Collaborators

Hal McAlister  GSU
Todd Henry  GSU
David Latham  Harvard-Smithsonian CfA
Geoff Marcy  UC Berkeley
Brian Mason  USNO
Doug Gies  GSU
Russel White  GSU
Theo ten Brummelaar  CHARA

William Cochran  McDonald Observatory
Artie Hatzes  Thuringia Observatory, Germany
Hugh Jones  Univ of Hertfordshire, UK
Jason Wright  Cornell University
Richard Gray  Appalachian State University
William Hartkopf  USNO
Dimitri Pourbaix  Institut d'Astronomie, Belgium
Andrei Tokovinin  CTIO
Willie Torres  Harvard-Smithsonian CfA
The CHARA Team
Presentation Outline

Motivation for this effort

- The sample of nearby solar-type stars
- Survey methods & observing techniques
- Current Results
Understanding Stellar Families

Do Sun-like stars have... Companions?

Do they have...?

Children?

No   Yes

No   Yes

You are here
Presentation Outline

• Motivation for this effort

➡️ The sample of nearby solar-type stars

• Survey methods & observing techniques

• Current Results
Defining the Sample

Solar-type stars in the solar neighborhood

Parallaxes ≥ 40 mas, error < 5%
Luminosity classes IV, V, VI
0.5 < B-V < 1.0

Final sample = 454 primaries
(including the Sun)

Data from the Hipparcos Catalog
Sample Distribution
Sample Completeness

Tycho-2 completeness: \( V < 11 \) (Hog et al. 2000)

Hipparcos completeness:
- \( V_{\text{lim}} < 7.9 + 1.1 \sin |b| \)  \( \text{SpT} < \text{G5} \)
- \( V_{\text{lim}} < 7.3 + 1.1 \sin |b| \)  \( \text{SpT} > \text{G5} \) (Turon et al. 1992)
Presentation Outline

• Motivation for this effort

• The sample of nearby solar-type stars

→ Survey methods & observing techniques

• Current Results
A Comprehensive Effort

CPM
- Sep ~ 10” – 600”

CHARA
- Sep ~ 10 – 80 mas
- $\Delta K \leq 2$ mag
- $K < 6$ mag
- For Separated Fringe Packets

RV
- Period $\leq 30$ yrs
- $a \leq 0.4”$ *
  - * for 1.5 solar-mass stars at 20 pc inclination effect

AO, Visual
- Sep ~ 0.5” – 10”
- $\Delta$mag $\leq 10$

Speckle
- Sep ~ 0.035” – 2”
- $\Delta$mag $\leq 3$

The First “Complete” Survey
Detection Limits of the Survey

![Graph showing the detection limits of a survey with axes labeled Semimajor Axis (AU) and log P (days). The graph includes markers for different detection methods such as SFP, Speckle, RV-CfA, RV-CCPS, AO, and CPM.](image-url)
CHARA Astrometry

CPM
Sep ~ 10” – 600”

CHARA
Sep ~ 10 – 80 mas
ΔK ≤ 2 mag
K < 6 mag
For Separated Fringe Packets

Speckle
Sep ~ 0.035” – 2”
Δmag ≤ 3

RV
Period ≤ 30 yrs
a ≤ 0.4” *
* for 1.5 solar-mass stars at 20 pc
inclination effect

AO, Visual
Sep ~ 0.5” – 10”
Δmag ≤ 10

The First “Complete” Survey
Modeling SFP Fringes

- All stars assumed to be 20 pc away
- fakecc parameters
  - b: 331 m (S1-E1 baseline)
  - f: If R0 >= 6 cm –f 750/150, else –f 500/100
  - n: photon count for primary \( N_{ph} = 2.37 \times 10^{(9- M)/2.5} \)
  - p: R0=10 cm (velocity assumed 10 m/s)
  - r: 145 microns (dither mirror scan range)
  - S: V,sep,beta
    - Separation in microns = Baseline * sep-arcsec * unit-conv
    - Beta = Sec-flux / Prim-flux
    - V = secondary visibility (B, diameter, wavelength)
  - V: primary’s visibility
Varying Flux: \( R_0 = 10 \text{ cm}, \) \( \text{Sep} = 50 \text{ mas} \)

- **G0 pair, \( K = 4.7 \)**
- **G5 pair, \( K = 5.0 \)**
- **K0 pair, \( K = 5.6 \)**
- **K5 pair, \( K = 6.1 \)**
- **M0 pair, \( K = 6.7 \)**
- **M2 pair, \( K = 7.3 \)**
Varying Seeing: G0+K0, Sep=50 mas

R0=20

R0=10

R0=6

R0=3
Varying Seeing: G0+K0, Sep=50 mas

R0=20

R0=10

R0=6

R0=3
Varying Separation: G0+G5, R0=10

Sep = 5 mas

Sep = 8 mas

Sep = 12 mas

Sep = 20 mas
Varying Separation: G0+G5, R0=10

Sep = 30 mas  Sep = 50 mas  Sep = 70 mas  Sep = 80 mas
Varying Separation: G0+G5, R0=10

Sep = 5 mas

Sep = 8 mas

Sep = 12 mas

Sep = 20 mas

Sep = 30 mas

Sep = 50 mas

Sep = 70 mas

Sep = 80 mas
Varying Contrast: G0, R0=10, Sep=20 mas

Comp K0, dK=0.9

Comp K5, dK=1.4

Comp M0, dK=2.0

Comp M2, dK=2.6
Varying Contrast: G0, R0=10, Sep=20 mas

Comp K0, dK=0.9

Comp K5, dK=1.4

Comp M0, dK=2.0

Comp M2, dK=2.6
Varying Contrast: K0, R0=10, Sep=20 mas

Comp K5, dK=0.5

Comp M0, dK=1.1

Comp M2, dK=1.7

Comp M5, dK=2.9

Example BP filtered Fringes with Envelope
Varying Contrast: K0, R0=10, Sep=20 mas

Comp K5, dK=0.5

Comp M0, dK=1.1

Comp M2, dK=1.7

Comp M5, dK=2.9
SFP Null Result

- Gap between spectroscopic and visual techniques 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, Msum=1.5MSun, d= 20pc, i=45°)

- Augmented by extensive high-resolution visual coverage
  - All 453 targets observed by speckle interferometry at least once
  - Separations \geq 30 mas

\begin{figure}
\centering
\includegraphics[width=\textwidth]{sfp-null_result.png}
\caption{SFP Null Result}
\end{figure}
Presentation Outline

• Motivation for this effort
• The sample of nearby solar-type stars
• Survey methods & observing techniques

➤ Current Results
  – Multiplicity statistics
  – Orbital elements & physical parameters
## Multiplicity Results

<table>
<thead>
<tr>
<th>Percentage of stars</th>
<th>★</th>
<th>★★</th>
<th>★★★</th>
<th>★★★★</th>
<th>★★★★★</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM91 observed (N = 164)</td>
<td>57</td>
<td>38</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>DM91 including P($\chi^2$) &lt; 0.01</td>
<td>51</td>
<td>40</td>
<td>7</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>DM91 incompleteness (q &gt; 0.1)</td>
<td>43</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM91 single stars ($M_2 &lt; 10 M_J$)</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, observed (N = 454)</td>
<td>57±3</td>
<td>33±2</td>
<td>8±1</td>
<td>2±1</td>
<td>0.4</td>
</tr>
<tr>
<td>This work, including candidates</td>
<td>55±3</td>
<td>34±2</td>
<td>9±2</td>
<td>2±1</td>
<td>0.2</td>
</tr>
<tr>
<td>This work, incompleteness analysis (q &gt; 0.01)</td>
<td>54±3</td>
<td>35±2</td>
<td>9±2</td>
<td>2±1</td>
<td></td>
</tr>
</tbody>
</table>

### Among Planetary Systems

<table>
<thead>
<tr>
<th></th>
<th>★</th>
<th>★★</th>
<th>★★★</th>
<th>★★★★</th>
<th>★★★★★</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raghavan et al. 2006 (N = 131)</td>
<td>77</td>
<td>21</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, observed (N = 34)</td>
<td>68</td>
<td>29</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, planet-host frequency</td>
<td>8±2</td>
<td>7±2</td>
<td>3±3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Multiplicity Results

<table>
<thead>
<tr>
<th></th>
<th>★</th>
<th>★★</th>
<th>★★★</th>
<th>★★★★</th>
<th>★★★★</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM91 observed (N = 164)</td>
<td>57</td>
<td>38</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>DM91 including P(χ²) &lt; 0.01</td>
<td>51</td>
<td>40</td>
<td>7</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>DM91 incompl analysis (q &gt; 0.1)</td>
<td>43</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM91 single stars (M₂ &lt; 10 M_J)</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, observed (N = 454)</td>
<td>57±3</td>
<td>33±2</td>
<td>8±1</td>
<td>2±1</td>
<td>0.4</td>
</tr>
<tr>
<td>This work, including candidates</td>
<td>55±3</td>
<td>34±2</td>
<td>9±2</td>
<td>2±1</td>
<td>0.2</td>
</tr>
<tr>
<td>This work, incompl analysis (q &gt; 0.01)</td>
<td>54±3</td>
<td>35±2</td>
<td>9±2</td>
<td>2±1</td>
<td></td>
</tr>
<tr>
<td>Among Planetary Systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raghavan et al. 2006 (N = 131)</td>
<td>77</td>
<td>21</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, observed (N = 34)</td>
<td>68</td>
<td>29</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, planet-host frequency</td>
<td>8±2</td>
<td>7±2</td>
<td>3±3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Multiplicity Results

<table>
<thead>
<tr>
<th></th>
<th>★</th>
<th>★★</th>
<th>★★★</th>
<th>★★★★</th>
<th>★★★★</th>
<th>★★★★</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM91 observed (N = 164)</td>
<td>57</td>
<td>38</td>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM91 including P(χ²) &lt; 0.01</td>
<td>51</td>
<td>40</td>
<td>7</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM91 incompl analysis (q &gt; 0.1)</td>
<td>43</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM91 single stars (M₂ &lt; 10 M_J)</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, observed (N = 454)</td>
<td>57±3</td>
<td>33±2</td>
<td>8±1</td>
<td>2±1</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>This work, including candidates</td>
<td>55±3</td>
<td>34±2</td>
<td>9±2</td>
<td>2±1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>This work, incompl analysis (q &gt; 0.01)</td>
<td>54±3</td>
<td>35±2</td>
<td>9±2</td>
<td>2±1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Among Planetary Systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raghavan et al. 2006 (N = 131)</td>
<td>77</td>
<td>21</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, observed (N = 34)</td>
<td>68</td>
<td>29</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, planet-host frequency</td>
<td>8±2</td>
<td>7±2</td>
<td>3±3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Multiplicity Results

<table>
<thead>
<tr>
<th>Percentage of stars</th>
<th>⭐</th>
<th>⭐⭐</th>
<th>⭐⭐⭐</th>
<th>⭐⭐⭐⭐</th>
<th>⭐⭐⭐⭐⭐</th>
<th>⭐⭐⭐⭐⭐⭐</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM91 observed (N = 164)</td>
<td>57</td>
<td>38</td>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM91 including P(χ²) &lt; 0.01</td>
<td>51</td>
<td>40</td>
<td>7</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM91 incompl alysis (q &gt; 0.1)</td>
<td>43</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM91 single stars (M₂ &lt; 10 M_J)</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, observed (N = 454)</td>
<td>57±3</td>
<td>33±2</td>
<td>8±1</td>
<td>2±1</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>This work, including candidates</td>
<td>55±3</td>
<td>34±2</td>
<td>9±2</td>
<td>2±1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>This work, incompl analysis (q &gt; 0.01)</td>
<td>54±3</td>
<td>35±2</td>
<td>9±2</td>
<td>2±1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Among Planetary Systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raghavan et al. 2006 (N = 131)</td>
<td>77</td>
<td>21</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, observed (N = 34)</td>
<td>68</td>
<td>29</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, planet-host frequency</td>
<td>8±2</td>
<td>7±2</td>
<td>3±3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Multiplicity Results

<table>
<thead>
<tr>
<th></th>
<th>★</th>
<th>★★</th>
<th>★★★</th>
<th>★★★★</th>
<th>★★★★</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM91 observed (N = 164)</td>
<td>57</td>
<td>38</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>DM91 including P(χ²) &lt; 0.01</td>
<td>51</td>
<td>40</td>
<td>7</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>DM91 incompleteness (q &gt; 0.1)</td>
<td>43</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM91 single stars (M_2 &lt; 10 M_J)</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, observed (N = 454)</td>
<td>57±3</td>
<td>33±2</td>
<td>8±1</td>
<td>2±1</td>
<td>0.4</td>
</tr>
<tr>
<td>This work, including candidates</td>
<td>55±3</td>
<td>34±2</td>
<td>9±2</td>
<td>2±1</td>
<td>0.2</td>
</tr>
<tr>
<td>This work, incompleteness analysis (q &gt; 0.01)</td>
<td>54±3</td>
<td>35±2</td>
<td>9±2</td>
<td>2±1</td>
<td></td>
</tr>
<tr>
<td>Among Planetary Systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raghavan et al. 2006 (N = 131)</td>
<td>77</td>
<td>21</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, observed (N = 34)</td>
<td>68</td>
<td>29</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, planet-host frequency</td>
<td>8±2</td>
<td>7±2</td>
<td>3±3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Multiplicity Results

<table>
<thead>
<tr>
<th>Percentage of stars</th>
<th>★</th>
<th>★★</th>
<th>★★★</th>
<th>★★★★</th>
<th>★★★★★</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM91 observed (N = 164)</td>
<td>57</td>
<td>38</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>DM91 including P(χ²) &lt; 0.01</td>
<td>51</td>
<td>40</td>
<td>7</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>DM91 incompleteness (q &gt; 0.1)</td>
<td>43</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM91 single stars (M₂ &lt; 10 M_J)</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, observed (N = 454)</td>
<td>57±3</td>
<td>33±2</td>
<td>8±1</td>
<td>2±1</td>
<td>0.4</td>
</tr>
<tr>
<td>This work, including candidates</td>
<td>55±3</td>
<td>34±2</td>
<td>9±2</td>
<td>2±1</td>
<td>0.2</td>
</tr>
<tr>
<td>This work, incompleteness analysis (q &gt; 0.01)</td>
<td>54±3</td>
<td>35±2</td>
<td>9±2</td>
<td>2±1</td>
<td></td>
</tr>
</tbody>
</table>

### Among Planetary Systems

<table>
<thead>
<tr>
<th>Percentage of stars</th>
<th>★</th>
<th>★★</th>
<th>★★★</th>
<th>★★★★</th>
<th>★★★★★</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raghavan et al. 2006 (N = 131)</td>
<td>77</td>
<td>21</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, observed (N = 34)</td>
<td>68</td>
<td>29</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This work, planet-host frequency</td>
<td>8±2</td>
<td>7±2</td>
<td>3±3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Presentation Outline

• Motivation for this effort
• The sample of nearby solar-type stars
• Survey methods & observing techniques

➤ Current Results
  – Multiplicity statistics
  – Orbital elements & physical parameters
Multiplicity by Spectral Type

The graph shows the fraction of stars with companions (%) plotted against spectral type. The data points are represented by markers, and error bars are included for each spectral type (O, B, A, F, G, K, M, L, T).
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

Mean log(P) = 5.03, $P = 293$ years
Consistent with DM91, components of triples seen to have higher eccentricity

- Period < 12 days circularized

**HD 45088 components**

- Very young system
- log (R'HK) = -4.27
- High rotation
- Emission in spectra
In contrast to DM91, no relationship is seen between period and eccentricity distribution.
• Another departure from DM91
  – Twins are definitely preferred (consistent with Abt & Levy 1976)
• 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
• Twins are not confined to short-period systems
Effect of Metallicity on Multiplicity
Conclusions

- Large sample of solar-type stars, comprehensive survey
- SFP survey identified no new companions
  - Gap between spectroscopic and visual companions bridged
- CPM search revealed four new companions
- Robust RV coverage
  - 4 new companions in CfA data, 2 in CCPS data
- Majority (55% ± 3%) of solar-type stars are single
- More massive and younger stars are more likely to have companions
- Period distribution is Gaussian with a mean of about 300 years
- Eccentricity distribution is largely flat beyond circularization regime
- Twins are preferred, suggesting multiple formation mechanisms
- Planets are equally likely to form around single, binary, and multiple stars
  - Most stellar companions are wide, implying larger real-estate for planets