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A Hot White Dwarf SDSS J134430.11+032423.1 with a Planetary Debris Disk

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Abstract

We discovered a debris disk around hot white dwarf (WD) SDSS J134430.11+032423.1 (SDSS J1344+0324). The effective temperature [$T_{\rm eff}$ = 26,071(±163) K], surface gravity [$\log g = 7.88(2)$], and mass [$M = 0.58(1)\,M_{\odot}$] of this WD have been redetermined based on the analysis of its SDSS spectrum. We found that SDSS J1344+0324 is currently the hottest WD with a debris disk. Two spectra observed by SDSS at different times show that this object is similar to SDSS J1228+1040 with variable near-IR Ca II triplet emissions from a gaseous disk. The parameters of the debris disk are derived from the IR excess analysis of SDSS J1344+0324. We found that the disk is the coolest of all debris disks around WDs, and that the inner and outer radii are very close to the tide radius of the WD. Thus, the debris disk is very narrow (about 0.22 $R_{\odot}$). This implies that it might be a newly formed disk resulting from the tidal disruption of a rocky planetary body that has just entered the tide volume of the WD. This might provide strong observational evidence for the formation of debris disks around WDs.

Key words: circumstellar matter – stars: individual: SDSS J134430.11+032423.1 – white dwarfs

1. Introduction

White dwarfs (WDs) are very common stellar remnants in our Galaxy, having evolved from the main-sequence stars with $0.8 \lesssim M \lesssim 8\text{–}10\,M_{\odot}$ (Girven et al. 2011). The high surface gravity of WDs indicates that all metals should sink out of the atmosphere toward the interior on a timescale shorter than the cooling time. Schatzman (1958) and Koester & Chanmugam (1990) estimated that the WDs that have been cooled down to an effective temperature of $T_{\rm eff} \approx 25{,}000$ K should have either H or He atmospheres. However, metal pollution was estimated to be present in a significant fraction (25%–50%) of all WDs with $T_{\rm eff}$ above 11,000 K (Zuckerman et al. 2003, 2010; Koester et al. 2014). To sustain the atmospheric metal content, these polluted WDs must accrete mass at a rate of at least 10^8 g s^{-1}, because the diffusion timescales are much shorter than the cooling times (Koester et al. 2014; Hartmann et al. 2016).

Two decades after the discovery of a dust disk around G29-38 (Zuckerman & Becklin 1987), Gänsicke et al. (2006) identified a gaseous disk around the WD SDSS J122859.93+104032.9 due to the detection of Ca II triplet emissions (at 8498.02, 8542.09, and 8662.14 Å), which are a result of Keplerian rotation in a flat disk (Horne & Marsh 1986). At least 35 dust disks (Veras et al. 2015; Rocchetto et al. 2015; and references therein) and eight gaseous disks (Gänsicke et al. 2006, 2007, 2008; Gänsicke 2011; Farihi et al. 2012; Melis et al. 2012; Wilson et al. 2014, 2015; Guo et al. 2015; Manser et al. 2016a, 2016b) around WDs have been detected. Because warm dust disks and gaseous disks are found around many polluted WDs, it is commonly accepted that accretion occurs from the debris disks. The debris disks around WDs are probably formed from the destroyed exoplanetary bodies that were perturbed into the tide volume of the host WDs due to the dynamical resettling of the planetary system (Debes & Sigurdsson 2002; Jura 2003; Zuckerman et al. 2003, 2010; Koester et al. 2014; Xu et al. 2016).

In this work, we present the discovery of a debris disk around SDSS J1344+0324 with an effective temperature above 26,000 K. The temperature of this WD is more than 3000 K higher than that of SDSS J1144+0529, implying that SDSS J1344+0324 is currently the hottest WD with a debris disk. We derived the parameters of the debris disk based on the IR excess analysis of the WD. We found that the disk around SDSS J1344+0324 is the coolest of all debris disks around WDs, and that its inner and outer radii are very close to the tide radius of SDSS J1344+0324. This suggests that the debris disk is probably newly formed from the disruption of a planetary body that was just perturbed into the tide volume of SDSS J1344+0324. This might provide evidence for the formation of debris disks around WDs. We also found that the cool debris disk around this WD displays the characteristics of a gaseous disk, as a spectrum of the WD shows emissions at the Ca II triplet. In addition, spectra observed by SDSS at different times reveal that a change in the morphology of the Ca II triplet emissions of this WD is similar to that of the objects SDSS J122859.93+104032.9, SDSS J084539.17+225728.0, and SDSS J104341.53+085558.2 (Wilson et al. 2015; Manser et al. 2016a, 2016b). This suggests that the change in the morphology of the Ca II triplet emissions of these WDs is probably a result of the same physical process, i.e., the intermittent sublimation of their debris disks and/or the newly formed eccentric debris disk proposed by Manser et al. (2016a).

2. Observational Data and Parameters

2.1. Spectral Data and Parameters

SDSS J1344+0324 was first identified as a DA WD (with only H atmosphere) by Kleinman et al. (2004), who derived its effective temperature [$T_{\rm eff}$ = 26,332(±138) K] and surface gravity [$\log g = 7.89(2)$] based on an early spectrum with Plate-MJD-Fiber (P-M-F): 0529-52025-0572 (S/N = 37.3) observed by SDSS on 2001 April 29. These spectral parameters were improved by Tremblay et al. (2011), who gave the effective temperature [$T_{\rm eff}$ = 26,420(150)K], surface gravity

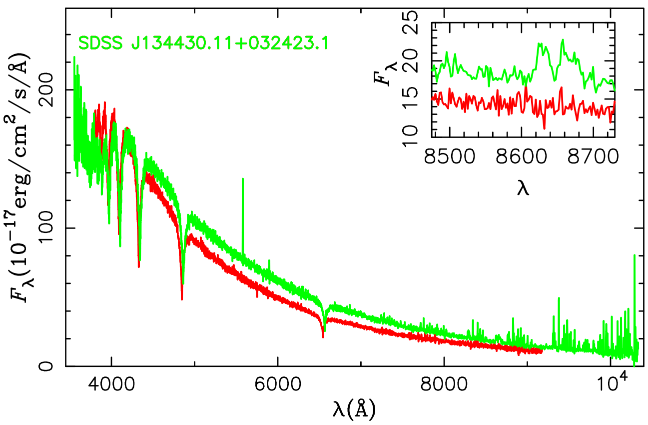


Figure 1. Spectra of SDSS J1344+0324 obtained by SDSS in 2001 (red) and 2011 (green). The Ca II triplet emissions with a double-peak profile are shown in the inset.

[$\log g = 7.85(1)$], and mass [$M_{\rm WD} = 0.56(1)M_\odot$] for this object based on the same observed spectrum as Kleinman et al. (2004). On 2011 March 31, this object was observed again by SDSS (spectrum with P-M-F: 4786-55651-0056). Both spectra of SDSS J1344+0324 are shown in Figure 1.

Based on a grid of WD model atmospheres (Koester 2010), we analyzed the spectrum (with P-M-F: 0529-52025-0572) of this object again and obtained an effective temperature [$T_{\rm eff}$ = 26,071(±163) K] and surface gravity [$\log g = 7.88(2)$]. We also analyzed a recent spectrum (with P-M-F: 4786-55651-0056) of SDSS J1344+0324 and obtained an effective temperature [$T_{\rm eff}$ = 26,057(±190) K] and surface gravity [$\log g = 7.87(2)$]. The difference between the results derived from the two SDSS spectra is very small, and the signal-to-noise ratio (S/N) of the first SDSS spectrum (with P-M-F: 0529-52025-0572) is higher than that of the recent SDSS spectrum. Because the temperature uncertainty derived from the first SDSS spectrum is smaller than that obtained more recently, the spectral parameters derived from the SDSS spectrum obtained in 2001 are used to determine the mass and cooling age of this object. Finally, we derived the mass [$M_{\rm WD} = 0.58(1)\, M_\odot$], cooling age [$\tau_c = 19.7(8)$ Myr], and radius [$R_{\rm WD} = 0.0145(2)\, R_\odot$] for this WD on the basis of a recently updated version of the cooling models (Bergeron et al. 1995). In addition, based on the well-known equation $d = \sqrt{\frac{\pi}{a}} \frac{R_{\rm WD}[R_\odot]}{1\rm pc}$ (where $a = F_{{\rm obs},\lambda}/F_{{\rm ast},\lambda}$ is a ratio of the observed spectral flux on the Earth to the astrophysical flux at the stellar surface; Heller et al. 2009), the spectroscopic distance of this object was estimated to be 271(±6) pc from the Earth. These results are in agreement with those derived by the previous investigators mentioned above. We show in the inset of Figure 1 and in Figure 2 that the recent spectrum (with a high S/N = 33.85) displays convincing emissions at the Ca II triplet, leading us to discover a debris disk around this WD.

However, the Ca II triplet emissions are almost absent in another SDSS spectrum (P-M-F: 0529-52025-0572). This suggests that the morphology of the Ca II triplet emissions is variable. This behavior also occurred in the WD SDSS J1617+1620 (Wilson et al. 2014), i.e., the Ca II triplet emissions disappeared in one of its two SDSS spectra (see Figure 2 of Wilson et al. 2014).

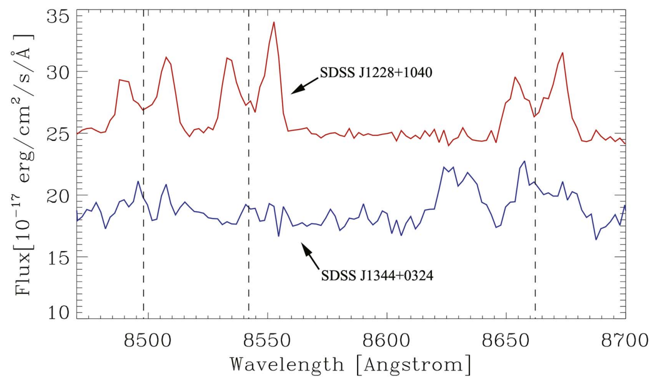


Figure 2. Spectral comparison between the SDSS J1344+0324 (blue) and SDSS J1228+1040 (red) Ca II triplet emissions. The dashed lines represent the locations of the central wavelengths of the Ca II triplet emissions.

Table 1
Photometry for SDSS J1344+0324

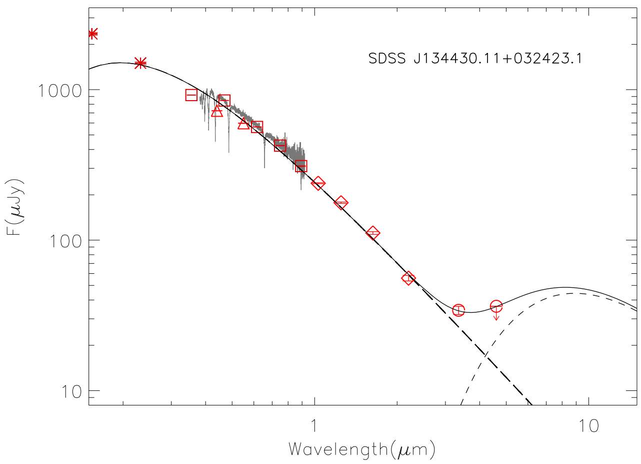
Bands	λ (μm)	Magnitude (mag)	Flux Density (μJy)
FUV	0.158	15.324(22)	2349.89(48.27)
NUV	0.227	15.924(18)	1500.37(24.98)
B	0.436	16.92(1)	723.74(2.58)
V	0.545	17.01(1)	597.76(2.35)
u'	0.3596	16.490(6)	920.45(2.91)
g'	0.4639	16.580(4)	847.23(1.77)
r'	0.6122	17.020(5)	564.94(1.61)
i'	0.7439	17.326(6)	424.62(1.53)
z'	0.8896	17.668(17)	310.46(2.20)
Y	1.02	17.319(14)	238.83(1.78)
J	1.2	17.339(22)	177.20(1.87)
H	1.6	17.394(50)	111.52(2.27)
K	2.2	17.627(110)	55.89(2.38)
W_1	3.35	17.38(14)	34.17(2.12)
W_2	4.60	16.68	36.33

2.2. Photometric Data

The optical photometry data SDSS $u'g'r'i'z'$ are obtained from SDSS DR7 (Abazajian et al. 2009), while the wide passbands *B* and *V* are taken from Zacharias et al. (2015). The near-infrared (near-IR) photometry data are taken from UKIDSS (*Y*, *J*, *H*, and *K;* Lawrence et al. 2007) and WISE (W_1 and W_2; Wright et al. 2010). The UV photometry data *FUV/NUV* for this object are found from *GALEX* (Martin et al. 2005). The magnitudes and flux densities in each passband for SDSS J1344+0324 are listed in Table 1 and the flux densities are plotted in Figure 3. As seen in Figure 3, SDSS J1344+0324 shows IR excesses from *K* to W_2, implying that a debris disk is surrounding this WD.

3. IR Excess Analysis and Results

IR excesses in WDs are usually explained by the existence of a debris disk or cool companion (a brown dwarf or planet). The parameters of the cool component (a cool debris disk or cool companion) of a WD are usually derived based on the analysis of the spectral energy distribution (SED) through a least χ^2 methods (Girven et al. 2011 and references therein). Although no uncertainty for W_2 is given due to a lower S/N of 2, the upper flux limit of W_2 is still included in our modeling. Otherwise, it



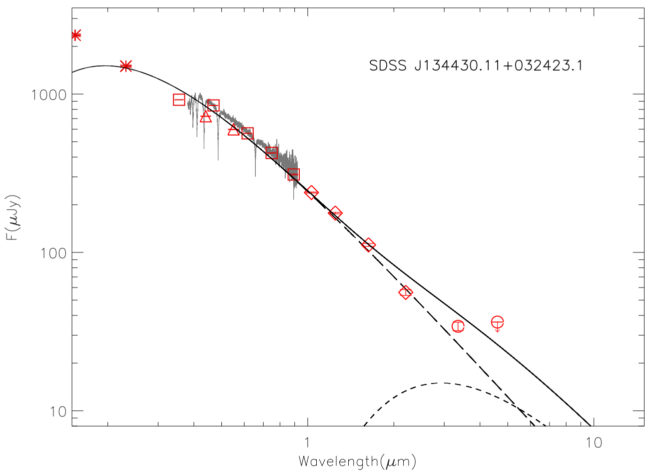


Figure 3. SED of SDSS J1344+0324. *GALEX FUV/NUV*, SDSS $u'g'r'i'z'$, *BV*, UKIDSS *YJHK*, and WISE W_1/W_2 are labeled as stars, squares, triangles, diamonds, and open dots, respectively. Top panel: a DA WD plus a debris disk. Bottom panel: a DA WD plus a low-mass companion. The long-dashed line represents the blackbody spectrum of the WD, the short-dashed line indicates the blackbody spectrum of the cool component (a debris disk or cool companion), and the solid line represents the best-fitting models of the DA plus a cool component.

would lead to an impossible structure for the debris disk in SDSS J1344+0324 in which both the inner and outer radii were much larger than the tide radius of the object, and the particles in the debris disk would coagulate into moons, asteroids, or planets (von Hippel et al. 2007). The best-fitting models for SDSS J1344+0324 are plotted in Figure 3. The top panel of Figure 3 shows a best-fitting disk model (within 3σ) with an inner disk temperature of 606 K, an outer temperature of 539 K, and an inclination of 22°. This corresponds to the inner and outer radii of 89.9 $R_{\rm WD}$ (1.30 $R_\odot$) and 104.9 $R_{\rm WD}$ (1.52 $R_\odot$) and the minimum $\chi^2 = 3.40$. This suggests that the debris disk around SDSS J1344+0324 is the coolest of all known debris disks and that it is very narrow (only 0.22 $R_\odot$), implying that it is probably newly formed from a destroyed planetary body that was just perturbed in the tide volume of SDSS J1344+0324.

In order to further determine the properties of the cool component of SDSS J1344+0324, we fitted the SED of this WD by using models with a WD plus a cool companion (a brown dwarf or planet). The bottom panel of Figure 3 shows a best-fitting model with an early-L (L3–L4) spectral type companion (corresponding to $T_{\rm eff,c} = 1739$ K and $R_{\rm c} = 0.083$ $R_\odot$) and the minimum $\chi^2 = 3.41$. Although the minimum χ^2 for the best model with a cool companion is slightly larger than that of the best one with a debris disk mentioned above, we cannot fully rule out the possibility that this WD is surrounded by a cool companion. However, the cool component of SDSS J1344+0324 should be a debris disk rather than a cool companion because of the morphology of its Ca II triplet emissions with a double-peak profile (see Figure 2). Some physical parameters of this WD, together with the WDs with gaseous disks, are listed in Table 2.

4. Discussion and Conclusions

In this work, we present the discovery of a cool debris disk around the hot WD SDSS J1344+0324 and find that the effective temperature ($T_{\rm eff}$) of the WD is 26,071($\pm$163) K. This is more than 3000 K higher than the temperature of SDSS J1144+0529, which was found to be the hottest WD with a gaseous disk by Guo et al. (2015). Therefore, SDSS J1344+0324 is currently the hottest of all WDs with a debris disk (see Table 2).

The tide radius of a WD can be written as $R_{\rm tide} \sim 1.5 C_{\rm tide}\, R_\odot$ (Jura 2003 and references therein), where $C_{\rm tide}$ is a numerical constant of order unity, implying that the tide radius of SDSS J1344+0324 is about 1.5 $R_\odot$. The inner and outer radii of the debris disk around SDSS J1344+0324 were derived to be 1.30 $R_\odot$ and 1.52 $R_\odot$, respectively, and they are close to the tide radius of SDSS J1344+0324. Therefore, the debris disk might have formed from a destroyed planetary body that was recently perturbed into the tide volume of SDSS J1344+0324 owing to dynamic resettling of the planetary systems. This debris disk is very narrow (about 0.22 $R_\odot$) and may be newly formed. This might provide strong evidence that the debris disks around WDs are formed from the disruption of a planetary companion.

Although the model with a debris disk around the WD reproduced the SED of SDSS J1344+0324 slightly better than that with a cool companion, we cannot conclude that the cool component around this WD is a debris disk, as the difference between the results for the two cases is too small. However, IR excesses in this object should be caused by a debris disk, since this is consistent with the observation that a spectrum (P-M-F: 4786-55651-0056) for SDSS J1344+0324 shows obvious Ca II triplet emissions with a double-peak profile (see Figure 2). The best-fitting disk model has $T_{\rm in} = 606$ K and $T_{\rm out} = 539$ K. This is the coolest of all debris disks that have been found around WDs.

In addition, the question of why such a cool debris disk shows the properties of a gaseous disk in SDSS J1344+0324 warrants further study. According to von Hippel et al. (2007), the sublimation radius of this WD is estimated to be about 1.67 $R_\odot$ by assuming $T_{\rm sub} = 2000$ K and $\lambda_0 = 1\ \mu$m. It is larger than the outer radius of the debris disk around SDSS J1344+0324; however, the sublimation radius might be smaller than the estimated value if the size of the grains in this newly formed disk is larger than 1 μm. Although the inner-rim temperature of all debris disks is much lower than 2000 K (see Table 1 of von Hippel et al. 2007), how can the temperature of the inner disk be so much cooler? There are two possible explanations for this phenomenon. One is the sublimation of a part of the dusty disk, as the sublimation of the materials in the debris disk must dissipate a large amount of heat energy to decrease the temperature of its inner disk. Another is that the

Table 2
Parameters of WDs with Ca II Triplet Emissions from a Gaseous Disk

Stars	T_{eff} (K)	log g (cgs)	M_{WD} ($M_\odot$)	R_{WD} ($R_\odot$)	Cooling Age (Myr)	References
SDSS J0738+1835	13950(100)	8.4(2)	0.84(13)	0.0096(15)	447(160)	1
SDSS J0845+2257	19780(250)	8.18(20)	0.73(11)	0.011	122(44)	2
SDSS J0959-0200	13280(20)	8.06(3)	0.64(2)	0.013	324(17)	3, 4
SDSS J1043+0855	17879(195)	8.124(33)	0.693(20)	0.0120(3)	153(10)	5, 6, 7
SDSS J1144+0529	23027(219)	7.74(3)	0.49(3)	0.016	21.2(1.9)	8
SDSS J1228+1040	20713(281)	8.150(89)	0.705(51)	0.0117(8)	100(5)	6, 9, 10, 11, 12
SDSS J1617+1620	13520(200)	8.11(8)	0.68(5)	0.0120(7)	350(50)	13
HE 1349-2305	18173	8.133	0.673	0.012	149.4	14, 15, 16
SDSS J1344+0324	26,071(163)	7.88(2)	0.58(1)	0.0145(2)	19.7(8)	this paper

References. (1) Dufour et al. (2012), (2) Wilson et al. (2015), (3) Farihi et al. (2012), (4) Xu & Jura (2014), (5) Gänsicke et al. (2007), (6) Melis et al. (2010), (7) Manser et al. (2016a), (8) Guo et al. (2015), (9) Gänsicke et al. (2006), (10) Gänsicke et al. (2012), (11) Koester et al. (2014), (12) Manser et al. (2016b), (13) Wilson et al. (2014), (14) Koester et al. (2005), (15) Voss et al. (2007), (16) Melis et al. (2012).

debris disk around SDSS J1344+0324 is a young one that still has an eccentric orbit and has not fully circularized (Manser et al. 2016a), so the average temperature of the inner-disk rim might become lower. Therefore, the variable Ca II triplet emissions could be a result of the intermittent sublimation of this cold debris disk and/or a newly formed eccentric debris disk (Manser et al. 2016a).

Two spectra obtained by SDSS show that SDSS J1344+0324 is similar to SDSS J1617+1620 in its variable near-IR Ca II triplet emissions. In addition, the near-IR Ca II triplet emissions sometimes disappear in their spectra. In the future, we would monitor the long-term spectral variation of SDSS J1344+0324 to study in detail the physical process that results in the variability of the Ca II triplet emissions.

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