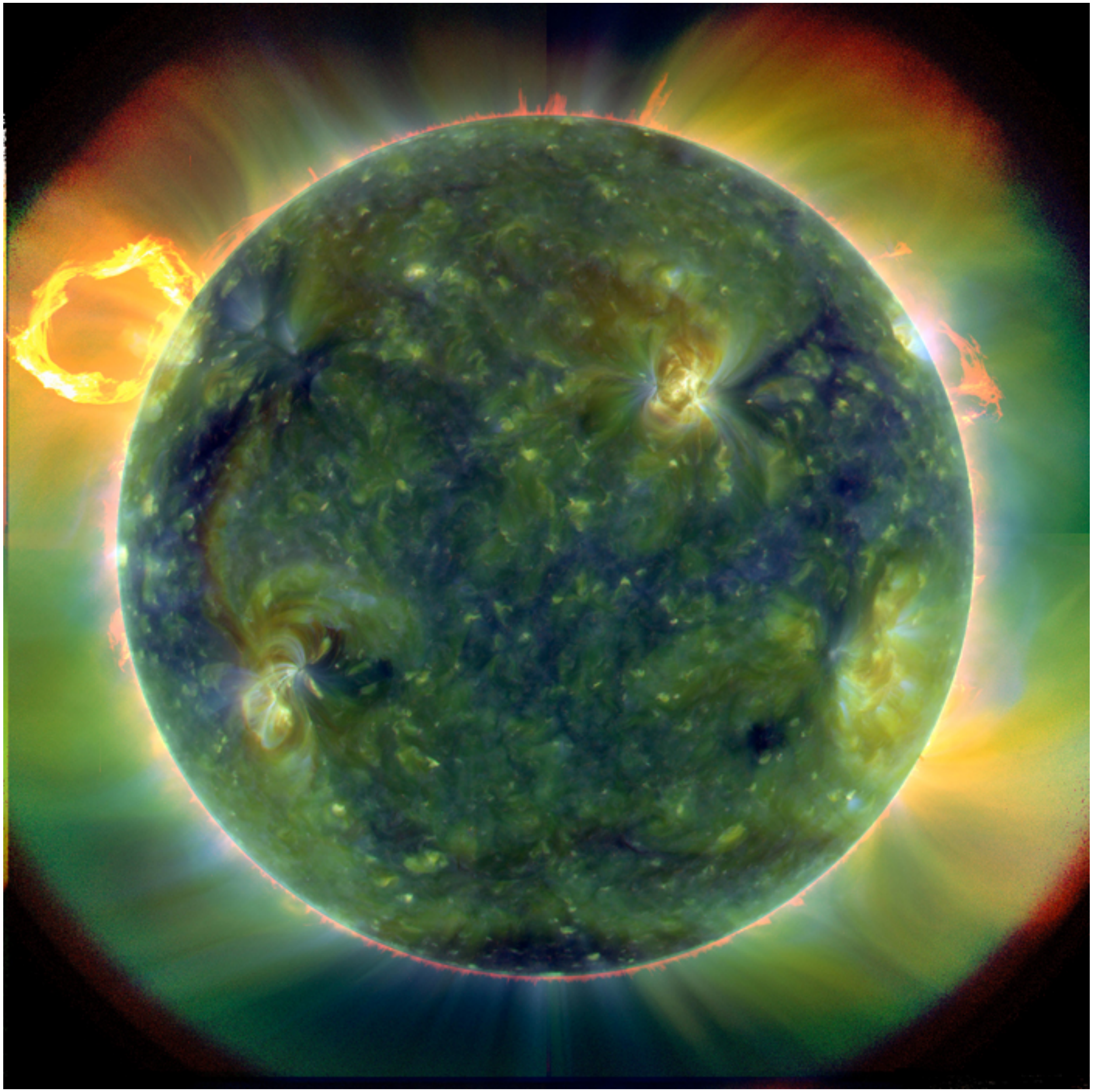
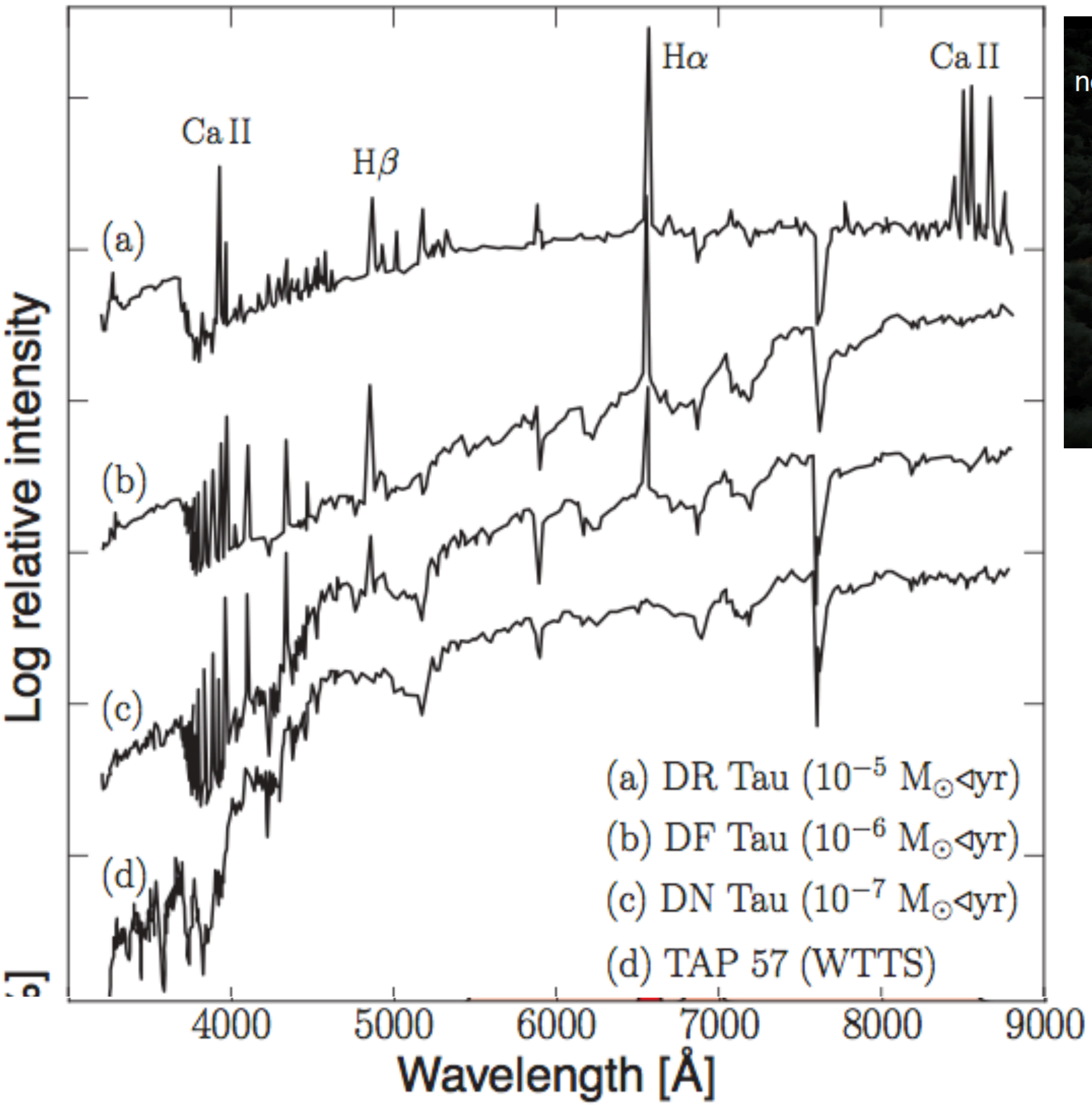
Infant Stars
Behave Like Teenagers

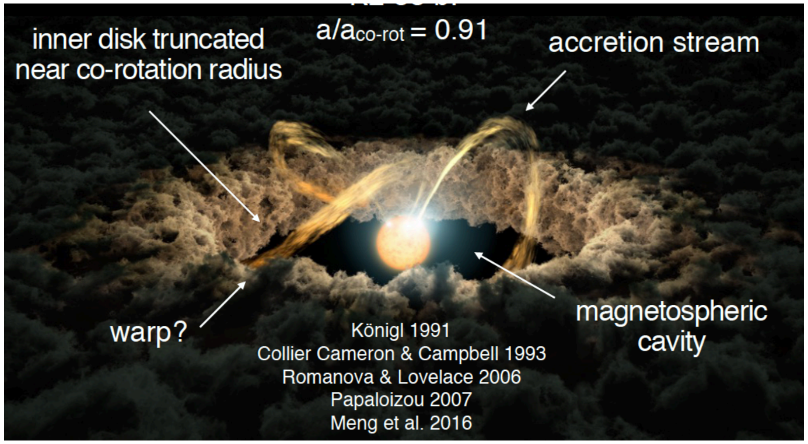
Le Difficolta` delle Stelle Giovani
(The Difficulties of Young Stars)

LYNNE A. HILLENBRAND
CALTECH





Barensten et al. 2013



Königl 1991
Collier Cameron & Campbell 1993
Romanova & Lovelace 2006
Papaloizou 2007
Meng et al. 2016

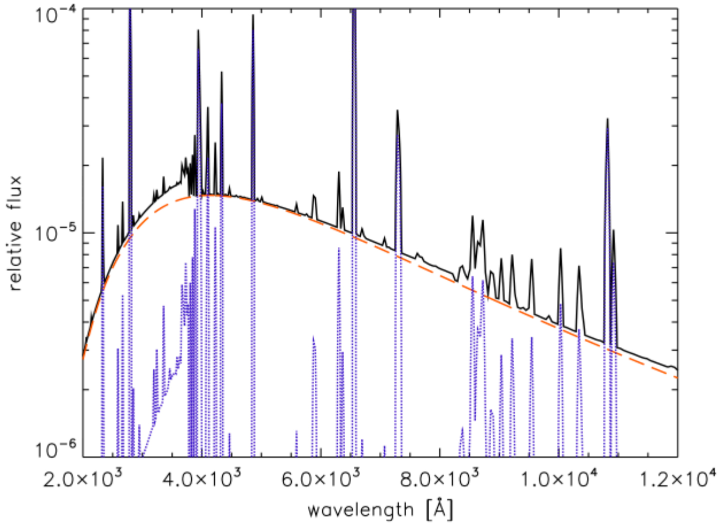


Figure 7. Accretion spectrum simulated with CLOUDY. The solid line is the total emission, which is the superposition of an optically thick emission, with $T_{\text{eff}} = 7000$ K, of the heated photosphere (dashed line) and the optically thin emission of ionized gas with density $n = 10^8$ cm^{-3} (dotted line).

Da Rio et al. 2010

1992

1993

HERBIG Ae/Be STARS: INTERMEDIATE-MASS STARS SURROUNDED BY MASSIVE CIRCUMSTELLAR ACCRETION DISKS

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Received 1991 December 26; accepted 1992 April 13

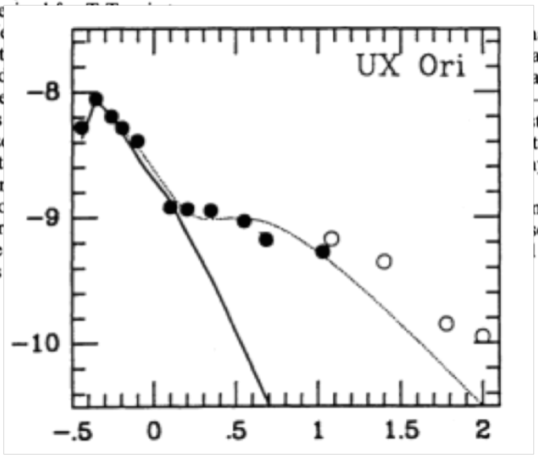
ABSTRACT

The hypothesis that Herbig Ae/Be stars are young stars of intermediate mass ($1.5 < M_*/M_\odot < 10$) surrounded by circumstellar accretion disks is examined. Analysis of the spectral energy distributions for 47 cataloged Herbig Ae/Be stars leads to their classification into three groups. *Group I* includes 30 stars with large infrared (IR) excesses characterized by spectral slopes $\lambda F_\lambda \sim \lambda^{-4/3}$. Infrared spectral energy distributions ($\lambda \gtrsim 2.2\ \mu$m) for these objects can be well fitted by assuming that excess emission above photospheric levels arises in a geometrically flat, optically thick circumstellar accretion disk. The inner regions of these accretion disks (from the stellar surface to a distance of several stellar radii) must be optically thin in order to account for distinctive inflections in their observed near-infrared ($1.2\ \mu\text{m} \lesssim \lambda \lesssim 2.2\ \mu$m) spectral energy distributions. *Group II* includes 11 objects with flat or rising infrared spectra. These objects appear best interpreted as young, intermediate-mass stars or star/disk systems surrounded by gas and dust which is not confined to a disk. Indirect arguments suggest that most of these systems may be viewed through remnant infalling envelopes and, if so, might be regarded as the evolutionary precursors of the group I objects. *Group III* consists of six stars with small infrared excesses, whose infrared spectral energy distributions appear similar to those of classical Be stars in which modest excesses above photospheric levels seem to arise from free-free emission in a *gaseous* circumstellar disk or envelope. Nevertheless, their association with star-forming molecular clouds and their proximity to other young stars suggests that they are young, intermediate-mass stars which lack disks and which may be analogs of diskless T Tauri stars.

Basic disk parameters for the group I objects are derived from extant optical and infrared photometry and from newly measured millimeter continuum flux densities: masses for the disks (along with any remnant envelope material contained within the millimeter-antenna beam) are in the range $0.01 < M_{\text{disk}}/M_\odot < 6$; lower limits to outer disk radii are in the range $15 < R_{\text{disk}}/\text{AU} < 175$; inner optically thin disk regions have radii $3 < R_{\text{hole}}/R_* < 25$; disk accretion luminosities are in the range $12 < L_{\text{acc}}/L_\odot < 1800$, while the deduced disk mass accretion rates are in the range $6 \times 10^{-7} < \dot{M}_{\text{acc}} < 8 \times 10^{-5}\ M_\odot\ \text{yr}^{-1}$. Derived Balmer line luminosities for the group I objects correlate well with our accretion luminosities and extend the relationships between these quantities de

The group I H … alogs of T Tauri stars, whose
unusual photomet … a variety of physical processes
(e.g., winds, bound … accretion disk. If disk material
arrives on the st … -main-sequence lifetime of an
intermediate-mass … tar must pass through a disk.
Moreover, becaus … ter than the stellar luminosity,
the energy input t … y cases to alter the pre–main-
sequence evolutio

Finally, it is n … n rates and possibly envelope
infall rates appear … ent an important step toward
understanding the … accretion rates, and ultimate-
ly the stellar mass



INFRARED STUDIES OF CIRCUMSTELLAR MATTER AROUND HERBIG Ae/Be AND RELATED STARS

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Received 1992 July 16; accepted 1992 September 28

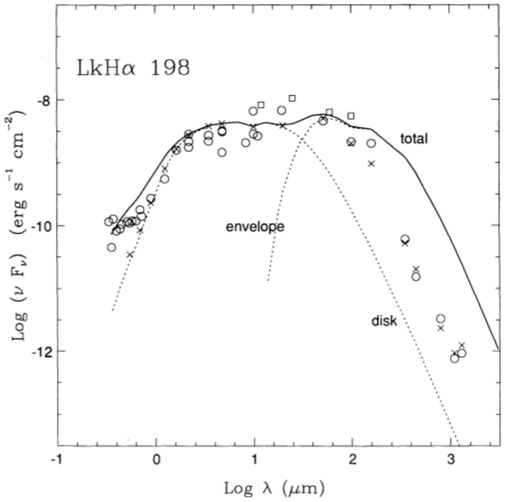
ABSTRACT

High spatial resolution data at 50 and 100 μm are presented for seven young, intermediate-mass stars with flat or rising spectral energy distributions. Five objects have been resolved in at least one direction at 100 μm, and two were resolved at 50 μm. The far-infrared emission from resolved sources comes from extended envelopes whose size varies between 5×10^3 and 8×10^4 AU. In most cases, the intensity profiles do not show large departures from spherical symmetry.

For the five resolved stars, we model the observations as emission from dust in an envelope, heated by a central source. The combination of the size information and the spectral energy distributions demonstrates that the central source spectra must be considerably redder than those of the stars. While several possible explanations exist, we adopt a model for the central source composed of a star and a circumstellar disk. By comparing the predictions of radiation transfer models to the observations (the far-infrared scans and the spectral energy distribution from visual to millimeter wavelengths), it is possible to separate the contribution of the star, the disk, and the envelope, and to investigate their physical properties.

The derived density profiles of the envelopes show that in two cases the dust has a steep density profile ($n \sim r^{-\alpha}$, $\alpha \sim 2$), while in three other objects the dust must be distributed with rather shallow gradients ($\alpha \sim 0.5$). Thus, our sample of five Herbig Ae/Be stars, all surrounded by a significant amount of matter, includes objects that are probably still in an accretion phase, and objects that are not. It is at present unclear
if this results from th … flects a difference in the
pristine physical cond

Circumstellar disks … anation for the spectral
energy distributions i … red wavelengths, if inter-
preted as due to vis … es. A resolution to the
problem of the origin … quence evolution awaits
more accurate determ … h as several independent
dust structures near t … iple possible.



Very small dust grains in the circumstellar environment of Herbig Ae/Be stars

A. Natta[1], T. Prusti[2], and E. Krügel[3]

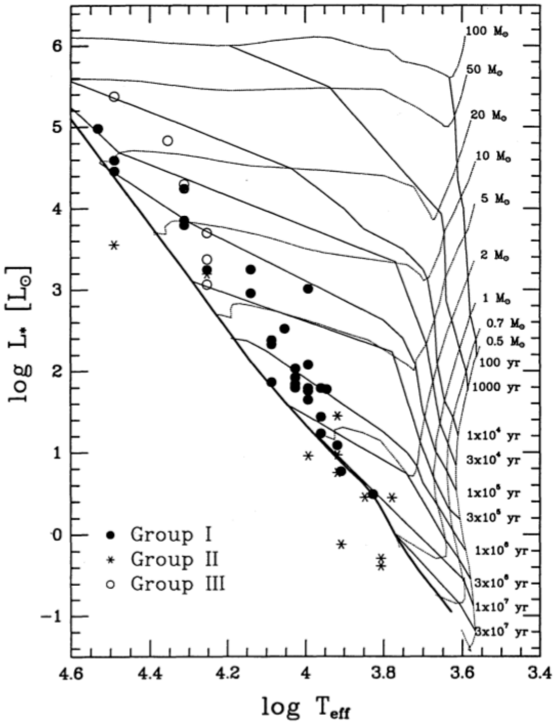


FIG. 13.—H-R diagram with luminosities and temperatures calculated as in § 3. Mass tracks are those of Ezer & Cameron (1965, 1967a, b), and age isochrones are derived from the tracks using polynomial interpolation. The zero-age main sequence is from VandenBerg & Bridges (1984). Group III objects (*open circles*) comprise only relatively massive stars ($M_* > 5\ M_\odot$); lower mass stars ($M_* < 3\ M_\odot$) predominate among group II objects (*asterisks*); while group I objects (*filled circles*) overlap groups II and III and span a wide range of ages and masses.

THE BIRTHLINE FOR INTERMEDIATE-MASS STARS

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Received 1990 May 10; accepted 1990 June 21

ABSTRACT

We combine the protostar mass-radius relation with standard pre-main-sequence evolutionary tracks to construct the birthline for stars of intermediate mass ($2 \lesssim M_*/M_\odot \lesssim 10$). Our theoretical birthline is in good agreement with the observed upper envelope of the distribution of Herbig Ae and Be stars in the H-R diagram. From the intersection of the birthline with the ZAMS, we predict that stars with $M_* \gtrsim 10\ M_\odot$ should never exhibit an optical pre-main-sequence phase; this prediction also agrees with existing observations. These findings show that stars of intermediate mass are first optically visible quite close to the main sequence. Hence, their contraction ages are less than the traditional ones derived assuming large initial radii. Our birthline is also well delineated by the locus in the diagram of optically visible stars with associated molecular outflows. The underlying protostar theory predicts that newly formed stars of intermediate mass burn deuterium in a subsurface shell. We propose that an outer convection zone maintained by this shell burning is the cause of the winds and surface activity commonly observed in these stars.

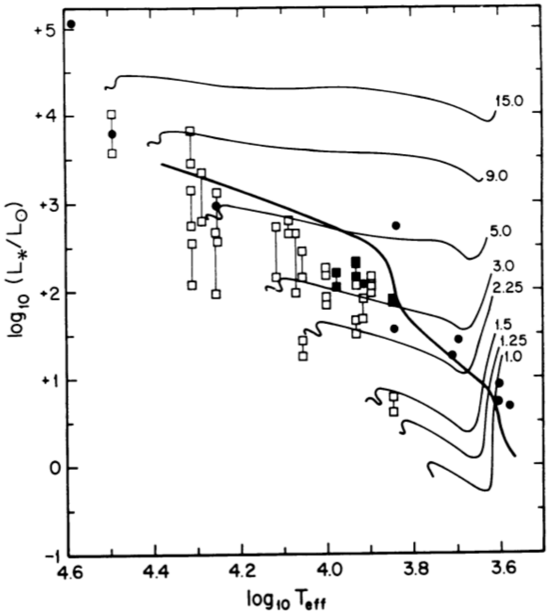

FIG. 3.—Location of the stellar birthline. The birthline is the heavy curve cutting across the lighter pre-main-sequence tracks of Iben (1965). Each track is labeled by the corresponding mass in solar units. The squares are observed Herbig Ae and Be stars from Finkenzeller and Mundt (1984), and the filled symbols (*circles* and *squares*) are the outflow sources from Levreault (1988).

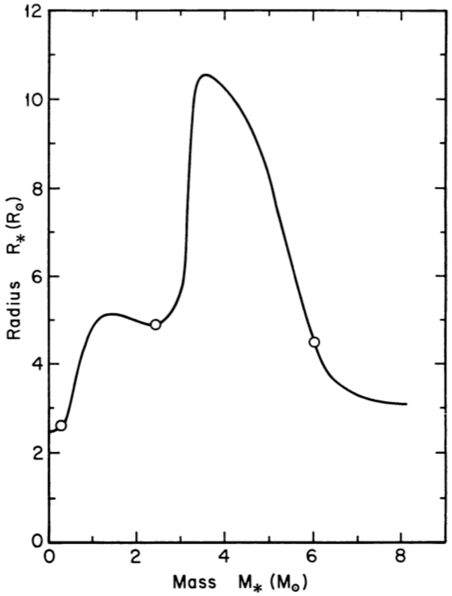

FIG. 2.—Evolution of the radius in an accreting protostar (from Palla and Stahler 1991). Shown is the radius vs. mass, in solar units, for a spherical protostar accreting at a rate of $10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$. The open circles represent, from left to right, the ignition of central deuterium, the start of deuterium shell burning, and the ignition of central hydrogen via the CN cycle.

1995

ISOLATED STAR-FORMING REGIONS CONTAINING HERBIG AE/BE STARS. I. THE YOUNG STELLAR AGGREGATE ASSOCIATED WITH BD +40° 4124

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Received 1994 July 5; revised 1994 August 24

ABSTRACT

We use optical and infrared photometry in combination with red optical spectra to study the star-forming region associated with the two Herbig Ae/Be stars BD +40° 4124 and V1686 Cyg. We identify a partially embedded, dense, isolated cluster of pre-main sequence stars concentrated within 0.15 pc of the two young high-mass stars. The cluster is isolated in that it is separated by approximately 0.7 pc from a surrounding Hα-bright rim and lies at the center of a molecular core with peak column density corresponding to 45 mag of visual extinction. The fraction of the stellar population with evidence for circumstellar activity is 100% amongst the optically visible cluster members and at least 50% amongst the embedded sources. This small region is characterized by an apparent age spread of approximately 3 Myr with evidence for both high- and low-mass stars forming relatively simultaneously (within several hundred thousand years). Comparison of the derived stellar mass distribution to that expected from Monte-Carlo sampling of the solar neighborhood
mass s … ate- and
high-m … and that
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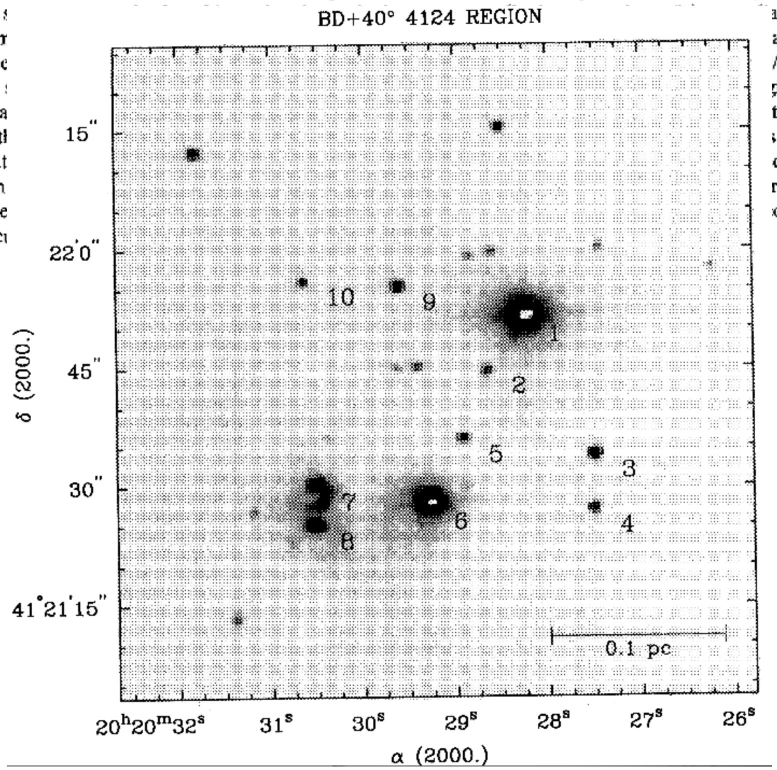

1998

A search for clustering around Herbig Ae/Be stars

II. Atlas of the observed sources*

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[1] Division of Physics, Mathematics and Astronomy, California Institute of Technology, MS 105-24, Pasadena CA 91125, U.S.A.
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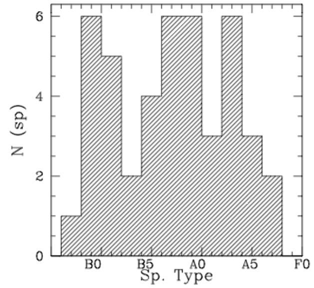
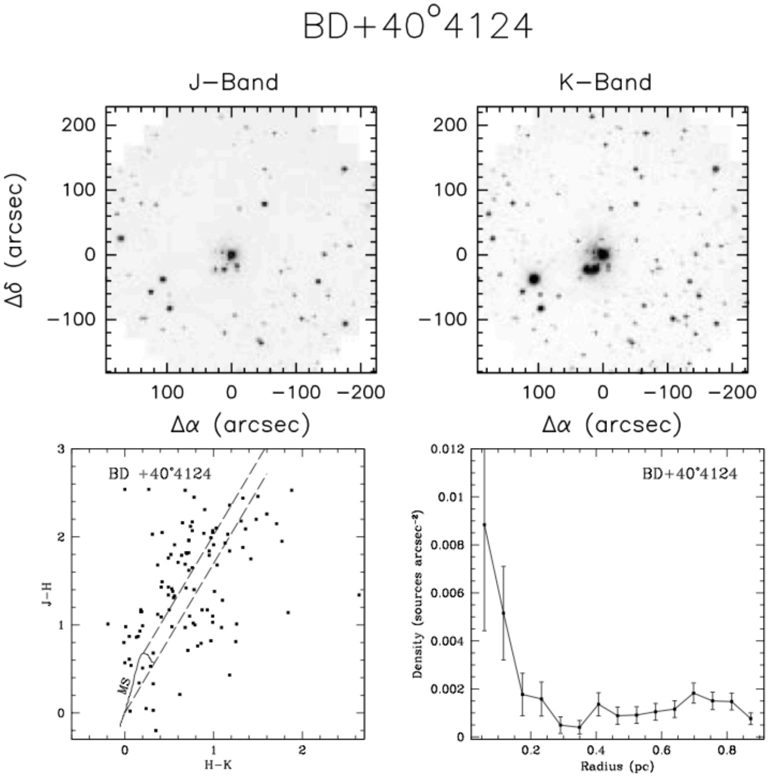
Received March 25; accepted May 11, 1998

Abstract. We present large field infrared images of a sample of 45 Herbig Ae/Be stars. Stellar parameters, such as age and luminosity, have been derived for all of them in a consistent way. The images have been used to identify stellar groups or clusters associated with the Herbig Ae/Be star. The results presented in this paper form the database for a study of clustering around intermediate mass stars (Testi et al. 1998).

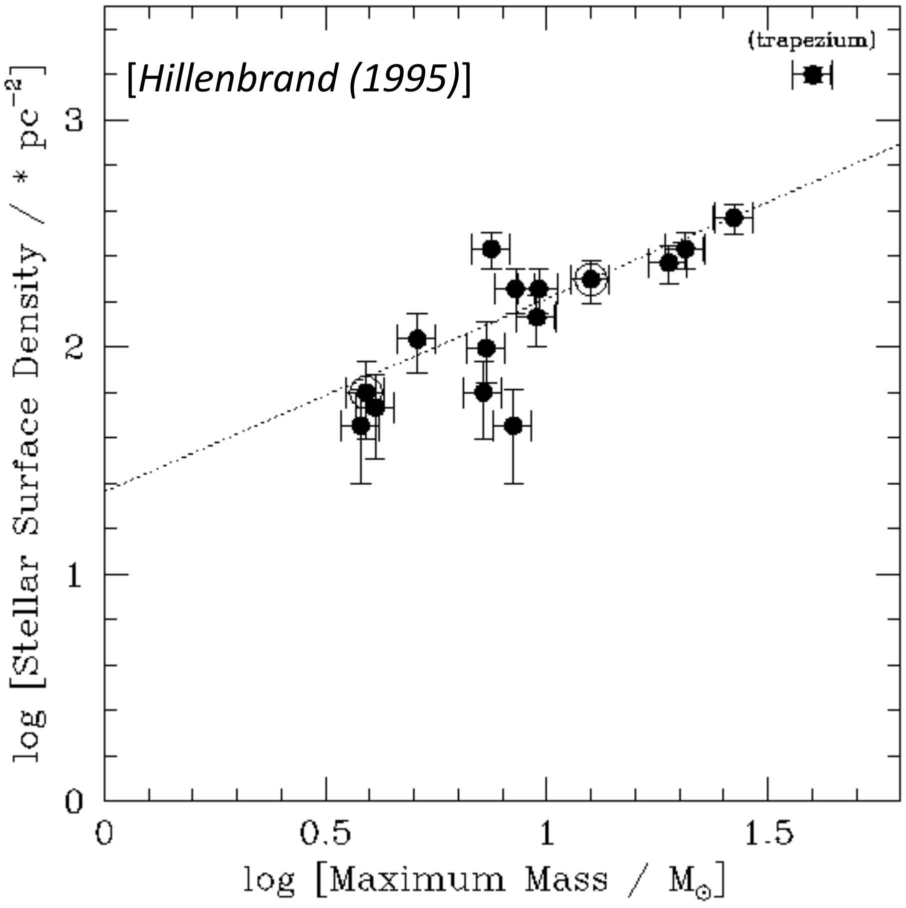
Key words: stars: formation — stars: pre-main sequence — infrared: stars



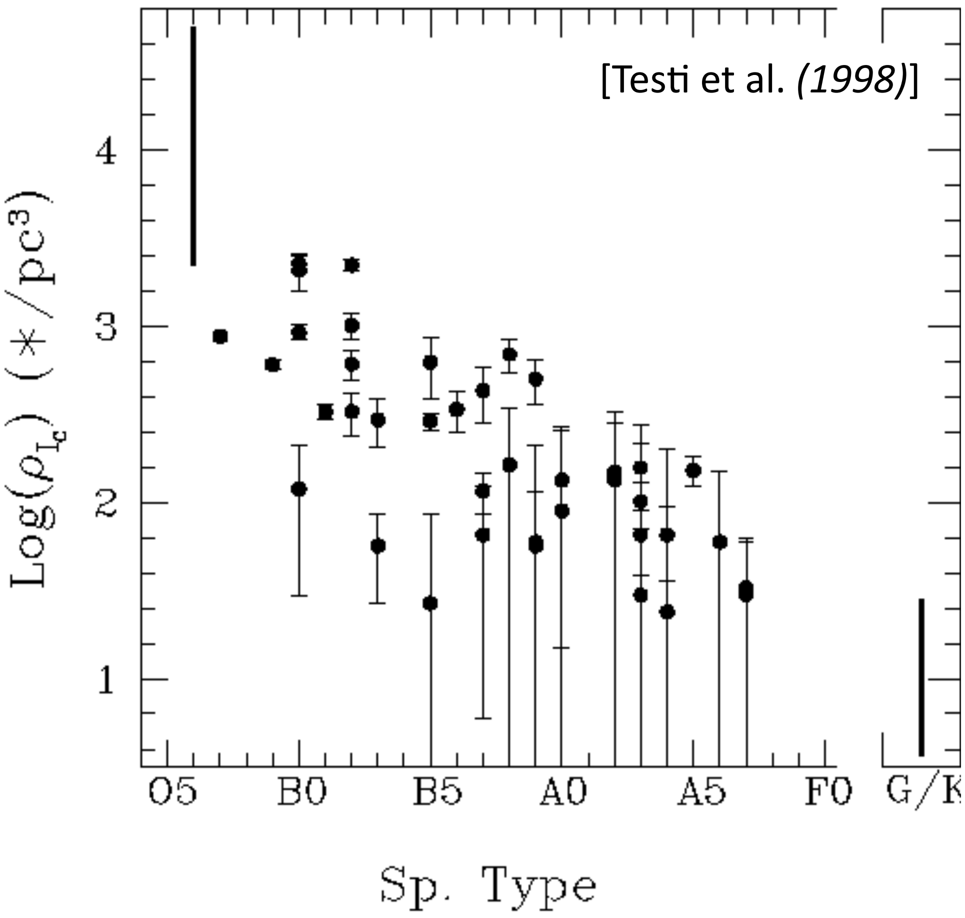


Observed Cluster Properties

Denser clusters are associated with higher mass stars.



[*Hillenbrand (1995)*]



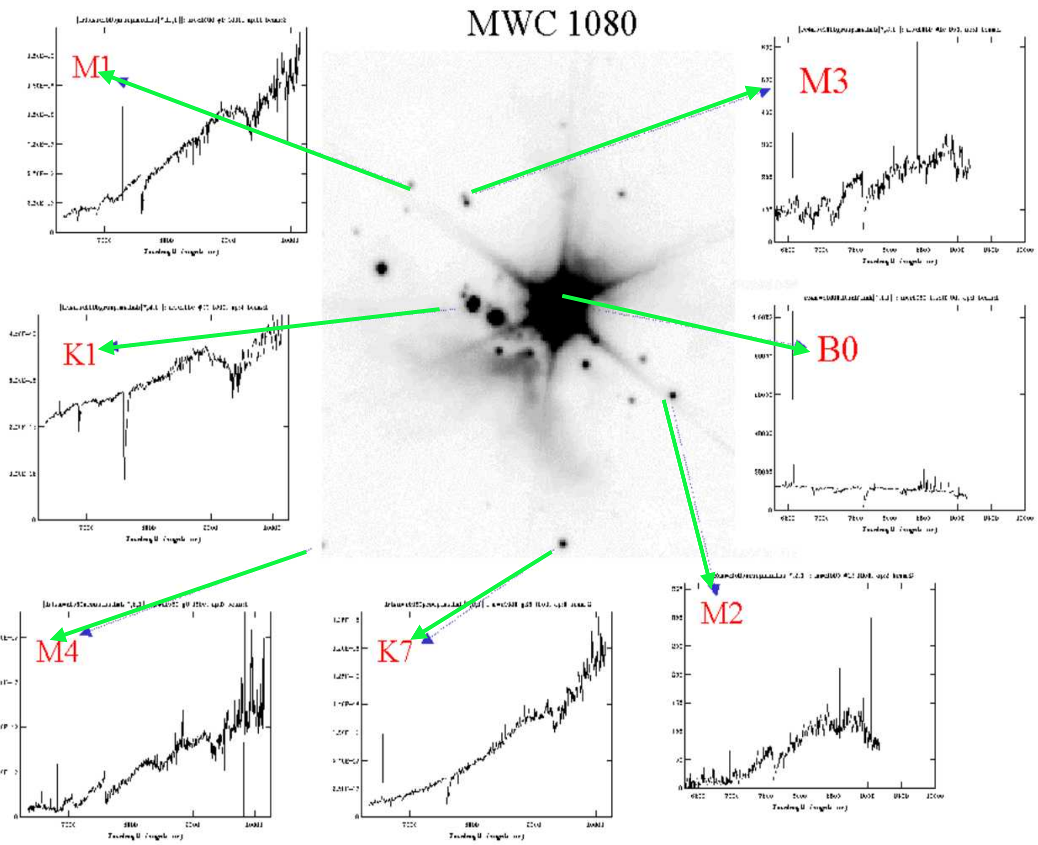
[Testi et al. *(1998)*]

Beyond Star Counts:
The Stellar/Sub-Stellar Mass Function

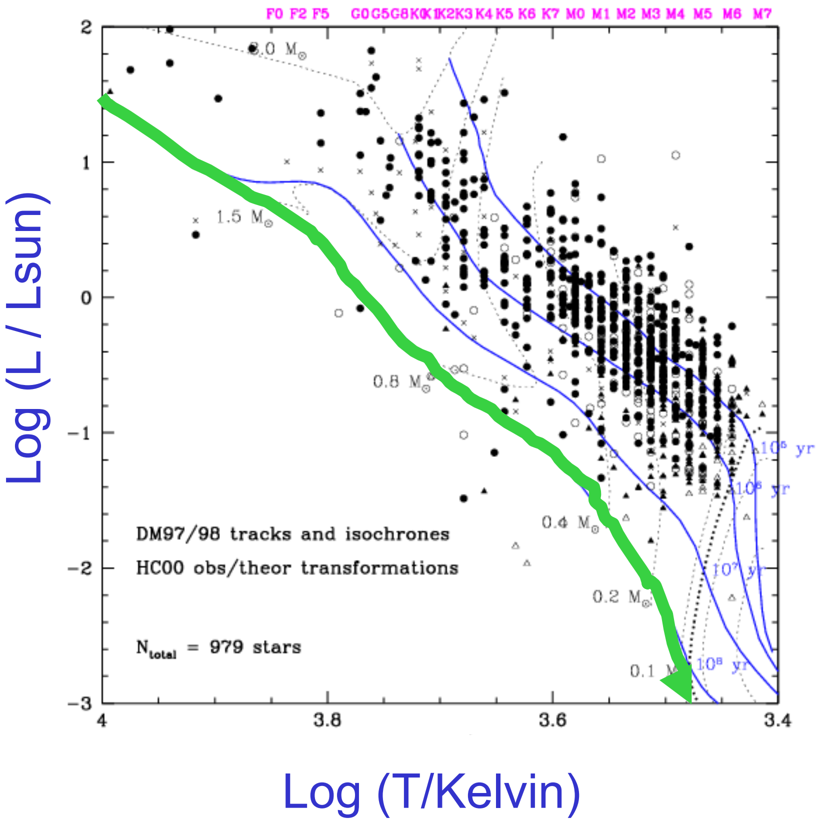
- Younger stars much brighter than similar-mass but older counterparts e.g. in open clusters.

- Herbig Ae/Be regions do not seem biased to high mass star formation overall; plenty of M-type stars too.

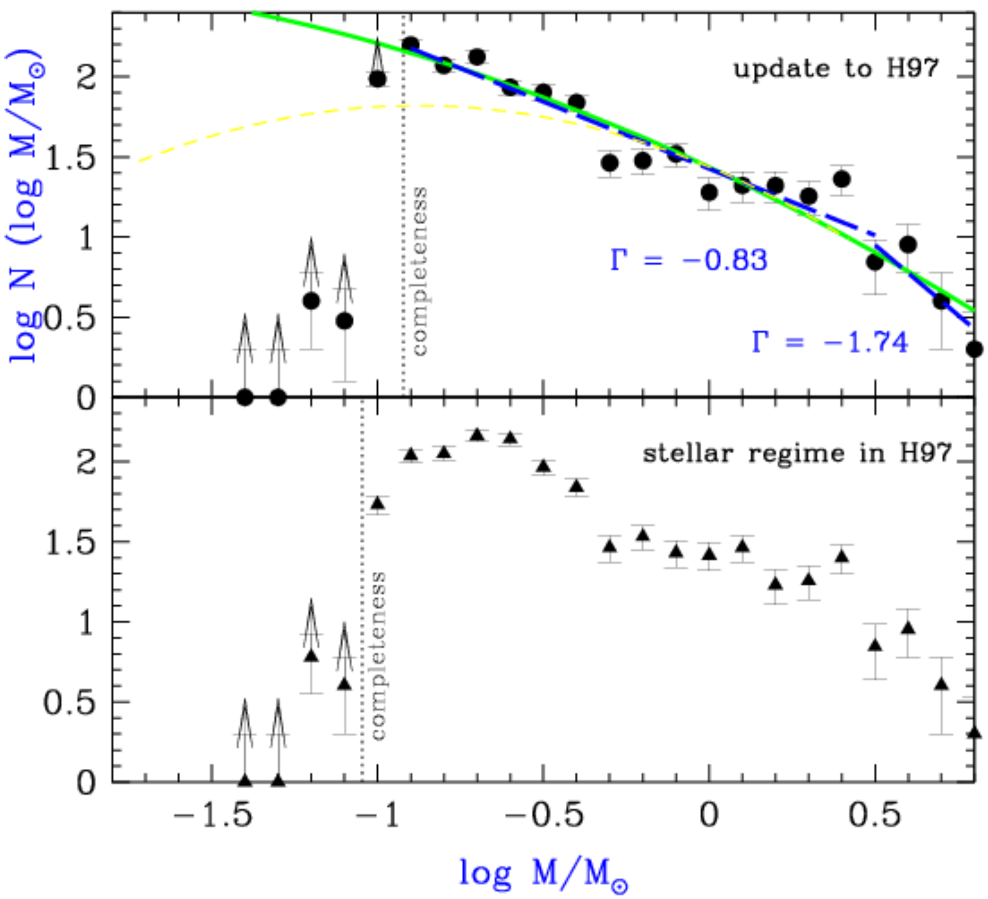
[MWC 1080 Cluster]



The ONC Initial Mass Function

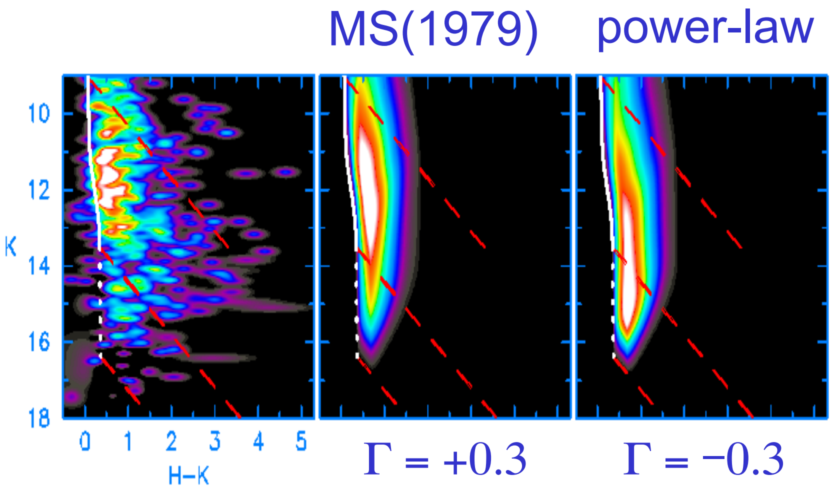


Hillenbrand (1997; updated)

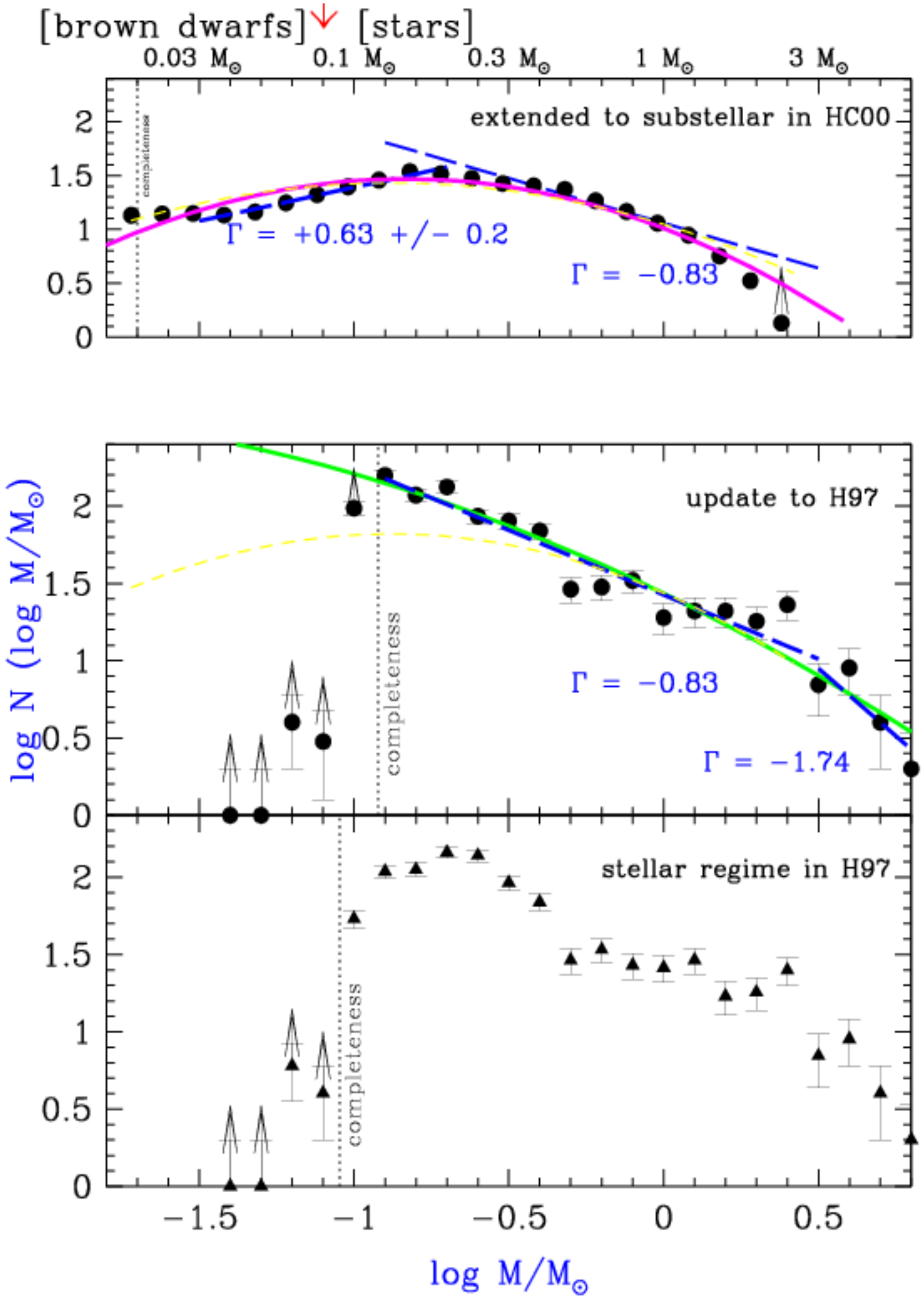


The ONC Initial Mass Function

Quadratic or log-normal functions fit best.



Hillenbrand & Carpenter (2000)



1999

STAR FORMATION IN THE ORION NEBULA CLUSTER

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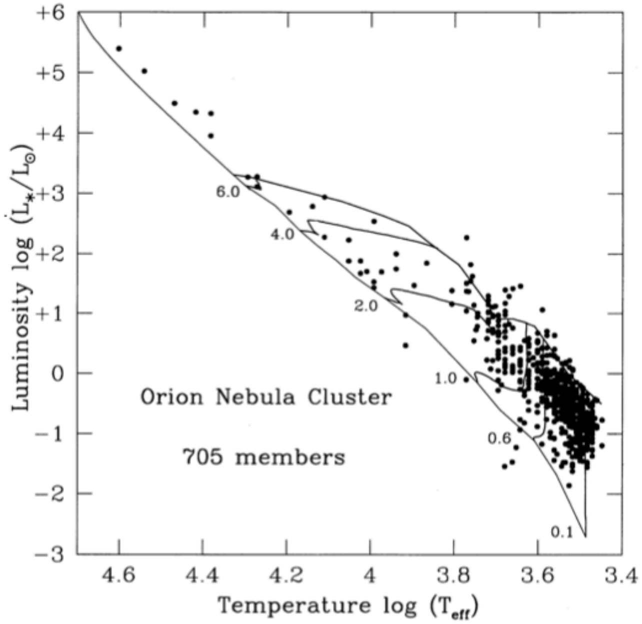
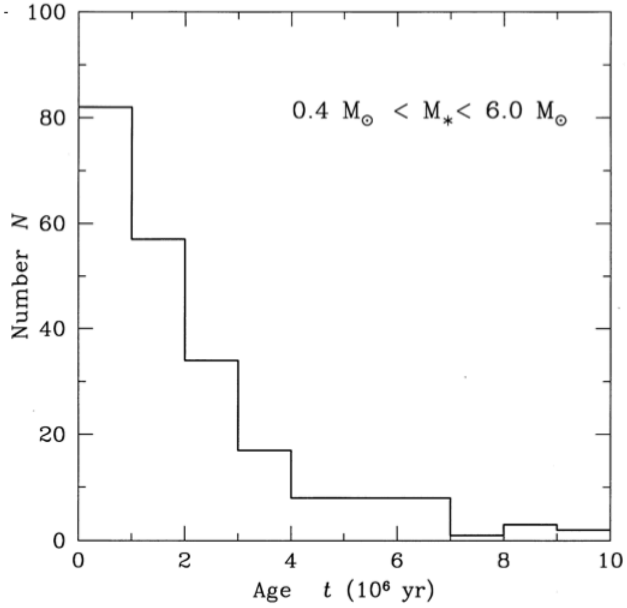
Received 1999 March 3; accepted 1999 June 23

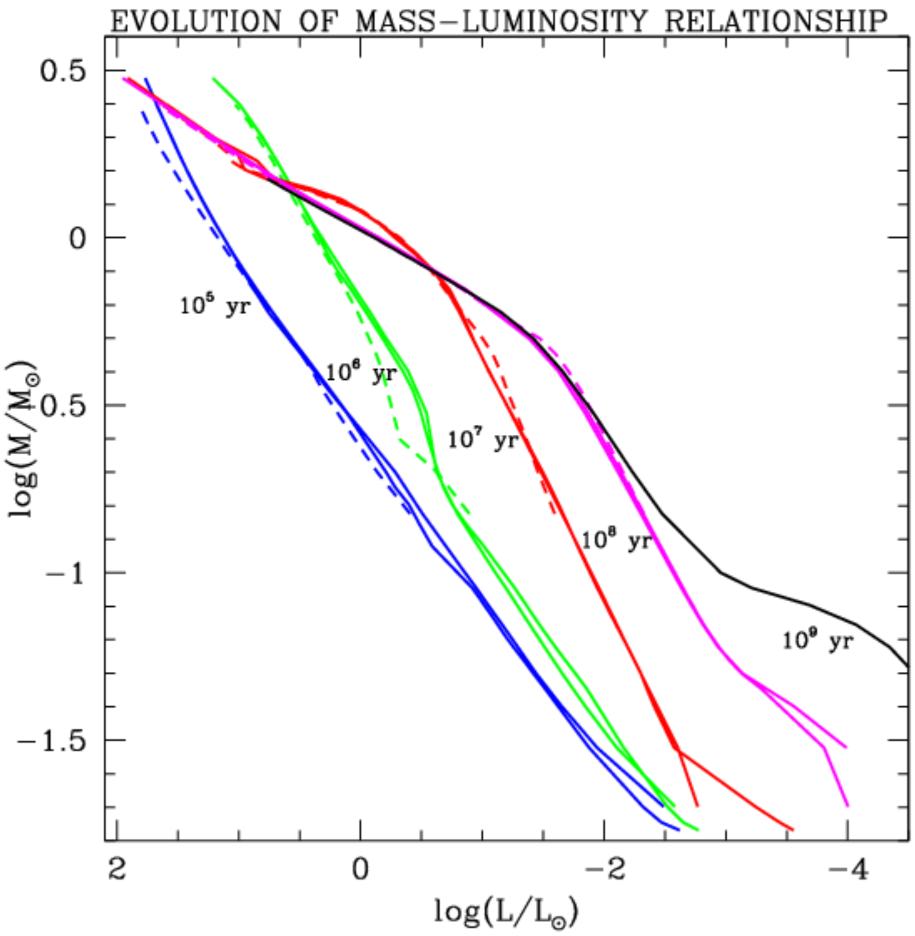
ABSTRACT

We study the record of star formation activity within the dense cluster associated with the Orion Nebula. The bolometric luminosity function of 900 visible members is well matched by a simplified theoretical model for cluster formation. This model assumes that stars are produced at a constant rate and distributed according to the field-star initial mass function. Our best-fit age for the system, within this framework, is 2×10^6 yr. To undertake a more detailed analysis, we present a new set of theoretical pre–main-sequence tracks. These cover all masses from 0.1 to 6.0 $M_\odot$, and start from a realistic stellar birthline. The tracks end along a zero-age main-sequence that is in excellent agreement with the empirical one. As a further aid to cluster studies, we offer an heuristic procedure for the correction of pre–main-sequence luminosities and ages to account for the effects of unresolved binary companions. The Orion Nebula stars fall neatly between our birthline and zero-age main-sequence in the H-R diagram. All those more massive than about 8 $M_\odot$ lie close to the main sequence, as also predicted by theory. After accounting for the finite sensitivity of the underlying observations, we confirm that the population between 0.4 and 6.0 $M_\odot$ roughly follows a standard initial mass function. We see no evidence for a turnover at lower masses. We next use our tracks to compile stellar ages, also between 0.4 and 6.0 $M_\odot$. Our age histogram reveals that star formation began at a low level some 10^7 yr ago and has gradually accelerated to the present epoch. The period of most active formation is indeed confined to a few $\times 10^6$ yr, and has recently ended with gas dispersal from the Trapezium. We argue that the acceleration in stellar births, which extends over a wide range in mass, reflects the gravitational contraction of the parent cloud spawning this cluster.

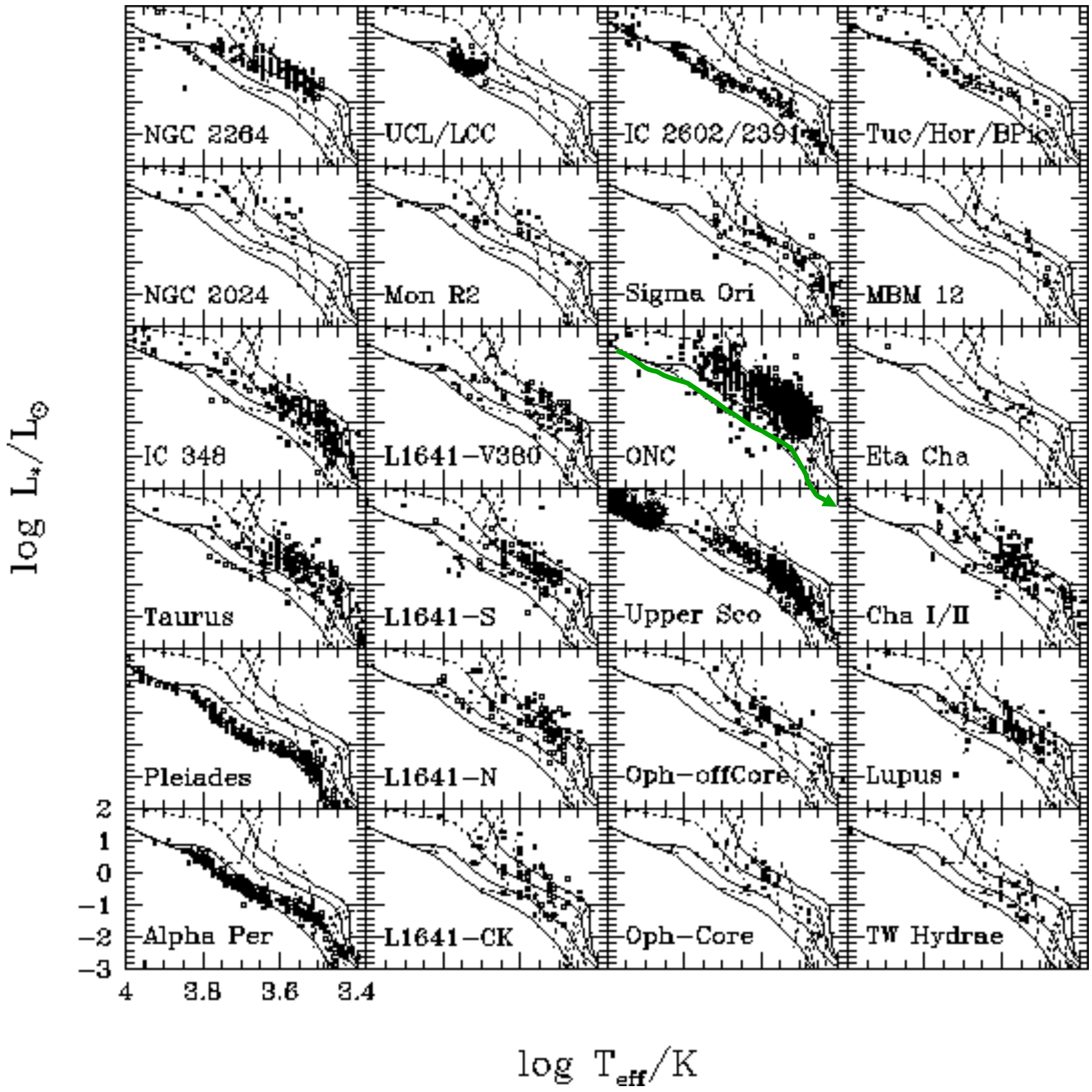




The Stellar and Sub-Stellar Initial Mass Function



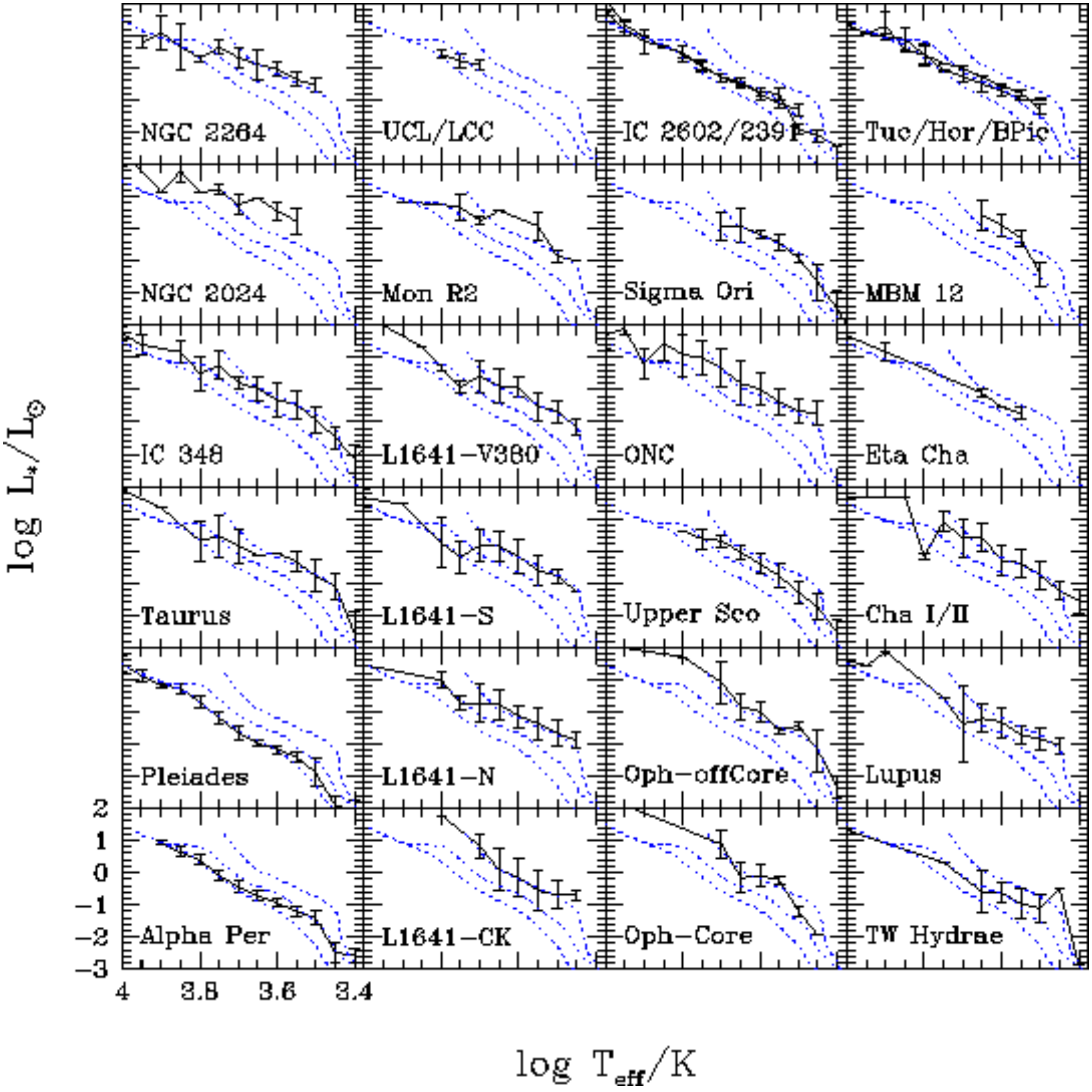
- Stellar masses (and ages) derived via comparison to evolutionary theory.
- Rapidly evolving mass-luminosity relation.
- But need large samples to determine *form* and *shape* of the IMF.
- *Cluster sequences don't really match isochrones though*, making evolutionary trends difficult to trust.



Stellar evolution towards the main sequence:

<1 - 120 Myr

(solar vicinity star-forming regions and young clusters)

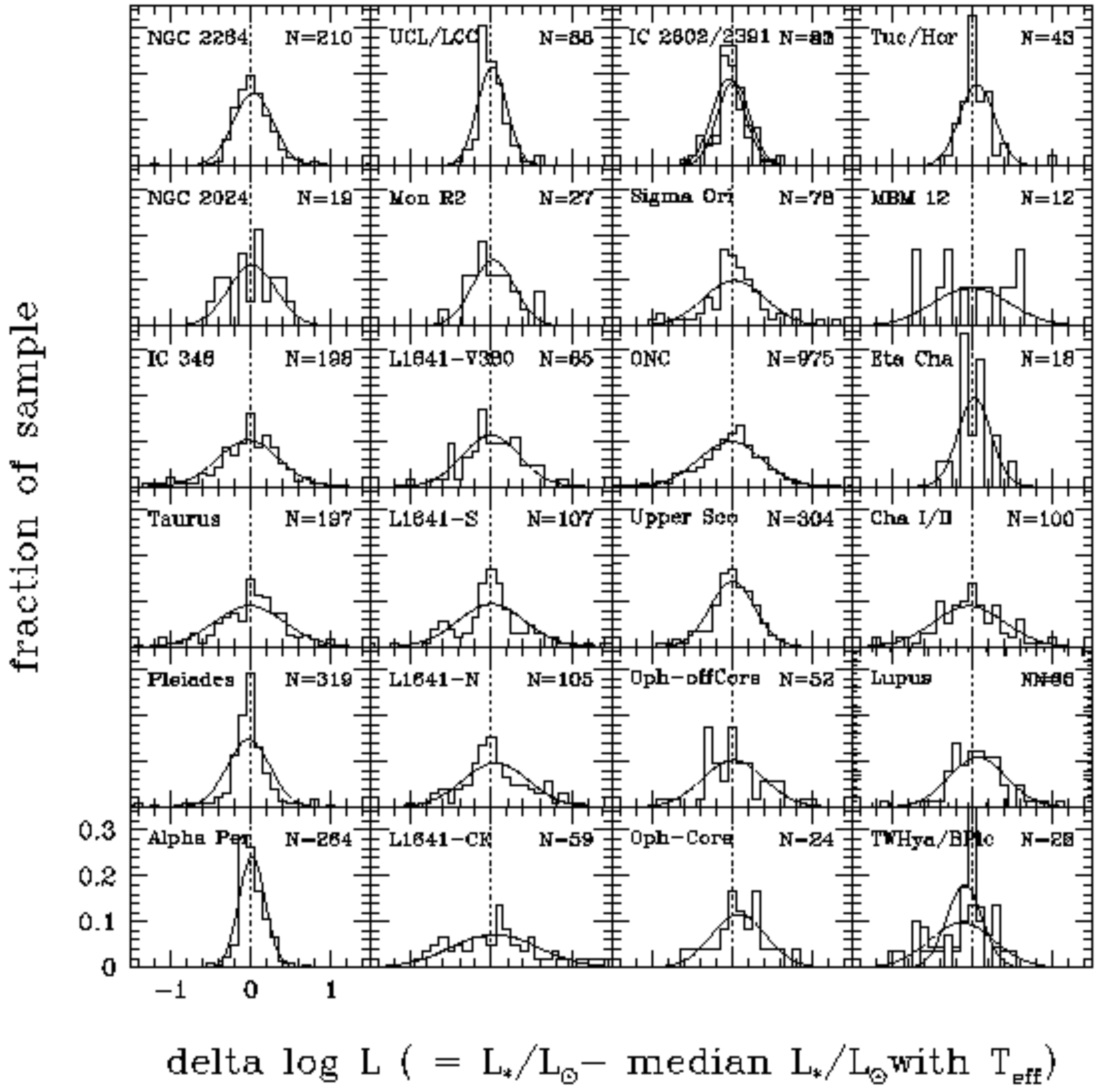


Observed median luminosity as a function of effective temperature

(empirical isochrones)

Do tracks correctly predict stellar ages?

Do luminosity spreads correspond to age spreads?

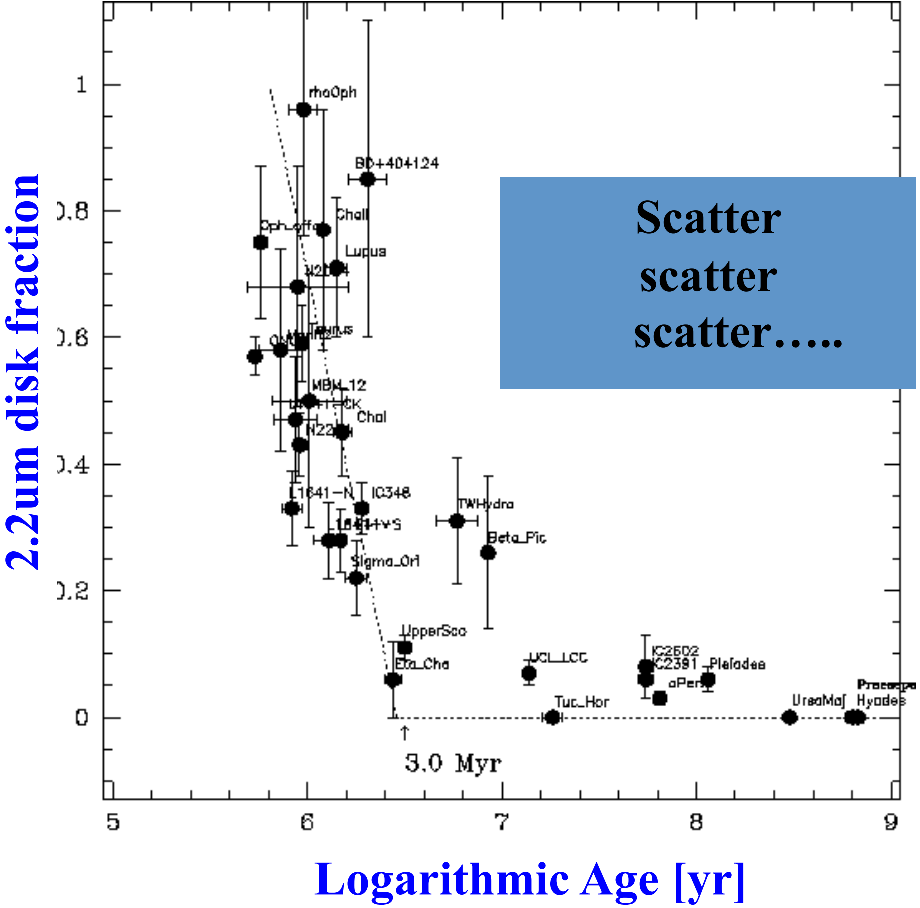


Observed luminosity dispersions

Gaussian fits appear adequate.

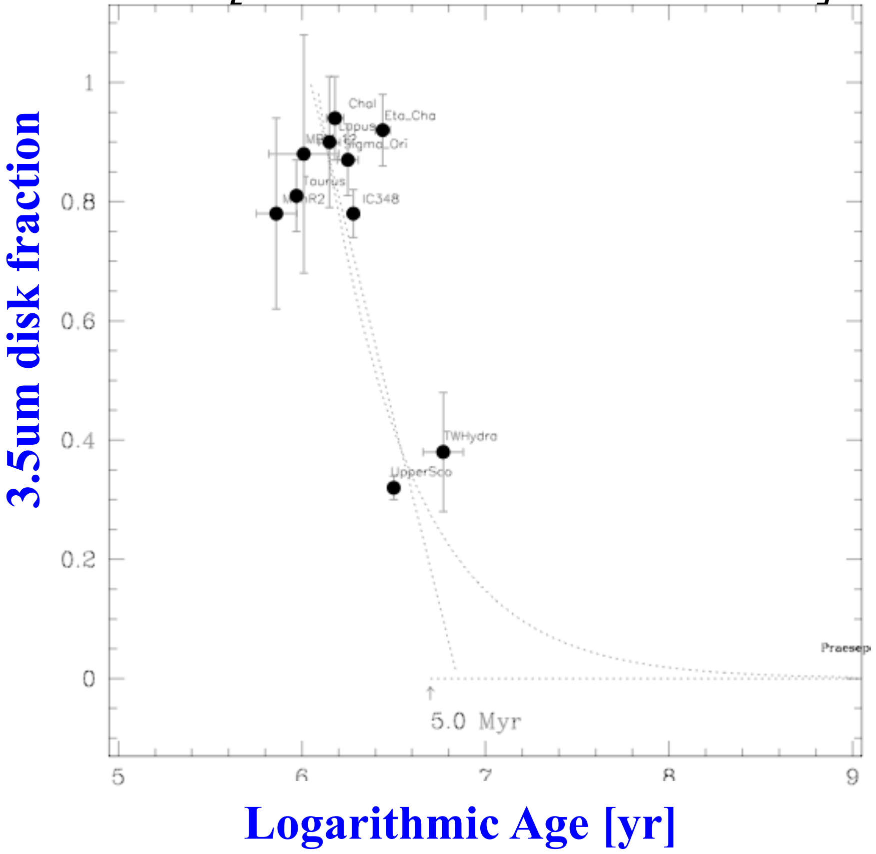
However, subtle deviations from pure Gaussian may convey important information apropos
- -- s.f. history
- -- binarity

Inner Disk Dissipation: Pre-Spitzer



Scatter
scatter
scatter…..

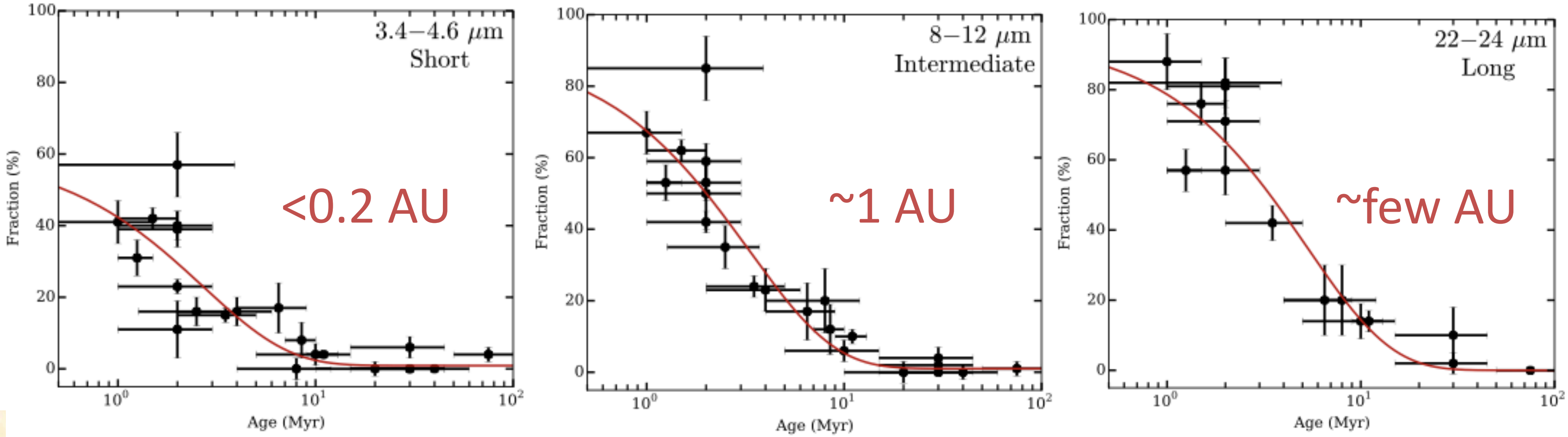
[Hillenbrand 1995 → 2005]



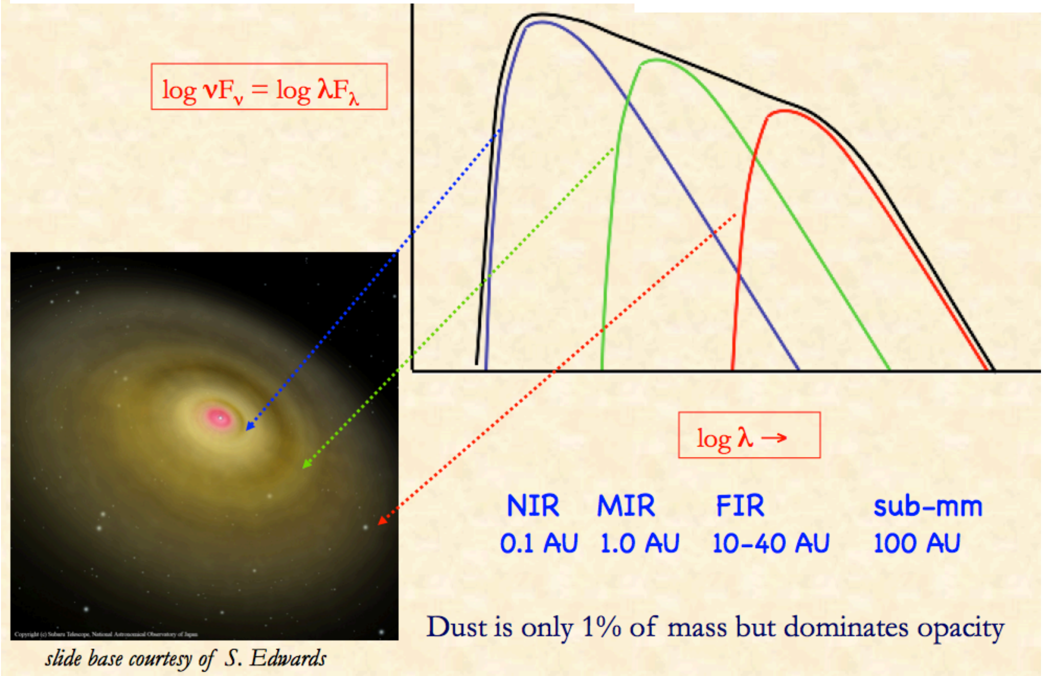
Near-IR: r < 0.1 AU,   M~ 2-10 M_{Ceres}.

Existing data suggest <3-10 Myr as maximum *accretion* disk lifetime

Dust Disk Dispersal Post-Spitzer



[Ribas et al. 2015]

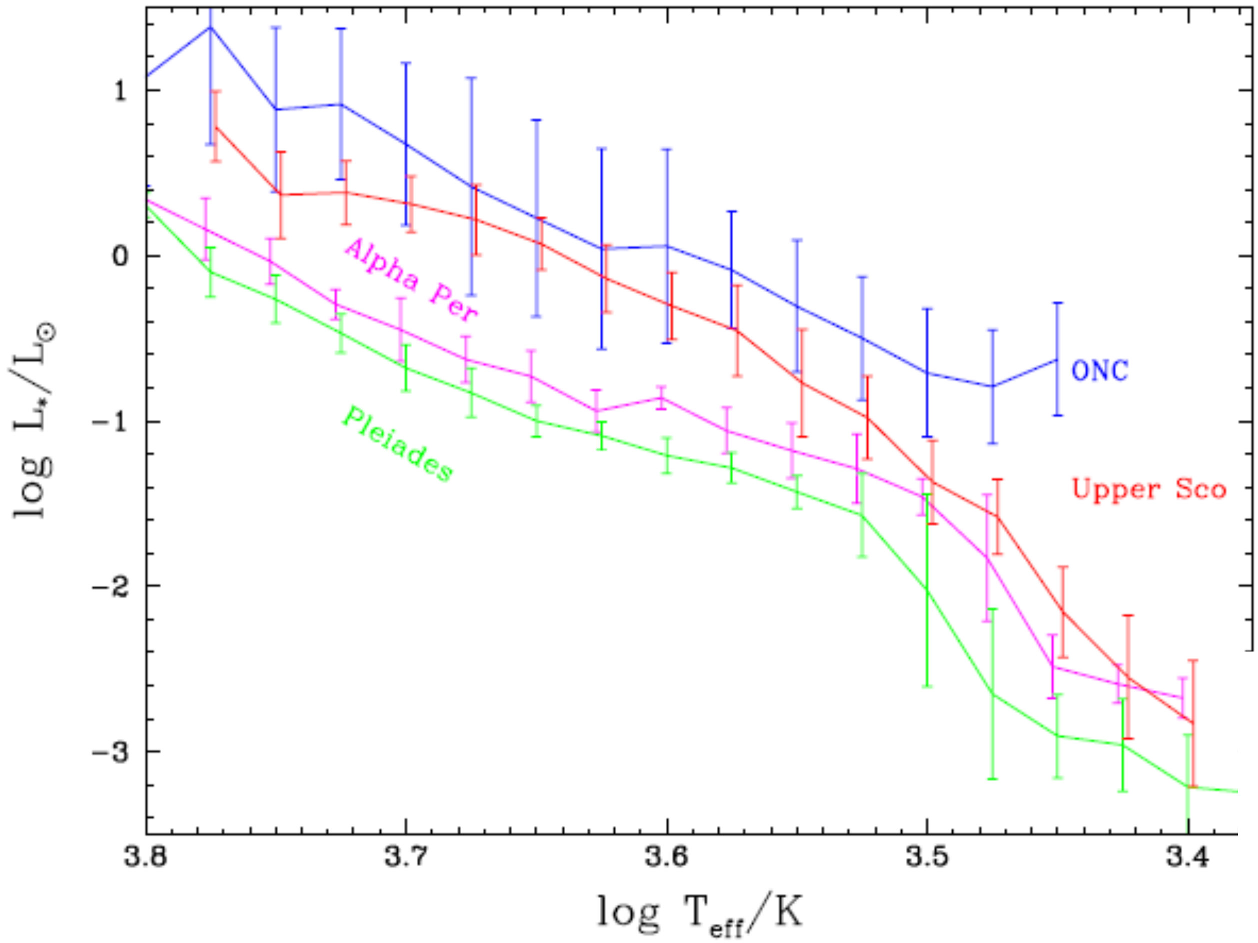


Dust is only 1% of mass but dominates opacity

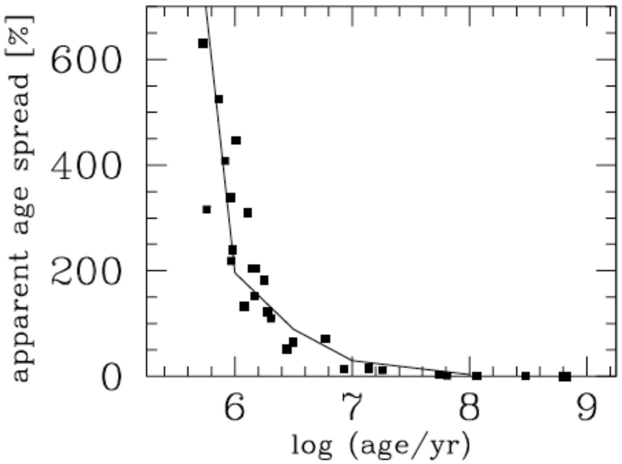
slide base courtesy of S. Edwards

Some evidence for “inside-out” clearing of circumstellar dust.

Mean Luminosity vs Effective Temperature



Observed scatter in log L/L_o diminishes from ~0.5 dex at 1 Myr to ~0.15 dex at >10 Myr, becoming consistent with estimated empirical uncertainties.



How to Test Reality of Luminosity Spreads

- Find a different clock than isochrones
  - Correlation with surface gravity
  - Correlation with lithium
  - Seismology checks in certain mass regimes

- Review systematics
  - Intrinsic colors and temperature / bolometric correction scales
  - Av errors

- Review effects that can lead to scatter
  - Error / binary effects
  - Scattered light effects
  - Accretion effects
  - Variability!

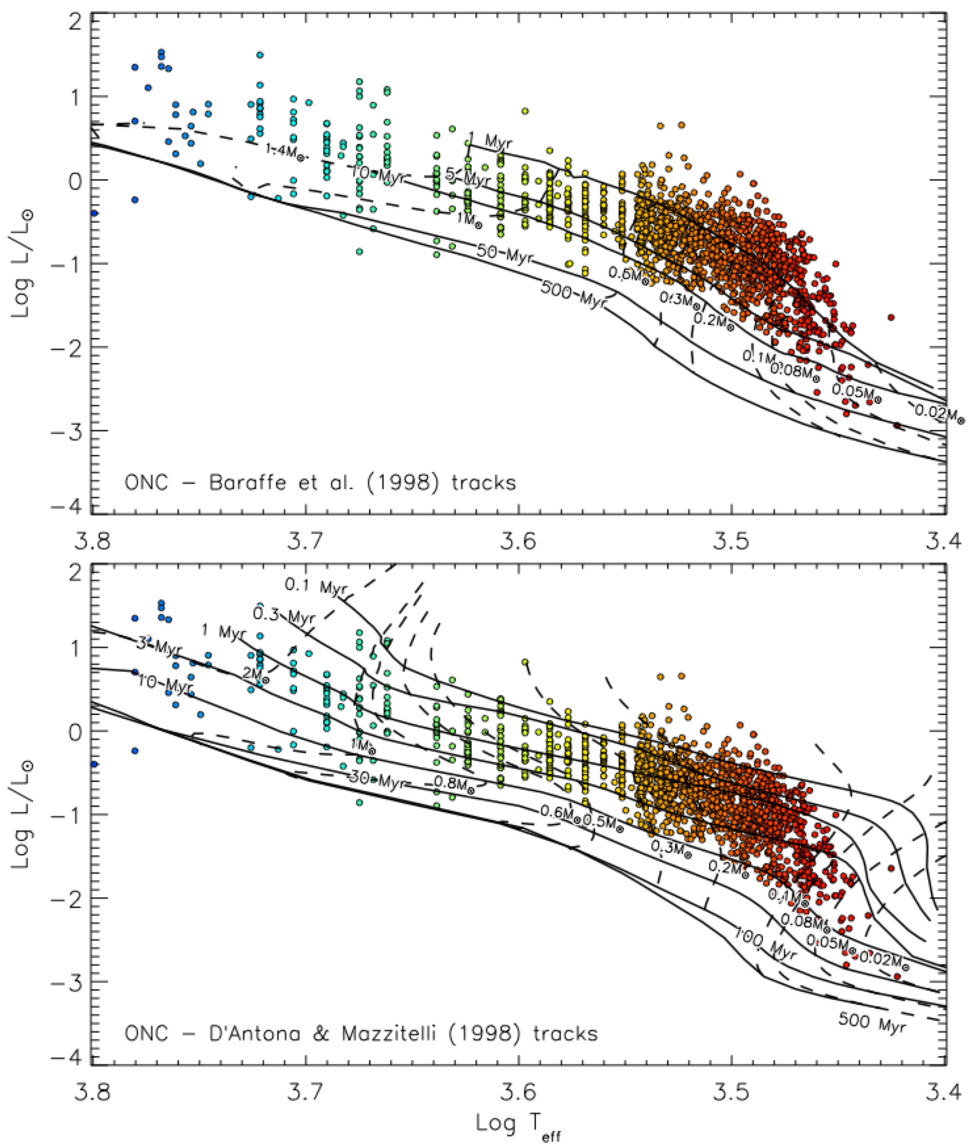
- Confirm membership – Gaia!
- Obtain exquisite photometry and high quality spectra……….

Robberto et al. 2006

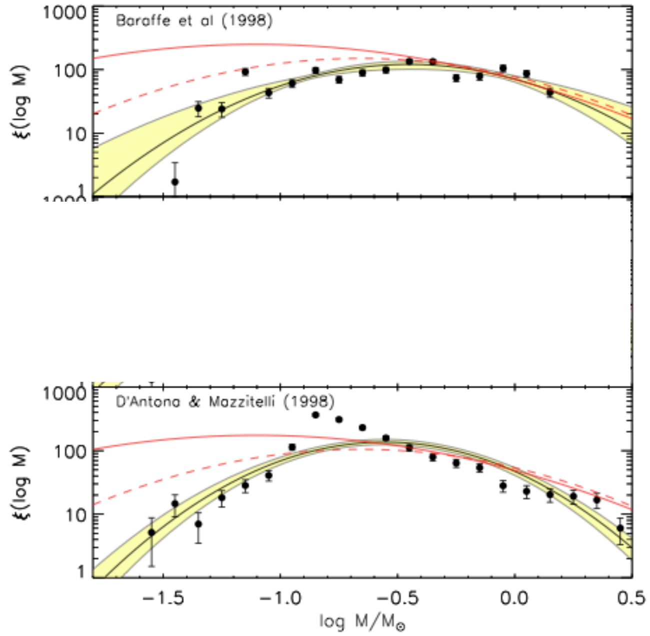
FP became a collaborator!

In Principle, Better HR Diagram BUT About the Same Stellar Mass and Age Distributions

Da Rio et al. 2011



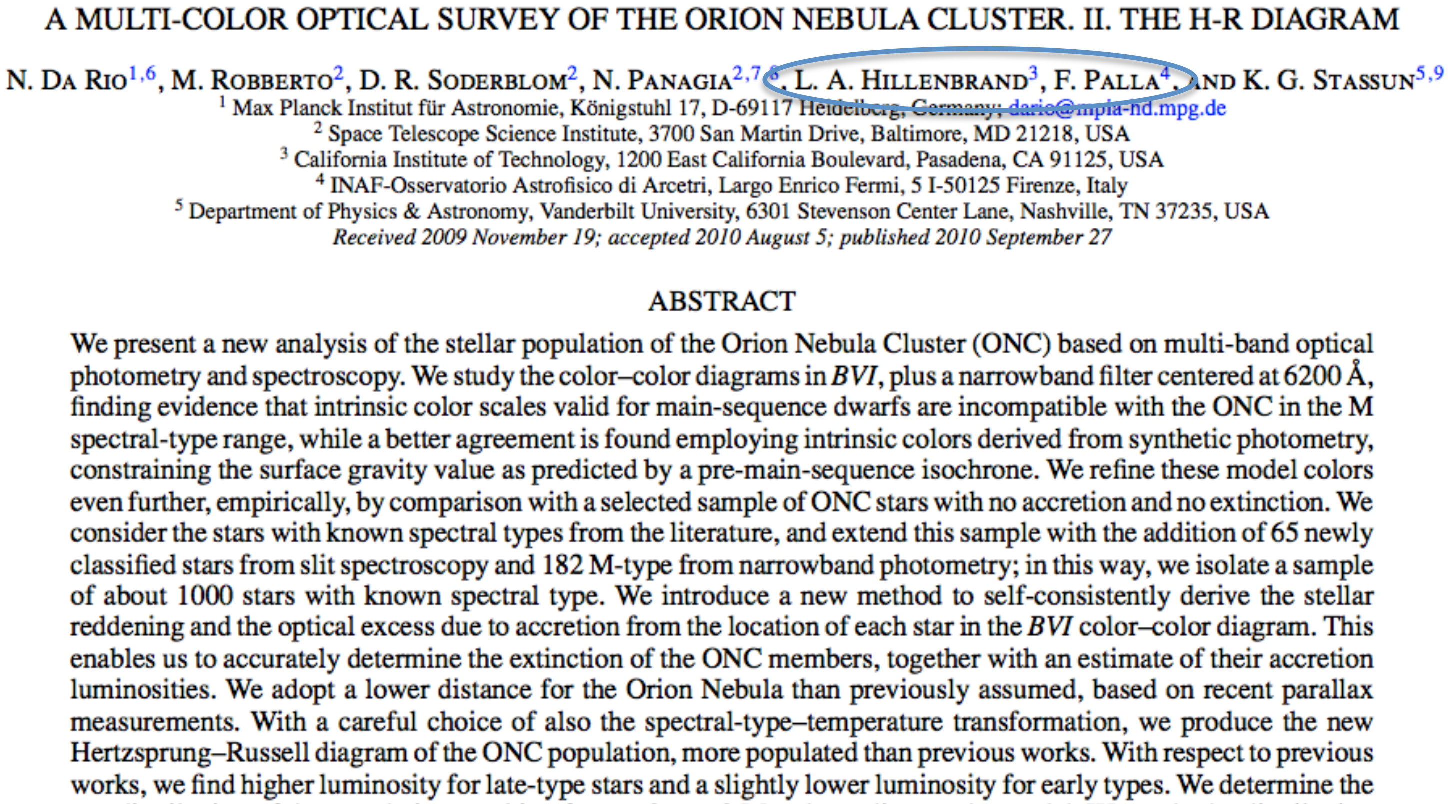
Da Rio



The IMF in the Orion Nebula Cluster turns over just before the hydrogen burning limit, declining for brown dwarfs.

The luminosity dispersion, of 0.3 dex, *persists* as an empirical effect; it may or may not correspond to real age spread .

2010



A MULTI-COLOR OPTICAL SURVEY OF THE ORION NEBULA CLUSTER. II. THE H-R DIAGRAM

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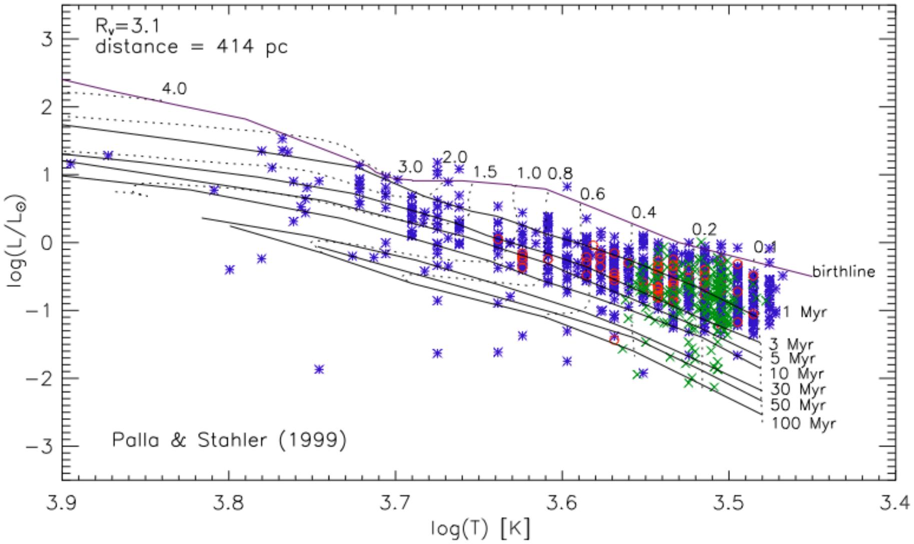
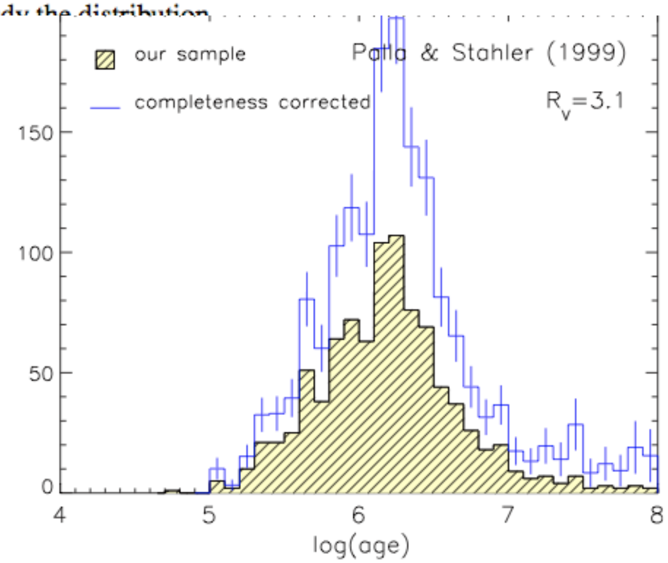
Received 2009 November 19; accepted 2010 August 5; published 2010 September 27

ABSTRACT

We present a new analysis of the stellar population of the Orion Nebula Cluster (ONC) based on multi-band optical photometry and spectroscopy. We study the color–color diagrams in *BVI*, plus a narrowband filter centered at 6200 Å, finding evidence that intrinsic color scales valid for main-sequence dwarfs are incompatible with the ONC in the M spectral-type range, while a better agreement is found employing intrinsic colors derived from synthetic photometry, constraining the surface gravity value as predicted by a pre-main-sequence isochrone. We refine these model colors even further, empirically, by comparison with a selected sample of ONC stars with no accretion and no extinction. We consider the stars with known spectral types from the literature, and extend this sample with the addition of 65 newly classified stars from slit spectroscopy and 182 M-type from narrowband photometry; in this way, we isolate a sample of about 1000 stars with known spectral type. We introduce a new method to self-consistently derive the stellar reddening and the optical excess due to accretion from the location of each star in the *BVI* color–color diagram. This enables us to accurately determine the extinction of the ONC members, together with an estimate of their accretion luminosities. We adopt a lower distance for the Orion Nebula than previously assumed, based on recent parallax measurements. With a careful choice of also the spectral-type–temperature transformation, we produce the new Hertzsprung–Russell diagram of the ONC population, more populated than previous works. With respect to previous works, we find higher luminosity for late-type stars and a slightly lower luminosity for early types. We determine the

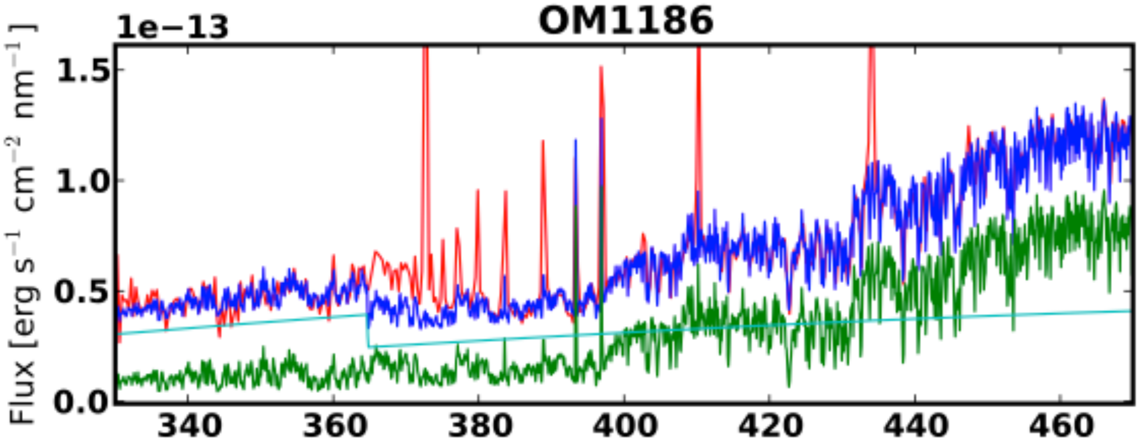
age distrib stu
of the mei ie t
removes ai ow
mass men er

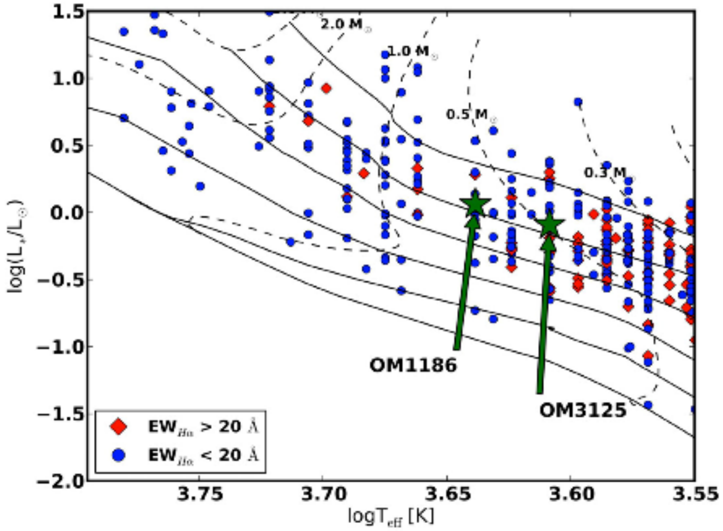




Careful Attention to Stellar Parameters Reduces Luminosity Spreads

Manara et al. 2013





Frasca et al. 2017

Simultaneously fit moderate dispersion spectra for spectral type, veiling/accretion, and extinction.

Much more reliable stellar parameters than those from broadband colors, which are affected by both scattered light and extinction.

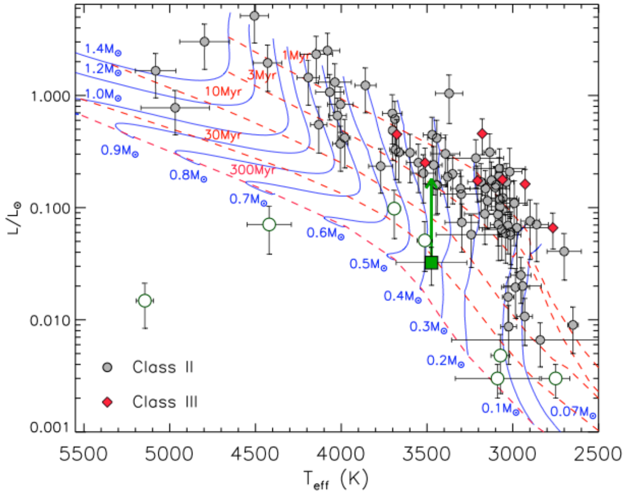
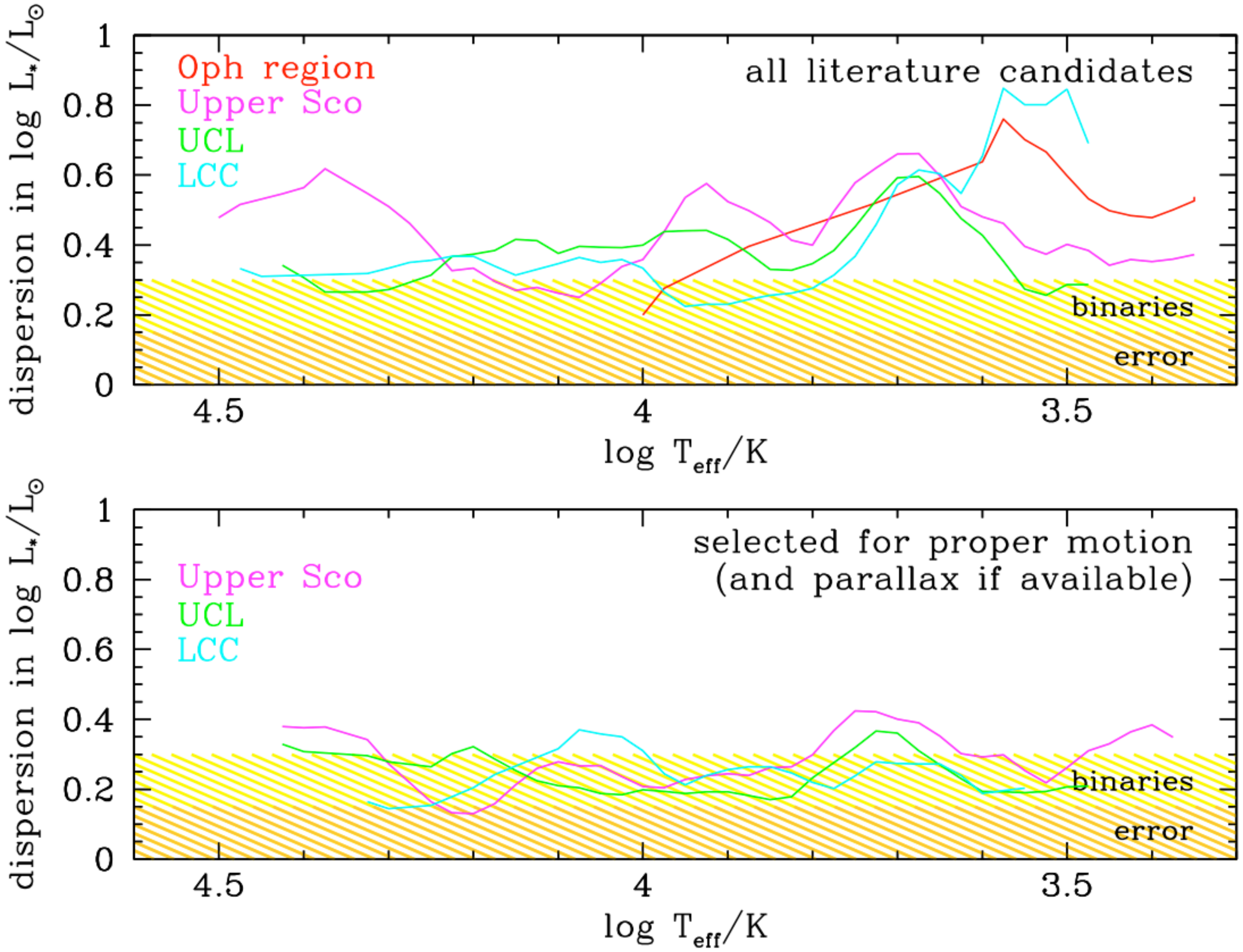


Fig. 6. Hertzsprung-Russell diagram of the Lupus members. The evolutionary tracks of Baraffe et al. (2015) are

Careful Membership Selection Reduces Luminosity Spreads

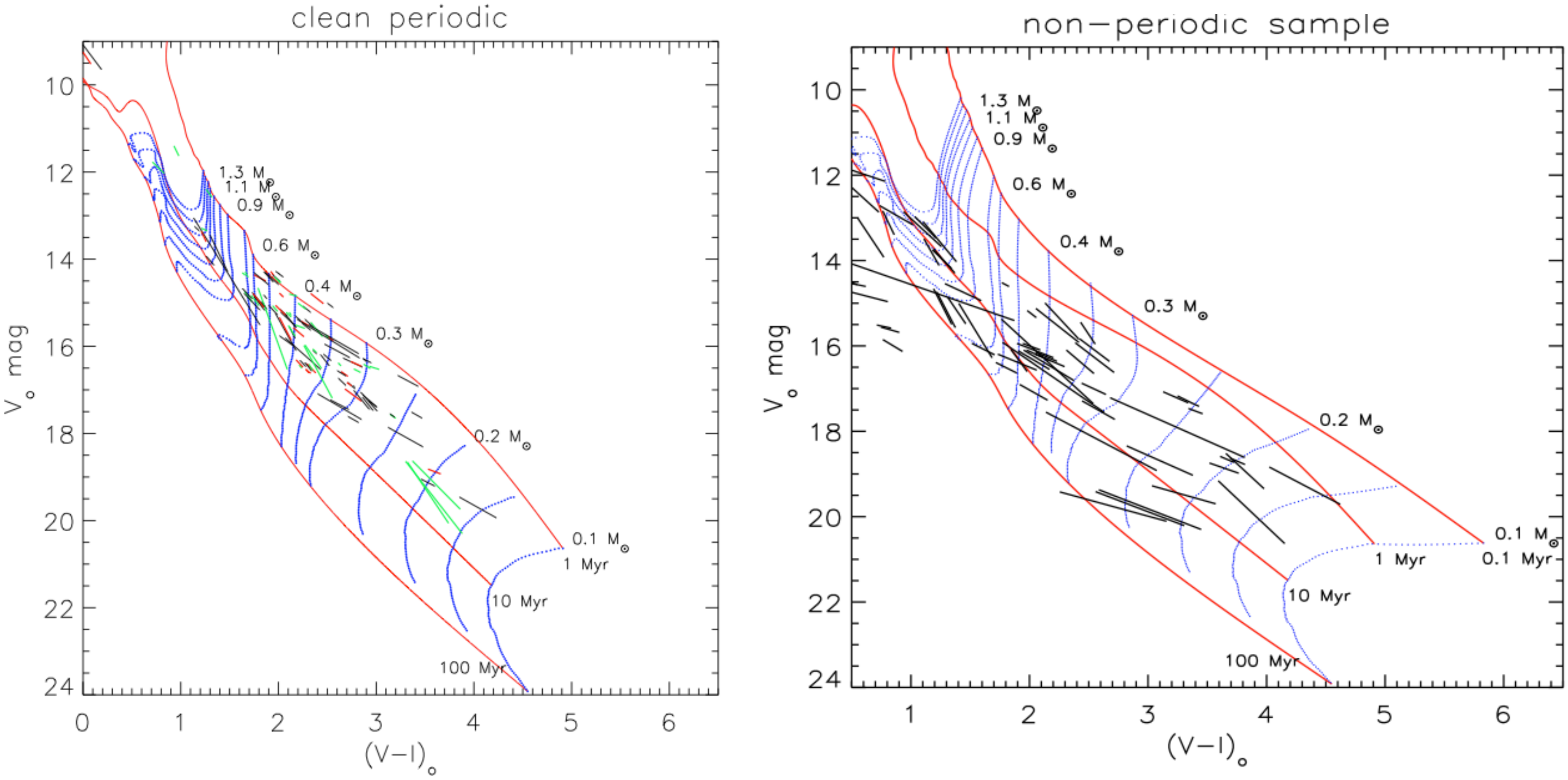


Hillenbrand et al. 2018, in preparation

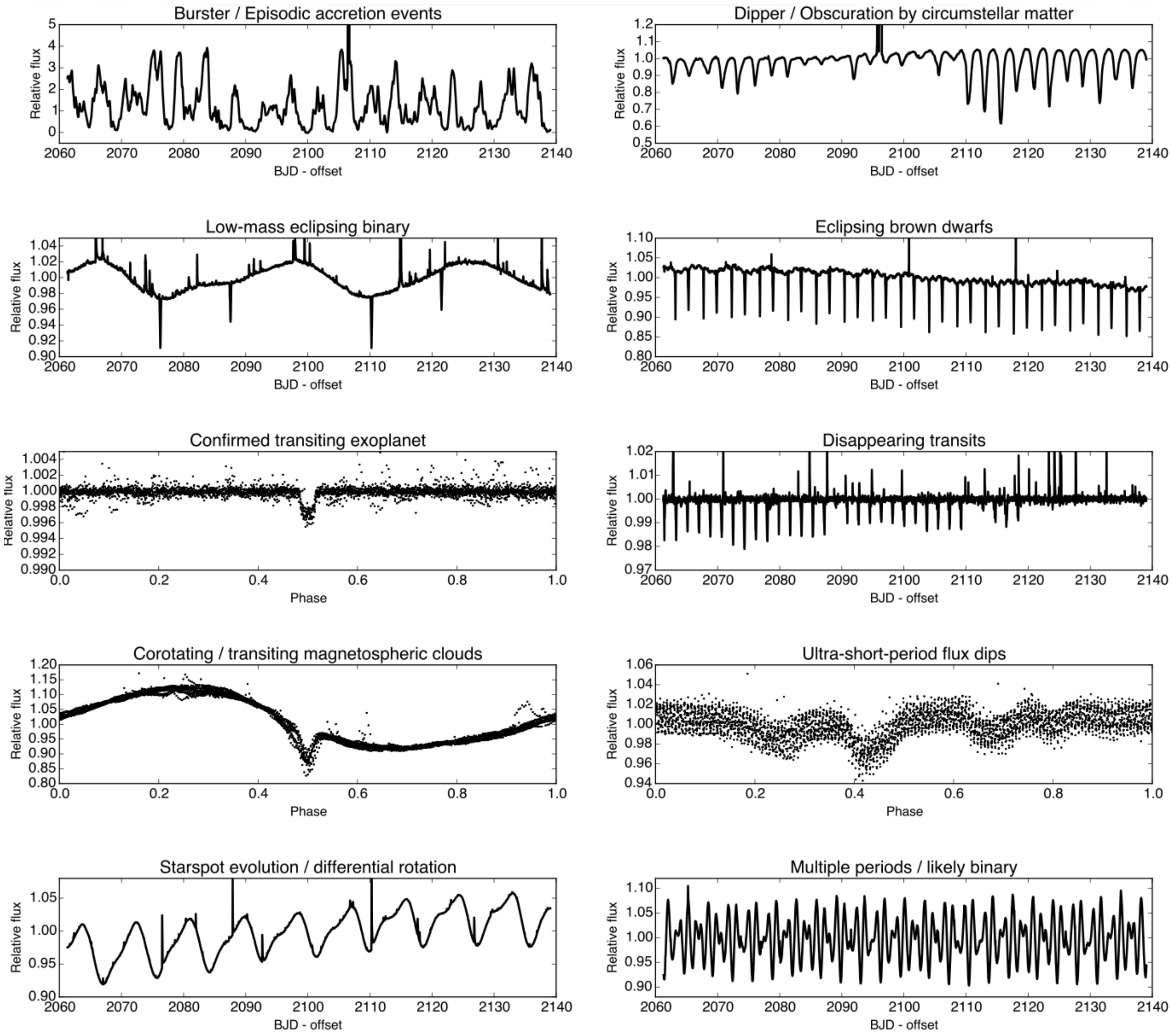
Figure 8. Dispersion in log $L/L_\odot$ with log T_{eff}. Pre-Gaia values are in the top panel, and post-Gaia values in the bottom. Although there is a reduction in the luminosity spreads when individual parallaxes are used, the luminosity spreads do not reach the maximum spread expected from propagation of various error sources (gold hatched region). The yellow hatched region extends to the maximum effect from equal-mass binaries.

Consideration of Variability Effects Reduces Luminosity Spreads

[*Messina et al. 2017*]



Lightcurve Gallery at 5-10 Myr



Burster / Episodic accretion events

Dipper / Obscuration by circumstellar matter

Low-mass eclipsing binary

Eclipsing brown dwarfs

Confirmed transiting exoplanet

Disappearing transits

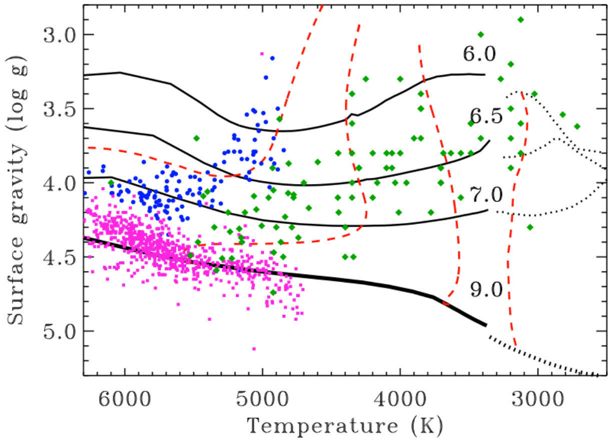
Corotating / transiting magnetospheric clouds

Ultra-short-period flux dips

Starspot evolution / differential rotation

Multiple periods / likely binary

Do Gravity Indicators Correlate with Luminosity Spreads?



IAU Symposium 258. Young Star Ages

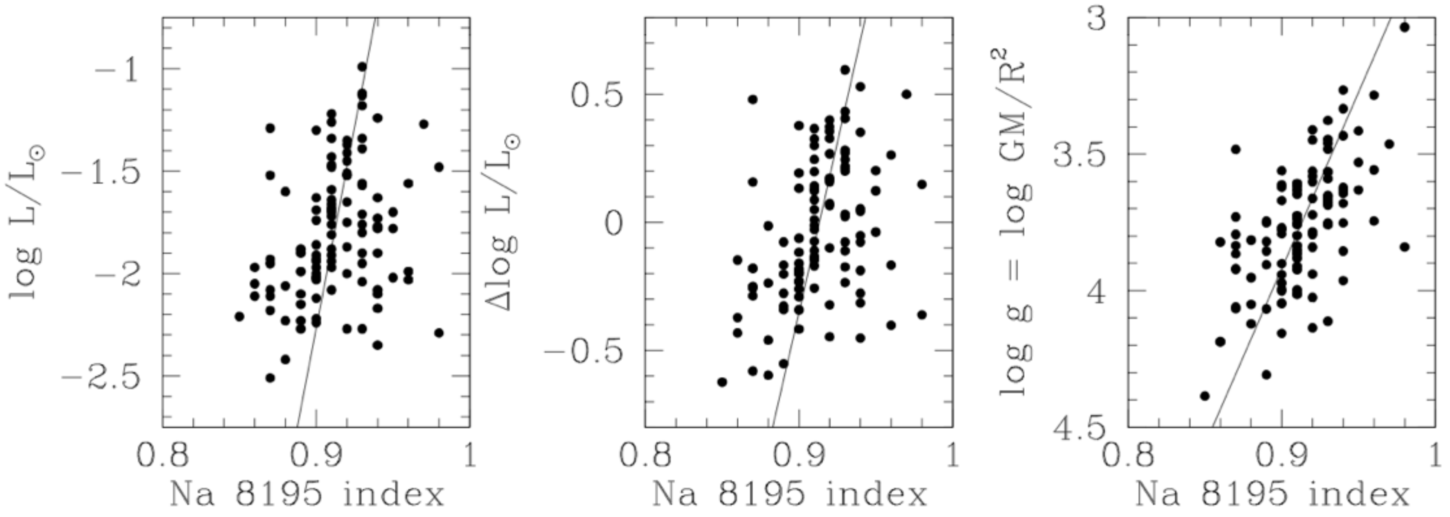


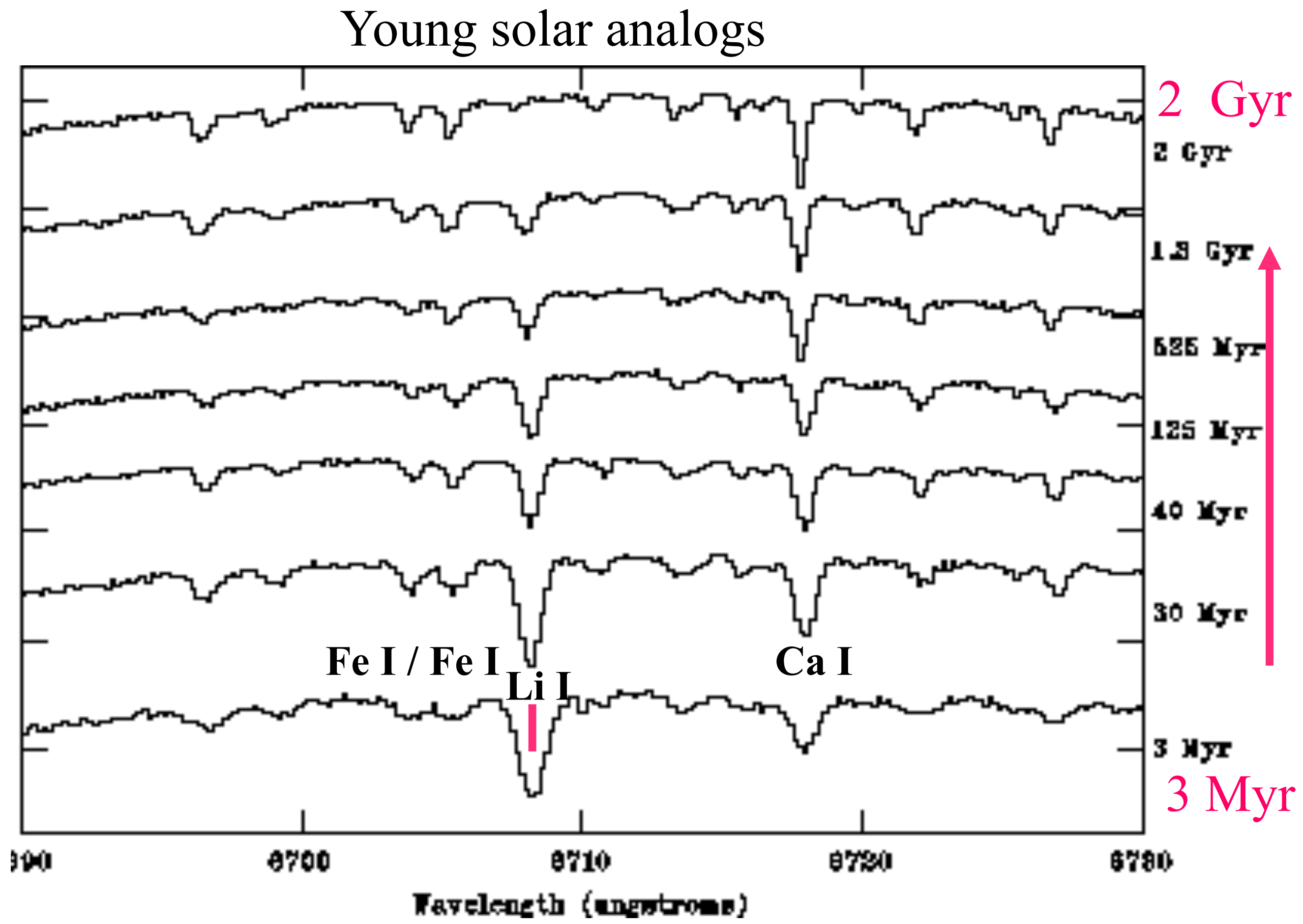
Figure 2. Based on data presented in Slesnick et al. (2008) for M4-M7 stars in the Upper Sco region. The left, middle, and right panels correlate log $L/L_\odot$ (stellar bolometric luminosity), Δlog $L/L_\odot$ (deviation from mean luminosity normalized to effective temperature), and log GM/R^2 (surface gravity) computed from the pre-main sequence log $L/L_\odot$ and log T_{eff} location in the HR diagram – all with the surface gravity sensitive Na I 8190 Å spectroscopic index defined by Slesnick et al. Correlation coefficients and the linear least squares fits are poor for the left and middle panels, but -0.6 (inversely correlated) in the right panel with 0.27 dex rms for the displayed fit of [log $g = (-12.9 \pm 0.7) \times NaI + (15.5 \pm 0.6)$].

[*Hillenbrand 2009*]

Meanwhile, FP was Pursuing Lithium Depletion

Li I absorption at 6707 A

decreases with stellar age.



Lithium Depletion in the ONC ?

Could be non-members, i.e foreground stars placed at the incorrect distance.

[*Palla et al. 2005*]

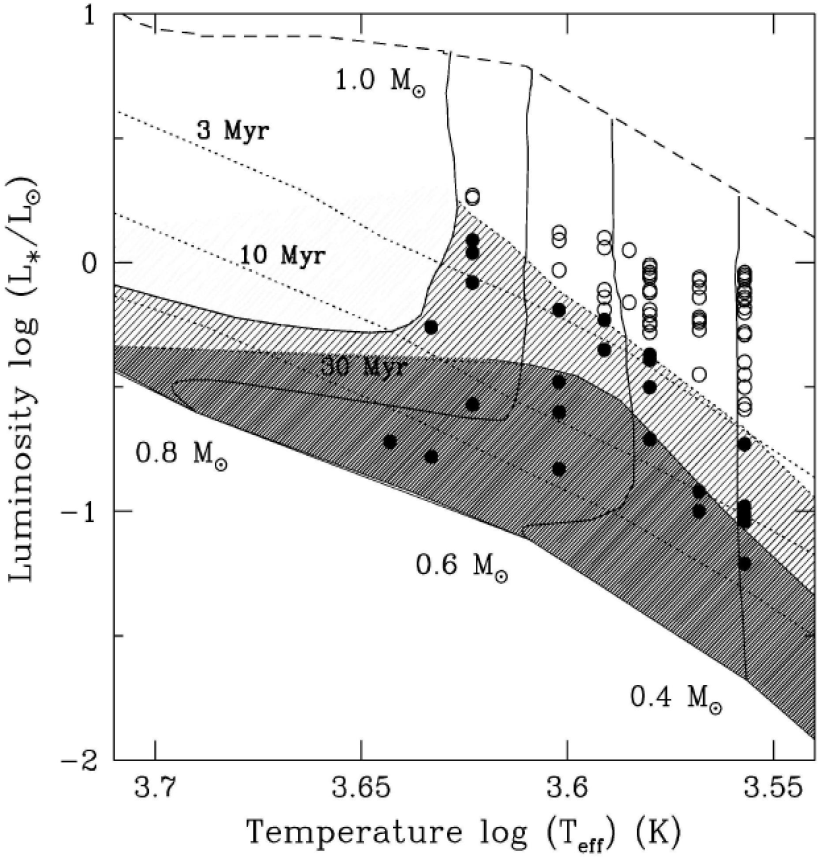
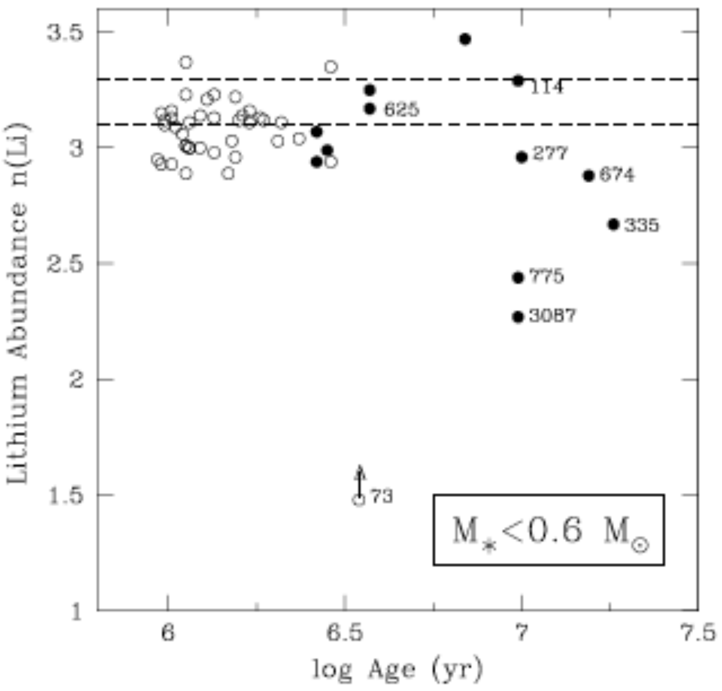


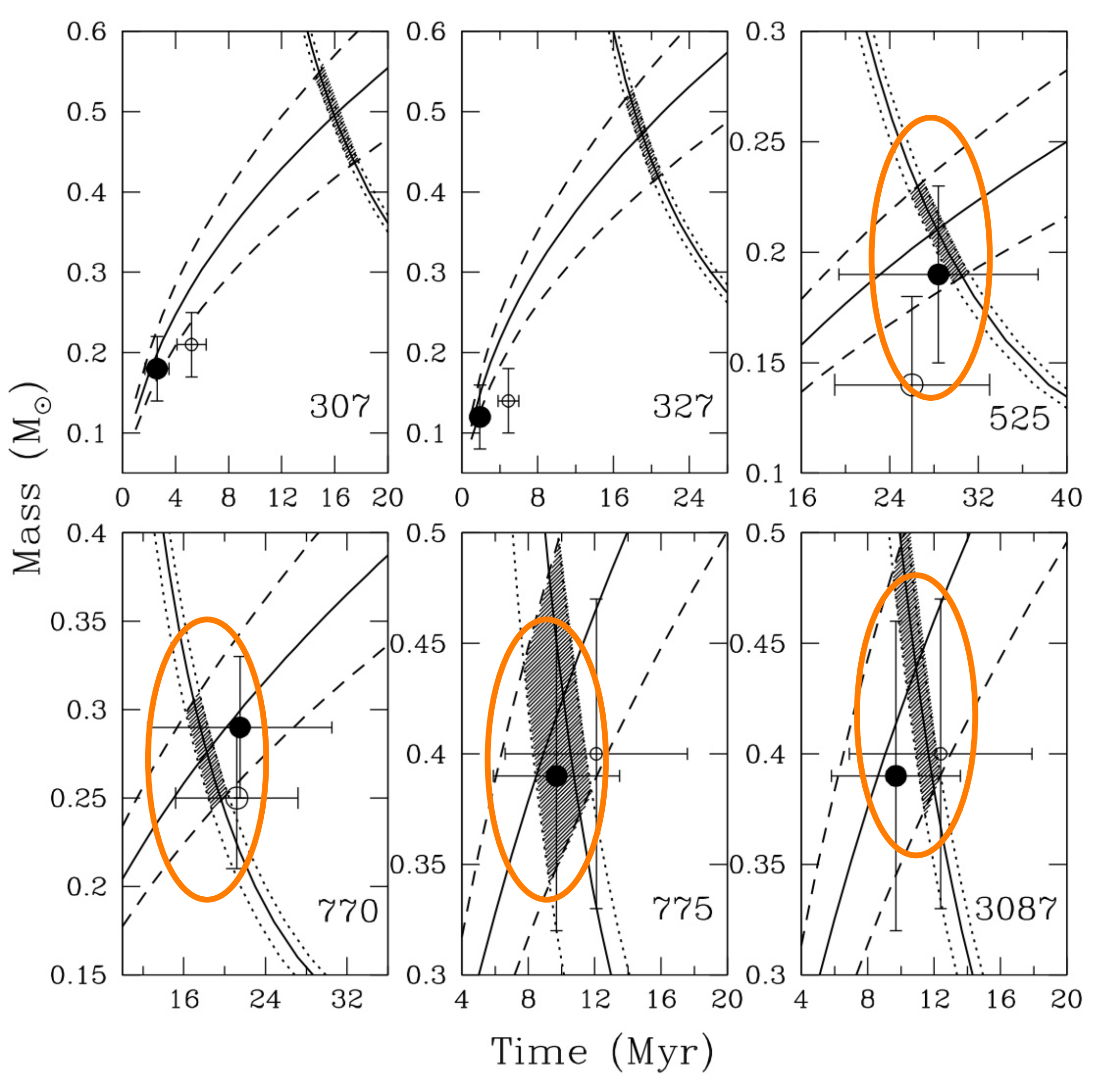
Fig. 1.— The distribution of the sample stars in the H-R diagram. The hatched regions indicate different levels of predicted Li depletion: up to a factor of ten (light grey) and more (dark grey) below the initial value according to the models of Siess et al. (2000). Selected masses and isochrones are indicated. Open and filled circles are for theoretically expected undepleted and depleted stars, respectively.



Comparing isochronal and Li-depletion ages

** FP's slide LAH was asked to present in 2008 **

PMS



6 stars - 4 stars:
M & age are fully consistent (5%!):

Li: $M \sim 0.43\ M_0$ $t \sim 12$ Myr
HR: $M \sim 0.39\ M_0$ $t \sim 10$Myr

Li: $M \sim 0.20\ M_0$ $t \sim 25$ Myr
HR: $M \sim 0.20\ M_0$ $t \sim 25$ Myr

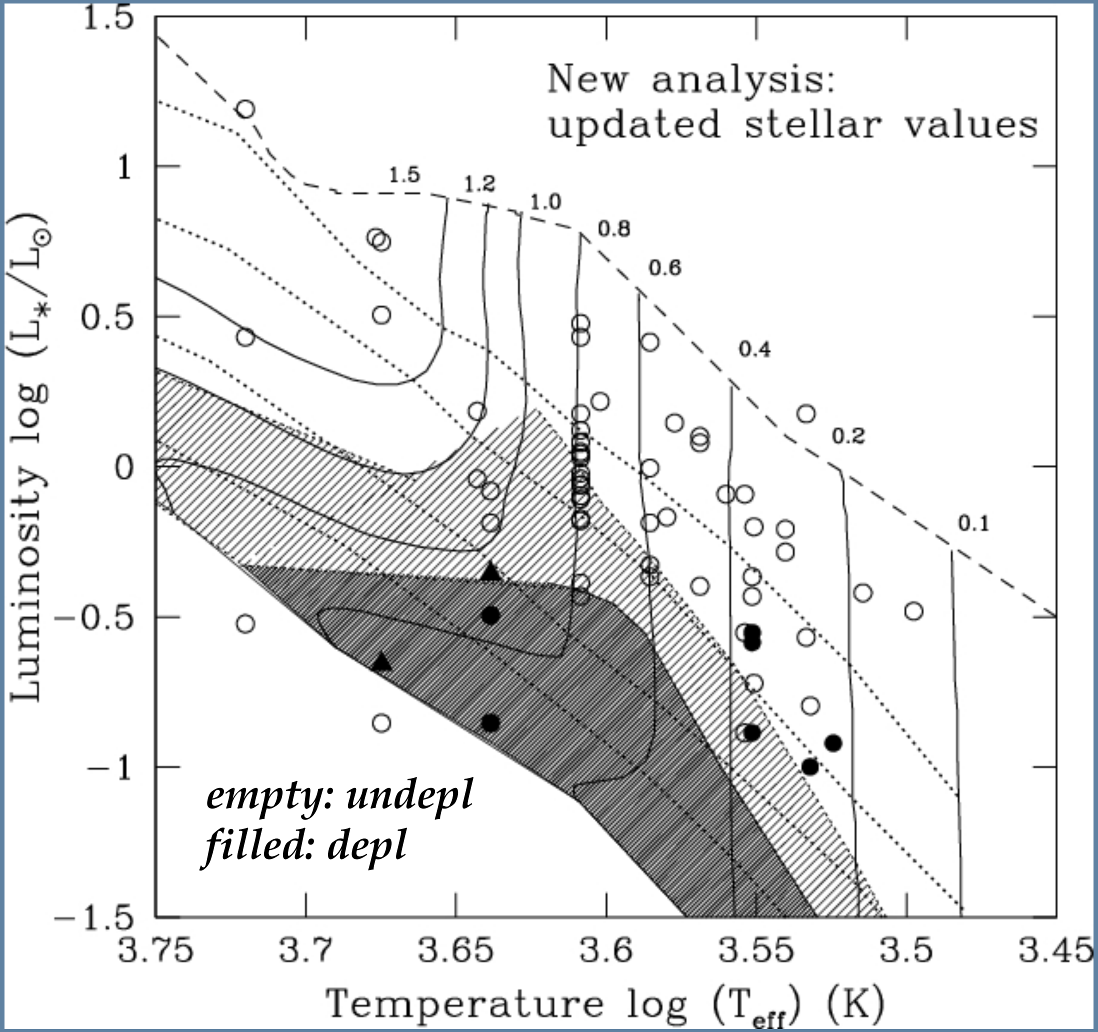
2 stars: inconsistency
$t_{HRD} < t_{Li}$

Orion Cluster did not form in a single, rapid burst…

Palla, Randich et al. 2005, 2007

Taurus-Auriga: older stars from Li-depleted stars

** FP's slide LAH was asked to present in 2008 **



Result:
most stars have n(Li)=initial consistent with HRD position

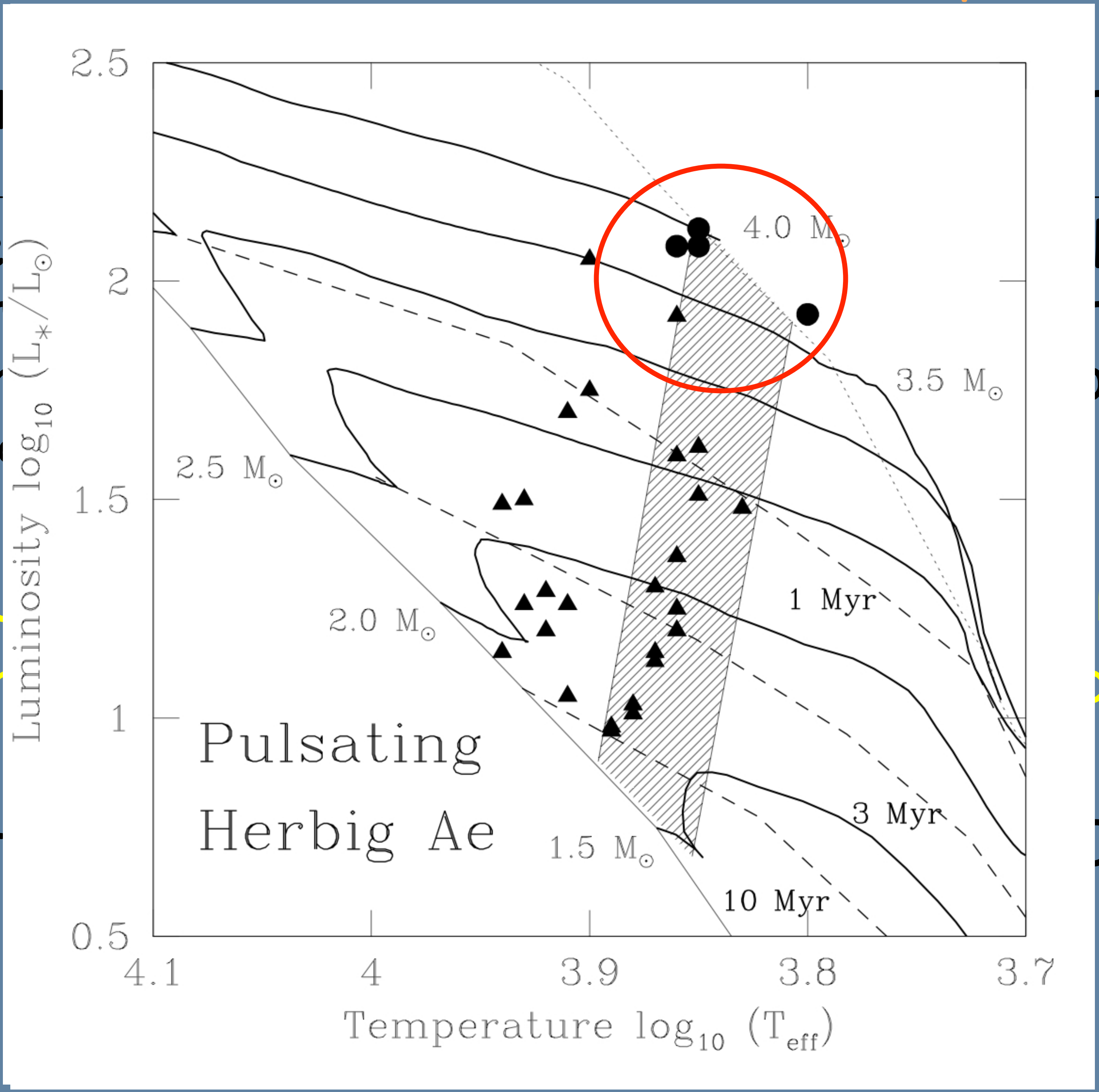
~10 Li-depleted stars approx. in the correct Li-depletion region

Also, case for St 34 from White & Hillenbrand 04

Sestito, Palla & Randich 2008 A&A

** FP's slide LAH was asked to present in 2008 **

Pu ars



Inte lity

str ars:

per des

(Marc 2007)

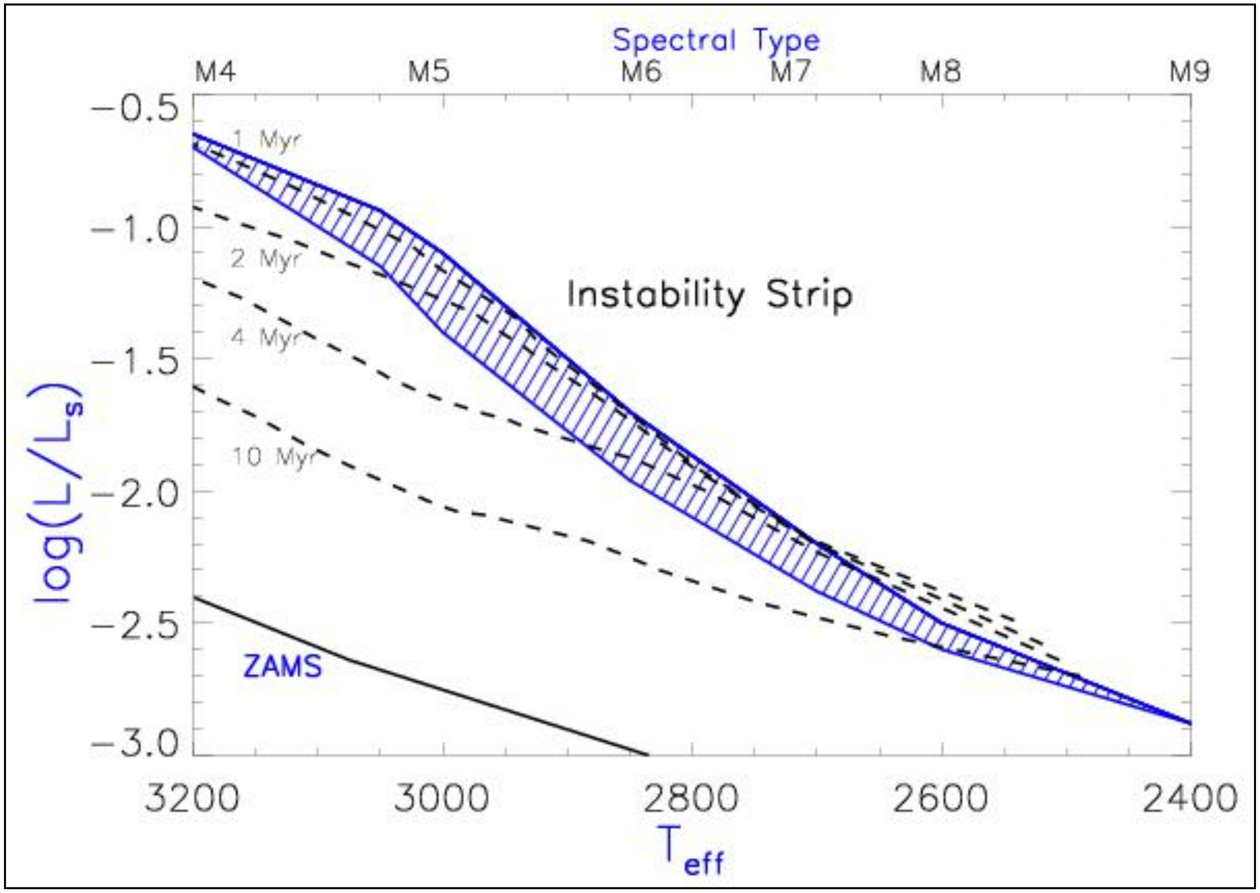
Uniqu re via

aster ditions

Plent ROT

(Ripepi

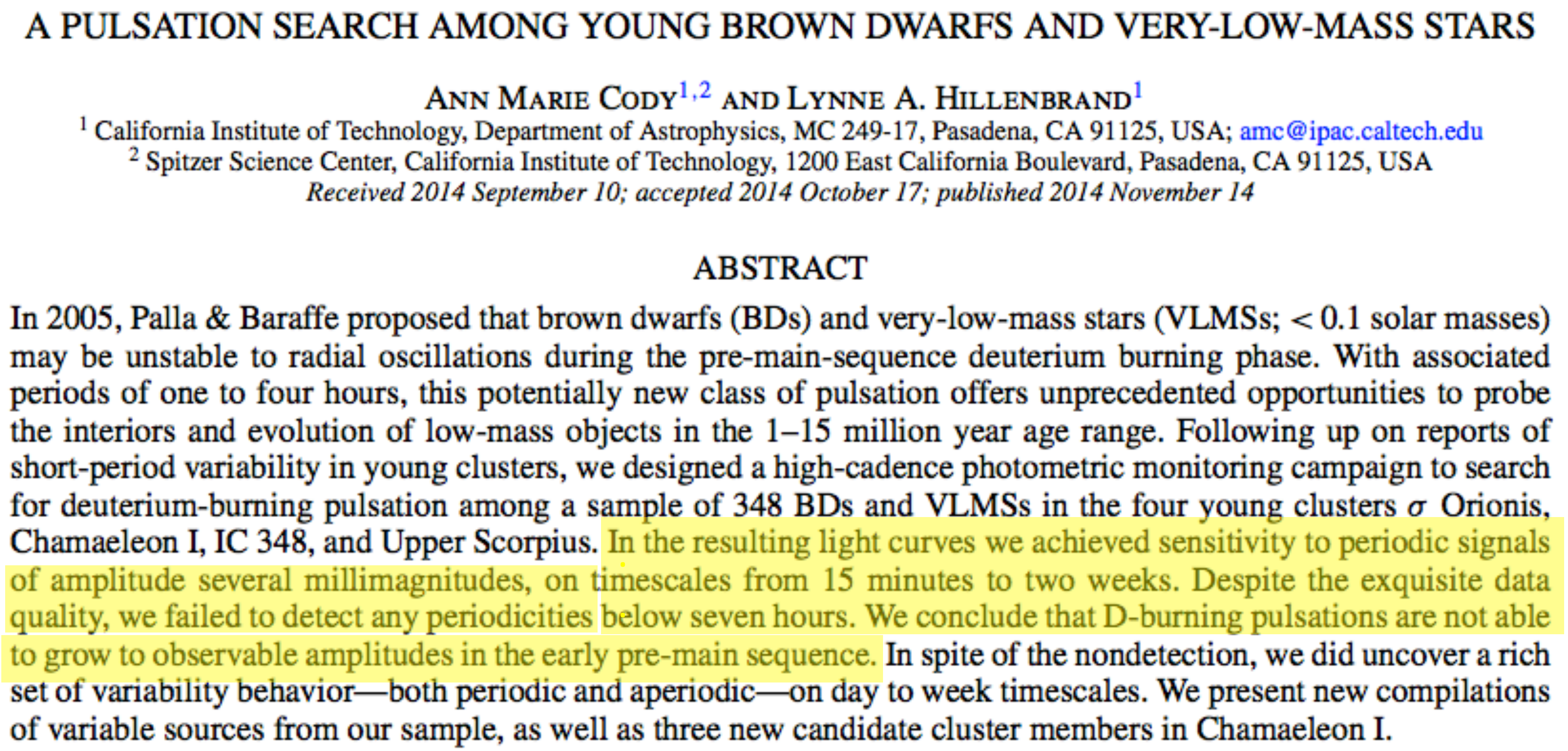
Pulsation in young brown dwarfs?



- Deuterium-burning objects predicted by Palla & Baraffe (2005) to pulsate at P=1-4 hr.
- Narrow instability strip offers strong age constraints -- if pulsators can be found.
- A.-M. Cody Ph.D. thesis based on testing P-B theory.
- Many young brown dwarfs located near the predicted instability strip.
- Campaign to monitor ~350 of them at high precision.

Pulsation in young brown dwarfs?

2014



A PULSATION SEARCH AMONG YOUNG BROWN DWARFS AND VERY-LOW-MASS STARS

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[1] California Institute of Technology, Department of Astrophysics, MC 249-17, Pasadena, CA 91125, USA; amc@ipac.caltech.edu
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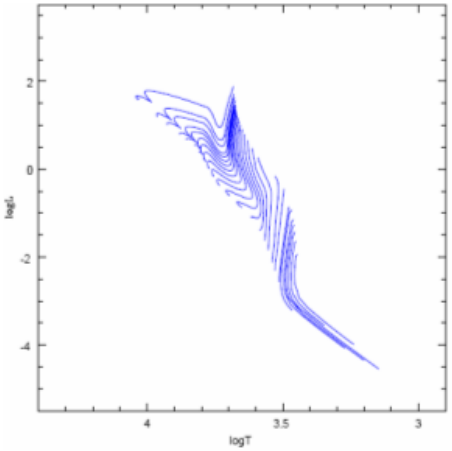
Received 2014 September 10; accepted 2014 October 17; published 2014 November 14

ABSTRACT

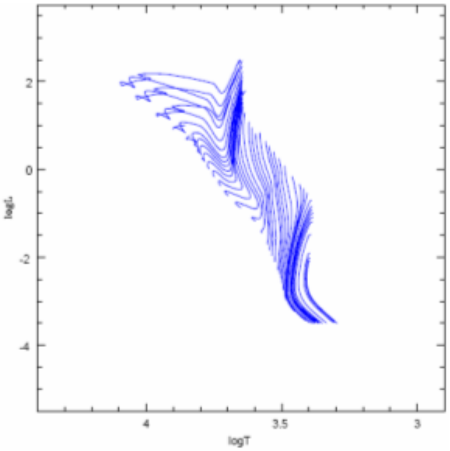
In 2005, Palla & Baraffe proposed that brown dwarfs (BDs) and very-low-mass stars (VLMSs; <0.1 solar masses) may be unstable to radial oscillations during the pre-main-sequence deuterium burning phase. With associated periods of one to four hours, this potentially new class of pulsation offers unprecedented opportunities to probe the interiors and evolution of low-mass objects in the 1–15 million year age range. Following up on reports of short-period variability in young clusters, we designed a high-cadence photometric monitoring campaign to search for deuterium-burning pulsation among a sample of 348 BDs and VLMSs in the four young clusters σ Orionis, Chamaeleon I, IC 348, and Upper Scorpius. In the resulting light curves we achieved sensitivity to periodic signals of amplitude several millimagnitudes, on timescales from 15 minutes to two weeks. Despite the exquisite data quality, we failed to detect any periodicities below seven hours. We conclude that D-burning pulsations are not able to grow to observable amplitudes in the early pre-main sequence. In spite of the nondetection, we did uncover a rich set of variability behavior—both periodic and aperiodic—on day to week timescales. We present new compilations of variable sources from our sample, as well as three new candidate cluster members in Chamaeleon I.

Could still be there, but either: lower amplitude than a few mmag, or unexpectedly damped by convection.

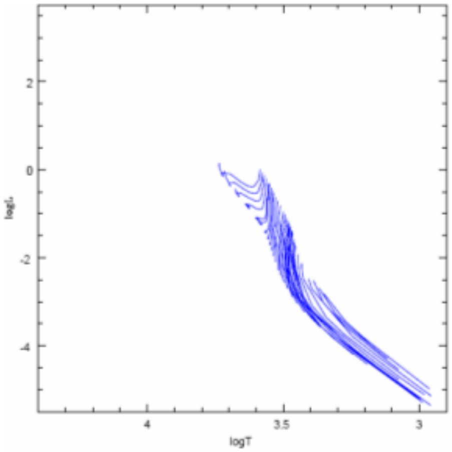
Different Theoretical Models / Tracks



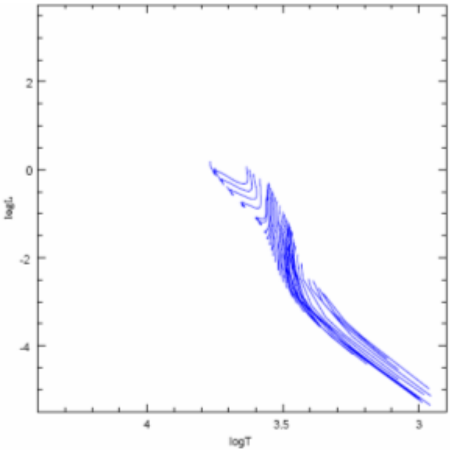
D'Antona and Mazitelli 1994



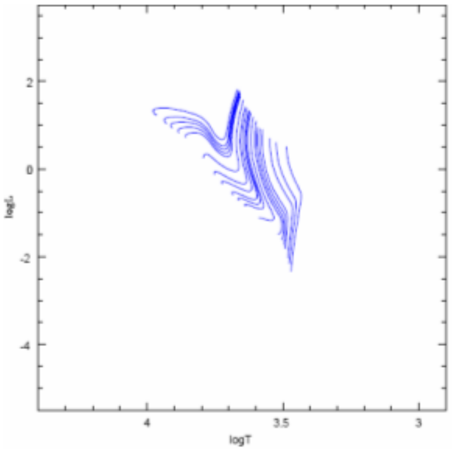
D'Antona and Maziltelli 1998



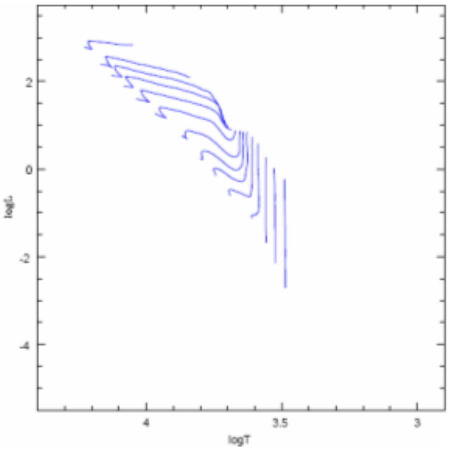
Baraffe et al. 1998 α =1.0



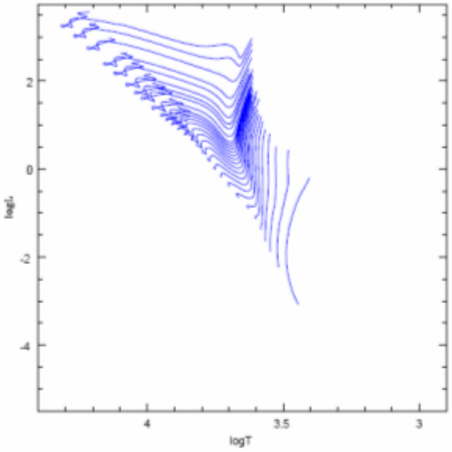
Baraffe et al. 1998 α =1.9



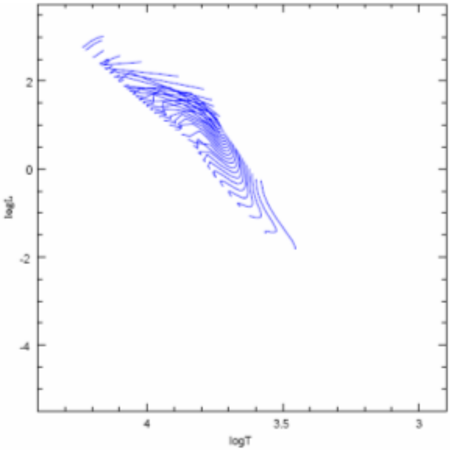
Swenson et al. 1994



Palla and Stahler 1998



Siess et al. 2000



Yi et al. 2002

Popular models

Baraffe & Chabrier +
1997, 1998…

Siess 2000

D'Antona & Mazzitelli
1994, 1997, 1998…

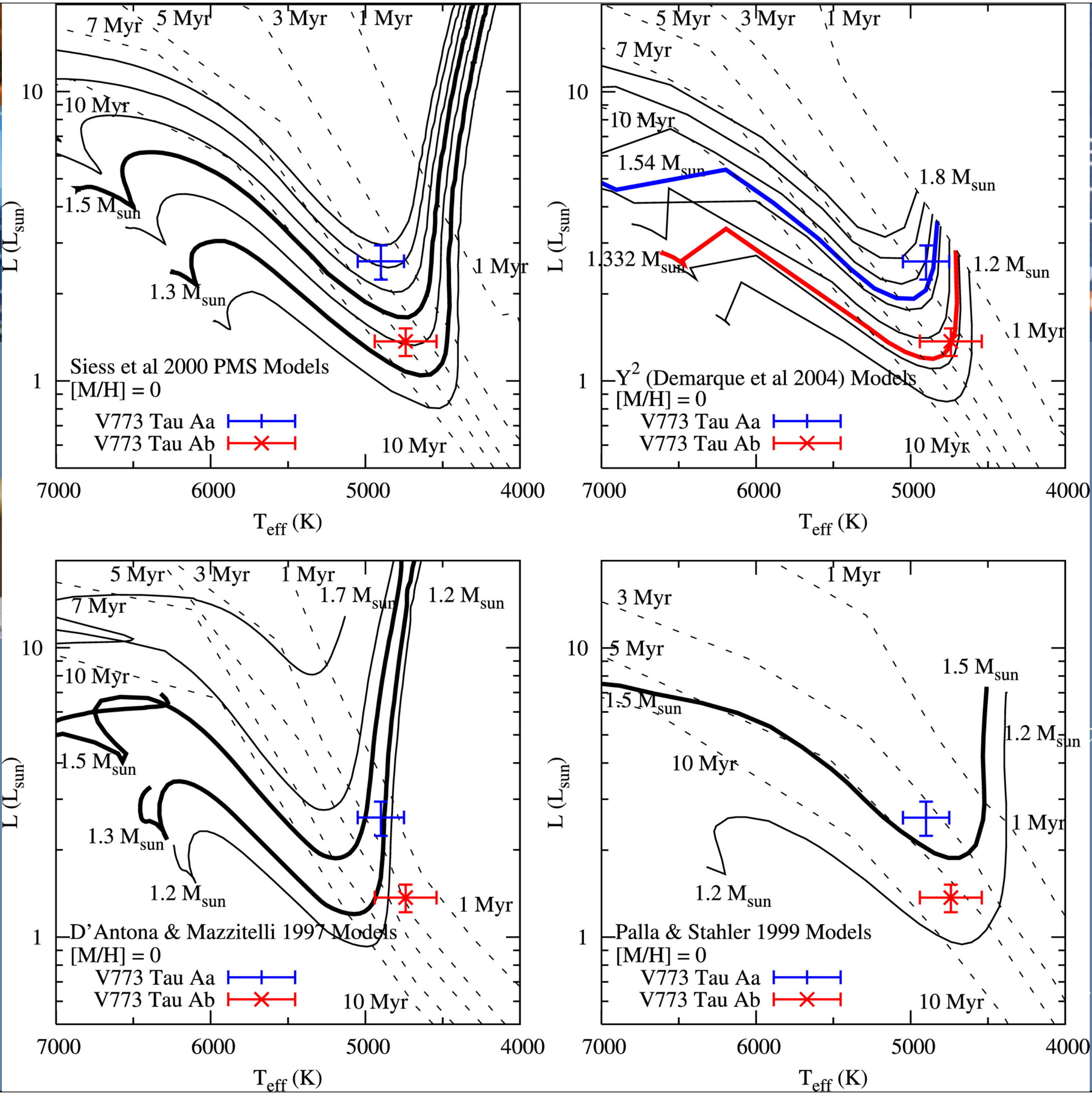
Palla & Sthaler
1993, 1999

Demarque Y^2
2001, 2002,2004…

** FP's slide LAH was asked to present in 2008 **


IAU


2008
M 258
d, USA


7 Myr
5 Myr
3 Myr
1 Myr
10 Myr
1.5 M_{sun}
1.3 M_{sun}
1 Myr
Siess et al 2000 PMS Models
[M/H] = 0
V773 Tau Aa
V773 Tau Ab
10 Myr
L (L_{sun})
T_{eff} (K)
7000
6000
5000
4000
10
1
5 Myr
3 Myr
1 Myr
7 Myr
10 Myr
1.54 M_{sun}
1.8 M_{sun}
1.332 M_{sun}
1.2 M_{sun}
1 Myr
Y^2 (Demarque et al 2004) Models
[M/H] = 0
V773 Tau Aa
V773 Tau Ab
10 Myr
5 Myr
3 Myr
1 Myr
1.7 M_{sun}
1.2 M_{sun}
7 Myr
10 Myr
1.5 M_{sun}
1.3 M_{sun}
1.2 M_{sun}
1 Myr
D'Antona & Mazzitelli 1997 Models
[M/H] = 0
V773 Tau Aa
V773 Tau Ab
10 Myr
1 Myr
3 Myr
5 Myr
1.5 M_{sun}
1.5 M_{sun}
1.2 M_{sun}
10 Myr
1 Myr
1.2 M_{sun}
Palla & Stahler 1999 Models
[M/H] = 0
V773 Tau Aa
V773 Tau Ab
10 Myr

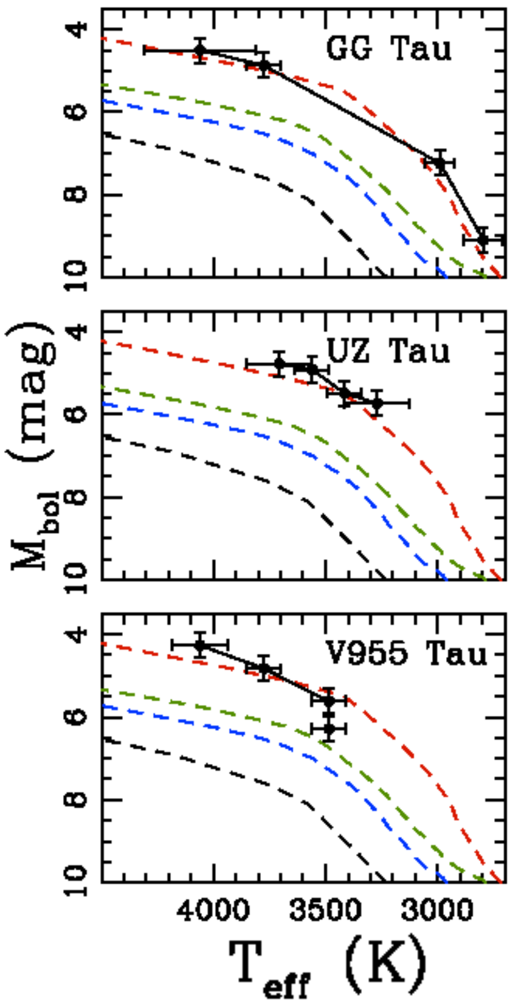
aler

…

Isochrones and Stellar Multiplicity

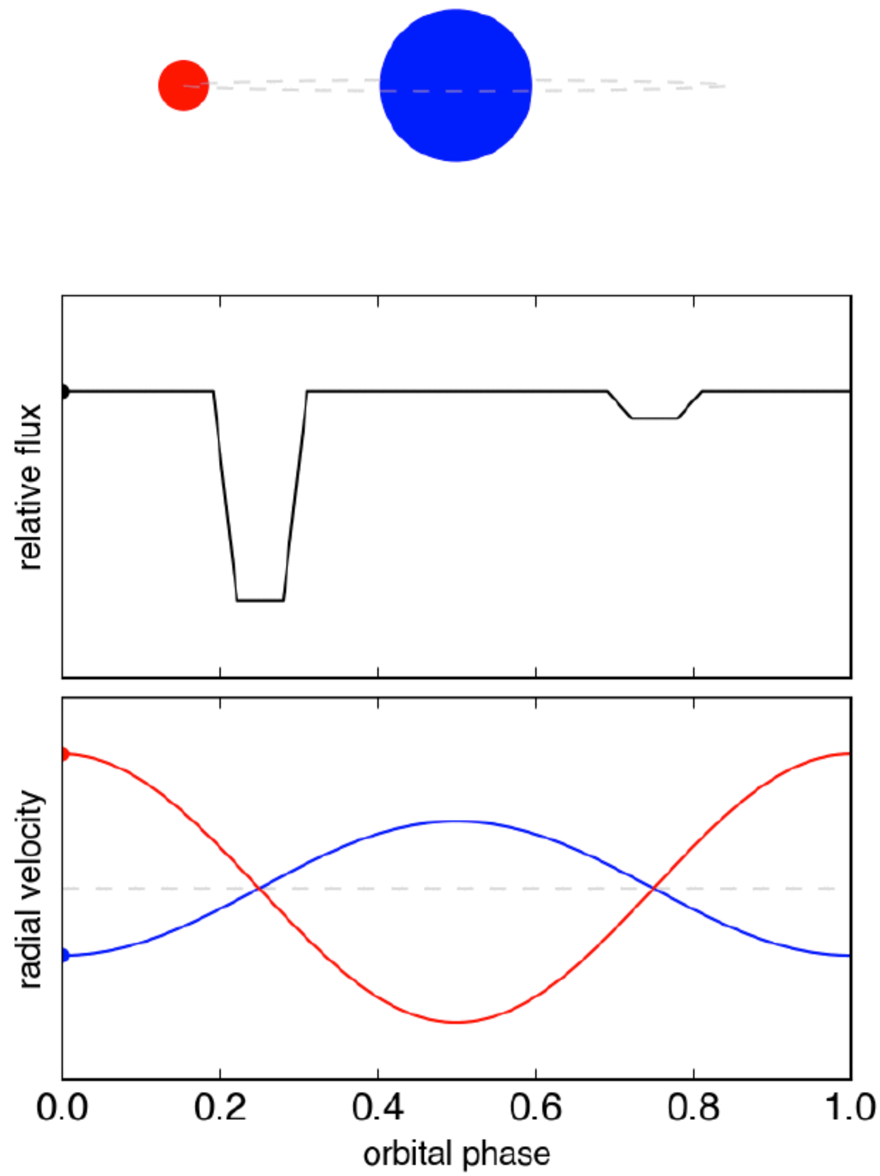
- Using standard HR diagram methods, binaries and higher order multiples are more coeval than random pairs

- Previous work:
  - Hartigan, Strom, Strom (1993)
  - White et al. (1999)



Kraus & Hillenbrand 2007

double-lined eclipsing binaries



$P, T_0, i, e, \omega, (R_1+R_2)/a, R_2/R_1$

$+$

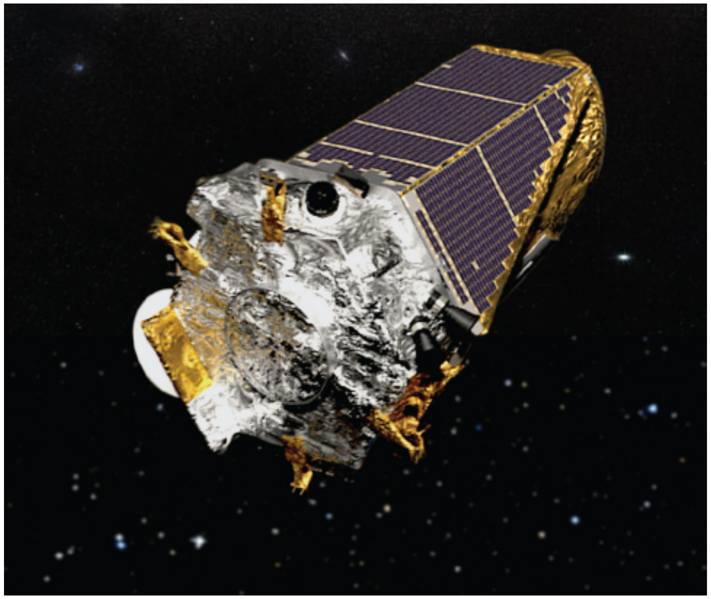
$P, T_0, i, e, \omega, M_1+M_2, a$

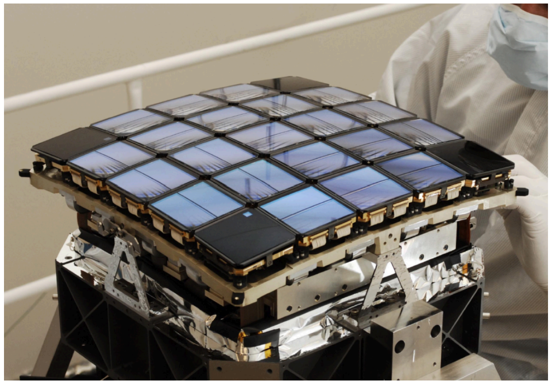
$\downarrow$

M_1, M_2, R_1, R_2

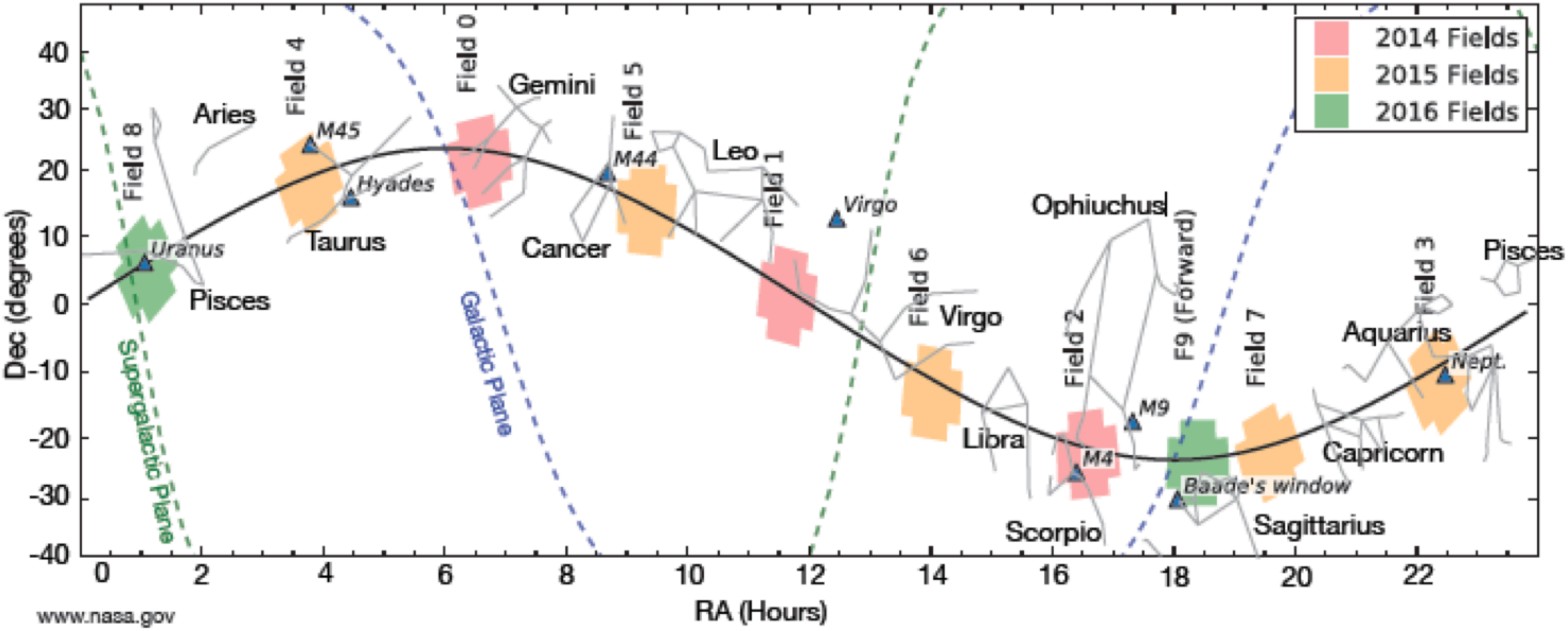
slide courtesy of T. David

Kepler/K2 to the Rescue



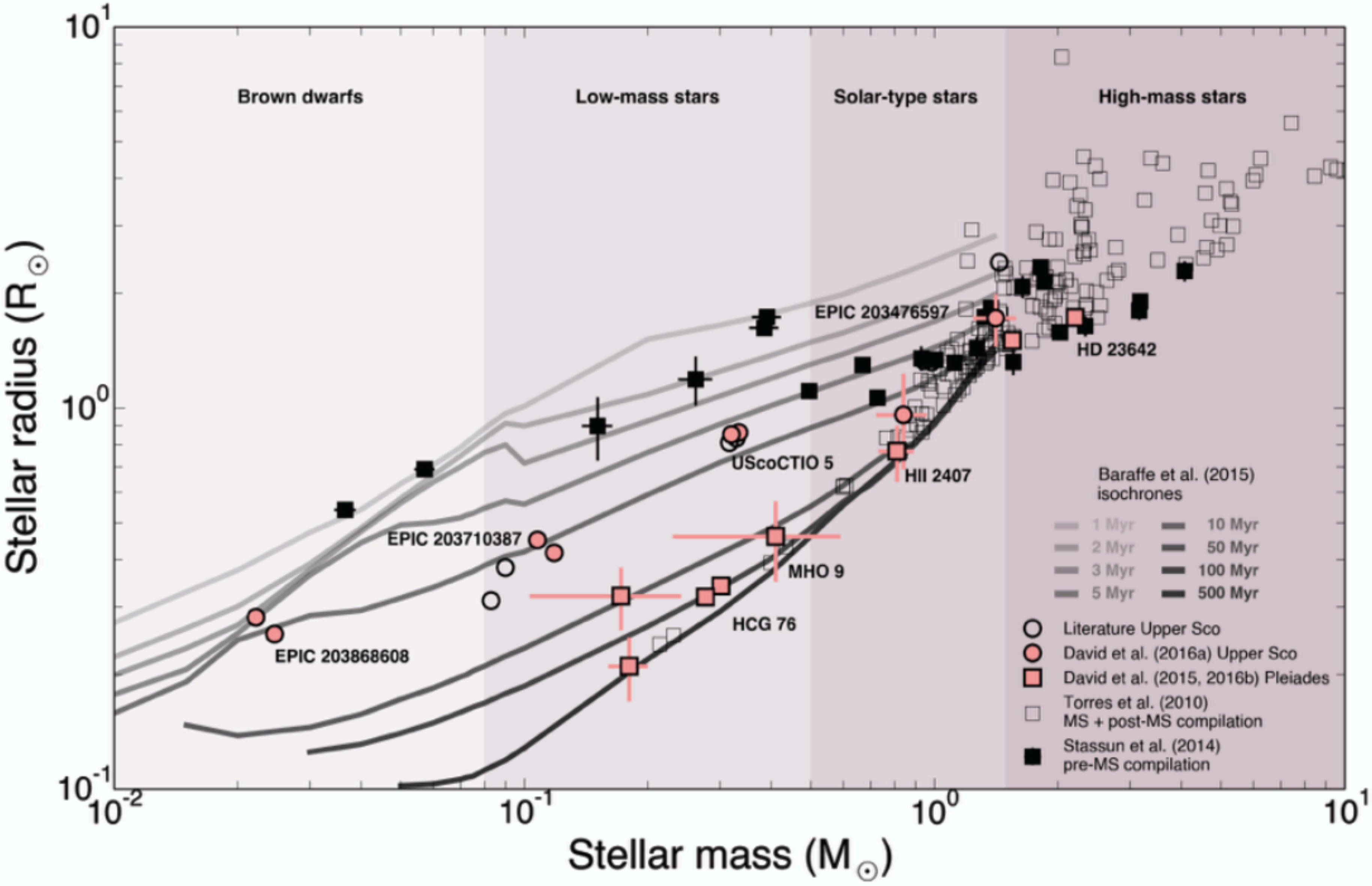


~100 deg^2 FOV!



www.nasa.gov

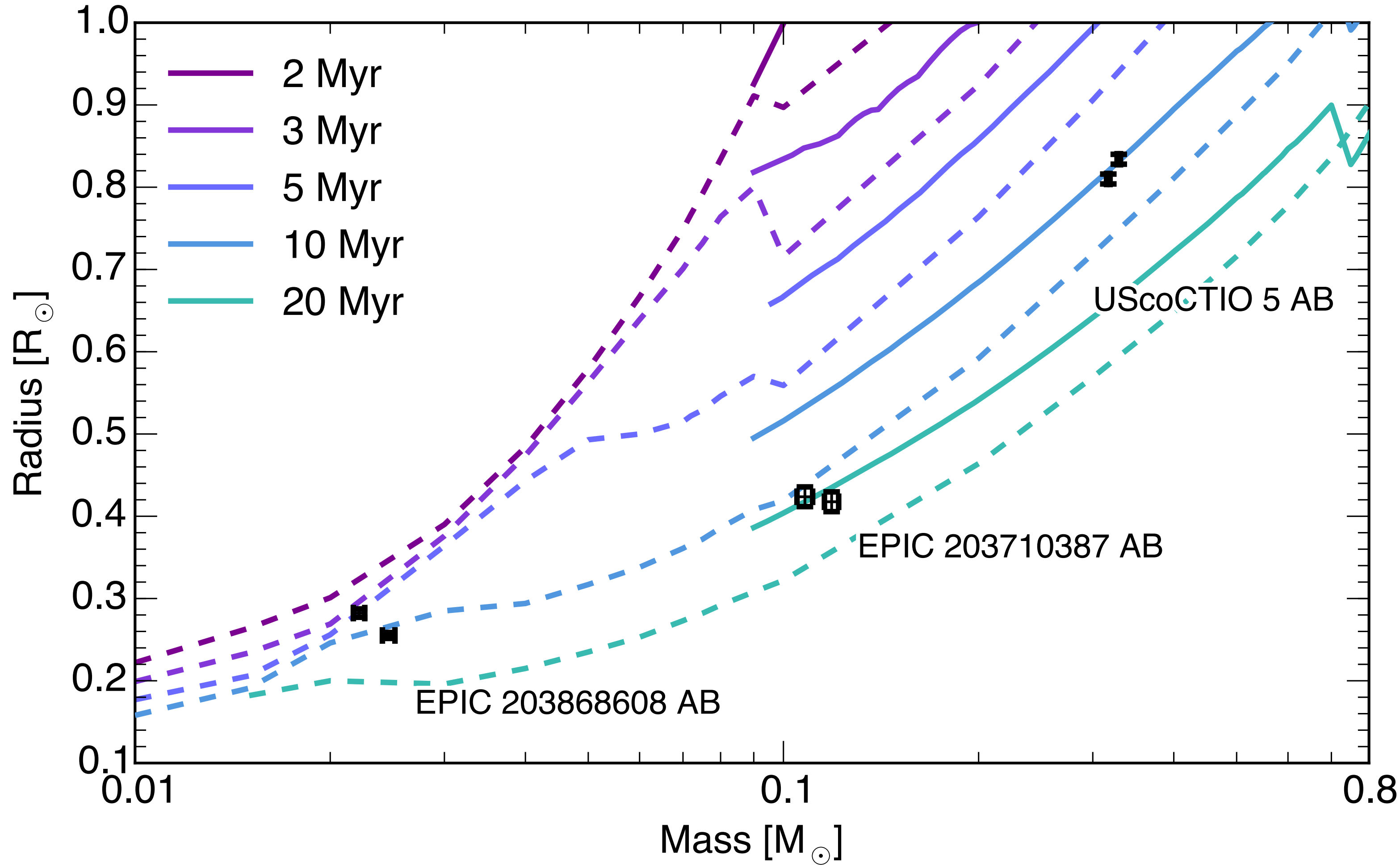
Low-mass eclipsing binaries are rare



[Trevor David, Ph.D. Thesis, 2017]

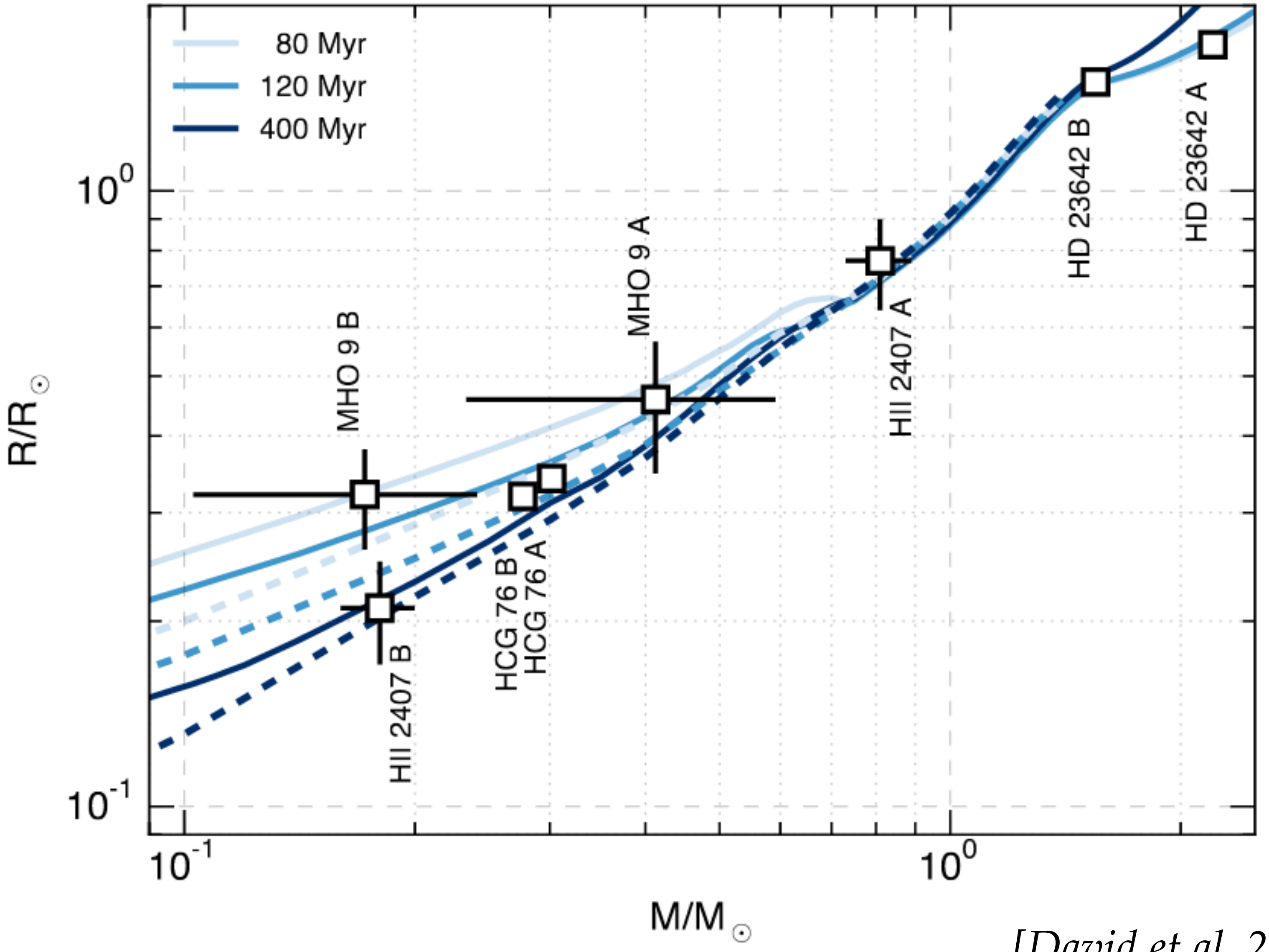
Upper Sco DLEBs: From None to Five

PARSEC (solid)
Baraffe (dashed)



[David et al. 2016a]

Pleiades DLEBs: From One to Four



[David et al. 2015, 2016]

Praesepe DLEBs: From None to 3-1/2

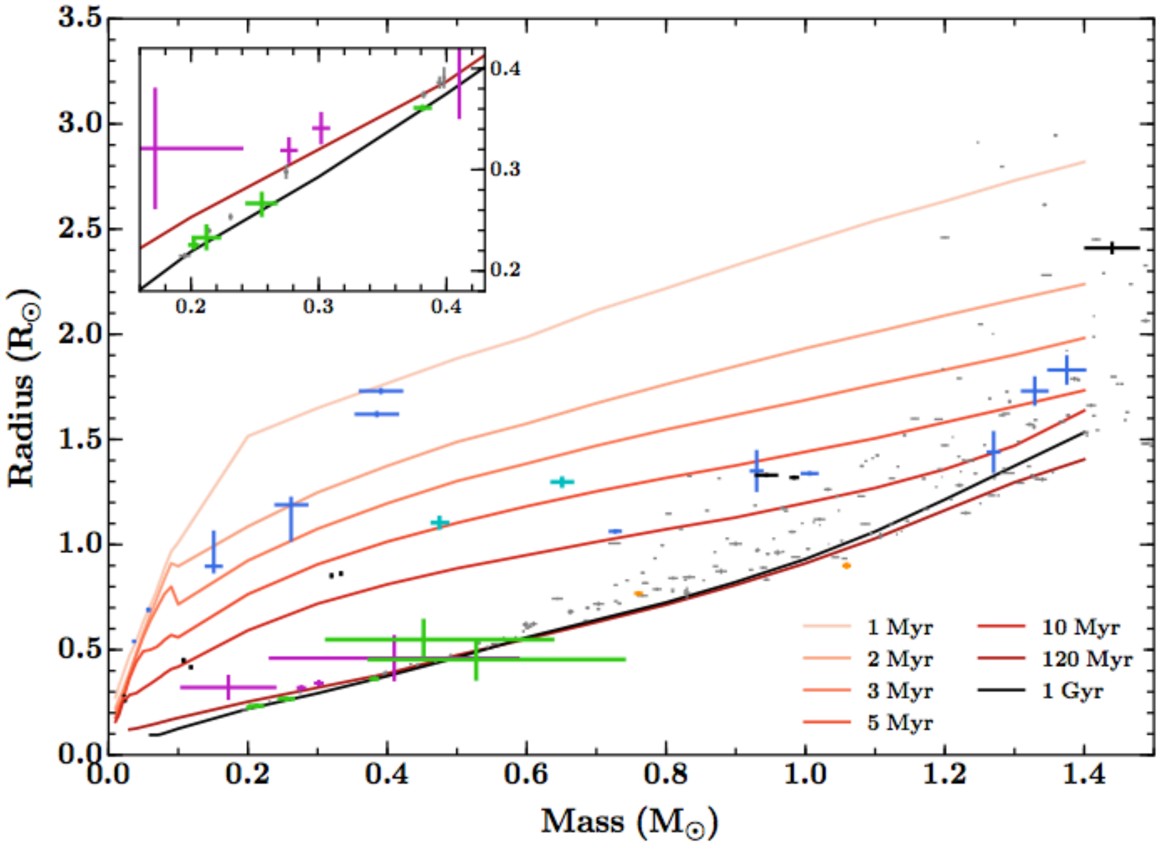


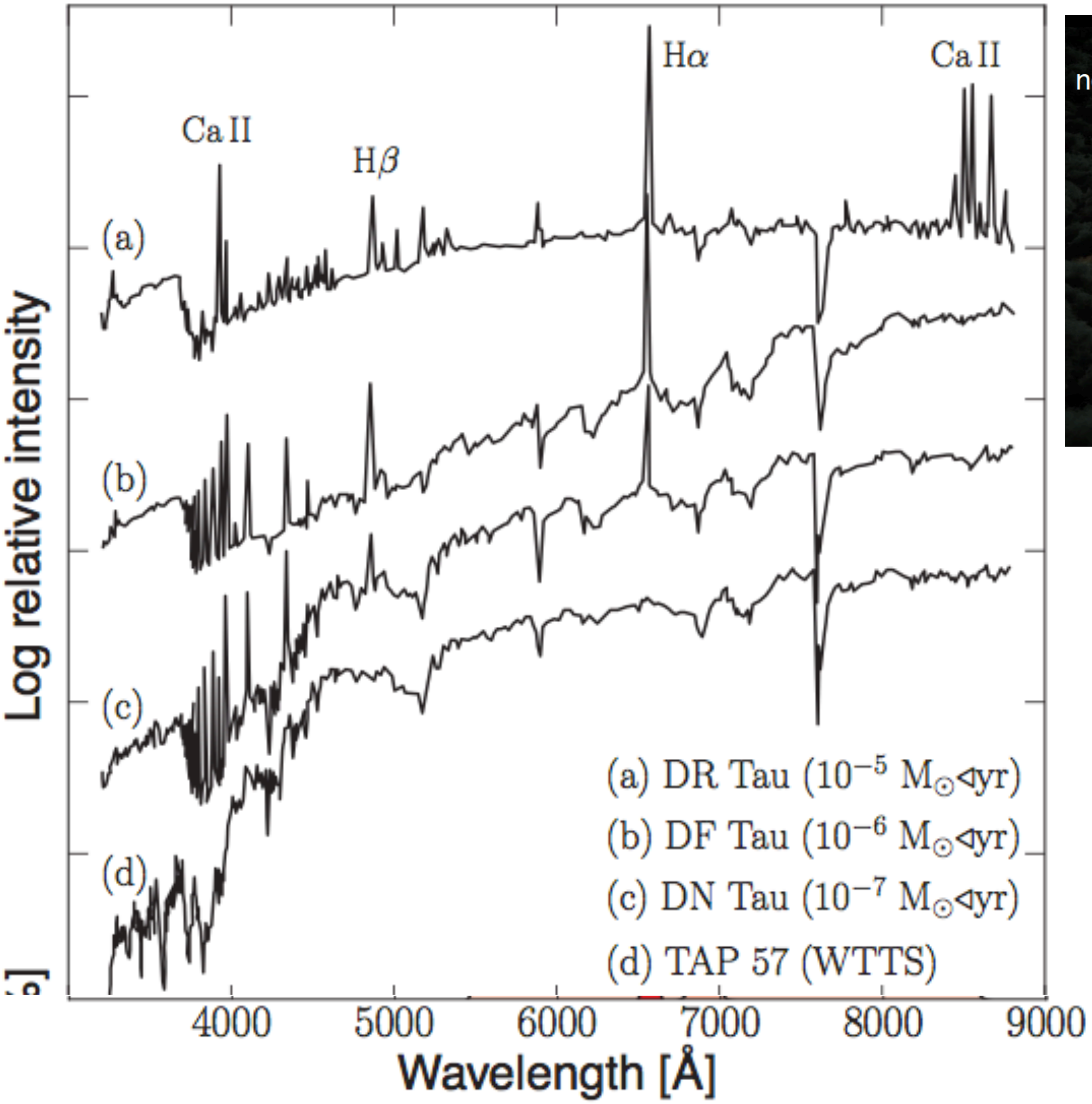
Figure 6. Mass-radius relation for detached double-lined eclipsing binaries (EBs) below 1.5 $M_\odot$. Data compiled from Table 4 and DEBCat (http://www.astro.keele.ac.uk/~jkt/debdata/debs.html). EBs that are members of open clusters are coloured while field EBs are shown in grey. The clusters containing known EBs are Orion (blue), Upper Scorpius (black), NGC2264 (cyan), Pleiades (magenta), Hyades (orange) and the new Praesepe EBs (green) presented here. The coloured lines represent solar metallicity isochrones of Baraffe et al. (2015) from 1 Myr to 1 Gyr (*top* to *bottom*). Inset (*top left*) is a zoom on the region containing ADs 3814 and 2615 to allow a closer comparison between the models and current observational constraints for low-mass stars.

[Gillen et al. 2017]

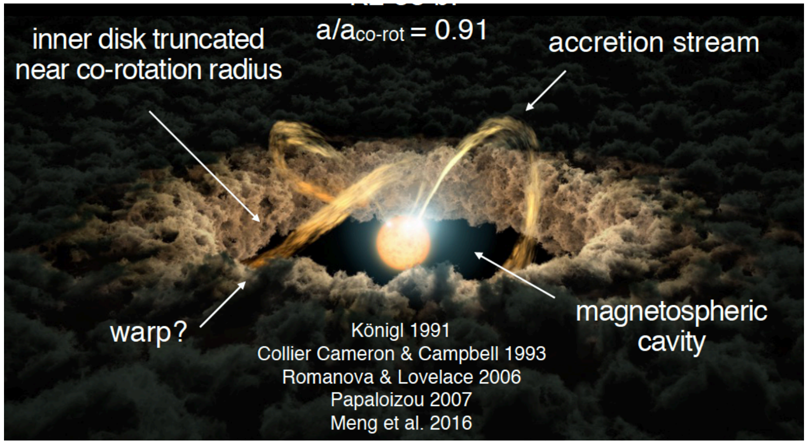
Characteristics of Youth

- Active and variable / moody
- (Believe that) everything orbits them
- Still gaining mass
- Can oscillate between steady low state and more punctuated episodes of rapid accretion.
- Prone to instabilities, outbursts and outflows
- Sometimes long term depressive states
- Obscured (or at least obscure)
- Hard to figure out!

LHillenbrand inspired by GHerczeg



Barensten et al. 2013



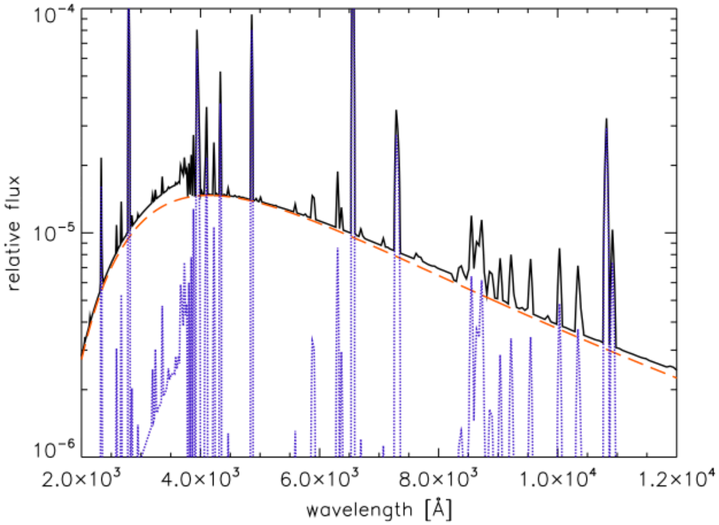
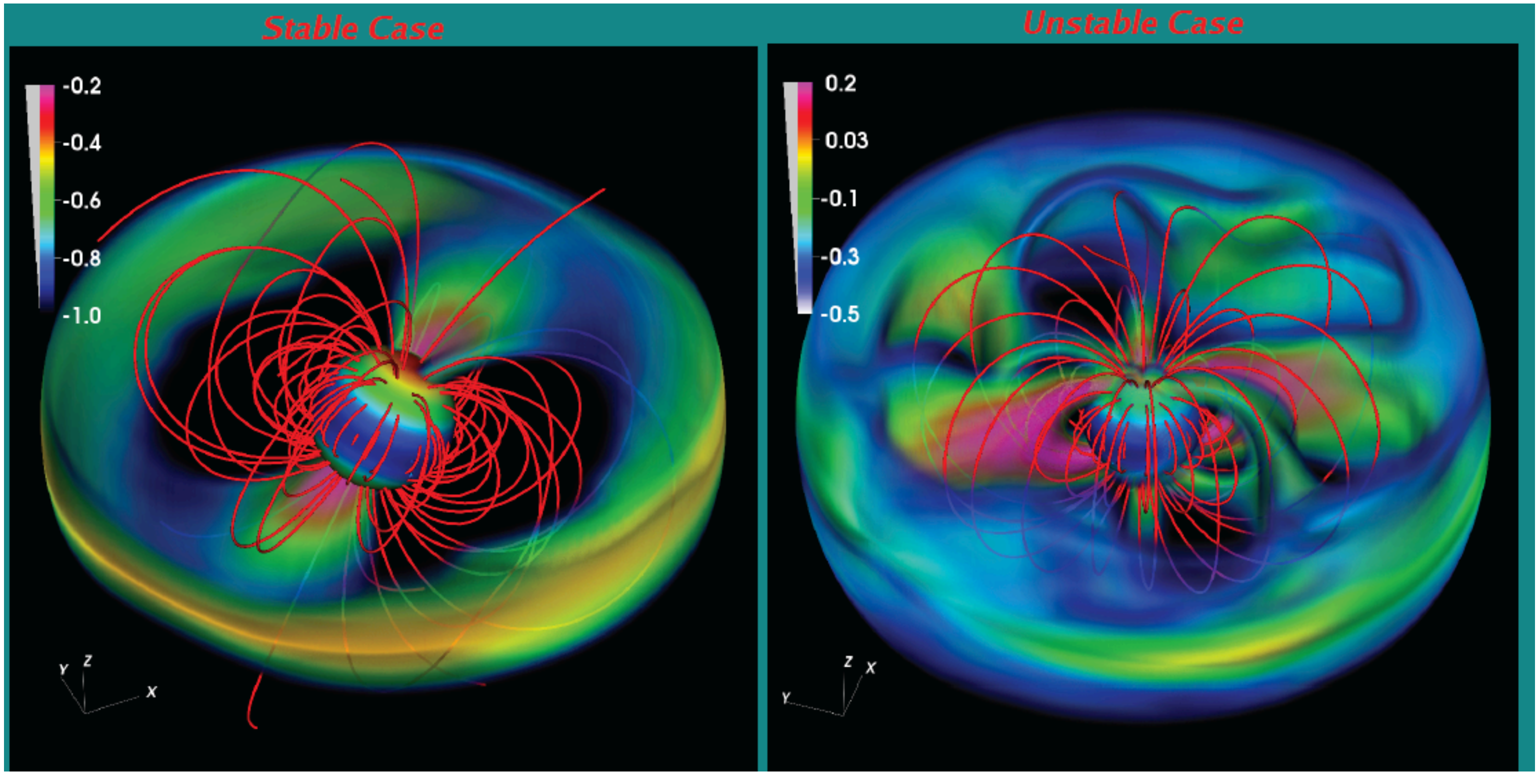


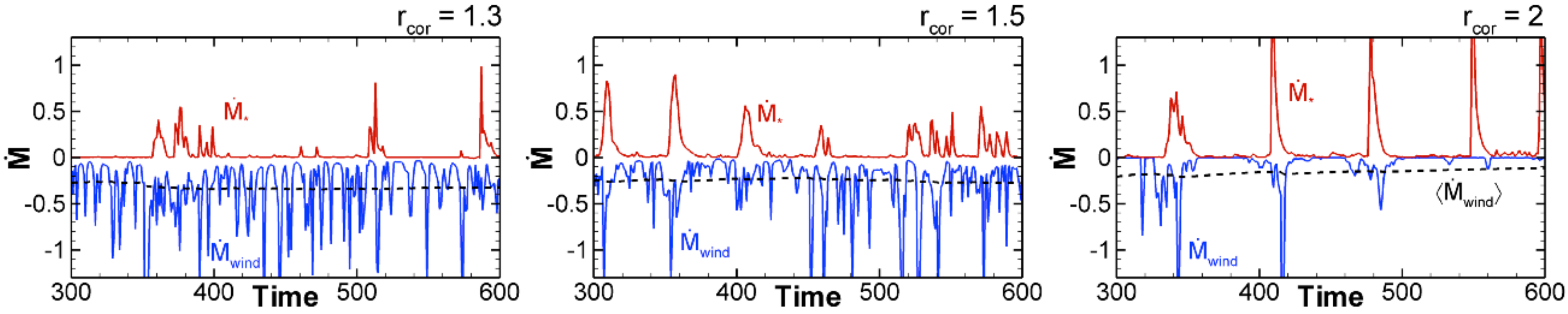
Figure 7. Accretion spectrum simulated with Cloudy. The solid line is the total emission, which is the superposition of an optically thick emission, with $T_{\rm eff} = 7000$ K, of the heated photosphere (dashed line) and the optically thin emission of ionized gas with density $n = 10^8$ cm^{-3} (dotted line).

Da Rio et al. 2010

How Does Gas get to the Star?



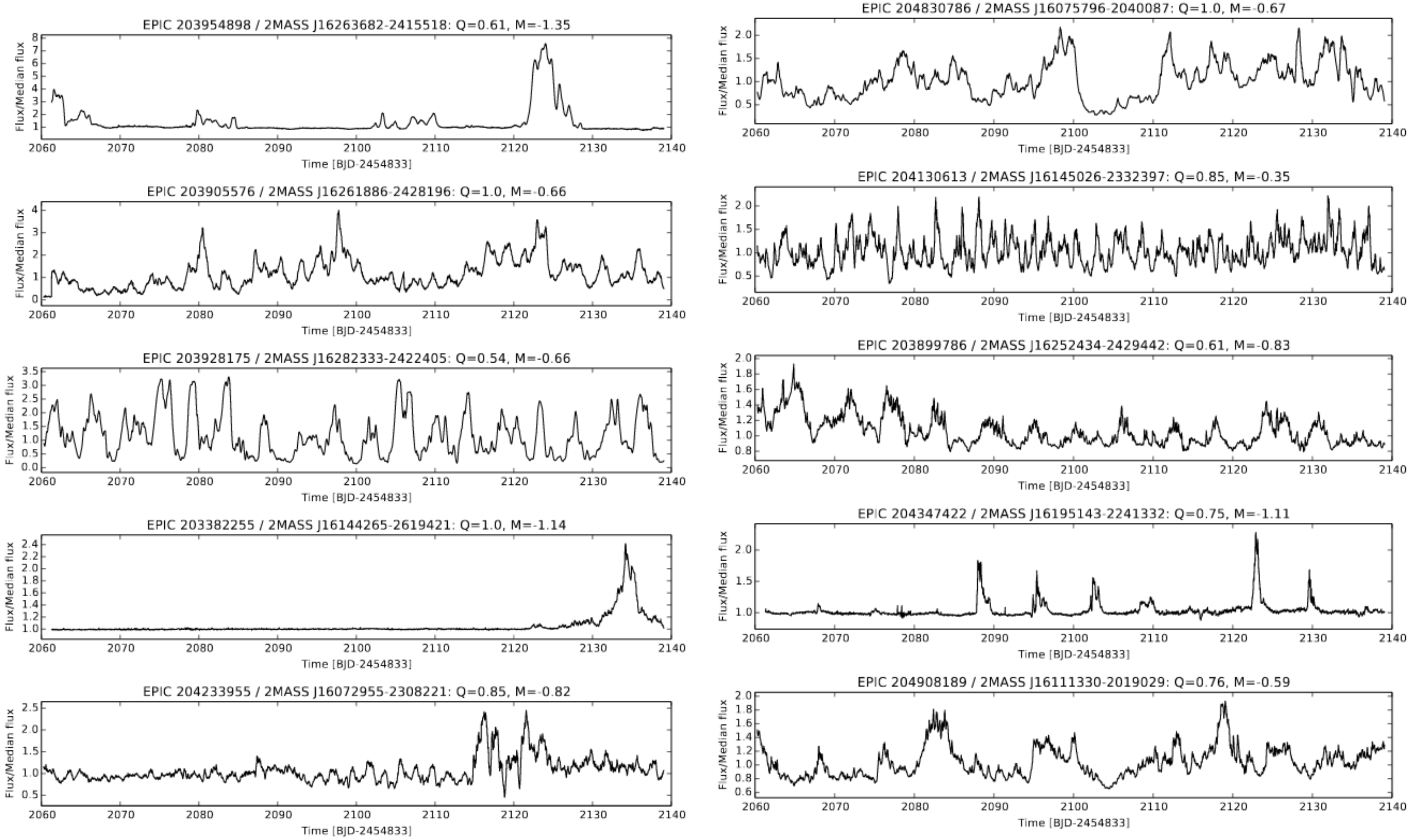
Kurosawa, Romanova



both accretion and ejection of material

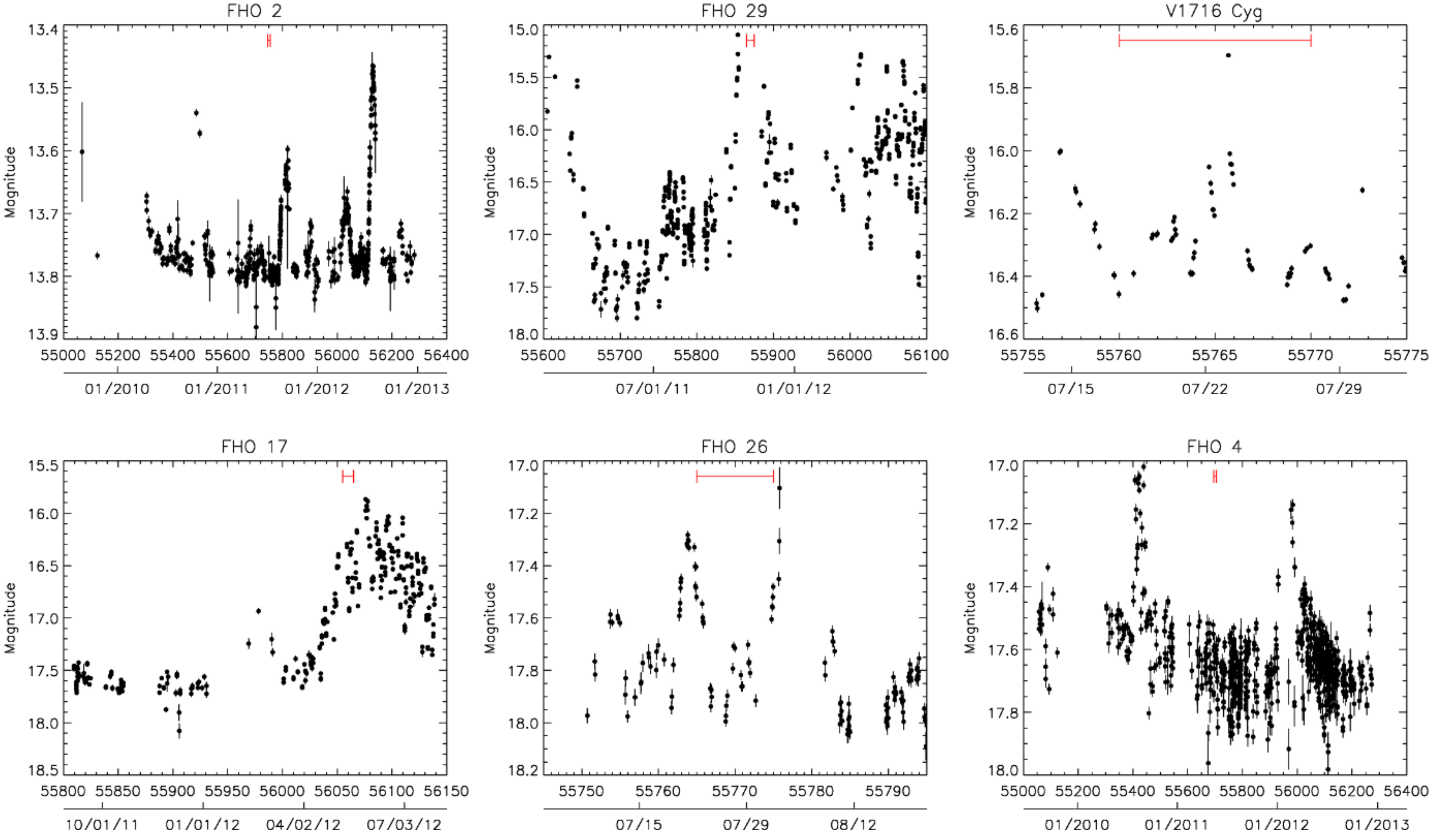
A Continuum of Accretion Burst Behavior

[Cody et al. 2017]



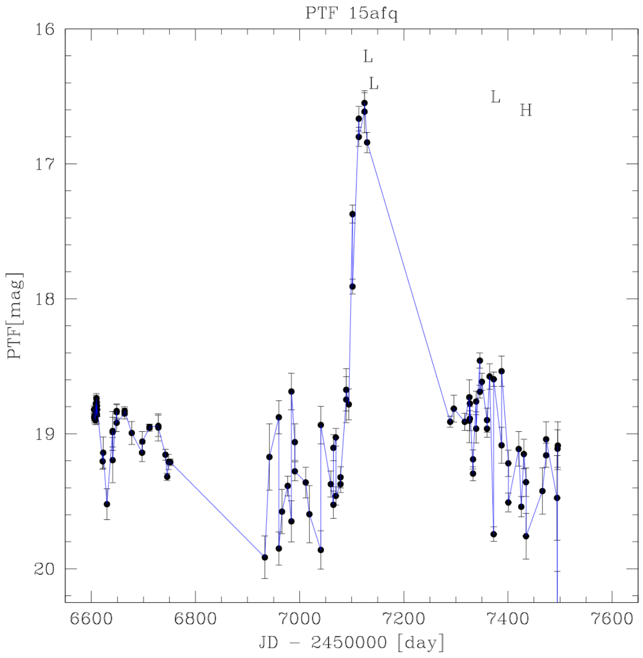
9% of the objects with disks exhibit with these types of lightcurves

Small and Moderate-Amplitude Bursters in PTF



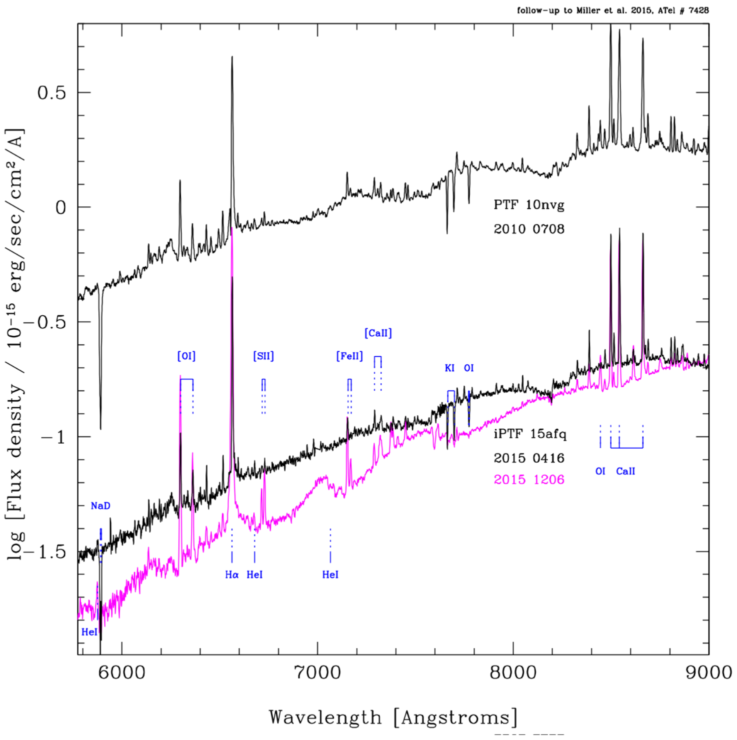
[Findeisen et al. 2013]

Large, Short-lived Burst

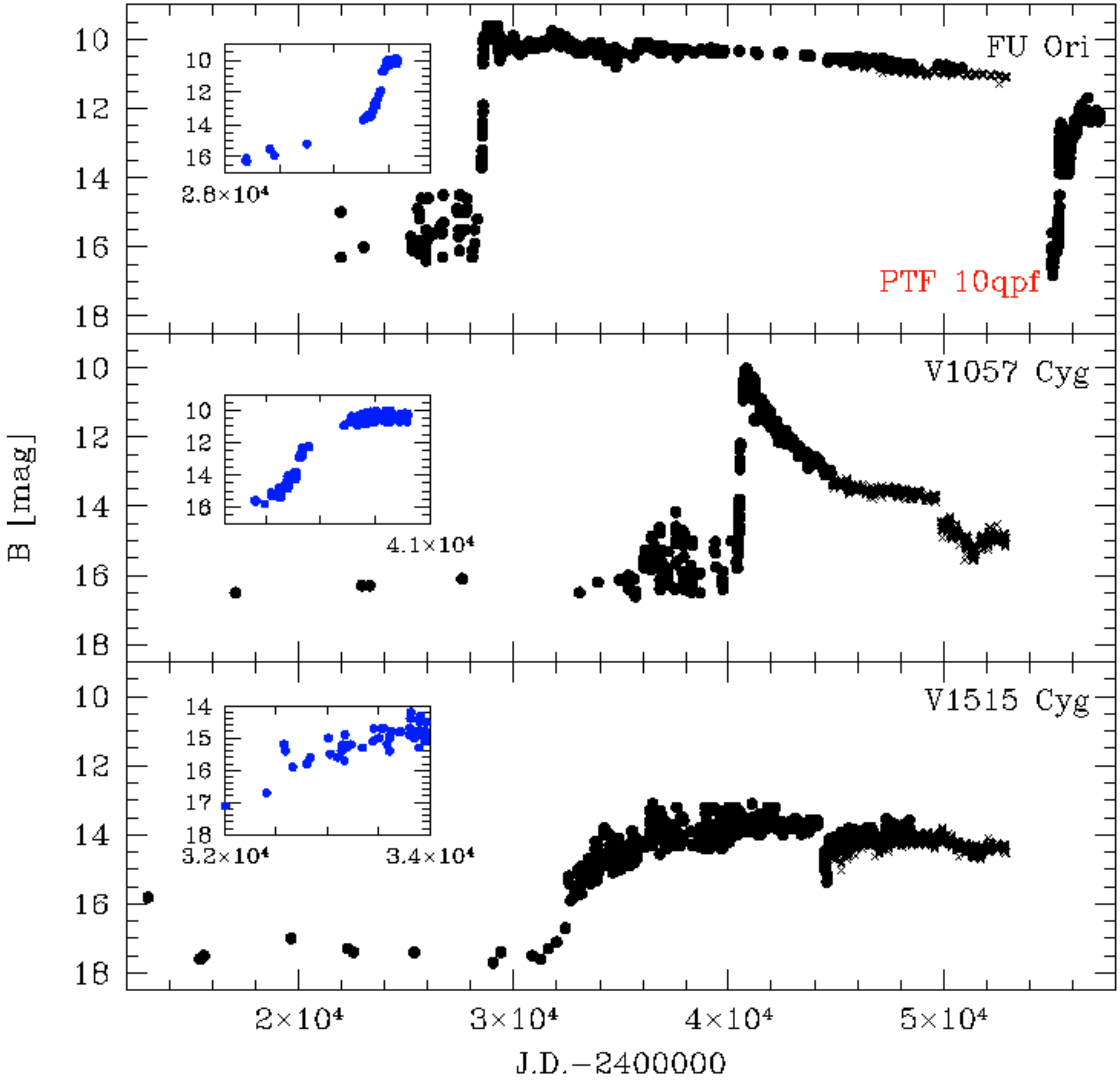


Increase in disk accretion rate caused ~3 mag brightening for several months accompanied by enhanced spectral veiling.

PTF15afq



Miller et al. (2015)



A New Addition to the FU Ori Class

Extreme Outbursts – How Frequent?

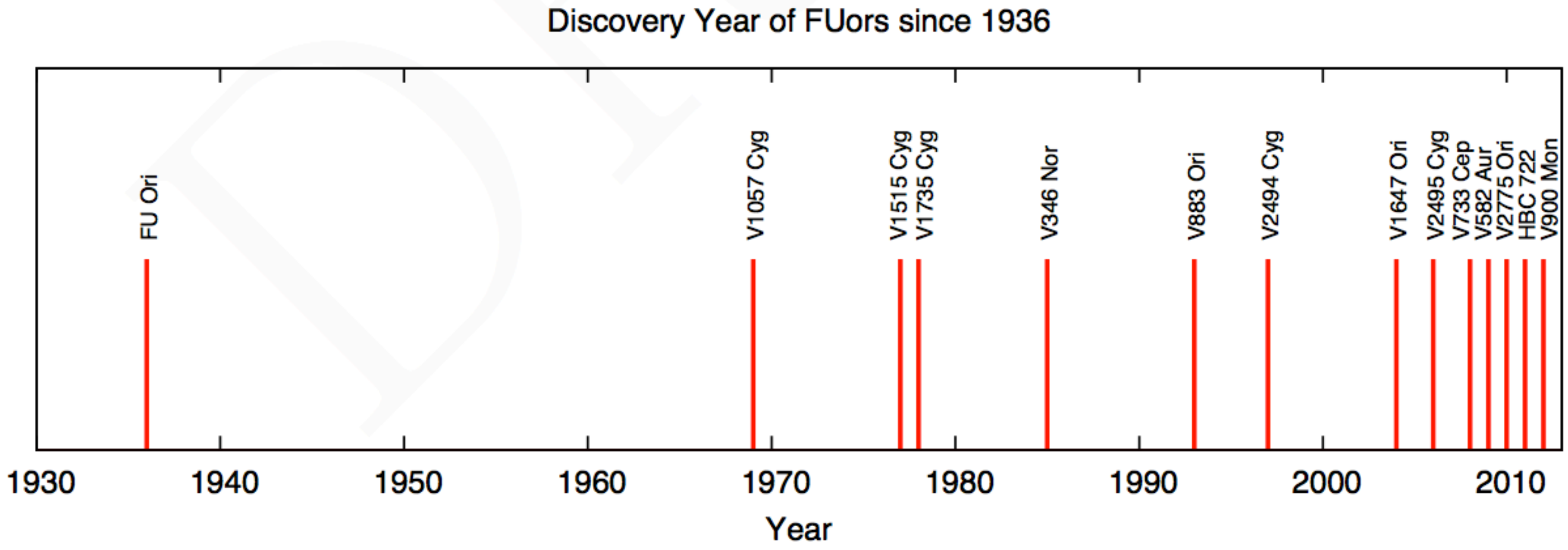
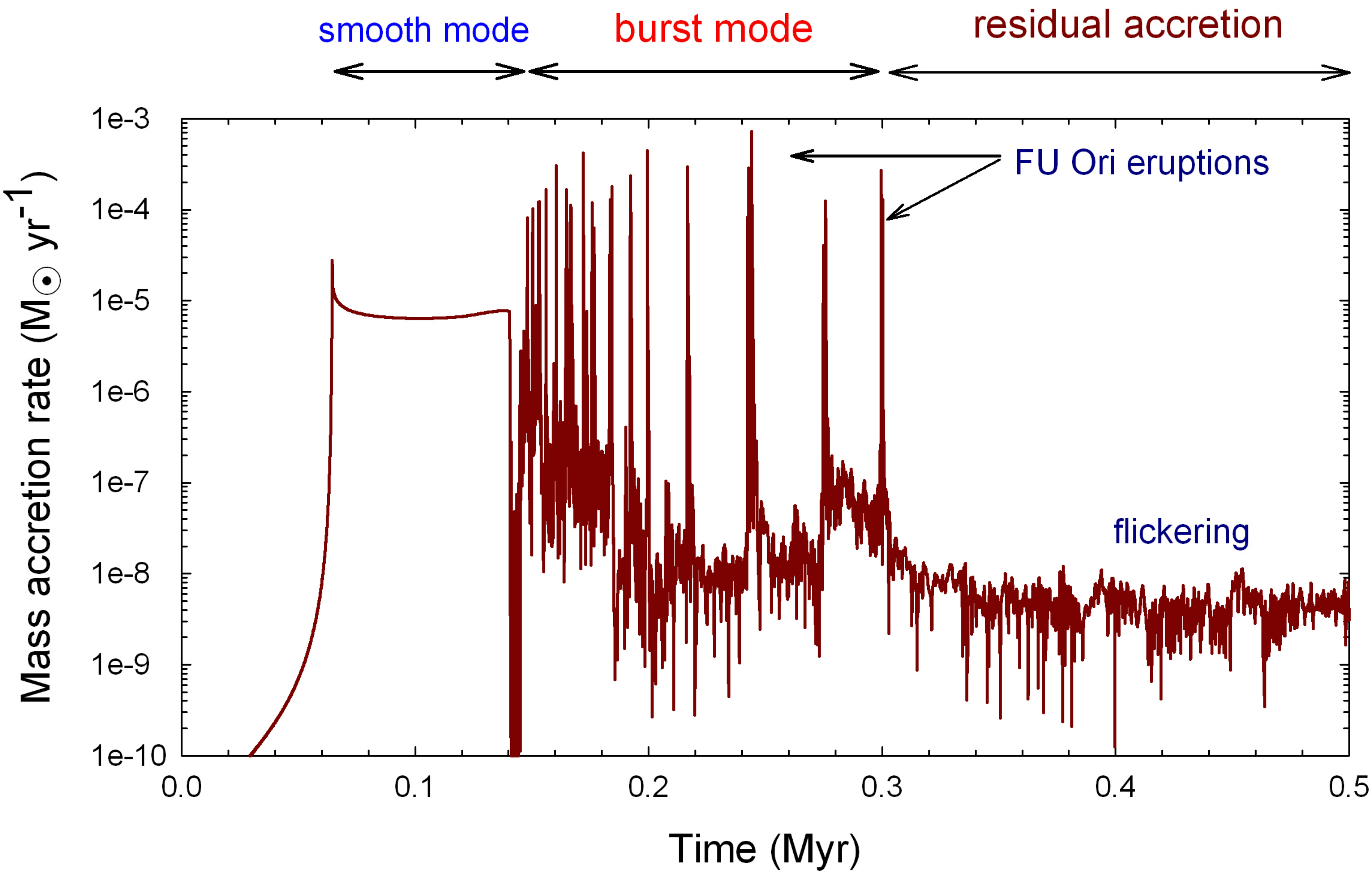


Figure 72: *The number of FUor discoveries has been increasing since the FU Ori outburst was observed in 1936.*

figure credit: B. Reipurth

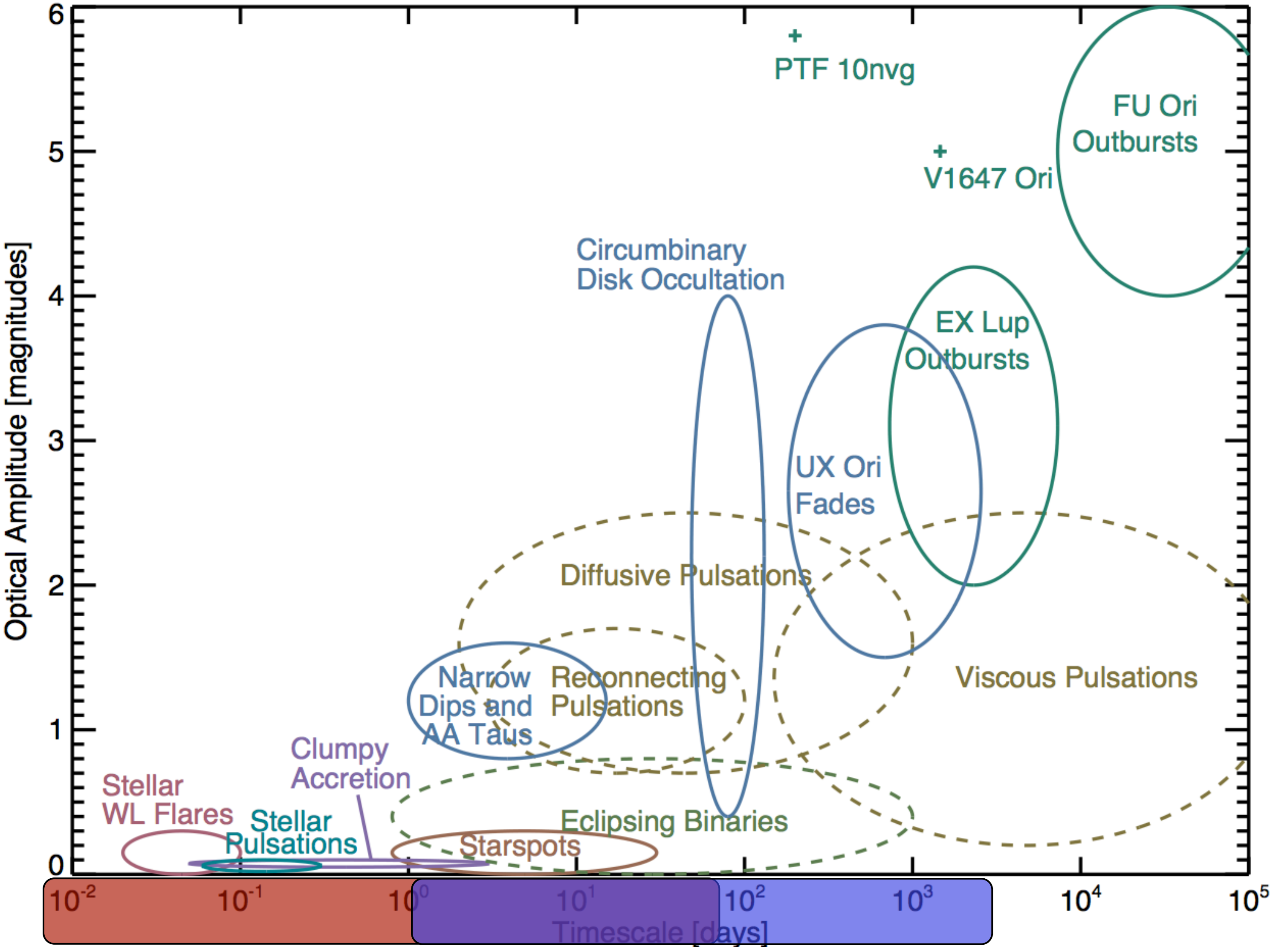
Extreme Outbursts – How Frequent?



Vorobyov 2006

Expected Parameter Space for Young Star Variability

Hillenbrand & Findeisen, 2015



YSOVAR

PTF-NAN

Accretion Affects HR Diagram Evolution

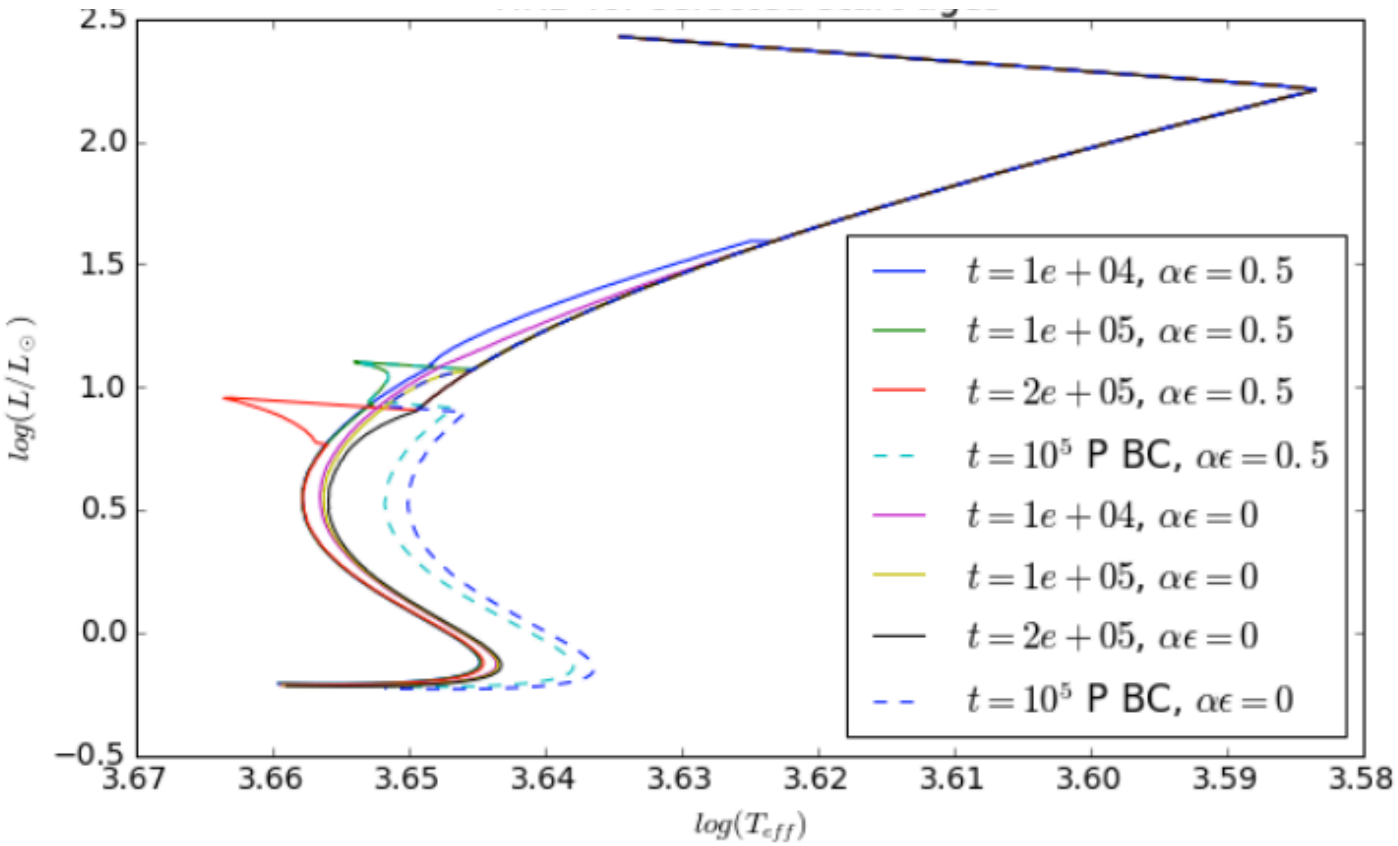


Figure 12. The effect of different start ages and boundary conditions for accretion on stellar evolution along the HRD. Photospheric boundary conditions are used except for the "P BC" cases, in which 100% pressure-only shock BCs are used. $\alpha\epsilon = 0.5$ cases tend to systematically increase surface temperature, and the age in which the accretion history is started plays a role in the width and extent of the ΔT_{eff} effect. When disk accretion is started earlier during hot accretion, the width of ΔT_{eff} is reduced, but the YSO seems more luminous for a given radius (resembling a higher mass YSO). For cold accretion, starting accretion provides a smooth transition between the lower mass and higher mass tracks. The shock pressure conditions provide a large ΔT_{eff} effect, so as to systematically decrease surface temperatures. Interestingly, in the shock pressure BC case with $\alpha\epsilon = 0.5$, the dynamical increase in T_{eff} that would be expected from the photospheric $\alpha\epsilon = 0.5$ case is suppressed.

Cao & Hillenbrand, 2018, in preparation

CLOSING THOUGHTS

- I admired FP *a lot*, even though I did not know him very well.
- I was a brash academic teenager when I first reached out to him, asking by email for a preprint of the PS91 paper, and to be put on his preprint list!
- We had email correspondence off/on over the next 20 years, ranging from early 1990's debates on how to put stars in the HR diagram to early 2010's discussions of young brown dwarf pulsation.
- Were he here today, I would have looked forward to discussing with FP the new results on eclipsing binaries, the complicated phase space of young star variability, recent work on pre-ms accretion histories…and impacts of all of these on HR diagrams.