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BROWN DWARFS AS CLOSE COMPANIONS TO WHITE DWARFS[1]

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ABSTRACT

The influence of the radiation flux emitted by a white dwarf primary on the evolution of a closely orbiting brown dwarf (BD) companion is investigated. Full stellar evolutionary calculations are presented for both isolated and thermal bath cases, including effects of large variations in the atmospheric grain opacities. High grain opacities significantly increase the radii of the BDs, but the thermal bath does not. The major influence of the thermal bath is to increase substantially the surface temperature and luminosity of the BD at a given age. These results are compared with the observational properties of the possible BD companion of the white dwarf G29–38. Inclusion of both physical effects, high grain opacities and thermal bath, increases the mass range (0.034–0.063 $M_{\odot}$) of viable models significantly, yet the final determination of whether the object is indeed a BD requires improvements in the observations of the system's properties.

Subject headings: infrared: sources — stars: binaries — stars: evolution — stars: individual (G29–38) — stars: interiors — stars: late-type — stars: luminosities — stars: white dwarfs

I. INTRODUCTION

Over the last decade there has been an ever increasing interest in both the observational and theoretical properties of substellar objects, stimulated in part by their potential role in the solution of the "dark matter problem" (Trimble 1987). Furthermore, there is a need to achieve a more satisfying level of understanding concerning the behavior and extent of the lower end of the main sequence (Liebert and Probst 1987) and of the so-called transition objects which are unable to support themselves fully through nuclear energy production (D'Antona and Mazzitelli 1985; Stringfellow 1986, 1989). Finally, the discovery of brown dwarfs (BDs) represents a step along the path toward detection of planetary systems (Black 1980; van de Kamp 1986).

While planets form through the accumulation of the nebular debris out of which the stars themselves have formed (see the review by Cameron 1988 and those in Black and Matthews 1985), BDs are thought to form in the same manner as their higher mass counterparts (Black 1986), possibly by fragmentation down to a minimum mass near 0.01 $M_{\odot}$ (Boss 1986, 1988). However, continued accretion of the cloud material could result in the substellar core growing into the stellar regime unless accretion is truncated very early. Stringfellow (1989) has suggested that BDs may form preferentially as companions to higher mass stars, whose winds could in principle disperse the nebular material before the BD has fully accreted. Consider the case of a close binary system (a few AU) with a primary mass ~ 2–$8\ M_{\odot}$; the primary eventually evolves into a cooling white dwarf (hereafter, WD). Detecting BDs in such a system is extremely difficult, if not impossible, during most of the evolution; it does become more promising during the WD phase, and more probable if the evolutionary time of the system is not too long ($< 10^9$ yr) so that the BD has not yet faded into obscurity. Alternatively, if the BD evolves through a common envelope phase to an orbital position very close to the WD, the radiation field of the primary could modify the observable properties of the BD.

Several significant discoveries have been made recently involving potential BDs as companions to WDs. Becklin and Zuckerman (1988) have discovered what appears to be a BD orbiting the WD GD 165 at a distance ~ 120 AU. They report the detection of seven additional very low mass companions to WDs, but details have not yet been published. Zuckerman and Becklin (1987*a*, hereafter ZB) report the discovery of an infrared excess in the WD Giclas 29–38 whose interpretation may likely be a BD, although its properties may not be consistent with standard evolutionary tracks of BDs (see § IV). In general a very high percentage of WDs seems to be companionless; these statistics are hard to reconcile. Greenstein (1986) has discussed such a glaring deficiency of companions to field WDs, and Zuckerman and Becklin (1987*b*) have found the same result in the Hyades and Pleiades.

We consider here the intriguing possibility that *the missing WD companions are in reality close, short-period BDs which are difficult to detect.* Most searches so far have been sensitive only to BD–WD binaries with large separations. In the case of G29–38, the IR companion is unresolved down to a separation of ~ 3 AU (Tokunaga *et al.* 1988; Haas and Leinert 1989). We may therefore inquire as to what influence the radiation of the primary WD imposes on the structure and evolution of the companion BD in such systems. Our results and their implications are generally applicable to any (ultra)short-period binary system with a very low mass secondary. The specific case of G29–38 is examined in § IV.

II. THE THERMAL BATH MODEL AND PHYSICS

Consider a BD companion orbiting close to a WD. When the separation of the pair is small ($\lesssim R_{\odot}$), the WD's diluted radiation flux at the orbit of the BD can be a sizable fraction of or even dominate the flux emitted by the BD. Tidal effects have probably brought the BD into synchronous rotation about the WD. The incident energy flux received from the WD will be absorbed in one hemisphere of the optically thick photosphere. Because this region is convectively unstable, we expect the excess energy to be quickly redistributed across the entire

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photospheric surface. Thus, hot-cold spots should be absent on the BD surface, which is in agreement with observations of G29–38 (see ZB). Hence, the BD is influenced by a "thermal bath" with constant temperature, independent of position on the surface of the BD. We note that Uranus, which also has a convective atmosphere, showed little dark-side bright-side temperature variation (Hanel *et al.* 1986). We require the absorbed flux to be (re)radiated along with that generated internally. The new BD boundary condition, written in terms of the effective temperature $T_{\rm eff}$, becomes

$$\sigma T_{\rm eff}^4 = \frac{L_{\rm BD}}{4\pi R_{\rm BD}^2} = \frac{L_{\rm int}}{4\pi R_{\rm BD}^2} + \sigma T_{\rm tb}^4 , \quad (1)$$

where $R_{\rm BD}$ is the radius of the BD. $L_{\rm BD}$ is the total luminosity emitted by the BD, $L_{\rm int}$ is the internal luminosity of the BD (with gravitational and thermonuclear sources), σ is the Stefan-Boltzmann constant, and $T_{\rm tb}$ is the equilibrium temperature of a black interstellar object located a distance D away from a WD with luminosity $L_{\rm WD}$. $T_{\rm tb}$ is given by

$$T_{\rm tb} = \left(\frac{L_{\rm WD}}{16\pi\sigma D^2}\right)^{1/4} = \left(\frac{R_{\rm WD}^2}{4D^2}\right)^{1/4} T_{\rm WD} . \quad (2)$$

An important consequence of equation (1) is that $T_{\rm eff} \geq T_{\rm tb}$. Thus, the thermal structure in the outer BD atmosphere can be substantially different when embedded in a thermal bath than in the isolated case.

The boundary condition given by equation (1) has been incorporated into the same code used previously by us (Stringfellow 1986; Stringfellow, Bodenheimer, and Black 1986) to compute the evolution of BDs. The code is derived from Eggleton (1971, 1972) and uses the Eggleton, Faulkner, and Flannery (1973) formulation of the equation of state, corrected by Stringfellow (1986) to handle properly the pressure ionization of both hydrogen and helium and the pressure dissociation of H_2. The thermonuclear processes important for this study are the (nonequilibrium) proton-proton reaction and deuterium burning (Fowler, Caughlan, and Zimmerman 1975; Harris *et al.* 1983). Both reactions include screening at high densities (weak, intermediate, or strong) according to the prescription devised by Graboske *et al.* (1973). The standard mixing-length treatment of convection is utilized, with the ratio of the mixing length over the pressure scale height set to 1.5. The composition is initialized with mass fractions of hydrogen, helium, deuterium, and metals of $X = 0.70$, $Y = 0.28$, $X_{\rm D} = 10^{-5}$, and $Z = 0.02$, respectively. The interior opacities are obtained from Cox and Stewart (1970).

Undoubtedly the most crucial and uncertain piece of physics concerns the atmospheric opacities. As in our previous studies we investigate the effects of two sets of atmospheric Rosseland mean opacities: (*a*) the molecular and grain opacities computed by Alexander, Johnson, and Rypma (1983, hereafter AJR), and (*b*) the grain opacities computed by Pollack, McKay, and Christofferson (1985, hereafter PMC). For the low-temperature ($T \lesssim 2000$ K) grain region, the PMC opacities can have values that are a factor of $\sim$10–200 larger than the AJR values. The AJR molecular opacities are used in both cases, but because of the discontinuous nature of the molecular-grain boundary, they must be smoothed upward somewhat near the edge of the PMC grid to avoid numerical nonconvergence. Thus, the PMC opacity set we use has somewhat enhanced molecular opacities over those of AJR for $T < 3000$ K. The question of grain survival in BD atmospheres will be deferred to our subsequent papers.

III. EVOLUTIONARY RESULTS

Figure 1 presents evolutionary tracks for isolated BDs and also indicates, with symbols, the effects of the thermal bath. The tracks in Figures 1*a* and 1*b* have been computed for the high-grain (HG) opacities of PMC and the intermediate-grain (IG) opacities of AJR, respectively. Several important differences should be noted: (1) the HG tracks have 10%–30% larger radii than the IG tracks (the trend for higher opacities to produce larger BD radii has been previously pointed out by Stringfellow 1986 and Lunine *et al.* 1989); (2) in the HG case, it takes longer ($\lesssim$40%) for a given mass to evolve to the same luminosity than in the IG case, and it arrives there with lower $T_{\rm eff}$; and (3) lower mass BDs computed with IG opacities look like higher mass BDs with HG opacities. For example, the 0.04 $M_\odot$ IG track is nearly identical to the 0.06 $M_\odot$ HG track, yet the age (at a given $L_{\rm int}$) of the 0.04 $M_\odot$ IG sequence is a factor of 2–3 shorter than that of the 0.06 $M_\odot$ HG sequence.

Most of the evolutionary sequences shown in Figure 1 have been recomputed with one or more constant values of $T_{\rm tb}$, ranging from 1000 K $\leq T_{\rm tb} \leq$ 1500 K. These sequences do not differ much from the isolated cases described above *until the surface of the BD cools to the level of the thermal bath.* There are slight increases of less than a few percent in the radii for thermal bath models (depending on the exact value of $T_{\rm tb}$), with the difference diminishing in time until $T_{\rm eff} \approx T_{\rm tb}$. At this time the surface of the BD is heated and maintained near, but slightly above, the value of $T_{\rm tb}$. Thus, during slow contraction the luminosity decreases with radius: $L_{\rm BD}/R_{\rm BD}^2 \approx$ constant. Once

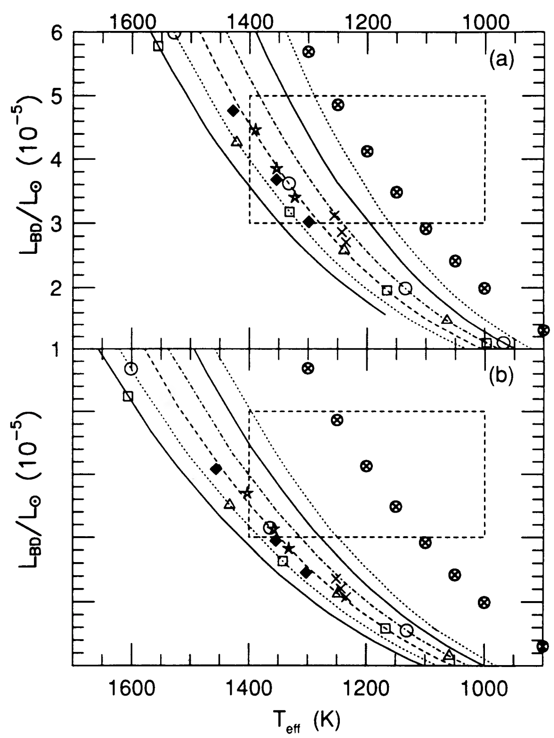

FIG. 1.—Evolutionary tracks in the H-R diagram of isolated BDs computed for two different sets of atmospheric opacities: (*a*) HG and (*b*) IG. The mass range for the curves in both frames is 0.02 $M_\odot$ (*rightmost curve*) to 0.07 $M_\odot$ (*leftmost curve*) in increments of 0.01 $M_\odot$. The open circles, triangles, and squares along the tracks indicate ages of 6, 8, and 10 × 10^8 yr, respectively. For these ages we also show models for 0.02 $M_\odot$ (*crosses*) and 0.04 $M_\odot$ (*stars*) with $T_{\rm tb}$ = 1200 K, and 0.05 $M_\odot$ with $T_{\rm tb}$ = 1000 K (*diamonds*). A constant radius cooling curve of 0.15 $R_\odot$ is indicated by the symbol ⊗. The dashed box gives the errors associated with the IR companion to G29–38 (see § IV).

BDs attain their degeneracy-limited radii, contraction is no longer possible, and they remain at the same location in the H-R diagram, so long as T_{tb} remains constant. Therefore, when T_{tb} becomes the dominant thermal energy component in the BD atmosphere, both T_{eff} and L_{BD} are significantly larger than in the isolated sequences, despite little or no increase in the radius. For example, for 0.02 $M_\odot$ with $T_{tb} = 1200$ K the luminosity in the HG sequence decreases from 2.7×10^{-5} $L_\odot$ at 10^9 yr to 1.6×10^{-5} $L_\odot$ at 2×10^{10} yr, due almost entirely to the 20% decrease in the radius over this time interval (T_{eff} cools from 1236 K to 1206 K).

Because the radii are not very different between isolated and thermal bath models, we have found that the thermal bath evolutionary sequences can be emulated very well analytically by adding to the isolated BD evolutionary sequences the contribution from T_{tb}. This procedure slightly underestimates the radius (by a few percent) during the early evolution and similarly overestimates T_{eff}. Overall, L_{BD} is in remarkable agreement with the numerical method, and the age is approximated to within $\sim 30\%$. A few examples of thermal bath sequences at equivalent ages to those indicated for the isolated sequences are shown in Figure 1. The important conclusion to be inferred here is that *BDs can maintain observable values of luminosities and surface temperatures for considerable durations when embedded in an external thermal bath.* The time dependence of T_{tb} and other evolutionary effects will be studied in a forthcoming paper.

IV. A CASE STUDY: GICLAS 29–38

Could G29–38 be such a system? In this section we compare our theoretical models with the observational properties of the system. The important observed properties of the WD are (1) L_{WD}, which determines T_{tb} for a given separation D, and (2) the mass M_{WD}, which, with L_{WD}, determines the age of the system. Greenstein (1988) provides the most complete analysis of the WD component to date. His preferred values, which we adopt, are $T_{WD} = 11{,}500 \pm 500$ K, a surface gravity log $g = 8.0$, $R_{WD} = 0.0105$ $R_\odot$, and $M_{WD} = 0.70$ $M_\odot$. These parameters give $L_{WD} = 1.71 \times 10^{-3}$ $L_\odot$, compared to the value $L_{WD} = 1.49 \times 10^{-3}$ $L_\odot$ (with $M_{bol\odot} = 4.70$) obtained from spectrophotometric colors (McCook and Sion 1987). L_{WD} is probably uncertain by $\sim 50\%$. The mass is also quite uncertain and could lie in the range 0.53–0.78 $M_\odot$ (e.g., Weidemann and Koester 1984). The corresponding evolutionary times through the WD cooling phase vary from $\sim 5 \times 10^8$ to 10^{10} yr. To preserve consistency with previous work where $M_{WD} \approx 0.70$ $M_\odot$ is assumed, we select ages of 6, 8, and 10×10^8 yr for comparison with the companion's properties.

Both ZB and Greenstein (1988) have performed blackbody fits to the IR excess fluxes of the companion to determine its luminosity L_{BD} and effective temperature T_{eff}. Two points should be kept in mind about the observations: (1) the flux measurements are obtained from broad-band photometry, and (2) the longest wavelength flux measured is at M and has a large error. Zuckerman (1989) finds that $L_{BD} = 2.5 \times 10^{-2} L_{WD}$, which for our L_{WD} gives $L_{BD} = 4.25 \times 10^{-5}$ $L_\odot$, while Greenstein (1988) estimates $L_{BD} = 4 \times 10^{-5}$ $L_\odot$. Considering reasonable uncertainties in both the observed properties of the WD and BD, we use $L_{BD} \approx 3\text{–}5 \times 10^{-5} L_\odot$ and $T_{eff} = 1200 \pm 200$ K (Fig. 1, *dashed box*). Obviously, more accurate data are needed along with observations at longer wavelengths (Berriman and Reid 1987) before the companion's properties can be better determined.

Examination of Figure 1 reveals that it is nearly impossible to account for the companion's observed properties in the isolated IG cases: BDs with masses < 0.048 $M_\odot$ evolve too quickly through the preferred region, while masses of 0.048–0.06 $M_\odot$ barely penetrate into the error box. Lunine *et al.* (1989) find the same result for G29–38 in their "high-grain" models, whose opacities are very similar to our IG opacities. The situation improves in our HG cases: $0.045 \lesssim M_{BD}/M_\odot \lesssim 0.063$ fall within the box for various permitted ages, but if the system is older than 10^9 yr, many of these models are then excluded. Thus, the problem with most of the isolated sequences lies in satisfying simultaneously the implied age of the system and the companion's properties.

The lengthening of the evolutionary time scale at observable levels of L_{BD} is in fact the main virtue of the thermal bath models, particularly for the lower masses. In Figure 1*a* the 0.04 $M_\odot$ BD (*stars*), previously excluded because of age considerations, now satisfies the companion's properties with $T_{tb} = 1200$ K for all ages considered. Similar results hold, although not nearly as well, for the same conditions in the IG case (Fig. 1*b*). The 0.02 $M_\odot$ BD with $T_{tb} = 1200$ K (*crosses*) satisfies the low end of the L_{BD} constraint for the youngest age considered, although the same conditions for the IG case are clearly subluminous, while both cases satisfy the T_{eff} constraint. Even higher mass BDs with $T_{tb} \neq 0$ satisfy better the age constraints than their isolated counterparts, for example the 0.05 $M_\odot$ BD with $T_{tb} = 1000$ K (Fig. 1, *filled diamonds*).

A further complication arises in the thermal bath models, that of induced mass loss resulting from the BD companion overflowing its Roche radius, R_R. Mass exchange cannot be ruled out. However, if we require the system *not* to be exchanging mass, then further constraints can be imposed on T_{tb}. Using the analytical prescription, we have mapped out those values of T_{tb} for each mass that satisfy the L_{BD}-T_{eff}-age constraints. The results are shown in Figure 2, where the two solid curves bound all viable models for G29–38B. The condition $R_{BD} = R_R$, where R_R has been calculated from equation (2) of Eggleton (1983), computed for $M_{WD} = 0.70$ $M_\odot$ and 0.53 $M_\odot$ is indicated by the dashed and dotted lines, respectively,

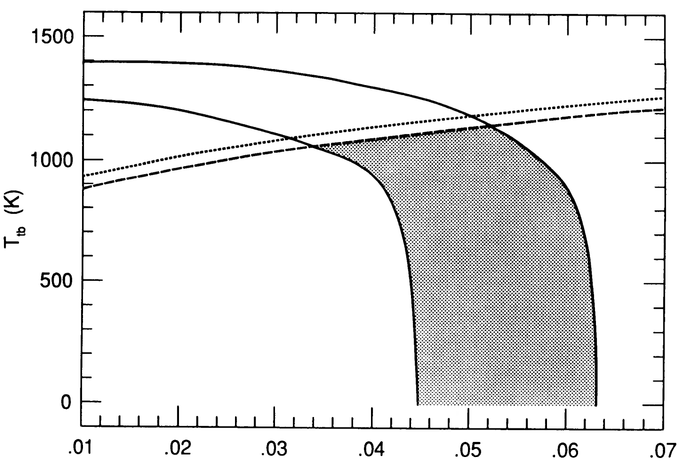

FIG. 2.—Values of T_{tb}, for HG tracks, required to satisfy the properties attributed to G29–38B for the indicated BD mass. The solid curves bound the region of viable BD models: for $T_{eff} = 1400$ K at 10^9 yr (*upper curve*) and $L_{BD} = 3 \times 10^{-5}$ $L_\odot$ at 6×10^8 yr (*lower curve*), between which all other constraints are implicitly satisfied. The dashed line indicates for each mass the condition $R_{BD} = R_R$, assuming $L_{WD} = 2.0 \times 10^{-3}$ $L_\odot$ and $M_{WD} = 0.70$ $M_\odot$; the dotted line is the same except for $M_{WD} = 0.53$ $M_\odot$. Models that lie above these lines would overfill their Roche radii. The shaded region indicates those models not undergoing mass loss which do satisfy the observed constraints. If IG opacities are used instead, the bounded region narrows considerably, and the dashed and dotted curves move upward by ~ 60 K.

assuming $L_{WD} = 2 \times 10^{-3}\ L_\odot$. Those models with T_{tb} above the dashed or dotted lines would be experiencing mass loss, those to the left of the lower solid curve would be too faint or too cool in the chosen age range, and those to the right of the upper solid curve would be too luminous or too hot in the chosen age range. Larger values of L_{WD} would shift the $R_{BD} = R_R$ curves up and extend the M_{BD} and T_{tb} range, which emphasizes the need to know accurately the WD properties.

V. DISCUSSION

We have shown that L_{BD} and T_{eff} of BDs embedded in a thermal flux bath provided by a WD primary can be increased significantly for considerable durations over those of isolated BDs. The radii evolved under such conditions are increased only slightly, if any, above those obtained in isolated sequences. In contrast, evolutionary sequences that include high atmospheric opacities result in BD radii that are up to 30% larger than those computed with lower opacities. When these different physical effects are combined and the results compared with the observed properties of the possible BD companion of the WD G29–38, the permitted mass of the BD increases substantially. High-opacity models with $T_{tb} = 0$ fall in the range 0.045–0.063 $M_\odot$. With $T_{tb} \neq 0$ and with no mass exchange, the range is extended to 0.034–0.063 $M_\odot$ and a wider range in the physical properties (L_{BD}-T_{eff}-age) for a given mass is possible. In the IG case with $T_{tb} = 0$, models in a very tight range between 0.048 and 0.06 $M_\odot$ fit, whereas with $T_{tb} \neq 0$ the range is extended to $\sim$0.038–0.063 $M_\odot$. Thus, with larger opacities and/or thermal bath models, we are able to satisfy better a limited range of the observed properties of G29–38B. Note, however, that the upper right half of the error box in Figure 1*a* cannot be accounted for with any current model. If subsequent observations maintain high values of L_{BD} but cooler T_{eff}, then interpretation as a BD for the companion remains difficult. Our HG results suggest that even larger surface opacities could facilitate better overall agreement between the theory and observations.

Several interesting questions regarding the evolution of BDs embedded in thermal baths have surfaced from the present investigation. Could the companion of G29–38 be a brown dwarf of $\sim$0.04 $M_\odot$, as suggested here? Could it actually be a lower mass BD (0.02 $M_\odot$) and be exchanging mass with the WD? Would this have any observable signatures? G29–38A is a normal DA4V WD showing no emission or absorption lines other than hydrogen (Greenstein 1988). Could a small accretion disk provide some of the IR excess observed? Perhaps the companion was originally a very low mass star that has evolved into a BD because of mass loss. In any case, what was its prior evolutionary history? Would a closely orbiting BD produce variations in the WD line profiles which could be used as a diagnostic? We predict that a radial velocity amplitude perturbation of $\sim$15–35 km s^{-1} should be evident in the WD spectrum *if* an orbiting BD with a period of up to several hours is present. G29–38A is a ZZ Ceti variable that displays complex structure in its low-frequency power spectrum (McGraw and Robinson 1975). Clearly, further detailed observational studies of the system are required to clarify its properties.

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