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Supporting Online Material for

A Gaseous Metal Disk Around a White Dwarf

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A gaseous metal disk around a white dwarf

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1 A dynamical model for the emission of a rotating gas ring

The SDSS spectroscopy of the white dwarf SDSS1228+1040 presented in the main paper gave reasons to believe that the Ca II emission line profiles observed in the $I-$band are are from a circumstellar gas disk. Here we outline the model we developed to fit the Ca II line profiles. It is apparent that there must be some form of asymmetry at work as the peaks of the line profiles are asymmetrical. The shape is very reminiscent of the "V/R" (violet/red) asymmetries seen in the emission line profiles of B-type emission line stars *(S1–S3)* . These are ascribed to a one-armed spiral wave which can be approximately modelled with a series of elliptical orbits. Drawing upon this analogy, we modelled the profiles of SDSS 1228+1040 by assuming that the orbits in the disk took the form of a series of co-aligned elliptical orbits of identical eccentricity. We further allowed the emission-line flux per unit area from the disk to vary as $1+\varepsilon\cos\theta$ where θ is the angle from periastron and ε is a measure of the asymmetry. A less obvious feature of the emission line profiles of Fig. 3 is that they are fainter at line centre relative to the double-peaks than can be explained by optically-thin line emission. That they are optically thick is also strongly suggested by the relatively equal line strengths within the Ca II triplet, even though Ca II 850 nm has only one tenth the oscillator strength of Ca II 854 nm. We therefore turned to the formalism of Horne & Marsh *(S4)* for optically thick line formation in which emission from any point in the disk takes on an azimuthal asymmetry owing to the local velocity shear, with strongest emission along the four directions at 45° to the radial direction and weakest emission in the radial direction and in the direction of gas flow. This has the effect of deepening the central dip between the line peaks. We had to modify the prescription of Horne & Marsh *(S4)* slightly to allow for elliptical as opposed to circular motion, although the effect overall was weak, since the ellipticity implied by the data was small.

Apart from an arbitrary normalisation factor, the following parameters were needed to specify the model fully: (a) $M_{\rm W} = 0.75$, the mass of white dwarf which determines the relation between orbital radius and speed, (b) $e = 0.021$, the eccentricity, (c) the angle of the periastron to our line-of-sight, defined so that at 0° we look along the major-axes from peri- towards apastron, while at 90° we look along the minor axis with the periastron emission red-shifted,

(d) inner semi-major axis $a_{\mathrm{in}} = 0.64\,\mathrm{R}_{\odot}$, (e) outer semi-major axis $a_{\mathrm{out}} = 1.2\,\mathrm{R}_{\odot}$, (f) exponent of the radial power law used to set the emissivity $\propto r^{\alpha}$ where $\alpha = -0.9$, (g) an optical depth parameter $Q' = 2.5$, analogous to the combination $Q \sin i \tan i$ from Horne & Marsh *(S4)*. Since $Q \sim 1$, this suggests that the orbital inclination $i \sim 70^{\circ}$, and finally (h) the azimuthal asymmetry factor mentioned above with value $\varepsilon = -0.19$. All parameters other than the mass of the white dwarf were allowed to vary. Experience from similar line profiles in cataclysmic variable stars suggests that systematic effects rather than statistical errors dominate, and the fit in this case, while qualitatively reasonable, is not a statistically good match to the data. Therefore we refrain from giving formal confidence intervals, but instead discuss which features in the data lead to constraints on these parameters to help the reader evaluate our model.

Apart from the allowance for optical depth, we made no allowance for inclination because its only effect is to scale the velocities in proportion to $\sin i$. This scaling can be counter-balanced by re-scaling the major-axis parameters a_{in} and a_{out} such that $a \propto \sin^2 i$. Thus the value of the outer semi-major axis $a_{out} = 1.2\,\mathrm{R}_{\odot}$, which is almost the outer radius since the eccentricity is small, is an upper limit to the real value. Since the optical depth parameter (which comes from the depth of central dip in the profiles) points to a large inclination, we believe this to be close to the true value, with a likely range of order 0.9 to $1.2\,\mathrm{R}_{\odot}$; this is quite robust as the outer major-axis limit is set by the velocities of the line peaks which are well-defined. An interesting feature of our model is that we also require a fairly large inner semi-major axis $a_{in} = 0.64\,\mathrm{R}_{\odot}$, which is subject to the same inclination uncertainties as a_{in}, but also additional uncertainty owing to correlation with parameter (f), the emissivity power law exponent. The inner cut-off is required to fit the steep drop-off in the line wings; this presumably reflects an absence of emission rather than an absence of material given the presence of metals in the white dwarf's photosphere. It could be caused, for instance, by ionisation of the Ca II ions close to the white dwarf.

The eccentricity, periastron angle and azimuthal asymmetry parameters are necessary because of the asymmetry of the profiles. The exact nature of the asymmetry is uncertain and thus we regard these parameters as the least reliable, although there is no doubt of the asymmetry. If our interpretation in terms of eccentric orbits contributing to a one-armed spiral is correct, further observations of the object are of considerable interest for we expect such orbits to precess. The asymmetries in Be stars precess within the distorted gravitational fields of the rapidly rotating stars for instance on decade-long timescales. The narrow photospheric Mg II absorption line shows that SDSS 1228+1040 is not rapidly rotating, but general relativity alone implies a precession rate of order 5° per year in the orientation of the outermost elliptical orbits, and pressure effects within the disk could contribute as well and may indeed be much more significant *(S5)*. Such precession effects must be computed within the framework of fluid disk models since the precession rate is a strong function of radius and would be expected to randomise the orbit orientations if fluid effects were not taken into account; the Be stars are proof that it is possible for similar asymmetries to persist over long timescales (years to decades).

Our data do not directly constrain the thickness of the disk, but we can argue that it must be thin as follows: LTE (local thermodynamic equilibrium) models of the disk suggest a temperature of around 4500 to 5500 K for the disk. Any hotter and numerous metal lines that are not observed start to appear, while any colder and the Fe II lines disappear. The sound speed, assuming dominance by CNO elements in the absence of hydrogen and helium, is of order $C_S = 2\,\mathrm{km\,s^{-1}}$. The thickness of the disk is then of order $H = (C_S/V_{\mathrm{Orb}})R$ where V_{Orb} is the orbital velocity at radius R in the disk *(S6)* (*6*). This works out at $\sim 0.005\,\mathrm{R}_{\odot}$, comparable to the size of the white dwarf. The same LTE models place a weak lower limit on the Ca II/H ratio which must be > 3 times solar; the data in hand are consistent with no hydrogen at all.

2 An investigation of white dwarfs in the SDSS

We have investigated all white dwarfs with hydrogen-dominated atmospheres brighter than $g = 17.5$ contained in Data Release 4 of the Sloan Digital Sky Survey (SDSS) *(S7)* (*7*) for signs of either photospheric metal absorption lines or Ca II emission in the I-band. Because the SDSS spectroscopy has a relatively low spectral resolution ($\lambda/\Delta\lambda \simeq 1800$), the detection of metal lines is limited to relatively high abundances such as observed in SDSS 1228+1040. We have not identified any additional white dwarf which exhibits significant metal absorption. The detection of Ca II emission with equivalent width comparable to the lines detected in SDSS 1228+1040 is robust for spectra in the considered magnitude range. However, we have identified only one additional white dwarf which shows flux excess in the region of the Ca II triplet (SDSS J104341.53+085558.2, Fig. S1). The equivalent width of the Ca II triplet in SDSS 1043+0855 is a factor three lower than in SDSS 1228+1040, and its SDSS spectrum suffers from strong residuals from imperfect night sky line subtraction in the I-band. A spectral fit to the SDSS spectrum of SDSS 1043+0855 results in a temperature of 18900 ± 300 K and a surface gravity of $\log g = 8.2 \pm 0.1$, similar to the parameters found for SDSS 1228+1040.

Circumstellar metal disks are most likely to be found around white dwarfs with substantial metal abundances. Published spectroscopy of known metal-polluted white dwarfs with temperatures in excess of 15 000 K does typically not cover the red end of the optical wavelength range (e.g. *S8*), and an assessment of the frequency of circumstellar gas disks will require a systematic survey of these stars.

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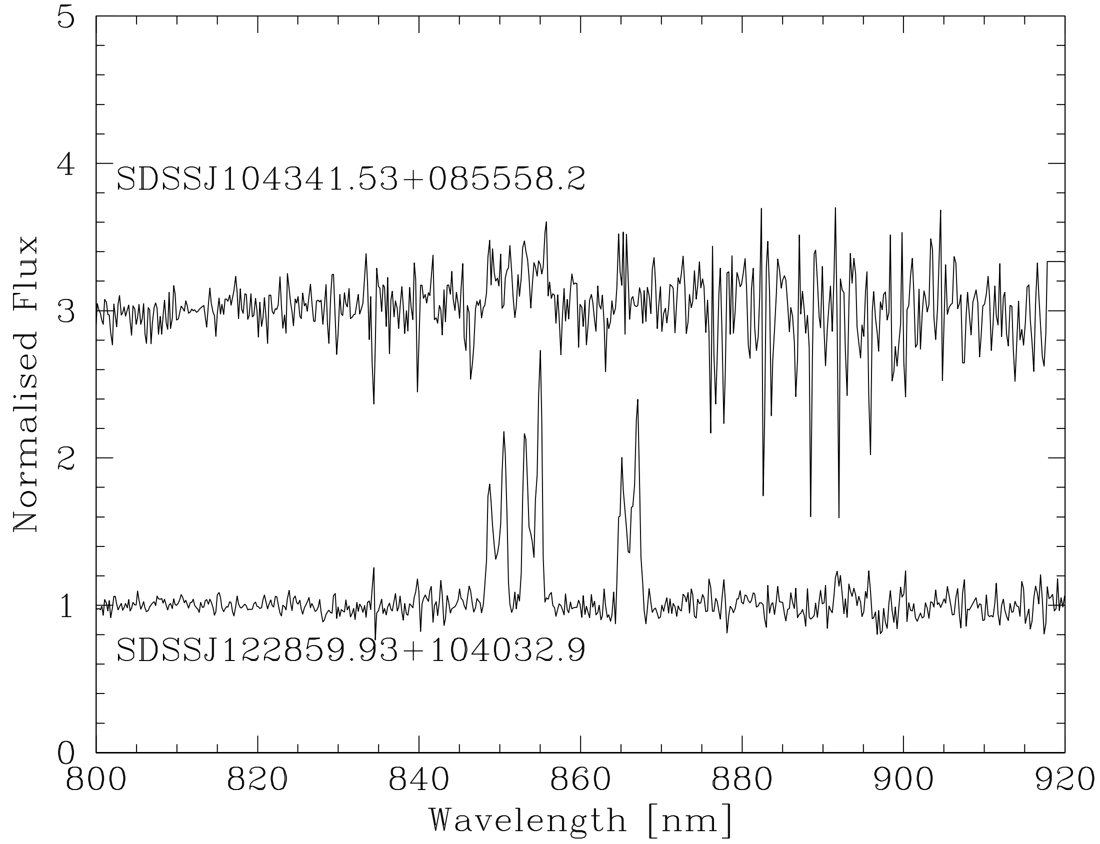

Supporting Figure 1. Normalised spectra of SDSS 1228+1040 and SDSS 1043+0855, the only other white dwarf among the brightest 406 hydrogen-dominated white dwarfs in Data Release 4 of the SDSS that exhibits excess emission in the region of the Ca II triplet. The spectrum of SDSS 1043+0855 has been offset by two units. The large amount of noise in the spectrum of SDSS 1043+0855 is due to imperfections in the removal of strong night sky lines.