

## A DUSTY DISK AROUND GD 362, A WHITE DWARF WITH A UNIQUELY HIGH PHOTOSPHERIC METAL ABUNDANCE

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### ABSTRACT

Eighteen years after an infrared excess was discovered associated with the white dwarf G29-38, we report ground-based measurements ( $JHK_s, KLN'$ ) with millijansky-level sensitivity of GD 362 that show it to be a second single white dwarf with an infrared excess. As a first approximation, the excess around GD 362, which amounts to  $\sim 3\%$  of the total stellar luminosity, can be explained by emission from a passive, flat, opaque dust disk that lies within the Roche radius of the white dwarf. The dust may have been produced by the tidal disruption of a large parent body such as an asteroid. Accretion from this circumstellar disk could account for the remarkably high abundance of metals in the star's photosphere.

*Subject headings:* circumstellar matter — minor planets, asteroids — white dwarfs

### 1. INTRODUCTION

It is likely that many planetary systems survive a star's evolution as a red giant and persist as the star becomes a white dwarf. Both infrared and optical studies of these systems can constrain the incidence and dynamical evolution of extrasolar comets, asteroids, and/or planets. Here we report excess near- and mid-infrared emission around the white dwarf GD 362 that might be explained as the result of the tidal disruption of a parent body such as an asteroid.

Because their initial complement of heavy elements gravitationally settles beneath the photosphere, most cool ( $T_{\text{eff}} < 20,000$  K) white dwarfs have atmospheres that are expected to be essentially either pure hydrogen or pure helium. However,  $\sim 25\%$  of cool DA (hydrogen-rich) white dwarfs display at least some measurable calcium in their photospheres (Zuckerman et al. 2003). Since the dwell times for atmospheric calcium in 0.6 and 1.0  $M_{\odot}$  hydrogen-rich white dwarfs with  $T_{\text{eff}} = 10,000$  K are only  $\sim 600$  and  $\sim 40$  yr, respectively (Paquette et al. 1986), it is likely that these DAZ stars currently are accreting.

The source of accreting material onto single white dwarfs is not known. One possible source is interstellar matter (Dupuis et al. 1993). However, interstellar calcium is largely contained within grains, and thus the amount that is accreted may be small (see Alcock & Illarionov 1980), especially from the low-density interstellar medium of the Local Bubble. Furthermore, in the case of Bondi-Hoyle accretion, a correlation would be expected between photospheric metals and white dwarf kinematics, yet none has been found (Zuckerman et al. 2003). An alternate possibility is that white dwarfs accrete circumstellar instead of interstellar matter (Aannestad et al. 1993). One such scenario is that comets directly impact the photosphere of the white dwarf (Alcock et al. 1986).

Because their outer convective envelopes are thin, metal accretion rates as low as  $10^6$  g s<sup>-1</sup> can account for the abundances of heavy elements in some white dwarfs (see Paquette et al. 1986 and Zuckerman et al. 2003). The zodiacal light in our solar system is explained by production of dust from the erosion

of comets and asteroids with a rate of  $3 \times 10^6$  g s<sup>-1</sup> (Fixsen & Dwek 2002), and analogous circumstellar dust debris produced by the destruction of parent bodies is common around main-sequence stars (Zuckerman 2001). It is plausible that the grinding of parent bodies into dust may be ongoing around white dwarfs. Because these stars have both low luminosities and low wind-outflow rates, any orbiting, ground-up dust ultimately can accrete onto its host star and pollute the photosphere.

With  $[\text{Ca}]/[\text{H}] = 1.2 \times 10^{-7}$ , G29-38 has the second greatest atmospheric calcium abundance in the survey of  $\sim 100$  white dwarfs by Zuckerman et al. (2003), and, to date, despite a large amount of effort it has been the only single white dwarf with a known infrared excess (Zuckerman & Becklin 1987; Farihi et al. 2005). Even observations with the *Infrared Space Observatory* failed to discover any more infrared excesses around white dwarfs (Chary et al. 1999). A plausible explanation for the excess around G29-38 is that an asteroid strayed within the tidal radius of the star, broke apart, and a cascade of self-collisions formed a dust disk that is now accreting onto the star (Jura 2003). Recently, Gianninas et al. (2004) found that the massive white dwarf GD 362 exhibits  $[\text{Ca}]/[\text{H}] = 6 \times 10^{-6}$ , which, remarkably, is even higher than the solar abundance of  $2 \times 10^{-6}$ . GD 362 has the highest known photospheric calcium abundance of any white dwarf with  $T_{\text{eff}} < 25,000$  K (Zuckerman et al. 2003, Koester et al. 2005). Because of the great advances in infrared instrumentation at the Gemini North telescope, it is now possible to achieve approximate millijansky-level sensitivity at mid-infrared wavelengths. Here we report ground-based detections of GD 362 that show it possesses an infrared excess that is probably produced by circumstellar dust. Our result strengthens the argument that photospheric metals in white dwarfs result from the accretion of circumstellar matter.

### 2. OBSERVATIONS

We have obtained ground-based observations of GD 362 in three separate observing runs.

On 2005 May 19 and 21 (UT), we observed with an  $N'$  (11.3  $\mu\text{m}$ ) filter in the MICHELLE (Glasse et al. 1997) mid-infrared spectrometer and imager at the Gemini North telescope. Data were obtained in a beam-switching chop-nod mode with a secondary mirror chop throw of 15" at 4.2 Hz. The total usable on-source integration time was 2587 s. The total flux uncertainty was calculated by summing in quadrature the measurement (0.24 mJy) and calibration (0.1 mJy) uncertainties.

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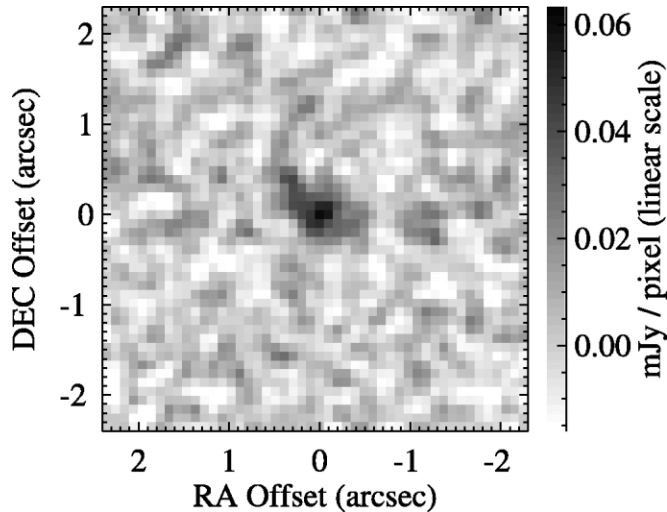


FIG. 1.—Unresolved MICHELLE  $N'$  image of GD 362, which was smoothed by convolution with a Gaussian for display purposes. The small amount of flux to the northeast of GD 362 is consistent with the level of noise in the image and does not significantly affect the aperture photometry.

The calibration uncertainty was derived from the scatter in the five measurements of the standard star HD 158899 combined with an estimate of the noise from structure due to imperfect background subtraction. Because both science and standard stars were observed within a narrow range of air mass, 1.0–1.3, we did not correct for air mass. The  $N'$  image of GD 362 is shown in Figure 1, and the flux is listed in Table 1.

Images of GD 362 were taken at  $H$  and  $K_s$  bands with Persson’s Auxiliary Nasmyth Infrared Camera (PANIC; Martini et al. 2004) on the Magellan I telescope on 2005 June 17 (UT). The night was partly cloudy, and the seeing was a rather poor  $\sim 0''.9$ . At  $K_s$  and  $H$ , a total of 550 and 225 s of integration time was collected, respectively. Data reduction proceeded in the usual way of combining the dithered observations to make source-free sky frames, linearizing the data, sky-subtracting each image, flat-fielding with a sky flat, correcting bad pixels by interpolation, distortion-correcting the images, and shifting and adding the dither positions together. Aperture photometry was performed on the white dwarf and on two bright stars in the field of view (2MASS 17313587+3705357 and 2MASS 17313555+3704541) with a signal-to-noise ratio (S/N) of  $>10$  detections at  $H$  and  $K_s$  in the Two Micron All Sky Survey (2MASS) catalog. The resulting magnitudes of GD 362 are listed in Table 1, where the stated uncertainties combine the statistical photometric uncertainty with the calibration uncertainty.

On 2005 June 25 (UT),  $JHKL'$  images of GD 362 were obtained with the Gemini North telescope using the Near-Infrared Imager (NIRI; Hodapp et al. 2003). At all wavelengths, images were taken in a four-point dither pattern for total integration times of 80, 100, 120, and 1880 s at  $J$ ,  $H$ ,  $K$ , and  $L'$ , respectively. Reduction of the  $JHK$  data included sky-subtracting each raw frame by the median of all four images, flat-fielding, image registration, and finally averaging. Aperture photometry was performed on both GD 362 and the standard star FS 146 (Hawarden et al. 2001), yielding S/N  $> 100$  in all bandpasses and  $\sim 3\%$  uncertainties. The  $L'$  image reductions proceeded similarly to the  $JHK$  reductions for the standard star FS 147 (Leggett et al. 2003). However, the  $L'$  image reductions for GD 362 were more complicated since the target was not visible in any single frame. After shifting by the telescope coordinates and co-adding, GD 362 appeared in the final image

TABLE 1  
INFRARED DATA

$\lambda$ ( $\mu\text{m}$ )	$m$ (mag)	$F_{\text{obs}}^a$ (mJy)	$F_*$	$F_{\text{ex}}$
1.22 <sup>b</sup> ( $J$ )	$16.09 \pm 0.03$	$0.60 \pm 0.020$	0.60	0.00
1.22 <sup>c</sup> ( $J$ )	$16.16 \pm 0.09$	...	...	...
1.65 <sup>b</sup> ( $H$ )	$15.99 \pm 0.03$	$0.42 \pm 0.01$	0.39	0.03
1.65 <sup>d</sup> ( $H$ )	$15.95 \pm 0.06$	...	...	...
2.16 <sup>d</sup> ( $K_s$ )	$15.85 \pm 0.06$	...	...	...
2.18 <sup>b</sup> ( $K$ )	$15.86 \pm 0.03$	$0.30 \pm 0.01$	0.26	0.04
3.76 <sup>b</sup> ( $L'$ )	$14.2 \pm 0.3$	$0.52 \pm 0.13$	0.10	0.42
11.3 <sup>b</sup> ( $N'$ )	...	$1.4 \pm 0.3$	0.01	1.4

NOTE.—Since they are only upper limits, we do not list the 2MASS fluxes for  $H$  and  $K$ .

<sup>a</sup> The observed flux plotted as filled circles in Fig. 2.

<sup>b</sup> Measured at the Gemini North telescope.

<sup>c</sup> Taken from the 2MASS catalog.

<sup>d</sup> Measured at the Magellan I telescope.

with an S/N  $\sim 3$ –5. The dominant source of uncertainty is structure in the “sky” from poor background cancellation. Aperture photometry was performed on GD 362 and FS 147. Results are shown in Table 1, where we use the flux calibration of magnitudes given by Tokunaga (2000).

We compute the expected photospheric flux from the star,  $F_*$ , from the simple blackbody expression

$$F_* = \pi \left( \frac{R_*}{D_*} \right)^2 B_\nu(T_{\text{eff}}). \quad (1)$$

According to Bergeron et al. (1995) and Rohrmann (2001), the atmospheres of hydrogen-rich white dwarfs in the temperature and wavelength range of interest here can be well reproduced by simple blackbodies. Gianninas et al. (2004) estimate that the distance to GD 362 is somewhere between 22 and 26 pc. We adopt  $D_* = 25$  pc in order to best reproduce the  $J$ -band data by purely photospheric emission for a star with  $T_{\text{eff}} = 9740$  and  $R_* = 3.5 \times 10^8$  cm, derived from the mass and gravity given by Gianninas et al. (2004). The total fluxes with the photospheric and excess contributions are listed in Table 1 and displayed in Figure 2.

Although our wavelength coverage is incomplete, we find that the observed integrated flux of the infrared excess is  $\sim 3\%$  of the total flux received from the star. This result substantially constrains any model for the dust emission.

### 3. MODEL FOR THE DUST DISTRIBUTION AND EMISSION

We now consider models to account for the infrared excess around GD 362. From the radius and effective temperature given above, the total luminosity of GD 362 is  $2.0 \times 10^{-4} L_\odot$ . Thus, the process producing the infrared excess has a luminosity of  $6 \times 10^{-6} L_\odot$ . If the excess is emitted by a companion, this secondary object must be substellar.

The evolutionary lifetime from the main sequence to the tip of the asymptotic giant branch of the  $\sim 7 M_\odot$  progenitor of a  $1.2 M_\odot$  white dwarf (Weidemann 2000) is likely to be less than 0.1 Gyr (Girardi et al. 2000), so that the white dwarf cooling age is an excellent proxy for its total age. According to Garcia-Berro et al. (1997), the cooling time of this  $1.2 M_\odot$  white dwarf is about 5 Gyr. However, the cooling age of a white dwarf with a luminosity of  $2.0 \times 10^{-4} L_\odot$  can be as low as  $\sim 2$  Gyr, depending on the star’s mass (Salaris et al. 1997; Hansen 2004). Burrows et al. (1993) show that some brown dwarfs with ages between 2 and 5 Gyr have luminosities near

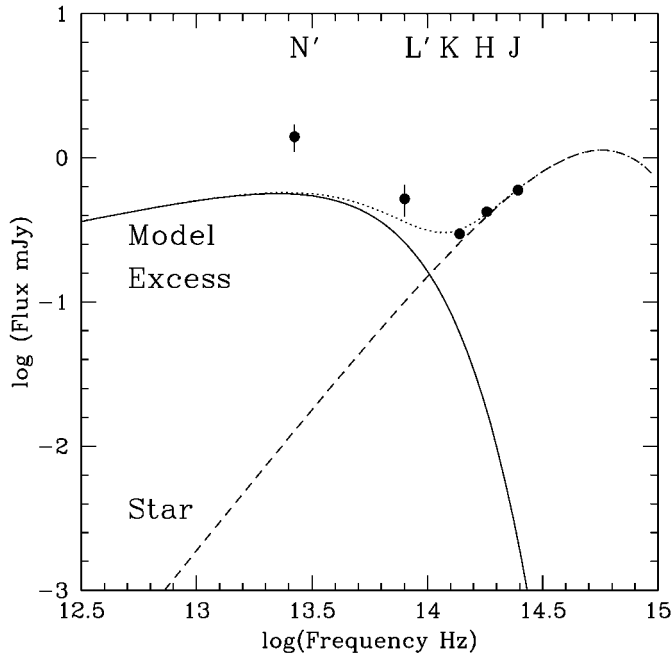


FIG. 2.—Data from Table 1 are compared with our model spectral energy distribution for the circumstellar dust around GD 362. The solid line shows the model calculation from eq. (3), where the outermost grains have a temperature of 0 K and the inner disk temperature is 1200 K (see text). The dashed line shows the emission from the star, while the dotted line shows the sum of the stellar and the modeled circumstellar fluxes.

$10^{-5} L_{\odot}$ . Their models also show that such brown dwarfs have radii near  $6 \times 10^9$  cm. The infrared excess around GD 362 can be roughly reproduced by a blackbody with a color temperature of 600 K. Such an object would require a radius of  $\sim 2 \times 10^{10}$  cm, much larger than expected for cooling brown dwarfs. Thus, it is very unlikely that the infrared excess around GD 362 is explained by direct emission from either a stellar or substellar companion.

A plausible model for the star's infrared excess is that circumstellar dust reprocesses 3% of the emitted starlight. To account for this result, we follow Jura (2003) and adopt a simple model of a passive, flat, opaque dust disk orbiting GD 362. The white dwarf's gravity is so strong that a standard estimate of the disk thickness of 1200 K gas orbiting at  $10^{10}$  cm from the star yields a height much less than the radius of the white dwarf. Therefore, the disk is taken as geometrically flat. As a first approximation, the dust at distance  $R$  from the star is characterized by a single temperature,  $T$ , given by the expression (see, e.g., Chiang & Goldreich 1997):

$$T \approx \left(\frac{2}{3\pi}\right)^{1/4} \left(\frac{R_*}{R}\right)^{3/4} T_{\text{eff}}. \quad (2)$$

With this temperature profile, the predicted flux,  $F_d$ , from the disk at the Earth, is (Jura 2003)

$$F_d \approx 12\pi^{1/3} \left(\frac{R_*^2 \cos i}{D_*^2}\right) \left(\frac{2k_B T_{\text{eff}}}{3h\nu}\right)^{8/3} \left(\frac{h\nu^3}{c^2}\right) \int_{x_{\text{in}}}^{x_{\text{out}}} \frac{x^{5/3}}{e^x - 1} dx. \quad (3)$$

In equation (3), we define  $x_{\text{in}} = h\nu/kT_{\text{in}}$  and  $x_{\text{out}} = \infty$ , corresponding to an outer temperature near 0 K or, equivalently, an infinitely extended disk. Our model is insensitive to this outer boundary temperature because cool dust does not emit appreciably

in the infrared bands for which we have data. With longer wavelength observations, we could constrain the outer structure of the circumstellar dust. We adopt an inner dust temperature of 1200 K, approximately where refractory silicate dust rapidly sublimates. We find that  $T = 1200$  K occurs at  $R = 9.7R_*$  or  $3.4 \times 10^9$  cm. We assume that the disk is face-on so that  $\cos i = 1$ .

We display in Figure 2 the comparison between the data for the infrared excess and the model. Given the simplicity of the model and that the only unconstrained parameter is the inclination of the disk, the approximate agreement with the data is sufficiently close that our model is viable. However, the model fails somewhat at  $L'$  and by about a factor of 2 to account for the observed  $N'$  flux. One possibility is that the dust around GD 362 has a prominent silicate emission feature, as has been found for G29-38 (Reach et al. 2005), and even possibly polycyclic aromatic hydrocarbon emission features. Emission lines are produced by an opaque disk if the warmest dust lies on the surface of the disk as can occur for a system heated from above. Another possibility is that the accretion rate onto the white dwarf is sufficiently high that dissipative heating of the disk is important and that the star's luminosity is also enhanced (see below). These effects would lead to more emission from the disk than predicted by our model.

#### 4. DISK PARAMETERS

Above, we have shown that the infrared excess around GD 362 can be modeled as a flat, opaque disk. Here we consider how the disk might have formed.

The amount of mass in this disk need not be very large compared to, say, the mass of a single massive solar system comet. If the disk extends to  $\sim 10^{10}$  cm, then its total area may be  $\sim 3 \times 10^{20}$  cm<sup>2</sup>. In order for the disk to be opaque even at  $10 \mu\text{m}$ , the mass column of dust needs to be at least  $10^{-3}$  g cm<sup>-2</sup> (Ossenkopf et al. 1992). Thus, the mass of the disk is greater or equal to  $\sim 3 \times 10^{17}$  g. However, since the disk is opaque, we can only place a lower bound on its mass; it could be orders of magnitude greater than this minimum.

It is likely that dust in the disk around GD 362 accretes onto the star and accounts for the metals in its photosphere. The required rate of accretion,  $\dot{M}_{\text{ac}}$ , is uncertain because suitable models have not been published for white dwarfs as massive as  $1.2 M_{\odot}$ . Extrapolation of the published models by Paquette et al. (1986) for stars with  $T_{\text{eff}} = 10,000$  K and 0.2, 0.6, and  $1.0 M_{\odot}$  suggests that in order to produce the observed, essentially solar calcium abundance, the  $\dot{M}_{\text{ac}}$  onto GD 362 must be  $\sim 10^{11}$  g s<sup>-1</sup>.

The inferred accretion rate onto GD 362 is sufficiently high that it could appreciably contribute to the star's luminosity. The total accretion luminosity,  $L_{\text{ac}}$ , is given by

$$L_{\text{ac}} = \frac{GM_* \dot{M}_{\text{ac}}}{R_*}. \quad (4)$$

Thus, if GD 362 only accretes metals from grains, then  $L_{\text{ac}} = 1 \times 10^{-5} L_{\odot}$ , about 5% of the star's bolometric luminosity. If, however, the star also accretes gas with 100 times the mass of the heavy metals, then the total luminosity from accretion would exceed the bolometric luminosity of the star by a factor of 5. It seems unlikely that GD 362 is accreting from the gas-rich interstellar medium.

Following the discussion in Davidsson (1999), we note that

any asteroid that passed  $\leq 10^{11}$  cm from GD 362 would venture within the Roche radius and be tidally disrupted. The debris from this event could eventually form a disk, an event analogous to scenarios for the formation of the rings around Saturn and other planets in our solar system (see, e.g., Dones 1991). Debes & Sigurdsson (2002) have described how the orbits of planets and asteroids are rearranged and become unstable when a star loses mass and becomes a white dwarf. It is possible that this picture may explain why an asteroid or planet could venture so near GD 362. However, with a cooling age of 5 Gyr, by now, the system should have achieved dynamic stability, and the probability may be very low that an asteroid or planet recently had its orbit dramatically altered. Since GD 362 is accreting  $\sim 10^{11}$  g s $^{-1}$  and it has a cooling age of  $5 \times 10^9$  yr, then either the hypothetical disrupted parent body had a mass of  $\sim 2 M_{\oplus}$  or the current disk has a lifetime appreciably less than the cooling age of the white dwarf.

### 5. CONCLUSIONS

GD 362 is a second white dwarf to be found to have an infrared excess that amounts to about 3% of its bolometric luminosity. This excess emission can be approximately ex-

plained as an opaque disk of refractory dust with an inner temperature of 1200 K. The circumstellar disk lies within the Roche radius of the white dwarf; the dust might arise from the tidal disruption of some larger parent body. Accretion from the dust disk probably accounts for the star's very large photospheric abundance of calcium.

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