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HIGH DISPERSION OBSERVATIONS OF $H\alpha$ IN THE SUSPECTED
BROWN DWARF, WHITE DWARF BINARY SYSTEM G29-38^a

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ABSTRACT

We report on high dispersion spectroscopy of the $H\alpha$ absorption line of the cool DA white dwarf G 29–38. This is the star for which a recently detected infrared excess has been suggested to be due to a possible brown dwarf companion by Zuckerman and Becklin (1986, 1987). Three echelle spectra obtained at the Multiple Mirror Telescope and at the Kitt Peak Mayall 4m telescope in 1987 December show no evidence for radial velocity variations larger than $\sim 1.1 \pm 8.7 \text{ km s}^{-1}$ and are used to derive a weighted heliocentric radial velocity $V_r = 33.7 \pm 4.3 \text{ km s}^{-1}$ for the white dwarf. No emission component from the hypothesized secondary star is detected.

These negative results do not constitute strong evidence against the companion hypothesis, since the expected orbital velocity of the white dwarf component could be quite small, and the companion's line emission could be too faint to be detected. However, the observation of a sharp absorption line core restricts the possible rotation of the white dwarf to $\leq 40 \text{ km s}^{-1}$ and ensures that any surface magnetic field has a strength $\leq 10^5$ gauss. These results make it unlikely that the DA white dwarf has previously been in a cataclysmic variable accretion phase.

I. INTRODUCTION

One of the important, unresolved questions of star formation and stellar populations is the frequency of occurrence of substellar mass “brown dwarfs”, both as isolated objects and as companions to stars. Of course, stellar companions too low in mass to burn hydrogen fit the definition of planets, and the discovery and study of such objects would be of far-reaching interest. Likewise, the possible existence of a large population of single brown dwarfs could help account for the potentially large amounts of unseen matter inferred dynamically for the galactic disk and halo. There have been many claimed discoveries of such objects, but it has been a far trickier task to verify the credentials of any one candidate.

One of the most interesting and unusual discoveries involving a possible brown dwarf is that of the infrared excess associated with the white dwarf G 29–38, as reported by Zuckerman and Becklin (1986, 1987; hereafter ZB). The radiation between 2 and 5 microns in excess over that expected from the 11,500 K DA white dwarf is attributed to a companion with a color temperature of 1,200 K, a radius of $0.15 R_\odot$, and a luminosity of $5 \times 10^{-5} L_\odot$. While the radius is 50% larger than that of both Jupiter and the predictions of models for degenerate hydrogen-rich configurations, this discrepancy might be rectified if the true surface temperature were closer to 1,500 K. Greenstein (1988) has confirmed and refined these results, using his extensive observational analysis of the white dwarf, which is a low amplitude pulsating (ZZ Ceti type) star. The inferred parameters would require that the companion be too cool and too low in mass to initiate hydrogen burning. Since other possible interpretations of the excess did not seem plausible, the brown dwarf explanation appeared to be the most likely.

In an important note added to the 1987 ZB paper, it was reported that K. Hodapp and M. Rigler had failed to resolve the companion in infrared CCD images

obtained at $1.65\mu\text{m}$ and $2.2\mu\text{m}$, wavelengths at which both components should be contributing significantly to the total luminosity. The 0.8 arc second image (FWHM) corresponds to an upper limit for the projected separation of the companion of 5 a.u.

Both ZB and Greenstein derive a lifetime for the gravitationally contracting brown dwarf which is comparable to the cooling time of the DA white dwarf, each about 6×10^8 years, the implication being that the latter had a short nuclear-burning (stellar) lifetime. The conclusion that the original primary was probably a massive star is also consistent with the derived mass of $0.84 M_{\odot}$ for the white dwarf, as estimated from the parameters directly determined from stellar atmospheres analysis and from the value of the trigonometric parallax (Shipman 1979). This is significantly higher than the average DA white dwarf mass, and implies an original (progenitor) mass in excess of $5 M_{\odot}$. The loss of more than 80% of the progenitor's mass (and accompanying orbital angular momentum) during post main sequence evolution would imply that the binary orbit has expanded substantially, unless the low mass companion was involved in common envelope evolution when the primary was a red supergiant (Shipman, MacDonald and Sion 1988). The implication from the evidence outlined above is that it may be necessary to consider the effects of the proximity of the white dwarf on the low mass companion (Greenstein 1988). There is also evidence that low mass stellar or substellar companions to white dwarfs generally are rare (Probst 1983, Greenstein 1986ab, Zuckerman and Becklin 1986).

Greenstein (1988) and Shipman, Sion and Macdonald (1988) have considered in detail possible close binary evolution scenarios which might result in what may be an atypical binary system. These include the possibilities (1) that the infrared excess is due to heating of a nonluminous, large planet in close proximity to the DA star, and (2) that the system is a kind of post-cataclysmic variable (CV) system. In either case the predicted separation would be quite small, of the order of a solar radius or less. For the former case, Greenstein (1988) predicts a circular orbital velocity of $\sim 60 \text{ km s}^{-1}$. Shipman, Sion and Macdonald (1988) are less optimistic. In two versions of the "dead CV" scenario, they estimate orbital velocities of 7–30 km s^{-1} (for a $0.05 M_{\odot}$ brown dwarf) and 8 km s^{-1} respectively.

Cool DA white dwarfs normally show sharp H-alpha absorption cores attributed to non-LTE effects (Greenstein and Peterson 1973; Greenstein *et al.*, 1977; Pilachowski and Milkey 1984, 1987; Milkey and Pilachowski 1985), making it possible to measure fairly accurate radial velocities in spite of the Stark-broadened line profiles. Moreover, the end of CV evolution might be expected to leave the primary star rapidly rotating, and the rotation rate could be measured by the same kind of observation. Finally, the presence and orbital modulation of the companion conceivably might be detectable if it were to show strong $\text{H}\alpha$ line emission, a characteristic of very low mass stars with ages of the order of one billion years or less (cf. Giampapa and Liebert 1986).

Such motivations led us to obtain three high resolution echelle observations of the $\text{H}\alpha$ line of G 29–38 before we were aware of specific predictions, using observing

time at our disposal in December 1987. These scans with the Kitt Peak 4m reflector and the Arizona-Smithsonian 4.5m Multiple Mirror Telescope are discussed in Section II, and the radial velocity measurements are presented. Some implications of these observations for models involving close binary evolution are briefly discussed in Section III.

II. LINE PROFILE AND RADIAL VELOCITY MEASUREMENTS

The journal of echelle observations is given as Table 1. Two of the spectra described here were obtained on UT 1987 December 6 and 7 at the Multiple Mirror Telescope (MMT) Observatory. The echelle spectrograph with an intensified Reticon array was centered at $H\alpha$, providing wavelength coverage $\lambda\lambda 6525 - 6595$ at a spectral resolution of $\sim 0.2\text{\AA}$ ($\sim 9\text{ km s}^{-1}$ at $H\alpha$). Th-Ar comparison spectra provided the wavelength calibration. Observations of the dusk and dawn sky and of several radial velocity standards were obtained and used to establish the radial velocity zero-point. The spectra were reduced using the Interactive Reduction System at Steward Observatory. Each spectrum was divided by a normalized spectrum of a quartz continuum lamp to remove pixel-to-pixel response variations in the detector. The Reticon pattern noise amplitude was unusually large, and the phase was variable on a scale of hours during the observing run. Consequently, flatfield division was not as effective as usual, and the spectra appear considerably noisier than photon counting statistics would lead one to expect. Fifth-order polynomial fits were made to establish the pixel-wavelength dispersion relation; the mean standard deviation of residuals to the fits was $0.02\text{\AA}$. The spectra then were resampled to a linear wavelength scale.

An additional spectrum was obtained on UT 1987 December 23 with the KPNO 4m echelle spectrograph. The spectrograph was configured with the 31.6 l/mm echelle grating, the 226-1 cross disperser, and the UV fast camera. The detector was the RCA2 CCD. The entrance slit was opened to 300 microns (2 arc-seconds) for a resolution of $0.45\text{\AA}$ ($\sim 20\text{ km s}^{-1}$). The exposure time was 2 hours, with a final signal-to-noise of 25 near the center of the Stark-broadened profile. The spectrum was calibrated and extracted from the CCD image using IRAF software developed at NOAO. Wavelength calibration followed that of the MMT spectra, and residuals to the fit were of the same order as those to the fits to the MMT comparison spectra.

It proved impossible to establish the true continuum of any of the echelle spectra because the Stark-broadened $H\alpha$ line profiles extend beyond the useful spectral range of both the MMT and Mayall instrument packages. In addition, the instrument throughput at both ends of the echelle order bandpass is significantly depressed, distorting the shape of the line profiles. In order to correct approximately for this effect, the spectra were divided by efficiency curves constructed from the quartz continuum lamp spectra. The efficiency curves were normalized to unity at the $H\alpha$ line center to preserve the object spectra photon counting statistics in the non-LTE line cores.

Radial velocities for each of the three spectra were measured by fitting the sharp, non-LTE cores of the absorption line profiles. The fits were made using the non-linear least squares algorithm of Levenberg and Marquardt, and standard internal errors were derived from the diagonal elements of the covariance matrix, as described by Press *et al.* (1986). The rms velocity error of the polynomial fit to the pixel-wavelength relation was added in quadrature to the errors derived from the fits to the line profiles. The zero-point correction was determined from the radial velocity standards. As is evident in the table, the measured radial velocities show no evidence for variations within the quoted errors. The MMT spectra therefore were averaged to improve the signal-to-noise ratio, and the radial velocity measured from the averaged MMT spectrum was combined with the Kitt Peak velocity to derive a weighted heliocentric radial velocity of $33.7 \pm 4.3 \text{ km s}^{-1}$.

The spectra are shown together in Figure 1. Although the relative flux scale is arbitrary, the Mayall spectrum (lower curve) accurately depicts the depth of the central core with respect to the Stark-broadened $H\alpha$ absorption line wings. The averaged MMT spectrum (upper curve) has been offset from the Mayall spectrum in order to compare the details of the line profile in the sharp, non-LTE cores. To within the limits imposed by the signal-to-noise of the data, the line profiles are identical. As is noted above, the true continuum lies beyond the limits of the figure.

III. IMPLICATIONS FOR CLOSE BINARY MODELS

The results of this preliminary search for radial velocity variations from the primary star do not rule out the presence of a close companion of very low mass. If the primary star has an orbital velocity amplitude detectable at this resolution, it is possible that our view is too close to pole-on or that the three observations happened to occur at nearly the same phase. Moreover, the mass ratio of the anticipated binary system would be quite large. As mentioned in the introduction, one of the binary evolution scenarios of Shipman, MacDonald and Sion (1988) includes a predicted orbital velocity amplitude for the primary of only 8 km s^{-1} . Under such circumstances, detection of the object as a spectroscopic binary by observations of the primary component will be extremely difficult.

The absence of a velocity-variable $H\alpha$ emission component attributable to the conjectured substellar companion also is not an important negative result. There is no direct evidence as to whether substellar mass objects are active chromospherically. However, stars low enough in mass to (also) have completely convective interiors frequently show strong $H\alpha$ emission (Giampapa and Liebert 1986) which presumably declines with age and rotation rate as for stars of higher mass. The problem is that, even if the line were at a strength (equivalent width $5\text{\AA}$) typical of late M dwarfs showing strong chromospheric and flare activity, and was narrow enough to be unresolved in these spectra, the peak flux would exceed the continuum level of the cool companion by only about a factor of 25. If we use the Wien approximation to extrapolate from Greenstein's (1988) predicted flux at $1.19\mu\text{m}$ for the optimistic choice of a 1500 K blackbody companion, the anticipated continuum flux at $6563\text{\AA}$

is only 0.004 milliJansky (mJy). Thus the emission line peak might reach a flux of ~ 0.1 mJy. This would be swamped by the observed white dwarf value (Greenstein's Table I) of 18 mJy and would not be detectable.

A more important constraint on a post-CV scenario is provided by the observation that G29-38 has a relatively sharp, non-LTE core of the same type as is observed in other cool DA white dwarfs investigated by one of us (C.A.P.). Appropriate model atmospheres to model the $H\alpha$ profile in stars as cool as G29-38 have become available only very recently (Koester, D., private communication), and, as yet, we do not have access to the new calculations. We therefore have used extrapolation of the profiles for warmer stars provided by Milkey and Pilachowski (1987) to slightly cooler temperatures. These suggest a limit of $v \sin i \leq 40 \pm 10$ km s $^{-1}$ for the rotation of G29-38. The line core is slightly broader than the other, slightly warmer white dwarfs 0943+44, 0401+25, and 2124+55, with temperatures of 14,500 K, 13,500 K, and 14,100 K, respectively, reported by Pilachowski and Milkey (1987).

The observations thus provide no evidence that G29-38 was recently in a normal CV mass transfer phase in which the accreting white dwarf typically is spun up to rotation periods of the order of tens of seconds or velocities of the order of thousands of km s $^{-1}$ (Robinson 1976). This conclusion should not be significantly affected by the extrapolation to cooler temperatures of the slightly warmer non-LTE line profiles. In addition, the same sharp, single core limits the strength of any magnetic field associated with the white dwarf to less than 10^5 gauss (Kemic 1974). This limit very nearly rules out the possibility that any magnetic field on the primary star could be strong enough to synchronize the rotation period of the white dwarf with the orbital period, as occurs in AM Herculis systems; these systems have white dwarf primary stars with surface fields in excess of 10^7 gauss (cf. Liebert and Stockman 1985). Thus, it is difficult to understand why the primary would not still be rotating rapidly if it has finished a CV phase of mass exchange. This result casts some doubt on such scenarios in the paper by Shipman, MacDonald and Sion (1988).

We thank Ben Zuckerman, Jesse Greenstein and Harry Shipman for early unpublished results and stimulating conversations about this unique object. Detlev Koester has made us aware of the existence of new non-LTE models for the $H\alpha$ line profile in cooler white dwarfs; these should be most useful in future work on the rotation of white dwarfs. We also thank the referee for the prompt and helpful critique given this paper. This work was supported in part by the National Science Foundation through grant AST 88-40482.

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Table 1
Journal of Echelle Observations

Telescope	UT Date	HJD 2447135+	Exp. Time	V_r	σ
MMT	1987 Dec 6	0.6972	60 min	36.4 km s ⁻¹	6.9 km s ⁻¹
MMT	1987 Dec 7	1.6792	60 min	35.9 km s ⁻¹	13.0 km s ⁻¹
Mayall	1987 Dec 23	17.5674	120 min	33.1 km s ⁻¹	5.8 km s ⁻¹

Figure Captions

Figure 1. High resolution spectra of the H α absorption line of G29–38. The upper spectrum is the average of two spectra obtained at the MMT; the lower spectrum was obtained at the Mayall 4-m. The Reticon pattern noise in the MMT spectra was large and variable in phase during the observations, and the spectra are noisier than photon statistics would lead one to expect. The relative flux scale is arbitrary, and the MMT spectrum has been offset from the Mayall spectrum in order to compare the details of the line profiles. To within the limits imposed by the signal-to-noise ratio, the line profiles are identical. The sharp, non-LTE line core is characteristic of cool DA white dwarfs.