Searching for Planets
Around White Dwarf Stars

- or -

I still haven’t found what I’m looking for

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The Big Goal

Direct Detection of Extra-solar planets
The Big Challenge:

Need high contrast observations:

HR 8799 (Marois et al. 2008)

~30AU

Formalhaut (Kalas et al. 2008)
White Dwarf Stars

mitigate our chief constraint
Other advantages

• High proper motions

• Improved contrasts for high mass progenitors

• Different age range ($10^8$--$10^9$ yr), compared to young MS stars
Finding planets around pulsating white dwarf stars
White Dwarf Stars

A brief review

• All stars with $M < 8 - 10 \, M_\odot$ will eventually become white dwarf stars
  • That’s ~ 98% of all stars
• Progenitor systems live for $10^8 - 10^{10}$ years, and age can be estimated
• Faint: $L^* \sim 10 - 3 - 10 - 4L_\odot$
• WD planets at larger orbital separations than progenitor star
• Few, very broad absorption lines
  • Unsuitable for precision radial velocity measurements

• Instrumentation coming on-line now that can detect Jovian analogues around WDs (GPI, HiCIAO).
DAVs are **multi-periodic, non-radial** pulsating white dwarf stars.
DAVs divide into two sub-types:

- **hDAVs**
  - Small number of modes
  - Symmetric pulse shapes
  - Periods of 100-400s
  - Low amplitude

- **cDAVs**
  - Often many modes
  - Sharply peaked pulse shapes
  - 500-1000s
  - Larger amplitude
Some DAVs show extreme stability in phase of pulsation
\[(\frac{dP}{dt} \approx 10^{-15})\]

Kepler et al. (2005)
Cooling of the star causes a *monotonic* increase in period

...which causes a parabolic trend in arrival time

...which can be used to measure core composition...

\[
\dot{P}(A) = (3-4) \times 10^{-15} \frac{A}{14} \text{ s s}^{-1}.
\]

Kepler (2005), Kawalar (1986)

Avg. atomic mass of nucleons in core

rate of period change

...which can be used to test models of stellar evolution
• Change in arrival time (O-C) greater for planets with:
  – Large Mass
  – Large orbital Separation
  – Orbits along our line of sight.

\[
\tau = \frac{2 \ a \ m_p \sin(i)}{M_* c}
\]
A planet around an sdB star

O-C values after effect of secular cooling removed

Silvotti et al. (2007)
The McDonald Observatory
WD Planet Search Program
Mullally et al. (2008)

Sample of 15 DAVs with the 2.1m Otto Struve telescope at McDonald Observatory

Searching for planets through variations in the pulsation arrival time (same as Silvotti 2008)

Data spans 2003 to 2009 with timing uncertainties of 0.5--2 seconds
Results

WD1354+0108

Mullally 2008
Results
WD1355+5454
Results

WD0214-0823

![Diagram 1: Time vs. O-C (seconds)]

![Diagram 2: Orbital Separation vs. Mass (M_j)]
Results
WD2214-0025
Results

R548

1970
Results
G117-B15A

![Graphs showing time series data and orbital separation distribution](image)
A Promising Candidate
GD66 as of July 2007

Pulsations later than expected

Pulsations earlier than expected
What else could it be?

Cooling of the star?

Cooling of the star produces a parabola in the O-C diagram

Effect of cooling predicted, and observed to be ~$10^{-15}$ in another DAV, G117-B15A, but $10^{-12}$ in GD66

Cooling rate is dependent on average atomic weight of core

Average atomic weight of core must be $\approx 5900$ to explain such a high
Proper motion produces a parabolic change in distance to the star and therefore a parabola in the O-C diagram.
Proper motion is a smaller effect even than cooling.

- $\mu = 133 \text{ mas/yr}$
- $P_{pm} = 2.430 \times 10^{-18} P \mu^2 d$
- $P = 302 \text{ s } d \approx 50 \text{ pc}$
- $\dot{P}_{pm} = 6.5 \times 10^{-16}$
- $\dot{P}_{obs} \sim 10^{-12}$
GD66

No known effect can explain observed O-C diagram for GD66

Of course, there’s always the unknown...
G29-38: A DAV that seemed to have a companion...

(but doesn’t)
Seeing is believing
Confirmation through direct detection with *Spitzer*
Combined Spectrum

10Mj 1 Gyr old model planet spectrum
10M $J$ 1 Gyr old model planet spectrum

Combined Spectrum

$10M_J$ 1 Gyr old model planet spectrum
The Plan

If the planet is bright enough, we can detect it as an excess flux at $4.5\mu m$ relative to $3.8\mu m$ using IRAC on Spitzer.

We observed GD66 for 1600s at $3.8\mu m$ and 6400s at $4.5\mu m$.

We observed ZZ Ceti and L19-2 as calibration stars to determine the expected flux ratio.

Limit on the least massive planet we can detect is set by the systematic uncertainty in IRAC.
Detection Limit

is set by our systematic uncertainty

Repeat observations of the same star produces a spread in values greater than the photometric error.

This places a detection limit on any excess of 0.54%
Result
Result

There does seem to be a slight excess, but it’s only 1.7σ significant.
Upper limit on companion mass requires an estimate of age

$T_{\text{eff}} = 11,989 \, \text{K}$  
(2004)  
Bergeron

$log(g)=8.05$

$\Rightarrow$ Mass = $0.64 \, M_\odot$  
(1992)  
Wood

Cooling Time = 500 Myr

$\Rightarrow$ Main-sequence Mass = $2.26--2.64 \, M_\odot$  
(2007),  
Kalirai

(2007)  
Dobbie (2006), Meng

Main-sequence Age = 700--1100 Myr  
(1998)  
Pols

Total Age: 1.2--1.6 Gyr
Isolated WD Planet models from Burrows (2003)
So, Spitzer observations didn’t see anything conclusive

But additional ground based observations will soon cover an entire orbit, right?
More ground based observations of GD66 as of July 2008
More ground based observations

GD66 as of July 2008
Most recent observations

![Graph showing circular and eccentric fits over time](image)

- Circular Fit
- Eccentric Fit
More ground based observations

Current best fit parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>5.42(33) sec</td>
</tr>
<tr>
<td>Period</td>
<td>6.50(28) years</td>
</tr>
<tr>
<td>Orbital Separation</td>
<td>3.003(99) AU</td>
</tr>
<tr>
<td>Mass</td>
<td>&gt;2.34(15) M_J</td>
</tr>
</tbody>
</table>
More ground based observations

Current best fit parameters to eccentric fit:

- **Amplitude**: $5.953(26)$ sec
- **Period**: $6.78(01)$ years
- **Eccentricity**: $0.237(24)$ AU
- **Mass**: $>2.34(15) \ M_J$
Future work

Confirmation from an independent pulsation period
The End.