Manuscript version: Published Version
The version presented in WRAP is the published version (Version of Record).

Persistent WRAP URL:
http://wrap.warwick.ac.uk/155810

How to cite:
The repository item page linked to above, will contain details on accessing citation guidance from the publisher.

Copyright and reuse:
The Warwick Research Archive Portal (WRAP) makes this work by researchers of the University of Warwick available open access under the following conditions.

Copyright © and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable the material made available in WRAP has been checked for eligibility before being made available.

Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge. Provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

Publisher’s statement:
Please refer to the repository item page, publisher’s statement section, for further information.

For more information, please contact the WRAP Team at: wrap@warwick.ac.uk
Magnetic dynamos in white dwarfs – II. Relating magnetism and pollution

Matthias R. Schreiber, 1,2* Diogo Belloni 1,3 Boris T. Gänsicke 4 and Steven G. Parsons 5

1 Departamento de Física, Universidad Técnica Federico Santa María, Av. España 1680, Valparaíso, Chile
2 Millennium Nucleus for Planet Formation (NPF), Valparaíso, Chile
3 National Institute for Space Research, Av. dos Astronautas, 1758, 12227-010 São José dos Campos, SP, Brazil
4 Department of Physics, University of Warwick, Coventry CV4 7AL, UK
5 Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK

ABSTRACT
We investigate whether the recently suggested rotation and crystallization driven dynamo can explain the apparent increase of magnetism in old metal polluted white dwarfs. We find that the effective temperature distribution of polluted magnetic white dwarfs is in agreement with most/all of them having a crystallizing core, and increased rotational velocities are expected due to accretion of planetary material that is evidenced by the metal absorption lines. We conclude that a rotation and crystallization driven dynamo offers not only an explanation for the different occurrence rates of strongly magnetic white dwarfs in close binaries but also for the high incidence of weaker magnetic fields in old metal polluted white dwarfs.

Key words: magnetic fields – white dwarfs – planetary systems.

Metal absorption lines in the spectra of white dwarfs have been firmly established to result from the accretion of planetary material that survived the transformation of their host star into a white dwarf. This idea was first proposed by Jura (2003) and later confirmed to be correct due to the detection of a transiting planetesimal in the process of tidal disintegration (Vanderburg et al. 2015; Gänsicke et al. 2016). This key evidence is complemented by the detection of dusty and gaseous debris discs (e.g. Zuckerman & Becklin 1987; Gänsicke et al. 2006), a planetesimal that is possibly the core of a differentiated rocky planet (Manser et al. 2019) and an evaporating planet in close orbit around a white dwarf (Gänsicke et al. 2019).

This growing observational evidence for the accretion of planetary material on to white dwarfs is in agreement with theoretical predictions. It is well established that planets can survive the transition of their host star into a white dwarf (e.g. Villaver & Livio 2009; Ronco et al. 2020). Some of the surviving planetary systems are predicted to become unstable which can push especially lower mass planets or asteroids into highly eccentric orbits (Veras & Gänsicke 2015; Smallwood et al. 2018; Maldonado et al. 2021). Tidal forces may then destroy these objects which offers a consistent explanation for the observations of planetary material being accreted on to 25–50 per cent of all white dwarfs (Koester, Gänsicke & Farihi 2014).

As noticed by Hollands, Gänsicke & Koester (2015), very old metal polluted white dwarfs are more frequently magnetic than younger systems. All magnetic metal polluted helium (DZ) white dwarfs and all but one known magnetic metal polluted hydrogen atmosphere white dwarfs (DAZ) have effective temperatures below 7500 K (Hollands et al. 2017; Kawka et al. 2019, 2021). In addition, three apparently isolated white dwarfs exhibiting Zeeman split emission lines which might be related to the existence of a conductive planet or planet core in a close orbit, cluster around temperatures of \( \sim 7500 \) K (e.g. Li, Ferrario & Wickramasinghe 1998; Gänsicke et al. 2020; Walters et al. 2021). This suggests that the accretion of planetary material and low temperatures may be linked to the generation of magnetic fields in white dwarfs.

Inspired by the earlier work of Isern et al. (2017), we recently proposed a dynamo similar to those operating in planets and low-mass stars to explain the observed incidence of strongly magnetic white dwarfs in close binary stars (Schreiber et al. 2021). The main ingredients for this dynamo to work are that the white dwarf’s core started to crystallize (which depending on the mass of the white dwarf generally occurs at white dwarf temperatures below \( \sim 8000 \) K) and increased rotational velocities due to accretion. We here test the hypothesis that the increasing fraction of magnetic white dwarfs among cold metal polluted (and therefore accreting) white dwarfs could be produced by the same dynamo mechanism. We start with a brief review of the dynamo mechanism recently suggested to work in accreting white dwarfs in close binaries.

2 THE CONVECTIVE DYNAMO APPLIED TO WHITE DWARFS

The magnetic fields of planets and rapidly rotating low-mass stars are generated by convection-driven dynamos (Christensen, Holzwarth & Reiners 2009). The main ingredients for these dynamos to work are a strong density stratification, an extended convection zone, and rotation. A similar configuration can occur in cooling white dwarfs.

As a carbon/oxygen white dwarf cools, the ions in the core begin to freeze in a lattice structure (Van Horn 1968), i.e. the white dwarf starts to crystallize. The phase diagram of the carbon–oxygen mixture is of the azeotrop form (e.g. Horowitz, Schneider & Berry 2010, Blouin et al. 2020) and consequently, the solid phase becomes richer in oxygen and sinks while the carbon excess mixes with the outer liquid envelope which is redistributed by the Rayleigh–Taylor instability.
If the white dwarf is also rapidly rotating, the conditions are appropriate for magnetic field generation through the convective dynamo.

For planets and low-mass stars, the magnetic field strength can be derived from fundamental properties of a given object using the convective energy flux scaling law (Christensen et al. 2009). Applying this scaling law to white dwarfs led to the prediction of field strengths below $\sim 1$ MG (Isern et al. 1997). However, the field strength generated by the dynamo likely depends on the magnetic Prandtl number (Brandenburg 2014) which is not taken into account in the scaling law (Christensen & Auber 2006). Given that the magnetic Prandtl number for crystallizing white dwarfs is orders of magnitude larger than that of planets and low-mass stars, the field strength generated by the dynamo is likely also much larger (Bovino, Schleicher & Schober 2013). For more details, see Schreiber et al. (2021).

According to measurements of activity and rotation in fully convective stars, the dynamo seems to saturate for Rossby numbers (rotation period divided by convective turnover time) below 0.1 which might indicate that the generated field strength becomes independent of the rotation rate for rapidly spinning stars. For white dwarfs, the condition on the Rossby number translates to rotation periods of the order of seconds/minutes as the threshold for saturation. For slower rotation rates, magnetic fields might still be generated but should on average be weaker.

Based on the reasonable assumption that strong magnetic fields can be generated if a crystallizing white dwarf is rotating in the saturated regime, Schreiber et al. (2021) explained the occurrence rates and characteristics of strongly magnetic white dwarfs in close binary stars. The very same mechanism may explain the large incidence of weaker magnetic fields in cool metal polluted white dwarfs if they have temperatures consistent with crystallizing cores and if the accretion of planetary material can significantly increase their rotation. In the next section, we evaluate whether the distribution of effective temperatures of magnetic DAZ and DZ white dwarfs is consistent with them having crystallizing cores.

3 CRystallizing Cores in Magnetic METAL POLLUTED White DWARFS

The onset of crystallization in white dwarfs, a requirement for the dynamo mechanism proposed by Schreiber et al. (2021), depends not only on the white dwarf effective temperature but also on the white dwarf mass. However, measuring the masses of magnetic white dwarfs is extremely challenging. The standard technique for non-magnetic DA white dwarfs, which make up the bulk of the white dwarf population (e.g. McCleery et al. 2020), is to measure the effective temperature and surface gravity from fitting the Balmer lines and then to determine the white dwarf mass using a mass–radius relation. There is currently no theory for the simultaneous treatment of the Zeeman effect and Stark broadening, and therefore, this method cannot be applied to magnetic DA(Z) white dwarfs.

An alternative method to derive white dwarf masses is to iteratively fit the photometric spectral energy distribution (SED; which for a given temperature, is very sensitive to the radius) and the spectrum (where the relative strengths of absorption lines provide a handle on the temperature), and to subsequently derive the mass adopting a white dwarf mass–radius relation. However, this method requires accurate knowledge of the distance to the white dwarf under analysis. Most cool and faint DZ white dwarfs in our sample have large parallax uncertainties in the available Gaia data releases, and consequently, estimated masses are unreliable (Coutu et al. 2019). Additional complications arise from the line blanketing caused by the metals in the magnetic DZ white dwarfs considered here, introducing the detailed photospheric abundances as additional free fit parameters. Finally, magnetic fields may suppress or weaken convection, which will affect the temperature structure and emerging spectrum of magnetic white dwarfs (Gentile Fusillo et al. 2018), and it is currently unclear whether the SEDs of magnetic white dwarfs are better fitted with radiative or convective models. Given the difficulties in determining the individual masses of the magnetic metal polluted white dwarfs, we here investigate whether the distribution of their effective temperatures is in agreement with their cores being in the process of crystallization.

Largely based on earlier work (Hollands et al. 2017), evidence is growing that the occurrence of magnetic fields in DZ white dwarfs increases with decreasing temperature (Kawka et al. 2021). All magnetic DZ white dwarfs have effective temperatures below 7500 K. At these low temperatures $\lesssim 40$ per cent of the known DZ white dwarfs are magnetic. In contrast, not a single magnetic DZ has been found in the temperature range 7500–10 000 K. The situation is very similar for DAZ white dwarfs among which the fraction of magnetic systems increases significantly with decreasing effective temperature and all but one magnetic DAZ white dwarfs are cooler than $\sim 7500$ K. A list of magnetic DAZ and DZ white dwarfs is provided in Table 1, where we ignored some candidate magnetic systems suggested in Kawka & Vennes (2014) and Coutu et al. (2019) as well as the magnetic Balmer emission line white dwarfs discussed by Gänsicke et al. (2020).

Comparing the measured temperatures with those expected for crystallizing white dwarfs, we find good agreement with ongoing crystallization in their cores (see Fig. 1). Roughly 80 per cent of single white dwarfs can be found in the mass range of 0.5–0.75 $M_\odot$ (Tremblay et al. 2016) and the distribution peaks at $\approx 0.6 M_\odot$. All magnetic DZ and all but one magnetic DAZ white dwarfs are cooler than the temperature at which a 0.75 $M_\odot$ white dwarf starts to crystallize ($\sim 8000$ K) and roughly half of them are below the crystallization temperature of a 0.6 $M_\odot$ white dwarf (see Fig. 1). Only the hottest ($\sim 11000$ K) metal polluted magnetic white dwarf, the DAZ white dwarf WD 2105$-$820, seems to contradict this finding as its temperature is too high to be crystallizing if its mass was that of a typical 0.5–0.75 $M_\odot$ white dwarf. However, apart from being the hottest metal polluted magnetic white dwarf, WD 2105$-$820 is also most likely the most massive one. Swan et al. (2019) estimated a white dwarf mass of 0.86 $M_\odot$ for which crystallization starts at much higher temperatures. The estimated mass is not high enough to reach the onset of crystallization, but assuming an uncertainty of just 0.05 $M_\odot$ would fix this apparent disagreement (which would be completely consistent with the uncertainty provided for $\log g$). We conclude that indeed most/all metal polluted magnetic white dwarfs might have passed the onset of crystallization in their cores.

The remaining question is whether the accretion of planetary material could spin-up the white dwarfs to reach significantly increased rotational velocities.

4 SPIN-UP OF THE WHITE DWARF

The second ingredient for the proposed dynamo to work is increased rotation of the white dwarf. It is well established that metal polluted white dwarfs accrete planetary debris that result from disintegrating planetesimals, asteroids, comets, or planets. During the accretion process, the white dwarf not only accretes mass, but also angular momentum (Stephan et al. 2020). We here estimate whether the
accreted angular momentum might sufficiently spin-up the white dwarf to cause the generation of detectable magnetic fields.

From a large sample of cold and old metal polluted white dwarfs, Hollands et al. (2017) derived a trend of decreasing accretion rates with an e-folding time of $\approx 1$ Gyr. This observed long term trend, however, does not cover short episodes of much larger accretion rates that occur when rocky or even gas giant planets come too close to the white dwarfs. Observational evidence for such events has been provided recently (Günsicke et al. 2019; Manser et al. 2019). In addition, the recently observed giant planet around WD 1856+534 shows that even Jupiter mass planets may end up in close orbits around white dwarfs either due to common envelope evolution (Lagos et al. 2021), triple dynamics (Muñoz & Petrovich 2020), or gravitational interactions (Maldonado et al. 2020). Indeed, using configurations of planetary systems derived from observed systems, Maldonado et al. (2020) showed that eccentricity pumping leading to the tidal disruption and/or evaporation of planets is by no means a rare event. For planetary systems consisting of five or six planets, star–planet collisions are expected in $\approx 10$ per cent of the cases.

The accretion of planetary material does not only lead to metal absorption lines in the spectra of white dwarfs, accretion of mass is accompanied by the accretion of angular momentum. The material from destroyed planetesimals, asteroids, comets, and planets accumulates in a Keplerian disc around the white dwarf and is then slowly accreted on to the white dwarf. King, Regev & Wynn (1991) derived the angular momentum balance equation for accreting white dwarfs in cataclysmic variables (CVs) and found

$$I \frac{d\omega}{dt} = \alpha (-M_2) \left(G M_{\text{WD}} R_{\text{WD}}\right)^{1/2} + (1 + \epsilon) M_2 \eta R_{\text{WD}}^2 \omega,$$

(1)

where $\omega$ is the white dwarf spin, $I$ its moment of inertia, $G$ the gravitational constant, $M_2$ the mass transfer rate averaged over nova cycles, and $M_{\text{WD}}$ and $R_{\text{WD}}$ are the white dwarf mass and radius. The first term on the right-hand side of the equation corresponds to the spin-up due to accretion and the parameter $0 \leq \alpha \leq 1$ (added by Schreiber et al. 2021) represents the spin-up efficiency. The second term represents the spin-down due to material leaving the white dwarf which can be ignored in this work as nova eruptions are generally not expected ($\epsilon = -1.0$) given the small amount of accreted hydrogen (the accretion of an entire Jupiter mass planet could be a rare exception). We solved the non-homogeneous differential equation (1) as in Schreiber et al. (2021) for total accreted mass (over a time span of several Gyr) of $10^{-6} - 10^{-3} M_\odot$, which roughly covers the mass range from Earth to Jupiter.

We find that the accretion of planetary material in polluted white dwarfs can easily lead to significantly shorter spin periods. Figure 2 shows the spin-up of a $0.6 M_\odot$ white dwarf for different total accretion rates as a function of the spin-up efficiency. For accreted masses exceeding $10^{-5} M_\odot$, we find rotation periods ranging from several minutes, as recently observed (Reding et al. 2020), to a few hours, much shorter than the assumed initial rotation rate of $1–3 \, \text{d}$ (Hermes...
distribution of crystallizing metal polluted white dwarfs is currently
in addition, making reliable model predictions for the temperature
only very likely biased towards hot white dwarfs but also incomplete.
of the currently available sample of DAZ and DAZ white dwarfs is not
rather futile exercise as the distributions of the effective temperatures
predictions. However, such a comparison would currently represent a
way to confront the observed temperature distribution with model
evolution codes and white dwarf cooling tracks could be an easy
distribution of crystallizing white dwarfs by combining stellar
At first glance, one might think that calculating the temperature
distributions are different. However, the ongoing SDSS -V survey
will provide spectra of ∼200 000 white dwarfs, many of which
will be metal polluted and a significant fraction of the latter will be
masses /2272.

Figure 2. Final white dwarf spin period (P WD) against the spin-up efficiency
parameter (α), for four different accreted masses, in M⊙, namely 10−6, 10−5,
10−4, and 10−3 and two initial spin periods. With the exception of accreted masses ≤ 10−5, the white dwarf spin periods become significantly shorter
(minutes to a few hours) for a large range of efficiencies.

et al. 2017). At the same time, the spin periods reached remain
longer than the spin period estimated by Isern et al. (2017) for
saturation of the dynamo which could be reached due to the accretion
of significantly more mass in CVs. One would therefore expect the
generated magnetic fields in DZ and DAZ white dwarfs to be weaker
than the up to several 100 MG fields of strongly magnetic white
dwarfs in CVs which is clearly the case (see Table 1).
We conclude that both conditions for the generation of magnetic fields due to a crystallization and rotation driven dynamo are most
likely fulfilled in DZ and DAZ white dwarfs. To the best of
our knowledge, no other scenario suggested for the generation of magnetic fields in white dwarfs offers an explanation for the increased incidence of magnetism in old metal polluted white dwarfs.
However, in the absence of a scaling law that takes into account
the dependence on the magnetic Prandtl number, let alone detailed
simulations of the dynamo in white dwarfs, we admit that the presented arguments are reasonable but phenomenological. More
detailed theoretical investigations as well as a representative sample of observed magnetic DZ and DAZ white dwarfs are clearly required
to further test the outlined scenario.

5 PREDICTIONS TO BE TESTED
At first glance, one might think that calculating the temperature
distribution of crystallizing white dwarfs by combining stellar
Figure 3. Predicted temperature distributions of crystallizing DAZ and DZ
white dwarfs assuming solar metallicty and a constant occurrence rate of
planetary systems around progenitor stars less massive than 3.0 M⊙. The
predicted distribution of temperatures of DZ white dwarfs is much broader
and peaks at higher temperatures than the observed DZ sample.
hardly possible as the occurrence rate of planetary systems around
the progenitor stars and its exact dependence on the stellar mass,
planet separation, planet mass, and stellar metallicty are, despite
recent progress (e.g. Fischer & Valenti 2005; Mulders, Pascucci & Apai 2015), not well known. Therefore, instead of performing such a
comparison, we here investigate whether the suggested dynamo
scenario leads to predictions that can be observationally tested in the
near future.
To that end, we calculated the temperature distribution of crystallizing
DZ and DAZ white dwarfs for solar metallicty and assuming
a constant probability for the existence of planetary systems up to
masses of the white dwarf progenitor of 3.0 M⊙. As the planet
occurrence rate seems to drop for larger stellar masses (e.g. Mulders
et al. 2015), we assumed that planets do not form around more
massive stars. We furthermore assumed a constant star formation
rate, an age of the Galactic disc of 10 Gyr, and an initial mass
function ∝ M−2.3. We used the the single star evolution code written
by Hurley, Pols & Tout (2000) and the white dwarf cooling models
of Bédard et al. (2020).
The resulting temperature distributions are shown in Fig. 3. As
the onset of crystallization for DZ white dwarfs occurs at higher
temperatures, their distribution peaks at a slightly higher temperature.
Given that, in addition, the late cooling of DZ white dwarfs is faster,
their predicted distribution also extends more towards cooler white
dwarfs. While the detailed shape of both distributions depends on
the assumed occurrence rate of planets as a function of stellar mass
and metallicity, the predicted differences should be present as long
as both samples suffer from the same observational biases and their
progenitor stars have the same planet occurrence rates.
The small number of magnetic DAZ and DZ white dwarfs currently
known does not allow us to asses whether the underlying temperature
distributions are different. However, the ongoing SDSS -V survey
will provide spectra of ∼200 000 white dwarfs, many of which
will be metal polluted and a significant fraction of the latter will be
magnetic. Thus, the required large sample of magnetic DZ and DAZ
white dwarfs is likely to be established within the next few years.
A second and obvious prediction of our model is that the rotation periods of magnetic DZ and DAZ white dwarfs should be on average shorter than those of non-magnetic white dwarfs with crystallizing cores. Fortunately, the rotation periods of magnetic white dwarfs can be measured through either photometric variability (Brinkworth et al. 2013) or circular spectropolarimetry of spectral lines (Bagnulo & Landstreet 2019) and thus the prediction can be tested. Interestingly, the three cold magnetic white dwarfs showing Balmer emission and potentially hosting a conductive planet or planetary core (G¨ansicke et al. 2020) clearly show reduced spin periods, which fits with the scenario outlined here.

Our scenario also predicts that a certain fraction of crystallizing white dwarfs currently not showing metal absorption lines should have increased rotation rates and be magnetic because accretion that spun up the white dwarf has occurred in the past. The cool magnetic white dwarfs found in the 20 pc sample (Bagnulo & Landstreet 2020) could be such systems.

Finally, another mechanism must be responsible for the magnetic fields observed in some hot white dwarfs and this alternative process must prevent the accretion of planetary debris (given the absence of hot magnetic metal polluted white dwarfs). Double white dwarf mergers could be such a mechanism, as planetary material is certainly unlikely to survive two phases of mass transfer.

6 CONCLUSION

Schreiber et al. (2021) recently suggested a crystallization and rotation driven dynamo for the origin of strong magnetic fields of white dwarfs in close binary stars. We here investigated whether the same mechanism might be responsible for the surprising increase of magnetism in metal polluted white dwarfs when they have cooled to temperatures \( \lesssim 7500 \text{ K} \). We found that the temperature distribution of metal polluted magnetic DAZ and DZ white dwarfs is consistent with them having crystallizing cores and that the accretion of planetary material can spin-up the white dwarf’s rotation to periods ranging from minutes to hours depending on the total amount of accreted material. Thus, the suggested dynamo represents a promising model for explaining the magnetic fields of old DA/DAZ white dwarfs.

ACKNOWLEDGEMENTS

MRS acknowledges support from Fondecyt (grant 1181404) and ANID – Millennium Science Initiative Program – NCN19_171. DB was supported by FAPESP, grant #2017/14289-3 and ESO/Gobierno de Chile. BTG was supported by a Leverhulme Research Fellowship and the UK STFC grant ST/T000406/1. SGP acknowledges the support of an STFC Ernest Rutherford Fellowship.

DATA AVAILABILITY

The simulated data will be provided upon request.

REFERENCES

Bagnulo S., Landstreet J. D., 2019, A&A, 630, A65
Bagnulo S., Landstreet J. D., 2020, A&A, 643, A134
Bédard A., Bergeron P., Brassard P., Fontaine G., 2020, ApJ, 901, 93
Blouin S., Daligault J., Saumon D., Bédard A., Brassard P. (2020) A&A L11, 0004-6361
Bovino S., Schleicher D. R. G., Schober J., 2013, New J. Phys., 15, 013055
Brandenburg A., 2014, ApJ, 791, 12
Brinkworth C. S., Burleigh M. R., Lawrie K., Marsh T. R., Knigge C., 2013, ApJ, 773, 47
Christensen U. R., Aubert J., 2006, Geophys. J. Int., 166, 97
Christensen U. R., Holzwarth V., Reiners A., 2009, Nature, 457, 167
Coutu S., Dufour P., Bergeron P., Blouin S., Loranger E., Allard N. F., Dunlap B. H., 2019, ApJ, 885, 74
Farihi J. et al., 2018, MNRAS, 474, 947
Farihi J., Dufour P., Napiwotzki R., Koester D., 2011, MNRAS, 413, 2559
Fischer D. A., Valenti J., 2005, ApJ, 622, 1102
Gänsicke B. T. et al., 2016, ApJ, 818, L7
Gänsicke B. T., Marsh T. R., Southworth J., Rebassa-Mansergas A., 2006, Science, 314, 1908
Gänsicke B. T., Rodríguez-Gil P., Gentile Fusillo N. P., Inghit K., Schreiber M. R., Pala A. F., Tremblay P.-E., 2020, MNRAS, 499, 2564
Gänsicke B. T., Schreiber M. R., Toloza O., Fusillo N. P., Koester D., Manser C. J., 2019, Nature, 576, 61
Gentile Fusillo N. P., Tremblay P.-E., Jordan S., Gänsicke B. T., Kalirai J. S., Cummings J., 2018, MNRAS, 473, 3693
Giannichele N., Bergeron P., Dufour P., 2012, ApJS, 199, 29
Hermes J. J. et al., 2017, ApJ, 832, 23
Hollands M. A., Gänsicke B. T., Koester D., 2015, MNRAS, 450, 681
Hollands M. A., Koester D., Alekseev V., Herbert E. L., Gänsicke B. T., 2017, MNRAS, 467, 4970
Horowitz C. J., Schneider A. S., Berry D. K., 2010, Phys. Rev. Lett., 104, 231101
Hurley J. R., Pols O. R., Tout C. A., 2000, MNRAS, 315, 543
Isern J., García-Berro E., Külebi B., Lorén-Aguilar B., 2017, ApJ, 836, L28
Isern J., Mochkovitch R., García-Berro E., Hernanz M., 1997, ApJ, 485, 308
Jura M., 2003, ApJ, 584, L91
Kawka A., Vennes S., 2011, A&A, 532, A7
Kawka A., Vennes S., 2012, A&A, 538, A13
Kawka A., Vennes S., 2014, MNRAS, 439, L90
Kawka A., Vennes S., Allard N. F., Leininger T., Gadéa F. X., 2021, MNRAS, 500, 2732
Kawka A., Vennes S., Ferrario L., Paunzen E., 2019, MNRAS, 482, 5201
King A. R., Regev O., Wynn G. A., 1991, MNRAS, 251, 30P
Koester D., Dreizler S., Weidemann V., Allard N. F., 1998, A&A, 338, 612
Koester D., Gänsicke B. T., Farihi J., 2014, A&A, 566, A34
Lagos F., Schreiber M. R., Zorotovic M., Gänsicke B. T., Ronco M. P., Hamers A. S., 2021, MNRAS, 501, 676
Landstreet J. D., Bagnulo S., Vassiliadis E., Fossati L., Jordan S., Monin D., Wade G. A., 2012, A&A, 545, A30
Li J., Ferrario L., Wickramasinghe D., 1998, ApJ, 503, L151
Maldonado R. F., Villaver E., Mustill A. J., Chávez M., Bertone E., 2021, MNRAS, 501, L48
Manser C. J. et al., 2019, Science, 364, 66
McClerey J. et al., 2020, MNRAS, 499, 1890
Mulders G. D., Pacucci I., Apai D., 2015, ApJ, 814, 130
Muñoz D. J., Petrovich C., 2020, ApJ, 904, L3
Reding J. S., Hermes J. J., Vanderbosch Z., Dennihy E., Kaiser Y., 2013, ApJ, 773, 47
Ronco M. P., Schreiber M. R., Giannichele N., Fabrèges D., Versas D., Cuadra J., Guijera O. M., 2020, ApJ, 898, L23
Schreiber M. R., Belloni D., Gänsicke B. T., Parsons S. G., Zorotovic M., 2021, Nat. Astron.
Smallwood J. L., Martin R. G., Livio M., Lubow S. H., 2018, MNRAS, 480, 57
Stephan A. P., Naoz S., Gaudi B. S., Salas J. M., 2020, ApJ, 889, 45
Subasavage J. P. et al., 2017, AJ, 154, 32
Swan A., Farihi J., Koester D., Hollands M., Parsons S., Cauley P. W., Redfield S., Gänsicke B. T., 2018, MNRAS, 470, 202
Tremblay P. E. et al., 2020, MNRAS, 497, 130
Tremblay P. E., Cummings J., Kalirai J. S., Gänsicke B. T., Gentile-Fusillo N., Raddi R., 2016, MNRAS, 461, 2100
van Horn H. M., 1968, ApJ, 151, 227
Vanderburg A. et al., 2015, Nature, 526, 546
Veras D., Gänsicke B. T., 2015, MNRAS, 447, 1049
Villaver E., Livio M., 2009, ApJ, 705, L81
Walters N. et al., 2021, MNRAS, 503, 3743
Zuckerman B., Becklin E. E., 1987, Nature, 330, 138
Zuckerman B., Koester D., Dufour P., Melis C., Klein B., Jura M., 2011, ApJ, 739, 101

This paper has been typeset from a \TeX/\LaTeX\ file prepared by the author.