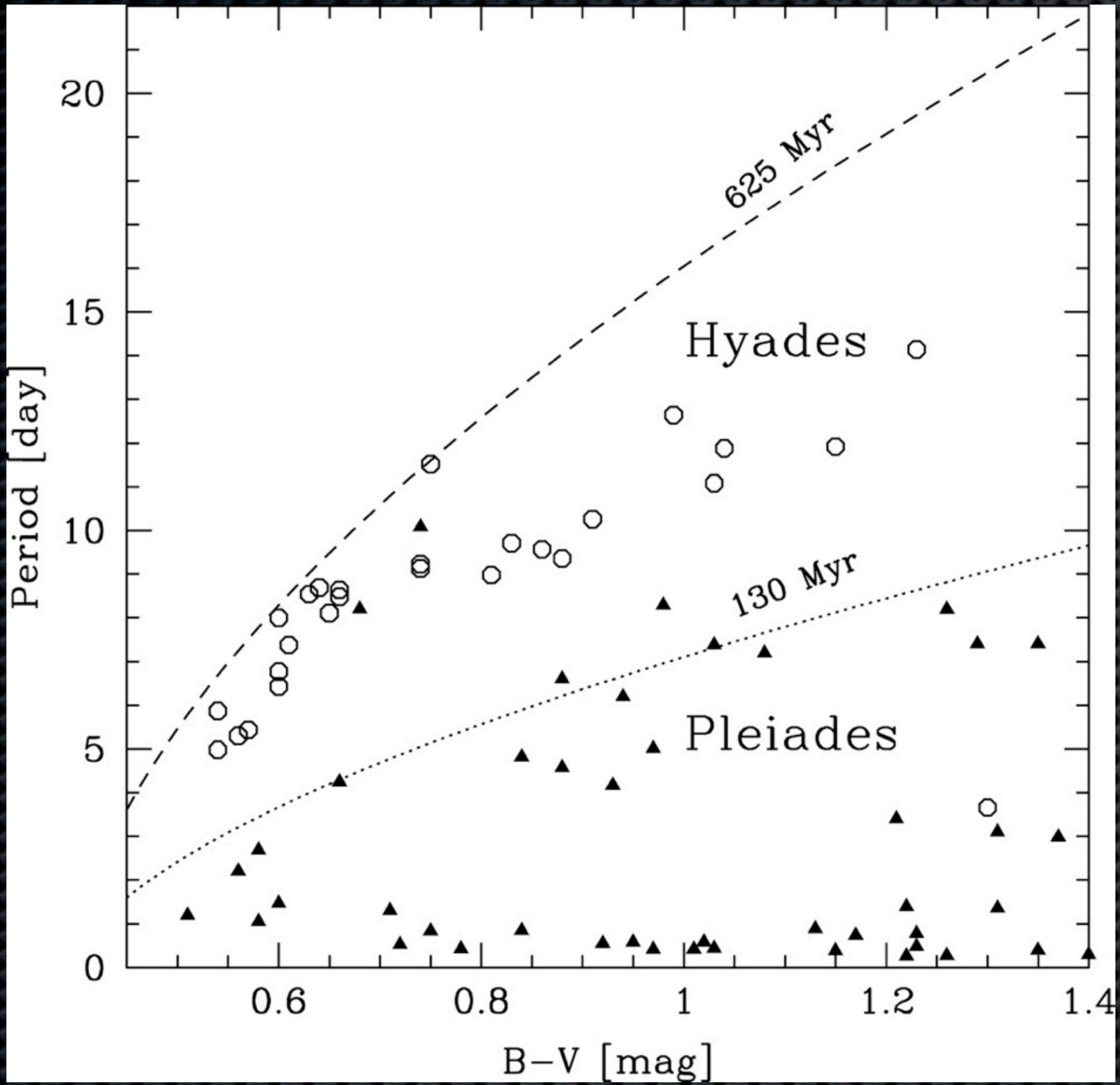
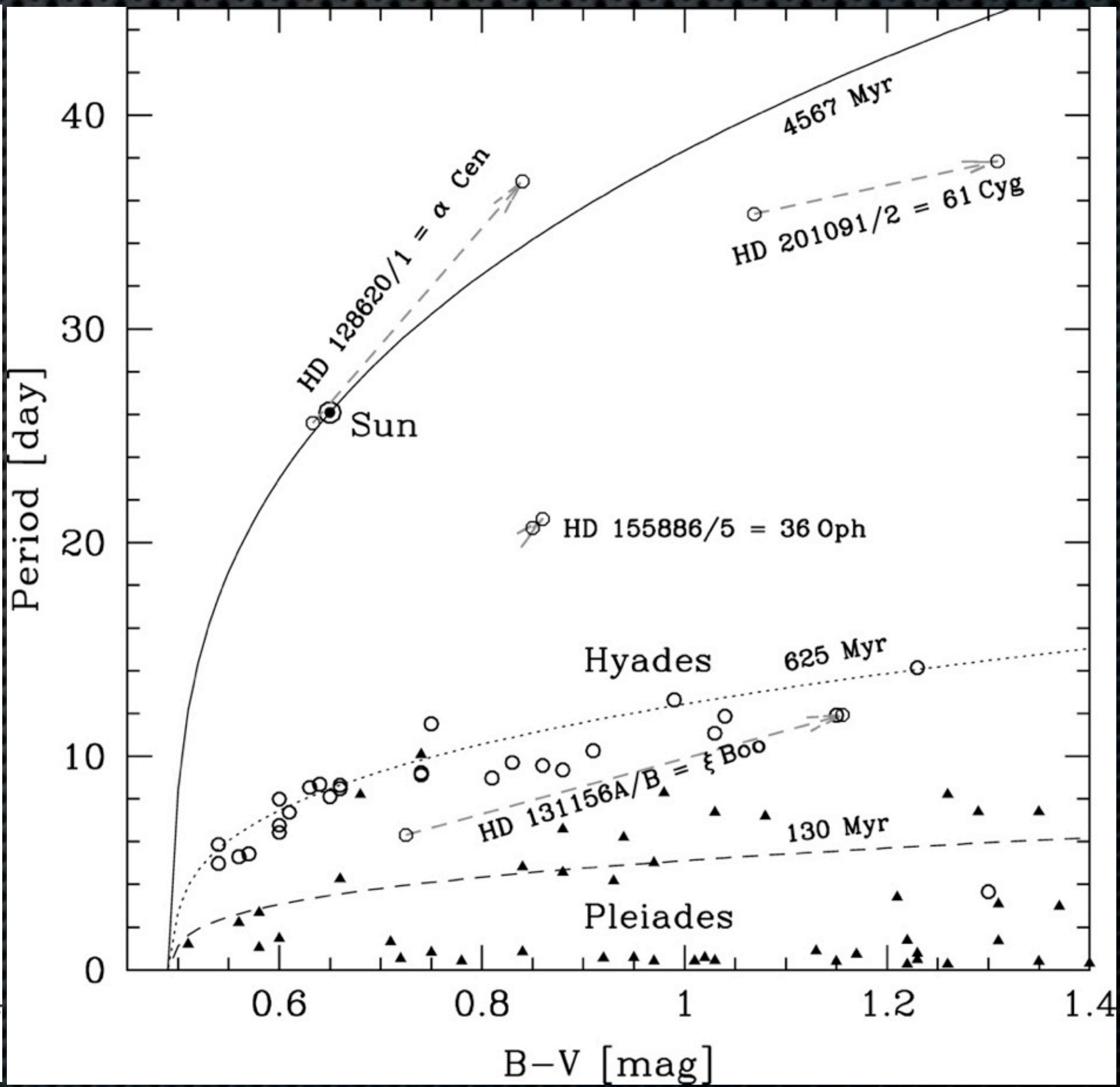


FIG. 5.—Fit to the mass dependence (*solid line*), using R: $f(B - V) = (0.7725 \pm 0.011) \times (B - V_0 - 0.4)^{0.601 \pm 0.024}$. The abscissa gives $(B - V_0 - 0.4)$ and the ordinate $P/\sqrt{t}$ for individual I sequence stars in the main-sequence open clusters listed in the text. The dashed line shows a smooth trend curve plotted using the function LOWESS in the R statistics package. Note the similarity of the two curves, which demonstrates that the fitting function is appropriate for these data.

- Barnes' calibration using cluster stars; note scatter.
- Barnes separates dependences: one for color (mass) and one for age.
- Initial assumption is $\Omega \propto t^{-1/2}$ (Skumanich relation).

Re-calibration of Barnes by Mamajek & Hillenbrand (2008)





What's wrong with these diagrams?

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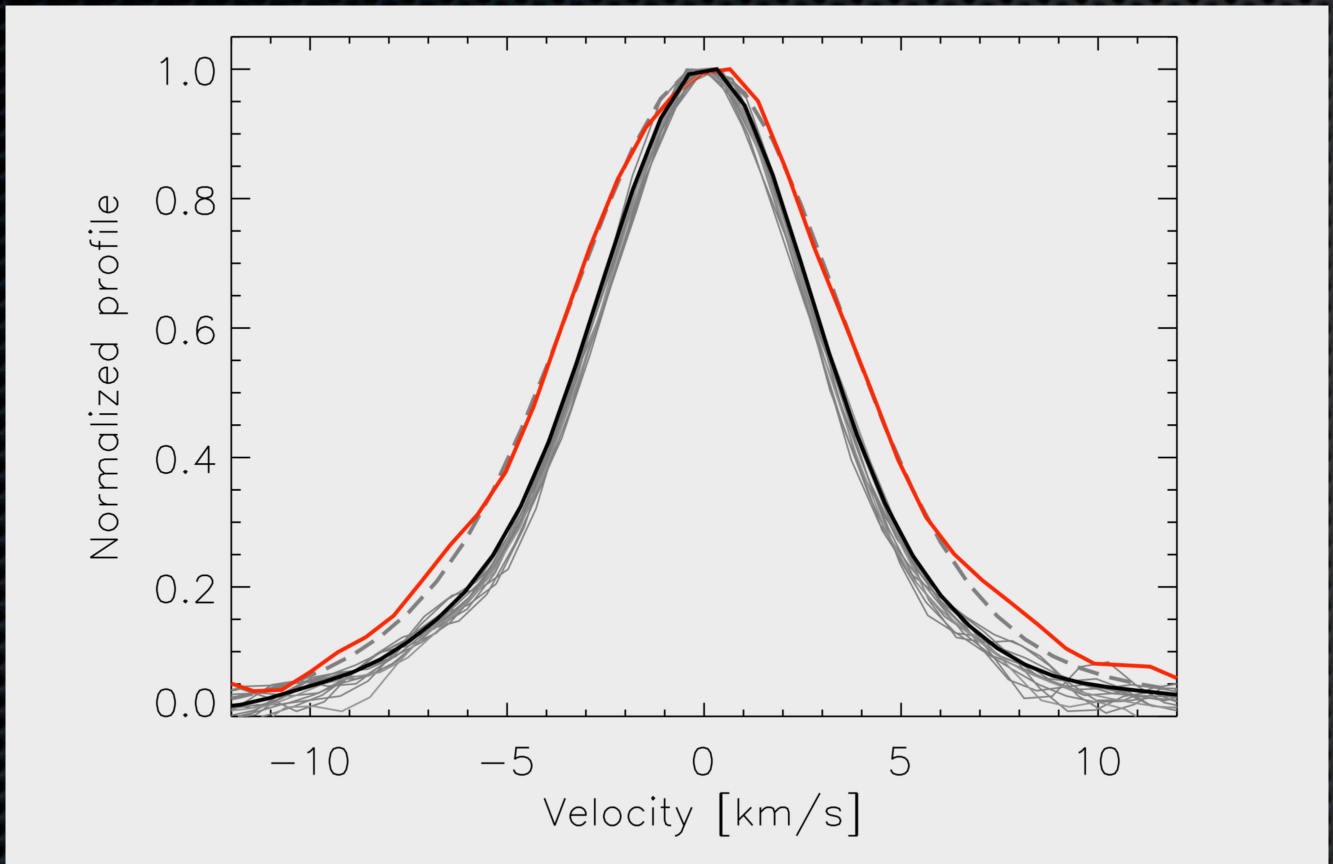
Gyrochronology: Is it valid?



- Reiners & Giampapa (2009, astro-ph) have just analyzed rotation for “over-active” stars in M67.
- One appears to have *v* sin *i* = 4 km/s, 2x Sun at 4.5 Gyr!
- Is the rotation-age paradigm even valid?

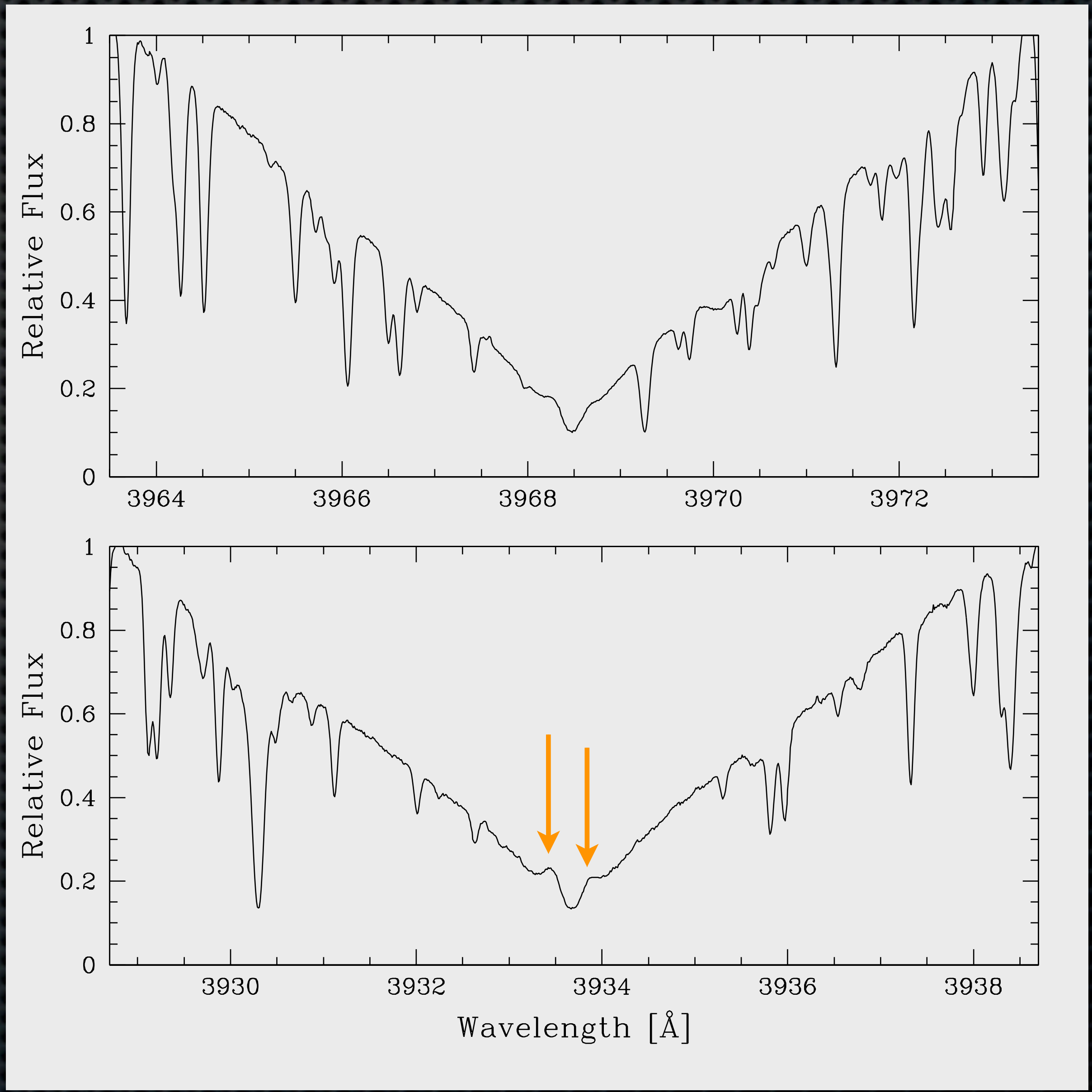
Another opportunity

- Observe rotation periods in solar-type stars in old clusters: Is there really a spread?

Empirical ages 2: Ca II HK

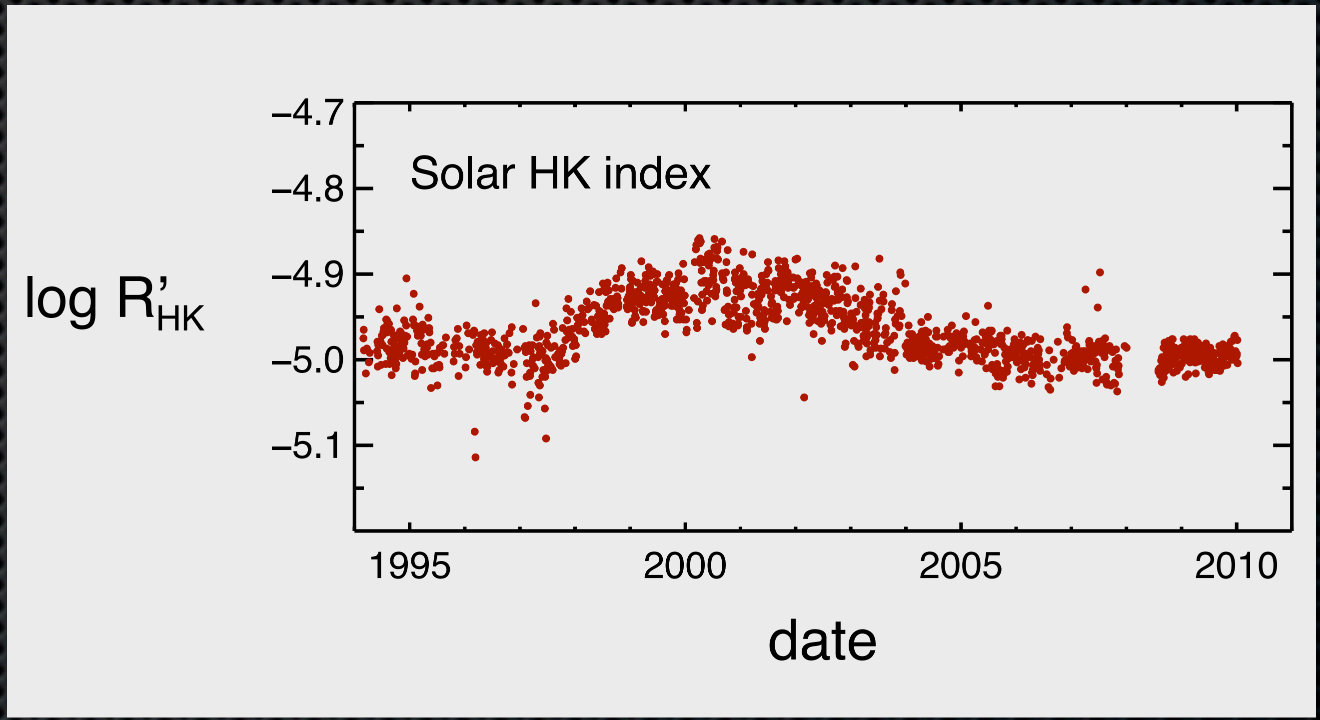
(see Ribas and Fischer)

- The cores of strong lines arise high in the atmospheres of stars, the chromosphere.
- Flux is low relative to continuum, and continuum is in UV. Contrast for old stars (like μ Arae here) is low.
- HK is indirect (driven by rotation) and variable.



The sun measured as a star

- Lowell data for 15 yr.
- Scatter is real.
- Note –4.9 to –5.0
  is spread of 0.2 dex
  in age.



HK vs. age calibration

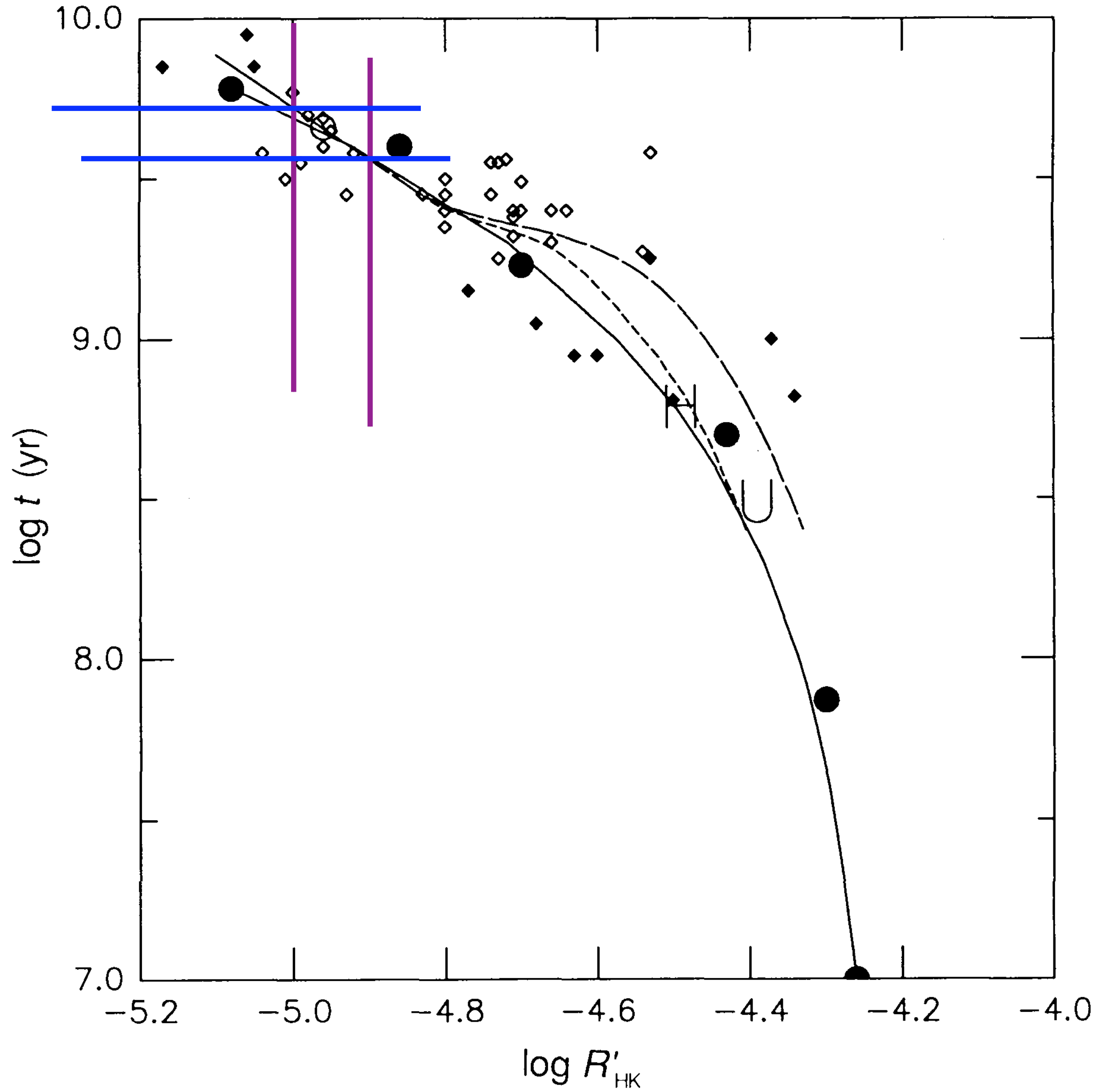
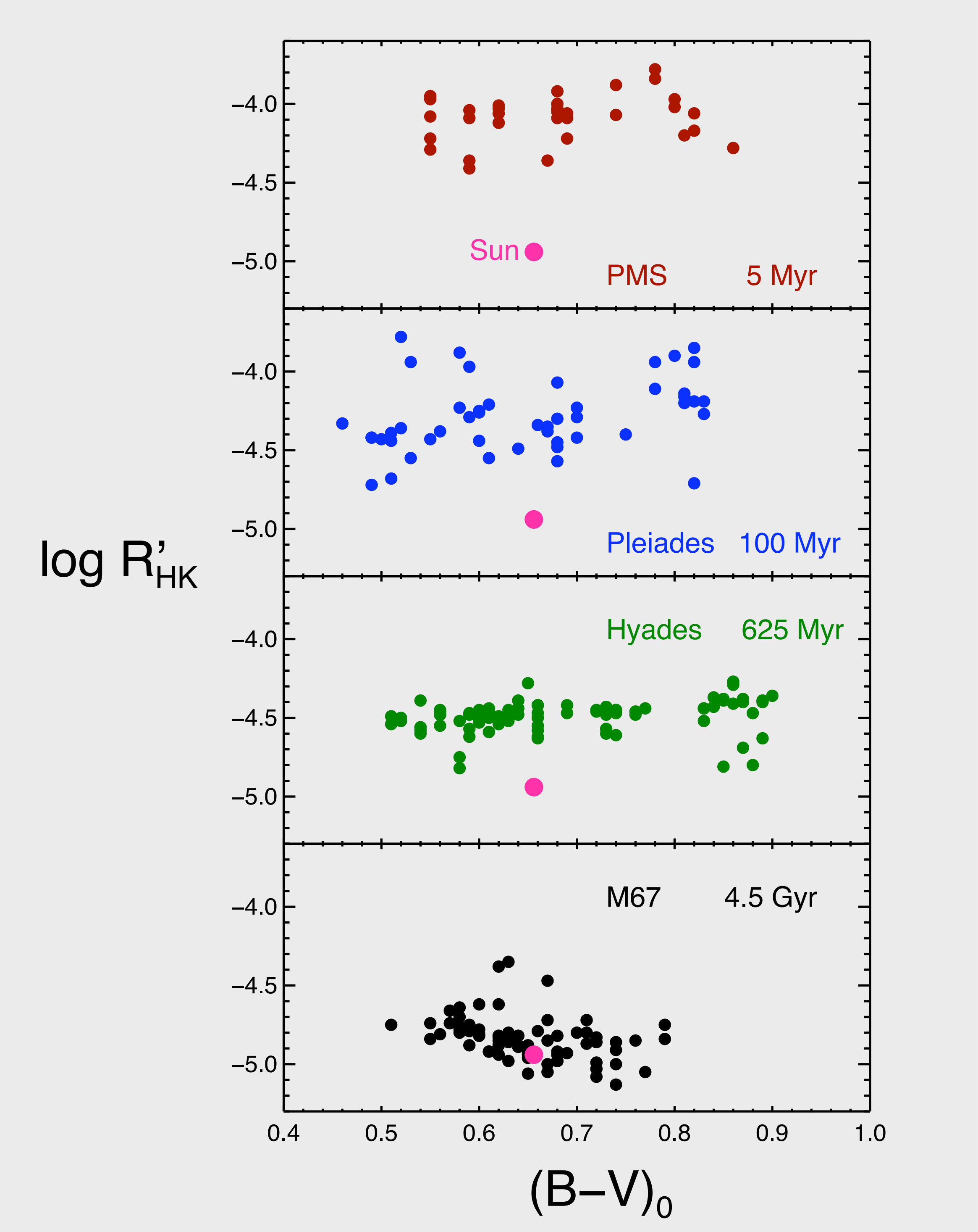


FIG. 13.—The recalibrated data of Barry et al. (Table 9), superposed on our cluster and binary star data (the same as Fig. 10). The dashed curves are the same as those shown in Fig. 10. The solid line is from Walter & Barry (1991): $R'_{HK} \propto \exp(-0.58t_9^{0.5})$.

- HK vs. age calibration from Soderblom et al. (1991): raw and corrected for disk heating.
- Saturation at young ages.
- These are averages!
- Note the scatter.

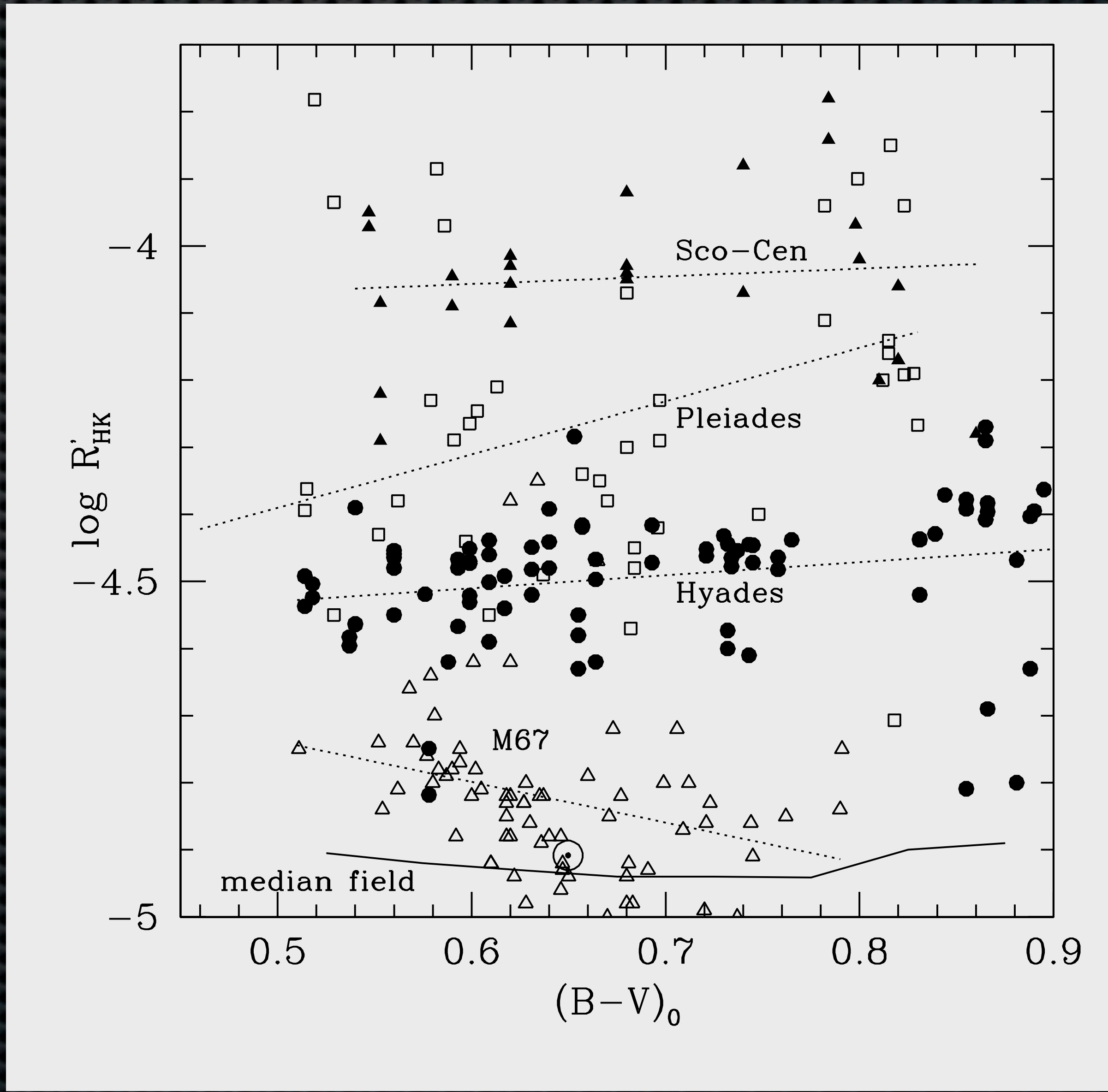
HK-age calibration: the reality

- Note the inherent scatter, even for old stars (M67).
- Rotation, spots, cycles, and random variability all contribute to ~±0.1 dex for the Sun.



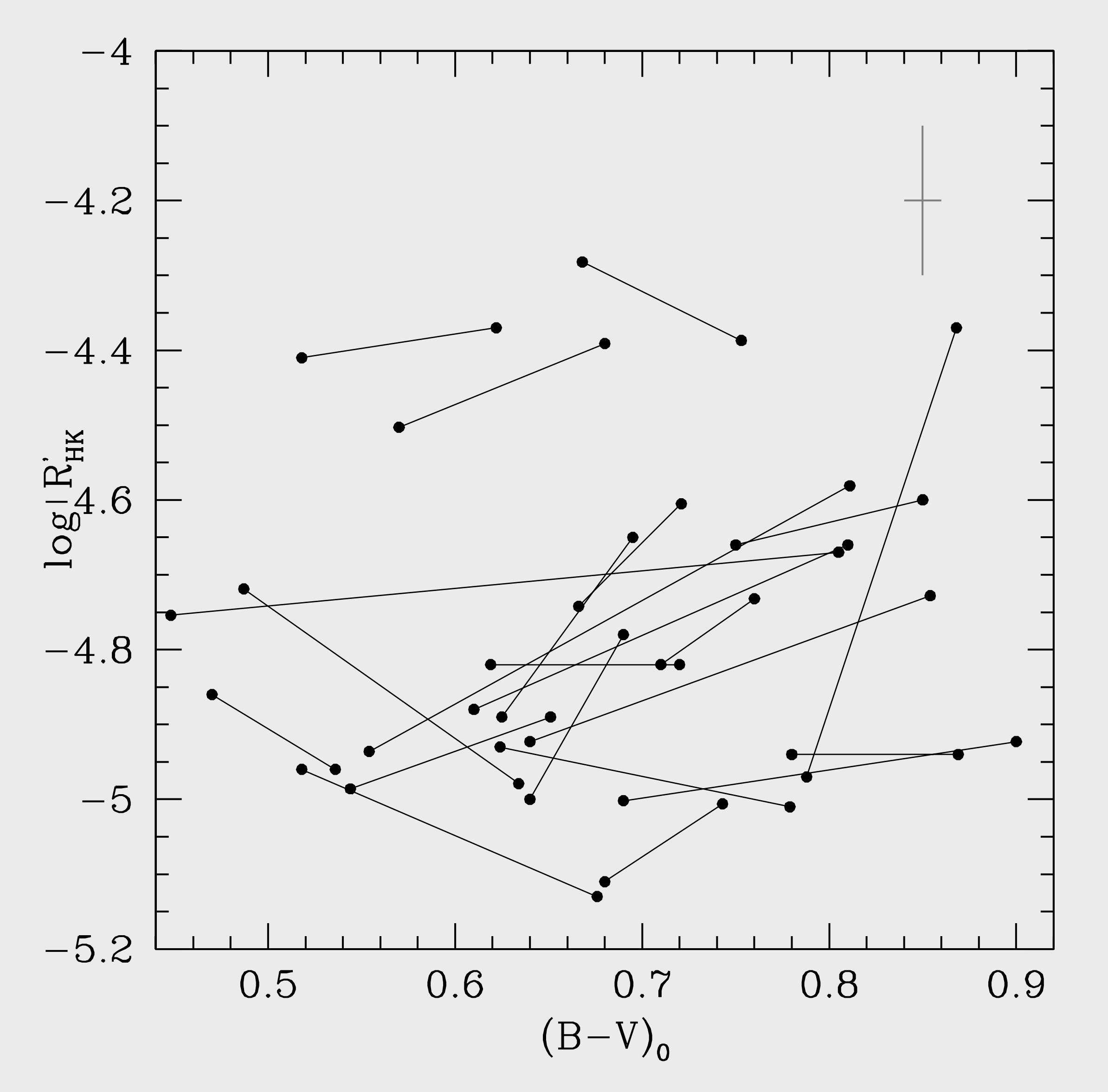
Ca II HK calibration: clusters

- Similar data to previous.
- Note lack of clear separation for very different ages.



Ca II HK calibration: binaries

- Consistency check: stars in binaries.
- Not impressive.



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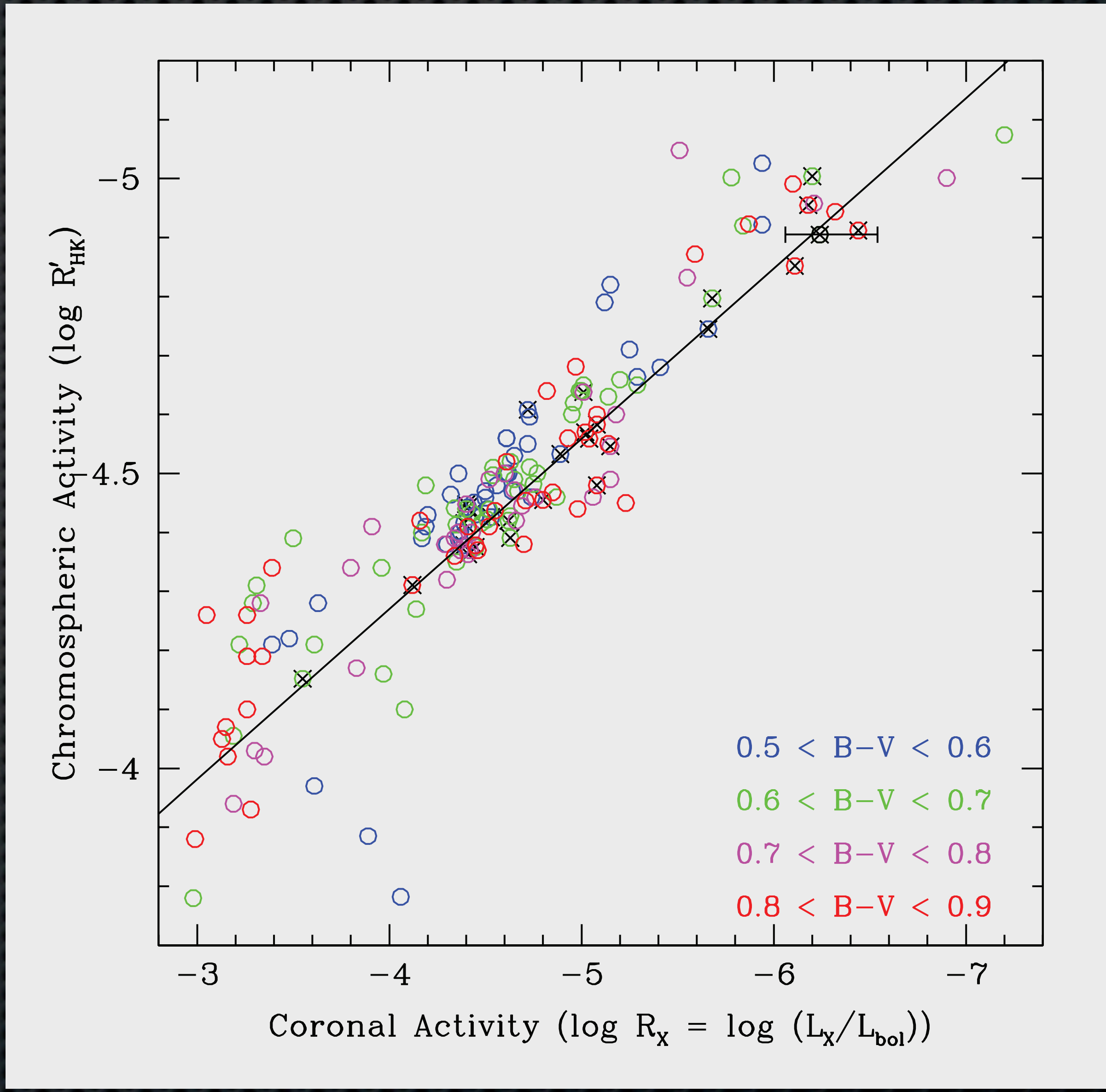
Ca II HK calibration check

- Consistency check: HK vs. x-rays
- Not bad, but this is log-log over 4 decades in L_X; scatter is ~0.1 dex.

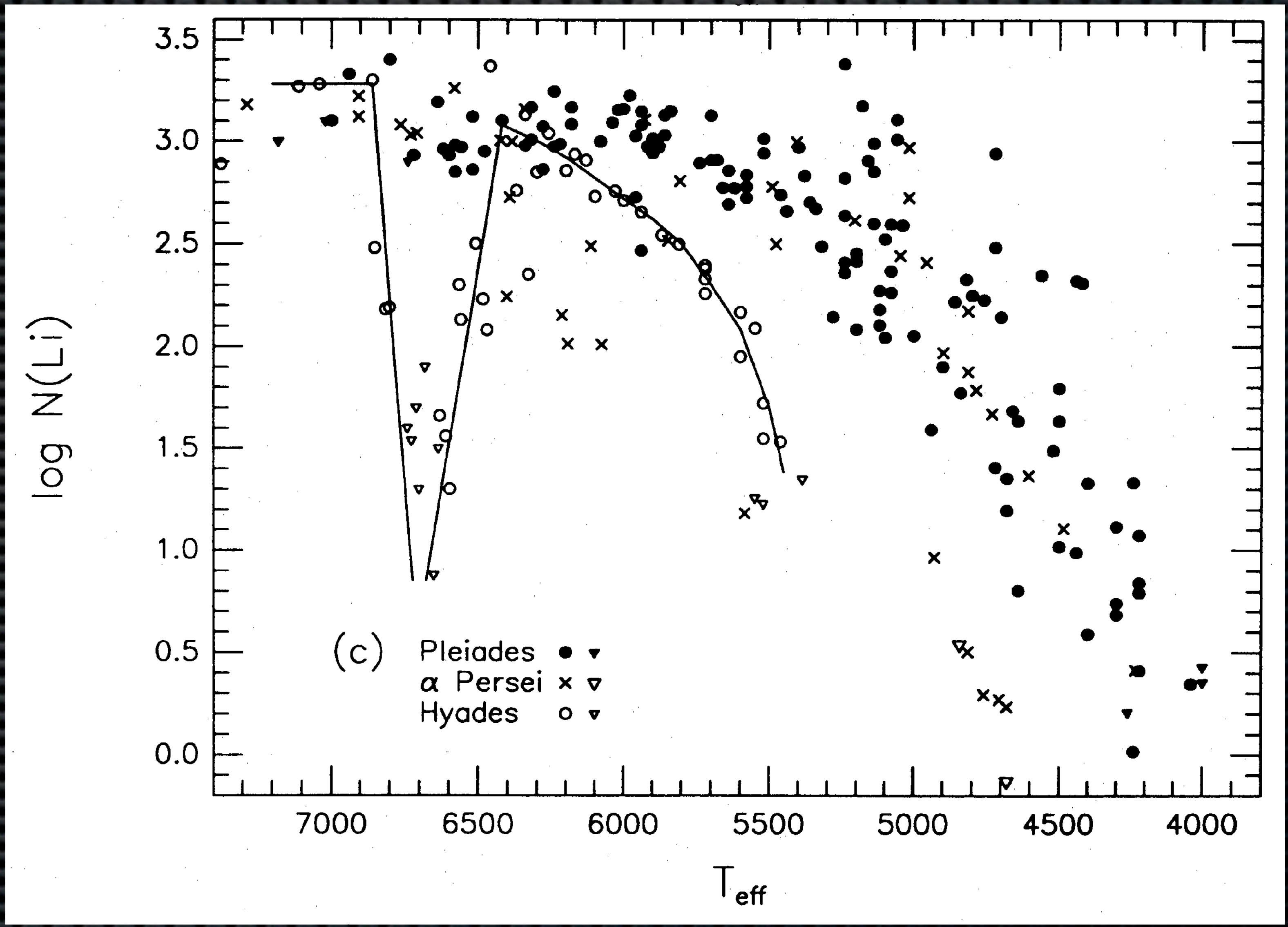


Empirical ages 3: Lithium

- The destruction of Li in the Sun is unambiguous: the surface now has A(Li) = 0.97, versus 3.20 for chondrites (log scale, H = 12). It's the path from one to the other that is unknown.
- In star-forming regions we see stars to have A(Li) = 3.2-3.3. This tells us:
  - They are undepleted.
  - Stars are now formed with the same initial Li the Sun had.
- In young clusters we also see abundant Li, but ...

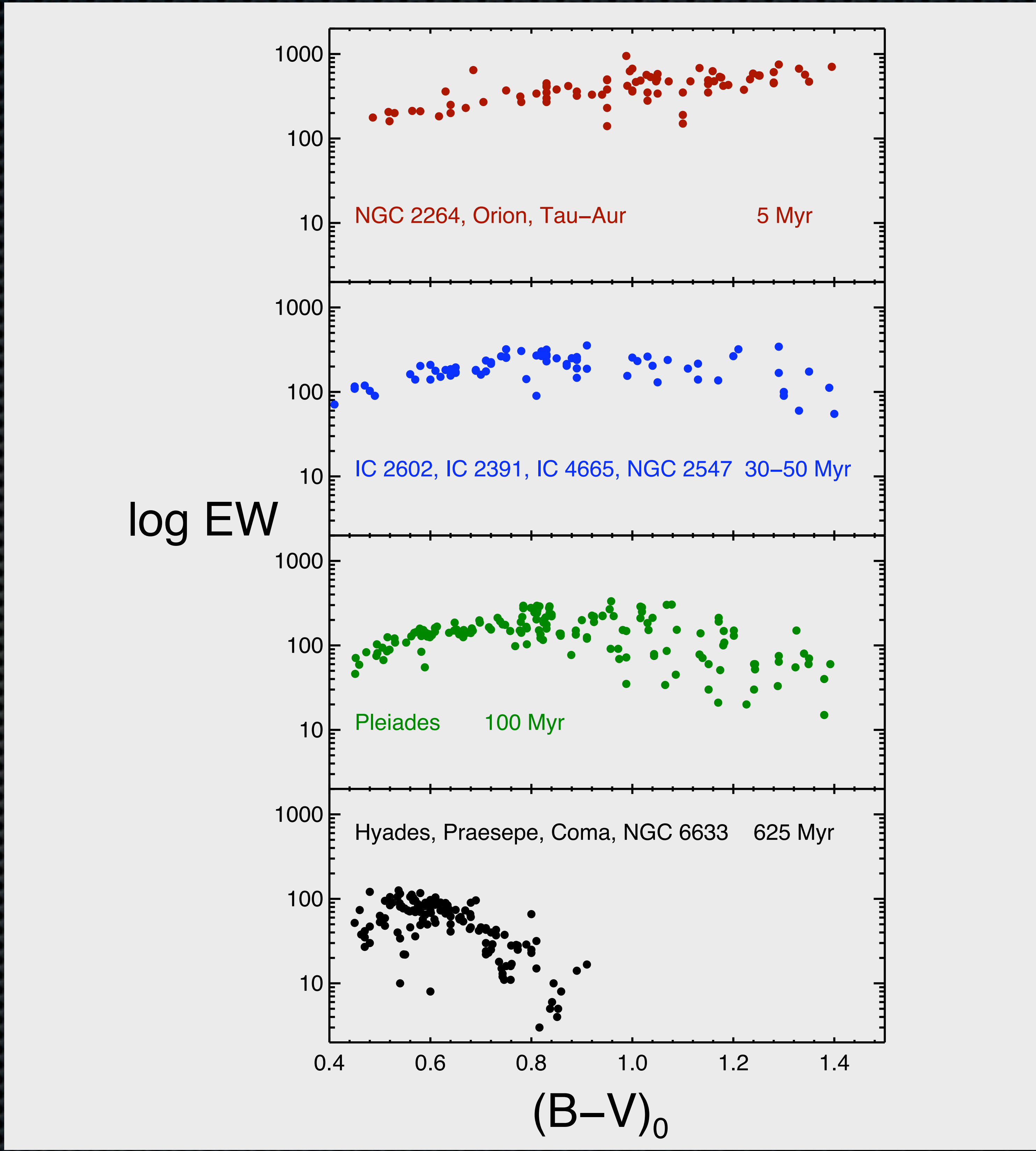
Pleiades data as abundances

- Scatter ≫ error
- Note low scatter in Hyades.
- Pleiades and α Per indistinguishable.



Differential analysis of observations

- Compare to Pleiades:
  - Lots of good data
  - Broad range of color
  - Few upper limits
- Work in observational units; errors understood.
- Why the scatter?



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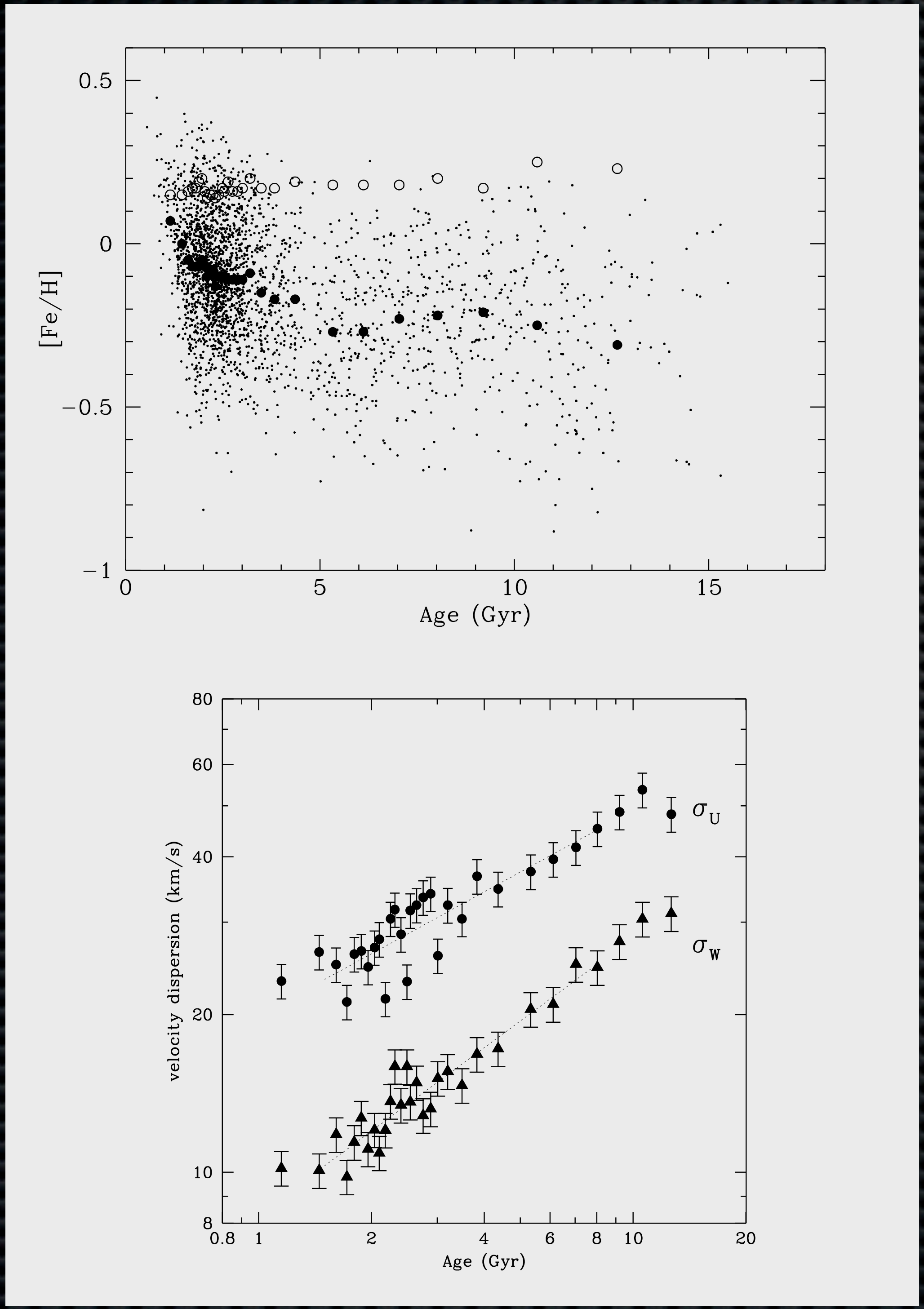
Usefulness of Li for ages

- The inherent large scatter at a single age means Li works for groups and not single stars, but only a few stars (~10–20) are needed.
- The biggest changes up to ~300 Myr are for K dwarfs.
- Scatter for G dwarfs is too large to be able to get ages, and metallicity dependence is likely.
- Li in PMS groups can test the same models used to calculate isochrones for K and M dwarfs.
- Li has been used to get ages for old solar-type stars, but that is highly model-dependent (see Ramirez POP).
- Li goes through plateaus at several ages ranges; e.g., alpha Per and Pleiades (70 Myr and 120 Myr) are indistinguishable.

Possible improvements for Li

- "Magneto-convection and lithium age estimates of the β Pictoris moving group," J. MacDonald and D. J. Mullan, 2010 astro-ph 1006.1308.
- β Pictoris moving group is one of a number of nearby groups of pre-main sequence stars identified as young from x-rays and having space motions in common.
- Strong Li used as a criterion for membership, and also as a way to estimate age.
- Primary age indicator is HRD, matching to PMS isochrones (these stars generally have Hipparcos parallaxes).
- By including effects of magnetic fields on convection, they can account for star-to-star differences in Li and determine a more consistent overall age. At 40 Myr it is high relative to other determinations of ~20 Myr.

Statistical methods



- Both metallicities and space motions show trends with age (but could be Galactic gradient too for [M/H]).
- These trends are important for studying the Galaxy but are purely statistial: they do not apply to individuals. (Note the space motions of the Sun and of the α Cen system.)

Age quality levels

- Fundamental:

  The physics of the process is fully understood and all the needed parameters can be measured.

- Semi-fundamental:

  Almost everything is known and the assumptions are not critical
  (U/Th decay; kinematic traceback)

- Model-dependent:

  The measured quantities can be predicted through calculations
  (asteroseismology, isochrones, lithium depletion boundary).

- Empirical:

  A physical scenario exists and an empirical age relationship can be established
  (rotation, activity, lithium).
  Calibrated against clusters and stars with model-dependent ages.

- Statistical:

  A tendency or trend exists (e.g., metallicity, kinematics).

Ages: Ensembles vs. individuals

- Ensemble ages:
  - Lithium depletion boundary (LDB)
  - Rotation (PMS and ZAMS)
  - Lithium (PMS and ZAMS)
  - Kinematic traceback (PMS)
  - Isochrone fitting
- Individual ages:
  - Isochrone placement
  - U/Th decay (Pop II)
  - Asteroseismology
  - Rotation
  - Activity

How well do they do?

1. Fundamental and semi-fundamental methods

Fundamental:

– A truly fundamental age is only available for the Sun (<0.1%)

U/Th decay:

+ U/Th decay ages can be applied to very old stars (no other methods)
+ U/Th decay works for individual stars
+ Systematic errors probably low
– U/Th only works for low-metals stars due to line blending
– Need high resolution and high S/N to resolve weak features (brightish stars)
– Large uncertainties (20%)

How well do they do?

1. Fundamental and semi-fundamental methods

Kinematic traceback:

+ Kinematic traceback is essentially astrometric and so free of PMS physics
+ Kinematic traceback works for very young ensembles, where other methods fail
– Works only for <~ 20 Myr
– Works only for groups.

Longer than ~50 Myr and the errors in the observations produce large age uncertainties. Also, the Galactic potential gets less certain.

Spectroscopic criteria (activity, Li) are generally applied as well.

Errors ~40-50%

How well do they do?

2. Model-dependent: isochrone ages

+ Isochrone ages are only as good as the underlying models, but for solar-type stars we should understand the physics.
– Isochrone ages require additional observations of very high accuracy (parallax, color, magnitude) and are still vulnerable to significant transformation uncertainties (esp. $T_{\rm eff}$).
– Isochrone ages cannot be determined directly, only a probability distribution results, with varying results. The results end up biased.
– Errors ~50%?

How well do they do?

3. Model-dependent: asteroseismology

Both isochrone ages and asteroseismology use essentially the same models, with the same vulnerabilities. They are measuring the same thing in different ways. Seismology places additional constraints.

– Seismology observations are very demanding and so possible only for small numbers of stars in general
– Seismological ages also need additional parameters (composition, luminosity, temperature)
+ Seismology works well for older MS stars
+ Asteroseismology appears to offer the best hopes for single, nearby stars
+ Asteroseismology applies essentially all the physics we know at one time
+ Errors ~10%

How well do they do?

4. Empirical methods

– All 3 methods (rotation, activity, lithium) must be calibrated against model-dependent ages (groups and clusters), so they are subordinate.

– All 3 properties show large scatter at young ages. This means they are better suited to groups of stars than to individual objects for ≲ 1 Gyr.

– The greatest variation is seen for the youngest stars, but also lots of scatter.

– Old stars rotate slowly and have achieved “inner peace” (i.e., few spots, which is good for us). But it is hard to detect a rotation period, and activity is weak.

+ Activity is easier to measure, but may have systematic problems for older stars.

+ Li maybe useful for K dwarfs up to ~300 Myr; M dwarfs up to 50 Myr?

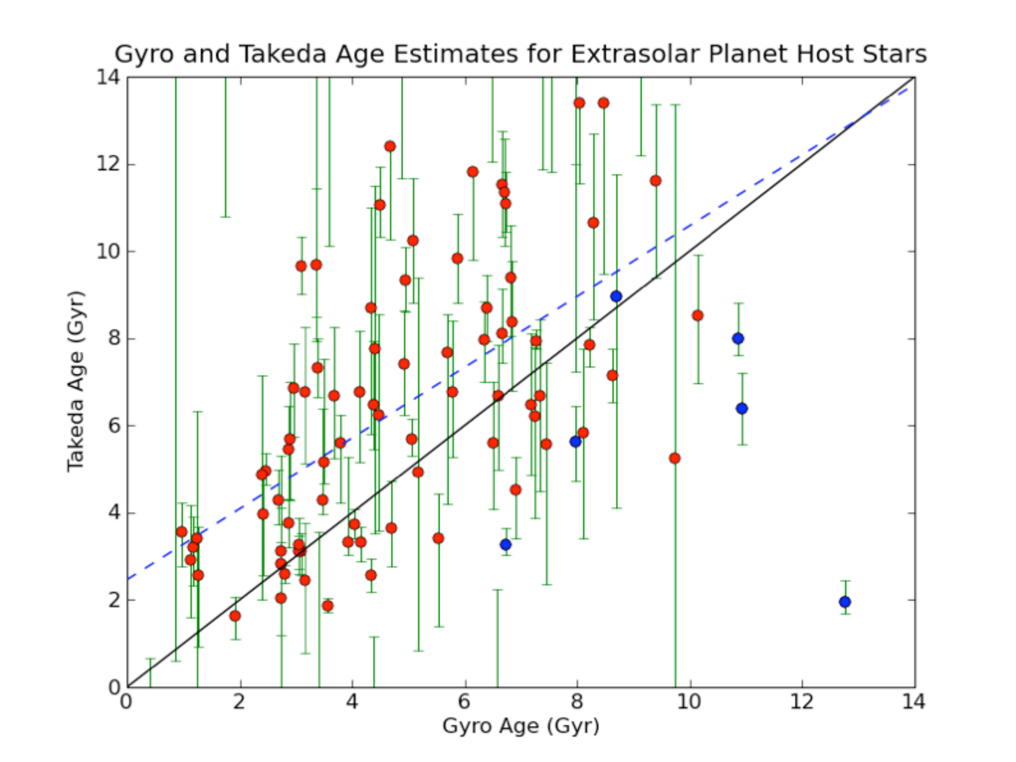
Errors >20%

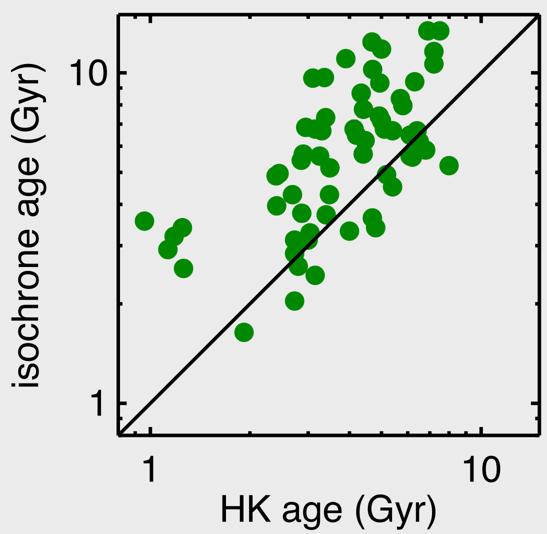
Isochrones ages compared to those from rotation
(Mamajek, 2009)

Formally there is a correlation, but $R = 0.5$.

Which to believe?

Note that gyro ages are deterministic, but isochrone ages are probablistic.





Summary of age dating methods

I = individual, E = ensemble

type	method	PMS	ZAMS	MS	Pop II
semi-fundamental	U/Th decay	–	–	–	I
	kinematics	**E**	–	–	–
model-dependent	isochrones	E, i	**E**	E, i	E, i
	LDB	**E**	**E**	–	–
	asteroseismology	–	–	**I**	I
empirical	gyrochronology	E	E	**E,** I	i
	activity	E	E	i	–
	Li	E	E	–	–

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How ages are used

- Kevin Schlaufman preprint, astro-ph 1006.2851:
  "Evidence of possible spin-orbit misalignment along the line of sight in transiting exoplanet systems."
- Notes use of Rossiter-McLaughlin effect to determine angle between stellar spin axis and planet's orbital axis. Result is often a clear misalignment.
- R-M effect not always detectable; also leads to results only in plane of sky.
- Schlaufman notes angle relative to LOS (i) can be estimated from radius, rotation period (P_{rot}), and $v \sin i$. P_{rot} not always known, so he tries a Monte Carlo simulation, with random distributions of a number of variables, including age, assuming $P_{\mathrm{rot}} \propto t^{+1/2}$ (t = age).
- Schlaufer identifies several stars with possible large misalignments.

Other masses

- Stars more massive than the Sun not so interesting for planet studies.
- Stars less massive are very difficult:
  - Essentially no movement in HRD.
  - Li depletes very rapidly (100s of Myr).
  - Hyades hints at scatter in rotation for K and later.
  - M dwarfs tend to show significant activity at all ages.
  - Are models good enough to analyze seismology?

Conclusions I

- Age is not a directly measurable property of a star, so we are left estimating ages in whatever ways we can.
- For PMS stars, placing stars on isochrones works if they have good distances.
  - Other indicators (activity, Li) help to confirm youth but getting quantitative ages is problematic.
  - The models need to be tested more.
  - Groups are more suitable than single stars.
- ZAMS and near-ZAMS stars remain challenging:
  - Little net movement in HRD.
  - Strong signals in rotation, activity, lithium, but also much noise.

Conclusions II

- For single MS stars, asteroseismology appears to offer ages good to ~10%, but
  - Ages are model dependent.
  - Getting the needed data is labor- and resource intensive.
  - Limited to bright stars.
  - Gyrochronology is also promising.
- Post-MS stars fairly easy due to rapid motion in HRD if a good parallax is available.
- The ages of clusters remain subject to significant uncertainties.

Hopes for the future

- The high-precision photometry/seismology of CoRoT and Kepler can give us enough good ages that we can more critically test other parts of the picture and calibrate other age indicators. (Kepler should yield numerous rotation periods too.)
- Gaia will essentially eliminate errors in parallax for nearby stars and remove ambiguities for clusters.
- We can measure stellar temperatures with real accuracy, or at least characterize them well.
- If we can someday understand the solar dynamo well enough to predict the behavior of the 11-year cycle, we can then start to understand stellar dynamos. Then maybe stellar spindown and the decline of activity can move from empirical to a model-dependent methods.
- We will find that planet with the biomarker, establish the age of its host star, and gain an entirely new insight into the story of life.

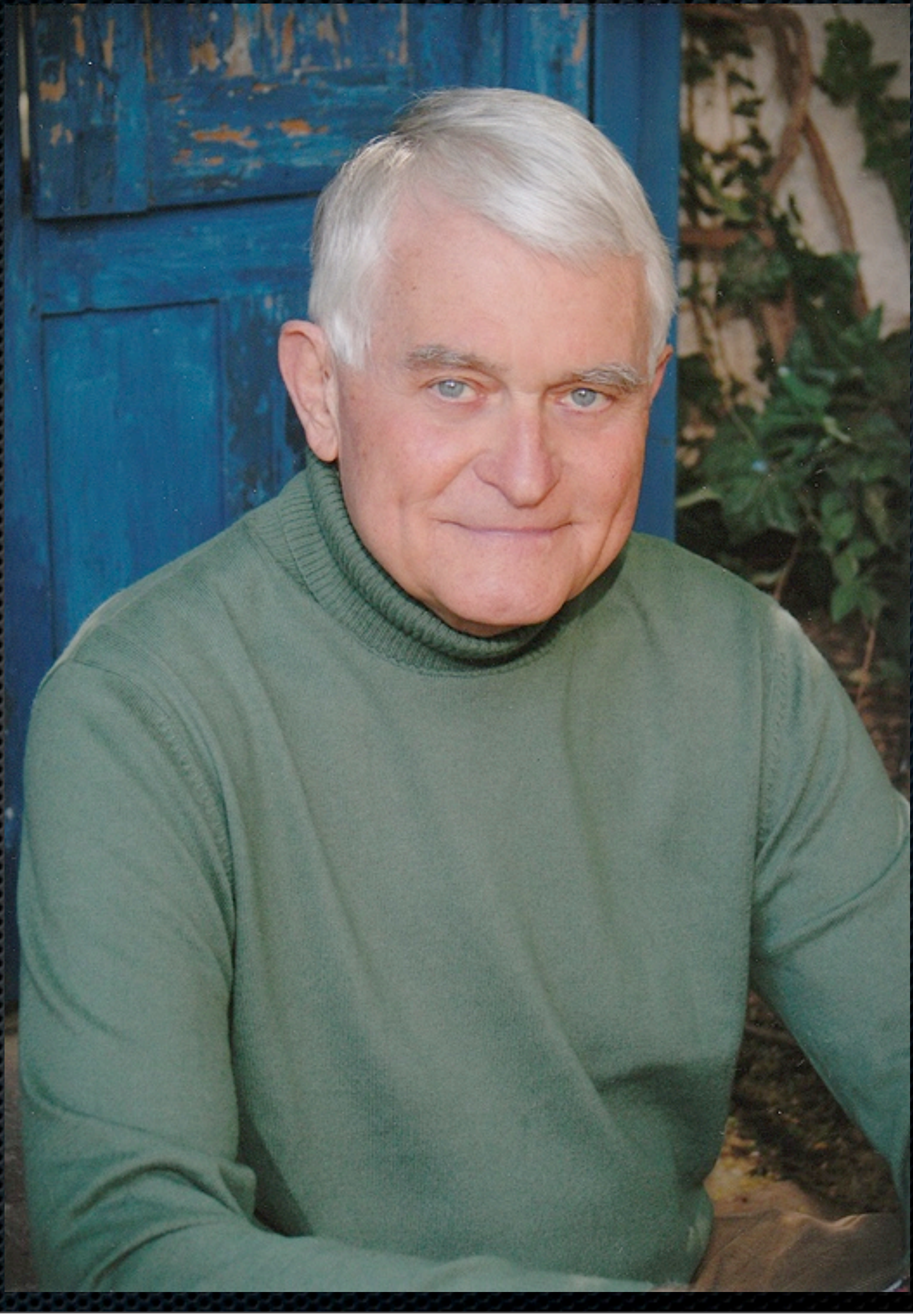
Jack Eddy
1931-2009

An inspiration for thinking about the Sun in the broadest possible context.

Let us also acknowledge others, including Olin Wilson, who started the work of detecting stellar activity in general and cycles in particular.

And Andy Skumanich, George Herbig, ...

D. Soderblom

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Resources

- *The Ages of Stars*, Proc. IAU Symp. 258
- Soderblom, 2010, Annual Reviews Astr. Ap., v. 48: *The Ages of Stars*
  - On astro-ph or from annualreviews.org
- SME: Spectroscopy Made Easy. Tuned to high-resolution spectra of solar-type stars.
- soderblom@stsci.edu