Imaging and Astrometry for the Coolest Brown Dwarfs

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Abstract

Doctor of Philosophy

Imaging and Astrometry for the Coolest Brown Dwarfs

by Daniela Opitz

The discovery of brown dwarfs of the new Y spectral type by the NASA Wide-field Infrared Survey Explorer (WISE) has allowed astronomers to study the physics of the coolest brown dwarfs and determine their prevalence in the Milky Way. This thesis exploits the high resolution and wide field–of–view of Gemini Multi–Conjugate Adaptive Optics System (GeMS) to perform diffraction-limited imaging to explore the binary properties of a sample of five WISE Y-dwarfs and measure astrometric distances. Regarding binarity, I report no evidence for binary companions in these data, which suggests these systems are not equal–luminosity (or equal–mass) binaries with separations larger than 0.5–1.9 AU. For equal-mass binaries at an age of 5 Gyr, we find that the binary binding energies ruled out by our observations (i.e. $10^{11}$ erg) are consistent with those observed in previous studies of hotter ultra-cool dwarfs. Regarding GeMS astrometric performance, I report the first parallaxes and proper motion measurements for the Y0 dwarf WISEA J071322.55–291752.0 and the Y1 dwarf WISEP J154151.65–225025.2 measured with a Multi–Conjugate Adaptive Optics System (MCAO). Parallaxes measurements for both objects are consistent with those delivered in previous studies while proper motion precisions are at least comparable ($\sim 4.2$ mas) with that delivered from the no-adaptive optics camera FourStar, installed in Magellan. Imaging and astrometric results presented in this thesis demonstrate the potential of GeMS to perform high-resolution and high-precision astrometric studies for sparse fields, and conclude that the high astrometric potential can be best exploited by targeting crowded fields.
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Chapter 1

Introduction

1.1 What are Brown Dwarfs?

The physical property that defines a brown dwarf is its mass. Brown dwarfs are compact objects whose masses are too small ($< 0.08 \, M_{\odot}$) that their core temperatures do not raise to the those required ($T_c \sim 3 \times 10^6$ K) to ignite hydrogen fusion (Kumar, 1963; Hayashi and Nakano, 1963; Burrows and Liebert, 1993; Baraffe et al., 1995).

In stars, hydrogen fusion prevents gravitational collapse as a result of the gas radiation and pressure generated by nuclear burning. However, as the luminosity and gas pressure of brown dwarfs are not sufficient to counteract gravity, they slow down gravitational collapse at early spectral types by electron degeneracy pressure, and at late spectral types by Coulomb pressure (Burrows and Liebert, 1993). As a consequence, brown dwarfs mass-radius relationship $R(M)$ varies between $R \propto M^{-1/3}$ and $R \propto M^0$ (Burrows and Liebert, 1993), indicating a nearly mass-independence.

Due to the lack of stable hydrogen burning these objects cool as they age, becoming very dim and emitting most of their energy in the near- & mid-infrared. This evolution is reflected in the following approximate relations from luminosity ($L$) and effective temperature ($T_{\text{eff}}$) as a function of mass ($M$) and time ($\tau$) due to Burrows et al. (2001).

$$L \propto \tau^{-1.3} \, M^{2.64} \quad (1.1)$$
Chapter 1. Introduction

Figure 1.1: The evolution of core temperature with time predicted by Burrows et al. (2001). Red lines are for models with masses equal to or below $13 \, M_J \sim 0.013 \, M_\odot$, the green lines are for objects above $13 \, M_J$ and below the edge of the main sequence, and the blue are for stars (red dwarfs) up to $0.2 \, M_\odot$.

\[ T_{\text{eff}} \propto \tau^{-0.32} \, M^{0.83} \]  

(1.2)

Luminosity and effective temperature time evolution depend on mass, with higher mass brown dwarfs cooling more slowly than lower mass objects. Fig. 1.1 and Fig. 1.2 show the evolution of solar abundance low-mass stars and brown dwarfs based on theoretical models developed by Burrows et al. (2001). There are three scenarios to highlight. First, the fusion of deuterium (at $T_c > 2 \times 10^5$ K) for bodies with $M \geq 0.013 \, M_\odot$; second, a transition state for objects with $M \geq 0.075 \, M_\odot$ in which a temporary hydrogen fusion occurs; and finally, stable hydrogen fusion for stars with $M \geq 0.08 \, M_\odot$.

In general, a brown dwarf’s spectral appearance (quantified as a spectral type) is strongly correlated with effective temperature (see Fig. 1.3). A brown dwarf can begin its evolution with temperatures hotter than 2200 K and spectral type M (Kirkpatrick et al., 1999b), but as it ages will evolve through the L ($1300 \lesssim T_{\text{eff}} \lesssim 2200$ K; Kirkpatrick et al., 1999b; Leggett et al., 2001) and T ($500 \lesssim T_{\text{eff}} \lesssim 1300$ K; Burgasser et al., 2002; Cushing...
1.2. Why Brown Dwarfs are Interesting?

The study of brown dwarfs has been inspired by diverse scientific questions. After these objects were predicted (Kumar, 1963; Hayashi and Nakano, 1963), confirming their existence and potential contribution to dark-matter, were the main drivers for early brown dwarfs searches.

The detection of first brown dwarfs (Zuckerman and Becklin, 1987; Nakajima et al., 1995; Rebolo, Zapatero Osorio, and Martín, 1995), and the subsequent acquisition of the

![Figure 1.2: The evolution of effective temperature with time predicted by Burrows et al. (2001) for the same mass set presented in Fig. 1.1](image)

et al., 2011) spectral types. This sequence is expected to continue through the even colder Y spectral type ($T_{\text{eff}} \lesssim 500$ K; Kirkpatrick et al., 2012) though there are hints that show that the current spectral classification scheme used for Y dwarfs may not be as strongly correlated with temperatures as it is for L and T dwarfs, suggesting an increasing role of other physical parameters, such as surface gravity, vertical mixing, clouds and metallicity (Dupuy and Kraus, 2013).
first brown dwarf spectrum (Nakajima et al., 1995), which looked remarkably like Jupiter, motivated scientists to pursue observational (e.g., Kirkpatrick et al., 1999b; Burgasser et al., 2006a) and theoretical (e.g., Burrows et al., 1997; Chabrier et al., 2000) studies to understand their unclear nature as well determine if they are the lowest mass products of the star formation process (e.g., Luhman et al., 2000; Muench et al., 2002; Zuckerman and Song, 2009).

The discovery of hundreds of brown dwarfs during the last 20 years, has permitted the development of a deeper understanding of their properties, origins and evolution. In turn, these discoveries along with results for the space density of low-mass stars (e.g., Reid and Gizis, 1997; Reid et al., 1999; Kirkpatrick et al., 2012) and gravitational microlensing studies (e.g., Tisserand et al., 2007; Alcock et al., 2000) have shown that while brown dwarfs are not uncommon, they are not so numerous to be an important component of the dark-matter.

The study of brown dwarfs has also been stimulated by their similarity to gas-giant planets. Young brown dwarfs near to and below the deuterium burning mass boundary can overlap temperatures, surface gravities and masses with those of gas-giant planets. This makes brown dwarfs ideal laboratories to study the atmospheres and fundamental properties of gas giant exoplanets (e.g., Faherty et al., 2016).

The similarities between brown dwarfs and gas-giant planets have also motivated the scientific debate about how brown dwarfs and planets should be distinguished. The different criteria proposed are described in Section 1.9.

1.3 Detection

Brown dwarfs were first predicted to exist in 1963 (Kumar, 1963; Hayashi and Nakano, 1963), but their extremely low luminosities meant that it was not until two decades later that they were first discovered. The best brown dwarf candidate up until 1995 was GD 165B discovered by Zuckerman and Becklin (1987). However, it was not confirmed as a brown dwarf until a decade later (Kirkpatrick et al., 1999a). The first confirmed brown
dwarfs were Gliese 229 (Nakajima et al., 1995) and Teide I (Rebolo, Zapatero Osorio, and Martín, 1995). The case of Gliese 229 was particularly interesting as its spectrum was completely different from that previously known star-like objects, with strong bands of methane absorption, reminiscent of the Solar System gas giants (Oppenheimer et al., 1995).

By the end of the 20th century a number of surveys had enabled the detection of large numbers of brown dwarfs. These surveys included the Two Micron all Sky Survey 2MASS, Skrutskie et al., 2006, the Deep Near Infrared Survey of the Southern Sky DENIS, Epchtein et al., 1997, the Sloan Digital Sky Survey SDSS, York et al., 2000, the UKIRT Infrared Deep Survey (UKIDS Lawrence et al., 2007) and the Canada-France Brown Dwarf Survey (CFBDS, Delorme et al. 2008; Albert et al. 2011). Most of those brown dwarfs were detected using either the J (1.2 \( \mu \)m) or \( z' \) (0.95 \( \mu \)m) bands. As a result these brown dwarfs were biased toward hotter objects, with either L type or early to mid T type spectral. This left a huge a gap in our knowledge for objects in the range between the coolest

**Figure 1.3:** Effective temperature against spectral type plotted by Bailey (2014). Spectral bar errors are of \( \pm 0.5 \) subtypes.
known brown dwarfs ($T_{\text{eff}} \sim 500 - 600$ K) and Jupiter ($T_{\text{eff}} \sim 128$ K).

Identifying the cooler brown dwarfs was one of the main science goals for the Wide-field Infrared Survey Explorer (WISE, Wright et al., 2010), the NASA mission surveyed the entire sky at 3.4 (W1), 4.6 (W2), 12 (W3) and 22 (W4) $\mu$m between 2010 and 2012. The WISE Brown Dwarf Science Team has identified $\sim 2000$ candidates brown dwarfs from this data and is still carrying out imaging spectroscopic follow-up to determine the properties of these cool objects. In particular, they identified the first Y type brown dwarfs with temperatures at, and below 500 K (e.g. Cushing et al., 2011; Kirkpatrick et al., 2012; Kirkpatrick et al., 2013).

1.4 Spectral classification

The substantial differences between brown dwarf spectra and those of the coolest stars led to the adoption of three new spectral types: L (Kirkpatrick et al., 1999b), T (Burgasser et al., 2003b) and Y (Kirkpatrick et al., 2012). A brief overview of the history of the classification of the types L, T and Y and a summary of their properties are presented below.

1.4.1 L dwarfs

The first L dwarf detected was GD 165B (Zuckerman and Becklin, 1987) though its status as an L dwarf would not become clear for a decade. It was discovered as a faint companion to a white dwarf. Its peculiar spectrum did not match that of any previously seen low mass object. In the absence of any model atmospheres predicting this unusual spectrum, it was considered a unique and unexplained object. It was not until a decade later when other additional L dwarfs examples with similar spectroscopic characteristics were detected (Delfosse et al., 1997; Kirkpatrick, Henry, and Irwin, 1997; Ruiz, Leggett, and Allard, 1997; Tinney, Delfosse, and Forveille, 1997) that its status became clear.

The majority of L dwarfs have been discovered by data from near-infrared all-sky-surveys the most notable being DENIS and 2MASS. These discoveries could not have been achieved without the development of large format infrared detectors in the 1990’s,
1.4. Spectral classification

which enabled surveys of the sky at J, H and K bands. As DENIS and 2MASS improved their survey coverage, a huge number of L dwarfs were detected allowing the definition of a classification scheme based on their spectra. Two classification systems were proposed (Martín et al., 1999; Kirkpatrick et al., 1999b). Both systems agreed on the onset of the 2.2 µm methane band as the trigger of the next coolest spectral type, however, Martín et al. (1999) established a sequence from L0 to L6, while Kirkpatrick et al. (1999b) argued the latest known dwarf as a L8. In the years since, the latter system has become more widely adopted, and that is now the de facto standard, which we follow here.

The main features of L dwarfs can be summarized as follows:

- Early L dwarfs show a mixture of atomic and molecular bands, the most prominent being the alkali lines (Na I, K I, Rb I, Cs I and Li I), oxide bands (TiO and VO), hydride bands (CrH and FeH), and CaOH.
- Mid-L dwarfs show a strengthening of Na I and K I lines and of the hydrides MgH, CaH, CrH and FeH whereas the oxides TiO and VO disappear.
- Late-L dwarfs show a strengthening of $H_2O$ line, the alkali lines are still strong and the hydrides have started to reduce its prominence.

1.4.2 T dwarfs

The first T dwarf, Gliese 229B, was identified by Nakajima et al. (1995). It is a companion of a nearby M dwarf and is considered as prototype for spectral class T. The impact of this discovery was tremendous, mainly because its spectrum looks remarkably like Jupiter’s, with strong absorptions due to methane and water (Oppenheimer et al., 1995).

After this discovery, there was a gap of four years before the next T dwarfs were found. Due to their extreme faintness, T dwarfs proved more difficult to detect than L dwarfs. By 1998, searches had produced a handful of L type brown dwarfs and only one T type brown dwarf. This changed in 1999 with the SDSS survey whose data allowed the detection of two new objects with strong methane absorption (Strauss et al., 1999; Tsvetanov et al., 2000), a clear signal of a class T dwarfs. Shortly after these SDSS discoveries,
Burgasser et al. (1999) using data from 2MASS, reported several T dwarfs that, along with the previous discoveries, enabled the establishment of a new spectral sequence.

While Gl 229B indicated the need for a new spectral type, it was not until more examples had been found spanning a large range in temperature, that the first classification system into subtypes and the identification of a transition from type L to T (Leggett et al., 2002) could be made. Two classification schemes were subsequently proposed (Burgasser et al., 2002; Geballe et al., 2002). Both systems relied on near-infrared spectra, where the methane and water bands dominate and though their underlying philosophies were different, the two system showed discrepancies of no more of 0.5 subclasses. However, the existence of two separate classification schemes for T dwarfs resulted in confusion in the literature. In 2006 (and with a doubled number of T dwarfs available), a scheme merging
1.4. **Spectral classification**

**Figure 1.5**: The near-infrared spectral sequence from L8 to T8 published in Burgasser et al. (2006a). Order is determined visually by comparison of the depth of the 1.15 \( \mu \text{m} \) H\(_2\)O/CH\(_4\) and 1.6 \( \mu \text{m} \) CH\(_4\) features.

The two previous classification systems was established (Burgasser et al., 2006a). That sequence is now widely adopted and is used in this work (See Fig. 1.5).

The main features for T dwarfs are:

- Early-T dwarfs show a deepening and broadening of the 1.15 \( \mu \text{m} \) feature and the adjacent H\(_2\)O/CH\(_4\) absorption at 1.4 \( \mu \text{m} \). A significant depression of the 1.243 and 1.52 \( \mu \text{m} \) K I doublet. A weak CH\(_4\) absorption, resulting in the dual presence of CH\(_4\) and CO bands at 2.2 and 2.3 \( \mu \text{m} \).

- Late-T dwarfs show a strengthening of CH\(_4\) bands and H\(_2\)O absorption whereas CO at 2.3 \( \mu \text{m} \), a prominent feature in late M and L dwarfs, disappears completely.
1.4.3 Y dwarfs

Despite the success of the detection of hundreds of L and T dwarfs, there was still an unexplored gap in temperatures between 500 K (the $T_{\text{eff}}$ of the coolest T dwarf, Lucas et al., 2010) and 124 K (the $T_{\text{eff}}$ of Jupiter, Conrath, Hanel, and Samuelson, 1989). The prediction of evolutionary models and the observations of star forming clusters and young associations, both indicating that brown dwarfs should cool to these temperatures once they have dispersed from their clusters of origin (Weights et al., 2009; Luhman et al., 2005; Chauvin et al., 2004) and the report of two brown dwarfs with estimated $T_{\text{eff}}$ of 300-400 K, (WD 0806-661B and CFBDSIR J145829 + 101343B Luhman, Burgasser, and Bochanski, 2011; Liu et al., 2011), suggested the existence of a new population of brown dwarfs waiting to be discovered.

These predictions became real when at the end of 2011, the \textit{WISE} survey team (Cushing et al., 2011) announced the discovering of seven brown dwarfs with spectral types later than UGPS J072227.21-054031.2, the latest-type T dwarf then known (Lucas et al., 2010). Six of these were classified as Y dwarfs and one as a T9.5. Shortly the same team reported six new objects, enabling a preliminary definition of the spectral type Y (Kirkpatrick et al., 2012). Currently twenty seven Y dwarfs are known (Cushing et al., 2011; Kirkpatrick et al., 2012; Tinney et al., 2012; Liu et al., 2012; Kirkpatrick et al., 2013; Cushing et al., 2014; Pinfield et al., 2014; Schneider et al., 2015), and as well as candidate Y dwarfs, that still is lack spectroscopic confirmation (Liu et al., 2011; Luhman, Burgasser, and Bochanski, 2011; Luhman, 2014). \textit{WISE} J085510.83-071442.5, is the coolest brown dwarf known and was recently detected by Luhman (2014) with an estimated $T_{\text{eff}}$ of 250 K, located at a distance of just 2.2 pc.

The five spectral features that suggested the need for a new spectral class (Burrows, Sudarsky, and Lunine, 2003; Kirkpatrick et al., 2012) are:

- The appearance of ammonia ($\text{NH}_3$) absorption in near-infrared (1 to 2.5 $\mu$m).
- The disappearance of alkali resonance lines Na D (0.589 $\mu$m) and K I (0.77 $\mu$m) near 450 K.
1.4. Spectral classification

- Water cloud formation below 400-500 K.

- The reversal of the blueward trend of J-H and J-K at the T/Y transition.

- The shift in position of the M band peak from \(~4\) to \(~5\) \(\mu\)m.

The study of Y-type brown dwarfs is still in its infancy, and data has only been presented on the possible triggers for the T/Y transition and a preliminary spectral sequence for objects to T2 (See Fig 1.6). Significant future work is needed to identify more examples and to characterize more fully the physical properties of Y dwarfs as they are discovered.

![Figure 1.6: The near-infrared spectral sequence from early-M through early Y. Spectral standards are displayed in even increments of three subclasses from M3 to Y0. Spectra for the Y1 standard as well as \(\geq\) Y2 dwarf, WISE 1828+2650, are also shown. All spectra are normalized to one at their peak flux and integral offset added to the vertical axis to avoid overlaps. Published by Kirkpatrick (2013).](image-url)
1.5 Photometric Colours

The most widely used colour for studying L, and T dwarfs is (J-K) because this is the colour that the large 2MASS and DENIS surveys deliver. L dwarfs become progressively redder in (J-K) as their luminosity and temperature decrease. T dwarfs become increasingly blue in (J-K) due to the $CH_4$ absorption which removes significant flux at longer wavelengths. Fig 1.7 shows the J-K colour versus spectral type for L and T dwarfs (Faherty, 2010). The rapid blueward evolution in (J-K) between spectral types L and T reflects the onset of methane absorption, and the suppression of flux in the 2.2 $\mu$m K passband in T dwarfs.

![Figure 1.7: J-K$_S$ diagram for all L and T dwarfs listed by September 2010 published in Faherty (2010). Red filled circles correspond to low surface gravity dwarfs, blue filled circles to sub dwarfs and black filled circles represent normal field stars.](image)

For Y dwarfs, a key focus has been on the 2MASS-WISE colours such as (J-W2) and (H-W2) (See Fig. 1.8). W2 is the passband in which Y dwarf are most strongly detected, while J & H are the easiest passbands in which to obtain deep near-infrared imaging. The resulting long baseline wavelength range from 1.2/1.5 $\mu$m to 3.2 $\mu$m is a strong probe of decreasing effective temperature. It shows that early-type T dwarfs are slight bluer for successive types before they become redder for late-type T dwarfs and Y dwarfs (Mace
et al., 2013). Another interesting colour for the study of T and Y dwarfs is (J-H). As the temperature of a brown dwarf decreases, the flux in the optical and near-infrared region plummets. The fourth trigger for T/Y transition therefore, is the collapse of the optical and near-infrared flux at temperatures below 350 K. Burrows, Sudarsky, and Lunine (2003) predict that this will reverse the near-infrared colour from the blue (which is characteristic of T dwarfs), to the red (Cushing et al., 2014). This effect is seen near the T/Y transition and is shown in the Fig. 1.9.

(a) J-W2 colour vs spectral type.  
(b) H-W2 colour vs spectral type.

**Figure 1.8:** J-W2 and H-W2 colours vs spectral type published in Mace et al. (2013). Red triangles and limit arrows indicate object from Kirkpatrick et al. (2011). Blue squares and limit arrows correspond to Y dwarfs published by Kirkpatrick et al. (2012). Black circles represent T dwarfs found by Mace et al. (2013).
As more parallax measurements have been delivered, colour–absolute magnitude diagrams have been expanded for later spectral types, which has allowed testing the fluxes produced by models. These diagrams have highlighted how poorly we understand the coolest brown dwarfs. Fig. 1.10 published in Tinney et al. (2014) for example, show a handful of Y dwarfs which appear to be over-luminous in M$_J$ and M$_{W2}$ relative to cloud-free models (which otherwise work well for remaining Y dwarfs). This suggest either the presence of binarity, or that cloud coverage is highly variable between Y dwarfs.

\[\text{Figure 1.9: J-H Colour diagram as a function of spectral type for M, L, T and Y dwarfs published in Aberasturi (2015). Black, blue and green points represent objects from the sample published in (Kirkpatrick et al., 2011). Red points represent Y dwarfs discovered until June 2015.}\]
1.5. Photometric Colours

Figure 1.10: Color–absolute magnitude diagrams in the JMKO and W2 passbands for Y dwarfs published in Tinney et al. (2014). Y0/Y0.5 objects are magenta and Y1 cyan. Open diamonds are from distance measurements published in (Dupuy and Kraus, 2013) open triangles correspond to measurements obtained by Beichman et al. (2014), Luhman (2014), and Kirkpatrick et al. (2013) while open circles are from Tinney et al. (2014). Red solid stars represent a reference sample of T dwarfs. Black lines refer to a cloudless model (CldFree, Saumon et al., 2012) at log g = 4.0 and 5.0. Green lines represent cloud models (S/Salt Cld, Morley et al., 2012) at log g = 4.5 for $f_{\text{sed}} = 2$. Blue Lines show water cloud models (H2O+S/Salt Cld, Morley et al., 2014) with log g = 5.0 and 4.0 at $f_{\text{sed}} = 5$. 
1.6 Astrometry

Measuring distances to stars has important implications for astronomical studies. On one hand, distance is the key quantity needed to calculate the luminosity and, (if a reliable estimation of the radius is available) the effective temperature of a star or brown dwarf. By combining luminosity, colour, and effective temperature, brown dwarf colour-magnitude diagrams can be developed and used to investigate other important parameters such as gravity, metallicity, or dust. The measurement of distances for large samples allows the creation of calibrating relationships of luminosity against spectral types, and these permit distance estimation for objects that lack direct distance measurements. And finally, distances for the nearest objects allow us to have a more complete view of our solar system’s neighbourhood, allowing us studying the importance of brown dwarfs in the Milky Way context.

Trigonometric parallaxes provide the most direct distance measurement for stars. While a handful of brown dwarfs were investigated using optical astrometry (e.g. Tinney, 1996; Dahn et al., 2002), parallax distances for significant samples did not arrive until the development of infrared programs in the early 2000’s (Tinney, Burgasser, and Kirkpatrick, 2003; Vrba et al., 2004). The results delivered by these programs along with the help of a handful of individual measurements enabled a preliminary definition of number of intrinsic properties and the spectral-type/absolute magnitude and colour-magnitude relations (Thorstensen and Kirkpatrick, 2003; Costa et al., 2006; Burgasser et al., 2008).

In the years since, other parallax programs in the optical and infrared wavelengths have delivered even more distances (e.g; Lépine et al., 2009; Marocco et al., 2010; Dupuy and Liu, 2012; Faherty et al., 2012; Dupuy and Kraus, 2013; Tinney et al., 2014) allowing the development of an even deeper understanding of the brown dwarf properties, particularly those in latest spectral types.

The first parallaxes programs for Y-dwarfs have been delivered by Dupuy and Kraus (2013), Marsh et al. (2013), Beichman et al. (2014), and Tinney et al. (2014). However not all these results are consistent, illustrating the limitations of each program. For example,
1.6. Astrometry

### Table 1.1: Summary of the Latest Brown Dwarfs Parallax Programs

<table>
<thead>
<tr>
<th>Program</th>
<th>N&lt;sup&gt;1&lt;/sup&gt;</th>
<th>J&lt;sub&gt;L&lt;/sub&gt;&lt;sup&gt;2&lt;/sup&gt; (median)</th>
<th>J&lt;sub&gt;T&lt;/sub&gt;&lt;sup&gt;2&lt;/sup&gt; (median)</th>
<th>J&lt;sub&gt;Y&lt;/sub&gt;&lt;sup&gt;2&lt;/sup&gt; (median)</th>
<th>π uncertainty (median) [mas]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F12</td>
<td>32 27 0</td>
<td>15.2</td>
<td>15.8</td>
<td>-</td>
<td>6.1</td>
</tr>
<tr>
<td>D12</td>
<td>18 25 0</td>
<td>15.2</td>
<td>16.2</td>
<td>-</td>
<td>1.1</td>
</tr>
<tr>
<td>D&amp;K13</td>
<td>0 10 6</td>
<td>-</td>
<td>17.9</td>
<td>20.9</td>
<td>17.0</td>
</tr>
<tr>
<td>B14</td>
<td>0 6 9</td>
<td>-</td>
<td>18.9</td>
<td>20.1</td>
<td>10.0</td>
</tr>
<tr>
<td>T14</td>
<td>0 0 9</td>
<td>-</td>
<td>19.1</td>
<td>20.6</td>
<td>4.0</td>
</tr>
</tbody>
</table>

1 N is the number of L, T and Y dwarfs in each study.
2 J<sub>L</sub>, J<sub>T</sub> and J<sub>Y</sub> are the median J magnitude of L, T and Y dwarfs in each study.

Beichman et al. (2014, hereafter B14) from combined observations with WISE, Spitzer, HST and Keck, and Tinney et al. (2014, hereafter T14), from Magellan observations, report parallaxes of 176.9±9 mas and 175.1±4.4 mas for the Y dwarf W1541 respectively, while Dupuy and Kraus (2013, hereafter D&K13) from Spitzer observations, report 74±31 mas for the same object.

Astrometric results from recent brown dwarfs parallax programs for earlier spectral types L and T, due to Dupuy and Liu (2012, hereafter D12) and Faherty et al. (2012, hereafter F12), as well as for spectral type Y (D&K13, B14 and T14) are summarized in Table 1.1.

The different results for W1541 between those due to B14 and T14, and that of D&K13, as is discussed by T14, and is largely considered to be due to a combination of the small number on epochs (3) in the D&K13 astrometric solution, and the poor Spitzer spatial resolution, which does not resolve W1541 from a nearby background star in several epochs.

All of these programs suffer from drawbacks in one form or another -B14 and Marsh et al. (2013) are based on heterogeneous data from multiple instruments, while T14 use a large ground-based telescope in visitor mode, resulting in a small number of epochs that are not always ideally placed to sample a broad range of parallax factors.

The various limitations of these parallax programs, and their somewhat inconsistent results, demonstrate that Y dwarfs parallax measurements are no-trivial to obtain. In
particular, these objects are faint in the near-infrared ($J = 19 - 24$) and space-based facilities like Spitzer and WISE have large pixels and are not optimized for astrometry. High precise ground-based observations, therefore, have a potential role to play in producing reliable distances.

The Gaia astrometry mission of the European Space Agency (ESA, Lindegren et al., 2016) is surveying the entire sky and will produce precision astrometry for millions targets down to 20th magnitude in its G passband.

Up to now, the most precise estimation of the number of isolated brown dwarfs observable by Gaia was performed by Sarro et al. (2013) showing it cannot detect a significant number of Y dwarfs. For an optimistic faint magnitude limit of $G = 21$ mag, Gaia would detect around 400,000 M5–L0, 600 L0–5, 30 L5–T0, and 10 T0–8 dwarfs and no Y dwarfs. Gaia will be a revolutionary facility, but its optical wavelength means it cannot do astrometry on the coldest brown dwarfs.

1.7 Adaptive Optics

Because ground-based telescopes will almost always have larger apertures than space-based ones, Adaptive Optics (AO) systems that sense and correct the wavefront distortions produced by atmospheric turbulence, have the potential to deliver higher spatial resolution than even the best space-based facilities. They can therefore, in principle, enable the astrometric observation of fainter targets or higher astrometric precisions, than non-AO corrected ground-based telescopes.

The concept of AO was initially proposed by Babcock (1953) and further developed in the 1970s by the U.S. Department of Defence, mainly motivated for the desire of improving the Soviet satellites observations (Davies and Kasper, 2012). However, it was not until the early 1990s, after the first astronomical AO instrument was tested (Rousset et al., 1990), and later installed at ESO’s 3.6–m telescope on La Silla (Rigaut et al., 1991), that the benefits to astronomy were validated.
1.7. Adaptive Optics

Currently, most of 8-10m telescopes are equipped with AO systems, that have contributed to important astronomical advances such as the study of the properties of the Milky Way’s central supermassive black hole (Ghez et al., 2008) or the first direct detection of a multiple planetary system (Marois et al., 2008).

1.7.1 Principles of Adaptive Optics

AO systems correct for distortions by measuring the optical path deviations using a wavefront sensor (WFS), calculating a suitable correction, and applying this correction to a deformable mirror (DM), which is deformed inversely to the incoming wavefront.

The measurement of wavefront distortions requires a point source which should be close the target in order to pass through the same turbulence, and be bright enough ($R \sim 15$). Unfortunately, such bright stars are not available in all parts of the sky, limiting AO correction with natural guide stars to a 10% of the sky (Davies and Kasper, 2012).

Increased sky-coverage can be obtained using laser guide stars (LGSs), which are artificial stars created with Rayleigh or Sodium beams and whose light is used as a reference for a WFS. Rayleigh and Sodium lasers were proposed in the early 1980s and tested in parallel.

The creation of Rayleigh LGSs relies on the Rayleigh scattering of light by the presence of molecules in atmosphere. Rayleigh LGSs are generated by propagating a laser into the atmosphere in order to emit light and scatter it back to be used to feed a WFS. As the atmospheric pressure falls off exponentially with altitude, Rayleigh beacons are generally limited to altitudes of 8 to 12 km.

Sodium LGSs are created by propagating a laser into the atmosphere to excites sodium atoms in the sodium layer in the mesosphere (at $\sim 90$ km of altitude) and re-emit the light (Thompson and Gardner, 1987). This was the first LGS adopted by astronomical facilities, and is the laser technology mostly used for major observatories around the world.

As both types of LGSs can be only propagated to a finite altitude, some turbulence can not be measured. In addition, LGSs are insensitive to tip-tilt correction as they moves
in the sky due to turbulence. In light of this, when LGSs are used, at least one natural guide star is requested.

Currently, most 8-10m telescopes are equipped with classical single-conjugate adaptive optics systems (SCAO), operating with either a single natural guide (NGS) or LGS, and a single deformable mirror. This configuration allows SCAO systems access to field-of-view (FoV) of tens of arcseconds (Neichel et al., 2014).

1.7.2 Multi-Conjugate Adaptive Optics

The scientific interest in reaching the diffraction limit across a wider field has resulted in the development of Multi-Conjugate Adaptive Optics (MCAO) technique. MCAO allows the correction of turbulence in three dimensions using multiple reference sources in different directions and more than one deformable mirror optically conjugated to different altitudes.

The concept of MCAO was first proposed by Dicke (1975) and then by Beckers (1988), while the theory was developed by Ellerbroek (1994). The first MCAO systems were implemented during the 2000s by Langlois et al., 2004 at the Dunn Solar Telescope and (Berkefeld, Soltau, and von der Luehe, 2005) at the Vacuum Tower Telescope, and were tested in context of solar astronomy. These firsts MCAO observations allowed increase AO corrections to fields up to 60′′. (Davies and Kasper, 2012). During the same decade, two mayor MCAO projects were planned: Multi-Conjugate Adaptive Optics Demonstrator at ESO (Marchetti et al., 2003) and Multi-Conjugate Adaptive Optics System at Gemini South telescope (GeMS, d’Orgeville et al., 2012).

MAD was commissioned in 2007 and demonstrated to be a successful MCAO tool providing a AO correction across of FoV of 2′ (Marchetti et al., 2007; Marchetti et al., 2008). However, as it did not use LGSs, was limited in the number of science targets and was decommissioned in 2008. GeMS was commissioned in 2011 and to date, this is the only operative MCAO facility. This uses a combination of three NGSs and five sodium LGSs to correct for turbulence over a FoV of ∼1.5′x1.5′.
1.7.3 Astrometry with Adaptive Optics

Adaptive Optics (AO) has the potential to be a very powerful astrometric tool as it increase the precision of the positional measurements by incrementing the signal-to-noise ratio and shrinking the point spread function (PSF). These enhancements are achieved by compensating in real time for deformation of the wavefront caused by atmospheric turbulence.

AO have already been considered for parallax programs. However, there has only been one attempt at producing a systematic parallax program using AO to date (Beichman et al., 2013). The advantage of using ground-based adaptive optics systems is that these can overcome atmospheric turbulence over small fields (< arc minute) delivering much improving image quality. The current generation of astronomical AO systems provide diffraction-limited image quality at near-infrared (NIR) wavelengths and increased signal-to-noise (SNR), resulting in a powerful combination for astrometry. These qualities reduce the errors in determining stellar centroids, increase the number of possible reference stars at small separations, and allow techniques for decreasing systematic errors (Cameron, Britton, and Kulkarni, 2009).

Despite these advantages, no extended parallax programs with AO have produced results yet. Beichman et al.’s program for example included only a few epochs with AO to be matched with epochs from other facilities. The main challenge in using AO techniques for parallax programs is the difficulty of dealing with variable astrometric distortions. AO systems are characterized by delivering a complex and spatially variable Point Spread Function (PSF), which additionally changes with the time along with a variable plate scale. These variations in the PSF and plate scale introduce astrometric distortions (i.e changes in centroid position which are not caused by a real change in the position of a star in the sky). Another limitation is the reduced field of view that makes it more difficult find enough high SNR/bright stars to set a good PSF.

Some brown dwarf parallax sources have been followed up with adaptive optics (AO) imaging and resolved as closed binaries. These observations have delivered the first precision dynamical masses (< 10%) for a brown dwarf (Liu, Dupuy, and Ireland, 2008;
Dupuy, Liu, and Ireland, 2009; Konopacky et al., 2010) and allowed us to test sub-stellar evolutionary models. AO is a powerful technique used for Ground-base Optical/Near-Infrared large Telescopes to compensate in real time for deformation of the wavefront caused by atmospheric turbulence and it is a key topic of this thesis.

The first results for precision dynamical masses, contrasted with evolutionary models of the Lyon (Chabrier et al., 2000) and the Tucson (Burrows et al., 1997) group have revealed significant discrepancies (See Fig. 1.11). The late M and early L systems have higher dynamical masses than the models predict, while one mid-L system is consistent with them, and the one T dwarf system observed has a lower dynamical mass (Konopacky et al., 2010).

In recent years, the number of brown dwarf dynamical masses measurements has increased (e.g. Dupuy, Liu, and Ireland, 2014; Burgasser et al., 2016). However, as these measurements require the detection of resolvable brown binaries with short enough orbital periods, this number does not exceed a dozen. (Burgasser et al., 2016).

**Figure 1.11:** Right Panel: The percent difference between the predictions of the Lyon (Chabrier et al., 2000) models and the total dynamical masses as a function of spectral type. Left Panel: The percent difference between the predictions of the Tucson (Burrows et al., 1997) models and the total dynamical masses as a function of spectral type. For both models each system is connected by a horizontal bar. Published by Konopacky et al. (2010).
Gemini Multi-Conjugate Adaptive Optics System, the recent Multi-Conjugate Adaptive Optics system commissioned by GEMINI (GeMS, d’Orgeville et al., 2012) has been pointed out as a promising astrometric tool, as it provides access to larger field of view ($85'' \times 85''$) and delivers a smaller PSF FWHM. Comparing with Fourstar for example (an infrared camera installed in Magellan Telescope, Persson et al., 2013), we have estimated that, for a target with a magnitude of $\approx 20$ in H, the astrometric accuracy (FWHM/SNR) for Fourstar (with signal noise of 100 and a FWHM of 400 mas) is $\sim 4$ mas while for GeMS (with a signal noise of 32 and a FWHM of 85 mas) is $\sim 2.67$ mas. In light of these improvements, developing a systematic parallax program using GeMS and exploring the trade between natural-seeing and AO-assisted astrometry is a focus of this thesis.

1.8 Brown dwarf binaries

Binary and multiple stellar systems have long been used to place important constraints on the star formation process, by requiring that theory explains the observed binary fraction and companion-mass distribution. With the discovery of the first brown dwarf binary systems, these constraints can be extended into the sub-stellar regime. High-resolution imaging for Y dwarfs has the potential to determine whether binary formation is a function of primary mass.

We summarize the results from searches for brown dwarfs around Solar-type stars and low-mass stars and their implications for the current models of star formation.

1.8.1 Brown dwarfs as companions of solar-type stars

Given that more than half of stars in our Galaxy reside in binary systems (Duquennoy and Mayor, 1991), early searches for brown dwarfs frequently chose to concentrate on discovering them as companions to already known stars. One of the detection strategies used was the radial velocity technique (RV). This method is the same as is now used to detect exoplanets and consists of observing the periodic effect of companion objects on the stars that they are orbiting. Despite brown dwarfs being much easier to detect
than exoplanets, by the end of 1990s the radial velocity surveys had discovered dozens of extra-solar gas giant planets but very few brown dwarfs. These unsuccessful searches gave rise to the idea of a "brown dwarf desert" - a much lower binary fraction \( f_{\text{bin}} \sim 0.5\% \) for brown dwarf companions at 0-3 AU compared with the exoplanet fraction (5-15\%) at the same distance from Sun-like stars (Marcy and Butler, 2000).

This shortage of close-in brown dwarfs encouraged the imaging of sub-stellar objects at wider separations (> 10 AU). In the late 1990s, high-contrast imaging became the main method of searching for companions at wide separations. Following the imaging program that discovered Gl 299B (Oppenheimer, Kulkarni, and Stauffer, 2000), more optimized surveys were developed using both ground-based AO systems (Lloyd, 2002; McCarthy and Zuckerman, 2004; Carson et al., 2005) covering the separation range 25-300 AU and space based facilities (e.g, Brandner et al., 2000; Lowrance et al., 2005) covering separations of 10-300 AU. However, despite some successes, by the end of 2003 the pace of detection remained slow. While the rate of detection of exoplanets by RV has grown rapidly, less than 20 brown dwarfs companions to Solar-type stars had been discovered through direct imaging (e.g, Oppenheimer et al., 2001; Gizis et al., 2001; Potter et al., 2002) spreading over a combined separation range of 10-1200 AU (Mason, 2008). This suggested that the brown dwarf desert could extends to separations up to \( \sim 1000 \) AU (McCarthy and Zuckerman, 2004).

In recent years, although improvements in AO systems, combined with new differential imaging techniques (Marois et al., 2005), have delivered an exceptional sensitivities for sub-stellar companions at separations of tens of AU and the picture has changed slightly. For example, Neuhäuser and Guenther (2004) report \( f_{\text{bin}} \sim 4\% \) for brown dwarfs at separations > 50 AU while Metchev and Hillenbrand (2009) deliver a \( f_{\text{bin}} \) of \( \sim 3.2\% \) for brown dwarfs at 28-1590 AU of separation.

The last radial velocity planet search surveys of nearby solar-type stars have continued to be unsuccessful in populating the brown dwarf desert. They still show a strong scarcity of brown dwarf companions within \( \sim 5 \) AU. For example, observations from the sub-programme 2 of the SOPHIE search for northern extrasolar planets (Bouchy et al.,
1.8. Brown dwarf binaries

2009), which monitors ~2000 main-sequence stars of F, G, and K spectral type, have detected only seven new sub–stellar companions with minimum masses between 10 and 90 $M_{Jup}$ (Díaz et al., 2012) and seven additional companions with minimum masses ranging from 3 to 70 $M_{Jup}$ (Wilson et al., 2016). Currently there is not a clear explanation for this lack of brown dwarf companions.

1.8.2 Brown dwarfs as companions of low–mass stars

Brown dwarfs also exist as companions of late-type main sequence stars. Searches for very low-mass binaries (defined as having a total system mass $M_{\text{tot}} < 0.2 M_\odot$ and primary mass $M_1 < 0.1 M_\odot$) have concentrated on high resolution imaging surveys, using both nearby field sources (e.g; Koerner et al., 1999; Burgasser et al., 2003b; Reid et al., 2008; Gelino et al., 2011; Aberasturi et al., 2014) and young cluster associations (e.g; Martín et al., 1998; Neuhäuser et al., 2002; Bouy et al., 2006; Todorov et al., 2014; Garcia et al., 2015). These studies have determined a brown dwarf binary fraction of $\sim 10\%–30\%$ (Burgasser et al., 2003a; Burgasser et al., 2006b; Burgasser et al., 2007; Aberasturi et al., 2014), which is substantially lower than the binary fraction of early-type M stars ($\sim 30\%–40\%$; Delfosse et al., 2004; Reid and Gizis, 1997; Close et al., 2003) and the binary fraction of solar-type stellar systems ($\sim 65\%$; Duquennoy and Mayor, 1991).

This trend could indicate either a mass dependence on the multiplicity or an as yet uncovered population of very low-mass binaries. The latter is strongly supported by the known incompleteness of the statistics for very tight ($a \lesssim 1$ AU) and wide ($a \gtrsim 100$ AU) binaries (see Konopacky, 2013, and references therein).

The binary status of Y type brown dwarfs is also both unclear and of considerable interest. Open questions include: Is there a lower mass limit for the formation of binary systems? How common are Y dwarf binary systems? What is the mass ratio distribution between the components of Y dwarf binaries? Some of these questions have been addressed for late T dwarfs by binary studies using Hubble Space Telescope’s Wide Field Camera 3 (WFC3), which has an angular resolution of 0.13′. These observations infer
Chapter 1. Introduction

an upper limit for the binary separation of 0.33 with a magnitude difference $\Delta m \leq 3.0$ (Aberasturi et al., 2014), and could be extended to early Y type objects.

However, the new generation of wide-field adaptive optics systems using laser-guide star constellations and deformable mirrors conjugating to multiple layers in the atmosphere, can deliver higher spatial resolutions from apertures four times larger. In advance of JWST’s diffraction-limited, large-aperture capabilities becoming available in space, they offer the prospect of addressing these questions from the ground.

1.8.3 Implications for star formation models

Classical star formation models considered brown dwarfs as failed stars (i.e. objects formed from the collapse of a prestellar core but which does not have enough mass to ignite hydrogen fusion, Reid and Hawley, 2005). These models adopted Jeans mass as a criteria for the minimal fragmentation mass possible of a molecular cloud to became unstable and begin to collapse (Elmegreen, 1999).

The Jeans mass is given by

$$M_J = \left( \frac{5R_gT}{2G\mu} \right)^{3/2} \left( \frac{4}{3\pi\rho} \right)^{-1/2}$$  \hspace{1cm} (1.3)

where $T$ and $\rho$ represent to the cloud temperature and the cloud density respectively, $\mu$ is the mean molecular weight of the gas, and $R_g$ and $G$ correspond to the gas constant and the gravitational constant respectively. The product of this core collapse is a star with a mass as small as 10% of Jeans mass (Reid and Hawley, 2005).

Considering this scenario, brown dwarf formation requires very low temperatures and high densities which are rare among known star-formation regions. These conditions result in a formation rate of brown dwarfs very low compared with the observations. In addition, models based on this scenario do not predict the overall multiplicity of protostars. In light of these disagreements, new mechanisms were developed and are summarized as follows.
1.8. Brown dwarf binaries

- **Accretion-Ejection**: Proposed by Reipurth and Clarke (2001), this model suggests that brown dwarfs are the result of the ejection of fragments by dynamical interactions between fragments or protostars. They conclude that binaries and multiple systems found in the field are the survivors of this process.

Simulations developed by Bate (2012), which explore this scenario are consistent in part with the data. They reproduce the observed distribution of initial mass (IMF) parametrized by Chabrier (2005) and the observed multiplicities of G, K, M and VLM objects. They deliver a multiplicity fraction \( f_{\text{mult}} \) of 0.2 for objects with primary masses between 0.03 M\( \odot \) and 0.2 M\( \odot \) and predict a continuous fall for lower mass stars.

However, Bate (2012)’s scenario faces other important issues which have made question the validity of this model (Chabrier et al., 2014). One of the main critics points to the initial conditions of the model, which are different to those typically observed in the Milky Way. Bate (2012)’s simulations are based on a molecular cloud about 4 or 5 times denser and more turbulent than those observed, which in turn strongly favors fragmentation and dynamical interactions and consequently, a significant production of ejected low-mass embryos.

Another important issue discussed by Chabrier et al. (2014) is the inconsistency in velocity dispersions and spatial distribution of brown dwarfs predicted by Bate’s (2012) simulations and those observed. Bate’s model predicts higher velocities and a wider spatial distribution for brown dwarfs than for stars. However, radial velocity measurements for brown dwarfs in young clusters and star–forming regions show that young brown dwarfs share similar velocity dispersions as young stars (e.g, Joergens, 2006; Kurosawa, Harries, and Littlefair, 2006). In turn, observations show that brown dwarfs have the same spatial distributions as stars (e.g, Bayo et al., 2011; Scholz et al., 2012).

- **Photoionization**: Proposed by Whitworth and Zinnecker (2004), this mechanism suggests that photoionizing radiation from OB stars disrupts accretion by removing
a part of the envelope and disk of low-mass protostars. However, as the brown dwarf mass function is about the same despite the presence or not of O stars, it is not considered as a major mechanism for brown dwarf formation (Chabrier et al., 2014).

- **Gravoturbulence Fragmentation**: This model, first developed by Padoan and Nordlund (2002) and subsequently improved by diverse authors e.g. McKee and Ostriker, 2007; Hennebelle and Chabrier, 2011, combines turbulence and gravity. This sustains that turbulent compression and fragmentation of a gas in a molecular cloud result in the collapse of pre-stellar cores over a wide range of masses. This mass range strongly deepens on the Mach number (the ratio of the speed of a object to the sound speed in the medium) instead of the Jean mass and also allows covering a more extended mass interval than one covered by purely gravitational models, which results in a reasonable number of pre-brown dwarf cores for appropriated molecular cloud conditions. The last results have reproduced the Chabrier IMF down to the least massive brown dwarfs. The most conclusive support for brown dwarf formation by this scenario is the agreement between the densities observed \( (n = 10^7 – 10^8 \text{ g cm}^{-3}) \) for the recent discovered pre-brown dwarf core Oph B-11 (André, Ward-Thompson, and Greaves, 2012) and the values predicted by the model.

- **Disk Fragmentation**: This scenario, proposed by Whitworth and Stamatellos (2006), suggests brown dwarfs, as well as giant planets, could be a result of disk fragmentation due gravitational instabilities produced by star-disk or disk-disk interactions. However, as many of the physical phenomenons associated to this formation mechanism, such as turbulence, magnetics fields and accreting envelope have not been included in this model, its pertinence is matter of debate (Chabrier et al., 2014).
1.9 Similarities to planets

The distinction between stars and brown dwarfs is well defined (see Section 1.1). However, as brown dwarf’s sizes, mass and atmospheric properties can overlap with those of gas–giant planets, making the distinction between brown dwarfs and planets still controversial.

Some researchers have supported the classification of an object based on its thermonuclear fusion capability (Basri and Marcy, 1997; Oppenheimer, Kulkarni, and Stauffer, 2000). They propose a definition of planets as objects for which no nuclear fusion of any kind takes place during their entire evolutionary history. The lower mass limit that would distinguish between a brown dwarf and a planet for this definition corresponds to $13 \, M_{\text{Jup}}$, since only objects with masses greater than $13 \, M_{\text{Jup}}$ can produce nuclear energy due to deuterium fusion in their core (See Fig. 1.1). However, this nuclear phase is very short $\lesssim 20 \, \text{Myr}$; Baraffe, 2014 and therefore, most brown dwarfs would have completed fusing deuterium long before their discovery, making them indistinguishable otherwise from super-massive planets (Basri, 2000).

Other authors have established an alternative definition, suggesting that planets and brown dwarfs should be distinguished by their formation process using luminosity as an observational signature. This idea emerged from the work of Marley et al. (2007), which suggests that young planets, formed in circumstellar debris disks via core accretion, should be fainter and smaller than brown dwarfs formed like stars via gravitational collapse, at early stages. That conclusion is established from the supposition that all the energy liberated in the accretion shock produced by matter falling onto the planet’s surface does not contribute to the internal energy content of the forming planet as is radiated away. However, Baraffe (2014) argues that this scenario has been oversimplified (which was lately confirmed by Mordasini et al. (2016)) and sustain that though luminosity of young objects is critical to understand the physics of the accretion process, is not a genuine signature of the formation process.

Finally, as aforementioned in Section 1.8.3, there is a third distinction between planets
and brown dwarfs based on the formation process. This distinction establishes that the
mechanism by which brown dwarfs are formed is different from that of either stars and
planets. In this scenario brown dwarfs are considered sub-products of the formations
process of hydrogen-burning stars, either ejected objects from small cluster environments
or resultant objects of an incomplete accretion terminated by photoionizing radiation. In
the absence of a widely accepted distinction between brown dwarfs and planets, more
data covering the gap between them are required.
Chapter 2

Data and Experimental Design

2.1 Experimental Design

A sample of five WISE Y dwarfs were targeted with the Gemini Multi-Conjugate System (GeMS) and the Gemini South Adaptive Optics Imager (GSAOI) to perform astrometry and determine binary status. Specifications for the instruments, targets, observations, data processing and observing efficiency are discussed below.

2.1.1 The Gemini Multi-Conjugate System (GeMS) and the Gemini South Adaptive Optics Imager (GSAOI)

GeMS (d’Orgeville et al., 2012) is an Adaptive Optics instrument installed at the Gemini South Telescope located in Cerro Pachon. It uses five laser sodium guide stars (LGS) asterisms and three natural guide stars (NGS) to correct the optical distortions produced by the atmosphere. Such correction is performed using two deformable mirrors.

GSAOI McGregor et al. (2004) and Carrasco et al. (2012) is a near-infrared adaptive optics camera which operates with GeMS. GSAOI has a pixel scale of 0.02″ and is composed of four 2048×2048 Rockwell HAWAII–2RG arrays that form a near-infrared imaging mosaic. Each detector offers access to a field-of-view of 41″x41″.

The extreme faintness of Y-type brown dwarfs, combined with the rarity of suitably bright natural guide stars, makes natural guide star adaptive optics for these targets completely impractical. The GeMS/GSAOI system was chosen for these observations over a traditional single-deformable mirror system, because its wide field of correction allows
the selection of off-axis tip-tilt stars over a large field, as well as delivering AO correction over a large \( \approx 2' \) diameter field. This (to-date) unique capability allows observations of Y dwarfs to address both "narrow field" binarity science and "wide-field" astrometric science.

Gaia, the current astrometry mission of the European Space Agency (ESA, Lindegren et al., 2016) is expecting to surveying the entire sky and follow up millions targets of the down to 20th magnitude in its G passband. Up to now, the most precise estimation of the number of isolated brown dwarfs observable by Gaia was performed by Sarro et al. (2013) showing it cannot detect a significant number of Y dwarfs. For a lowered limit of \( G = 21 \) mag, Gaia would detect around 400,000 M5–L0, 600 L0–5, 30 L5–T0, and 10 T0–8 dwarfs and no Ydwarfs. Gaia will be a revolutionary facility, but its optical wavelength means it cannot do astrometry on the coldest brown dwarfs.

2.1.2 Targets

The five WISE Y dwarfs for which suitable GeMS guide star asterisms are available were targeted in the J3 passband.

J3 passband is an intermediate bandwidth filter available on FourStar centred at 1.28 \( \mu \). For Y-dwarfs it collects essentially all the flux obtained by a standard Johnson J filter. This J3 photometry has been calibrated using 2MASS J photometry in the field, and so can be used as a reasonable proxy for a J magnitude for these targets. Details and bandpass information is available at \(^1\). The full WISE designation, near-infrared photometry in the J3 passband and spectral type for the sample are listed in Table 2.1. Parallaxes for the targets delivered by Beichman et al. (2013), Dupuy and Kraus (2013), Marsh et al. (2013) and Tinney et al. (2014) are showed in Table 2.2.

All these objects lie 5-10 pc from the Sun (Kirkpatrick et al., 2012; Beichman et al., 2014; Tinney et al., 2014) which was expected to enable the measurement of precise distances in a few years. The observation of these systems at multiples epochs allowed a robust testing of GeMs astrometric stability over an extended period and by extension its ability

\(^1\)http://instrumentation.obs.carnegiescience.edu/FourStar/OPTICS/filters.html
Table 2.1: Y dwarf sample

<table>
<thead>
<tr>
<th>Full designation</th>
<th>Short name</th>
<th>J3 (mag)</th>
<th>Spectral type</th>
</tr>
</thead>
<tbody>
<tr>
<td>WISEA J035934.07–540154.8</td>
<td>W0359</td>
<td>21.40 ± 0.09</td>
<td>Y0</td>
</tr>
<tr>
<td>WISEA J053516.87–750024.6</td>
<td>W0535</td>
<td>22.09 ± 0.07</td>
<td>≥Y1</td>
</tr>
<tr>
<td>WISEA J071322.55–291752.0</td>
<td>W0713</td>
<td>19.42 ± 0.03</td>
<td>Y0</td>
</tr>
<tr>
<td>WISEP J154151.65–225025.2</td>
<td>W1541</td>
<td>20.99 ± 0.03</td>
<td>Y1</td>
</tr>
<tr>
<td>WISEA J163940.83–684738.6</td>
<td>W1639</td>
<td>20.57 ± 0.05</td>
<td>Y0pec</td>
</tr>
</tbody>
</table>

Note: Target magnitudes are provided in the J3 passband (1.28 µm) as described in Tinney et al. (2014), along with parallaxes from the same source. Spectral types are from: Kirkpatrick et al. (2013) and Schneider et al. (2015).

Table 2.2: Literature Parallaxes

<table>
<thead>
<tr>
<th>Target</th>
<th>( \pi ) T14 (mas)</th>
<th>( \pi ) B13 (mas)</th>
<th>( \pi ) D&amp;K13 (mas)</th>
<th>( \pi ) M13 (mas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W0359</td>
<td>63.2 ± 6.0</td>
<td>-</td>
<td>-</td>
<td>145.0 ± 39.0</td>
</tr>
<tr>
<td>W0535</td>
<td>74.0 ± 14.0</td>
<td>-</td>
<td>-</td>
<td>250.0 ± 79.0</td>
</tr>
<tr>
<td>W0713</td>
<td>108.7 ± 4.0</td>
<td>106.0 ± 13.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>W1541</td>
<td>175.1 ± 4.4</td>
<td>176.0 ± 9.0</td>
<td>74.0 ± 31</td>
<td>-21.0 ± 94</td>
</tr>
<tr>
<td>W1639</td>
<td>202.3 ± 3.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>


to do astrometry of targets that are challenge for 8 m-class telescopes without AO. These Y dwarfs were also targets of a program at Magellan (Tinney et al., 2014) which allowed it make a comparison of the astrometric precision obtained by a seeing limited instrument and a multi-conjugate adaptive optics system (MCAO). The GeMS images obtained were also used to study the binary properties of these objects (Opitz et al., 2016).

At present there are no other southern Y-dwarfs that can be observed with GeMS -they are all either too far south (i.e. below -75 deg) or have unfavourable guide star asterisms. A forthcoming upgrade to GeMS (Rigaut et al., 2016) will replace its current tip-tilt wavefront sensors with a fast-frame readout CMOS system, enabling the use of guide stars 10 times fainter. Once complete this will significantly expand the set of Y dwarfs GeMS can observe.
2.2 Observations

The sample of five nearby Y dwarfs were observed with GSAOI and corrected for atmospheric aberrations by GEMS. All observations were carried out in the GSAOI CH4S passband (1.486–1.628 µm). This filter was chosen as it provides the optimal sensitivity for these faint objects with very strong methane absorption (See Figure 2.1). That is it collects light at the wavelength where Y dwarfs emit, without collecting sky background at wavelength where Y dwarfs do not emit.

Initially a sixth Y dwarf (WISE 0734–7157) was included in the sample, however we removed this object from the target list as it required excellent conditions (a seeing of \( \lesssim 75 \)) due to its low elevation, which were unable to be achieved on any regular basis.

A log listing the observations obtained is given in Table 2.3. The first sets of images
2.2. Observations

for the Y dwarfs W1541, W0713 and W1639 observed between March 2013 and May 2013 were mostly obtained with a total integration time of approximately 1 hour, using 54 exposures of 66s each and random telescope dithering every 6 exposures inside a box size of $\sim 1.6'' \times 1.6''$. Experience with this observing mode showed that observing overheads were too high and therefore, subsequent observations for W1541, W0713 and W1639 and all the observations for W0535 and W0359 were carried out by dithering every exposure (but using longer exposure times to control overheads).

2.2.1 Data Reduction

Data processing was performed using the Gemini GSAOI pipeline, which operates in the IRAF environment. This applies a standard bad pixel mask (BPM), creates and subtracts an averaged dark from all images, applies a flat-field generated using dome flats and generates sky frames using dithered data sets which are then subtracted.

The GSAOI bad pixel mask included in the Gemini GSAOI IRAF package was created using 150s darks. This mask flags 1.7%, 0.9%, 1.1% and 1.1% of the pixels as bad in the arrays 1, 2, 3 and 4 (respectively). The document describing the process followed to derive the standard BPM is available on the Gemini Website.

The dark current for GSAOI is low ($\sim 0.01$ e$^-$/s/pixel) and the dark noise from an exposure of 360s is $\sim \sqrt{3.6} e^-$/pix. Typical read noise for arrays 1, 2, 3 and 4 are of 13.63, 9.85, 14.22 and 16.66 e-.

After this processing, the FWHM was determined for all the images using a Point Spread Function (PSF) analysis as described in Chapter 3 (Opitz et al., 2016). Images with significantly poorer quality than the rest were removed from the list. Finally dithered images were combined using reference stars to produce a single mosaicked image. The number of frames effectively combined for each epoch is displayed in Column 4 in Table 2.2. Stacking and mosaicking were performed in two ways. The first consisted in

\footnote{http://www.gemini.edu/sciops/data–and–results/getting–started#gsaoi}
\footnote{http://www.gemini.edu/sciops/instruments/gsaoi/documents/GSAOI_BPM_forweb.pdf}
### Table 2.3: Log of GSAOI–GeMS Observations

<table>
<thead>
<tr>
<th>Short name</th>
<th>UT Date</th>
<th>Exp.</th>
<th>N(^1) (\text{pixel} \times \text{pixel})</th>
<th>N(^2) obtained</th>
<th>N(^3) stacked</th>
<th>Array(^4)</th>
<th>FWHM (pix)</th>
<th>FWHM ((\prime))</th>
</tr>
</thead>
<tbody>
<tr>
<td>W0359</td>
<td>2013 Dec 20</td>
<td>360s</td>
<td>9</td>
<td>7</td>
<td>3</td>
<td></td>
<td>5.51</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>2014 Jan 22</td>
<td>360s</td>
<td>9</td>
<td>6</td>
<td>3</td>
<td></td>
<td>8.50</td>
<td>0.17</td>
</tr>
<tr>
<td>W0535</td>
<td>2014 Dec 04</td>
<td>360s</td>
<td>9</td>
<td>8</td>
<td>3</td>
<td></td>
<td>6.14</td>
<td>0.12</td>
</tr>
<tr>
<td>W0713</td>
<td>2013 Mar 22</td>
<td>66s</td>
<td>9</td>
<td>9</td>
<td></td>
<td></td>
<td>3.77</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>2013 Apr 17</td>
<td>66s</td>
<td>9</td>
<td>9</td>
<td></td>
<td></td>
<td>4.35</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>2013 Dec 20</td>
<td>360s</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td></td>
<td>5.80</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>2013 Dec 21</td>
<td>360s</td>
<td>9</td>
<td>9</td>
<td>2</td>
<td></td>
<td>8.50</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>2014 Dec 07</td>
<td>360s</td>
<td>9</td>
<td>5</td>
<td></td>
<td></td>
<td>5.81</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>2015 Jan 05</td>
<td>360s</td>
<td>5</td>
<td>5</td>
<td></td>
<td></td>
<td>7.54</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>2015 Jan 07</td>
<td>360s</td>
<td>5</td>
<td>4</td>
<td></td>
<td></td>
<td>5.13</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>2016 Apr 08</td>
<td>360s</td>
<td>10</td>
<td>5</td>
<td></td>
<td></td>
<td>6.78</td>
<td>0.14</td>
</tr>
<tr>
<td>W1541</td>
<td>2013 Apr 20</td>
<td>66s</td>
<td>9</td>
<td>9</td>
<td></td>
<td></td>
<td>4.20</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>2013 May 24</td>
<td>66s</td>
<td>9</td>
<td>8</td>
<td></td>
<td></td>
<td>3.86</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>2014 Apr 12</td>
<td>360s</td>
<td>10</td>
<td>9</td>
<td>2</td>
<td></td>
<td>6.14</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>2014 May 28</td>
<td>360s</td>
<td>5</td>
<td>4</td>
<td></td>
<td></td>
<td>7.42</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>2014 Jun 18</td>
<td>360s</td>
<td>11</td>
<td>8</td>
<td></td>
<td></td>
<td>5.64</td>
<td>0.11</td>
</tr>
<tr>
<td>W1639</td>
<td>2013 Apr 21</td>
<td>66s</td>
<td>9</td>
<td>9</td>
<td></td>
<td></td>
<td>4.92</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>2014 Apr 13</td>
<td>360s</td>
<td>10</td>
<td>8</td>
<td></td>
<td></td>
<td>7.65</td>
<td>0.15</td>
</tr>
</tbody>
</table>

\(^1\) Exposure time for each epoch.
\(^2\) Number of frames obtained. N\(_{f}^\) < 9 indicates an incomplete sequence.
\(^3\) Number of frames effectively used in stacking process.
\(^4\) Mosaic detector where each target is located.
the stacking of images using the Gemini-IRAF package IMCOADD and subsequent mosaicking using the tool Gemini tool GAMOSAIC. This strategy does not take in account astrometric distortion. The images resulting were used to study the binary properties of the Y dwarfs W0713, W1541, W1639, W0359 and W0535 as described in Chapter 3.

The astrometric analysis of W0713 and W1541 required a more sophisticated combining process. This adopted the Distortion Correction and Stacking Utility (Disco-Stu)\(^4\) and is described in Chapter 4.

### 2.2.2 Observing Efficiency

Time was awarded through Australia, Chile and USA via programs GS-2013A-Q-4, GS-2013B-Q-26, GS-2014A-Q-4, GS-2014B-Q-32 and GS-2015B-Q-47 and also via Guaranteed Time program GS-2013-B-C-1, GS-2014B-C-1, GS-2015A-C-2, GS-2016A-C-2 and GS-2016B-C-2. These programs attempted take enough data (6-8 epochs per target) to measure parallaxes and perform a binary analysis for the five Y dwarfs. However, over the four years 2013-2016, sufficient epochs to attempt an astrometric analysis were obtained for only two targets - W0713 (8 epochs) and W1541 (5 epochs). Table 2.4 summarizes the allocated and effective time observed by GeMS per each observing program in queue (GS-XXXXX-Q-X) and classical modes (GS-XXXXX-C-X).

One of the main issues which prevented GEMINI collecting data was a series of laser failures, which disabled GeMS for extended periods of times. In addition, GeMS is very sensitive to poor weather and poor seeing, resulting in several classically allocated nights being completely lost.

\(^4\)https://www.gemini.edu/sciops/data–and–results/processing–software
Table 2.4: Allocations of Gemini telescope time

<table>
<thead>
<tr>
<th>Reference</th>
<th>Time allocated</th>
<th>Time observed</th>
<th>% of time observed</th>
<th>N° Epochs observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS-2013A-Q-4</td>
<td>15.8h</td>
<td>13.53h</td>
<td>86</td>
<td>5</td>
</tr>
<tr>
<td>GS-2013B-Q-26</td>
<td>13.5h</td>
<td>08.35h</td>
<td>62</td>
<td>6</td>
</tr>
<tr>
<td>GS-2014A-Q-4</td>
<td>14.8h</td>
<td>12.66h</td>
<td>85</td>
<td>5</td>
</tr>
<tr>
<td>GS-2014B-Q-32</td>
<td>12.9h</td>
<td>00.00h</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GS-2015B-Q-47</td>
<td>4.3h</td>
<td>00.00h</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GS-2013B-C-1</td>
<td>2nights</td>
<td>06.72h</td>
<td>42</td>
<td>3</td>
</tr>
<tr>
<td>GS-2014B-C-1</td>
<td>2nights</td>
<td>04.00h</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>GS-2015A-C-2</td>
<td>2nights</td>
<td>04.25h</td>
<td>27</td>
<td>2</td>
</tr>
<tr>
<td>GS-2016A-C-2</td>
<td>1night</td>
<td>02.64h</td>
<td>33</td>
<td>1</td>
</tr>
<tr>
<td>GS-2016B-C-2</td>
<td>1night</td>
<td>00.00h</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Chapter 3

Searching for Binary Y Dwarfs with the Gemini Multi-conjugate Adaptive Optics System (GeMS)

This chapter details the results for binary properties of a sample of five WISE Y dwarfs with the Gemini Multi-Conjugate Adaptive Optics System. The work and writing presented here is largely taken from the paper Searching for Binary Y Dwarfs with the Gemini Multi-conjugate Adaptive Optics System (Opitz et al., 2016), reproduced in Appendix B.

3.1 Abstract

The NASA Wide-field Infrared Survey Explorer (WISE) has discovered almost all the known members of the new class of Y-type brown dwarfs. Most of these Y dwarfs have been identified as isolated objects in the field. It is known that binaries with L- and T-type brown dwarf primaries are less prevalent than either M-dwarf or solar-type primaries, they tend to have smaller separations and are more frequently detected in near-equal mass configurations. The binary statistics for Y-type brown dwarfs, however, are sparse, and so it is unclear if the same trends that hold for L- and T-type brown dwarfs also hold for Y-type ones. In addition, the detection of binary companions to very cool Y dwarfs may well be the best means available for discovering even colder objects. We present
results for binary properties of a sample of five *WISE* Y dwarfs with the Gemini Multi-Conjugate Adaptive Optics System (GeMS). We find no evidence for binary companions in these data, which suggests these systems are not equal-luminosity (or equal-mass) binaries with separations larger than $\sim 0.5\text{-}1.9$ AU. For equal-mass binaries at an age of 5 Gyr, we find that the binary binding energies ruled out by our observations (i.e. $10^{11}$ erg) are consistent with those observed in previous studies of hotter ultra-cool dwarfs.

### 3.2 Introduction

The discovery of the coolest $Y$ spectral class of brown dwarfs has extended the temperature range for isolated star-like objects down to $\sim 250$ K (Cushing et al., 2011; Luhman, 2014). Their discovery enables the study of the properties of objects in the temperature gap between the coolest previously known sub-stellar objects ($T_{\text{eff}} \sim 500$ K) and gas-giant planets ($T_{\text{eff}} \sim 130$ K). Currently twenty–one $Y$ dwarfs are known (Cushing et al., 2011; Kirkpatrick et al., 2012; Tinney et al., 2012; Liu et al., 2012; Kirkpatrick et al., 2013; Cushing et al., 2014; Pinfield et al., 2014), as well as three candidates awaiting spectroscopic confirmation (Liu et al., 2011; Luhman, Burgasser, and Bochanski, 2011; Luhman, 2014; Schneider et al., 2015).

Most of the spectroscopically confirmed $Y$ dwarfs have been identified as isolated field objects by the NASA Wide-field Infrared Survey Explorer (*WISE*, Wright et al., 2010). *WISE* has only moderate resolution (6.1$''$ at W1 and 6.4$''$ at W2), and so can only resolve and detect very wide binary systems (i.e. $> 120$ AU at 20 pc).

Previous multiplicity studies for solar type stars and for fainter and less massive $M$, $L$ and $T$ dwarfs have revealed multiplicity frequency declines with spectral type, from 65% (for solar type stars; Duquennoy and Mayor, 1991) to 10-35% (for $L$ and $T$ dwarfs; Delfosse et al., 2004; Burgasser et al., 2007; Aberasturi et al., 2014). If this trend continues to the $Y$ dwarfs or if it is just an observational bias is still unclear. There have been only a limited number of higher resolution binary searches for very late $T$ dwarfs - for example the use of the Keck II AO system to resolve T5+T5 and T8.5+T9 systems (Gelino et al.,...
and T9+Y0 and T8+T9.5 systems (Liu et al., 2012). New generation of Adaptive Optics systems could help to extend binary studies to more Y-type objects.

Binarity, in addition, has been proposed as an explanation for some of the spread seen in the absolute magnitudes of otherwise similar Y dwarfs (Tinney et al., 2014; Leggett et al., 2015). The latest atmospheric models (Morley et al., 2012) are consistent with the majority of the observed absolute magnitudes for Y dwarfs. However, some (including WISEA J053516.87–750024.6 and WISEA J035934.07–540154.8 studied in this paper) show disparities. These objects appear to be over-luminous in MJ and MW2 relative to cloud-free models suggesting either the presence of condensate clouds or equal-mass binarity. Binary Y dwarf systems, once identified, also offer the opportunity to empirically measure dynamical masses (e.g; Dupuy, Liu, and Ireland, 2009; Konopacky et al., 2010).

These issues motivated a diffraction-limited study to determine the binary status of five Y dwarfs using the Gemini Multi-Conjugate Adaptive Optics System (GeMS). In Section 3.3, the properties of our sample, observations and data reduction are detailed. In Section 3.4 the binary status of our targets is examined, and conclusions are presented in Section 3.5.

### 3.3 Observations and data reduction

The Y dwarfs W1541, W0713, W1639, W0359 and W0535 used to the binary analysis were observed between March 2013 and Dec 2014 following the process described in Chapter 2. The creation of the final mosaicked image relied on the presence of sufficient reference stars in the field to perform an astrometric registration. For four of our targets (W0535, W0713, W1541, W1639) this analysis could be done for the single detector containing our target. However, for W0359 we needed to process all four detectors together to make a 2×2 mosaic in order to acquire sufficient reference stars for this step. The FWHM in the final mosaics for each target, determined from Point Spread Function (PSF) analysis described in Section 3.4, are listed in Table 3.1.
Chapter 3. Searching for Binary Y Dwarfs with GeMS

Table 3.1: Log of GSAOI–GeMS Observations

<table>
<thead>
<tr>
<th>Short name</th>
<th>UT Date</th>
<th>Exp. (s)</th>
<th>Array</th>
<th>Gain (e-/ADU)</th>
<th>FWHM (pix)</th>
<th>FWHM (&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W0359</td>
<td>2013 Dec 20</td>
<td>360s×9</td>
<td>3</td>
<td>2.41</td>
<td>5.51</td>
<td>0.11</td>
</tr>
<tr>
<td>W0535</td>
<td>2014 Dec 04</td>
<td>360s×9</td>
<td>3</td>
<td>2.41</td>
<td>6.37</td>
<td>0.13</td>
</tr>
<tr>
<td>W0713</td>
<td>2013 Mar 22</td>
<td>66s×54×9</td>
<td>2</td>
<td>2.01</td>
<td>3.99</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>2013 Apr 17</td>
<td>66s×54×9</td>
<td></td>
<td></td>
<td>4.47</td>
<td>0.09</td>
</tr>
<tr>
<td>W1541</td>
<td>2013 Apr 20</td>
<td>66s×54×9</td>
<td>2</td>
<td>2.01</td>
<td>4.13</td>
<td>0.08</td>
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<td></td>
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<td>66s×54×9</td>
<td></td>
<td></td>
<td>3.98</td>
<td>0.08</td>
</tr>
<tr>
<td>W1639</td>
<td>2013 Apr 21</td>
<td>66s×54×9</td>
<td>4</td>
<td>2.64</td>
<td>4.92</td>
<td>0.09</td>
</tr>
</tbody>
</table>

1–Mosaic detector where each target is located. For W0359 we processed all the GSAOI arrays into a combined mosaic. For the other targets only the individual detector with the target was processed to a final image.

Postage-stamp images zooming on a 0.8"×0.8" region around each of our targets along with a nearby unresolved reference star are shown in Figure 3.1. These show that no obvious binary companions are found in these data.

3.4 Binary analysis

Figure 3.1 shows no obvious evidence for close binary companions in our data. To examine this more closely we have performed two analyses to understand the presence (or absence) of binary companions. We concentrate in this study on close binary companions—the presence (or absence) of wider companions is better probed by multiple epochs of natural-seeing data (since the confirmation of wider companions will critically rely on the observations of common proper motions) and is therefore deferred to a future paper.
3.4. Binary analysis

Figure 3.1: Left: Y dwarfs imaged in the CH$_4$S filter. For each object two panels are shown, with the left displaying a 0.8” × 0.8” sub-image centered on the Y dwarf, and the right showing a nearby reference star. All images are north up and east to the left.
3.4.1 Point spread function analysis

We obtained a Point Spread Function (PSF) model for each stacked image using the DAOPHOT II package (Stetson, 1987) implemented within the Starlink\(^1\) environment. Unsaturated stars were selected and used to determine an initial model PSF, which was used to fit and subtract all known stars within each image in a first pass processing. Any objects detected in the first-pass PSF-subtracted image (and in particular any objects detected near the PSF stars) are added into the list of known stars and included in a second pass of analysis, so as to iterate toward an uncontaminated single-star PSF. This final PSF was then used to simultaneously fit to all objects in the field, allowing a final subtraction of all known objects from the mosaics. This process did not reveal any companions within \(\approx 1.0''\) of our targets. It also yielded a PSF model for each image that was used in subsequent image injection simulations.

For each target, the PSF was approximated by a spatially invariant Moffat function. For W0359 and W0535 observations, where we had to use a full mosaic of the whole array, significant variations in the PSF shape were not observed. However, as the PSF for these targets was generated using a small number of stars and the FWHM was poor, this is not necessarily conclusive that PSF variations are not present – just that modeling PSF variation is neither possible, nor clearly necessary, for the data quality we obtained on these targets.

A most robust test of GSAOI+GeMS’s PSF variation cross the full four detector mosaic has been performed by Santos et al. (2016), using observations for the cluster LS 94. This study did reveal a tendency for smaller FWHM and smaller image ellipticity at positions closer to the locations of the Natural Guide Stars in the field-of-view, as well as slightly larger values on the opposite sides of the field. This was reflected in a dispersion in FWHM of \(0.21 \pm 0.02''\) and \(0.10 \pm 0.02''\) for J and H passband respectively. Once again, though, we note that we saw no evidence requiring the use of a variable PSF for our images, given the data quality available.

\(^1\)http://www.star.bris.ac.uk/~mbt/daophot/
3.4. Binary analysis

3.4.2 Companion detection simulations

We used two methods to explore the detectability of potential binary companions of our target stars, and to determine the magnitude-difference and separation-limits implied by our non-discovery of companions.

Artificial star injection simulations

This method injects synthetic binaries with a variety of separations and magnitude differences into the stacked images, then treats these new systems as both single and binary systems and fits PSF models to them.

We first construct a 160x160 pixels sub-image centered on each Y dwarf. Into those sub-images, we inject a pair of synthetic stars at 4 positions 1.13′′ away from the Y dwarf at position angles of 45°, 135°, 225° and 315° (i.e. pixel positions (40,40), (40,120), (120,40) & (120,120) in the sub-image). This radial separation from the Y dwarf is small enough that the injected systems have the same sky background as the actual Y dwarf, and far enough away that they are uncontaminated by the Y dwarf. (The exception to this is the W1541 data which has a bright star that contaminated the (120,120) position, so it was moved to an offset of (130,100)). The synthetic binaries were injected with radial separations of 1,2,3,.. 10 pixels at positions angles of 0–360° in steps of 45°, and with magnitude differences (Δmag) corresponding to flux ratios of 1.00–0.05. In total we injected 2280 synthetic binary systems into each Y dwarf image.

After the injection of artificial binaries, we used DAOPHOT to fit both single and binary models generally following the analysis used by Aberasturi et al., 2014. We made an initial guess for the position of the primary (by detecting a peak identified in the region of the injected stars and fitting to it as a single star) and the secondary (by detecting a peak in the residual image obtained after subtracting the first object detected), and then used DAOPHOT to fit for both a single and a binary model. An illustration of this process is shown in Fig. 3.2.

The relative statistical significance of the single-star and binary-star fits was assessed using the one-sided F-test.
\[ F = \frac{\chi_{\sin} / \nu_{\sin}}{\chi_{\text{bin}} / \nu_{\text{bin}}} \]  

(3.1)

where \( \chi_{\sin} \) and \( \chi_{\text{bin}} \) are the usually defined \( \sqrt{\chi^2} \) for each model fit, and \( \nu_{\sin} \) and \( \nu_{\text{bin}} \) are the degrees of freedom for a single and binary model fit. The latter were computed using the following expressions:

\[ \nu_{\sin/bin} = \text{pix}_{\text{eff}} - N \]  

(3.2)

where \( \text{pix}_{\text{eff}} \) are the "effective pixels" involved in each fit (essentially a normalised measure of the number of pixels meaningfully involved in each fit - see Aberasturi et al. (2014)) and \( N \) is the number of parameters for the model (3 for a single star and 6 for a binary). A significance level (\( \alpha \)) of 0.05 was required to pass this test – i.e we are required to have more than 95% confidence that the binary model is preferred over the single star model. We then use the 2280 synthetic binary systems to determine the separations and magnitude-differences at which >50% and >90% of injected binaries were recovered with 95% confidence. These results are plotted in Fig. 3.3 for each independent observation, with grey symbols showing the 50% confidence curves and blue symbols showing the 90% confidence curves. A counter-intuitive feature of these curves also seen by Aberasturi et al., 2014 is that equal-luminosity binaries are slightly harder to detect than slightly non-equal luminosity binaries. That is, the separation limit for non–equal luminosity binaries is smaller than the separation limit for equal–mass binaries, because DAOPHOT more readily distinguishes between two peaks with slightly different brightnesses than closely adjacent peaks with the same brightness.

**Photon-counting**

The artificial star injection simulations above show that (in general) binary companions up to 1.5 magnitudes fainter than the primary can be detected to within one half of an image FWHM. To explore the sensitivity of our data to wider (and fainter) companions, we
3.4. Binary analysis

Figure 3.2: Synthetic Y dwarf binary with a $\Delta$mag = 2.0 created using a W0713 point-spread function. The upper panel shows the binary at a separation of 3 pixels (0.06$''$). The middle panel displays the same binary after the subtraction of a single PSF model, displaying a clear residual source. The bottom panel displays the binary after the subtraction of a binary model. All images are at the same gray scale and show a 0.8$''$×0.8$''$ region on a side with north up and east to the left.
compute the flux a hypothetical companion would need to have in order to be detected with S/N=3 (or equivalently photometric uncertainty 0.33 mag) at a series of annular radii from the brown dwarf (following the analyses performed by Gelino et al., 2011). To estimate these limits we constructed a set of 50 annuli with 1 pixel of width and radius between 3 & 50 pixels from the brown dwarfs. We computed the standard deviation of the pixel values in each annulus ($\sigma_a$). Then, we estimated the flux F a companion would have from the standard equations for the magnitude uncertainty,

$$\sigma_m = \frac{C \cdot \sigma_F}{F}$$  \hspace{1cm} (3.3)

$$\sigma_F = \sqrt{(A \cdot \sigma_a^2) + (A^2 \cdot \sigma_a^2/N_a) + F/G}$$  \hspace{1cm} (3.4)

where C is a constant equal to 1.0857, G is the gain of the detector (see Table ??), $\sigma_m$ is 0.33, the magnitude error for detection limits at 3$\sigma$ over the sky, A is the area of the aperture for the detection of the companion ($\pi \cdot [3 \text{ pixels}]^2$) and $N_a$ is the number of pixels in the sky annulus.

Combining 3.3 and 3.4 and solving for F results in:

$$F = \frac{C^2/(G \cdot \sigma_m^2) + \sqrt{(C^2/(G \cdot \sigma_m^2))^2 + 4(1+(A \cdot \sigma_a^2 + A^2 \cdot \sigma_a^2/N_a) \cdot C^2/\sigma_m^2)}}{2}$$  \hspace{1cm} (3.5)

The flux F of the hypothetical secondary was then converted to a magnitude ($m_2$) using the standard equation

$$m_2 \propto -2.5 \cdot \log_{10}(F)$$  \hspace{1cm} (3.6)

and the magnitude difference was computed as the difference between $m_2$ and the magnitude of the target ($m_T$). DAOPHOT is occasionally unable to determine a reliable modal sky value. When this happens we simply discount that $\sigma_a$ and its trial radii. The resulting separation- and magnitude-difference-limits are shown in Fig. 3.3 as red symbols.
### 3.4. Binary analysis

#### Table 3.2: Signal-to-Noise Data

<table>
<thead>
<tr>
<th>Short name</th>
<th>S/N</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>W0713</td>
<td>200</td>
<td>166.67</td>
</tr>
<tr>
<td>W1541</td>
<td>58.82</td>
<td>76.92</td>
</tr>
<tr>
<td>W1639</td>
<td>76.92</td>
<td>52.63</td>
</tr>
<tr>
<td>W0535</td>
<td>21.28</td>
<td>29.41</td>
</tr>
<tr>
<td>W0359</td>
<td>37.04</td>
<td>18.52</td>
</tr>
</tbody>
</table>

Estimate of the S/N ratios obtained for the Y dwarfs and reference stars displayed in Fig. 3.1.

#### 3.4.3 Results

The regions of magnitude-difference versus separation space ruled out by these observations are shown in Fig. 3.3, with Table 3.3 summarizing some key features of these diagrams – namely the largest separation allowed for an unresolved equal-luminosity binary, and the largest magnitude difference ruled out by these data.

As a general rule, the artificial star injection technique is more powerful at small radial separations, where the Y dwarf is imaged with good S/N. In this case an accurate model of the PSF is critical for determining the ability to resolve two closely separated targets. The photon-counting technique readily extends to large separations, and so estimates the faintest companion that our data can rule out. Our artificial injection simulations with a recovery fraction of 90% allow us to strongly conclude that none of these Y dwarfs are equal-mass/equal-luminosity binaries with separations larger than \( \sim 0.5-1.9 \) AU. These limits can be slightly extended for a less-confident recovery fraction of 50% to \( \sim 0.3-1.9 \) AU. Our best data is for W0713 and it shows no evidence for binarity to limits \( \sim \Delta \text{mag} = 4.4 \) mag at separations beyond 1.7 AU (0.18")

#### 3.4.4 Equal mass/luminosity binaries

**WISE 1541, WISE 0713 and WISE 1639**

WISE 0713, WISE 1541 and WISE 1639 are the objects for which our GeMS images have the highest quality, and the artificial star injection simulations show, with high levels of
### Table 3.3: Limits in separation and magnitude from PSF injecting and photon-counting techniques

<table>
<thead>
<tr>
<th>Short name</th>
<th>UT Date</th>
<th>N&lt;sub&gt;PSF&lt;/sub&gt;</th>
<th>∆mag</th>
<th>ρ&lt;sub&gt;phot&lt;/sub&gt; (')</th>
<th>ρ&lt;sub&gt;inj,50&lt;/sub&gt; (AU)</th>
<th>ρ&lt;sub&gt;inj,90&lt;/sub&gt; (')</th>
<th>ρ&lt;sub&gt;inj,90&lt;/sub&gt; (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W0713</td>
<td>2013 Mar 22</td>
<td>13</td>
<td>4.28</td>
<td>0.14</td>
<td>1.29</td>
<td>0.04</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>2013 Apr 18</td>
<td></td>
<td>4.39</td>
<td>0.18</td>
<td>1.66</td>
<td>0.04</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>2013 Apr 20</td>
<td></td>
<td>3.53</td>
<td>0.16</td>
<td>0.91</td>
<td>0.06</td>
<td>0.34</td>
</tr>
<tr>
<td>W1541</td>
<td>2013 May 24</td>
<td>10</td>
<td>3.28</td>
<td>0.18</td>
<td>1.03</td>
<td>0.06</td>
<td>0.34</td>
</tr>
<tr>
<td>W1639</td>
<td>2013 Apr 21</td>
<td>18</td>
<td>3.30</td>
<td>0.08</td>
<td>0.47</td>
<td>0.06</td>
<td>0.30</td>
</tr>
<tr>
<td>W0359</td>
<td>2013 Dec 20</td>
<td>6</td>
<td>2.84</td>
<td>0.18</td>
<td>2.84</td>
<td>0.06</td>
<td>0.95</td>
</tr>
<tr>
<td>W0535</td>
<td>2014 Dec 20</td>
<td>19</td>
<td>2.16</td>
<td>0.16</td>
<td>2.16</td>
<td>0.14</td>
<td>1.89</td>
</tr>
</tbody>
</table>

1 – Number of stars used to create the the point-spread function model. 2 – Magnitude difference limits computed by the photon counting method. 3 – Limits in separation between the primary and the secondary at the magnitude difference limit in arcsec and astronomical units respectively computed by the photon counting method. 4 – Limits in separation for an equal-mass/equal-luminosity binary (magnitude difference of 0.75 mag) computed by the PSF injection method (for 50% of objects recovered). 5 – Limits in separation for an equal-mass/equal-luminosity binary (magnitude difference of 0.75 mag) computed by the PSF injection method (for 90% of objects recovered).
3.4. Binary analysis

FIGURE 3.3: Magnitude difference (Δmag) and separation (ρ) limits for five Y dwarfs at which 50% (grey symbols) and 90% (blue symbols) of companions were recovered, as computed using artificial star injection. Limits computed using photon-counting technique are represented with red symbols. The horizontal lines intersect the magnitude axis at 0.75 mag (corresponding to an equal-luminosity binary) and at the maximum Δm.
confidence (i.e. 90%), that none of these are equal-mass/equal-luminosity binaries with separations larger than 0.5-1.9 AU. Using a weaker confidence limit on binary recovery (50%), we get only a slightly tighter range of limits on separation.

WISE 0535 and WISE 0359

Recently Tinney et al. (2014) have highlighted a handful of Y dwarfs that are over-luminous in $J_{MKO}$ and W2 4.6 $\mu$m, Wright et al., 2010 relative to cloud-free models. W0359 and W0535, in particular, were highlighted as being over-luminous by 0.6 and 1.1 mag respectively. If their over-luminosity were due to unresolved multiplicity, they would have to be nearly equal-luminosity/equal-mass binaries or triples.

The Y-dwarfs W0359 and W0535 are the faintest in our sample, and so the most challenging targets for measuring binary limits. From the artificial injection simulations, with a recovery fraction of 90%, we estimated that W0359 is not an equal-luminosity binary with a separation larger than $\sim 1.9$ AU. For this object, the analysis is made more difficult by the small number of available stars in the field–of–view for generating a PSF.

For W0535 our data is of sufficiently poor signal-to-noise that our simulations cannot achieve 90% recovery over the separation limits studied. This is simply an outcome of the fact that the artificial star injection technique is not powerful when the signal-to-noise of the object detection is $\lesssim 20$ as is the case for W0535. Using the more relaxed 50% recovery limit we estimate less stringent limits for the separation of a possible equal-luminosity binary companion of 1.9 AU for W0535.

If these Y dwarfs are not binaries, the more plausible explanation for their over-luminosity is the presence of clouds. Equal mass binarity essentially doubles the flux from a system, while leaving the overall spectrum unchanged, resulting in objects appearing to be overluminous (for a given colour) in $M_J$ and $M_{W2}$ colour-absolute magnitude diagrams. Models of the impact of condensate cloud formation can also produce an apparently similar effect (e.g Morley et al., 2012; Morley et al., 2014) by shifting hotter and more luminous objects to cooler apparent J-W2 colours.
3.4. Binary analysis

As discussed by Tinney et al. (2014), the fact that some Y dwarfs show over-luminosity while others do not, could indicate different levels of cloud coverage between similar Y dwarfs or time-variable cloud coverage for the same object. Cloud coverage has already been detected on brown dwarfs. The presence of water ice clouds in the coolest brown dwarf known (WISE J085510.83-071442.5; Luhman, 2014) was first suggested by Faherty et al. (2014) and later confirmed by Skemer et al. (2016), while photometric variability due heterogeneous cloud coverage has been reported in some T (Buenzli et al., 2012; Apai et al., 2013; Buenzli et al., 2015) and Y (Cushing, Hardegree-Ullman, and Trucks, 2014) dwarfs.

3.4.5 Faint companions

In general, both techniques deliver consistent results where they overlap at separations of \( \sim 0.1'' \), with the photon counting technique extending to fainter potential companions at larger radial separations. Our best data on our brightest target (W0713) allow us to conclude that GSAOI–GeMS should able to resolve a brown dwarf companion with a contrast \(< 4.4 \text{ mag} \) with respect to W0713 at separations beyond 1.66 AU (0.18\( '' \)) (Fig. 3.3). For W1541 and W1639 we rule out companions up to \( \approx 3.5 \text{ mag} \) fainter than the known Y dwarf at separations beyond 0.5 AU, while for W0359 and W0535 we rule out companions with a contrast \(< 2.0 \text{ mag} \) with respect to the Y dwarfs at separations greater than \( \sim 2 \text{ AU} \) from the Y dwarf.

3.4.6 Binary fraction and mean separation

Observations show a decreasing binary fraction with later primary spectral type (see e.g. Close et al., 2003; Burgasser et al., 2003b; Burgasser et al., 2006a; Duchène et al., 2013; Aberasturi et al., 2014). A recent study of brown dwarf multiplicity (Aberasturi et al., 2014) infers an upper limit of between 16\% and 25\% for the binary fraction of brown dwarf companions to primaries of T5 and later. This is in agreement with previous brown dwarf multiplicity studies (Burgasser et al., 2006a; Burgasser et al., 2007).
Chapter 3. Searching for Binary Y Dwarfs with GeMS

**Figure 3.4:** Binding energy vs. total mass for known very low-mass systems. Objects marked with filled circles are tight very low-mass systems (typically $M_{\text{tot}} \sim 0.2 M_\odot$ and $\rho \sim 20$ AU). Wide systems ($\rho \sim 100$ AU) containing a ultra cool dwarf (UCD) companion are marked as five point stars. Those marked as squares are systems containing a tight or widely separated UCD with an age $< 500$ Myr. Objects marked by open circles come from stellar companion catalogs. Our targets are marked with green arrows. The minimum binding energy corresponding to tight very low mass systems from Close et al. (2003) and Close et al. (2007) and Burgasser et al. 2003 is labeled. We put the limits on each of the systems using an assumed mass of $20M_{\text{Jup}}$ and an age of $5$ Gyr (Dupuy and Kraus, 2013).

**Figure 3.5:** Total mass vs separation. Symbols are described in Fig. 3.4. The curves correspond to the empirical limits for the stability of binary systems set by (Reid et al., 2001) and (Burgasser et al., 2003b), where the stability area is located above and to the right side of each line. Both curves delineate the cutoff for the formation of stellar binary systems but Burgasser et al. (2003b) is specific for a total mass of the system $M_{\text{Tot}} \leq 0.2\odot$. 
3.4. Binary analysis

Table 3.4: Binary fraction for late T-dwarfs ans early Y-dwarfs

<table>
<thead>
<tr>
<th>Reference</th>
<th>SpT</th>
<th>N° Late BDs</th>
<th>N° Late-BD Binaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aberasturi et al. (2014)</td>
<td>Late T-dwarfs</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>Burgasser et al. (2003a)</td>
<td>Late T-dwarfs</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>Burgasser et al. (2006b)</td>
<td>Late T-dwarfs</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Gelino et al. (2011)</td>
<td>Late T-dwarfs</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>Liu et al. (2012)</td>
<td>Late T-dwarfs</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Opitz et al. (2016)</td>
<td>Early Y-dwarfs</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

1 – Spectral type. 2 – Number of late dwarfs in the sample. 3 – Number of late brown dwarf binaries detected.

Combining the results for binarity presented here (and published in Opitz et al., 2016) with previous multiplicity studies for late brown dwarfs (Burgasser et al., 2003a; Burgasser et al., 2006b; Gelino et al., 2011; Aberasturi et al., 2014) we obtain a preliminary estimate of the binary fraction for late brown dwarfs (excluding the duplicated targets) of 14.6% ± 0.8%, which is consist with binary fraction reported by Burgasser et al. (2006a) and Burgasser et al. (2007). A summary of the late brown dwarf binaries detections is displayed in Table 3.4.

This trend in the binary fraction could be explained by either a mass dependence in the star formation process, or an observational bias. The latter is supported by the fact that multiplicity has been largely studied from resolved imaging programs, which are limited in resolution. Burgasser et al. (2007) noted that the peak in the binary angular separation distribution was coincident with the resolution limit of Hubble Space Telescope and ground–based adaptive optics facilities, and suggested an undiscovered population of tight binaries (a ≤ 1 AU).

There is scarce evidence for tight binary systems with mid–T to late–T dwarf primaries–observed separations typically lie between ~ 2 to 15 AU (Aberasturi et al., 2014). However, recently Dupuy, Liu, and Leggett (2015) have extended multiplicity statistics into smaller separations by reporting a tight sub–stellar binary at the T/Y transition with a separation of ~ 0.93 AU.
Chapter 3. Searching for Binary Y Dwarfs with GeMS

In our sample of five Y dwarfs, we did not find evidence for companions down to separation limits of 0.3-1.9 AU, which is in agreement with the binary fraction estimates by Aberasturi et al. (2014). However, our sample is not large enough to confirm whether the decreasing binary fraction with later spectral type primaries is a real trend or an observational bias.

In addition, we do not discount the possibility that some of the Y dwarfs of our sample harbor tighter binaries than our data can resolve, as the mean separation of known binaries also drops as a function of primary type. Very low–mass binaries are expected to be more bound as the gravitational potential well of each component drops as a function of the primary type (Close et al., 2003; Close et al., 2007; Burgasser et al., 2003b).

In Fig. 3.4 we compare the estimated binding energy of our targets (for the assumption that they are unresolved binaries), with known binary systems collected in Faherty et al. (2011) assuming near equal-mass companions of 20 M_{Jup} (from Dupuy and Kraus, 2013) for our targets. The objects of our sample fall within the binding energy limitation set by known tight low-mass (M_{tot} < 0.2 M_⊙) multiples (the dotted line in the figure).

Fig. 3.5 shows the M_{tot} versus separation for the same companion systems described in Fig. 3.4, along with the maximum separations allowed to keep the binary system stable, as suggested by both Reid et al. (2001) and Burgasser et al. (2003b). In both cases, these empirical limits were derived from the binary systems known at that time. As has been noted by Dhital et al. (2010) and Faherty (2010), these cutoffs break down for more massive and widely separated systems as well as very young (< 10 Myr) systems. Nonetheless, the trends predicted by (Reid et al., 2001) and (Burgasser et al., 2003b) provide a means to extrapolate the properties observed for more massive binary systems, to the lower masses relevant for our Y dwarf observations. This suggests that the upper-limits we observe for binary separation in our five Y dwarfs are not inconsistent (based on binding energy and stability arguments) with the binary separations seen at larger masses.

Finally, although no companions to these Y dwarfs were discovered, we have reached limiting angular separations as small as 0.04″. GSAOI–GeMS therefore, is an excellent
instrument to expand multiplicity statistics of the coldest brown dwarfs.

3.5 Summary and conclusions

I have observed five WISE brown dwarfs with the Gemini GeMS Multi-Conjugate Adaptive Optics System to identify ultra-cool companions and have implemented two methods to compute sensitivities as a function of separation and luminosity. Combining the results computed by two different techniques I conclude:

- We detect no binary companions to the five Y dwarfs observed.

- None of these Y dwarfs are equal-mass/equal-luminosity binaries with separations larger than $\sim 0.5$-1.9 AU. Our best data are for W1541, where artificial star injection (at a recovery fraction of 90%), shows no evidence of an equal-mass/equal-luminosity binary at separations down to 0.5 AU (0.08"").

- GSAOI-GeMS would be able to detect binary companions as much as $\sim 4.4$ mag fainter than the known Y dwarf at separations beyond 0.08"".

Although no binary companions to Y dwarfs were detected, these data probe an interesting range of orbital separations for these nearby Y dwarfs and demonstrated the power of GSAOI-GeMS for this science.
I present the first results from our high-precision infrared astrometry program at the Gemini Multi-Conjugate Adaptive Optics System (GeMS) -a parallax measurement for the Y0 dwarf WISEA J071322.55–291752.0.

4.1 Introduction

Astrometric distance is a critical parameter for the study of brown dwarfs properties. It is essential for the measurement of luminosities, on which much analysis and comparison with models rest.

Spectroscopic study of these very cool objects is difficult, as the presence of complex molecules in their atmospheres makes matching with current Y dwarf atmospheric models very hard, providing little constraint on models for Y dwarf formation and evolution. Luminosities in contrast, emerge in a much less model-dependent fashion from interiors models. Unfortunately, the most interesting Y dwarfs are also the faintest \( (H \geq 22) \) making astrometric measurements challenging on seeing-limited telescopes.

Adaptive Optics (AO) has the potential to be a very powerful astrometric tool as it increase the precision of the positional measurements by incrementing the signal-to-noise ratio and shrinking the point spread function (PSF). These enhancements are achieved by
compensating in real time for deformation of the wavefront caused by atmospheric turbulences. The measurement of wavefront distortions requires a point source which should be close to the target in order to pass through the same turbulence, and be bright enough (\(R \sim 15\)). Unfortunately, such bright stars are not available in all parts of the sky, limiting AO correction with natural guide stars to a 10% of the sky. Increased sky-coverage can be obtained using artificial laser guide stars (LGS). However, laser guide stars also have pitfalls as they can be only propagated to a finite altitude, and they require at least one natural guide star to measure the tip-tilt correction which a LGS cannot provide.

Currently, most 8-10m telescopes are equipped with classical single-conjugate adaptive optics systems (SCAO), operating with either a single natural guide (NGS) or LGS, and a single deformable mirror (DM). This configuration allows SCAO systems access to field-of-view (FoV) of tens of arcseconds (Neichel et al., 2014).

Multi-conjugate adaptive optics (MCAO) systems were designed to overcome the limitations of SCAO systems, by using more than one DM to allow AO correction over areas 10 to 20 times larger. To date, the only operative MCAO facility is the Gemini Multi-Conjugate Adaptive Optics System (GeMS, d’Orgeville et al., 2012) at the Gemini South telescope.

MCAO and SCAO systems introduce image distortions arising from multiple sources. For the particular case of GeMS, one part of the distortions comes from the DM and the off-axis parabola in the AO bench. Another source of possible astrometric errors will come from dynamical distortions, which depends on details of the NGS asterisms, the telescope pointing and the dithering.

Astrometric tests with several crowded stellar field observations acquired during GeMS/GSAOI commissioning were performed by Neichel et al. (2014). They show that GeMS is able to reach an astrometric precision of \(\sim 0.2\) mas for exposure times exceeding one minute at single-epochs. However, for multi-epoch observations (required to detect proper motions or parallaxes), that performance was not reproducible delivering an error of 2.6 mas correcting distortions with a polynomial of 3 degrees of freedom and 0.5 mas with a polynomial of 15 degrees of freedom. According to the authors, the main
limitation to reproduce the astrometric precision achieved at single-epochs with multi-
epoch observations from GeMS, is time variability of the astrometric distortions. These
could be produced by changes in the gravity vector due to the movement of GSAOI and
CANOPUS -the GeMS AO-bench (Neichel et al., 2014; Lu et al., 2014; Ammons et al.,
2014; Massari et al., 2016).

Development of AO astrometric analysis techniques and system characterization is
still at early stage. Astrometric studies with GeMS multi-epoch observations separated
by years are critical to the design of future AO systems. In light of the scarcity of multi-
epoch astrometric studies and to take advantage of the unique high resolution imaging
and wide field-of-view provided by GeMS, we implemented a parallax program target-
ing 5 WISE Y dwarfs. Here I present results for our most observed target, the Y0 brown
dwarf WISEA J071322.55–291752.0 (hereafter W0713). In Section 4.2, observations and
data reduction are detailed. In Section 4.3 the astrometric analysis is described. Results
are presented in Section 4.4 while the GEMS astrometric performance is discussed in Sec-
tion 4.5. Finally, conclusions are presented in Section 4.7.

4.2 Data Acquisition and Processing

4.2.1 Observations and Data Reduction

The observations of W0713 (Kirkpatrick et al., 2013) used in this study were obtained with
GeMS and the near-infrared camera GSAOI on eight epochs between March 22, 2013 and
Apr 21, 2016 (see Table 2.2). Data from 2015 Jan 05 were excluded because of the poor
pointing performed on that night, which resulted in highly shifted images compared with
those obtained for rest of epochs and so insufficient overlapping background reference
stars. Data processing was performed using the Gemini GSAOI pipeline, as described in
Chapter 2.
4.2.2 Distortion Correction and Stacking

A key step for astrometry with adaptive optics is the removal of distortions and stacking of individual exposures to create a final mosaic at each epoch. GSAOI images show large static distortions that can be removed with a pre-defined distortion model generated from previous GeMS observations. Dynamical distortions in contrast are more complicated to model as they are not constant, but will vary from field-to-field due to the different NGS asterisms available for each target, the instrument distortions introduced by gravity at the position of each target, and the variable amount of AO correction delivered from night-to-night due to variable atmospheric conditions. These change with the dithering pattern and the size of the offset selected and change with the natural guide stars selected. In an ideal world, one would use both a static distortion model (to correct the fixed astrometric distortion of the GeMS/GSAOI system) and higher-order variable distortion model determined by reference stars in the field (to correct the time variable-components of astrometric distortion). Unfortunately fields with a sufficiently dense system of reference stars to achieve this are incredibly rare.

A tool to address some aspects of this problem has been provided by the Gemini team. The recently released package Disco-Stu can remove static and variable distortions, then align and stack GSAOI/GEMS images. It first detects and estimates the position in pixel coordinates of the all possible sources presented in each image, then transforms the pixel coordinates to celestial coordinates using a static distortion determined with previous GSAOI/GEMS images, as is described in Section 4.2.3. It then determines an overall offset via cross-correlation and matches individual sources between the frames to finally align and stack the images. If an external reference catalog is supplied, the tool performs a match between the reference catalog and the sources.

Disco-Stu was the tool used to align and stack all the GSAOI/GEMS epochs used for the astrometric analysis presented here. The creation of the final mosaicked image relies on the presence of sufficient reference stars in the field to perform an astrometric registration. For W0713 this analysis was performed using just the single detector containing the target (see Figure 4.2).
4.2.3 Static Distortion Model

The pre-defined static distortion correction included in Disco-Stu, was generated by Rodrigo Carrasco from the Gemini team with Large Magellanic Cloud (RA = 05:21:4.144, DEC = -69:29:59.76) observations in J, H and K filters. The positions of the stars in the field were calibrated with position measurements obtained from observations using the Advanced Camera for Surveys (ACS) in the Hubble Space Telescope (HST), with a precision of 1 mas (rms) for a star brighter than V=21 mag. The calibration was performed with MSCTPEAK and CCMAP IRAF tools, which allow mapping world coordinate systems (WCS) to image pixel coordinates and create a WCS database with specific sky projection geometry.

The resulting database for the astrometric fit generated, using the TNX projection (a tangent plane projection with distortion polynomials), is provided in Appendix A. The high order terms of that database are propagated by Disco-Stu to remove the static distortion in other GSAOI/GeMS images.

The four detectors are mounted in the combined GSAOI+GEMS optical system such that they have small, but measurable rotations and tilts relative to each other, as well as potential overall plate scale changes from the optical system. The scale of these effects can be seen in Figure 4.1.
4.3 Astrometric Analysis

Astrometry for W0713 was performed in two ways. The first consisted of an astrometric analysis considering all the images individually, without removing the static distortion and without stacking to make a mosaic at each epoch. This preliminary analysis, allowed us to examine the "worst-case" upper limit to the astrometric precision that could be obtained. The second analysis involved the measurement of proper motions and parallax using the images previously corrected for static distortions and stacked to make a single mosaic image at each epoch (as is described in Section 4.2.2.) to determine whether it delivered an astrometric performance improvement.

The astrometric analysis involved in both strategies, was performed following the same methods adopted in earlier astrometric studies by our team (e.g Tinney, 1996; Tinney et al., 2012; Tinney et al., 2014). Briefly, positional measurements were obtained using the DAOPHOT II package, which performs aperture photometry, obtains the point spread function (PSF) and fits it to the sources to calculate their positions. Details of this
4.3. Astrometric Analysis

procedure are explained in Section 3.4.1. After obtaining the positions of objects in each image, each epoch was transferred to a master frame using a linear transformation that allows field rotation, plate scale change and field offset. The master frame was rotated 29° (as indicated in the instrument file header) in order to align the N-S with the Y axis. The orientation angle reported by the instrument will only be precise to tenths of a degree, and cannot deliver a precise orientation of cardinal directions on the detector. Obtaining a precise field orientation requires performing transformations between detector star positions and an external catalogue like Gaia (Lindegren et al., 2016) or 2MASS (Skrutskie et al., 2006) and the GSAOI images. Unfortunately, neither GAIA nor 2MASS provide enough stars in our fields to perform such a solution.

A set of five reference stars was chosen to surround W0713 in the field of view (see Figure 4.2). Finally, proper motions and parallaxes for W0713 were determined.

The effect of differential chromatic refraction (DCR, the different amount of refraction the atmosphere produces in different wavelengths) on our results was not considered. Correction for DCR requires either obtaining each object’s spectrum (to obtain its effective wavelength within a given bandpass, e.g. Fritz et al., 2016a) or deriving a DCR calibration based on the observed correlation between stellar colours and DCR coefficients (Monet et al., 1992). Derivation of the latter requires the observation of the fields as they rise and set on a single night to measure only apparent stars shifts due to DCR.

We chose not to request this type of calibration data since, (as is discussed in Tinney, Burgasser, and Kirkpatrick, 2003), the impact of DCR in the near-infrared observations for T dwarfs is small (between 2-10 mas/tan(ZD) in the J–passband). All our observations are were carried out in the GSAOI CH4S passband (1.486–1.628 μm) where DCR is even smaller than in the J–band, and all observations were carried out in a narrow range of hour angles corresponding to a maximum difference in tan(ZD) for each target of < 48. As a result the maximum impact of DCR on our observations if < ±0.2 mas.
4.4 Results

The residuals of the astrometric transformations for both methods are displayed in Table 4.1. Data processed without correcting for static distortions show a rms scatter about the reference star frame transformation of 0.1 to 0.3 pixels (2-6 mas) while data processed to correct the static distortion demonstrate a rms precision of 0.04 to 0.2 pixels (0.8-4.0 mas).

In every case the scatter about the reference star transformation in the distortion-corrected solution is improved over that from the solutions uncorrected for distortion. Tests with background stars of brightness equivalent to the Y dwarf W0713 revealed a GeMS astrometric precision for W0713 of \( \sim 4-6 \) mas.
4.4. Results

Plots of the astrometric solutions from data processed without removing the static distortions are shown in the Figure 4.3 and Figure 4.4, while the astrometric solution from images corrected for static distortion and stacked by Disco-Stu, are displayed in Figure 4.5 and Figure 4.6.

Astrometric parameters obtained by the two methods, N -the number of images for the undistorted solution and the number of epochs for distorted solution- and a comparison with parallax measurements obtained by Tinney et al. (2014), are presented in Table 4.2.

Parallax measurements obtained from both analyses performed are consistent with the solution delivered from Magellan data (Tinney et al., 2014). Proper motions in contrast, show discrepancies. Proper motions $\mu_\alpha$ and $\mu_\delta$ obtained from data corrected for static distortions exceed in $\sim 10$ mas/y to those determined by Tinney et al. (2014).

<table>
<thead>
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<th>Distortion-corrected$^2$</th>
</tr>
</thead>
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<td></td>
<td>Mean $d_x$</td>
<td>rms$_x$</td>
</tr>
<tr>
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<td>0.42</td>
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<td>0.11</td>
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</tr>
<tr>
<td>3</td>
<td>0.34</td>
<td>0.20</td>
</tr>
<tr>
<td>4</td>
<td>-0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>5</td>
<td>-0.83</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Mean of the difference in x and y (i.e. dx and dy) and root mean square (rms) of the star transformations for:

1 Data uncorrected for static distortions and not-stacked.

2 Data corrected for static distortions and stacked.
**Figure 4.3:** Proper motion for W0713 after processing all frames individually and without removing the static distortions. The panel shows actual motion on the sky with proper motion and parallax solution superimposed.
4.4. Results

Figure 4.4: GeMS astrometry for W0713 obtained from data without correcting for static distortions and without stacking. The panel show the right ascension and declination solutions with the fitted proper motion removed for clarity.
Figure 4.5: Proper motion for W0713 after removing the static distortion. The panel show actual motion on the sky with proper motion and parallax solution superimposed.
FIGURE 4.6: GeMS astrometry for W0713 obtained from data corrected for static distortions and stacked. The panel show the right ascension and declination solutions with the fitted proper motion removed for clarity.
4.5 Discussion

In general, our best astrometric solution (obtained from data corrected for the static distortions and stacked) gets a rms of 0.04 to 0.2 pixels which is equivalent to 0.8-4 mas. This is at least 1.4 times better than the rms obtained from FourStar observations (Tinney et al., 2012; Tinney et al., 2014).

<table>
<thead>
<tr>
<th>Astrometric parameters</th>
<th>Magellan¹</th>
<th>GeMS²</th>
<th>GeMS³</th>
</tr>
</thead>
<tbody>
<tr>
<td>π (mas)</td>
<td>108.7 ± 4.0</td>
<td>106.7 ± 2.6</td>
<td>107.9 ± 4.9</td>
</tr>
<tr>
<td>μ (mas/y)</td>
<td>540.2 ± 7.3</td>
<td>546.3 ± 2.4</td>
<td>554.5 ± 4.7</td>
</tr>
<tr>
<td>μα (mas/y)</td>
<td>350.3 ± 4.7</td>
<td>350.7 ± 2.0</td>
<td>361.2 ± 4.2</td>
</tr>
<tr>
<td>μδ (mas/y)</td>
<td>-411.3 ± 5.6</td>
<td>-418.9 ± 1.5</td>
<td>-420.8 ± 2.6</td>
</tr>
<tr>
<td>V_{tan} (km/s)</td>
<td>23.6 ± 4.6</td>
<td>24.3 ± 3.8</td>
<td>24.4 ± 5.2</td>
</tr>
<tr>
<td>N⁴</td>
<td>7</td>
<td>41</td>
<td>7</td>
</tr>
<tr>
<td>N_{ref}</td>
<td>21</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

¹ Tinney et al. (2014)
² Obtained from data processed without removing the static distortion.
³ Obtained from data considering the static distortion.
⁴ Number of images for the undistorted solution and number of epochs for the distorted solution.

Static distortion treatment allowed us lower the astrometric noise from GSAOI/GeMS to below 4 mas. Part of the residual astrometric scatter may be caused by the use of dithered observations. Neichel et al. (2014) have shown that the use of undithered frames delivers the best astrometric precision over multiple epochs, albeit at the cost of having fixed bad-pixel impacts and not being able to observe targets to great depth. Our data was taken using dithering, because some of our targets are at the faint limit of what GeMS+GSAOI can observe, and this necessitates the integration on sky for long-periods. Additionally, the overheads to place a given target at a given pixel position at Gemini...
are prohibitive. It is acknowledged that in the absence of a detailed static and non-static astrometric distortion map for each field, this may introduce astrometric noise.

Another important part of the astrometric scatter is caused by a combination of variable seeing conditions and the variable PSF that the AO system produces as a result, and variable astrometric distortion from epoch–to–epoch produced by the AO system. The image quality of our W0713 data was variable and ranged from 80 to 140 mas. That is, in almost all cases it was poorer than expected given the diffraction limit of an 8m telescope (50 mas).

Due to its recent commissioning and the early development stage of distortion removing techniques, GSAOI/GeMS astrometric performance studies are scarce. A comparison of GSAOI/GeMS astrometric performance with NIRC2 at the W. M. Keck Observatory (which is equipped with a SCAO system) and HST WFC3IR, was performed by Lu et al. (2014) using crowded fields observations. Assuming the random component of the positional uncertainty errors scale with integration time and flux as $t^{-1/2}$ and $f^{-1/2}$, and a systematic astrometric floor for each instrument, measured from very dense field observations (385 µas for GeMS, 150 µas for NIRC2 and WFC3IR), they estimate that for an 18th magnitude star in 15 minutes of exposure, Gemini, HST WFC3IR and Keck NIRC2 deliver astrometric errors of 1350 (µas), 960 (µas) and 370 (µas) respectively.

NIRC2 has a field of view of $10" \times 10"$ then, when the region of interest is small and crowded, this should be the optimal instrument to use. GeMS delivers observation over a wider field ($85" \times 85"$), and (although not as precise over that wide field as Keck + AO + NIRC2) can be calibrated to deliver 0.4 mas astrometry. Our data does not reach that level of precision, unfortunately, because of our sparse field.

The sparse set of reference stars in our fields is only sufficient to perform a “solid body” astrometric solution between epochs, meaning that variable astrometric distortion from epoch–to–epoch contributes noise that we cannot remove. If a high-order model is fitted, apparent astrometric shifts that are not really there can be introduced resulting in a under–predictive astrometric noise. We therefore choose to “underfit” our data, to avoid the chance of “overfitting”, given we do not have enough reference stars to robustly
constrain a high-order transformation.

The formal proper motion uncertainties for the distortion-uncorrected solutions in Table 4.2 are slightly smaller than those for the distortion-corrected solutions, as a result of the averaging of multiple images at each epoch in the unstacked distortion-uncorrected data, compared to single stacked images in the distortion-corrected data. As a result, the smaller proper-motion uncertainties for the distortion-uncorrected processing are not considered to be physically meaningful.

The W0713 proper motion uncertainties are similar to those delivered by FourStarTinney et al. (2014) suggesting GeMS is an instrument potentially able to deliver high quality brown dwarf astrometric measurements in sparse fields.

The parallax and proper motions presented here are the first astrometric measurements obtained for a brown dwarf from GSAOI/GeMS observations. Proper motions of stars in crowded field are also scarce. At the present day, only two measurements obtained from this instrument have been published, delivering accuracies of \( \sim 0.03/\text{y mas} \) by (Massari et al., 2016) and \( \sim 0.3 \text{ mas}/\text{y} \) (Fritz et al., 2016b), which are much better than proper motions uncertainties presented for W0713, which is not surprising as these were obtained from globular cluster observations.

### 4.6 Comparing the Disco-Stu Distortion Map

During the implementation of this parallax program, other authors have performed astrometric studies to measure the GeMS distortion. Massari et al. (2016) used Hubble Space Telescope (HST) and GeMS observations of the globular cluster NGC 6681 to measure GeMS distortion and deliver the proper motions for several stars in the cluster. The map constructed by Massari et al. (2016) is displayed in Figure 4.7.
4.6. Comparing the Disco-Stu Distortion Map

FIGURE 4.7: GeMS distortion map constructed by Massari et al. (2016). Each arrow corresponds to the position of the stars studied by Massari et al. (2016) in the HST reference frame and the displacements due GeMS distortions.

Much like the static distortion map from by Disco-Stu, the distortion map constructed by Massari et al. (2016) shows a roughly circular structure at the centre of each detector, as well as a change in the plate-scale significantly larger in the X-axis than in the Y-axis. However, the amplitude of the distortions measured by Massari et al. (2016) is larger than that in the field used by Disco-Stu. The former spans an interval ranging from 0 to 7.2 pixels in the X-axis (right ascension) and from 0.6 to 2.1 pixels in the Y-axis (declination) while the later spans an interval ranging from 0 to 53 pixels in the X-axis and from 0.1 to 21 pixels in the Y-axis. The astrometric distortion in GeMS would appear to be not terribly static. In this situation we feel it is better to make minimal assumptions, and apply as simple a distortion correction as possible, and so have adopted the Disco–Stu map.
4.7 Conclusions

In this chapter, I have presented the first MCAO astrometric measurements for the Y0 dwarf WISEA J071322.55–291752.0 obtained from observations with the only MCAO facility operative, GeMS. Using two methods to perform an astrometric analysis and comparing with Magellan, I conclude:

GeMS suffers from static and variable astrometric distortions that impact severely its astrometric performance. Static distortion can be removed with a pre-defined distortion model generated from crowded field observations improving by at least a factor of 1.4 the precision of stellar transformations in our sparse field. The treatment of variable distortions is essential to improve the GeMS astrometric precision but is not possible to perform for our observations. This requires the field to contain many more reference stars than are available for W0713.

However, parallax and proper motions measurements from GSAOI/GeMs data corrected for only the static distortions, presented in this chapter, are consistent with that obtained from FourStar in Magellan reported by Tinney et al. (2014). We have raised proper motion accuracies by at least a factor of 1.1 better than FourStar, demonstrating GSAOI/GeMS has the potential to deliver high-quality astrometric measurements in sparse fields.
Chapter 5

Astrometry for the Y1 dwarf WISEP J154151.65–225025.2

I present the second result from our high-precision infrared astrometry program at the Gemini Multi-Conjugate Adaptive Optics System (GeMS), a parallax measurement for the Y1 dwarf WISEP J154151.65–225025.2.

5.1 Introduction

WISEP J154151.65–225025.2 was one of the first Y dwarfs discovered in 2011 from Wide-field Infrared Survey Explorer (WISE) observations (Kirkpatrick et al., 2011) and one of the first objects classified as a Y1 (Schneider et al., 2015). Astrometric measurements for W1541 have been determined by diverse teams (Tinney et al., 2014; Beichman et al., 2014; Dupuy and Kraus, 2013) from both space- and ground-based observations. Tinney (using FourStar observations at Magellan), and Beichman (using combined observations from Keck, the Hubble Space Telescope (HST), Spitzer and WISE), show consistent parallax measurements for W1541, reporting 175.1 ± 4.4 mas and 176 ± 9 mas respectively. Dupuy et al. on other hand, using observations from Spitzer, deliver a parallax of 74 ± 31 mas. This discrepancy has been attributed (Tinney et al., 2014) to the large pixels of Spitzer leading to confusion with a background source at some epochs of the Dupuy et al. solution. This highlights an important role for ground-based observations working at higher imaging resolutions for faint Y dwarf targets.
In Chapter 4, we demonstrated the GeMS potential capability to perform high precision astrometric measurements for the Y0 WISEA J071322.55–291752.0 by (Tinney et al., 2014). Here I present results for our second most observed target, the Y1 brown dwarf WISEP J154151.65–225025.2 (hereafter W1541). In Section 5.2, observations and data reduction are detailed. In Section 5.3 the astrometric analysis is described. Results are presented in Section 5.4 while the GEMS astrometric performance is discussed in Section 5.5. Finally, conclusions are presented in Section 5.6.

5.2 Data Acquisition and Processing

The observations of Y0 dwarf W1541 used in this study were obtained on five epochs between Apr 20, 2013 and Jun 18, 2014 with GeMS and the near–infrared camera GSAOI (see Table 2.2). Data processing was performed using the Gemini GSAOI pipeline, distortion-corrected and stacked, as is described in Chapter 4.

5.3 Astrometric Analysis

Astrometry for W1541 was performed using the distortion correction procedure developed for W0713 as described in Section 4.2.2. That is, the images were corrected for static distortions, resampled and stacked to make a single mosaic image at each epoch. Astrometric analysis was carried out using the same methods adopted in Tinney (1996), Tinney et al. (2012), and Tinney et al. (2014), by determining the positions of objects in each image and transferring each epoch to a master frame using a linear transformation that allows field rotation, plate scale change and field offset. The master frame was rotated 192° (as indicated in the instrument file header) in order align the Y axis of the master frame image with the celestial N-S direction. The orientation angle reported by the instrument will only be precise to tenths of a degree, and cannot deliver a precise orientation of cardinal directions on the detector. Obtaining a precise field orientation requires performing transformations between detector star positions and an external catalogue like Gaia (Lindegren et al., 2016) or 2MASS (Skrutskie et al., 2006) and the GSAOI
images. Unfortunately, neither GAIA nor 2MASS provide enough stars in our fields to perform such a solution.

A set of five reference stars was chosen to surround W1541 in the field of view (see Figure 5.1). Finally, proper motions and parallaxes for W1541 were determined. Differential chromatic refraction correction for W1541 was not performed.

One important difference between the W1541 field studied here and W0713 observations described in Chapter 4 is that our target is substantially fainter than our reference frame stars. In this scenario, the residuals about the reference frame transformation cannot be used to model the epoch–by–epoch precision of positions for the target object. Ideally one would use other stars in the field of similar magnitude to the target to estimate a per–epoch uncertainty, however the paucity of reference stars in this field makes that impossible. For W1541, we instead extrapolated the precision achieved for the reference frame (2.6 mas) at its mean magnitude\(^{1}\), to the magnitude of W1541 (17.4\(^{2}\)), scaling precision with magnitude resulting in a precision of 12 mas.

\(^{1}\)DAOPHOT magnitude
\(^{2}\)DAOPHOT magnitude
5.4 Results

The residuals of the astrometric transformations are displayed in Table 5.1 and show a rms scatter about the reference star frame transformation of 0.1 to 0.5 pixels (2-10 mas). Plots of the astrometric solutions are shown in the Figure 5.2 and Figure 5.3.

Astrometric parameters obtained are presented in Table 5.2 along with the number of epochs (N) and a comparison with parallax measurements obtained by Tinney et al. (2014). The Parallax obtained from the astrometric analysis presented here is consistent with the solution delivered from Magellan data by Tinney et al. (2014). Proper motions in contrast, show discrepancies. The $\mu_\delta$ delivered here is some 5$\sigma$ smaller than that determined by Tinney et al. (2014).
5.4. Results

<table>
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<tr>
<th>ID</th>
<th>Mean $d_x$ (pix)</th>
<th>$r_{ms_x}$ (pix)</th>
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</table>

Figure 5.2: Proper motion for W1541. The panel show actual motion on the sky with proper motion and parallax solution superimposed.
Figure 5.3: GeMS astrometry for W1541 obtained from data corrected for static distortions and stacked. The panel show the right ascension and declination solutions with the fitted proper motion removed for clarity.
5.5 Discussion

The scatter about our astrometric solution ranges from 0.1 to 0.5 pixels (depending on epoch), corresponding to a precision of 2-10 mas. This is as much as 2 times poorer than the per epoch results obtained from FourStar (Tinney et al., 2012; Tinney et al., 2014) and 2.5 times poorer than for our W0713 field. The high residual astrometric scatter is caused, as for our W0713 field, by a combination of variable seeing conditions and, variable astrometric distortions from epoch-to-epoch that, because of sparse nature of our W1541 field, are not possible to remove.

<table>
<thead>
<tr>
<th>Astrometric parameters</th>
<th>Magellan$^1$</th>
<th>GeMS</th>
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<td>$\pi$ (mas)</td>
<td>175.1 ± 4.4</td>
<td>169.9 ± 16.6</td>
</tr>
<tr>
<td>$\mu$ (mas/y)</td>
<td>899.0 ± 4.2</td>
<td>894.3 ± 13.9</td>
</tr>
<tr>
<td>$\mu_\alpha$ (mas/y)</td>
<td>-894.7 ± 4.2</td>
<td>-894.1 ± 13.6</td>
</tr>
<tr>
<td>$\mu_\delta$ (mas/y)</td>
<td>-87.9 ± 4.7</td>
<td>16.8 ± 13.1</td>
</tr>
<tr>
<td>$V_{tan}$ (km/s)</td>
<td>24.3 ± 3.9</td>
<td>24.9 ± 7.8</td>
</tr>
<tr>
<td>$N^2$</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>$N_{ref}$</td>
<td>23</td>
<td>5</td>
</tr>
</tbody>
</table>

$^1$ Tinney et al. (2014)
$^2$ Number of epochs

W1541 has the additional difficulty of being much fainter than W0713, and much fainter than its field of reference stars, resulting in substantial poorer asymmetry at every epoch.

Our astrometric analysis for W1541 delivered lower proper motions and parallax precisions (> 13 mas) than previous studies with ground- and space-based instruments, albeit from a smaller number of epochs. The small (∼2') field of view of GeMS+GSAOI means we have a small sample of reference stars that are much brighter than our target,
forcing us to extrapolate per-epoch precisions from the brightness of the frame to the
brightness of our target - this may cause us to overestimate the uncertainties attached to
our W1541 astrometry.

Experience with parallax programs on other common-user telescopes (e.g. Tinney,
1996; Tinney, Burgasser, and Kirkpatrick, 2003; Tinney et al., 2014) indicates that a mini-
imum of 5–6 well spaced epochs over at least 2 years are required to produce robust
parallax estimates, with an uncertainty on the parallax similar to the astrometric uncer-
tainty on individual epochs. Additional data thereafter shrinks parallax uncertainties as
additional data points are accumulated.

In the case of W1541, where data spans only 1 year and a limited range of parallax
factors, a minimum of a further 2 epochs at well-chosen parallax factors will be required
to produce a robust parallax, with a precision of 5-6 mas.

5.6 Conclusions

In this chapter, I have presented the first astrometric measurements of the Y1 dwarf
WISEP J154151.65–225025.2 obtained from observations with GeMS. From the astromet-
ric analysis performed and from a comparison of our results with Magellan, I conclude:

GeMS suffer from static and astrometric variable distortions that impact its astromet-
ric performance in our sparse field. Astrometric measurements obtained for our W1541
field show a rms 2.0 times poorer than the rms obtained from FourStar observations pub-
lished in Tinney et al. (2014) and 2.5 times poorer than the rms obtained for our W0713
field. Proper motions and parallax measurements also show lower accuracies (> 13 mas).
However, as this astrometric analysis is based on only five epochs with more than the half
epochs with a seeing > 110 mas, higher accuracies could be delivered by additional ob-
servations obtained in better seeing conditions.
Chapter 6

Conclusions

In this thesis I have exploited the high resolution and (compared to other adaptive optics systems) wide field-of-view of $85'' \times 85''$ of the Gemini Multi-Conjugate Adaptive Optics System (GeMS) to observe five WISE brown dwarfs to identify ultra-cool companions and measure astrometric distances.

6.1 Binaries

The study of binary properties for these objects did not reveal any companions. To explore the detectability of potential binary companions of ours targets, and to determine the magnitude–difference and separation-limits implied by our non-discovery of companions, two methods were implemented. Combining the results computed by these two techniques, two conclusions arise. First, none of these Y dwarfs are equal-mass/equal-luminosity binaries with separations larger than $\sim 0.5$-1.9 AU. Our best data are for W1541, where artificial star injection (at a recovery fraction of 90%), shows no evidence of an equal-mass/equal-luminosity binary at separations down to 0.5 AU (0.08$''$). Second, GSAOI-GeMS would be able to detect binary companions as much as $\sim 4.4$ mag fainter than the known Y dwarf at separations beyond 0.08$''$.

Although the sample of Y-dwarfs studied here is not large enough to deliver a conclusive binary fraction for Y-dwarfs, combining our results with early multiplicity studies for late brown dwarfs (Burgasser et al., 2003a; Burgasser et al., 2006b; Gelino et al., 2011; Aberasturi et al., 2014) we obtain a preliminary estimation of the binary fraction for late
brown dwarfs of $19.5\% \pm 0.8\%$, which is consistent with the binary fraction reported by Burgasser et al. (2006a) and Burgasser et al. (2007) for brown dwarfs of early spectral types.

6.2 GSAOI+GeMS Astrometric Performance

The astrometric analysis performed for W0713 and W1541 presented in this thesis reveals that GSAOI/GeMS suffer from both static and variable distortions that have an impact on astrometric performance for our sparse fields. Astrometric results for our W0713 field from images observed in less than ideal seeing conditions and corrected only for static distortion, show an rms scatter ranging from 2 to 6 mas, which is at least 1.4 times better than the rms obtained from FourStar observations (Tinney et al., 2012; Tinney et al., 2014). Proper motions in turn displayed accuracies at least 1.1 times better than that delivered with FourStar, indicating GSAOI+GeMS has the potential to deliver high-quality astrometric measurements.

The W1541 astrometric measurements presented here, obtained from images processed using the distortion correction procedure developed for W0713, showed a rms 2 times poorer than the per epoch results obtained from FourStar and 2.5 times poorer than for our W0713 field. In turn, proper motions measurements showed low accuracies ($> 13$ mas). This lower performance, could be explained because of the insufficient epochs on our astrometric analysis was based and the poor seeing obtained for most of the W1541 observations.

6.3 GeMS Long Term Stability and Completion of Y–dwarf Parallax Program

Initially, we planned to observe 6 Y-type brown dwarfs with GeMS/GSAOI to perform astrometry and determine binary status. Our astrometric study was intended to acquire 6-8 epochs per each target. Unfortunately, we were unable to obtain all epochs expected
so our Y-dwarf parallax program could not be completed with success. There are two main reasons which prevented us to take all data planned. First, the GeMS laser guidestar projection system was knocked out of alignment by significant earthquakes in Chile in 2013, stopping GEMS/GSAOI from operating for almost a year. Second, our classical observations were dominated by poor weather and poor seeing, resulting in several classically allocated nights being completely lost.

Considering the substantial loss of allocated classical nights due to poor weather, the impact of variable distortions and the slightly better astrometric performance obtained for our best data (W0713) compared with that raised by FourStar, I conclude that, at the current stage of GeMS development, GSAOI+GeMS is not a powerful combination to implement an parallax program for sparse fields. Variable distortions cannot be removed from sparse fields as this process requires high order transformations and consequently, many reference stars. The limited GeMS precision due to the variable distortions could be slightly improved in excellent seeing conditions, but these are hard to obtain, even in the queue mode. In light of this, the astrometric potential of GeMS can be best exploited performing astrometric studies by targeting crowded fields.

You can certainly point out that for the small fraction of the sky where you can get a rich field of reference stars (e.g. W049 results) you can solve for more complex (and changeable) distortions. But for most of the sky (after all I we only targeted 6 southern Y dwarfs, which is less than half the number available in the south), MCAO is not so great for astrometry.

6.4 The Future of Astrometry with the Gemini Multi-Conjugate Adaptive Optics System

Dynamic astrometric distortion correction requires a suitably dense network of background reference stars, with known, external astrometry. Gaia’s Data Release 2 (DR2) will deliver such a network over the whole sky, extending down to $G \sim 20$ (Lindegren et al., 2016). The question for any individual object will then become, how many stars with
G < 20 are present in the GeMS field-of-view? Recent results for Luhman 16AB (Garcia et al., 2017; Bedin et al., 2017) show that in some favourably dense fields, sufficient stars do indeed exist, and that dynamic astrometric distortion may become solvable for some targets in the near future now that Gaia DR2 is available.
Appendix A

Static Distortion Database

A.1 The TNX World Coordinate System

The TNX World Coordinate System is a non-standard system for representing celestial coordinates from the image pixel coordinate. This consists of a tangent sky projection (linear term) plus distortion (no-linear term).

The standard sky coordinates $\varepsilon$ and $\eta$ are represented from the linear equation (A.1) and (A.2),

$$\varepsilon = CD_{11}(x - CRPIX1) + CD_{12}(y - CRPIX2) \quad (A.1)$$

$$\eta = CD_{21}(x - CRPIX1) + CD_{22}(y - CRPIX2) \quad (A.2)$$

where $x$ and $y$ are the pixel coordinates of any point in the image, CRPIX1 and CRPIX2 are the pixel coordinates of the reference tangent point and $CD_{ij}$ are the elements of the coordinate transformation matrix.

The corrected sky coordinates $\varepsilon'$ and $\eta'$ are represented from the no-linear equations (A.3) and (A.4),

$$\varepsilon' = \varepsilon + lngcor(\varepsilon, \eta) \quad (A.3)$$
Appendix A. Static Distortion Database

\[ \eta' = \eta + \text{latcor}(\varepsilon, \eta) \]  

(A.4)

where lngcor(\varepsilon, \eta) and latcor(\varepsilon, \eta) are polynomial functions represented as

\[ \text{lng} (\varepsilon, \eta) = \sum a_{mn} \varepsilon^m \eta^n \]  

(A.5)

\[ \text{lat} (\varepsilon, \eta) = \sum b_{mn} \varepsilon^m \eta^n \]  

(A.6)

The RA and DEC of any point in the image are computed using the equations (A.7) and (A.8),

\[ RA = CRVAL1 + \varepsilon' \]  

(A.7)

\[ DEC = CRVAL2 + \eta' \]  

(A.8)

where CRVAL1 AND CRVAL2 correspond to RA, DEC of reference tangent in the sky

A.2 Plate Solution

Database with the plate solution generated with Large Magellanic Cloud observations by Rodrigo Carrasco from the Gemini team. The interpretation of high order terms (the static distortion map) is provided in Section A.3.
A.2. Plate Solution

cosystem j2000
projection tnx
lngref 5.363651111111106
latref -69.49993333333331
lngunits hours
latunits degrees
xpixref 173.7071643271124
ypixref 2403.391646719334
geometry general
function polynomial
xishift -3.767293338535515
etashift -47.40723615004112
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ymag 0.01971450124499278
xrotation 359.5396135462445
yrotation 0.4689580328811265
wcsxirms 0.002304323244250163
wcsetarms 0.004517713702252843
xirms 0.00230432324425027
etarms 0.004517713702252851
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  2. 2.
  2. 2.
  0. 0.
  5. 5.
2044. 2044.
  5. 5.
2044. 2044.
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0.01945507134593546 1.563299085656958E-4
1.613586631961425E-4 0.01971384089214057
surface2 18
### Appendix A. Static Distortion Database

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yrefmean 993.4711230769234
lngmean 5.362324709401706
latmean -69.50770688034188
pixsystem physical
coonsystem j2000
projection tnx
lngref 5.3636511111111106
latref -69.49993333333331
lngunits hours
latunits degrees
```
A.2. Plate Solution

xpixref 2363.932792542347
ypixref 2402.928473628532
general
function polynomial
xishift -47.77441111281951
etashift -47.76547084404991
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ymag 0.01971943312890162
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yrotation 0.5390723762449558
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4. 4.
4. 4.
2. 2.
5. 5.
2044. 2044.
Appendix A. Static Distortion Database

5. 5.
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2.788514653546706E-4 2.689748894070916E-5
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2.675437435818343E-12 2.785894821583605E-12
-1.353132791439666E-7 -7.291062769196125E-9
1.450848713190932E-12 1.549659955759916E-12
4.966560575231940E-13 -1.631768127489460E-12

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coonsystem j2000
projection tnx
lngref 5.3636511111111106
latref -69.49993333333331
lngunits hours
latunits degrees
xpixref 2373.332945688426
ypixref 208.7789406472366
geometry general
function polynomial
xishift -47.41388591702555
etashift -4.654717879799149
A.2. Plate Solution

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ymag 0.01970074149553265
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wcsetarms 0.00320746473518645
xirms 0.003469246772969245
etarms 0.00320746473518481
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surface2 18
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Appendix A. Static Distortion Database

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latmean -69.49492801318268

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coosystem j2000
projection tnx
lngref 5.363651111111106
latref -69.4999333333331
lngunits hours
latunits degrees
xpixref 189.8208756078813
ypixref 211.6960945378711

geometry general
function polynomial
xishift -3.608039600938993
etashift -4.196595494921446
xmag 0.01941903634454984
ymag 0.01969998613502834
xrotation 359.5816429428497
yrotation 358.9283147769436
wcsxirms 0.00248746299205392
wcsetarms 0.00408565092436945
xirms 0.00248746299205922
etarms 0.004085650924369216
A.2. Plate Solution

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2. 2.
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surface2 18
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4. 4.
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2. 2.
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2044. 2044.
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2044. 2044.

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1.283023891016379E-12 6.870431670792159E-12
A.3 Decomposing the Distortion Map

CCDMAP IRAF task computes the projected sky coordinates $\epsilon$ and $\eta$ using the equations (A.3) and (A.4). The linear terms of these expressions in the plate solution generated by CCDMAP are grouped under the expression $surface1$, while the no-linear terms are grouped under the expression $surface2$. These no-linear terms allow it define a static distortion map for each GSAOI array which can be used to correct the static distortions of any GSAOI image.

To understand how to decompose the distortion map into parameters and coefficients, the plate solution for GSAOI array 2 is put in Table A.1.

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</tbody>
</table>

Table A.1: Decomposing High Order Terms from the Plate Solution

The list of coefficients is interpreted as follows

1. The first number corresponds to the function type. Chebyshev, legendre and polynomial functions are represented by numbers 1, 2 and 3 (respectively). In this case the function is a polynomial.
A.3. Decomposing the Distortion Map

2. The next two numbers are the orders of the function in $\varepsilon$ and $\eta$. In this case, all the GSAOI detectors has functions of order 4, which means cubic polynomials ($m=0$ to 3 and $n=0$ to 3).

3. The fourth number specifies the type of cross-terms. It is the terms of where $m$ and $n$ are non-zero. No cross-terms, full cross-terms and half-cross-terms are represented by numbers 0, 1 and 2 (respectively).

4. The next four numbers describe the region of validity of the fits in $\varepsilon$ and $\eta$.

5. The remaining terms are the coefficients of the polynomial term. For $\varepsilon$ in array 2 these are:

$$
\begin{align*}
a_{00} & = -0.1949408064796304 \\
a_{10} & = 2.87778046298606E - 4 \\
a_{20} & = -1.495360882919546E - 7 \\
a_{30} & = 5.523962776560459E - 12 \\
a_{01} & = 2.788514653546706E - 4 \\
a_{11} & = -1.417656730511652E - 8 \\
a_{21} & = 2.675437435818343E - 12 \\
a_{02} & = -1.353132791439666E - 7 \\
a_{12} & = 1.450848713190932E - 12 \\
a_{03} & = 4.966560575231940E - 13
\end{align*}
$$

while for $\eta$ these are:
\( b_{00} = -0.01563985104451207 \)
\( b_{10} = 1.397817242056433E - 5 \)
\( b_{20} = -1.808648145552520E - 9 \)
\( b_{30} = -1.598683318558063E - 12 \)
\( b_{01} = 2.689748894070916E - 5 \)
\( b_{11} = -1.262163320882350E - 8 \)
\( b_{21} = 2.785894821583605E - 12 \)
\( b_{02} = -7.291062769196125E - 9 \)
\( b_{12} = 1.549659955759916E - 12 \)
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Appendix B

Published Papers
SEARCHING FOR BINARY Y DWARFS WITH THE GEMINI MULTI-CONJUGATE
ADAPTIVE OPTICS SYSTEM (GeMS)

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5 Research School of Astronomy & Astrophysics, Australian National University, Canberra, ACT 2611, Australia
6 Infrared Processing and Analysis Center, MS 100-22, California Institute of Technology, Pasadena, CA 91125, USA
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ABSTRACT

The NASA Wide-field Infrared Survey Explorer (WISE) has discovered almost all the known members of the new class of Y-type brown dwarfs. Most of these Y dwarfs have been identified as isolated objects in the field. It is known that binaries with L- and T-type brown dwarf primaries are less prevalent than either M-dwarf or solar-type primaries, they tend to have smaller separations and are more frequently detected in near-equal mass configurations. The binary statistics for Y-type brown dwarfs, however, are sparse, and so it is unclear if the same trends that hold for L- and T-type brown dwarfs also hold for Y-type ones. In addition, the detection of binary companions to very cool Y dwarfs may well be the best means available for discovering even colder objects. We present results for binary properties of a sample of five WISE Y dwarfs with the Gemini Multi-Conjugate Adaptive Optics System. We find no evidence for binary companions in these data, which suggests these systems are not equal-luminosity (or equal-mass) binaries with separations larger than ~0.5–1.9 AU. For equal-mass binaries at an age of 5 Gyr, we find that the binary binding energies ruled out by our observations (i.e., 1042 erg) are consistent with those observed in previous studies of hotter ultra-cool dwarfs.

Key words: binaries: general – brown dwarfs – methods: observational – stars: low-mass – techniques: image processing

I. INTRODUCTION

The discovery of the coolest Y spectral class of brown dwarfs has extended the temperature range for isolated star-like objects down to ~250 K (Cushing et al. 2011; Luhman 2014). Their discovery enables the study of the properties of objects in the temperature gap between the coolest previously known sub-stellar objects (Teff ~ 500 K) and gas-giant planets (Teff ~ 130 K). Currently 21 Y dwarfs are known (Cushing et al. 2011; Kirkpatrick et al. 2012, 2013; Liu et al. 2012; Tinney et al. 2012; Cushing et al. 2014b; Pinfield et al. 2014), as well as 3 candidates awaiting spectroscopic confirmation (Liu et al. 2011; Luhman et al. 2011; Luhman 2014; Schneider et al. 2015).

Most of the spectroscopically confirmed Y dwarfs have been identified as isolated field objects by the NASA Wide-field Infrared Survey Explorer (WISE, Wright et al. 2010). Searches for very low-mass binaries (defined as having a total system mass Msys < 0.2 M⊙ and primary mass M1 < 0.1 M⊙) have concentrated on high resolution imaging surveys, using both nearby field sources (e.g; Koerner et al. 1999; Burgasser et al. 2003; Reid et al. 2008; Gelino et al. 2011; Aberasturi et al. 2014) and young cluster associations (e.g; Martin et al. 1998; Neuhäuser et al. 2002; Bouy et al. 2006; Todorov et al. 2014). These studies have determined a brown dwarf binary fraction of ~10%–30% (Burgasser et al. 2007), which is substantially lower than the binary fraction of solar-type stellar systems (~65%; Duquennoy & Mayor 1991) and the binary fraction of early-type M stars (~30%–40%; Reid & Gizis 1997; Delfosse et al. 2004). This trend could indicate either a mass dependence on the multiplicity or an as yet uncovered population of very low-mass binaries. The latter is strongly supported by the known incompleteness of the statistics for very tight (a ≤ 1 AU) and wide (a ≥ 100 AU) binaries (see Konopacky 2015, and references therein).

The binary status of Y type brown dwarfs is also both unclear and of considerable interest. Open questions include: is there a lower mass limit for the formation of binary systems? How common are Y dwarf binary systems? What is the mass ratio distribution between the components of Y dwarf binaries? A new generation of wide-field adaptive optics systems using laser-guide star constellations and deformable mirrors conjugating to multiple layers in the atmosphere offer the prospect of addressing these questions from the ground (in advance of JWST’s capabilities becoming available in space).

Binarity, in addition, has been proposed as an explanation for some of the spread seen in the absolute magnitudes of otherwise similar Y dwarfs (Tinney et al. 2014; Leggett et al. 2015). The latest atmospheric models (Morley et al. 2012) are consistent with the majority of the observed absolute magnitudes for Y dwarfs. However, some (including WISEA J05516.87–750024.6 and WISEA J035934.07–540154.8 studied in this paper) show disparities. These objects appear to be over-luminous in MJ and MW2 relative to cloud-free models suggesting either the presence of condensate clouds or equal-mass binarity. Binary Y dwarf systems, once identified, also offer the opportunity to empirically measure dynamical masses (e.g; Dupuy et al. 2009; Konopacky et al. 2010).
These issues motivated a diffraction-limited study to determine the binary status of five Y dwarfs using the Gemini Multi-Conjugate Adaptive Optics System (GeMS). In Section 2, the properties of our sample, observations and data reduction are detailed. In Section 3 the binary status of our targets is examined, and conclusions are presented in Section 4.

2. OBSERVATIONS AND DATA REDUCTION

We observed a sample of five nearby Y dwarfs discovered by WISE (see Table 1). The full WISE designation, near-infrared J3 photometry, parallax and spectral type for the sample are also listed. These objects were observed with the Gemini South Adaptive Optics Imager (GSAOI; McGregor et al. 2004; Carrasco et al. 2012) and corrected for atmospheric aberrations by GeMS (d’Orgeville et al. 2012). GSAOI has a pixel scale of 0.02′ and is composed of four 2048 × 2048 Rockwell HAWAII-2RG arrays that form a near-infrared imaging mosaic. Each detector offers access to a field of view of 41′ × 41′. All observations were carried out in the GSAOI CH₄₃ passband (1.486–1.628 μm). This filter was chosen as this provides the optimal sensitivity for these faint objects with very strong methane absorption.

The extreme faintness of Y brown dwarfs combined with the rarity of suitably bright natural guide stars makes natural guide star adaptive optics for these targets completely impractical. The GeMS system was chosen for these observations over a traditional single-deformable mirror system, because its wide field of correction allows the selection of off-axis tip-tilt stars over a large field, as well as delivering AO correction over a large ≈2′ diameter field. This to-date unique capability allows observations of Y dwarfs to address both “narrow field” binarity science, as presented here, and wide-field astrometric science, to be presented in a future publication.

A log listing the observations is given in Table 2. The Y dwarfs W1541, W0713, and W1639 were observed between 2013 March and May with a total integration time of approximately 1 hour, using 54 exposures of 66 s each and random telescope dithering every 6 exposures inside a box size of ∼1″6 × 1″6.

Experience with this observing mode showed that observing overheads were high and therefore, subsequent observations for W0359 and W0535 were carried out by dithering and co-adding every 9 exposures. These observations delivered a typical FWHM of 86 mas for W1541, W0713, and W1639 and an FWHM of 120 mas for W0359 and W0535. The difference in the FWHM for these two groups of objects are caused by the different observing conditions.

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Data processing was performed using the Gemini GSAOI pipeline, which operates in the IRAF environment.9 This applies a bad pixel mask, creates and subtracts an averaged dark from all images, applies a fl image, and corrects for atmospheric aberrations by GeMS for this field to perform an astrometric registration. For four of our targets (W0355, W0713, W1541, W1639) this analysis could be done for the single detector containing our target. However, for W0359 we needed to process all four detectors together to make a 2 × 2 mosaic in order to acquire sufficient reference stars for this

9 http://www.gemini.edu/sciops/data-and-results/getting-started#gsaoi
The FWHM in the final mosaics for each target, determined from point-spread function (PSF) analysis described in Section 3, are listed in Table 2. Postage-stamp images zooming on a $0.8 \times 0.8$ region around each of our targets along with a nearby unresolved reference star are shown in Figure 1. These show that no obvious binary companions are found in these data.

3. BINARY ANALYSIS

Figure 1 shows no obvious evidence for close binary companions in our data. To examine this more closely we have performed two analyses to understand the presence (or absence) of binary companions. We concentrate in this study on close binary companions—the presence (or absence) of wider companions is better probed by multiple epochs of natural-seeing data (since the confirmation of wider companions will critically rely on the observations of common proper motions) and is therefore deferred to a future paper.

3.1. PSF Analysis

We obtained a PSF model for each image using the DAOPHOT II package (Stetson 1987) implemented within the Starlink\textsuperscript{10} environment. Unsaturated stars were selected and used to determine an initial model PSF, which was used to fit and subtract all known stars within each image in a first pass processing. Any objects detected in the first-pass PSF-subtracted image (and in particular any objects detected near the PSF stars) are added into the list of known stars and included in a second pass of analysis, so as to iterate toward an uncontaminated single-star PSF. This final PSF was then used to simultaneously fit to all objects in the field, allowing a final subtraction of all known objects from the mosaics. This process did not reveal any companions within $\approx 1''0$ of our targets. It also yielded a PSF model for each image that was used in subsequent image injection simulations.

\footnote{http://www.star.bris.ac.uk/~mbt/daophot/}

\textbf{Figure 1.} Left: Y dwarfs imaged in the CH$_4$ filter. For each object two panels are shown, with the left displaying a $0.8 \times 0.8$ sub-image centered on the Y dwarf, and the right showing a nearby reference star. All images are north up and east to the left.
Appendix B. Published Papers

3.2. Companion Detection Simulations

We used to two methods to explore the detectability of potential binary companions of our target stars, and to determine the magnitude-difference and separation-limits implied by our non-discovery of companions.

3.2.1. Artificial Star Injection Simulations

This method injects synthetic binaries with a variety of separations and magnitude differences into the images, then treats these new systems as both single and binary systems and fits PSF models to them.

We first construct a 160 × 160 pixel sub-image centered on each Y dwarf. Into those sub-images, we inject a pair of synthetic stars at 4 positions 1713 away from the Y dwarf at position angles of 45°, 135°, 225°, and 315° (i.e., pixel positions (40, 40), (40, 120), (120, 40), and (120, 120) in the sub-image). This radial separation from the Y dwarf is small enough that the injected systems have the same sky background as the actual Y dwarf, and far enough away that they are uncontaminated by the Y dwarf. (The exception to this is the W1541 data which have a bright star that contaminated the (120,120) position, so it was moved to an offset of (130, 100).) The synthetic binaries were injected with radial separations of 1, 2, 3, ..., 10 pixels at positions angles of 0°–360° in steps of 45°, and with magnitude differences (Δmag) corresponding to flux ratios of 1.00–0.05. In total we injected 2280 synthetic binary systems into each Y dwarf image.

After the injection of artificial binaries, we used DAOPHOT to fit both single and binary models (generally following the analysis used by Aberasturi et al. 2014). We made an initial guess for the position of the primary (by detecting a peak identified in the region of the injected stars and fitting it to as a single star) and the secondary (by detecting a peak in the residual image obtained after subtracting the first object detected), and then used DAOPHOT to fit for both a single and a binary model. An illustration of this process is shown in Figure 2.

The relative statistical significance of the single-star and binary-star fits was assessed using the one-sided F-test

\[
F = \frac{\chi^2_{\text{bin}}/\nu_{\text{bin}}}{\chi^2_{\text{sing}}/\nu_{\text{sing}}}
\]

where \(\chi^2_{\text{bin}}\) and \(\chi^2_{\text{sing}}\) are the usually defined \(\chi^2\) for each model fit, and \(\nu_{\text{bin}}\) and \(\nu_{\text{sing}}\) are the degrees of freedom for a single and binary model fit. The latter were computed using the following expressions:

\[
\nu_{\text{bin}} = \nu_{\text{eff}} - N
\]

where \(\nu_{\text{eff}}\) are the “effective pixels” involved in each fit (essentially a normalised measure of the number of pixels meaningfully involved in each fit—see Aberasturi et al. 2014) and \(N\) is the number of parameters for the model (3 for a single star and 6 for a binary). A significance level (α) of 0.05 was required to pass this test—i.e., we are required to have more than 95% confidence that the binary model is preferred over the single star model. We then use the 2280 synthetic binary systems to determine the separations and magnitude-differences at which >50% and >90% of injected binaries were recovered with 95% confidence. These results are plotted in Figure 3 for each independent observation, with gray symbols showing the 50% confidence curves and blue symbols showing the 90% confidence curves. A counter-intuitive feature of these curves (also seen by Aberasturi et al. 2014) is that equal-luminosity binaries are slightly harder to detect than slightly non-equal luminosity binaries.

Figure 2. Synthetic Y dwarf binary with a Δmag = 2.0 created using a W0713 point-spread function. The upper panel shows the binary at a separation of 3 pixels (0\(^{\prime\prime}\)06). The middle panel displays the binary after the subtraction of a single PSF model, displaying a clear residual source. The bottom panel displays the binary after the subtraction of a binary model. All images are at the same gray scale and show a 0\(^{\prime\prime}\)8 × 0\(^{\prime\prime}\)8 region on a side with north up and east to the left.
3.2.2. Photon-counting

The artificial star injection simulations above show that (in general) binary companions up to 1.5 mag fainter than the primary can be detected to within one half of an image FWHM.

To explore the sensitivity of our data to wider (and fainter) companions, we compute the flux a hypothetical companion would need to have in order to be detected with signal-to-noise ratio \( S/N = 3 \) (or equivalently photometric uncertainty

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**Figure 3.** Magnitude difference (\( \Delta \text{mag} \)) and separation (\( \rho \)) limits for five Y dwarfs at which 50\% (gray symbols) and 90\% (blue symbols) of companions were recovered, as computed using artificial star injection. The horizontal lines intersect the magnitude axis at 0.75 mag (corresponding to an equal-luminosity binary) and at the maximum \( \Delta \text{mag} \).

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**B.0.5**
B.0.6

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#### Table 3

<table>
<thead>
<tr>
<th>Short Name</th>
<th>S/N</th>
<th>S/N (ref star)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W0359</td>
<td>200</td>
<td>166.67</td>
</tr>
<tr>
<td>W1541</td>
<td>58.82</td>
<td>76.92</td>
</tr>
<tr>
<td>W1639</td>
<td>76.92</td>
<td>52.63</td>
</tr>
<tr>
<td>W0535</td>
<td>21.28</td>
<td>29.41</td>
</tr>
<tr>
<td>W0359</td>
<td>37.04</td>
<td>18.52</td>
</tr>
</tbody>
</table>

Note. Estimate of the S/N ratios obtained for the Y dwarfs and reference stars displayed in Figure 1.

As a general rule, the artificial injection simulations show, with high levels of confidence (i.e., 90%), that none of these are equal-mass/equal-luminosity binaries with separations larger than 0.5–1.9 AU. Using a weaker confidence limit on binary recovery (50%), we get only a slightly tighter range of limits on separation.

3.4. Equal Mass/Luminosity Binaries

3.4.1. WISE 1541, WISE 0713, and WISE 1639

WISE 0713, WISE 1541, and WISE 1639 are the objects for which our GeMS images have the highest quality, and the artificial star injection simulations show, with high levels of confidence (i.e., 90%), that none of these are equal-mass/equal-luminosity binaries with separations larger than 0.5–1.9 AU. Using a weaker confidence limit on binary recovery (50%), we get only a slightly tighter range of limits on separation.

3.4.2. WISE 0535 and WISE 0359

Recently Tinney et al. (2014) have highlighted a handful of Y dwarfs that are over-luminous in 

\[
\text{F} = C^2/(G + \sigma_n^2) + \sqrt{\left[\frac{C^2}{(G + \sigma_n^2)}\right]^2 + 4 \left(A + \sigma_t^2 + A^2 + \sigma_t^2/2N_a\right) \frac{C^2}{\sigma_n^2}} \right] / 2
\]

The flux \( F \) of the hypothetical secondary was then converted to a magnitude \( m_2 \) using the standard equation

\[
m_2 \approx -2.5 \log_{10}(F)
\]

and the magnitude difference was computed as the difference between \( m_2 \) and the magnitude of the target \( m_1 \). DAOPHOT is occasionally unable to determine a reliable modal sky value. When this happens we simply discount that \( \sigma_t \) and its trial radii. The resulting separation- and magnitude-difference-limits are shown in Figure 3 as red symbols.

3.3. Results

The regions of magnitude-difference versus separation space ruled out by these observations are shown in Figure 3, with Table 4 summarizing some key features of these diagrams—namely the largest separation allowed for an unresolved equal-luminosity binary, and the largest magnitude difference ruled out by these data.

As a general rule, the artificial star injection technique is more powerful at small radial separations, where the Y dwarf is imaged with good S/N, in cases an accurate model of the PSF is critical for determining the ability to resolve two closely separated targets.
3.5. Faint Companions

In general, both techniques deliver consistent results where they overlap at separations of \( \sim 0.1 \), with the photon counting technique extending to fainter potential companions at larger radial separations. Our best data on our brightest target (W0713) allow us to conclude that GSAOI-GeMS should be able to resolve a brown dwarf companion with a contrast \(< 4.4 \) mag with respect to W0713 at separations beyond \( 1.66 \) AU (0''18) \( (1) \). For W1541 and W1639 we rule out companions with a contrast \(< 2.0 \) mag with respect to the Y dwarfs at separations greater than \( \sim 2 \) AU from the Y dwarf.

3.6. Binary Fraction and Mean Separation

Observations show a decreasing binary fraction with later primary spectral type \( (\text{e.g., Duchêne and Kraus 2013, and references therein}) \). A recent study of brown dwarf multiplicity \( (\text{Aberasturi et al. 2014}) \) infers an upper limit of between 16\% and 25\% for the binary fraction of brown dwarf companions to primaries of T5 and later. This is in agreement with previous brown dwarf multiplicity studies \( (\text{Burgasser et al. 2006; Burgasser et al. 2007}) \).

This trend in the binary fraction could be explained by either a mass dependence in the star formation process, or an observational bias. The latter is supported by the fact that multiplicity has been largely studied from resolved imaging programs, which are limited in resolution. Burgasser et al. \( (2007) \) noted that the peak in the binary angular separation distribution was coincident with the resolution limit of Hubble Space Telescope and ground-based adaptive optics facilities, and suggested an undiscovered population of tight binaries \( (\psi < 1 \text{ AU}) \).

There is scarce evidence for tight binary systems with mid-T to late-T dwarf primaries—observed separations typically lie between \( \sim 2 \) and \( 15 \) AU \( (\text{Aberasturi et al. 2014}) \). However, recently Dupuy et al. \( (2015) \) have extended multiplicity statistics into smaller separations by reporting a tight substellar binary at the T/Y transition with a separation of \( \sim 0.93 \) AU.

In our sample of five Y dwarfs, we did not find evidence for companions down to separation limits of \( 0.3\sim 1.9 \) AU, which is in agreement with the binary fraction estimates by Aberasturi et al. \( (2014) \). However, our sample is not large enough to confirm whether the decreasing binary fraction with later spectral type primaries is a real trend or an observational bias.

In addition, we do not discount the possibility that some of the Y dwarfs of our sample harbor tighter binaries than our data can resolve, as the mean separation of known binaries also drops as a function of primary type. Very low-mass binaries are expected to be more bound as the gravitational potential well of each component drops as a function of the primary type \( (\text{Burgasser et al. 2003; Close et al. 2003, 2007}) \).

In Figure \( 4 \) we compare the estimated binding energy of our targets \( (\text{for the assumption that they are unresolved binaries}) \), with known binary systems collected in Faherty et al. \( (2011) \) assuming near equal-mass companions of \( 20 M_{\oplus} \) (from Dupuy \& Kraus 2013) for our targets. The objects of our sample fall within the binding energy limitation set by known tight low-mass \( (M_{\text{tot}} < 0.2 M_{\odot}) \) multiples (the dotted line in the figure).

Figure \( 5 \) shows the \( M_{\text{tot}} \) versus separation for the same companion systems described in Figure \( 4 \), along with the maximum separations allowed to keep the binary system stable, as suggested by both Reid et al. \( (2001) \) and Burgasser et al.
4. SUMMARY AND CONCLUSIONS

We have observed five WISE brown dwarfs with the GeMS to identify ultra-cool companions and have implemented two methods to compute severities as a function of separation and luminosity. Combining the results computed by two different techniques we conclude:

1. We detect no binary companions to the five Y dwarfs observed.
2. None of these Y dwarfs are equal-mass/equal-luminosity binaries with separations larger than ≲0.5–1.9 AU. Our best data are for W1541, where artificial star injection (at a recovery fraction of 90%), shows no evidence of an equal-mass/equal-luminosity binary at separations down to 0.5 AU (0.7iras).
3. GSAOI-GeMS would be able to detect binary companions as much as ~4.4 mag fainter than the known Y dwarf at separations beyond 0.7iras.

Although no binary companions to Y dwarfs were detected, these data probe an interesting range of orbital separations for these nearby Y dwarfs and demonstrated the power of GSAOI-GeMS for this science.

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Facilities: GEMINI (GeMS-GSAOI).

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Figure 4. Binding energy vs. total mass for known very low-mass systems. Objects marked with filled circles are tight very low-mass systems (typically $M_2 \approx 0.2 M_\odot$ and $\rho \sim 20$ AU). Wide systems ($\rho \sim 100$ AU) containing an ultra cool dwarf (UCD) companion are marked as five point stars. Those marked as squares are systems containing a tight or widely separated UCD with an age < 500 Myr. Objects marked by open circles come from stellar companion catalogs. Our targets are marked with green arrows. The minimum binding energy corresponding to tight very low mass systems from Close et al. (2003, 2007) and Burgasser et al. (2003) is labeled. We put the limits on each of the systems using an assumed mass of 20 $M_\odot$ and an age of 5 Gyr (Dupuy & Kriv 2013).

Figure 5. Total mass vs. separation. Symbols are described in Figure 4. The curves correspond to the empirical limits for the stability of binary systems set by Reid et al. (2003) and Burgasser et al. (2003), where the stability area is located above and to the right side of each line. Both curves delineate the cutoff for the formation of stellar binary systems but Burgasser et al. (2003) is specific for a total mass of the system $M_{\text{tot}} < 0.2 M_\odot$. The Astrophysical Journal, 819:17 (9pp), 2016 March 1 Opitz et al.

In both cases, these empirical limits were derived from the binary systems known at that time. As has been noted by Dhillon et al. (2010) and Faherty et al. (2010), these cutoffs break down for more massive and widely separated systems as well as very young (<10 Myr) systems. Nonetheless, the trends provide a means to extrapolate the properties observed for more massive binary systems, to the lower masses relevant for our Y dwarf observations. This suggests that the upper-limits we observe for binary separation in our five Y dwarfs are not inconsistent (based on binding energy and stability arguments) with the binary separations seen at larger masses.

Finally, although no companions to these Y dwarfs were discovered, we have reached limiting angular separations as small as 0.004. GSAOI-GeMS, therefore, is an excellent instrument to expand multiplicity statistics of the coldest brown dwarfs.
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