Planets around lonely White Dwarfs

Matt Burleigh
with thanks to:

- Sarah Casewell, Martin Barstow, Richard Jameson, Katherine Lawrie, Nathan Dickinson, Melissa McHugh (Leicester)
- Jay Farihi (Cambridge)
- Paul Steele (MPA Garching)
- Paul Dobbie (AAO)
- Francesca Faedi (Warwick)
- Fraser Clarke (Oxford), Emma Hogan (Gemini South), Simon Hodgkin (Cambridge)
- Ted von Hippel, Fergal Mullally (Kepler)
- Avril Day-Jones, Ben Burningham, David Pinfield (Herts)
Short history of searches for planets around white dwarfs

• 80s and 90s: First near-IR surveys of WDs (Probst, Zuckerman & Becklin) found BD GD165B & dust disk at G29-38
• 2002: Burleigh, Clarke & Hodgkin used new giant planet evolutionary models to predict WD planets should be observable with 8m telescopes
• 2002: First theoretical modeling of post-MS evolution by Debes & Sigurdsson
• 2005: Dust disk at GD362 discovered – many followed
• 2000s: First targeted IR surveys from ground (Hogan et al. 2009), HST (eg Debes et al. 2005), Spitzer (eg Mullally et al. 2008, Farihi et al. 2009).
  – Also surveys for BD companions (Farihi et al 2005, Maxted et al. 2006, Steele et al. 2011, Girven et al. 2011, Day-Jones et al. 2011)
• 2011: First transit survey published (SuperWASP, Faedi et al.), first considerations of habitable zones (Algol et al.)
• Now-2020?: Spitzer & HST, JWST, GAIA....
1. Planets have been found by radial velocity technique around evolved giant stars
   - >3% of stars M>1.8M$_{\text{sun}}$ have planets >5M$_{\text{Jup}}$ (Lovis and Mayor 2007)

2. White dwarfs have been identified as wide companions of planet-hosting stars
   - CD-38 10980 (Mayor et al. 2004),
   - eps Ret (Raghavan et al. 2006, Chauvin et al. 2006, Farihi et al. 2011)
   - Gl86 (Farihi et al. 2013)

3. Growing number of brown dwarf companions in close and wide orbits
   - WD+BD fraction >0.5+/−0.3% (Steele et al. 2011, Girven et al. 2011, Debes et al. 2011)

4. Metal-rich circumstellar dust and gas disks discovered around white dwarfs
   - require perturbing planets?
HR8799 as a white dwarf...

- HR8799: A5V 1.2-1.8M\textsubscript{jup} 39pc 30-160Myr old
- Planets: 5M\textsubscript{jup} @ 68AU, 10M\textsubscript{jup} @ 38AU, 10M\textsubscript{jup} @ 24AU, 7M\textsubscript{jup} @14AU

- Will evolve after 1.75Gyr to a 0.58M\textsubscript{sun} white dwarf
- Planet orbits expand by factor ~3 to ~200AU,~120AU, 75AU & 45AU

- Let WD cool to 10,000K over ~0.5Gyr....system age now 2.25Gyr...
- 10M\textsubscript{jup} planet will be J=23.8 @39pc
  – How common are HR8799-like systems?
Limits on exoplanet companions to WDs from ground & space

<table>
<thead>
<tr>
<th></th>
<th>UKIDSS (all separations)</th>
<th>DODO (resolved, &gt;few 10s AUs)</th>
<th>Spitzer (unresolved, &lt;few 10s AUs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;75M_{Jup}</td>
<td>0.5 +/- 0.3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;13M_{Jup}</td>
<td>&lt;5%</td>
<td></td>
<td>&lt;3%</td>
</tr>
<tr>
<td>&gt;10M_{Jup}</td>
<td>&lt;7%</td>
<td></td>
<td>&lt;4%</td>
</tr>
<tr>
<td>&gt;6M_{Jup}</td>
<td>&lt;1/3</td>
<td></td>
<td>&lt;12%</td>
</tr>
</tbody>
</table>

UKIDSS: Steele et al. 2011, Girven et al. 2011: ~1000 WDs
Spitzer warm mission programme

• Repeat observations of ~90 white dwarfs originally observed 2004/5
  – Prog ID: 60161
  – Title: “Cool, spatially resolved substellar & exoplanetary analogues at white dwarfs”
    – PI: Burleigh, co-Is Farihi, Steele, Mullally, von Hippel

• Look for common proper motion companions
  – 4.5micron band only
Spitzer 4.5micron image

GJ3483 (LTT3059 / WD0806-661)

I am the white dwarf

I maybe a planet... or a brown dwarf

130" / 2500AU
"Planetary systems around evolved stars", RAS, 11th January 2013
"Planetary systems around evolved stars", RAS, 11\textsuperscript{th} January 2013
Proper motion

- PM error +/-25mas/yr
Candidate parameters

- **WD**
  - $0.58M_{\text{sun}}$
  - Progenitor mass $1.8-2.4M_{\text{sun}}$
  - Total age $1.2-2.5\text{Gyr}$
  - Distance 19.2pc
- **Candidate**
  - 4.5micron mag = $16.75+/-0.08$
  - 6-10$M_{\text{Jup}}$
  - 310-380K
- **Binary**
  - Projected separation 130” / 2500AU
  - Original separation 700AU
Candidate parameters

- **WD**
  - $0.58M_{\text{sun}}$
  - Progenitor mass $1.8-2.4M_{\text{sun}}$
  - Total age $1.2-2.5\text{Gyr}$
  - Distance $19.2\text{pc}$

- **Candidate**
  - 4.5micron mag = $16.75\pm0.08$
  - $6-10M_{\text{Jup}}$
  - $310-380K$

- **Binary**
  - Projected separation 130” / 2500AU
  - Original separation 700AU
Y band observation

- VLT Hawk-I May 2012
- No detection
- Sensitivity limit Y~22.2
J-band observations

- Three hours with Magellan FourStar in March 2012
- No detection to $J \sim 23.5$
  - $J-[4.5] > \sim 7$
  - Redder than any known T dwarf
    - a Y dwarf?
  - Suggest mass $6-9M_{\text{Jup}}$ and $310K < T_{\text{eff}} < 350K$
- Limiting sensitivity of field:
  - $2.5M_{\text{Jup}} / 200K$ (COND models)
  - For unresolved companions
    $\sim 10M_{\text{Jup}} / 400K$
Planet or brown dwarf?

• Is GJ3483B a brown dwarf or a planet?

• Forget deuterium burning limit as the discriminator
  – can we classify by formation mechanism?

• Original *projected* separation ~700AU
  – Too large for core accretion in a disk
  – Suggests disk fragmentation -> BD
    • Rodriguez et al. 2011

• But unstable, eccentric orbits expected in end states of stellar evolution
  – Disk of 2M_{sun} star may be massive enough to make 6M_{Jup} companion
  – Progenitor could be an HR8799-like system
    • A5V+7M_{Jup} @68AU + 10M_{Jup}@38AU + 10M_{Jup}@24AU
Spitzer survey completeness

- **Black**: Spitzer resolved
- **Red**: DODO resolved (Hogan et al. 2009)
- **Green**: Spitzer unresolved (Farihi et al. 2008)

Percentage of Sample vs. Mass (Jupiters)

Matt Burleigh
“Planetary systems around evolved stars”, RAS, 11th January 2013
Limits on *resolved* exoplanet companions to WDs from ground & space

<table>
<thead>
<tr>
<th></th>
<th>DODO</th>
<th>Spitzer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt;13M_{\text{Jup}}$</td>
<td>$&lt;5%$</td>
<td>$\sim1%$</td>
</tr>
<tr>
<td>$&gt;10M_{\text{Jup}}$</td>
<td>$&lt;7%$</td>
<td>$1-2%$</td>
</tr>
<tr>
<td>$&gt;6M_{\text{Jup}}$</td>
<td>$&lt;1/3$</td>
<td>$1-2%$</td>
</tr>
</tbody>
</table>

UKIDSS: Steele et al. 2011, Girven et al. 2011, incidence of BDs 0.5% +/-0.3%
The lowest mass companions to WDs

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass ($M_{\text{jup}}$)</th>
<th>Period</th>
<th>$a$ (AU)</th>
<th>Evolutionary status</th>
<th>Detection method</th>
<th>Comment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GD66 b</td>
<td>&gt;2.4</td>
<td>~7y</td>
<td>&gt;3AU</td>
<td>WD</td>
<td>Pulsation timing</td>
<td>Retracted</td>
<td>Mullally et al. 2008</td>
</tr>
<tr>
<td>GJ3483 b (WD0806-661 b)</td>
<td>6-9</td>
<td>2500</td>
<td></td>
<td>WD</td>
<td>Direct imaging</td>
<td>Y dwarf? 310K&lt;T&lt;350K</td>
<td>Luhman et al. 2011, Burleigh et al. 2013</td>
</tr>
<tr>
<td>WD0837+185</td>
<td>25-30</td>
<td>4.2hr</td>
<td>0.006</td>
<td>WD, Post-CE</td>
<td>Radial velocity</td>
<td>In Praesepe open cluster</td>
<td>Casewell et al. 2012</td>
</tr>
<tr>
<td>WD0137-349 B</td>
<td>53</td>
<td>1.93hr</td>
<td>0.003</td>
<td>WD, Post-CE</td>
<td>Radial velocity</td>
<td>L8 dwarf, T~1300K</td>
<td>Maxted et al. 2006</td>
</tr>
<tr>
<td>PHL5038 B</td>
<td>55</td>
<td></td>
<td>55</td>
<td>WD</td>
<td>Direct imaging</td>
<td>L8 dwarf, T~1400K</td>
<td>Steele et al. 2009</td>
</tr>
<tr>
<td>GD1400 B</td>
<td>60</td>
<td>9.98hr</td>
<td>0.009</td>
<td>WD, Post-CE</td>
<td>Radial velocity</td>
<td>L6/7 dwarf, T~1500K</td>
<td>Burleigh et al. 2012</td>
</tr>
<tr>
<td>LSPM 1459+0857 B</td>
<td>60-75</td>
<td></td>
<td>26500</td>
<td>WD</td>
<td>Direct imaging</td>
<td>T4.5 dwarf, T~1000K</td>
<td>Day-Jones et al. 2011</td>
</tr>
<tr>
<td>NN Ser b</td>
<td>6.9</td>
<td>15.5y</td>
<td>5.4</td>
<td>Pre-CV (WD+M)</td>
<td>Eclipse timing</td>
<td></td>
<td>Beuermann et al. 2010</td>
</tr>
<tr>
<td>NN Ser c</td>
<td>2.3</td>
<td>7.7y</td>
<td>3.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Transits of white dwarfs

- Transit of a Jupiter: 100% or total eclipse
- Transit of an Earth: up to 100%
- Transit of Moon: ~5%
- Transit of UK: $5 \times 10^{-4}$ (0.05%)
Transits of white dwarfs

- Faedi et al 2011
- Agol et al 2011
- Fossati et al 2012
- Barnes & Heller 2012
A search for eclipsing and transiting planets with SuperWASP

Faedi, West, Burleigh, Goad, & Hebb, (2011), MNRAS, 410, 899

• SuperWASP has observed ~300 confirmed white dwarfs since 2004
  • 1% photometry to V=13, detection limit V~15
• No eclipsing or transiting companions detected
• Limiting factors:
  • cadence: 8min for WASP v transit times of 1-few mins
  • unknown frequency of close planetary companions
    • Survivors of common envelope evolution?
    • 2nd generation planets?
    • Can rocky bodies even exist close to a WD?
    • Shepherd moons for dust disks?
• Future:
  • Wide field: (NGTS, Pan-Starrs, LSST, Plato)?
  • Target individual objects with 0.5-1.0m telescopes?
  • Kepler can detect asteroids in long period orbit

Upper limits on frequency of planets in close orbits to white dwarfs from SuperWASP
GAIA Astrometry

- Gaia will find 400,000 WDs extending complete sample to 50-100pc
  - At 25pc the sample is currently only 40% complete
- Can detect giant planets (>2M_{Jup}) with periods from 2.5-5 years around ~1000 WDs
- 15M_{Jup} with 10% error around ~5000 WDs
- Launch late 2013, first full astrometry data release after 40 months (2017?)

- Numbers courtesy Roberto Silvotti (Silvotti et al. 2011)
Open questions, future directions

• How common are GJ3483-like objects?
  – More direct imaging searches for wide companions
  – What are their formation mechanisms?
  • Disk fragmentation?
  • Core accretion and subsequent ejection?
• Where are the perturbers that help create dust disks around white dwarfs?
  – Mid-IR photometric searches; HST, JWST, E-ELT
  – Astrometry with GAIA
• What is the lowest mass that can survive CE evolution intact to the white dwarf stage?
  – IR surveys, Transit/eclipse searches
• What is the orbital period distribution for substellar companions?
  – Are there “deserts”?
• Can rocky planets exist in close orbits to WDs?
  – Transit searches
• Can 2nd generation planets form?
  – Hot, young gas giants, metal-rich terrestrial planets?