Spitzer Planet Limits around a Pulsating White Dwarf

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Abstract. We present infrared observations in search of a planet around the white dwarf GD66. Time-series photometry of GD66 shows a variation in the arrival time of stellar pulsations consistent with the presence of a planet with mass $\geq 2.4 \, M_J$. Any such planet is too close to the star to be resolved, but the planet’s light can be directly detected as an excess flux at 4.5 $\mu$m. We observed GD66 with the two shorter wavelength channels of IRAC on Spitzer but did not find strong evidence of a companion, placing an upper limit of 5–7 $M_J$ on the mass of the companion, assuming an age of 1.2–1.7 Gyr.

1. Introduction
The advantage of searching for sub-stellar companions around white dwarf stars (WDs) has long been recognized. The improved contrast between a WD and a companion was first exploited by Probst (1983) and the first L dwarf around a WD (or indeed any star) was discovered around GD165 by Becklin & Zuckerman (1988). In recent years, improved instrumentation has enabled searches for lower mass objects, to the point where direct detection searches for planetary mass objects are possible from the ground (e.g. Debes et al. 2005; Hogan et al. 2008, in press). Searches utilizing the Spitzer Space Telescope (Werner et al. 2004) can obtain mass limits as low as $\sim 10 \, M_J$ (Farihi et al. 2008a; Mullally 2007).

WDs are interesting targets for more reasons than just their luminosity. By looking at WDs we can sample a range of progenitor masses from about 1-8 $M_\odot$, including higher mass stars not amenable to radial velocity surveys. Higher mass main-sequence stars form more, and more massive planets (Johnson et al. 2007), but suffer from higher contrast ratios with those planets. However, those stars die faster, and produce more massive (and hence lower radius) WDs. WDs formed from high mass progenitors therefore make the best targets for direct detection searches.

Currently, the best main-sequence targets for direct detection of planetary companions are either transiting systems or very young stars. Detection of a planet around a WD would open up a older, more sedate region of parameter space where the predictions of planet models could be tested against observation for ages ranging from hundreds of millions to billions of years. With lower constrasts and older ages, WD planets are key to testing our models of planetary evolution and the prime target for direct detection searches. Moreover, the lower contrast means future instruments will always be able to extract more detail from spectra of WD companions than main-sequence.
WDs also lend insight into the ultimate fate of planetary systems. Livio & Soker (1984) first estimated the conditions necessary for a gas giant planet to survive the red giant phase of its parent star. Sackmann et al. (1993) concluded that the Earth would survive the red giant phase of the Sun, but more recent calculations by Schröder & Connon Smith (2008) concluded the opposite. These calculations depend on stellar mass loss rates that are weakly constrained by observation due to the rapid evolution of evolved stars. Determining the distribution of planets around WDs will provide a key test for these models. The winds from evolved stars pollute the interstellar medium with the material that creates the next generation of terrestrial planets, so surveys for planets around dead stars will inform our understanding of planets around stars not yet born.

Early empirical success comes from the detection of a planet around a sub-dwarf star using pulsation timings (Silvotti et al. 2007), and the detection of silicate rich debris disks around WDs (e.g. Reach et al. 2005b; Farihi et al. 2007). Analysis of the composition of material raining down onto the surface of a WD from such a disk by Zuckerman et al. (2007) concluded that the pattern of elemental abundances is consistent with a species of asteroid. Asteroids are markers of planetary systems, and so the frequency of debris disk WDs may eventually provide an independent measure of the fraction of stars that bear (or bore) planetary systems.

Mullally et al. (2008, hereafter M08) published the results of a survey that sought to detect evidence of planets as variations in the arrival time of pulsations from variable WDs (in a manner analogous to sub-dwarf and pulsar planets). For one object, GD66, they discovered a variation consistent with a 2.1 $M_J$ planet in a 4.5 yr orbit. Unfortunately, the span of their data was not long enough to cover an entire orbit and their detection remains provisional. We observed GD66 with the two short wavelength bands of IRAC on Spitzer in an attempt to confirm the existence of this object by direct detection in the infrared. Although the candidate system is too distant to resolve into individual components, the low luminosity of the star means that the flux from the planet at 4.5 $\mu$m rivals that of the WD. The goal of these observations is to measure an excess flux at 4.5 $\mu$m over the bare photosphere of GD66 due to the light from the planet. We observed the flux ratio (i.e. the color) between channels 2 and 1 on IRAC (4.5 and 3.6 $\mu$m respectively, Fazio et al. 2004) and comparing this ratio to a sample of other similar stars.

Figure 1. Left: Fluxes of three WDs in all 4 IRAC bands. The solid line connecting the points is a 12,000 K DA white dwarf atmosphere model. The model is normalised to agree with the flux at 3.6 $\mu$m. Right: Flux ratio for three WDs. The dash line is the weighted average flux of the two comparison WDs.
Table 1. Observed fluxes. Note. – Integration times are for channels 2 and 4, and are four times shorter for channels 1 and 3. The flux from G238–53 is probably overestimated due to the presence of a diffraction spike from a nearby star. The quoted uncertainties in these measurements include a 5% absolute calibration uncertainty added in quadrature.

| Star       | J (mag) | Integration (s) | Ch 1 (mJy) | Ch 2 (mJy) | Ch 3 (mJy) | Ch 4 (mJy) |
|------------|---------|-----------------|------------|------------|------------|------------|
| GD66       | 15.7    | 6400            | 0.1349(68) | 0.0875(44) | 0.0593(50) | 0.0277(35) |
| L19-2      | 13.6    | 768             | 0.941(47)  | 0.600(30)  | 0.383(22)  | 0.219(12)  |
| ZZCeti     | 14.4    | 1920            | 0.470(24)  | 0.299(15)  | 0.189(12)  | 0.1105(67) |
| G238-53    | 15.7    | 6400            | 0.1385(69) | 0.0911(46) | 0.0573(39) | 0.0405(26) |

2. Observations
We observed GD66 (WD0517+307) with all four IRAC channels on 17th October 2007 (AORs 22855424 and 22856448) as part of program 40255. We recorded sixteen 100 second exposures simultaneously in channels 1 and 3, using a spiral dither pattern. We repeated the procedure for channels 2 and 4, recording 4 sets of sixteen images for a total exposure time of 6,400 seconds. The raw frames were calibrated using version S16.10.0 of the IRAC pipeline to create bcd frames.

We also observed 3 WDs with similar temperatures to calibrate our observations. L19-2 (AORs 22856192 and 22857216), ZZ Ceti (AORs 22855936 and 22856960) and G238-53 (AORs 22855680 and 22856704) are all DAVs, and Bergeron et al. (2004) reports temperatures within 120 K of GD66 based on optical spectroscopy. This agreement is better than the quoted uncertainty in the measurements, and so we can consider our sample to have a uniform temperature. As an independent, albeit cruder approach, we also insisted on broadly similar pulsation properties for each star, as Mukadam et al. (2006) showed that pulsation properties are correlated with temperature. We observed each of these stars in a similar pattern as GD66, scaling our total exposure time with magnitude.

We extracted photometry from these frames using the astrolib package in IDL. We first convert the recorded flux into units of electrons. Pixels with bits set in any of the pmask, imask or rmask images were marked as bad and their values set to the median value of pixels in a box 21 pixel on a side centered on the bad pixel in question. We ignored bit 13 of the imask, indicating crosstalk, which was set in a large number of pixels that did not seem to be affected by any noticeable problem. We see no evidence of a systematic drift in the measured flux in any channel.

We extract the flux using a sky annulus of 10-20 pixels and series of apertures ranging from 2 to 7 pixels radius. We choose the aperture that gives the greatest signal to noise (2 pixels), adding in quadrature a contribution to the error term due to the read noise, as listed in the header of the bcd frame. We then apply corrections to the observed flux as suggested by the Data Handbook: array location dependence, aperture correction, color correction and a pixel phase correction for channel 1.

3. Results
In Figure 1 we show spectral energy distributions (SEDs) for GD66, L19-2 and ZZ Ceti. The close correspondence between the observed and expected SED rules out the presence of debris disks similar to those found around other WDs. We show a table of observed fluxes for all observed stars in Table 1.
We show the flux ratio between channels 2 and 1, $r$, for each star in Figure 1 and Table 2. GD66 and G238-53 are noticeably redder (higher value of $r$) than the other two stars. However, careful analysis of the images shows that this flux excess is most likely an artefact for G238-53. The diffraction spike from a nearby bright star passes very close to the position of G238-53 on the chip. Unlike the other three stars, the observations for the two channels for this star were not taken sequentially, but separated by $\sim 1$ week. The slightly different viewing angle between the two visits means that the diffraction spike is closer to the star in the epoch of channel 2. Although some of these pixels are masked, we consider the measured flux ratio to be untrustworthy. The flux ratio is significantly higher (0.675 versus 0.657) for a 3 pixel aperture, a further indication that flux is contaminated. We therefore ignore G238-53 in our analysis.

### 3.1. Error Analysis

We now determine whether this excess in $r$ for GD66 is statistically significant. The error budget of an IRAC observation is divided to photometric, systematic and calibration components. The IRAC data handbook gives a value of 3% for the calibration uncertainty while Farihi et al. (2008) concludes, based in part on a literature survey that 5% is more appropriate. However, because we are measuring a flux ratio, we need not concern ourselves with the absolute calibration error in converting from electrons to mJy necessary to compare IRAC fluxes to other photometric systems. We do, however, include a conservative uncertainty term of 5% in Table 1 to facilitate comparison with other stars.

The photometric uncertainty in channel 1 can be computed from the rms scatter of individual bed frames. Adding the fractional uncertainties in quadrature gives the fractional uncertainty in the flux ratio. Our observations were designed to achieve $<1\%$ photometric accuracy, and this goal was comfortably exceeded, as shown in Table 2.

The systematic uncertainty is measure of the variability in the performance of the instrument, and the spread in values we would obtain by performing the same experiment multiple times. The Observers’ Manual quotes a stability for IRAC of $<1\%$. To more accurately measure this value, we examined data on BD +60 1753, a calibration star that has been repeatedly observed by IRAC over the lifetime of the instrument (Reach et al. 2005a) and determined the systematic repeatability limit to be 0.54%.

We add our independent estimate of the systematic uncertainty in quadrature to the photometric uncertainty to get a total (1$\sigma$) uncertainty in the ratio, $\delta r$, which is given in the third column of Table 2. The excess flux, $E$ is the difference between $r$ for GD66, 0.6482(62) and the mean value of $r$ for the other two stars, 0.6365(31), or $E=0.0117(69)$. The excess flux is only 1.7 times greater than the uncertainty and therefore not statistically significant.
4. Limits on Planet Mass

While we did not detect an excess, this does not rule out the evidence from timing measurements, and we can use our observations to constrain the mass of any companion. We can state with 3σ confidence that the flux ratio is less than 0.6556. To compare this number to planet models and place an upper bound on the mass of the companion we first need the age of the system.

Based on the measured surface temperature and gravity (11,989 K and log g=8.05 Bergeron et al. 2004), and comparing to models from Wood (1992), we determine a mass of 0.64(03) M⊙ and a cooling age of 500 Myr. The age of the progenitor main-sequence star is more difficult to estimate. Estimates of the initial-final mass relationship (IFMR) for WDs are based on comparing the masses of WDs in open clusters to the main-sequence turn-off age of the cluster itself. Until recently, this relationship was only empirically constrained for young, and hence high mass progenitors. However, newer observations have begun to extend the IFMR down to the relatively lower mass of GD66. Using the linear fits to the IFMR from Dobbie et al. (2006), Kalirai et al. (2007) and Catalán et al. (2008) we estimate an initial mass of 2.20(46), 2.26(46) and 2.64(57) M⊙ respectively, which agree within the uncertainties. A theoretical relationship from Meng et al. (2007) gives an intermediate value of 2.49(41) M⊙, while the semi-empirical method of Salaris et al. (2008) suggests 2.31(22) M⊙. Calculations from Pols et al. (1998) indicate that the lifetime of a 2.5 M⊙ star is 830 Myr. The lifetime of a main sequence star scales roughly as $M^{-2.5}$ in this mass regime, so the calculated main-sequence lifetime of GD66 is 700 Myr to 1.2 Gyr. Including the WD cooling age, the total age of the system is 1.2–1.7 Gyr.

We take atmosphere models of a 12,000 K DA courtesy of D. Koester (Finley et al. 1997), and combine them with models of planetary mass objects from Burrows et al. (2003). We perform synthetic photometry on the combined model to determine the flux ratio between channels 1 and 2 for planets of different masses. We repeat the procedure for models with ages from 0.3 to 5 Gyr and show the results in Figure 2. Given our limit on the flux excess, and the uncertainty in the age, the 3σ upper bound on the mass of the planet is approximately 5–6 M⊕.
5. Additional Time Series Observations

We also present additional ground-based optical time-series observations of GD66 taken with Argos (Nather & Mukadam 2004) on the 2.1 m telescope at McDonald Observatory. A full description of our observational technique is given in M08, but we repeat a brief summary here. We performed time series differential photometry on GD66 with a continual sequence of exposures over a period of 4–8 hours per night. We used Wqed (Thompson & Mullally, this volume) to divide the lightcurve of the target star by the sum of one of more reference stars to remove the effects of seeing and transparency variations and we corrected our times for the motion of the earth around the sun using the method of Stumpff (1980). We combined all observations over the span of a week into a single data set, and measured the difference between the observed time of arrival of the 302s pulsation mode and that calculated based on the assumption of a constant period (O-C). We show our updated O-C diagram in Figure 3.

M08 predicted that the orbit would turn over in late 2007 and the slope of the O-C diagram would be negative in 2008. This has clearly not happened and the orbital period is longer than previously expected. Our current best fit parameters are a period of 5.69(30) yr, an orbital separation of 2.75(11) AU and \( m_p \sin i = 2.36(17) \, M_J \), where \( m_p \) is the mass of the planet and \( i \) the inclination of the orbit to the line of sight. With previous experience in mind we are cautious in predicting the future behavior of the orbit, but we note that our current circular best fit orbit appears to be on the verge of turning over. Inspection of the fit, especially in the years 2004/2005 also suggest that an eccentric fit would better match the data. However, without a full orbit, the eccentric fit is unconstrained. Consequently, the true orbital period may be very much longer than 6 years.

6. Discussion

Although confirmation of the existence of this planet remains frustratingly elusive, it is interesting to assume that it does exist and speculate on its history. Livio et al. (2005) suggest...
that planets could form during a binary WD merger, but the low mass of GD66 makes this scenario unlikely. It is possible that there is a second epoch of planet formation after the red giant stage. Only a tiny fraction of the carbon and silicon rich material ejected by a star needs to fall back onto a circumstellar disk to create a minimum mass solar nebula, although such a disk would have to survive the high UV flux of the newly born WD (Villaver & Livio 2007). In this scenario, the planet’s age would be less than 0.5 Gyr, and our observations would constrain the mass to $<3 \, M_J$, uncomfortably close to the lower mass limit set by our timing measurements.

If the planet was born co-eval with the star, conservation of angular momentum would have caused it to drift outward linearly with the mass loss that pressaged the birth of the WD (Jeans 1924; Burleigh et al. 2002). If this were the only force acting on the orbit, the initial orbit would have been only 0.6–0.8 AU. At maximum extent, the envelope of the AGB phase of a 2.5 AU star extends out as far as 4–4.5 AU (Pols et al. 1998), engulfing the planet and presumably destroying it. Farihi et al. (2008) propose the idea of a sacrificial interior planet which donates angular momentum to the AGB envelope. The envelope is ejected before it can engulf the outer planet(s), while the interior planet spirals onto the red giant core and it is destroyed.

A star goes through a series of pulses during the final stages of evolution, where the radius increases dramatically for a short period of time. If the planet is engulfed (or nearly so) during one of these pulses, viscous drag (or tidal forces) will cause the orbit to spiral inward. For a planet that was only engulfed for short periods of time, its orbits would spiral in a small amount, which might explain the GD66 system.

7. Conclusion
We report on Spitzer IRAC observations of the white dwarf GD66 in an attempt to directly detect a companion planet. We fail to detect an excess with any statistical significance. However, combined with our ground based timing observations we can now constrain the planet candidate’s mass to between 2.4 and $\approx 5–6 \, M_J$.

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