NEAR-ULTRAVIOLET AND OPTICAL EFFECTS OF DEBRIS DISKS AROUND WHITE DWARFS

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Received 2009 June 4; accepted 2009 September 17; published 2009 September 30

ABSTRACT

Studies of debris disks around white dwarfs (WDs) have focused on infrared wavelengths because debris disks are much colder than the star and are believed to contribute to the spectrum only at longer wavelengths. Nevertheless, these disks are made of dust grains that absorb and scatter near-UV and optical photons from the WD, leaving a fingerprint that can be used to further constrain disk properties. Our goal is to show that it is possible to detect near-UV and optical effects of debris disks in the star + disk integrated spectrum. We make theoretical calculations and discuss the necessary observational conditions to detect the near-UV and optical effects. We show how these effects can be used to infer the disk mass, composition, optical depth, and inclination relative to the line of sight. If the IR excess is due to a disk, then near-UV and optical effects should be observed in only some systems, not all of them, while for dust shells the effects should be observed in all systems.

Key words: circumstellar matter – white dwarfs

1. INTRODUCTION

White dwarfs (WDs) are degenerate stellar nuclei with a mass roughly that of the Sun and radii one hundredth that of the Sun; consequently, their surface gravity is $\sim 10^4$ greater than the Sun’s. Liebert (1984) identified some odd WDs with metal-rich atmospheres. With such a powerful gravity pulling the chemical elements toward the stellar nucleus, it is somewhat unusual to have a metal-rich atmosphere. In fact, the timescales for an element heavier than hydrogen or helium to sink to the center of a WD are small: $\sim 10^2$ yr in WDs with hydrogen atmospheres (DAs) and $\sim 10^3$ yr with helium atmospheres (DBs) (Jura 2008; von Hippel & Thompson 2007; Paquette et al. 1986).

Interstellar material accretion onto the WD surface was one of the first explanations for the metal-rich atmospheres. Knowing the diffusion timescales of metals in the stellar atmospheres and the metallicity of a given star, it is possible to calculate the necessary accretion rate to keep this metallicity constant in time (Koester & Wilken 2006). Typical values are $10^{-18}$ to $10^{-15} M_{\odot}$ yr$^{-1}$. These values are too high to be explained exclusively by interstellar accretion. Furthermore, if there were accretion from the interstellar medium onto the DBs, there should be a large amount of hydrogen pollution in their spectra, but this pollution has not been detected (Dupuis et al. 1993; Farihi et al. 2008).

Zuckerman & Becklin (1987) observed an IR excess in the spectrum of G29-38. The shape of this IR excess is a bump that peaks at $\sim 10 \mu$m. Its width is roughly $20 \mu$m and can be fitted with a blackbody of $T_{\text{eff}} \sim 10^3$ K. Graham et al. (1990) argued that an asteroid closely approaching G29-38 could explain this infrared excess. When the asteroid orbit reaches the Roche radius it is disrupted and forms a disk around the star. This disk is heated up by the stellar radiation and emits in the infrared. The disk material falls down continuously on the WD giving rise to the observed metal-rich atmospheres.

Using a disk model, Jura & collaborators (Jura 2003; Jura et al. 2007a, 2007b; Jura 2008) were able to fit the IR excess of many WDs. Through these fits they determined disk physical parameters. With a different approach, Reach et al. (2005) fit the spectrum to a thin dust shell model.

While searching for interacting binary WDs, Gänsicke et al. (2006, 2007, 2008) observed double peaks in calcium lines in a few DAZs and DBZs. Although these observations strongly suggest the disk hypothesis, it is still possible that in some cases the emitting region could be a torus or a shell (Reach et al. 2009) rather than a disk.

Previous works focused on the IR emission properties of debris disks around the WD. In this work, we propose a new and complementary observational test looking at the absorption and scattering properties instead. We develop a simple theoretical framework to predict what will be observable and measurable according to the properties of the system. We also suggest an observational program to reach our goal.

We investigate the possibility of detection of debris disks’ effects in the near-UV and optical. We start the analysis in the limit of an optically thick disk in Section 2 and in Section 3 we extend this to the optically thin limit case. In Section 4, we discuss the observational predictions of our models. Our conclusions are presented in Section 5.

2. OPAQUE DISK

The optically thick limit is the natural first approach to investigating the possible effects of a debris disk in the spectrum of a WD. This limit can be achieved not only in massive disks but also in certain regions of all disks especially if the disk has some gas like some recently discovered gaseous disks (Gänsicke et al. 2006, 2007, 2008). Also, the mathematical treatment developed in this section will be used in the next section when dealing with the optically thin limit.

A completely opaque disk will not have any spectral features because it is totally opaque and absorbs any photon whatever its energy. The only effect of an obscuring disk will be a decrease in the received flux from the star. The most the disk can obscure the star is half of the projected stellar surface, $\pi R_{\text{WD}}^2/2$. The increase in the apparent magnitude of the star will be 0.75 mag.

This value is much higher than current photometric accuracy, and if present, would have been detected for those WDs that have an observed parallax, a good spectrum, and an IR excess. The “good spectrum” permits a determination of $T_{\text{eff}}$ and log $g$ and hence a luminosity. Clearly, the luminosity inferred from the parallax should agree with the luminosity inferred from the spectral fit. At the very least, this procedure will allow us to affirm that there is not a big opaque disk in the known WDs with IR excess or, at least, this disk is not in a favorable inclination.
The stellar radius is $R_\star$ where we assumed that the intensity ($\phi_i$) of the disk. The angles $\phi_i$ and $\phi_e$ show where the disk starts and stops obscuring the star.

For the general case of a disk with arbitrary inclination and any combination of inner and outer radii, the flux received at the Earth from the system (target) is

$$F_{\text{target}} = \int_{\Omega_{\text{tot}}} I \cos \theta d\Omega = I \left( \frac{R_\star}{D} \right)^2 \int_0^{\pi/2} \int_{\phi_{\text{min}}}^{\phi_{\text{max}}} \sin \theta \cos \phi d\phi d\theta, \quad (1)$$

where we assumed that the intensity ($I$) is uniform over the stellar surface. The stellar radius is $R_\star$ and $D$ is the distance from the Earth to the system. There are three possible projections for the disk, as seen in Figure 1. This gives different values of $\phi_{\text{min}}$ and $\phi_{\text{max}}$:

1. $\int_{\phi_{\text{min}}}^{\phi_{\text{max}}} d\phi = 2 \left[ \int_{-\pi/2}^{\phi_{\text{max}}} d\phi + \int_{\phi_{\text{max}}}^{\pi/2} d\phi \right] = 2\pi - 2(\phi_e - \phi_i)$,
2. $\int_{\phi_{\text{min}}}^{\phi_{\text{max}}} d\phi = 2 \int_{-\phi_{\text{max}}}^{\phi_{\text{min}}} d\phi = \pi + 2\phi_i$,
3. $\int_{\phi_{\text{min}}}^{\phi_{\text{max}}} d\phi = 2 \int_{-\pi/2}^{\phi_{\text{min}}} d\phi = 2\pi$.

Using the dimensionless radii $r_{i,e} = R_{i,e}/R_\star$, we define the function $g \equiv g(\theta, r_i, r_e)$:

$$g = \begin{cases} \pi - (\phi_e - \phi_i), & r_e \cos i < \sin \theta \\
\pi/2 + \phi_i, & r_i \cos i < \sin \theta \\
\phi_i, & r_i \cos i \geq \sin \theta 
\end{cases} \quad (2)$$

and write the flux

$$F_{\text{target}} = I \left( \frac{R_\star}{D} \right)^2 \int_0^{\pi/2} \sin(2\theta)g(\theta, r_i, r_e)d\theta, \quad (3)$$

where

$$\phi_{i,e} = \arctan \left( \sqrt{\sin^2 \theta - r_{i,e}^2 \cos^2 i} \right) / \sin i. \quad (4)$$

The total flux received from an unobscured system is $\pi I (R_\star/D)^2$. We call the hypothetical unobscured star “template” and the obscured star “target.” Defining $p$ as the ratio of the obscured to the total projected area:

$$p \equiv \frac{A_{\text{obsured}}}{A_{\text{total}}} = \frac{A_{\text{target}}}{A_{\text{template}},} \quad (5)$$

we write the increase in magnitude as

$$\Delta m = -2.5 \log(1 - p). \quad (6)$$

In the completely opaque hypothesis, we may obviously write that

$$p = \frac{F_{\text{target}}}{F_{\text{template}}} = \frac{F_{\text{target}}}{\pi I} \left( \frac{D}{R_\star} \right)^2 \quad (7)$$

The solution of Equation (7) with Equations (2) and (4) gives the flux received from the system, as can been seen in Figure 2. The probability of finding a system more inclined than a given angle is the ratio of the solid angle occupied by these systems to the total solid angle: $P(i > i_0) = \cos i_0$.

Figure 2 shows that it is possible to detect a completely opaque debris disk. For an inclination angle causing any blocking, the bigger the disk is, the easier it is to detect the effect. The inner and outer radii are based on physical constrains. If the inner radius is small, the dust particles sublimate because the temperature exceeds $\sim 1200$ K (Jura et al. 2007a). On the other hand, if the outer edge of the disk is big ($\gtrsim 100$ $R_{\text{wd}}$), the dust grains will be cold and any emission will be undetectable in practice. The exact values depend on the dust type and grain size.

The presence of an obscuring disk might be inferred by comparing the expected increase in stellar magnitude with the luminosity derived from $T_{\text{eff}}$ and $\log g$ and parallax. If the observed and the expected magnitudes are correct and not equal, the flux deficiency can probably be explained by obscuration from a debris disk.

We use the measured parallax of GD 362 to illustrate the previous analysis with one real case. Kilic et al. (2008) obtained $d = 50.6^{+3.5}_{-3.0}$ pc for GD 362. Using simple error propagation, we have a rough estimate for the highest acceptable difference between expected and measured magnitude: $\sigma_m \approx 0.15$ mag.
Kilic et al. (2008) did not find any discrepancies between parallax and flux, implying no obscuration of the star. From a geometrical perspective this is expected since from Figure 2 $\Delta m \approx 0.15$ mag implies an inclination higher than $\sim 80^\circ$ and less than $\sim 20\%$ of the systems will be more inclined than this. Indeed, Jura et al. (2007b) showed that GD 362 must be seen nearly face on to be able to reproduce its IR excess flux with physically reasonable inner and outer radii. Assuming an almost edge on system would require a big disk and an unusual mechanism to heat it to reproduce the measured IR excess flux. Therefore, our work is in agreement with the previous results and this analysis illustrates what kind of study must be done with other systems that may be found to be nearly edge on.

3. OPTICALLY THIN DUST DISK

After having derived the basic concepts of the problem with the optically thick limit we generalize the equations to the optically thin limit. The ratio ($\xi_v$) of the flux from obscured (target) to the equivalent star with no obscuration (template) is composed of three main components:

$$\xi_v \equiv \frac{F^\text{target}}{F^\text{template}} = \xi_v|\text{unobscured} + \xi_v|\text{obscured} + \xi_v|\text{scattered}. \quad (8)$$

The unobscured ratio component is simply $1 - p$. The obscured ratio is given by $p e^{-\tau_v|\text{scattered}}$. The extinction optical depth $\tau_v$ of the disk regions obscuring the star accounts for the absorbed and scattered light along the line of sight to the star. The scattered component comes from the disk regions which do not obscure the star but scatter photons to the line of sight. There is no emission component because the dust temperature is lower than the dust sublimation temperature ($\sim 1200$ K) and thus the dust emission only contributes in the infrared.

Using the dimensionless extinction efficiency ($Q^\text{ext}_v$) instead of extinction cross section ($|C^\text{ext}_v| = \text{cm}^2$) we write the differential extinction optical depth in the disk as

$$d\tau_v = nC^\text{ext}_v dz = n Q^\text{ext}_v \pi a^2 dz, \quad (9)$$

where $n$ (cm$^{-3}$) is the number of dust grains per unit volume, $a$ (cm) is the grain radius, and $z$ (cm) is the vertical dimension of the disk. The disk volume density ($\rho$) is related to the density of a typical dust grain ($\rho_d$) through

$$\rho = \frac{4}{3} \pi a^3 \rho_d n. \quad (10)$$

Assuming the disk to be vertically uniform we integrate to write

$$\tau_v^\text{ext} = \int_{-H/2}^{H/2} \frac{Q^\text{ext}_v \rho}{4a\rho_d} dz = \frac{3Q^\text{ext}_v}{4a\rho_d} H = \frac{3Q^\text{ext}_v}{4a\rho_d} \Sigma, \quad (11)$$

where $\Sigma$ (g cm$^{-2}$) is the disk surface density and $H$ is the disk height.

We define

$$\tau_0 = \frac{3\Sigma}{4a\rho_d} \quad (12)$$

and write Equation (8) as

$$\xi_v = (1 - p) + p e^{-\tau_0 Q^\text{ext}_v \cos i} + \xi_v|\text{scattered}. \quad (13)$$

To simplify the scattering term, we assume isotropic and coherent scattering and also that the light is not attenuated before and after being scattered by the disk. The last hypothesis is valid in the optically thin case and causes an overestimation of the scattering because we ignore the absorbed photons. The scattered intensity is given by

$$I^\text{sca}_v = \epsilon_v \frac{H}{\cos i} = \pi a^2 Q^\text{sca}_v n J^\text{wd} \frac{H}{\cos i}, \quad (14)$$

where $\epsilon_v$ is the emissivity, $Q^\text{sca}_v$ is the scattering efficiency and $J^\text{wd}$ is the mean stellar intensity

$$J^\text{wd} = I^\text{wd} \frac{\pi R^2_{wd}}{4\pi r^2}. \quad (15)$$

Ignoring the disk regions hidden by the star we integrate over the disk surface to obtain the flux

$$F_v = \frac{3\Sigma}{2} Q^\text{sca}_v \ln \left(\frac{r_e}{r_I}\right) \cos i \pi I^\text{wd} \left(\frac{R_{wd}}{D}\right)^2 \quad (16)$$

using Equation (12) and dividing by the template flux,

$$\xi_v|\text{scattered} = \frac{1}{2} \tau_0 Q^\text{sca}_v \ln \left(\frac{r_e}{r_I}\right) \cos i, \quad (17)$$

which allows us to write Equation (13) as

$$\xi_v = (1 - p) + p e^{-\tau_0 Q^\text{ext}_v \cos i} + \frac{1}{2} \tau_0 Q^\text{sca}_v \ln \left(\frac{r_e}{r_I}\right) \cos i. \quad (18)$$

Besides the parameters $p$ and $\tau_0$, we have the absorption efficiencies which are characteristic of the dust type. We used the tables of optical constants of silicate glasses from Dorschner et al. (1995). The authors prepared two different glasses in the laboratory: pyroxene, Mg$_6$Fe$_{1-x}$SiO$_3$, with $x = 0.4$, 0.5, 0.6,
0.7, 0.8, 0.95, 1.0 and olivine, Mg$_2x$Fe$_{2-2x}$SiO$_4$, with $x = 0.4$ and 0.5.

Figures 3 and 4 display the results from Equation (18) for different optical depths and system geometries. Figure 3 represents inclinations where the disk obscures the star, and light is absorbed and Figure 4 when there is no obscuration and we see only scattering plus the stellar light. For observational tests, the region from 3000 Å to 5000 Å is the most interesting, because it shows a sharp change in the ratio between the target and the template which cannot be easily discarded as bad flux calibrations.

4. OBSERVATIONAL TEST

Our modeling gives rise to direct observational tests. We can test the effects of the disk in the near-UV and the optical, dividing the spectrum of the target by the template. In the optically thin case, the result will be color dependent and can provide physical parameters for the disk structure.

The template star should be as similar to the target star as possible. Ideally, it would be the same WD without the obscuring disk. As that is not possible to have, we need a similar WD without any peculiarity in the spectrum. Any other WD will differ from the target star in $T_{\text{eff}}$ and $\log g$ and this difference can make the division of the spectra resemble the expected disk effects.

In Figure 5, we present these effects using theoretical WD spectra from Koester (2008). We assume a target star of $T_{\text{eff}} = 12,000$ K and $\log g = 8.0$, similar to G29-38 (Reach et al. 2009). In the upper panel, we keep $T_{\text{eff}}$ fixed and vary $\log g$ by 0.05 dex and in the lower we keep $\log g$ fixed and vary $T_{\text{eff}}$ by 150 K. According to Liebert et al. (2005), the uncertainties in temperature are of the order of 1.2% $\approx$ 150 K and 0.038 in $\log g$. So, larger temperature or $\log g$ differences would be readily noticed. One can see from Figure 5 that modification of UV flux densities by disks that absorb or scatter light, as in Figures 3 and 4, can be distinguished from observational uncertainties in template stars.

The White Dwarf Catalog (McCook & Sion 1999) currently lists 12,456 stars. Therefore, it is not too hard to find a template star with a temperature similar to the target. As an example, G29-38 and Ross 548 have exactly the same temperature and $\log g$. One needs to be careful about this comparison as these values of $T_{\text{eff}}$ and $\log g$ were obtained from different determinations. When comparing the target with the template it will be necessary to use $T_{\text{eff}}$ and $\log g$ obtained from similar data and the same models.

4.1. Parameter Determination

It is difficult to compare directly the definition of $p$ and $\tau_0$ with the expected values for real disks. We use disk parameters obtained in earlier works to give observational expectations and also to help design future observations.

For disks, the fraction of the obscured to the total projected area, $p$ (Equation (5)), varies between 0 when there is no obscuration and 0.5 for a disk which obscures half of the stellar surface. However, if the infrared emission region is not a disk but a shell around the star (Reach et al. 2005) $p$ will be always 1.
Hence, this work provides an independent method for testing the disk hypothesis. In addition to $p$, we can also determine $\tau_0$. Estimates for the expected values are more uncertain, but we can get a rough idea by using some mean values for the dust and disk properties. Krügel (2003) gives $2.5 \text{ g cm}^{-3}$ as a typical value for the interstellar dust and we assume it as a good order of magnitude value for the dust in the disk. Jura et al. (2007b) constrain the disk mass of GD 362 between $10^{18}$ and $10^{24}$ g. Using typical disk sizes of $10 R_{\text{wd}}$ and $100 R_{\text{wd}}$ for the inner and outer disk radii, respectively, we get a range of $\tau_0$ from $10^{-4}$ to somewhat greater than 1, depending on the disk mass and the type of dust (Dorschner et al. 1995). Therefore, the parameters used in Figure 3 are realistic.

The disk inclination angle can be inferred from the presence of a flux excess due to scattering into the line of sight. Figure 4 shows this for inclinations of 0° and 60°. Flux excess in near-UV has already been detected by Gänscicke et al. (2006) in SDSS 1228+1040 and could be caused by light scattering. For larger inclinations there is a flux deficiency due to absorption and scattering out the line of sight, as shown in Figure 3 computed for $i = 85^\circ$. The dividing line between the first or the second case is $\sim 80^\circ$.

5. CONCLUSIONS

In this work, we introduce a new way of looking at the cause of IR excess in white dwarf stars. By looking in the near-UV and optical instead of IR we add a new constraint to test the disk hypothesis.

One important distinction of our method is the fact that the presence of disks would cause flux deficiencies in some systems and flux excess in others. We also point out that shells would only introduce flux deficiencies effects, and these effects would be detectable in all shells. If we find flux deficiencies in every star we observe this would strongly indicate the presence of shells rather than disks. Flux deficiencies in only some objects and flux excess in others corroborate the idea of a disk.

If we are convinced disk models are more adequate, detailed comparisons between disk models and data will provide disk mass (Jura et al. 2007b), composition, optical depth and inclination relative to the line of sight.

The authors acknowledge financial support from CNPq-MCT/Brazil. We thank Paola D’Alessio, Detlev Koester, and Don Winget for helpful discussions, William Reach for providing data, and Shashi Kanbur for reading the manuscript. We are also grateful to Nikolai Voshchinnikov for his Mic-Theory program. Finally, we thank the anonymous referee for helpful comments on the paper.

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