EVIDENCE OF A MERGER OF BINARY WHITE DWARFS: THE CASE OF GD 362

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ABSTRACT

GD 362 is a massive white dwarf with a spectrum suggesting a H-rich atmosphere that also shows very high abundances of Ca, Mg, Fe, and other metals. However, for pure H-atmospheres, the diffusion timescales are so short that very extreme assumptions have to be made to account for the observed abundances of metals. The most favored hypothesis is that the metals are accreted from either a dusty disk or an asteroid belt. Here we propose that the envelope of GD 362 is dominated by He, which at these effective temperatures is almost completely invisible in the spectrum. This assumption strongly alleviates the problem, since the diffusion timescales are much larger for He-dominated atmospheres. We also propose that the He-dominated atmosphere of GD 362 is likely to be the result of the merger of a binary white dwarf, a very rare event in our Galaxy, since the expected Galactic rate is \( \sim 10^{-2} \) yr\(^{-1} \).

Subject headings: stars: chemically peculiar — stars: individual (GD 362) — white dwarfs

Online material: color figure

1. INTRODUCTION

GD 362 has been interpreted as a massive, rather cool \( (T_{\text{eff}} \approx 9740 \pm 50 \) K), white dwarf with a heavy accretion disk surrounding it (Kilic et al. 2005; Becklin et al. 2005; Gianinas et al. 2004). The dusty disk around GD 362 produces an excess of infrared radiation that amounts to \( \sim 5\% \) of the total stellar luminosity. The chemical composition of GD 362 is also rather singular, showing a hydrogen-rich atmosphere with very high abundances of Ca, Mg, Fe, and other metals (Gianinas et al. 2004). Thus, it is classified as a massive DAZ (hydrogen-rich) white dwarf. The origin of such particularly photometric abundances—\( \log (N_{\text{Ca}}/N_{\text{H}}) = -5.2 \), \( \log (N_{\text{Mg}}/N_{\text{H}}) = -4.8 \), and \( \log (N_{\text{Fe}}/N_{\text{H}}) = -4.5 \)—and of the surrounding dusty disk around it still remains a mystery. Since the diffusion timescales for metals in H-rich white dwarfs are of only a few years (Koester & Wilken 2006), very extreme assumptions have to be made in order to explain these abundances. At present, the most widely accepted scenario is disruption and accretion of a planetary body, although for this scenario to be feasible the planetary system should survive during the advanced stages of stellar evolution, which by no means is guaranteed. Thus, the formation of an asteroid would require the previous existence of a disk around this white dwarf (Livio et al. 1992, 2005). Particularly, a recent analysis (Villaver & Livio 2007) has shown that planets around white dwarfs with masses \( M_{\text{wd}} > 0.7 M_{\odot} \) are generally expected to be found at orbital radii \( r > 15 \) AU because they cannot survive the planetary nebula phase and that if planets are to be found at smaller orbital radii around massive white dwarfs, they had to form as the result of the merger of two white dwarfs. It is also interesting to note that there have been previous suggestions about white dwarfs that are merger products—see, for instance, Liebert et al. (2005)—but these claims do not yet have any observational support.

2. THE SCENARIO

Another possibility is that some massive white dwarfs are the result of the merger of a double white dwarf close binary system. This scenario has been studied in several papers. However, in most of these papers, either the resulting nucleosynthesis was not addressed (Ségretain et al. 1997), the spatial resolution was poor (Benz et al. 1990), or the calculations were performed using crude approximations (Mochkovitch & Livio 1990). Very recently, and using a smoothed particle hydrodynamics (SPH) code, a series of simulations with adequate spatial resolution were performed, and the nucleosynthesis of the merger was studied (Guerrero et al. 2004; Lorén-Aguilar et al. 2005). The main results of such simulations are that the less massive white dwarf of the binary system is totally disrupted in a few orbital periods. A fraction of the secondary is directly accreted onto the primary, whereas the remnants of the secondary form a heavy, rotationally supported accretion disk around the primary, and little mass is ejected from the system. The resulting temperatures are rather high (\( \sim 9 \times 10^4 \) K) during the most violent phases of the merger, allowing for extensive nuclear processing.

The enhancement of the abundances of the most relevant nuclear isotopes occurs when one of the coalescing white dwarfs is made of pure He. Table 1 shows the average chemical composition of the resulting disk and the main characteristics of some selected simulations. It should be noted, however, that the distribution of the different elements in the disk is rather inhomogeneous. Obviously those parts of the disk in which the material of the secondary has been shocked have undergone major nuclear processing. Hence, these regions are C- and O-
which are C- and O-rich—atomic lines of C\textsubscript{362} were to be accretion from the inner regions of the disk—producing the unusual photospheric abundance pattern of GD
is also rather uncertain. More importantly, if the mechanism
nevertheless, that the He abundance is rather uncertain since equally
be obtained by adopting other masses. In passing, we note, nev-
that the atmospheric pressure and the opacity
bands should be rather apparent in the spectrum. But the strength
accretion of He-rich material is required.
Since He is also accreted onto the surface of GD 362, the
photospheric layers may contain significant amounts of He that,
at the effective temperature of GD 362, would be almost spectrosco-
visible. Thus, GD 362 would still be classified as a DA white dwarf provided that some H is present in its
atmosphere. Consequently, the H/He ratio can be regarded as a
free parameter. However, the presence of He in a cool hydrogen-
rich atmosphere affects the surface gravity determined from spec-
troscopy and thus the mass determination (Bergeron et al. 1991).
In Figure 1 we show three almost identical synthetic spectra
representative of GD 362 with various assumed He abundances.
If He/H = 10 is adopted, then log g = 8.25 is obtained
(M_{\text{wd}} \sim 0.8 M_\odot), whereas if we adopt He/H = 1, then
the surface gravity turns out to be log g = 8.72. This corresponds
to a mass of the primary of M_{\text{wd}} \sim 1.0 M_\odot, which can be
obtained from the coalescence of a 0.4+0.8 M_\odot binary system. In
addition, in this case the largest abundances of the relevant el-
ments are obtained. Thus, we choose the 0.4+0.8 M_\odot simu-
lation as our reference model, although reasonable results can be
obtained by adopting other masses. In passing, we note, never-
theless, that the He abundance is rather uncertain since equally
good fits to the observed spectrum of GD 362 can be obtained
with very different He abundances. Thus, the mass of GD 362
is also rather uncertain. More importantly, if the mechanism
producing the unusual photospheric abundance pattern of GD
362 were to be accretion from the inner regions of the disk—
which are C- and O-rich—atomic lines of C\textsubscript{1} and C\textsubscript{2} molecular
bands should be rather apparent in the spectrum. But the strength
of these spectral features depends very much on the adopted He
abundance, because the atmospheric pressure and the opacity
also depend very much on the H/He ratio, which is rather
certain.

In order to know whether the chemical abundances of GD 362 can be reproduced by direct accretion from the Kep-
erian disk, we proceed as follows. Given the surface gravity and the effective temperature of our model, we compute
the luminosity, the radius, and the cooling time of the white
dwarf according to a set of cooling sequences (Salaris et al.
2000). We obtain, respectively, log (L_{\text{wd}}/L_\odot) = -3.283,
log (R_{\text{wd}}/R_\odot) \approx -2.096, and t_{\text{cool}} \approx 2.2 \text{ Gyr}. Hence, in this
scenario, GD 362 has had enough time from the moment in
which the merger occurred to cool down, to accrete most of the
C- and O-rich region, to settle down the accretion
disk, and to form dust. In addition, the central white dwarf
has had time enough to accrete (at a rate much smaller than
the Bondi-Hoyle accretion rate) the small amount of hydro-
gen from the interstellar medium (ISM) to show spectro-
scopic hydrogen features. We further assume that the ac-
cretion luminosity

\[ L_{\text{acc}} = \frac{GM_{\text{wd}}}{R_{\text{wd}}} \]  

is, in the worst of the cases, smaller than the luminosity of the
white dwarf. This provides us with an (extreme) upper limit to
the accretion rate, which turns out to be \( 1.3 \times 10^{-3} M_\odot \text{ yr}^{-1} \). Next, we assume that the abundance of Ca is the result
of the equilibrium between the accreted material and gravita-
tional diffusion:

\[ MX_{\text{disk}} = \frac{M_{\text{env}} X_{\text{abs}}}{\tau_{\text{diff}}}, \]  

where \( X_{\text{disk}} \) is the abundance in the accretion disk, \( X_{\text{abs}} \) is the
photospheric abundance, \( M_{\text{env}} \) is the mass of the envelope of GD
362, and \( \tau_{\text{diff}} \) is the diffusion timescale. The diffusion time-
volume of Ca for H-rich atmospheres is of the order of a few
years. However, the accreted material is He-rich, so the dif-
fusion timescale is probably more typical of a He-rich envelope,
which is much larger (Paquette et al. 1986), of the order of

| TABLE 1 | MAIN RESULTS OF THE SPH SIMULATIONS |
|------------------------------|------------------|------------------|------------------|------------------|
| PARAMETER | 0.4+0.8 | 0.4+1.0 | 0.4+1.2 | 0.6+0.6 | 0.6+0.8 |
| System Masses |
| \( M_{\text{wd}} (M_\odot) \) | 0.99 | 1.16 | 1.30 | 0.90 | 1.09 |
| \( M_{\text{disk}} (M_\odot) \) | 0.21 | 0.24 | 0.30 | 0.30 | 0.29 |
| \( M_\odot (M_\odot) \) | 10\textsuperscript{-3} | 10\textsuperscript{-3} | 10\textsuperscript{-5} | 10\textsuperscript{-2} | 10\textsuperscript{-2} |
| Abundances |
| He | 0.94 | 0.93 | 0.99 | 0.99 | 0.99 |
| C | 3 \times 10\textsuperscript{-2} | 2 \times 10\textsuperscript{-2} | 5 \times 10\textsuperscript{-3} | 5 \times 10\textsuperscript{-3} | 5 \times 10\textsuperscript{-3} |
| O | 1 \times 10\textsuperscript{-2} | 3 \times 10\textsuperscript{-3} | 3 \times 10\textsuperscript{-3} | 3 \times 10\textsuperscript{-3} | 3 \times 10\textsuperscript{-3} |
| Ca | 4 \times 10\textsuperscript{-5} | 2 \times 10\textsuperscript{-4} | 9 \times 10\textsuperscript{-5} | 9 \times 10\textsuperscript{-5} | 9 \times 10\textsuperscript{-5} |
| Mg | 3 \times 10\textsuperscript{-5} | 3 \times 10\textsuperscript{-5} | 6 \times 10\textsuperscript{-5} | 6 \times 10\textsuperscript{-5} | 6 \times 10\textsuperscript{-5} |
| S | 8 \times 10\textsuperscript{-5} | 2 \times 10\textsuperscript{-4} | 5 \times 10\textsuperscript{-5} | 5 \times 10\textsuperscript{-5} | 5 \times 10\textsuperscript{-5} |
| Si | 1 \times 10\textsuperscript{-4} | 2 \times 10\textsuperscript{-4} | 3 \times 10\textsuperscript{-4} | 3 \times 10\textsuperscript{-4} | 3 \times 10\textsuperscript{-4} |
| Fe | 9 \times 10\textsuperscript{-3} | 7 \times 10\textsuperscript{-3} | 5 \times 10\textsuperscript{-4} | 5 \times 10\textsuperscript{-4} | 5 \times 10\textsuperscript{-4} |
The evolution of the angular velocity due to the coupling of the interaction between the white dwarf and the surrounding disk. Assume that the central white dwarf has a weak magnetic field, \( B \approx 1 \times 10^{-5} \) T for our fiducial composition (He/H at the base of the convective zones and the appropriate chemical composition). For our fiducial composition (He/H at the base of the convective zones and the appropriate chemical composition), the central white dwarf rotates very fast. However, an unobservable magnitude of GD 362, we obtain a distance of 33 pc. The upper limit to the rotation speed of km s\(^{-1}\) for pure H, He/H\(_{11229}\), He/H\(_{20885}\), He/H\(_{11002}\), and He/H\(_{11002}\). The magnetic torques that lead to spin-down are caused by the interaction between the white dwarf and the surrounding disk. The evolution of the angular velocity due to the coupling of the white dwarf with an effective temperature of 9740 K and \( g = 8.72 \), which corresponds to a mass of about 1 \( M_\odot \); the dashed line shows the spectrum of a passive, flat, opaque dust disk; and the solid line depicts the composite spectrum. The observational data were obtained from Becklin et al. (2005).

\[
F_{WD} = \pi \left( \frac{R_{WD}}{D_{WD}} \right)^2 B_{WD}(T_{\text{eff}}) \cdot (3)
\]

Given the luminosity of our model and the apparent magnitude of GD 362, we obtain a distance of \( D_{WD} = 33 \) pc. The second contribution to the total flux comes from the emission of the disk, which, for a passive flat, opaque dust disk, is (Chiang & Goldreich 1997; Jura 2003)

\[
F_{\text{disk}} \approx 12\pi^{1/3} \cos i \left( \frac{R_{WD}}{D_{WD}} \right)^2 \left( \frac{2k_BT_{\text{in}}}{3h\nu} \right)^{8/3} \left( \frac{h\nu}{e^2} \right)^{28/3} \int_{x_{\text{in}}}^{1} \frac{x^{5/3}}{e^x - 1} dx \cdot (4)
\]

where \( i \) is the inclination of the disk (which we adopt to be face-on), \( x_{\text{in}} = h\nu/k_BT_{\text{in}} \) and \( T_{\text{in}} = 1200 \) K is the condensation temperature of silicate dust. The outer radius is taken from the results of our SPH simulations and turns out to be \( R_{\text{out}} \approx 1 \) \( R_\odot \). The result is displayed in Figure 2. The dots are the observational data for GD 362.

The proposed scenario has apparently two weak points. The first one is that infrared observations indicate the presence of SiO. This requires that O should be more abundant than C in order to form it. However, our simulations show that the ratio of C to O is a function of the distance to the primary and that, in some regions of the disk, the ratio is smaller than 1, allowing for the formation of SiO in the accretion disk. Furthermore, after 2.2 Gyr of evolution, the resulting disk has had time to form planets or asteroids with the subsequent chemical differentiation.

The second apparent drawback of the model is that the central white dwarf rotates very fast. However, an unobservable magnetic field can slow down the central star to acceptable velocities. Using the observed spectrum of GD 362, it is possible to set an upper limit to the rotation speed of \( v \sin i \approx 500 \text{ km s}^{-1} \). We assume that the central white dwarf has a weak magnetic field, \( B \). The magnetic torques that lead to spin-down are caused by the interaction between the white dwarf and the surrounding disk. The evolution of the angular velocity due to the coupling of the white dwarf magnetosphere and the disk is given by (Livio & Pringle 1992; Armitage & Clark 1996; Benacquista et al. 2003)

\[
\dot{Q} = -\frac{2\mu^2}{3Ic^3} \sin^2 \alpha + \frac{\mu^2}{3I} \left[ \frac{1}{(R_m/R_\text{mc})^{5/3}} - \frac{2}{(R_m/R_\text{mc})^{7/2}} \right] + \frac{MR_\text{W}^2 \Omega}{I} \cdot (5)
\]

where \( \mu = BR_{\text{W}}^3 \), \( R_m \) is the magnetospheric radius of the star, \( I \) is the moment of inertia, \( \alpha \) is the angle between the rotation and magnetic axes (which we adopt to be 30°), and

\[
R_c = \left( \frac{GM_\text{WD}}{\Omega^2} \right)^{1/3} \cdot (6)
\]

is the corotation radius. The first term in this expression corresponds to the magnetic dipole radiation emission, the second to the disk-field coupling, and the last one to the angular momentum transferred from the disk to the white dwarf. The magnetic linkage between the star and the disk leads to a spin-down torque on the star if the magnetospheric radius is large enough relative to the corotation radius:

\[
\left( \frac{R_m}{R_c} \right) \geq 2^{-2/3} \cdot (7)
\]

We adopt \( R_m = R_c \). Solving numerically the previous differential equation with the appropriate parameters for our case, the evolution of the rotation velocity is shown in Figure 3. As can be seen, a weak magnetic field of about 50 kG is able to slow down the white dwarf to velocities below the observational limit. This magnetic field is much smaller than the upper limit of about 0.7 MG obtained from the spectrum of GD 362. Hence, our scenario also accounts for the low rotational velocity of GD 362, without adopting extreme assumptions.
3. CONCLUSIONS

We have shown that the anomalous photospheric chemical composition of the DAZ white dwarf GD 362 and of the infrared excess of the surrounding disk can be quite naturally explained by assuming that this white dwarf is the result of the coalescence of a binary white dwarf system. This scenario provides a natural explanation for the observed photospheric abundances of GD 362 and for its infrared excess without the need to invoke extreme assumptions, like the accretion of a planet or an asteroid, since direct accretion from the surrounding disk provides a self-consistent way of polluting the envelope of the white dwarf with the required amounts of Ca, Mg, Si, and Fe. Moreover, this last scenario can also be well accommodated within the framework of our scenario given that the formation of planets and other minor bodies is strongly enhanced in metal-rich disks. Hence, GD 362 could be the relic of a very rare event in our Galaxy: the coalescence of a double white dwarf binary system.

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