

The ‘DODO’ survey – I. Limits on ultra-cool substellar and planetary-mass companions to van Maanen’s star (vMa 2)

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Accepted 2008 January 21. Received 2008 January 18; in original form 2007 December 19

ABSTRACT

We report limits in the planetary-mass regime for companions around the nearest single white dwarf to the Sun, van Maanen’s star (vMa 2), from deep *J*-band imaging with Gemini North and *Spitzer* Infrared Array Camera (IRAC) mid-IR photometry. We find no resolved common proper motion companions to vMa 2 at separations from 3 to 45 arcsec, at a limiting magnitude of $J \approx 23$. Assuming a total age for the system of 4.1 ± 1 Gyr, and utilizing the latest evolutionary models for substellar objects, this limit is equivalent to companion masses $> 7 \pm 1 M_{\text{Jup}} (T_{\text{eff}} \approx 300 \text{ K})$. Taking into account the likely orbital evolution of very low mass companions in the post-main-sequence phase, these *J*-band observations effectively survey orbits around the white dwarf progenitor from 3 to 50 au. There is no flux excess detected in any of the complimentary *Spitzer* IRAC mid-IR filters. We fit a white dwarf model atmosphere to the optical *BVRI*, *JHK* and IRAC photometry. The best solution gives $T_{\text{eff}} = 6030 \pm 240 \text{ K}$, $\log g = 8.10 \pm 0.04$ and, hence, $M = 0.633 \pm 0.022 M_{\odot}$. We then place a 3σ upper limit of $10 \pm 2 M_{\text{Jup}}$ on the mass of any unresolved companion in the $4.5 \mu\text{m}$ band.

Key words: stars: low-mass, brown dwarfs – planetary systems – white dwarfs – infrared: stars.

1 INTRODUCTION

Direct imaging of extra-solar planetary-mass companions to solar-type stars is complicated by problems of contrast and resolution. At the time of writing, no planet has been directly imaged around a solar-type star. An alternative solution to these difficulties is to target intrinsically faint stars instead, such as white dwarfs. Stellar evolution lends two huge advantages when searching for very faint companions: white dwarfs are up to $\sim 10^4$ times fainter than their main-sequence progenitors, and the orbits of any planetary-mass companions that lie outside the stellar envelopes during the giant phases will expand outwards as mass is lost from the central star, increasing the projected separation by a maximum factor $M_{\text{MS}}/M_{\text{WD}}$ (Jeans 1924). Thus, the problems of contrast and resolution are greatly reduced. The possible evolution of planetary systems in the

post-main-sequence phase is discussed in more detail by Duncan & Lissauer (1998), Burleigh, Clarke & Hodgkin (2002), Debes & Sigurdsson (2002) and Villaver & Livio (2007).

The direct detection of such low-mass companions to white dwarfs opens up the possibility for spectroscopic investigation of a previously unobserved class of object: evolved low-mass brown dwarfs and planetary-mass gas giants as low in temperature as $T_{\text{eff}} \approx 300 \text{ K}$. In contrast, the directly imaged planetary-mass ($\approx 5 M_{\text{Jup}}$) companion to the brown dwarf 2MASS WJ1207 has the spectrum of a mid-L dwarf (Chauvin et al. 2004, 2005), because it is still young ($\sim 10^7$ yr old). The coolest known brown dwarf, ULAS J003402.77 – 005206.7, has a temperature $600 < T_{\text{eff}} < 700 \text{ K}$ (Warren et al. 2007) and a spectral type T 8.5. The letter ‘Y’ has been suggested for the next, cooler, spectral type (Kirkpatrick 2005), which might include evolved planetary-mass companions to white dwarfs. Alternatively, if no obvious spectral change triggers the use of a new letter, then the T classification will need to be extended beyond T 8.5.

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The idea of using white dwarfs to find intrinsically faint, low-mass companions is not new. Probst (1983) and Becklin & Zuckerman (1988) used the low luminosity of white dwarfs to search for brown dwarf companions as near-infrared photometric excesses, and indeed the latter achieved success with GD 165 B (L 4). More recently, Farihi, Becklin & Zuckerman (2005) have conducted a comprehensive search for brown dwarf companions to several hundred white dwarfs but detected only one new pair (GD 1400, L 6–7; Farihi & Christopher 2004; Dobbie et al. 2005), while Maxted et al. (2006) and Burleigh et al. (2006b) have detected a close L 8 companion to the white dwarf WD 0137–349. No other detached substellar companions to white dwarfs are known.

The most intriguing circumstantial evidence for the existence of old planetary systems that have survived to the final stage of stellar evolution comes from the discovery of metal-rich circumstellar dust and gas discs around a growing number of white dwarfs (Zuckerman & Becklin 1987; Becklin et al. 2005; Kilic et al. 2005, 2006; Gänsicke et al. 2006; von Hippel et al. 2007; Jura, Farihi & Zuckerman 2007a; Kilic & Redfield 2007). *Spitzer* mid-infrared spectroscopy has now revealed that the dust discs are composed largely of silicates (Reach et al. 2005a; Jura et al. 2007b). The favoured explanation for the origin of this material is the tidal disruption of an asteroid that has wandered into the Roche radius of the white dwarf (Jura 2003), perhaps through interaction with planets in a Solar system that has become destabilized in the wake of the planetary nebula phase (Debes & Sigurdsson 2002). Jura (2006) suggests that at least 7 per cent of white dwarfs possess asteroid belts. If that is indeed the case, it is likely that at least this number of white dwarfs also possess planetary systems.

The recent discovery of a $M \sin i = 3.2 M_{\text{Jup}}$ planet in a 1.7 au orbit around the extreme horizontal branch star V391 Pegasi by Silvotti et al. (2007) proves that such objects can survive red giant branch evolution, strongly suggesting that it is simply a matter of time before a planet is discovered around a white dwarf.

Burleigh et al. (2002) made predictions concerning the likely near-infrared brightness of putative resolved, giant planetary companions to nearby white dwarfs, based on their likely total ages and distances. In 2002, we initiated a programme to search for wide, spatially resolved very low mass common proper motion companions to white dwarfs via direct imaging. In particular, we aim to find substellar companions with masses greater than a few M_{Jup} around white dwarfs within ≈ 20 pc of the Sun. Such companions are expected to have near-IR magnitudes brighter than $J \sim 23.5$, commensurate with the expected sensitivity of an 8-m telescope in a 1-h exposure.

We christened our project ‘DODO’ – Degenerate Objects around Degenerate Objects. Preliminary results and progress reports have been published elsewhere (Clarke & Burleigh 2004; Burleigh, Hogan & Clarke 2006a; Hogan, Burleigh & Clarke 2007). Here, we report our results for the nearest single white dwarf to the Sun in our sample, van Maanen’s star (vMa 2, WD 0046+051, $d = 4.41$ pc; Perryman et al. 1997). We combine two epochs of deep, ground-based *J*-band imaging from the 8-m Gemini North telescope with *Spitzer* mid-infrared photometry to place limits on the masses and temperatures of any common proper motion and unresolved ultra-cool substellar and planetary-mass companions.

1.1 vMa 2 and previous infrared observations

vMa 2 was discovered serendipitously by van Maanen (1917) in a survey for common proper motion companions to an unrelated star, HD 4628. It has a cool, helium-rich atmosphere and strong reso-

nance Ca II H & K lines in its optical spectrum, and is classified as a DZ white dwarf. The heavy elements are expected to sink below the photosphere on a time-scale much shorter than the white dwarf cooling time. Their presence has been explained previously in terms of episodic accretion from the interstellar medium (Dupuis et al. 1992), but this scenario requires the accretion rate of hydrogen to be at least two orders of magnitude lower than the metals (Dupuis, Fontaine & Wesemael 1993; Wolff, Koester & Liebert 2002; Dufour et al. 2007). Alternatively, the presence of metals in DZs might be explained from accretion of cometary material or tidally disrupted asteroids and planets. However, no DZ has been identified with an infrared excess due to dust emission, possibly because the diffusion time-scale for heavy elements in cool white dwarf helium-rich atmospheres is long and the material may have been accreted as much as $\sim 10^6$ yr ago. None the less, DZ white dwarfs are a speculative candidate for hosting old planetary systems and vMa 2, as the nearest single white dwarf to the Sun, is an ideal target for such a search.

Through the analysis of *Hipparcos* data, Makarov (2004) claimed to have astrometrically detected a $0.06 \pm 0.02 M_{\odot}$ substellar companion to vMa 2, with an orbital period of 1.57 yr and a maximum separation on the sky of 0.3 arcsec. Farihi, Becklin & Macintosh (2004) carried out a search for this companion by direct imaging with adaptive optics in the mid-infrared *L'* band. They also looked for an unresolved companion as a near- and mid-infrared photometric excess in ground-based and *Infrared Space Observatory (ISO)* photometry. They refuted the existence of Makarov’s companion, and of any excess emission due to dust, and placed a limit of $T_{\text{eff}} \lesssim 500$ K on the temperature of any putative substellar companion.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Gemini NIRI *J*-band imaging

Two deep *J*-band images centred on vMa 2 were acquired using Gemini North and the Near-Infrared Imager (NIRI; Hodapp et al. 2003) with the *f*/6 camera (0.117 arcsec pixel $^{-1}$, field of view 120×120 arcsec 2) on 2004 December 25 and 2005 August 25, in queue scheduled mode under programs GN-2004B-Q-23 and GN-2005B-Q-19. The images were acquired with 60 s integrations at each position in a 54 point dither pattern, for total exposure times of 54 and 75 min, respectively. The measured full width at half-maximum (FWHM) of stars in the images was 0.39 and 0.69 arcsec in the two epochs, respectively. The data were reduced in the standard manner using the Gemini NIRI package in IRAF. A more detailed description of our data reduction method will be described in a later publication (Hogan et al., in preparation). We note here that both these images were degraded by intermittent 60 Hz electronic pick-up noise, which manifests itself as a diagonal herringbone pattern (Hodapp et al. 2003).

2.2 *Spitzer* IRAC mid-infrared observations

Mid-infrared observations of vMa 2 were obtained with the Infrared Array Camera (IRAC; Fazio et al. 2004) on the *Spitzer* Space Telescope (Werner et al. 2004) on 2004 July 4 as part of Guaranteed Time program PID00033 (PI: G. Fazio). IRAC obtains images in four channels with central wavelengths of 3.6, 4.5, 5.8 and 8.0 μm . We downloaded the *Spitzer* IRAC data from the public archive as Basic Calibrated Data (BCD), which have been reduced and flux calibrated with the S14 version of the IRAC pipeline. The BCD

images were corrected in two different ways as a check on our reduction method. First, we corrected the individual images for array-location dependence, using the correction images provided by the Spitzer Science Center (SSC), before carrying out the photometry on the individual corrected BCDs. Second, we corrected the BCDs for array-location dependence using the correction images that had been divided by the pixel-distortion images (also provided by the SSC). We combined these corrected BCDs with dual-outlier rejection to produce a mosaicked image for each channel using the SSC mosaicking software, MOPEX (Makovoz & Marleau 2005). By dividing the array-location-dependence images by the pixel distortion images, we avoid doubly correcting for pixel distortion when combining the BCDs with MOPEX. Both of the reduction methods gave the same results to well within uncertainties.

3 DATA ANALYSIS

3.1 *J*-band images

Each Gemini NIRI *J*-band image was set to the World Co-ordinate System using stars in the field with good 2MASS *J*-band detections (Skrutskie et al. 2006). We used the SExtractor task to detect all point sources in the final stacked image with a flux $\geq 3\sigma$ above deviations in the local background, and computed the motions of these objects in RA and Dec. between the two epochs (Fig. 1). We also show in Fig. 1 the 1σ and 3σ scatter of the distribution of all the measurements (excluding the white dwarf).

The instrumental magnitude of each detected source was corrected to apparent magnitude using stars in the field with 2MASS *J*-band fluxes (Skrutskie et al. 2006). To calculate the 3σ completeness limit of these data, we inserted a total of 10 000 fake stars into each image at a variety of magnitudes from $J = 19$ to 2.4, and attempted to recover them using SExtractor. Fig. 2 shows the fraction of implanted stars recovered as a function of their brightness at each epoch. The number of implanted stars recovered is always

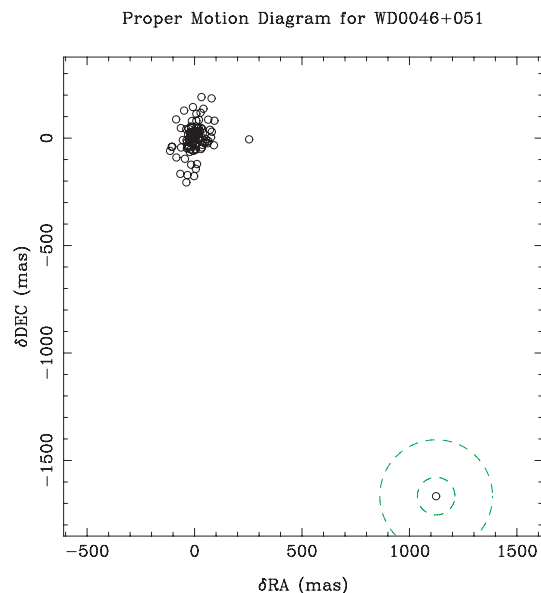


Figure 1. Proper motions of all point sources detected in both the NIRI *J*-band images, between 2004 December 25 and 2005 August 25. The white dwarf's motion is clearly discriminated from all other objects in the field. The dashed circles represent the 1σ and 3σ scatter of the distribution of the proper motions, centred on the white dwarf for clarity.

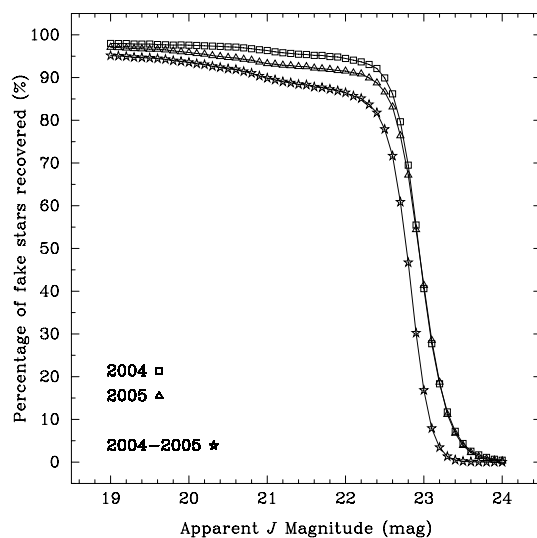


Figure 2. The completeness limit of each NIRI observation is determined by injecting fake stars into each image and recording the fraction recovered by our source detection method against magnitude, as described in the text. We also show the fraction recovered in *both* images.

less than 100 per cent of those injected as some stars are lost behind or within the wings of other real or implanted stars. The fake stars were inserted at the same positions in *both* images. However, each implanted star may not necessarily be recovered in both images, especially towards the completeness limit, in which case it would not be available for a proper motion measurement. The curve with the star markers takes this into account.

3.2 *Spitzer* IRAC mid-infrared photometry

We performed aperture photometry on the mosaicked IRAC images using standard IRAF tools. A full description is given in Brinkworth et al. (2007). Briefly, we adopted an aperture size of 2.5 pixel, and subsequently corrected to an aperture size of 10 pixels using corrections of 1.190, 1.199, 1.211 and 1.295 for Channels 1–4, respectively. The IRAC fluxes of *vMa 2* are given in Table 2. The errors consist of the quadratic addition of the standard deviation of the fluxes in individual frames plus the systematic error on the calibration of each filter as determined by Reach et al. (2005b).

4 RESULTS

4.1 Limits on common proper motion companions

Fig. 1 shows the proper motions of all point sources detected in the NIRI images, between the two epochs. The white dwarf is clearly discriminated from everything else in the field, i.e. we do not detect any common proper motion companions to *vMa 2*. We recover 90 per cent of fake stars injected into both images at $J \approx 20.9$ mag and 50 per cent at $J \approx 22.7$ mag (Fig. 2). These sensitivity estimates can be translated into limits on the mass and temperature of any resolved companions, using appropriate evolutionary models for substellar objects. We adopt the COND models of Baraffe et al. (2003), which give the temperature and luminosity of substellar objects evolving in isolation, i.e. we assume no isolation from the white dwarf, and neglect any possible heating during previous evolutionary phases. The age of *vMa 2* can be calculated by combining the white dwarf cooling age (3.17 ± 0.29 Gyr, see below) with an estimate of the

Table 1. Adopted parameters for van Maanen’s star.

μ^a (mas yr ⁻¹)	θ^a (mas yr ⁻¹)	d^a (pc)	T_{eff}^b (K)	$\log g^b$	M_{WD}^b (M_{\odot})	t_{WD}^c (Gyr)	M_{MS}^d (M_{\odot})	t_{MS}^e (Gyr)	t_{total} (Gyr)
1231.72	-2707.67	4.41	6030 (240)	8.10 (0.04)	0.633 (0.022)	3.17 (0.29)	2.6	0.9	4.1

^a*Hipparcos* measurements.^bFrom our new fit to the optical, near-IR and IRAC mid-IR photometry (see Section 4.2).^cEstimated using evolutionary models appropriate for He-atmosphere white dwarfs with C/O core compositions, see <http://www.astro.umontreal.ca/bergeron/CollingModels/>^dDerived from the initial-final mass relation of Dobbie et al. (2006).^eWood (1992).**Table 2.** Predicted and observed *Spitzer* IRAC fluxes.

λ_0 (μm)	Predicted F_{ν} (mJy)	Observed F_{ν} (mJy)
3.56	7.991	8.030 ± 0.262
4.51	5.370	5.451 ± 0.170
5.76	3.551	3.611 ± 0.126
7.96	2.038	2.092 ± 0.089

main-sequence lifetime. Using the initial–final mass relation of Dobbie et al. (2006), we estimate that the progenitor of vMa 2 ($M_{\text{WD}} = 0.633 \pm 0.022 M_{\odot}$, see below) had a mass $\approx 2.6 M_{\odot}$. We estimate the lifetime of such a main-sequence star as ≈ 0.9 Gyr, from the relationship of Wood (1992). Thus, we adopt a total age for vMa 2 of 4.1 Gyr. At this age, and taking the *Hipparcos*-derived distance to vMa 2 of 4.41 pc, the 90 per cent completeness limit ($J \approx 20.9$ mag) translates to a limit on the mass of resolved companions of $\approx 0.009 M_{\odot}$ ($\approx 9 M_{\text{Jup}}$, $T_{\text{eff}} \approx 320$ K), and the 50 per cent limit ($J \approx 22.7$ mag) translates to a limiting mass of $\approx 0.007 M_{\odot}$ ($\approx 7 M_{\text{Jup}}$, $T_{\text{eff}} \approx 280$ K).

These mass and temperature estimates are of course model-dependent. For example, the white dwarf initial–final mass relation is empirical and the subject of several current studies (e.g. Ferrario et al. 2005; Kalirai et al. 2005; Dobbie et al. 2006), white dwarf evolutionary models are constantly being revised and improved, and the lifetimes of field main-sequence stars are notoriously difficult to estimate. At ages > 1 Gyr, the evolutionary models for substellar objects predict that they cool very slowly, and are relatively insensitive to age. Therefore, even if we adopt a very conservative error of ± 25 per cent (± 1 Gyr) on the total age of vMa 2, then the errors on the masses and temperatures of putative companions are small: $9 \pm 1 M_{\text{Jup}}$ (300 ± 20 K) at the 90 per cent completeness limit and $7 \pm 1 M_{\text{Jup}}$ (also, 300 ± 20 K) at the 50 per cent completeness limit.

The minimum projected physical separation surveyed is given by the distance from the centre of its point spread function where the white dwarf is indistinguishable from the background. We estimate this as ≈ 3 arcsec², equivalent to ≈ 13 au at the distance of vMa 2. The maximum projected physical separation surveyed is given by the field of view covered by both NIRI images. Although the field of view of the NIRI *f*/6 camera is nominally 120×120 arcsec², the dither pattern used during the observations restricts the useable field of view to a maximum radius of 45 arcsec, equivalent to ≈ 200 au. As mass is lost from the central star during the post-main-sequence phase, the projected star–planet separation for planets outside the red giant envelope will increase by a maximum factor $M_{\text{MS}}/M_{\text{WD}} = 2.6 M_{\odot}/0.63 M_{\odot} \approx 4$ (Jeans 1924). From this, we estimate the

range of orbital radii surveyed around the white dwarf progenitor as 3–50 au.

4.2 Limits on unresolved companions through *Spitzer*

mid-infrared photometric excesses

In order to place limits on the masses and temperatures of unresolved companions to vMa 2, we compare the *Spitzer* IRAC photometry to an appropriate white dwarf model atmosphere plus COND models calculated for the IRAC bandpasses (Fig. 3 and Table 2). First, we fitted a grid of DZ white dwarf model atmospheres to the optical (Bessel) *BVRI*, near-IR 2MASS *JHK* and the IRAC fluxes. The best-fitting solution gives $T_{\text{eff}} = 6030 \pm 240$ K and, when combined with the parallax, $\log g = 8.10 \pm 0.04$. Within the formal uncertainties, these values are consistent with those determined by Dufour et al. (2007), which were based on fitting the same *BVRI* data but a different set of CIT *JHK* photometry, and did not include the IRAC photometry. The IRAC fluxes now give us a much better leverage on the atmospheric parameters. We then folded this model through the IRAC filter passbands to predict the IRAC fluxes (Table 2). Our new predicted model is consistent with the observed fluxes in *all* optical and infrared bandpasses, within uncertainties. From evolutionary models, the best-fitting parameters lead to estimates for the white dwarf mass of $0.633 \pm 0.022 M_{\odot}$ and cooling age 3.17 \pm 0.29 Gyr.

By adding COND models to the predicted IRAC 4.5 μm flux, again assuming an age for vMa 2 of 4.1 ± 1.0 Gyr and adopting a distance of 4.41 pc, we find that in this band *Spitzer* could have detected a $10 \pm 2 M_{\text{Jup}}$, $T_{\text{eff}} \approx 280$ –360 K planet at the 3σ level.

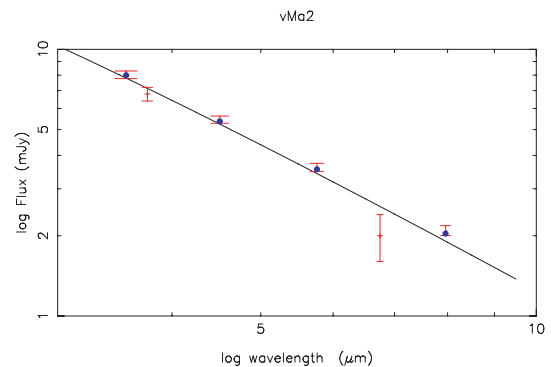


Figure 3. Mid-infrared spectral energy distribution of vMa 2 from 3 to 10 μm . The observed *Spitzer* IRAC fluxes are shown by error bars. The DZ white dwarf model monochromatic flux is shown as a solid line, and the model fluxes averaged over the filter passbands are indicated by filled circles. Also shown for comparison are the 3.76 μm *L'* band flux from Farihi et al. (2004) and the ISO 6.75 μm LW2 flux from Chary, Zuckerman & Becklin (1999).

5 SUMMARY

We have placed limits on ultra-cool substellar and planetary-mass objects around the nearest single white dwarf, *vMa 2*, through a search for common proper motion companions and mid-infrared photometric excesses. The red giant progenitor to *vMa 2* had a maximum radius of $\sim 1000 R_{\odot}$ (4.6 au; Hurley, Pols & Tout 2000). Therefore, taking into account the post-main-sequence evolution of the orbits of any companions, our *J*-band images have covered all orbits of substellar objects that originally lay beyond the maximum extent of the red giant envelope, up to 50 au distance. The complimentary *Spitzer* IRAC photometry places slightly higher limits on the masses and temperatures of any spatially unresolved substellar companion whose orbit fortuitously lies along the line of sight to *vMa 2*, or that currently has an orbit within ≈ 13 au of the white dwarf. These limits are significantly lower than those reported by previous studies, e.g. Farihi et al. (2004) and Farihi et al. (2005).

A variety of searches for planetary companions to white dwarfs are currently underway (e.g. Debes, Sigurdsson & Woodgate 2005; Burleigh, Hogan & Clarke 2006a; Mullally, Winget & Kepler 2007). Further, extensive results from the *DODO* survey are in preparation (Hogan et al., in preparation).

ACKNOWLEDGMENTS

MB acknowledges receipt of a STFC Advanced Fellowship. EH acknowledges the support of a STFC Postgraduate Studentship. This work is supported in part by the NSERC Canada. PB is a Cottrell Scholar of Research Corporation. Based in part on observations obtained at the Gemini Observatory. We thank Isabelle Baraffe and Jay Farihi for their enlightening thoughts and comments.

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