Constraints on Theoretical Stellar Models: Empirical Measurements of the Masses of Stars and Brown Dwarfs at Young Ages

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Dynamical Masses of PMS Stars circa 2010

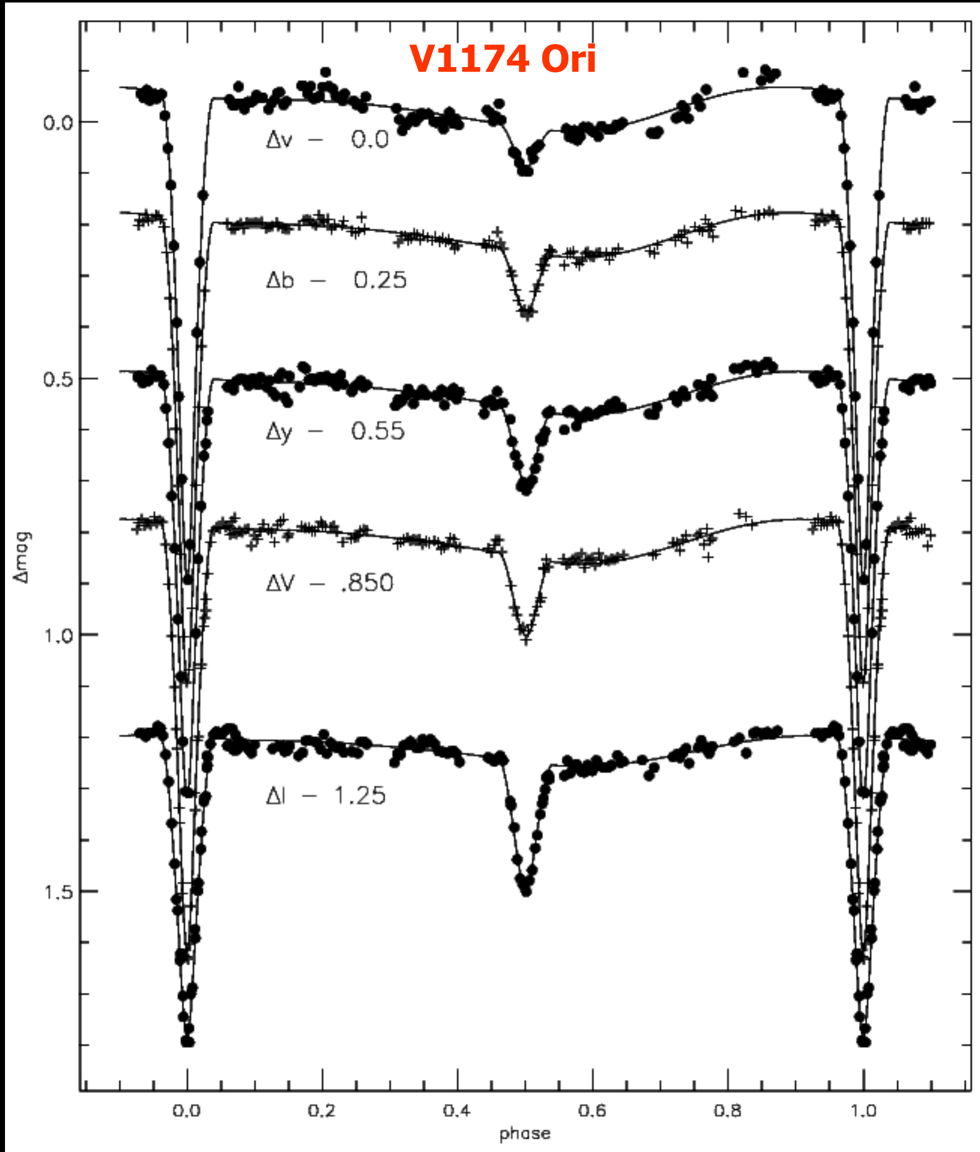
N=33
M < 2 Msun

Single stars
- Circumstellar disk "rotation curve"

Binary stars
- Astrometric
- Eclipsing

Name	Mass (M_{o})	Mass Err	Type	Radius (Ro)	SpT	Log (Teff)	Log (L/Lo)
RS Cha A	1.858	0.9%	EB	2.137±0.055	A8	3.883±0.010	1.144±0.044
RS Cha B	1.821	1.0%	EB	2.338±0.055	A8	3.859±0.010	1.126±0.043
MWC 480	1.65	4.2%	DK	...	A2-3	3.948±0.015	1.243±0.10
TY CrA B	1.64	0.6%	EB	2.080±0.140	...	3.690±0.035	0.380±0.145
045251+3016 A	1.45	13.1%	AS	...	K5	3.643±0.015	-0.167±0.053
ASAS 0528+03 A	1.375	0.8%	EB	1.83±0.01	...	3.708±0.020	0.312±0.078
ASAS 0528+03 B	1.329	0.6%	EB	1.73±0.01	...	3.677±0.021	0.140±0.080
BP Tau	1.32	15.2%	DK	...	K7	3.608±0.012	-0.78±0.10
0529.4+0041 A	1.25	4.0%	EB	1.700±0.200	K1-2	3.701±0.009	0.243±0.037
EK Cep B	1.124	1.1%	EB	1.320±0.015	...	3.755±0.015	0.190±0.070
UZ Tau Ea	1.016	6.4%	DKS	...	M1	3.557±0.015	-0.201±0.124
V1174 Ori A	1.009	1.5%	EB	1.339±0.015	K4.5	3.650±0.011	-0.193±0.048
LkCa 15	0.97	3.1%	DK	...	K5	3.643±0.015	-0.165±0.10
MML 53 A	0.94	4.3%	EB	1.19±0.07	...	3.691±0.015	-0.129±0.1
0529.4+0041 B	0.91	5.5%	EB	1.200±0.200	...	3.604±0.022	-0.469±0.192
GM Aur	0.84	6.0%	DK	...	K7	3.602±0.015	0.598±0.10
045251+3016 B	0.81	11.1%	AS	...	M2	3.535±0.015	-0.830±0.086
MML 53 B	0.806	3.7%	EB	1.05±0.07	...	3.643±0.015	-0.428±0.1
V1174 Ori B	0.731	1.1%	EB	1.065±0.011	...	3.558±0.011	-0.761±0.058
DL Tau	0.72	15.3%	DK	...	K7-M0	3.591±0.015	0.005±0.10
HD 98800 Ba	0.699	9.2%	AS	...	...	3.623±0.016	0.330 ± 0.075
NSVS 06507557 A	0.66	13.0%	EB	0.60±0.030	K9	3.560±0.009	-1.097±0.057
HD 98800 Bb	0.582	8.8%	AS	...	...	3.602±0.016	0.167 ± 0.038
DM Tau	0.55	5.5%	DK	...	M1	3.557±0.015	-0.532±0.10
CY Tau	0.55	60.0%	DK	...	M2	3.535±0.015	-0.491±0.10
Par 1802 A	0.414	3.6%	EB	1.82±0.05	M2	3.596±0.025	-0.143±0.14
Par 1802 B	0.406	3.4%	EB	1.69±0.05	M2	3.563±0.027	-0.337±0.26
UZ Tau Eb	0.294	9.2%	DKS	...	M4	3.491±0.015	-0.553±0.124
NSVS 06507557 B	0.28	16.1%	EB	0.44±0.02	...	3.527±0.010	-1.647±0.062
JW 380 A	0.262	9.5%	EB	1.189±0.175	M1.5	3.555±0.012	-0.676±0.136
JW 380 B	0.151	8.6%	EB	0.897±0.170	...	3.495±0.014	-1.163±0.178
2M0535–05 A	0.0541	8.5%	EB	0.669±0.034	M6.5	3.423±0.016	-1.699±0.078
2M0535–05 B	0.034	7.9%	EB	0.511±0.026	...	3.446±0.016	-1.848±0.076

Accurate masses and radii: Eclipsing binaries



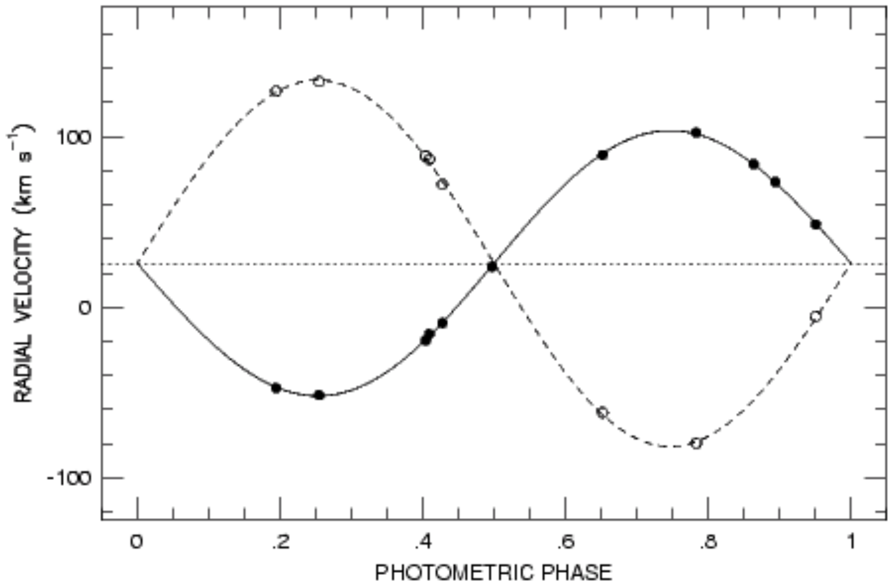
$M_1 = 1.01 \pm 0.015\ M_{sun}$ $T_1 = 4470 \pm 120$ K

$M_2 = 0.73 \pm 0.008\ M_{sun}$ $T_2 = 3615 \pm 10$ K

$R_1 = 1.34 \pm 0.015\ R_{sun}$ $\log g_1 = 4.19 \pm 0.01$

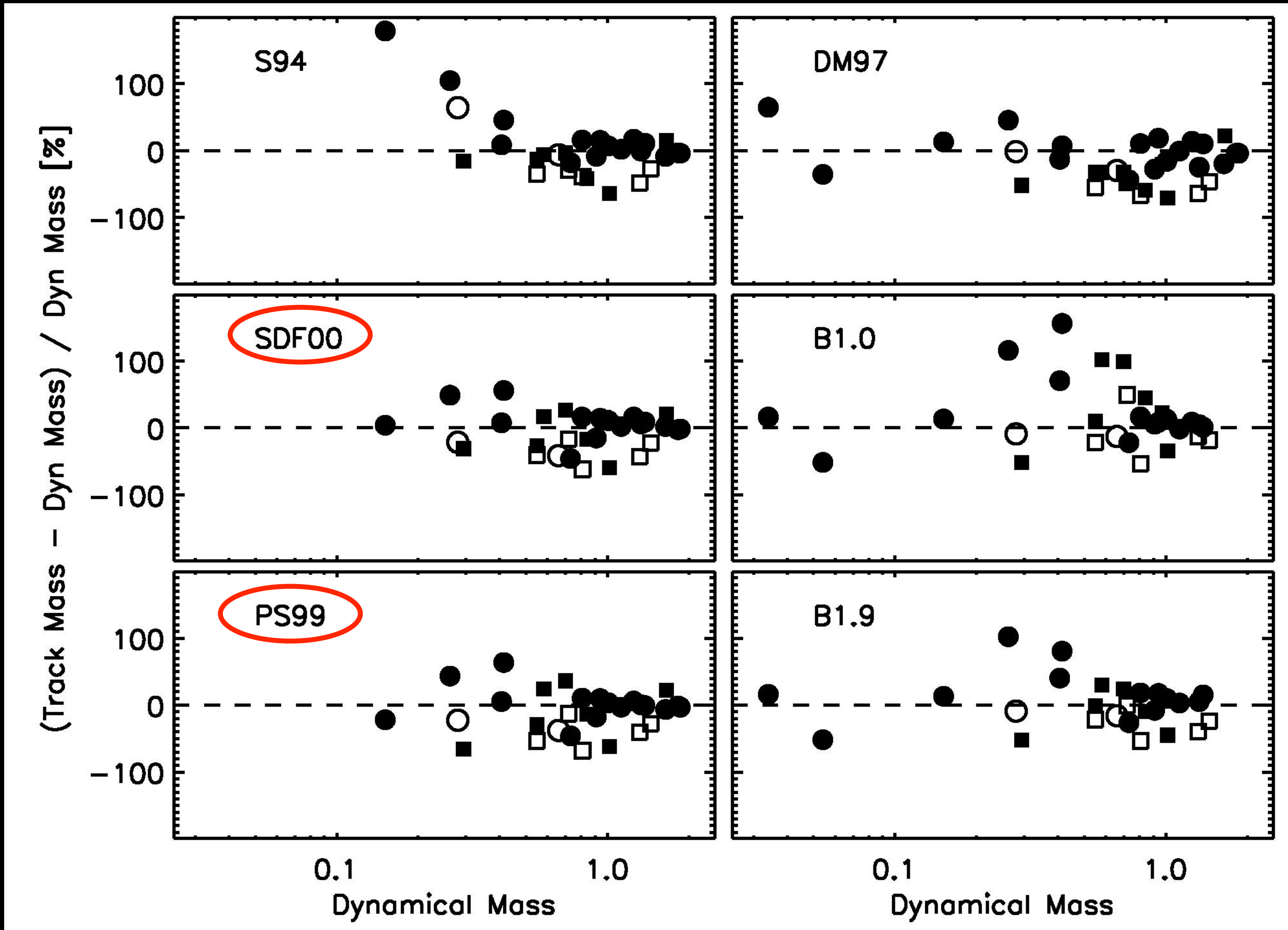
$R_2 = 1.07 \pm 0.011\ R_{sun}$ $\log g_2 = 4.25 \pm 0.01$

Teff ratio measured very precisely.
Luminosities are distance independent.



Stassun et al. (2004)

Comparison of dynamical masses to theoretical models in HR diagram



Updated from Hillenbrand & White (2004)

***Above 1 Msun*:**

- Good agreement: Mean difference 10%, scatter ~10%.

***Below 1 Msun*:**

- Poorer agreement: Differences as large as ~100%, large scatter.

***Best overall agreement: Siess et al (2000), and Palla & Stahler (1999)*:**

- Overall consistency to ~5%, though with scatter of ~25%.

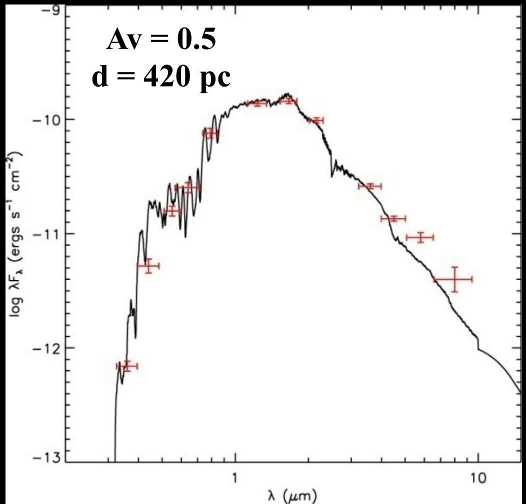
Case Study: Par 1802
A pair of dissimilar ‘identical twins’

Par 1802: Non-coevality?

1. In protobinary phase, original secondary preferentially accreted mass.
2. Secondary ended accretion phase later.
3. Apparent age difference because different t=0 due to different accretion histories.

e.g. Simon & Stobie (2009), Clarke (2007), Bate (2004)

No disk, no evidence for strong magnetic activity.



$M_1 = 0.41 \pm 0.02\ M_{sun}$

$M_2 = 0.40 \pm 0.02\ M_{sun}$

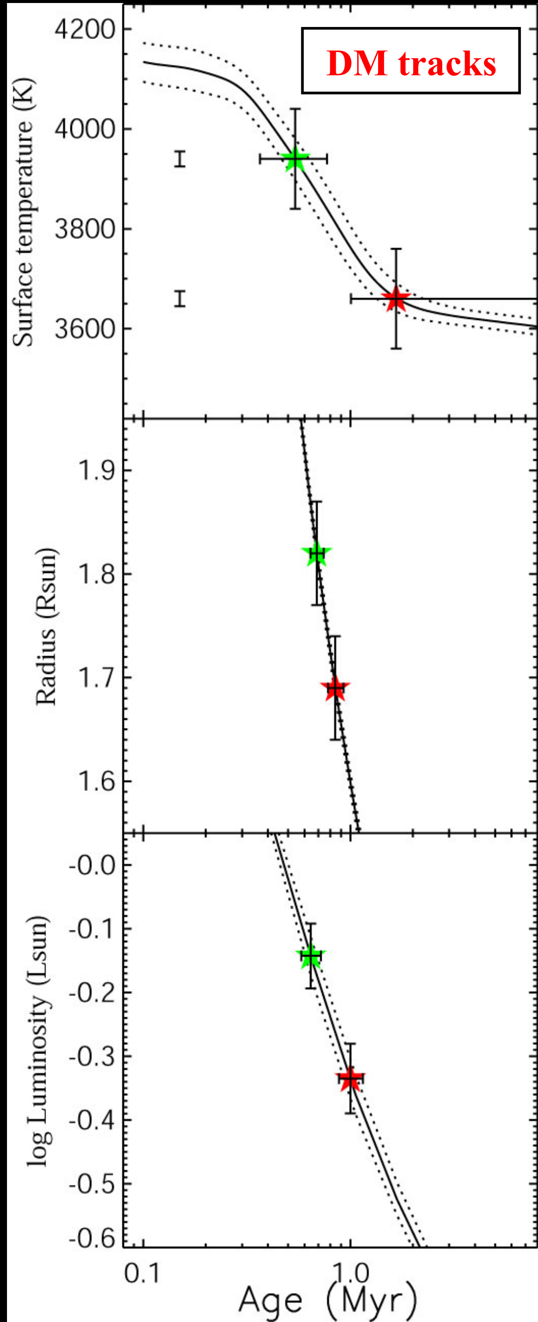
$q = 0.98 \pm 0.01$

$T_1/T_2 = 1.084 \pm 0.007$

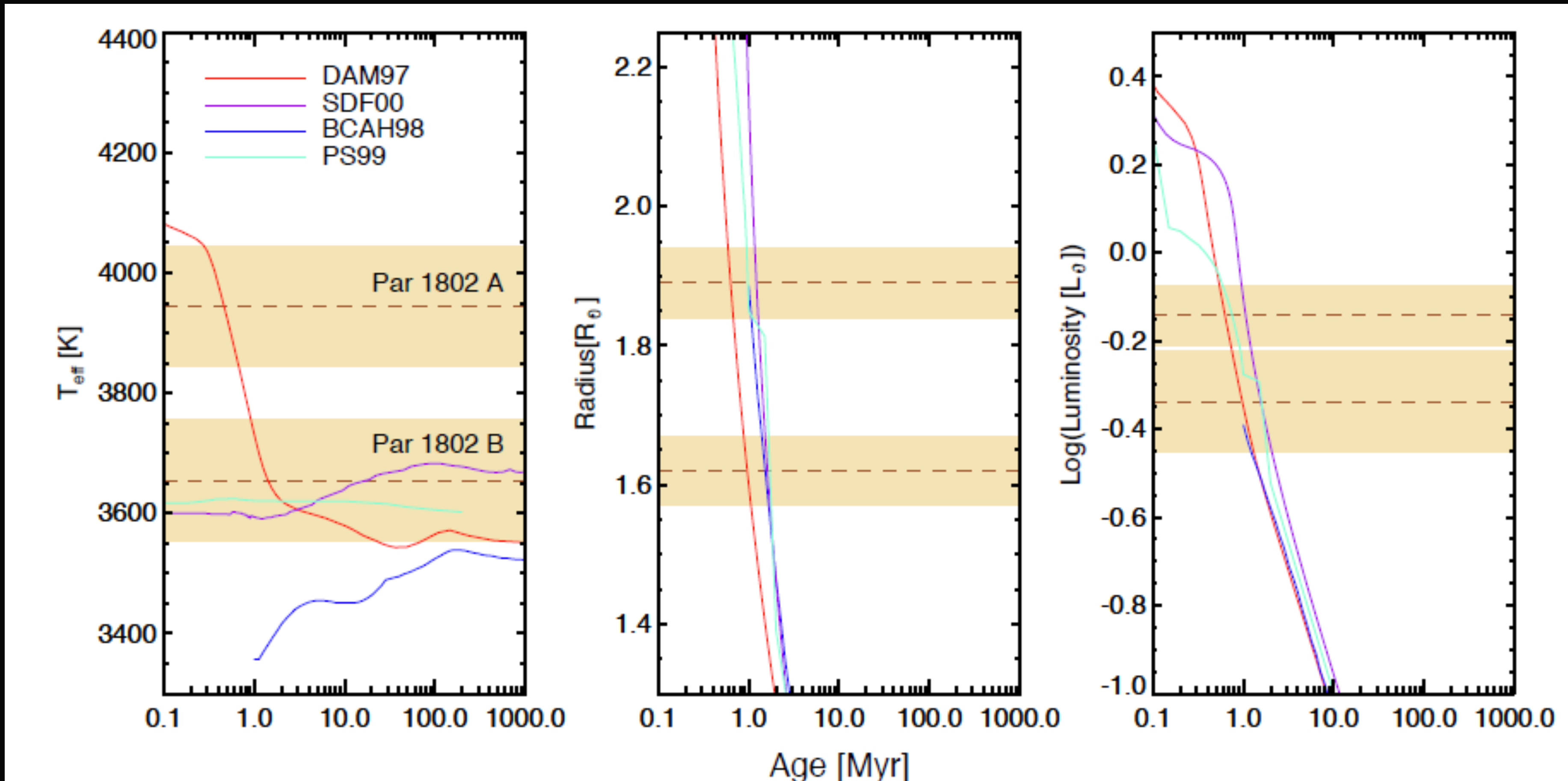
$R_1 = 1.82 \pm 0.05\ R_{sun}$

$R_2 = 1.69 \pm 0.05\ R_{sun}$

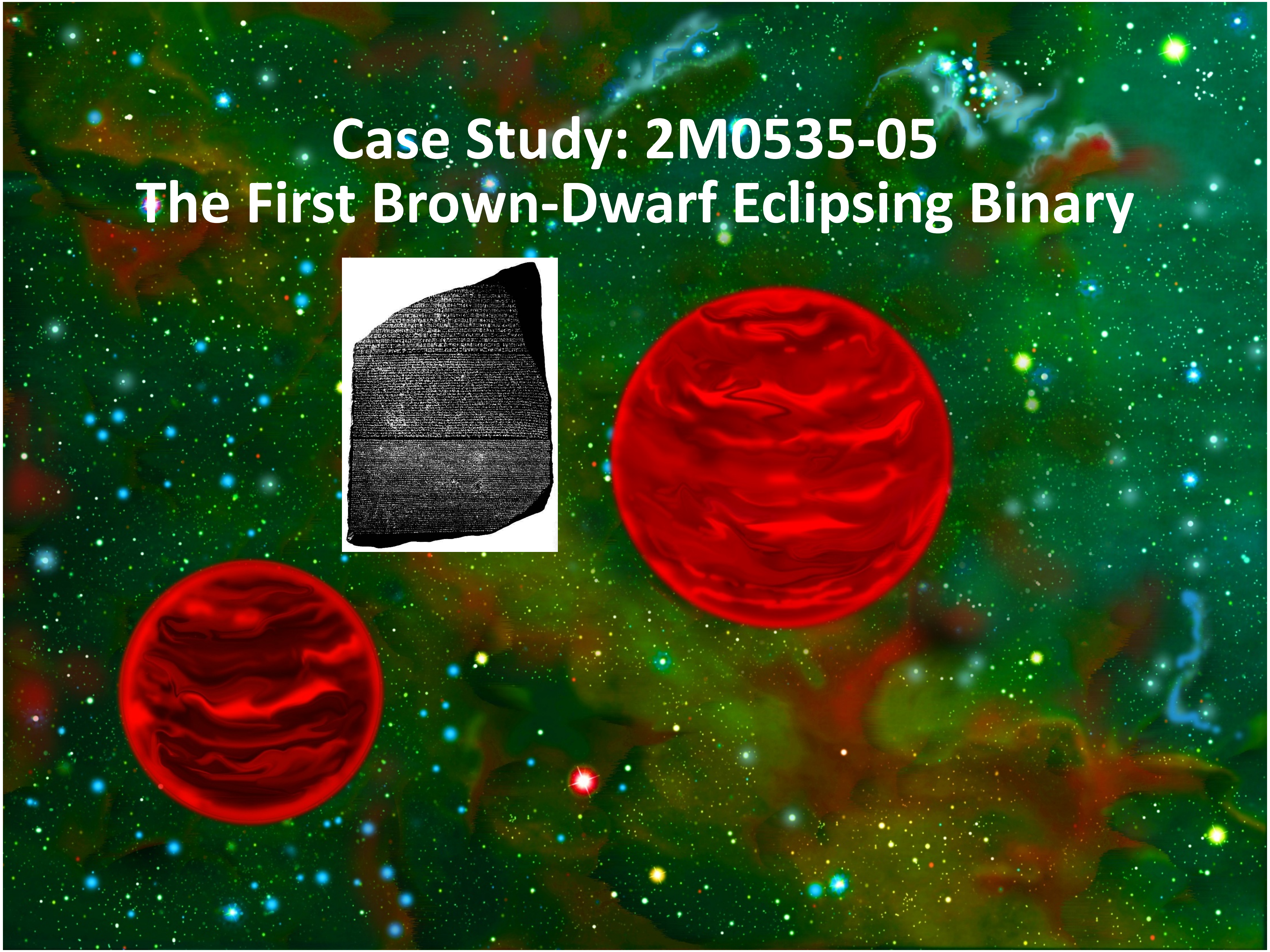
Stassun et al. (Nature, 2008)



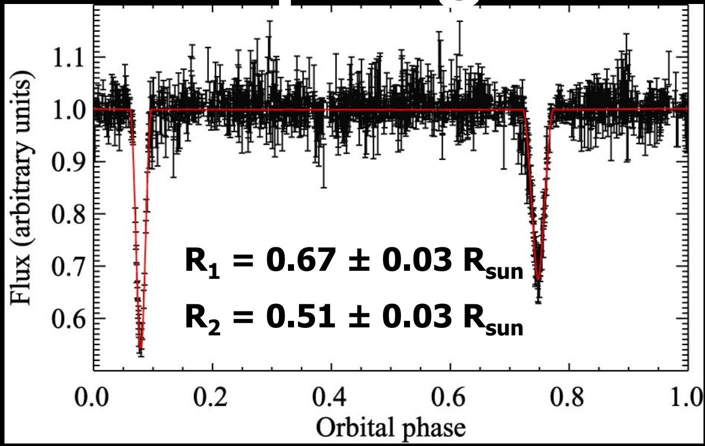
Par 1802: Morphology of tracks matters

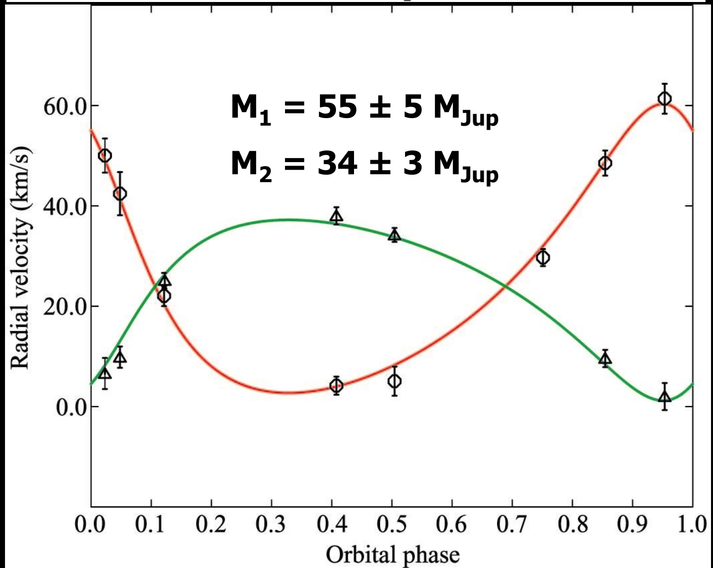


Cargile (2010)


Case Study: 2M0535-05
The First Brown-Dwarf Eclipsing Binary

BD eclipsing binary

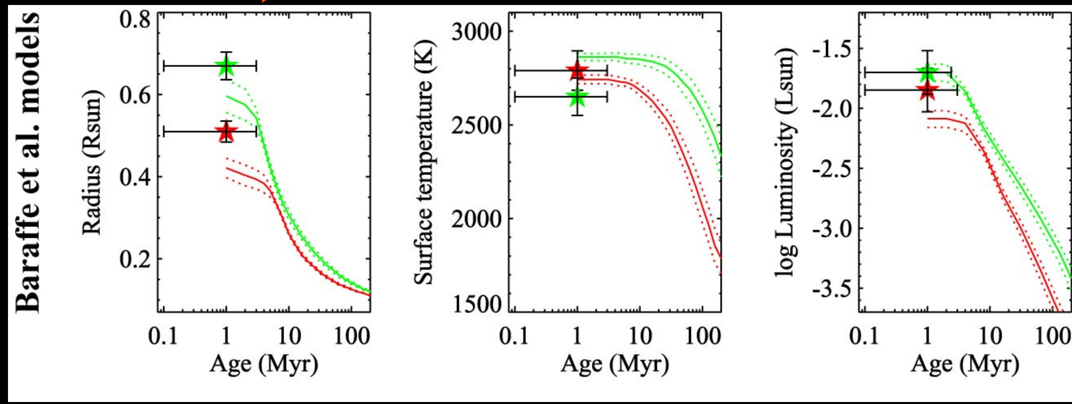




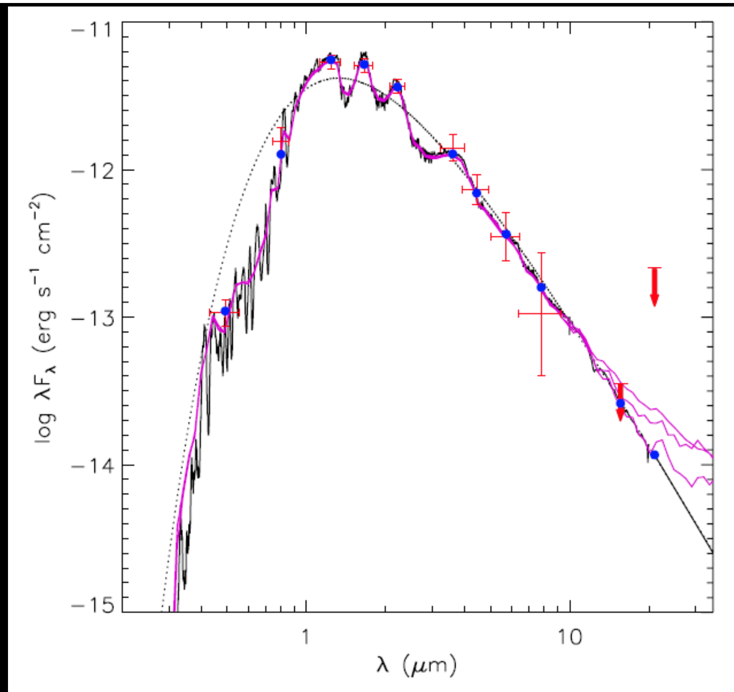
Stassun et al.
(Nature, 2006)

Oversized radii

Temperature reversal



Stassun et al.
(ApJ, 2007)



Mohanty et al.
(ApJ, 2009)

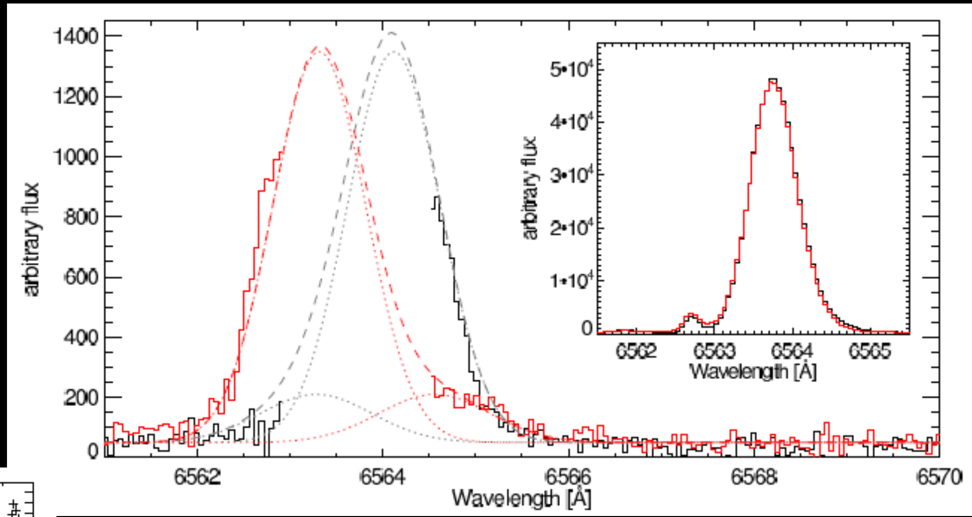
Surface activity in BD eclipsing binary

TABLE 2
ROTATION AND ACTIVITY OF
2MASS 0535-0546.

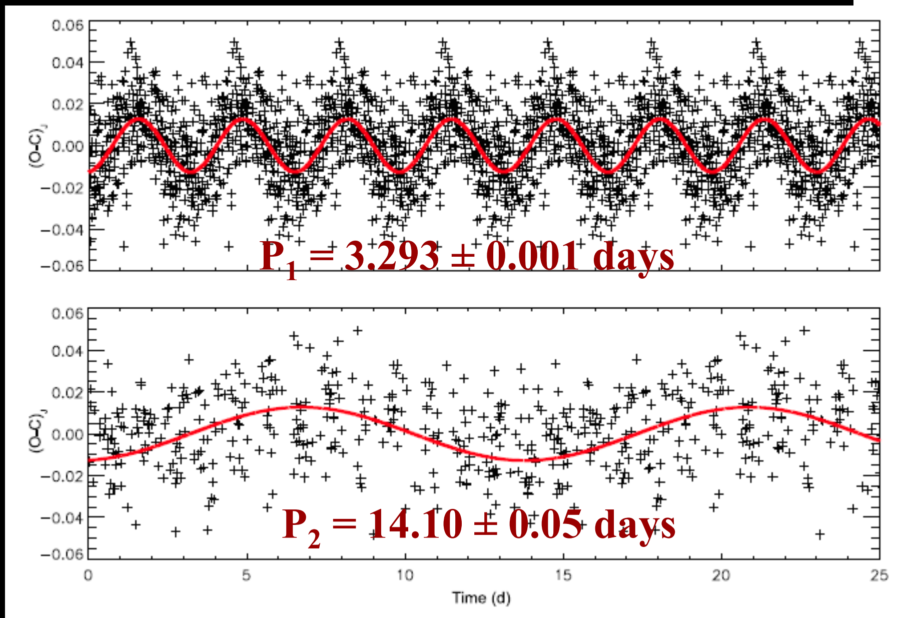
	$v \sin i$ [km s^{-1}]	$\log L_{H\alpha}/L_{bol}$
Primary	10	−3.47
Secondary	<5	−4.30

B ~ 4 kG

Primary brown dwarf ~10× more magnetically active than secondary.

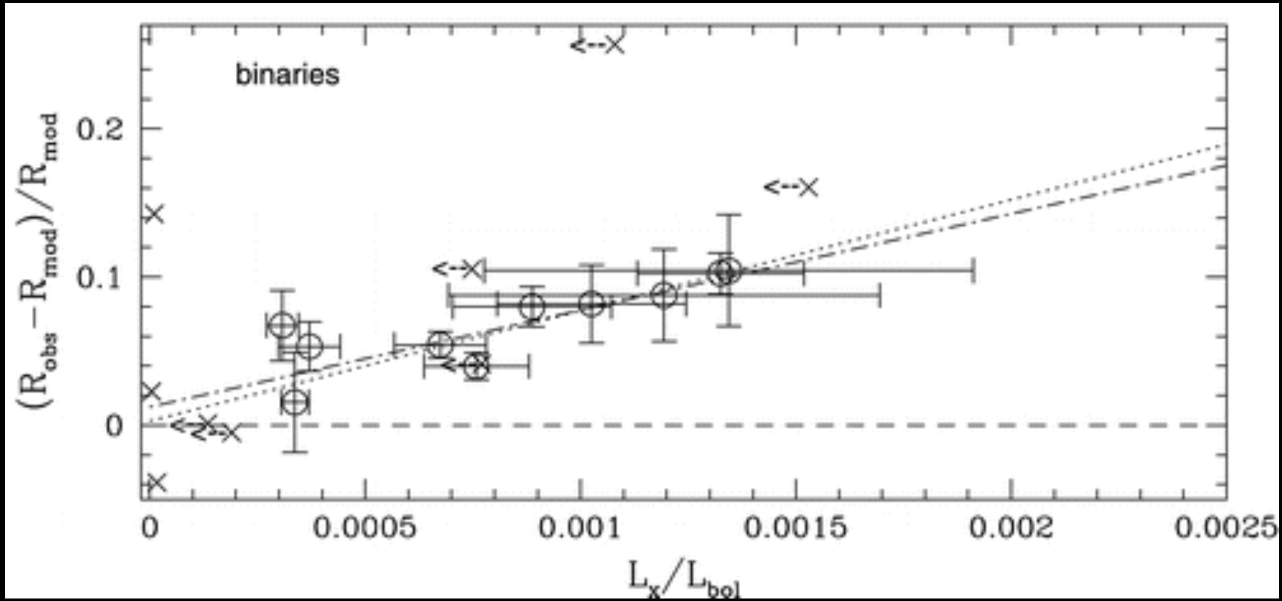


Reiners et al. (ApJ, 2007)



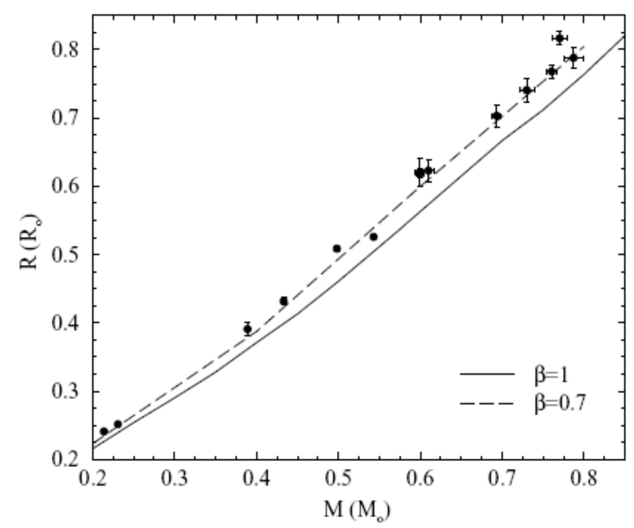
Gómez Maqueo Chew et al. (ApJ, 2009)

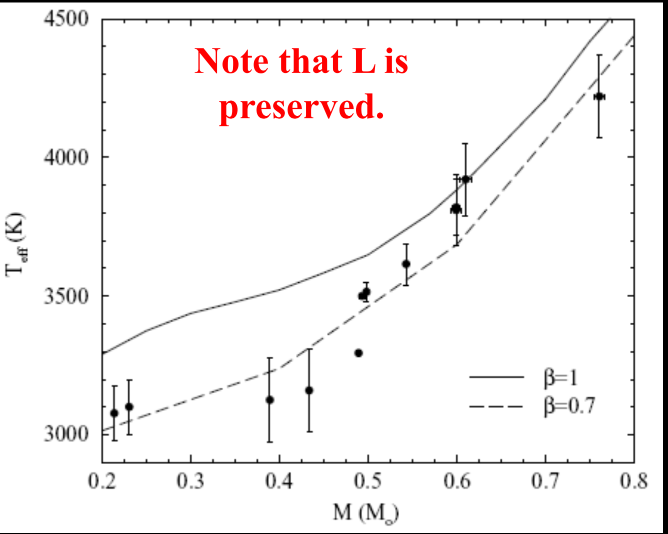
The effect of activity on low-mass stellar radii and temperatures



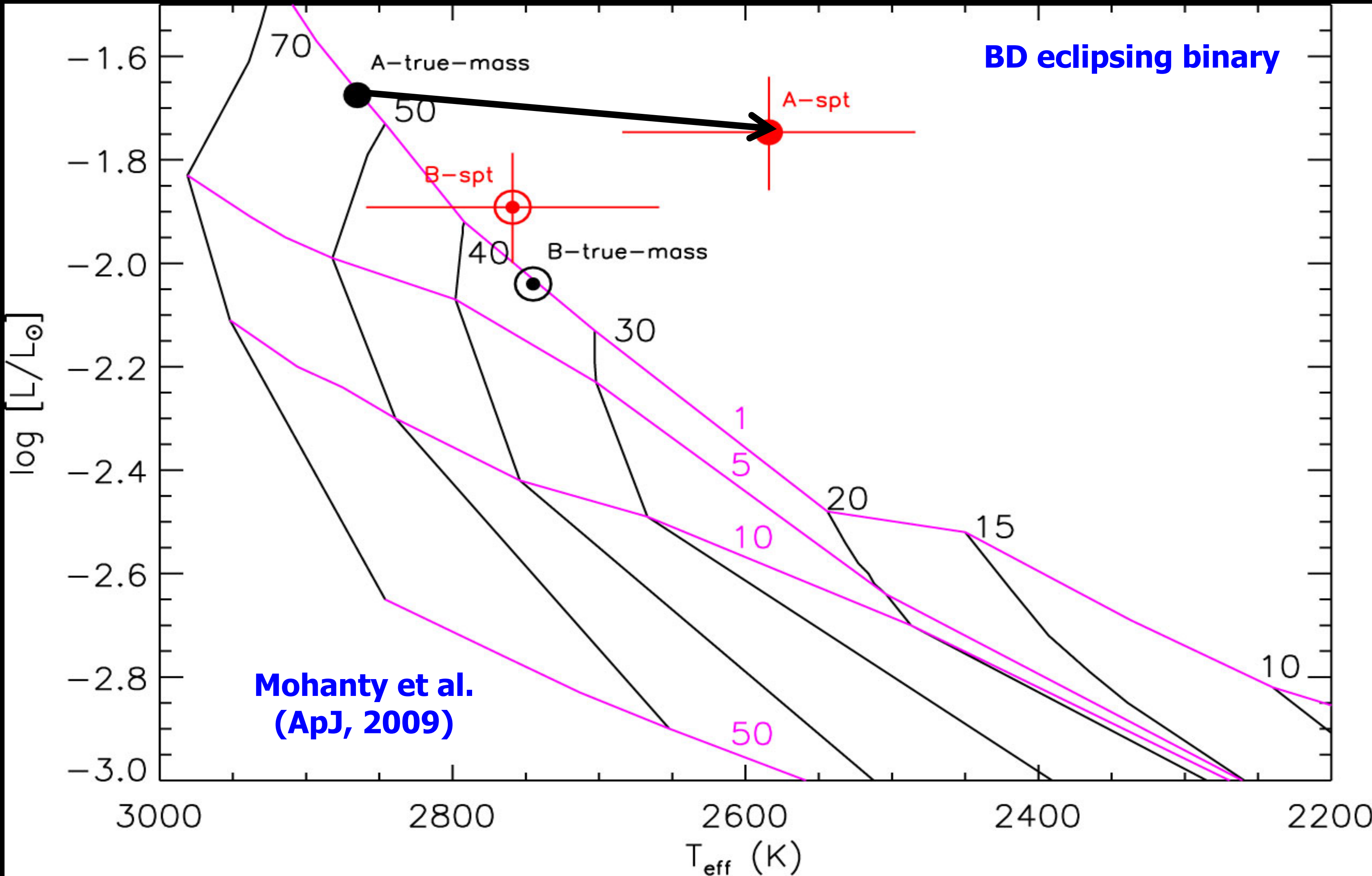
López-Morales (2007)

Ribas et al. (2010); Chabrier et al. (2007)





Surface activity: Shift to cooler T_{eff}, *apparently* lower mass



Census of known PMS eclipsing binaries

Name	Mass (M_0)	Mass Err	Radius (Ro)	SpT	Log (Teff)	Log (L/Lo)	Third body (EBs only)
RS Cha A	1.858	0.9%	2.137±0.055	A8	3.883±0.010	1.144±0.044	No
RS Cha B	1.821	1.0%	2.338±0.055	A8	3.859±0.010	1.126±0.043	...
TY CrA B	1.64	0.6%	2.080±0.140	...	3.690±0.035	0.380±0.145	Yes (SB)
V618 Per B	1.558	1.6%	1.138±0.069	...	3.903±0.054	0.77±0.08	No
ASAS 0528+03 A	1.375	0.8%	1.83±0.01	...	3.708±0.020	0.312±0.078	No
ASAS 0528+03 B	1.329	0.6%	1.73±0.01	...	3.677±0.021	0.140±0.080	...
0529.4+0041 A	1.25	4.0%	1.700±0.200	K1-2	3.701±0.009	0.243±0.037	Yes (3rd light, visual)
EK Cep B	1.124	1.1%	1.320±0.015	...	3.755±0.015	0.190±0.070	No
V1174 Ori A	1.009	1.5%	1.339±0.015	K4.5	3.650±0.011	-0.193±0.048	Yes (NIR excess, SB in NIR)
MML 53 A	0.94	4.3%	1.19±0.07	...	3.691±0.015	-0.129±0.1	Yes (eclipse timings, SB)
0529.4+0041 B	0.91	5.5%	1.200±0.200	...	3.604±0.022	-0.469±0.192	...
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V1174 Ori B	0.731	1.1%	1.065±0.011	...	3.558±0.011	-0.761±0.058	...
NSVS 06507557 A	0.66	13.0%	0.60±0.030	K9	3.560±0.009	-1.097±0.057	No
Par 1802 A	0.414	3.6%	1.82±0.05	M2	3.596±0.025	-0.143±0.14	Yes (3rd light, disentangling)
Par 1802 B	0.406	3.4%	1.69±0.05	M2	3.563±0.027	-0.337±0.26	...
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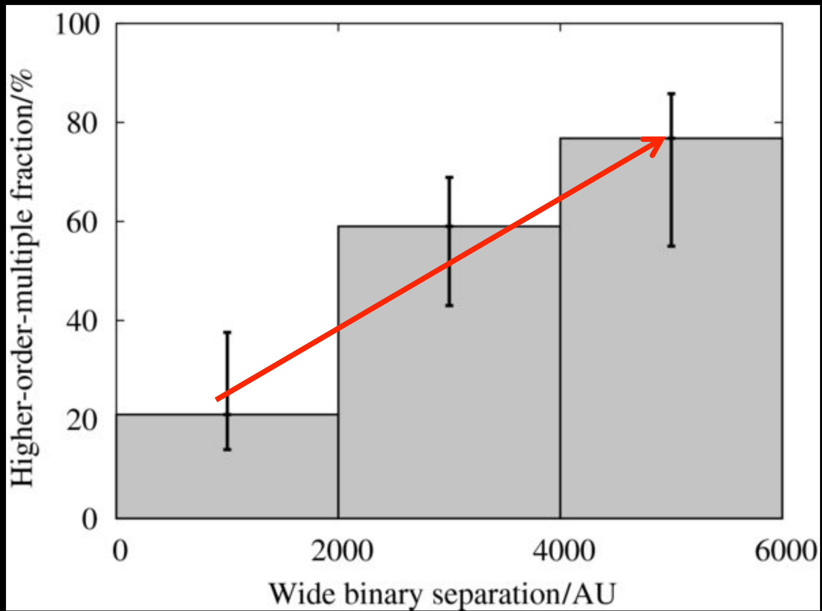
JW 380 A	0.262	9.5%	1.189±0.175	M1.5	3.555±0.012	-0.676±0.136	Yes (3rd light, SB)
JW 380 B	0.151	8.6%	0.897±0.170	...	3.495±0.014	-1.163±0.178	...
2M0535–05 A	0.0541	8.5%	0.669±0.034	M6.5	3.423±0.016	-1.699±0.078	No
2M0535–05 B	0.034	7.9%	0.511±0.026	...	3.446±0.016	-1.848±0.076	...

- 7 triples : 40 doubles = 18% (MS all; Duquennoy & Mayor 1991)
- 2 triples : 19 doubles = 11% (PMS all; Ghez et al. 1997)
- 8 triples : 13 doubles = 61% (PMS SBs; Guenther et al. 2007)
- 8 triples : 6 doubles = 133% (PMS EBs; Stassun & Hebb in prep.)

Higher-order multiplicity in the field is a function of wide system separation



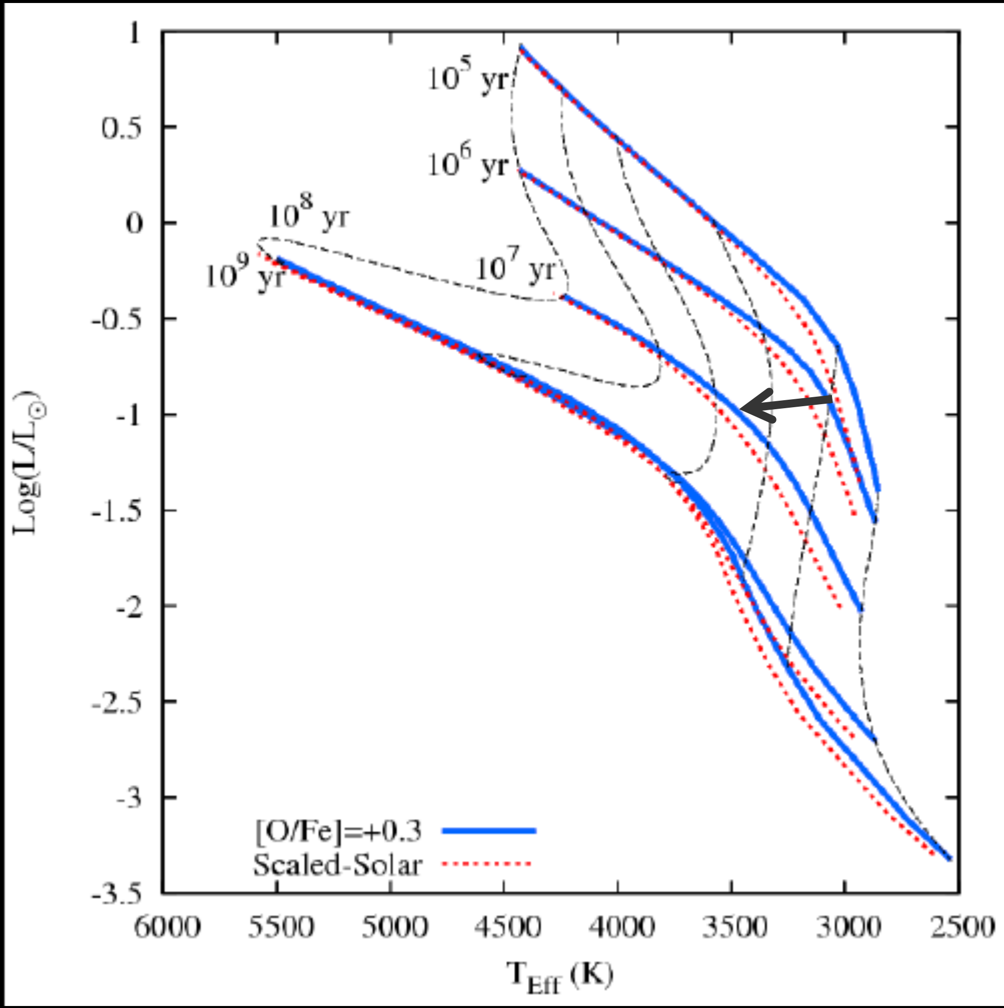
Dhital et al. (AJ, 2010), Law et al. (ApJ, 2010)

- Higher-order fraction for <u>M field stars</u> (SLoWPoKES)
  - Increases with wide system separation, from 20% to 80%.
- Higher-order fraction for <u>solar-type field stars</u> (Tokovinin et al. 2006)
  - Increases with wide system separation, from 63% to 96%.

Summary

- **Large uncertainties remain in theoretical stellar evolution models.**
  - Some models perform better than others in HR diagram.
    "Right for the wrong reason" because of activity effects on T_{eff}?
  - But differences in track morphology do matter, especially at M ~ 0.5 M_{sun}.
- **Magnetic activity alters T_{eff} and R of low-mass stars and brown dwarfs (but L_{bol} appears to be ok).**
  - Beware mass and age estimates for active VLM field objects.
  - Beware calibrations based on this system and other active VLM objects.
- **Non-coevality of ~40% possible in low-mass binaries at ~1 Myr.**
  - Accretion history of protobinaries likely important for setting final masses.
  - Beware calibrations based on assumption of binary coevality at young ages.
- **Frequency of higher-order multiples in PMS phase is very high.**
  - Formation of small-N clusters? Dynamical evolution?
  - Is this interesting?

The next challenge:
Measuring accurate stellar *abundances*



Dotter et al. (CS16, 2010)