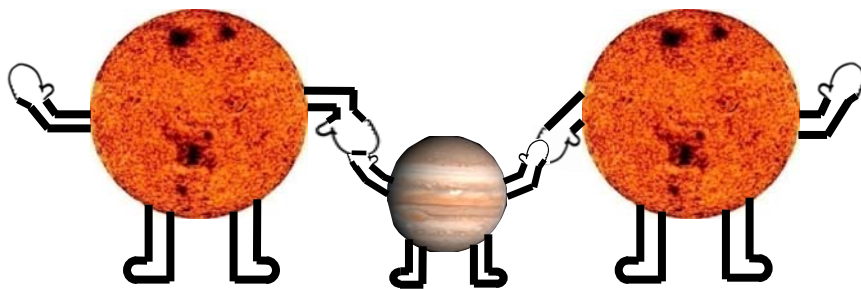# A Survey of Stellar Families
Multiplicity of Solar-type Stars

Deepak Raghavan

Ph.D. Dissertation Talk

March 17, 2009

Advisor:

Dr. Hal McAlister GSU

Committee members:

Dr. Doug Gies GSU

Dr. Todd Henry GSU

Dr. David Latham Harvard-Smithsonian CfA

Dr. Brian Mason USNO

Dr. Unil Perera GSU

Dr. Russel White GSU

Thanks to the CHARA team

Presentation Outline

- Motivation for this effort

- The sample of nearby solar-type stars
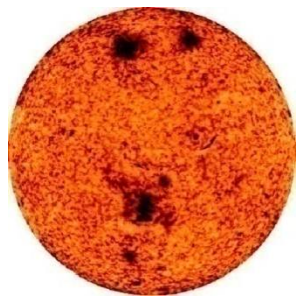
- Survey methods & observing techniques

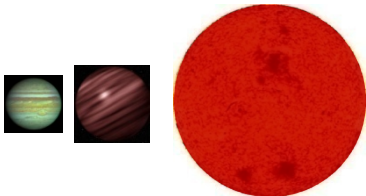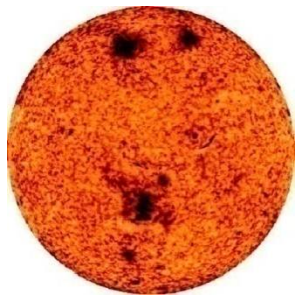- Results

Understanding Stellar Families

Do Sun-like stars have…
C o m p a n i o n s ?

No   **Yes**

Do they have… C h i l d r e n ?

Yes

You are here

No
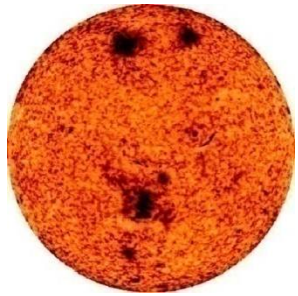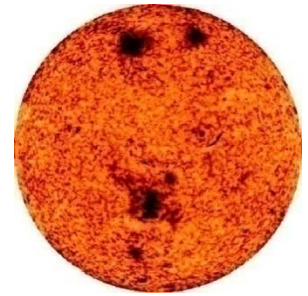
A Modern Update to the DM91 Survey

Citations/Publication Year for 1991A&A...248..485D

- Unrefereed
- Refereed

Total citations: 1197
Total refereed: 961

Publication Year
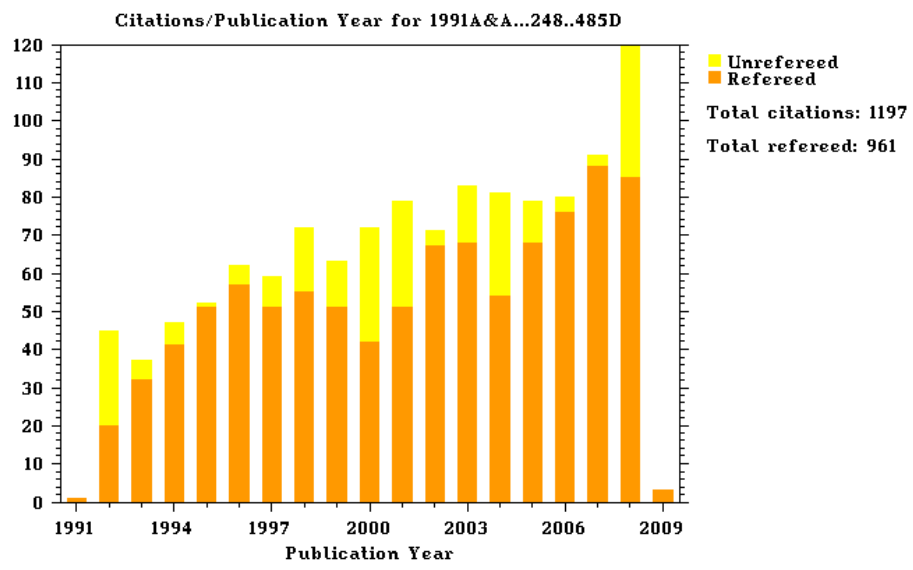
67%

of Sun-like stars have companions with mass > 10 M_{Jup}

- Larger and more accurate sample

- More complete survey
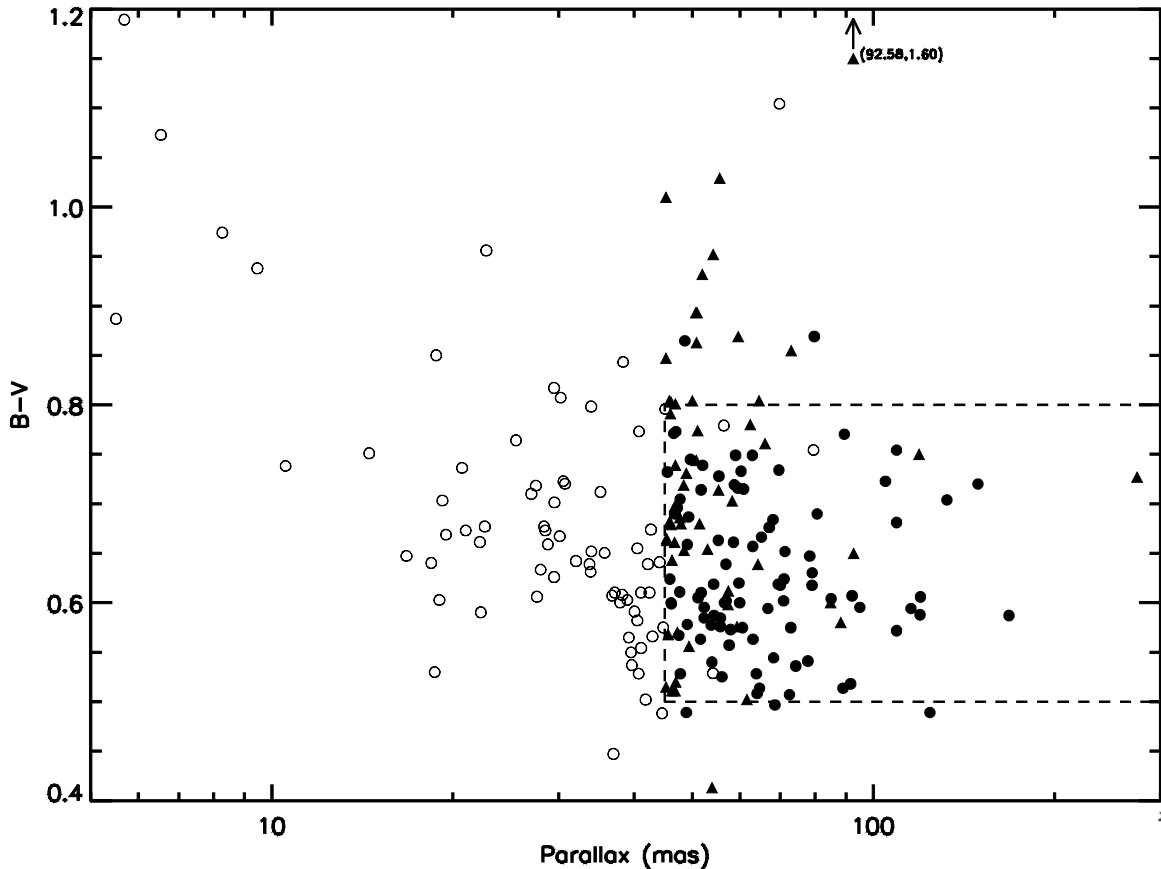
- Check longstanding beliefs

Is the Sun weird?
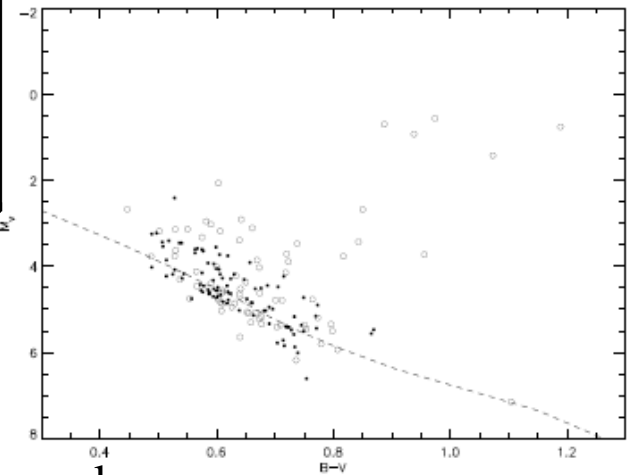
DM91 = Duquennoy & Mayor (1991) A&A 248, 485

The DM91 Sample

Selected from
Gliese (1969)

- F7 – G9
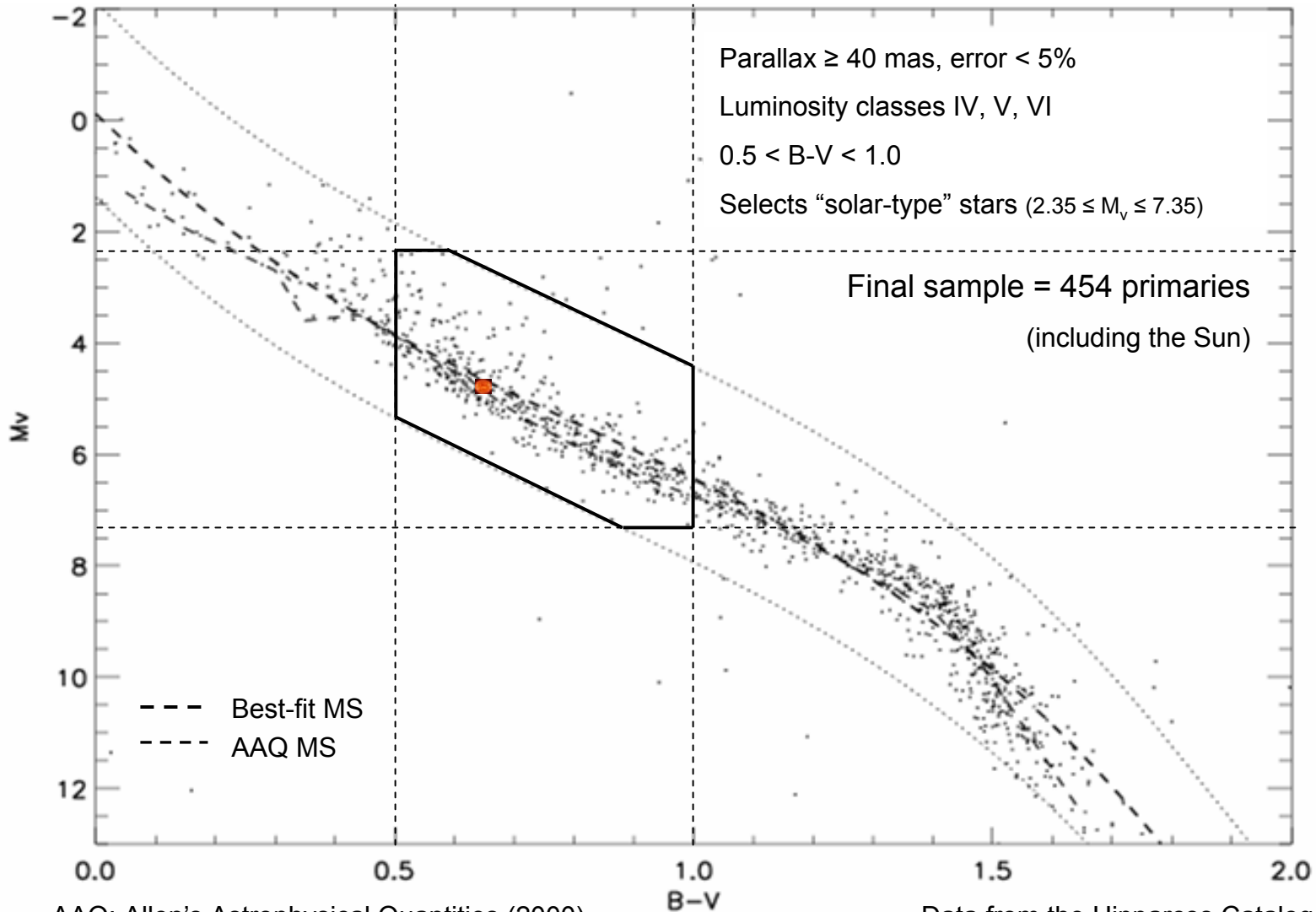- IV-V, V, VI
- Dec > -15°
- π > 45 mas
- N = 164

Using Hipparcos data (N=148):

○ 72 (44%) fall outside their criteria

▲ 56 (38%) match their criteria, but are not in their sample

Defining the Sample

Parallax ≥ 40 mas, error < 5%

Luminosity classes IV, V, VI

0.5 < B-V < 1.0

Selects "solar-type" stars ($2.35 \leq M_v \leq 7.35$)

Final sample = 454 primaries

(including the Sun)

- - - Best-fit MS
- - - - AAQ MS

Mv

B–V

AAQ: Allen's Astrophysical Quantities (2000)

Data from the Hipparcos Catalog
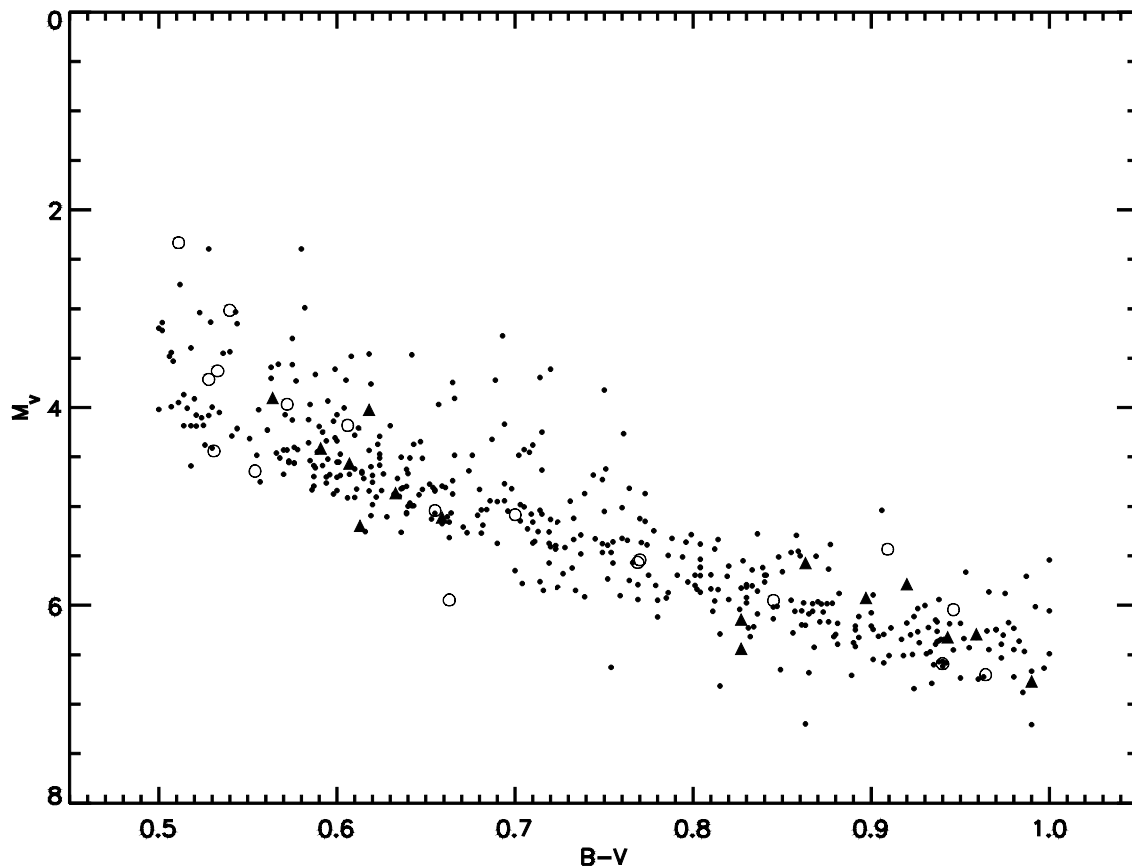
The Current Sample of Solar-type Stars

Selected from

Hipparcos (1997)

- $0.5 < B-V < 1.0$
- IV-V, V, VI
- All-sky
- $\pi > 40$ mas
- N = 454
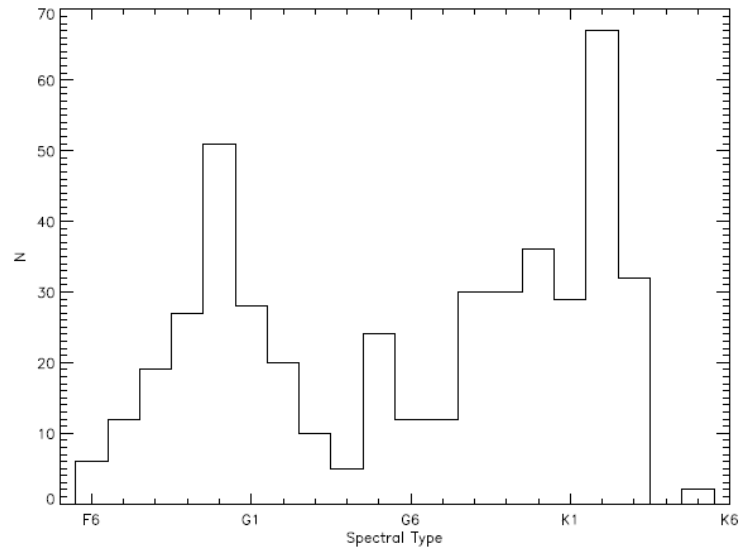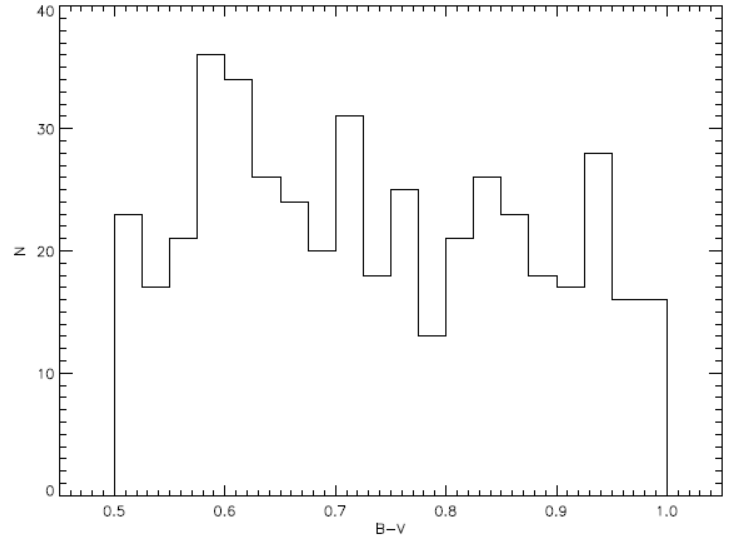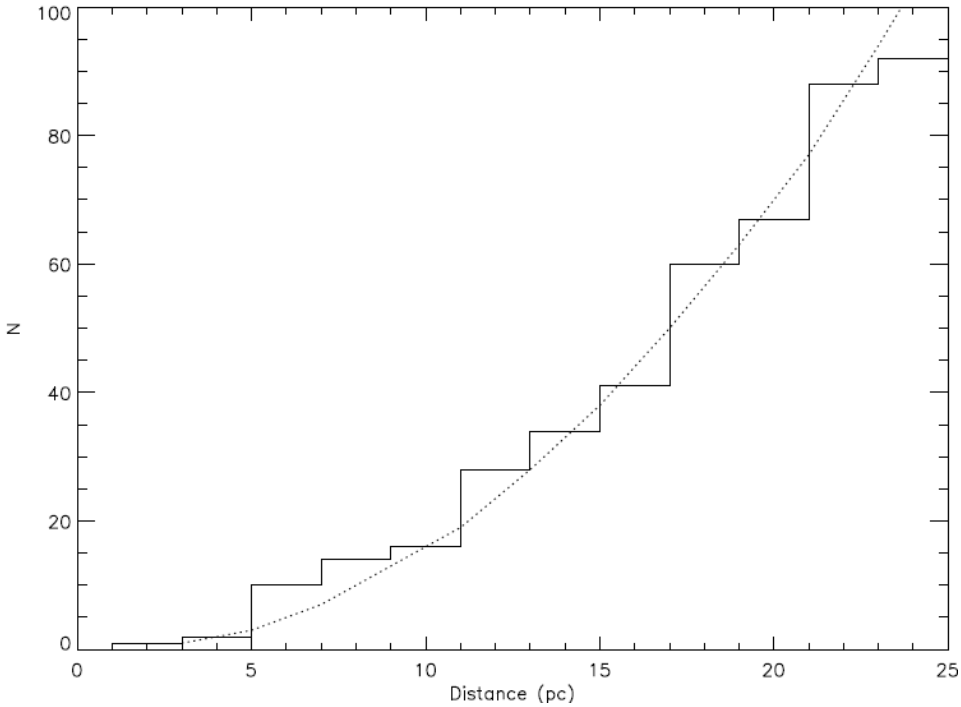
Using van Leeuwen (2007) revisions (N=451):

○ 18 (4%) fall outside the criteria

▲ 15 (3%) matching the criteria not in the sample

Sample Completeness

A Comprehensive Effort

CPM, Visual

Sep ~ 1" – 600"

CHARA

Sep ~ 10 – 120 mas

$\Delta K \lesssim 2$ mag

K < 6 mag

For Separated Fringe Packets

Speckle

Sep ~ 0.035" – 2"

$\Delta mag \lesssim 3$

RV

Period $\lesssim$ 20 yrs

$a \lesssim 0.46"$ *

* for 2 solar-mass stars at 20 pc

Inclination effect

AO

Sep ~ 0.5" – 10"

$\Delta mag \lesssim 10$

The First "Complete" Survey

Georgia State University

Observatoire de la CÔTE d'AZUR

Common Proper Motion

Indicates Companionship, Helps Identify Optical Pairs

HIP 7513
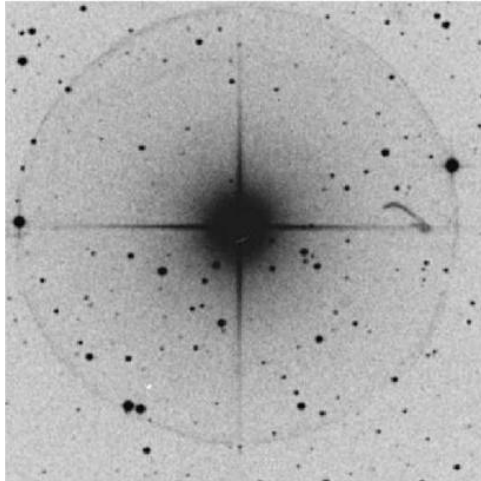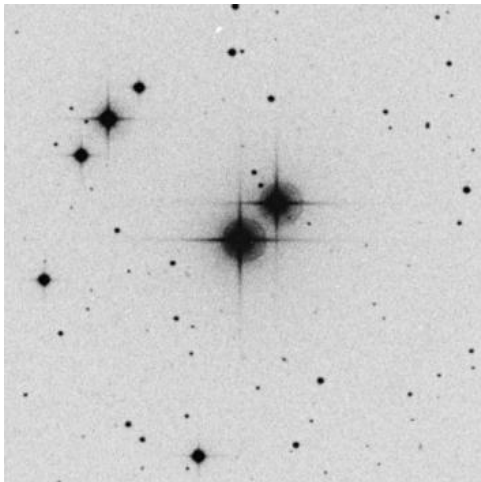
September 1953
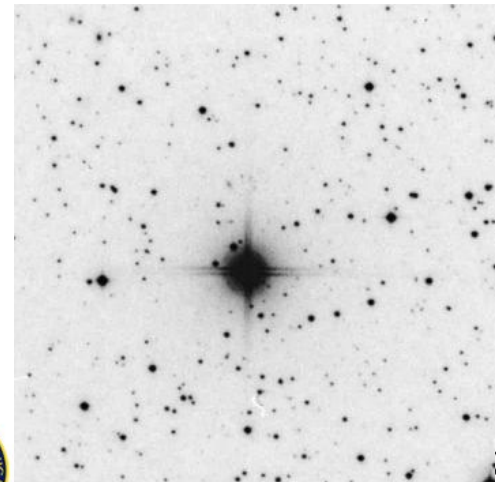
HIP 19859

December 1954

N

E

10' X 10'

HIP 114456
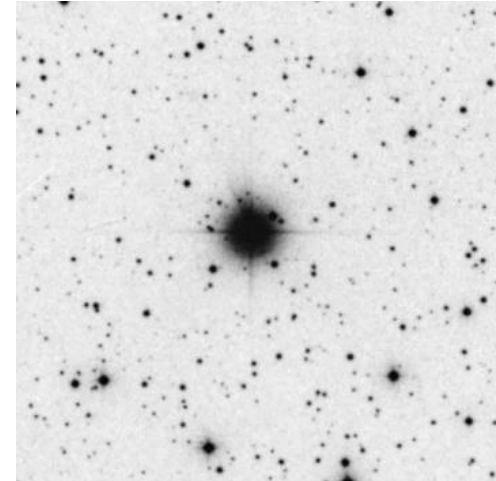
October 1953

HIP 94336

September 1953

Wide CPM Companions
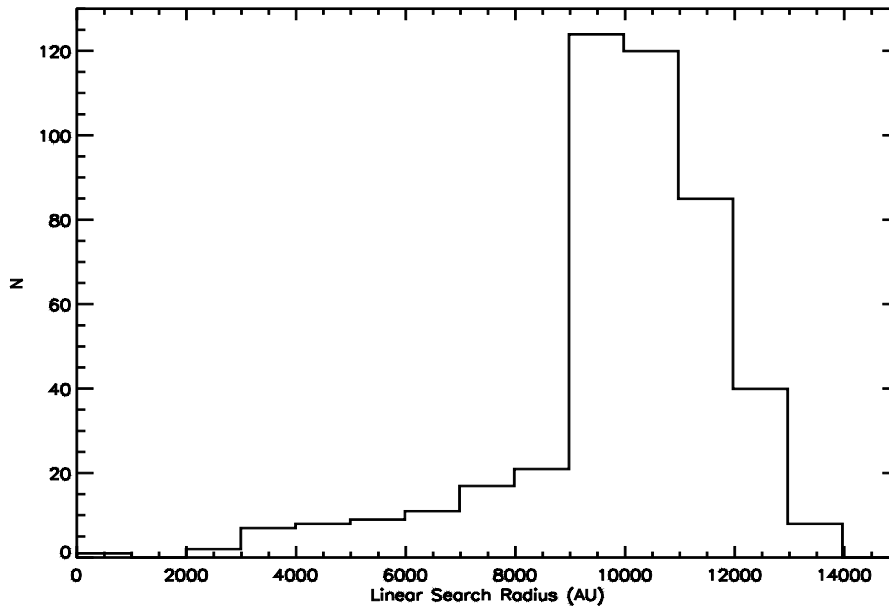
84 candidates
17 refuted
67 confirmed
4 new!

- 90% of the sample investigated
  - 366 (81%) investigated effectively (proper motion clearly seen on blinking)
  - An additional 43 (9%) investigated via marginal motion between images blinked
- Search radius:
  - For d < 20 pc, searched out to 660'' (22' images)
  - For d > 20 pc, searched out to 450'' (15' images)
- Effectively searched 400 – 10,000 AU for companions with $R < 17$
- Confirmed or refuted by follow-up photometry

CHARA: Separated Fringe Packets

Efficient for surveys (> 15 targets per night)

Detection limits

- V ≤ 9, K ≤ 6, Dec ≥ -10°
- Separations ~ 10 – 120 mas
- ΔK ≤ 2

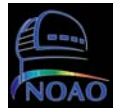   Can detect early M for G primary and mid M for K primary (q ≥ 0.5)

187 targets + 92 observed by CF

233 null detections, 7 companions seen   0 new
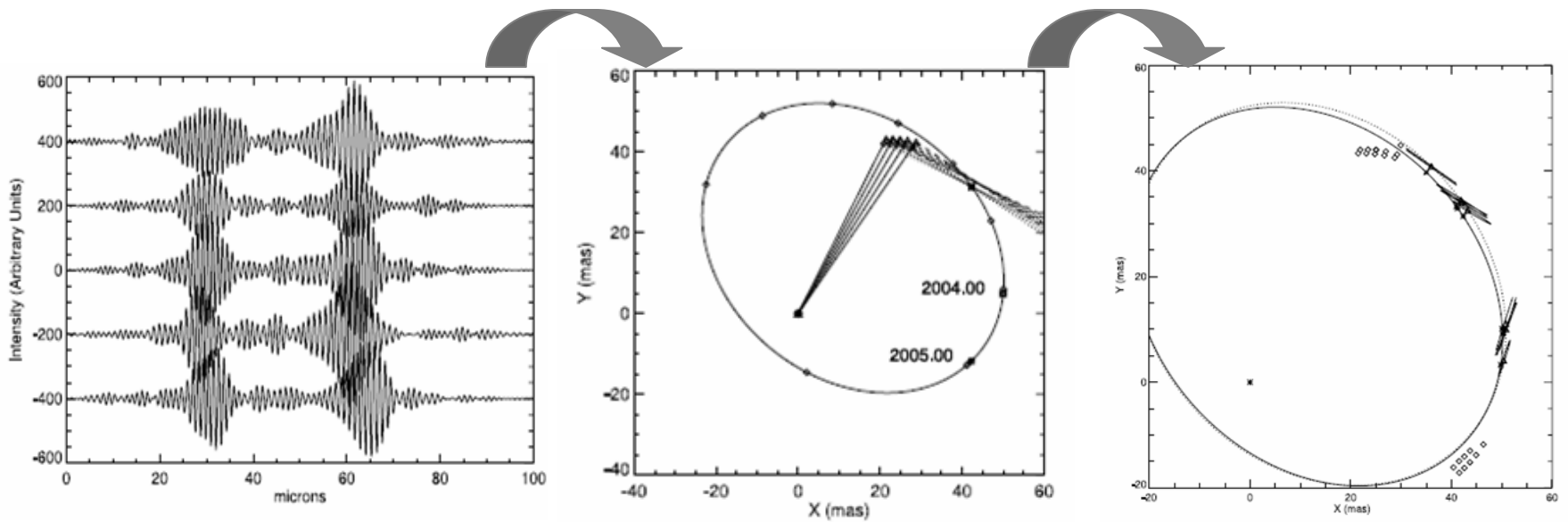
Source: Bagnuolo et al. (2006) AJ 131, 2695

SFP Survey Null Result

- Gap between spectroscopic and visual techniques has been previously seen
  - Bouvier et al. 1997, Mason et al. 1998
- No such gap in the current study
- Excellent spectroscopic coverage…
  - Longstanding RV studies over 30 years, ± 0.5 km/s precision
    - CORALIE, CfA
  - High-precision measures over 12 years, ± 3 m/s precision
  - Can detect orbits of few tens of years
    - Separations out to 400 mas (P=30y, M_{sum}=1.5M_{Sun}, d= 20pc, i=45°)
- Augmented by extensive high-resolution visual coverage
  - 450 / 453 targets observed by speckle interferometry at least once
  - Separations ≥ 30 mas

Spectroscopic

Visual

CHARA Visual Orbits

- Four short-period binaries resolved
  - HD 8997, 45088, 146361, 223778

- Separations 1.2 – 8.1 mas

- HD 146361 (σ^2 CrB) published results
  - Shortest period (1.1 day) SB resolved
  - Central pair of a quintuple system
  - $M_1 = 1.137 \pm 0.037$ M_{sun}
  - $M_2 = 1.090 \pm 0.036$ M_{Sun}

Component Masses (M_{sun})

HD 8997
    $M_1 = 1.446 \pm 0.122$ Prelim
    $M_2 = 1.193 \pm 0.101$

HD 45088
    $M_1 = 0.831 \pm 0.101$ Prelim
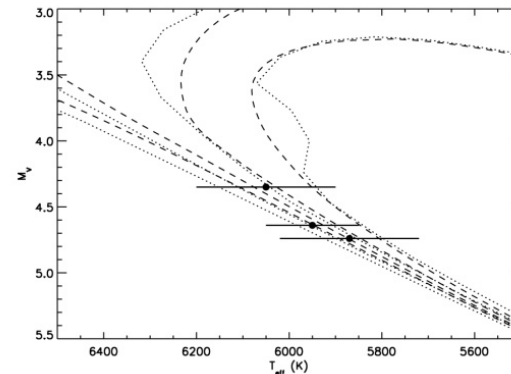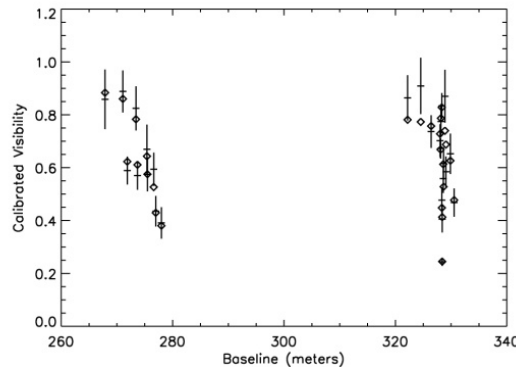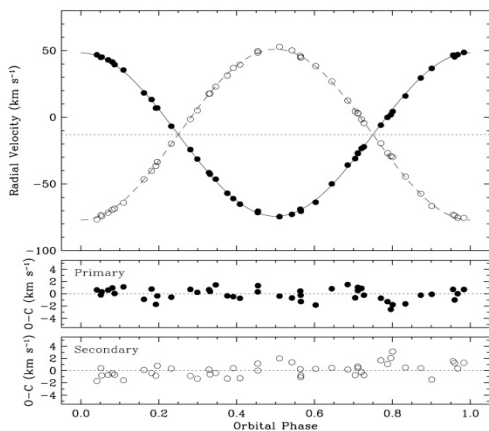 $M_2 = 0.709 \pm 0.087$

HD 223778
    $M_1 = 0.786 \pm 0.014$ Final
    $M_2 = 0.784 \pm 0.014$

Source: Raghavan et al. 2009 ApJ 690, 394

Georgia State University

Other Astrometric Companions

- ## Speckle Interferometry
  - 450 / 453 targets observed (99% completion)

- ## Washington Double Star Catalog (WDS)
  - 504 pairs investigated
    - 184 confirmed companions, 313 confirmed optical, 7 candidates
  - The Sixth Visual Orbit Catalog (37 orbits + 31 prelim)
  - The Fourth Interferometric Catalog (includes null results)

- ## Catalog of Nearby Stars (CNS)
  - 198 companions investigated
    - 148 CPM companions: 142 confirmed, 6 refuted
      - Two extra-wide companions (15' and 20') unique in this source
    - 50 SB/RV companions: 22 confirmed, 25 refuted, 3 candidates

- ## Hipparcos Double Stars (C, G, O, X)
  - 99 companions investigated
   - 91 confirmed, 6 refuted, 2 candidates

Radial Velocity Studies

- The Ninth Catalog of Spectroscopic Binaries

- The CfA radial velocity survey (D. Latham)
  - Accuracies of ~ 0.5 km/s
  - Coverage of up to 30 years!
  - Obtained data on 355 stars (78%)

- Planet search velocities (G. Marcy, A. Hatzes, W. Cochran)
  - Accuracies below 10 m/s
  - Coverage of over 10 years in many cases
  - Obtained data on 306 stars (67%)

- 48 SB1, 27 SB2, 2 (+ 4 candidate) RV-var   6 new

- 254 / 454 (56%) stars are RV constant
  - This is a lower limit!

Radial Velocity Coverage: CfA
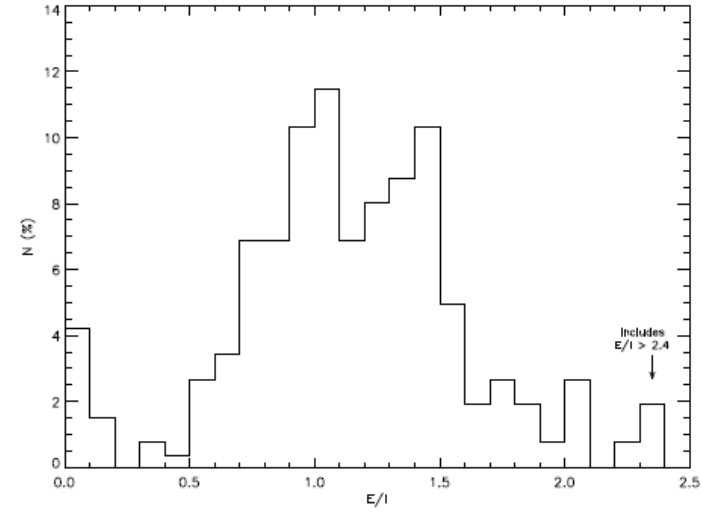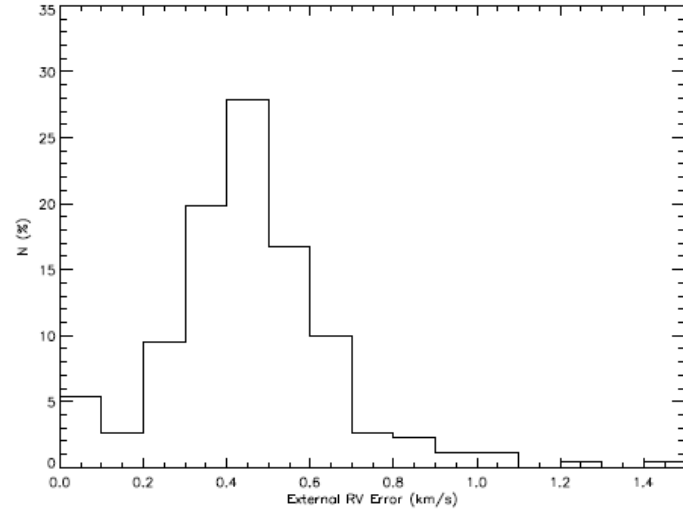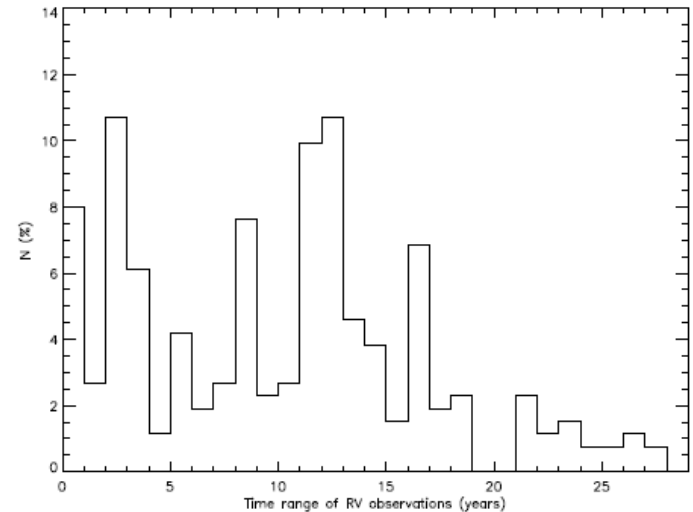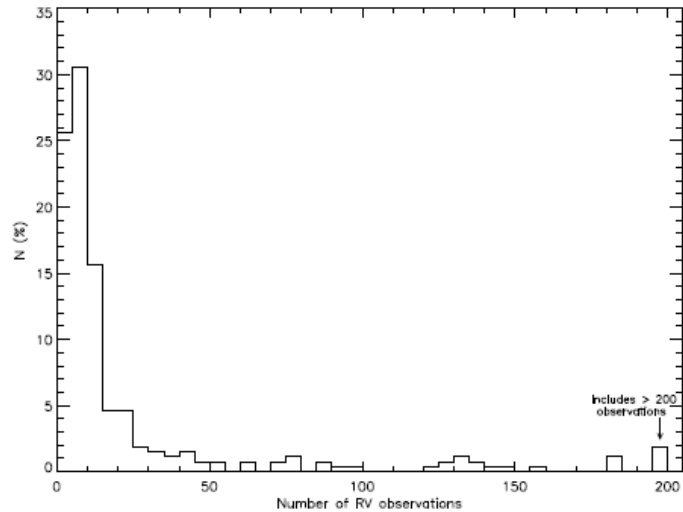
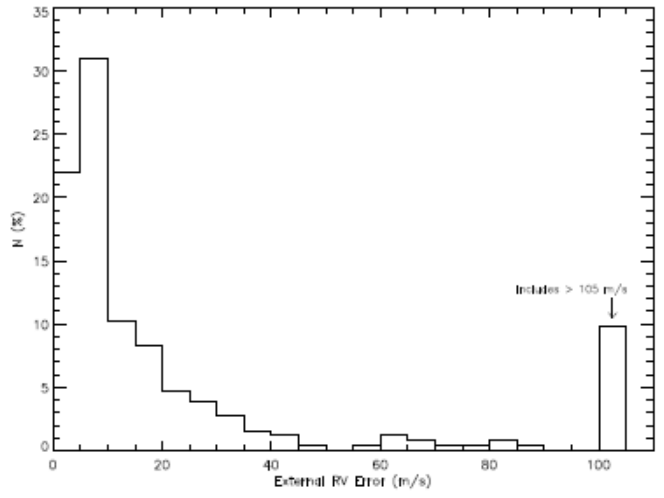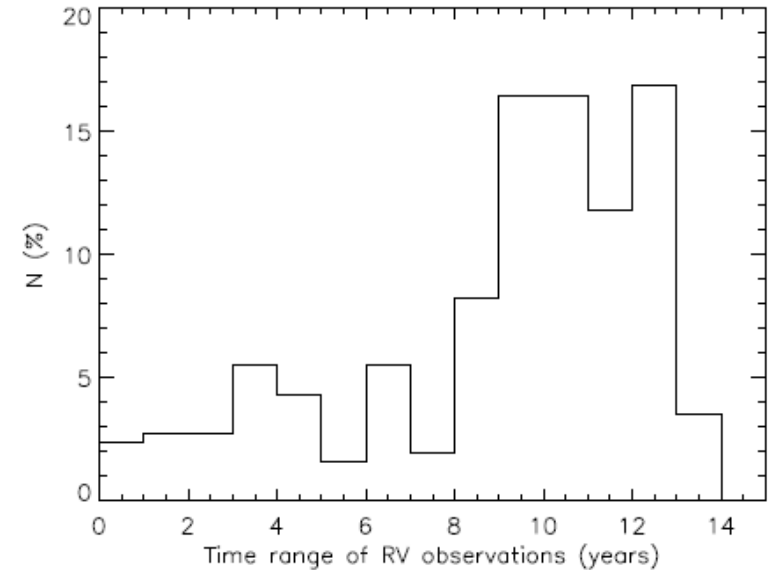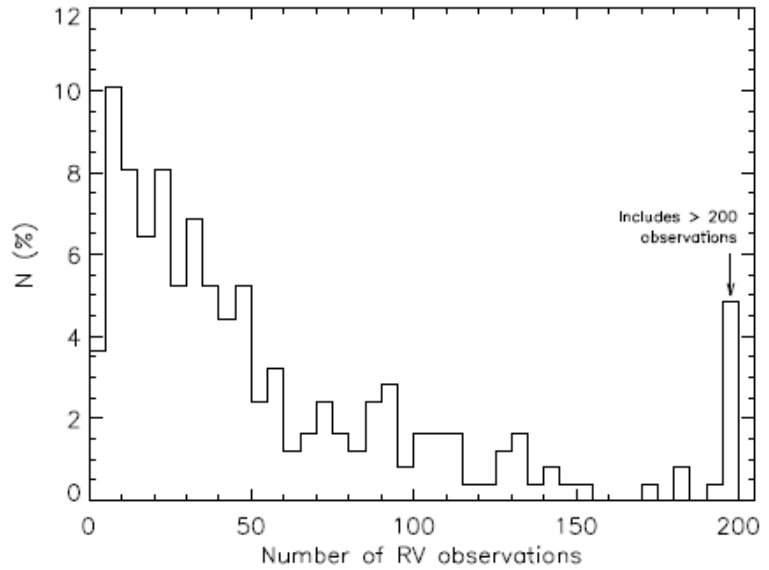Note: Only constant-velocity stars included in the bottom two plots

Radial Velocity Coverage: CCPS

P(χ^2) not a Good Variability Indicator
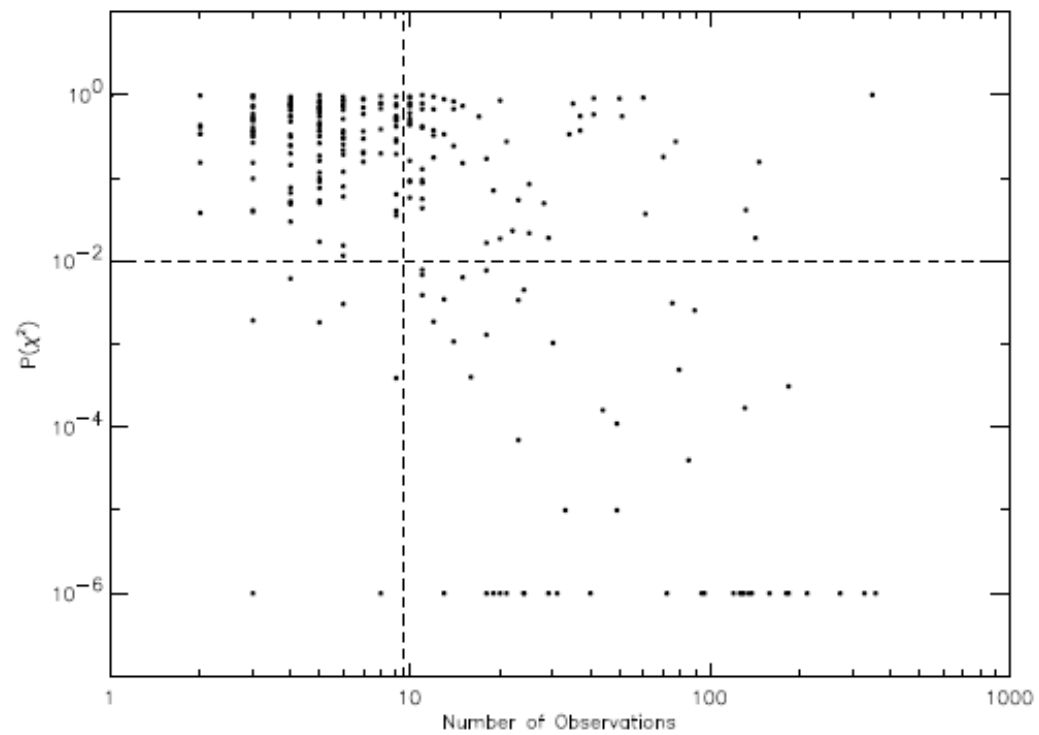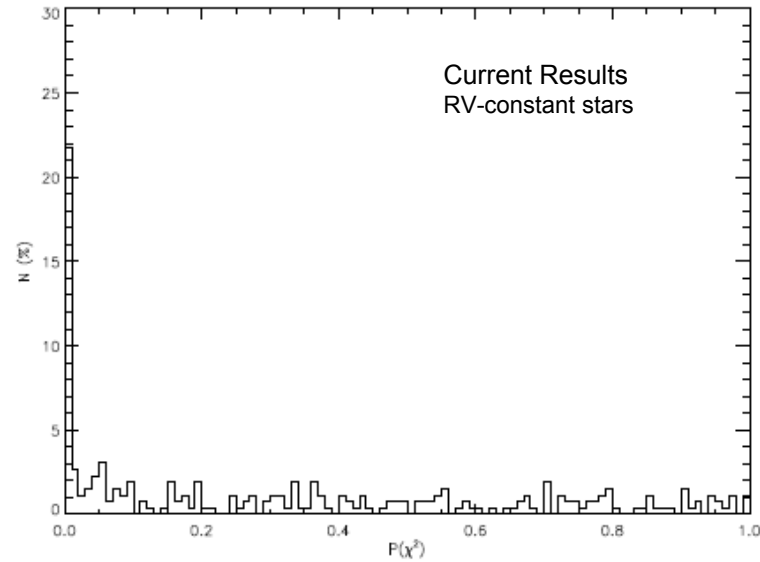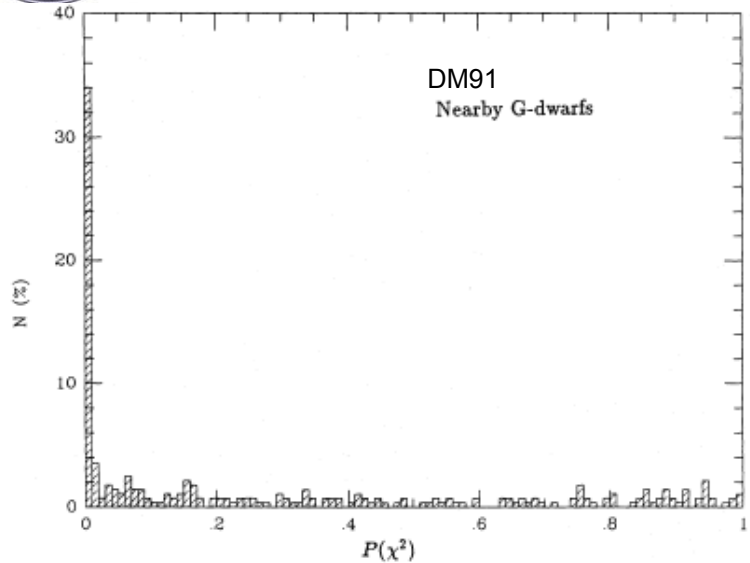
Multiplicity Results: Companion Counts

TABLE 7.3: Classification of 258 Confirmed Companions in the sample of 454 Solar-Type Stars

Code	Description	U	VBO	VBP	VBU	SB1	SB2	SBV	CPT	CPP	CPS	CPO	CPM	CPR	URE	URL	URM	CHS	CHV
VB-O	VBO: Definitive	7	38	...	...	3	18	1	...	...	...	...	...	...	...	...	17	6	3
VB-P	VBO: Preliminary	12	...	33	...	4	...	...	1	...	...	...	...	...	...	...	18	...	...
VB-U	VBO: Photocentric Motion	1	...	...	21	14	1	1	...	...	...	...	...	7	...	...	10	2	...
SB-1	SB1: Orbital Solution	16	3	4	14	48	...	...	...	...	...	...	...	1	...	...	21	1	...
SB-2	SB2: Orbital Solution	4	18	...	1	...	27	...	...	...	...	...	...	1	1	...	10	6	4
SB-V	RVV: RV Variations	1	1	...	1	...	...	9	...	...	...	1	1	2	...	...	4	...	...
CP-T	CPM: Matching π_{trig}	29	...	1	...	...	...	...	30	...	...	...	...	...	...	...	...	...	...
CP-P	CPM: Matching π_{phot}	39	...	...	...	...	...	...	...	42	...	...	...	...	...	...	3	...	...
CP-S	CPM: Matching π_{spec}	5	...	...	...	...	...	...	...	...	6	...	...	...	...	...	1	...	...
CP-O	CPM: Orbital Motion	3	...	...	...	...	...	1	...	...	...	10	...	...	...	...	6	...	...
CP-M	CPM: Matching μ	20	...	...	...	...	...	1	...	...	...	...	26	...	...	...	5	...	...
CP-R	CPM: Other (Published)	2	...	...	7	1	1	2	...	...	...	...	...	11	...	...	6	1	...
UR-E	Unres: Eclipsing Binary	1	...	...	...	...	1	...	...	...	...	...	...	...	2	...	...	...	...
UR-L	Unres: Over-luminous	1	...	...	...	...	...	...	...	...	...	...	...	...	...	1	...	...	...
UR-M	Unres: Accelerating μ	8	17	18	10	21	10	4	...	3	1	6	5	6	...	...	85	2	...
CH-S	CHARA: SFP	...	6	...	2	1	6	...	...	...	...	...	...	1	...	...	2	8	...
CH-V	CHARA: Visibility	...	3	...	...	...	4	...	...	...	...	...	...	...	...	...	...	...	4

Multiplicity Results

	Percentage of stars					
	★	★★	★★★	★★★★	★★★★★	★★★★★★
DM91 observed (N = 164)	57	38	4	1		
DM91 including $P(\chi^2) < 0.01$	51	40	7	2		
DM91 incompleteness analysis (q > 0.1)	43					
DM91 single stars ($M_2 < 10$ M_J)	33					
This work, observed (N = 454)	57±3	33±2	8±1	2±1	0.4	
This work, including candidates	54±2	34±2	9±2	2±1	0.2	0.2
This work, incompl analysis (q > 0.01)	54±3	35±2	9±2	2±1		
Among Planetary Systems						
Raghavan et al. 2006 (N = 131)	77	21	2			
This work, observed (N = 34)	68	29	3			
This work, planet-host frequency	8±2	7±2	3±3			

Multiplicity by Spectral Type
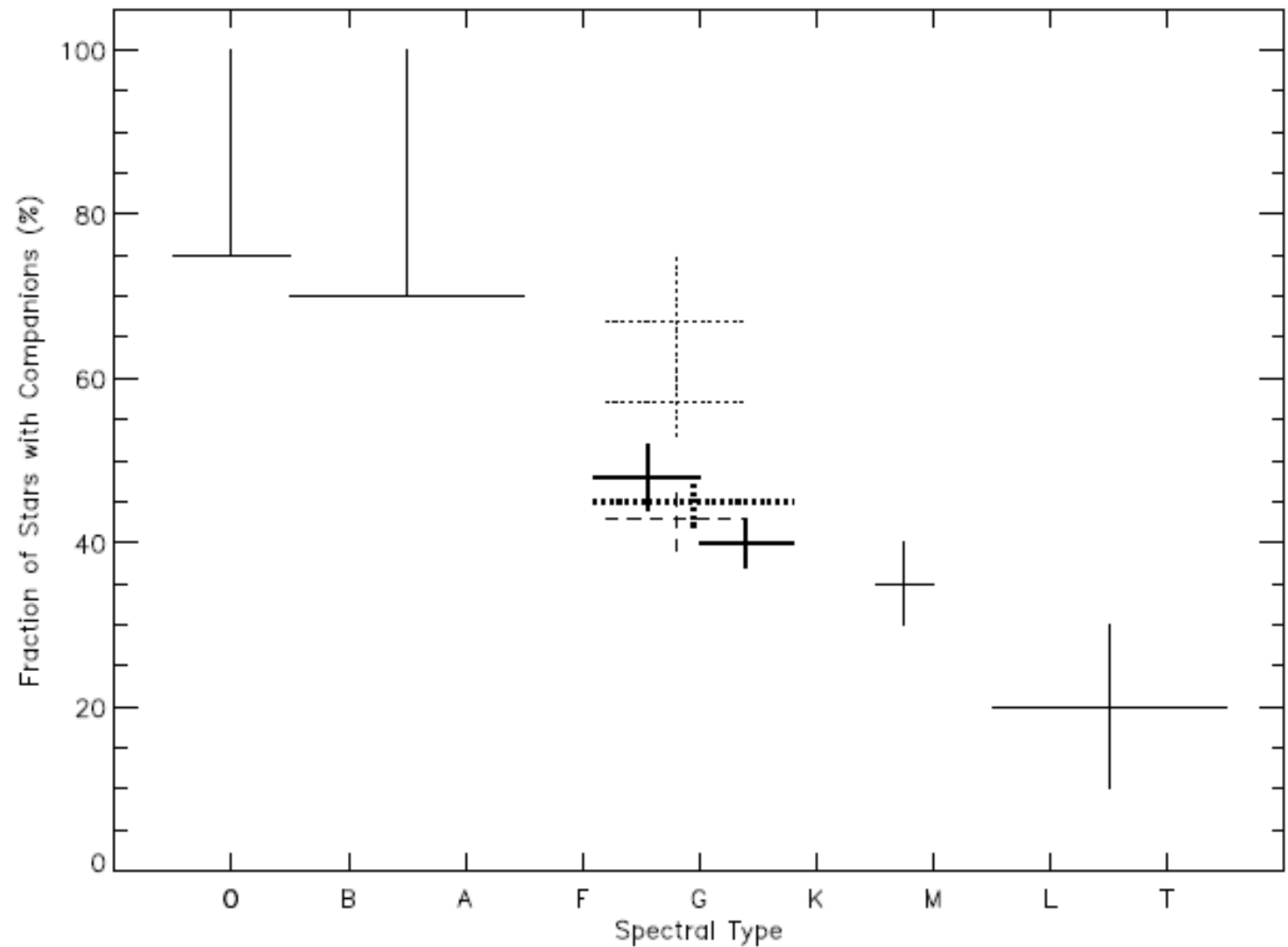
Companions Erode with Age
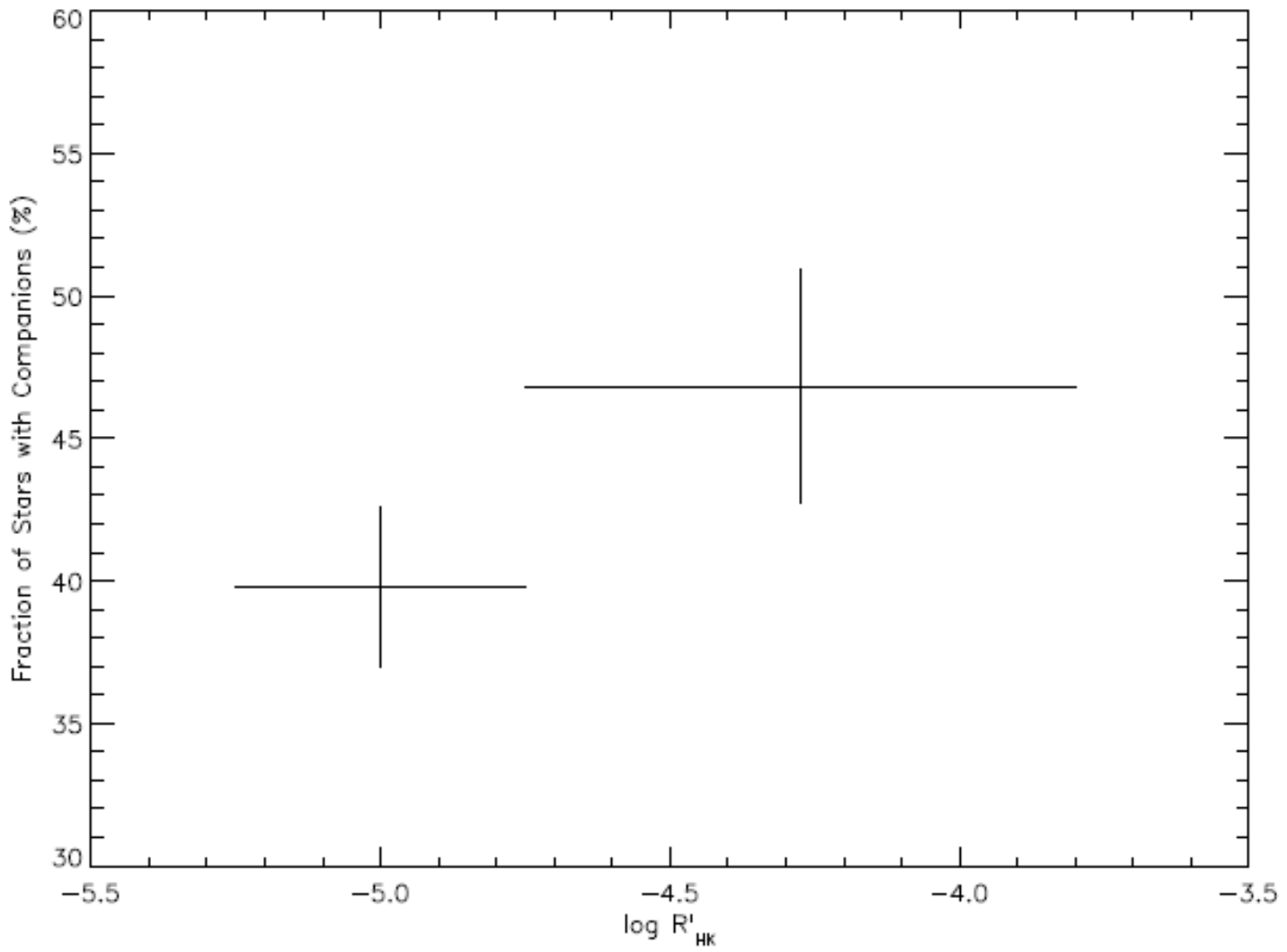
Effect of Metallicity on Multiplicity

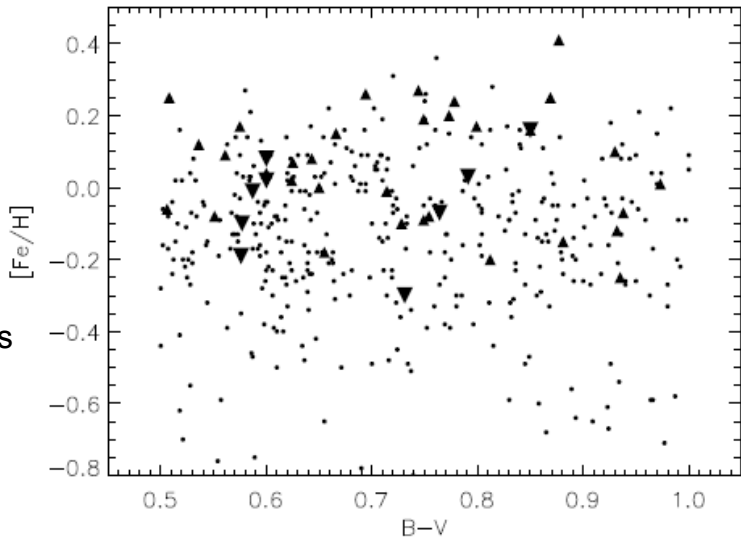- ● Stars without companions

- ▲ Stars with companions
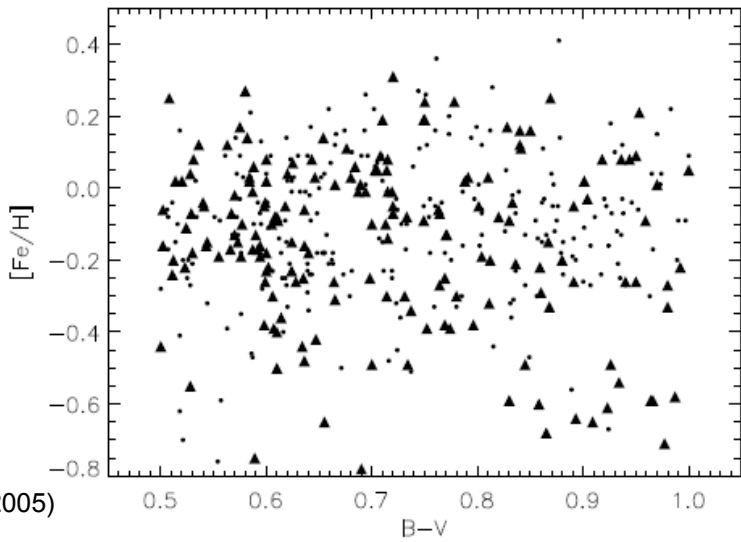
No correlation between metallicity and stellar companions, as expected

"Stars form like stars"

Planet-Metallicity Correlation
First reported by Fischer & Valenti (2005)
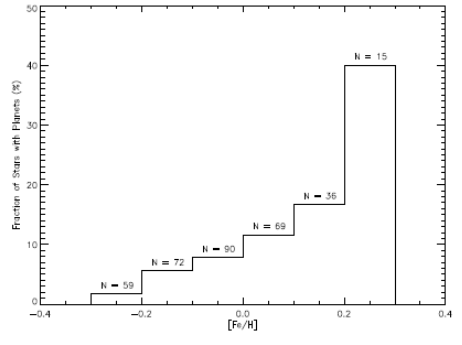
- ● Stars without planets or BDs

- ▲ Stars with planets

- ▼ Stars with brown dwarfs

Tantalizing indication that brown dwarfs form like planets rather than like stars, at least when they are companions to stars

Georgia State University

Period Distribution
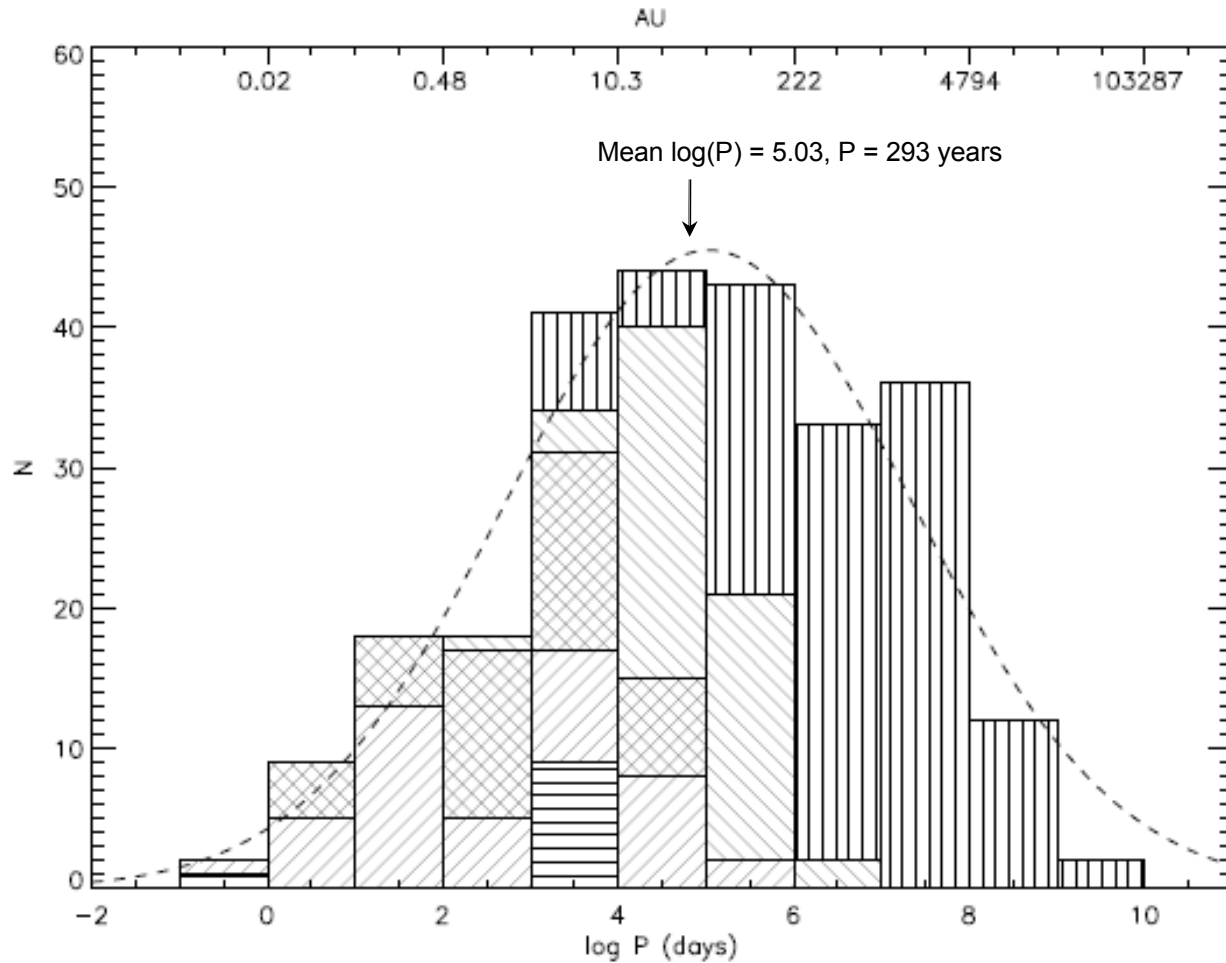
- Significant overlap of techniques in all but the longest period bins (SB, VB gap closed)
- 66% of pairs have separations greater than 10 AU, leaving room for planets

Period-Eccentricity Relationship
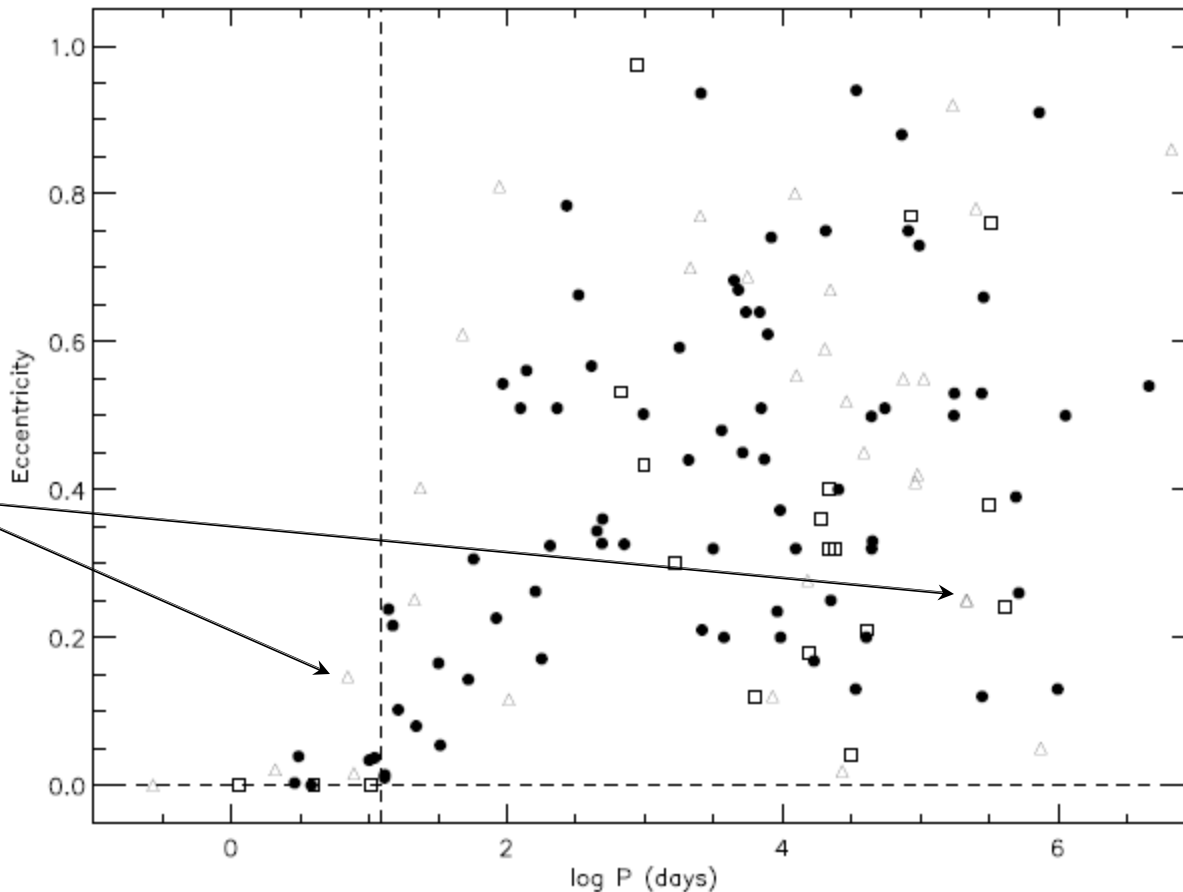
HD 45088 components

Very young system
log (R'$_{HK}$) = -4.27
High rotation
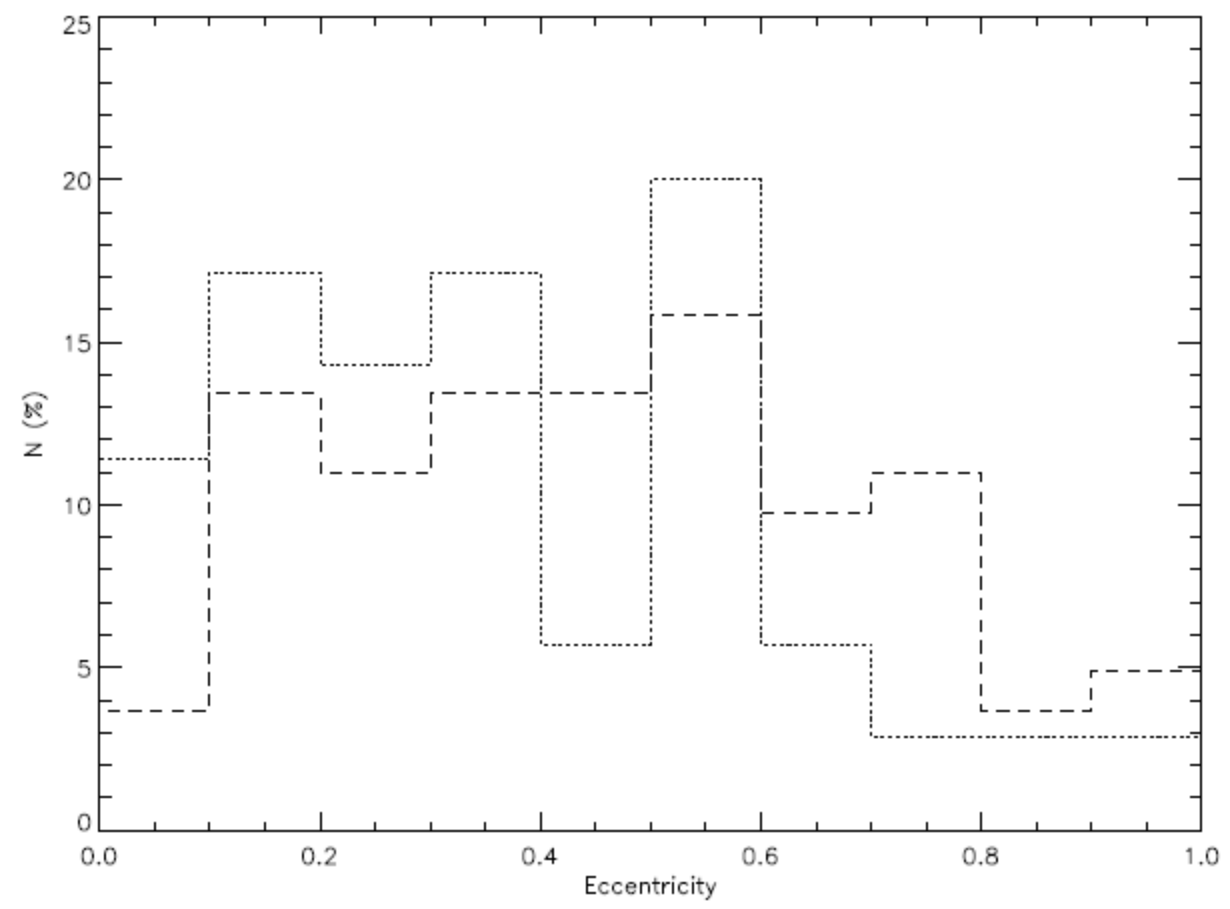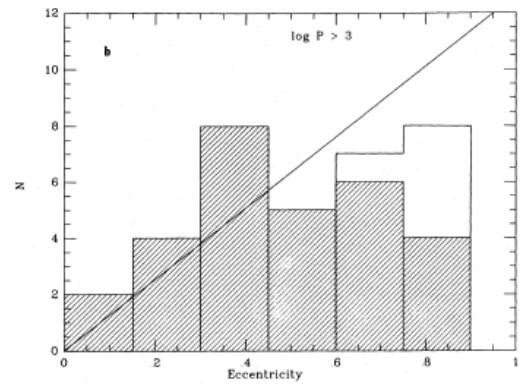Emission in spectra

- ● Binaries
- △ Triple
- □ Quadruple

- Consistent with DM91, components of triples seen to have higher eccentricity

Eccentricity Distribution
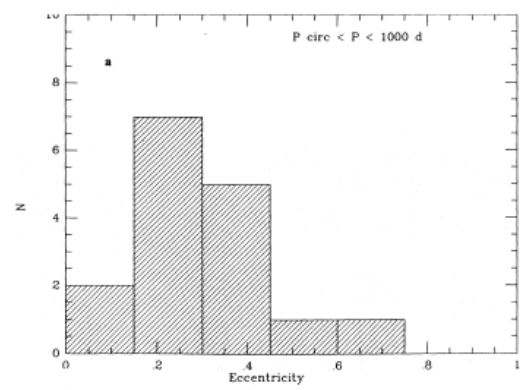
DM91 results

- In contrast to DM91, no relationship is seen between period and eccentricity distribution
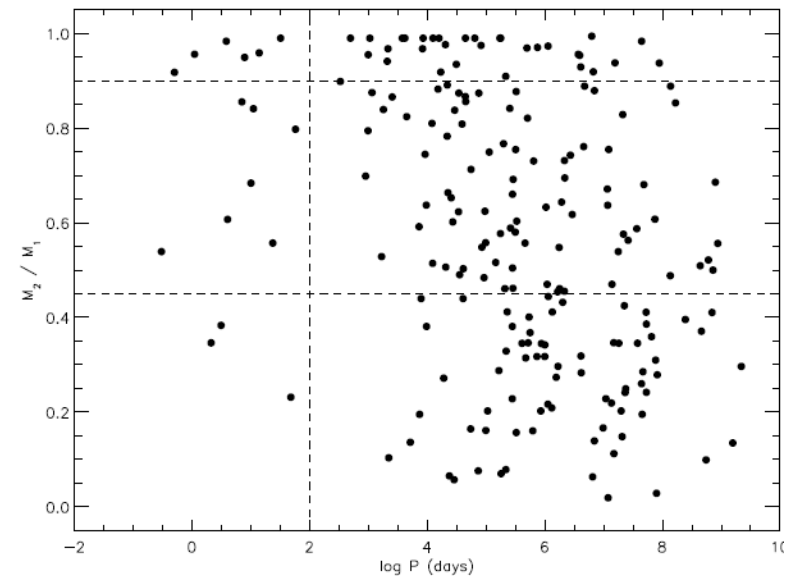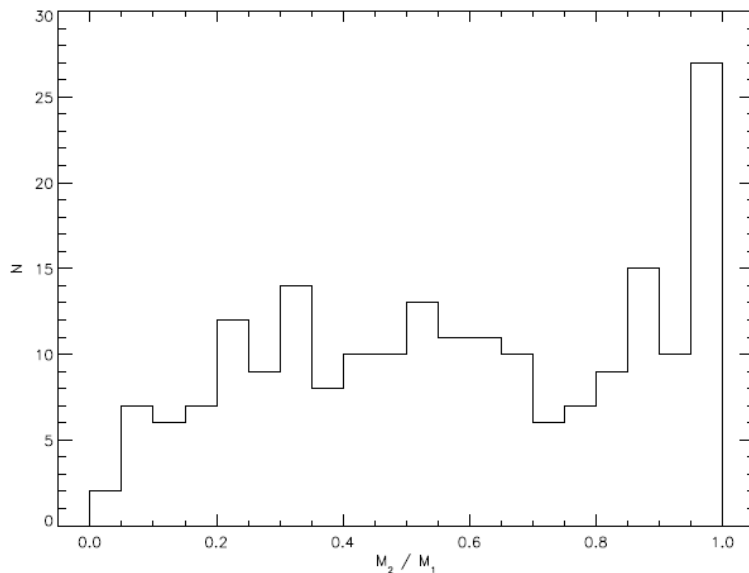
.... P < 1000 days (35 systems)

- - - - P > 1000 days (82 systems)

Mass-Ratio Distribution

- Another departure from DM91
  - Twins are definitely preferred (consistent with Abt & Levy 1976)
- Twins are not confined to short-period systems
  - Fragmentation is only one of the formation mechanisms
- Correlation between mass-ratio and period
  - Percentage of systems with P < 100 days
    - 4% for mass-ratio < 0.45;   8% for 0.45 < mass-ratio < 0.9;   16% for mass-ratios > 0.9
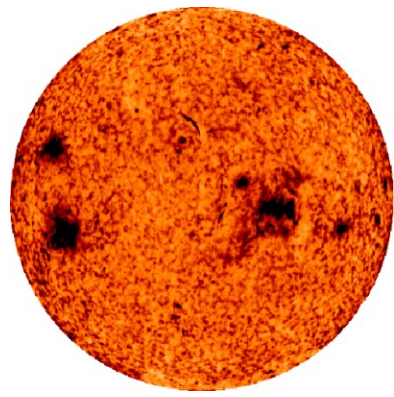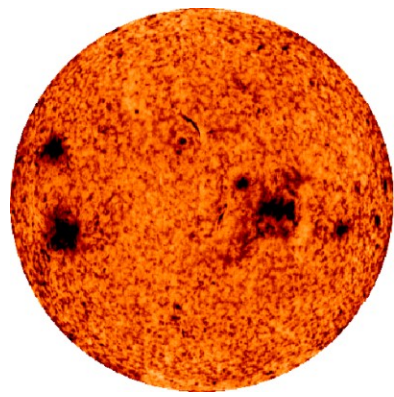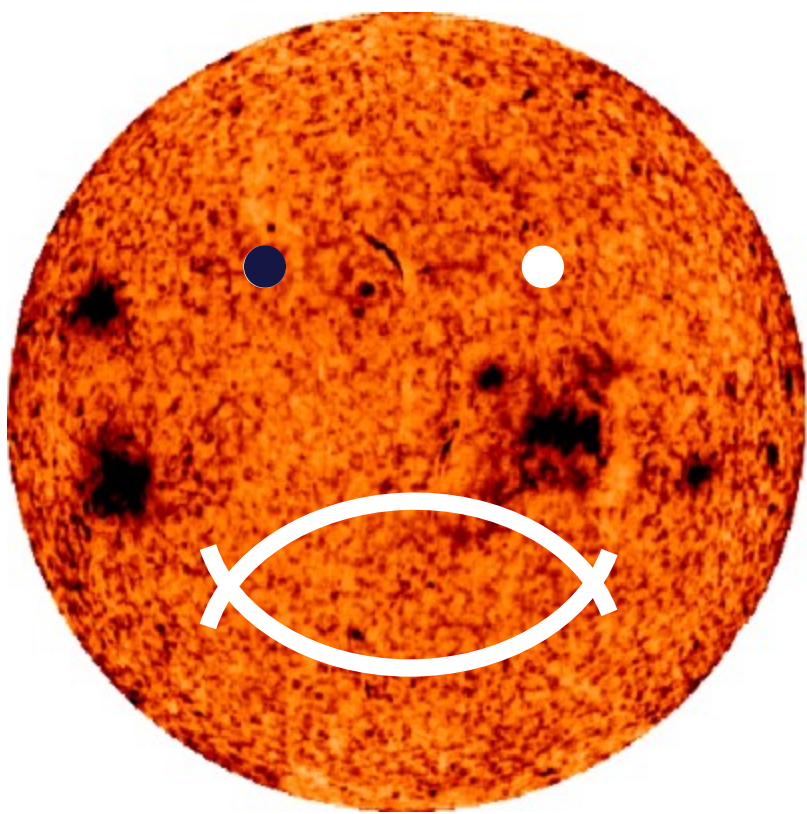
So, is the Sun Weird?

DM91 results

67%
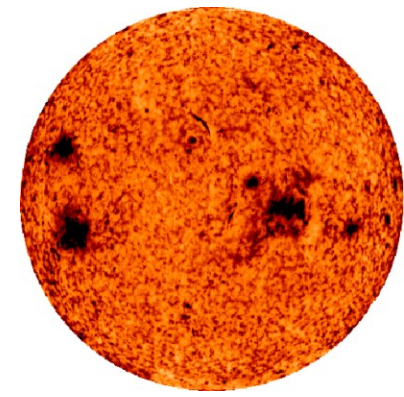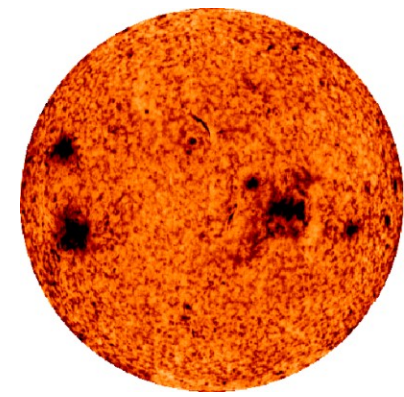
So, is the Sun Weird?

54% Updated results