DETECTION OF A VARIABLE INFRARED EXCESS AROUND SDSS J121209.31+013627.7

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Received 2006 June 4; accepted 2006 July 7; published 2006 August 7

ABSTRACT

We present near-infrared JHK, photometry and light curves of the candidate magnetic white dwarf + brown dwarf binary SDSS J121209.31+013627.7 and report on the detection of near-infrared excess and variability in the K band. The observed near-infrared excess can be explained by the presence of an L7 brown dwarf and an extra emission source. The J and H light curves appear flat, which rules out eclipses deeper than 0.2 mag and the presence of an accretion hot spot on the white dwarf. From the variable K, light curve, we get a refined period for the system of 88 ± 1 minutes. We show that the observed variability in the K band can be explained by cyclotron emission, which can be modeled by a small spot on the surface of the white dwarf. SDSS J121209.31+013627.7 exhibits similarities to the ultra–short-period Polar EF Eridani; however, the lack of evidence for Roche lobe overflow accretion suggests that it may be a pre-Polar.

Subject headings: binaries: spectroscopic; infrared: stars — stars: individual (SDSS J121209.31+013627.7) — stars: low-mass, brown dwarfs — white dwarfs

Online material: machine-readable table

1 INTRODUCTION

SDSS J121209.31+013627.7 (hereafter SDSS 1212) was first reported by Schmidt et al. (2003) as a magnetic white dwarf with an equivalent dipolar magnetic field of B_0 = 13 MG. Recently, Schmidt et al. (2005a) published a new study suggesting that SDSS 1212 is a white dwarf/probable brown dwarf binary. Their follow-up spectroscopy revealed the presence of a narrow Hα emission line with a semi-amplitude radial velocity variation of 320 ± 20 km s⁻¹ and an orbital period of 93.6 ± 14.4 minutes, indicating the presence of a nearby irradiated companion. The Hα emission disappeared when the companion faced the white dwarf, suggesting a high-inclination orbit. From the Zeeman splitting of hydrogen absorption lines in the photosphere, Schmidt et al. (2005a) measured a mean magnetic surface field of 7 MG. Their J-band photometry yielded 17.91 ± 0.05 mag, placing an upper limit on the mass of the companion and thus suggesting the brown dwarf scenario.

In this Letter, we present near-infrared JHK, observations of SDSS 1212, aimed at detecting the brown dwarf companion and determining the presence or absence of eclipses of the white dwarf.

2 OBSERVATIONS AND DATA ANALYSIS

We observed SDSS 1212 in JHK, over five nights, 2006 February 15 and 17 UT with the Wide Field Infrared Camera (WIRC) on the 2.5 m DuPont telescope and from 2006 June 4 to 7 UT with the Persson’s Auxiliary Nasymth Infrared Camera (PANIC) on the 6.5 m Baade Telescope at Las Campanas Observatory, Chile. The near-infrared filter set at Las Campanas (the LCO system) is described by Persson et al. (1998).

With WIRC, we observed SDSS 1212 with an ~1 minute sampling in all three filters, observing in J for 84 minutes and H for 15 minutes. For the second night, we observed in J and K for 80 minutes and in H for 15 minutes. Our PANIC observations sampled SDSS 1212 every 30 s for all three filters, with observations spanning ~120 minutes for each filter. Typical seeing over the five nights ranged from 0′.6 to 1′.3. We used a five-point dither pattern for each data set.

The images were processed using standard IRAF routines or equivalent IDL programs. Each frame was flat-fielded, background-subtracted, and bad-pixel–corrected. We then performed simultaneous differential aperture photometry on each image of SDSS 1212 and comparison stars in the field. All of the comparisons behaved similarly, showing no individual photometric variation trends over the time span of the observations. We derived differential magnitude light curves for each comparison using aperture sizes that were approximately equal to the width of the seeing and averaged them to obtain the final light curves.

We used six comparison stars in the images. The 2MASS apparent magnitudes of those stars are summarized in Table 1. Our dithering pattern precluded all six stars from being present in every frame. The PANIC data had three of the comparison stars, due to its smaller field of view. For each night, we took two bright comparison stars in the field to calculate the absolute photometry of SDSS 1212, based on their 2MASS photometry. The final JHK, photometry is presented in Table 2. Transforming the comparison star 2MASS photometry into the LCO system gives values that are the same within the photometric errors (Carpenter 2001).

Based on observations obtained with the 2.5 m DuPont telescope and the 6.5 m Magellan Telescopes at Las Campanas Observatory (LCO), which is operated by the Carnegie Institution of Washington.

1 Carnegie Fellow.

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configuration with an SDSS 1212 in the band (see below) as phase 0. The phased light curves from all nights are shown in Figure 1.

The light curves of SDSS 1212 were folded using the ephemeris equation

\[ T = (\text{HJD}) 2453783.8375 + 0.061E, \]

where we have adopted the orbital period of 0.061 ± 0.001 days derived by finding a period that minimized the phased point-to-point variations in our \( K_s \) light curves (Lafler & Kinman 1965). We have chosen the midpoint of the magnitude dip observed in the \( K_s \) band (see below) as phase 0. The phased light curves from all nights are shown in Figure 1.

The \( J \) and \( H \) light curves appear featureless up to the 1 standard deviation precision level of our photometry (~0.07 mag for \( J \) and \( H \)), which precludes eclipses deeper than 0.2 mag. However, there is a marginally detected dip in the \( H \) curve at a phase of 0.5 that appears in both nights of data. The emission of SDSS 1212 in the \( J \) band is dominated by the white dwarf; therefore, if eclipses were present, one would clearly observe the primary eclipse (occultation of the white dwarf by the companion), but the eclipse of the secondary would still be undetectable. A white dwarf of typical radius \( R \) with a radius of 0.03 \( R_\odot \) brown dwarf would produce an \( \sim 0.11 \) \( R_\odot \) white dwarf would produce an \( \sim 5 \) minute eclipse of the white dwarf. Using the most recent version of the Wilson-Devinney program (WD2003; Wilson & Devinney 1971; Wilson 1979), we generated model light curves for a range of inclinations and radii of the secondary, keeping the white dwarf radius and the orbital separation fixed, and compared the results to the light curve in the \( J \) band to conclude that the inclination of the system is constrained to \( i \approx 78.5^\circ \).

The \( K_s \)-band light curve is marked by a flat dip that lasts for \( \sim 41 \) minutes. That dip is followed by a brightening of the \( J \) and \( H \) bands, and we measure mag. In the \( K_s \) band, we derived two values for the total flux. The first

\begin{table}
\centering
\begin{tabular}{lll}
\hline
Name & \( J \) & \( H \) & \( K_s \) \\
2MASS 12120989+0135259 & \( 16.23 \pm 0.12 \) & \( 15.89 \pm 0.17 \) & \( 15.54 \pm 0.23 \) \\
2MASS 12120582+0135157 & \( 15.61 \pm 0.08 \) & \( 14.99 \pm 0.07 \) & \( 14.95 \pm 0.14 \) \\
2MASS 12120408+0135365 & \( 15.65 \pm 0.07 \) & \( 15.05 \pm 0.06 \) & \( 14.78 \pm 0.12 \) \\
2MASS 12121658+0137042 & \( 14.95 \pm 0.04 \) & \( 14.29 \pm 0.04 \) & \( 14.14 \pm 0.07 \) \\
2MASS 12121667+0135257 & \( 14.45 \pm 0.03 \) & \( 13.86 \pm 0.02 \) & \( 13.80 \pm 0.06 \) \\
SDSS J121205.54+013720.2 & ... & ... & ... \\
\hline
\end{tabular}
\caption{Calibration Stars}
\end{table}

Given that the \( J \)-band light curve is flat, we derived an apparent magnitude of \( J = 17.90 \pm 0.06 \) by averaging over all phases. Similarly, there appears to be no significant variability in the \( H \) band, and we measure \( H = 17.56 \pm 0.05 \) mag. In the \( K_s \) band, we derived two values for the total flux.
value, \( K = 16.53 \pm 0.08 \) mag, corresponds to the average magnitude of the system between phases \( \phi = 0.2 \) and \( 0.4 \) (stage 1), where we are detecting emission from the white dwarf, its companion, and any additional radiation present in the system. The second value, \( K = 17.23 \pm 0.09 \) mag, was computed as the average magnitude between phases \( \phi = 0.0-0.2 \) and \( 0.85-1.0 \) (stage 2) that corresponds to the white dwarf and the companion being visible.

The resultant spectral energy distribution (SED) of SDSS 1212 is shown in Figure 2. The open diamonds correspond to the average flux of the system in the Sloan Digital Sky Survey (SDSS) \( ugriz \) bands (Fukugita et al. 1996) and the \( J, H, \) and \( K_s \) photometry in stage 2, when SDSS 1212 is dimmer. The open square represents the average \( K \) flux of the system during the brighter phase of stage 1.

The flux of SDSS 1212 from the optical to \( J \) is reproduced by a blackbody model of a single white dwarf with an effective temperature of about 10,000 K (see solid line in Fig. 2), in agreement with the conclusion reached by Schmidt et al. (2005a). Our \( H \)- and \( K_s \)-band data, on the other hand, clearly show infrared excess in each one of the stages considered above. Therefore, we conclude that there is a substellar companion, most likely of middle-to-late L spectral type and with a temperature of about 10,000 K (see solid line in Fig. 2), in agreement with the conclusion reached by Schmidt et al. (2005a). The values used for the \( J \), \( H \), and \( K_s \) magnitudes in \( J \), \( H \), and \( K_s \) of \( >13.8, 13.4 \pm 0.2, \) and \( 12.4 \pm 0.3 \), respectively. These absolute magnitudes match with a spectral type of \( L7 \). SDSS 1212’s distance is uncertain by 14% and is based on theoretical modeling of the white dwarf’s atmosphere. This uncertainty translates into an error of \( \pm 1 \) spectral type. Figure 2 shows a comparison of the observed SDSS 1212 photometry (open diamonds) and the combination of the expected white dwarf (WD) fluxes and those from an L7 brown dwarf (dashed line). By definition, the model does not fit the observed photometry in the \( J \) band since we are assuming a 3\( \sigma \) upper limit.

4. DISCUSSION

There are two possible explanations for the SDSS 1212 light curve: (1) the excess emission is due to a hotter irradiated side of the companion, or (2) the excess is produced by a separate mechanism, such as cyclotron emission.

In the case of irradiation, the SDSS 1212 system would appear brighter during the phases when the hot side of the companion is facing toward us, with its brightness dropping once per orbit as the hot side of the companion faces away from us. The difference in flux between stage 1 and stage 2 is approximately a factor of 1.5. Assuming flux from two pure blackbodies, one would expect the temperature ratio between the hot and cool sides of the companion that account for this difference to be \( T_{\text{hot}}/T_{\text{cool}} = 1.1 \).

We attempted to model the \( J \)-, \( H \)-, and \( K_s \)-band light curves of SDSS 1212 with WD2003 by adopting various irradiation scenarios with effective temperatures of the secondary down to 600 K and assuming that the secondary corotates with the white dwarf in its orbit. The values of the orbital period and initial epoch of the light curves were adopted from equation (1). We assumed a mass of 0.6 \( M_\odot \), a radius of 0.012 \( R_\odot \), and a \( T_{\text{eff}} \) of 10,000 K for the white dwarf. The model for the companion was set to 0.06 \( M_\odot \), and the radius to the size of its Roche lobe, although there is no sign of undergoing accretion, as reported by Schmidt et al. (2005a). The values used for the albedos and the limb-darkening and gravity-brightening coefficients are the same as those adopted by Harrison et al. (2003) in their irradiation models of EF Eri. The model providing the closest resemblance to the light curves corresponds to a \( T_{\text{eff}} = 1000 \) K brown dwarf with a 1400 K irradiated side. That model is represented by the dashed line in Figure 1. Clearly, irradiation alone cannot reproduce the observed light curves, since the irradiation curves produce a smooth rounded drop in flux that does not match the sharpness or the depth of the drop.

In the second scenario, cyclotron emission associated with the magnetic pole region of the white dwarf causes excess flux in \( K_s \). Other magnetic white dwarf binaries, such as EF Eri, exhibit strong cyclotron features even in the absence of accretion features (Harrison et al. 2004). We postulate that the majority of the cyclotron emission is confined to a spot near the magnetic pole of the white dwarf and is obscured by the white dwarf when it rotates out of view. Given a total excess above the white dwarf and its companion of 0.08 mJy, the cyclotron...
emission would have an approximate luminosity of $\sim 3 \times 10^{37}$ ergs s$^{-1}$. This is a lower limit on the total luminosity caused by accretion of a wind from the companion, and the inferred mass accretion rate would be $4 \times 10^{-16} M_{\odot}$ yr$^{-1}$, assuming a white dwarf mass of $0.6 M_{\odot}$ and a white dwarf radius of $0.01 R_{\odot}$. Assuming a magnetic field strength of 13 MG, the cyclotron emission observed at the wavelength of 2.06 $\mu$m corresponds to a harmonic number of 4. Cyclotron emission should be present at 4.1 and 8.2 $\mu$m and is accessible in Spitzer's Infrared Array Camera channels 2 and 4, respectively.

We have generated a simple geometric model of a spot on the white dwarf to model the observed light curve. Our model includes the sum of the $K_{\alpha}$-band white dwarf + companion flux plus the flux from the spot as a function of the spin phase. We assume that the spot is not affected by limb darkening relative to the disk of the white dwarf. The radius of the spot, the flux ratio of the spot to the white dwarf + companion, and the latitude of the spot’s position are free parameters. The results are mostly insensitive to the spot radius or latitude, assuming that the spot is close to the equator and that the spot radius is <10% of the white dwarf radius. We assume a flux ratio of spot to white dwarf of 1.5, which is derived from the difference in flux due to the dip compared to that expected from the white dwarf alone. The solid line in Figure 1 shows our results for a model with a spot of radius 0.03$R_{\text{wd}}$, located at the equator. The bottom diagram shows the residuals from this model. Some structure still remains visible in those residuals, e.g., the dip around phase 0.5, which could be caused by beaming of the cyclotron emission, self-shielding of the cyclotron emission column that presents less surface area as it points toward Earth, or an eclipse of the emission region by the companion. Overall, our simplistic cyclotron emission model provides a good first-order approximation to the $K_{\alpha}$ light curve.

5. CONCLUSIONS

We report the detection of the brown dwarf companion to the magnetic white dwarf SDSS J121209.31+013627.7, whose presence was inferred by the detection of a variable Hα emission line by Schmidt et al. (2005a). We provide a more accurate period for the system of 0.061 ± 0.001 days. No eclipses are apparent; however, our data constrain the inclination of the system to $\pm 78.5^\circ$. We are only able to place an upper limit of $L_{\text{eff}}$ to the spectral type of the companion, given that the $K_{\alpha}$-band photometry appears to be contaminated by an additional source. We propose cyclotron radiation as the most likely cause of the extra emission, although our hypothesis requires phase-resolved infrared spectroscopy to be confirmed. Spectroscopy will reveal the presence or absence of cyclotron radiation peaks and determine the spectral type of the companion. It is possible that high-precision J- and H-band photometry may reveal a shallow eclipse or other subtle structure in the light curves. SDSS 1212 shows no evidence of ongoing accretion from Roche lobe overflow and may differ from similar objects, like EF Eri, by being a pre-Polar system (Schmidt et al. 2005a).

Finally, high-resolution optical spectra of SDSS 1212 will better measure the radial velocity variations of the Hα line and link the variations with those observed in $K_{\alpha}$. Measuring the radial velocity of the white dwarf through its hydrogen lines will be difficult given the high probability that changes in the projected mean field strength will erase any signature from the companion. High-resolution spectroscopy will also provide a direct measure of any material that is accreted onto the white dwarf evidenced by the presence of weak metal lines. Magnetic white dwarf binaries can efficiently capture the stellar wind of their companions and radiate the accretion energy entirely in cyclotron emission (Schmidt et al. 2005b; Webbink & Wickramasinghe 2005). Metal lines in DAZ white dwarfs have proved useful for measuring low levels of mass accretion onto isolated white dwarfs and white dwarfs with close companions and would provide an independent measure of the material accreted by the white dwarf (Holberg et al. 1997; Koester et al. 1997; Zuckerman et al. 2003; Debes 2006).

We thank our referee Gary Schmidt for his constructive suggestions for this manuscript. We thank Larry Petro for his insightful discussion regarding cyclotron spots and accretion columns for magnetic white dwarfs. We also thank Sara Seager and Hannah Jang-Condell for their helpful suggestions. M. L.-M. acknowledges research and travel support from the Carnegie Institution of Washington through a Carnegie Fellowship. A. Z. B. acknowledges research and travel support from the Carnegie Institution of Washington through a Vera Rubin Fellowship. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. 6

6 The SDSS Web site is http://www.sdss.org/.

REFERENCES

Carpenter, J. M. 2001, AJ, 121, 2851
Cutri, R. M., et al. 2003, 2MASS All Sky Catalog of Point Sources (Pasadena: NASA/IPAC), http://irsa.ipac.caltech.edu/applications/Gator/
Debes, J. 2006, ApJ, submitted
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, AJ, 111, 1748
Harrison, T. E., Howell, S. B., Huber, M. E., Osborne, H. L., Holtzman, J. A., Cash, J. L., & Gelino, D. M. 2003, AJ, 125, 2609
Harrison, T. E., Howell, S. B., Szekody, P., Homeier, D., Johnson, J. J., & Osborne, H. L. 2004, ApJ, 614, 947
Holberg, J. B., Barstow, M. A., & Green, E. M. 1997, ApJ, 474, L127
Howell, S. B., Walter, F. M., Harrison, T. E., Huber, M. E., Becker, R. H., & White, R. L. 2006, ApJ, submitted
Koester, D., Provençal, J., & Shipman, H. L. 1997, A&A, 320, L57
Lafler, J., & Kinman, T. D. 1965, ApJS, 11, 216
Pessson, S. E., Murphy, D. C., Krzeminski, W., Roth, M., & Rieke, M. J. 1998, AJ, 116, 2475
Schmidt, G. D., Szekody, P., Silvestri, N. M., Cushing, M. C., Liebert, J., & Smith, P. S. 2005a, ApJ, 630, L173
Schmidt, G. D., et al. 2003, ApJ, 595, 1101
———. 2005b, ApJ, 630, 1037
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Vrba, F. J., et al. 2004, AJ, 127, 2948
Webbink, R. F., & Wickramasinghe, D. T. 2005, in ASP Conf. Ser. 330, The Astrophysics of Cataclysmic Variables and Related Objects, ed. J.-M. Hameury & J.-P. Lasota (San Francisco: ASP), 137
Wilson, R. E. 1979, ApJ, 234, 1054
Wilson, R. E., & Devinney, E. J. 1971, ApJ, 166, 605
Zuckerman, B., Koester, D., Reid, I. N., & Hübsch, M. 2003, ApJ, 596, 477