The Accretion Geometry of the Asynchronous Polar V1432 Aql

Qishan, Wang1,2,3*, Shengbang, Qian1,2,3,4, Liying, Zhu1,2,3,4

1Yunnan Observatories, Chinese Academy of Sciences (CAS), P. O. Box 110, 650216 Kunming, China
2Key Laboratory of the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, P. O. Box 110, 650216 Kunming, China
3University of Chinese Academy of Sciences, Yuquan Road 19#, Sijingshang Block, 100049 Beijing, China
4Center for Astronomical Mega-Science, Chinese Academy of Science, 20A Datun Road, Chaoyang Distric, Beijing, 100012, P.R. China

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

As the only eclipsing asynchronous polar (AP), V1432 Aql provides an excellent laboratory to study the interaction between the accreted matter and the magnetic field. However, due to its complex emission, a more physical understanding of its accretion geometry is still outstanding. Here, we report an X-ray spectral study using contemporaneous observations from NuSTAR and Swift. We detect significant Compton reflection and confirm earlier reports of a high soft X-ray temperature ~ 52 keV. We suggest that the multi-temperature emission is due to a distribution of the specific accretion rate over the accretion region, which leads to a continuous temperature distribution over the heated area and explains the high temperature of the soft X-rays. We interpret these characteristics as the results of the inefficient accretion in APs. Thus the accretion stream can punch deeply into the magnetosphere and feed the white dwarf (WD) over a much narrower accretion region near its equator. Additionally, the broad-band X-rays provide details of the accretion; the low total accretion rate of ~ 1 x 10^{-10} M_⊙ yr^{-1} contradicts the speculation that V1432 Aql was a recent nova, while the high specific accretion rate of ~ 5.6 g cm^{-2} s^{-1} explains the significant reflection from the surface of the WD.

Key words: stars: individual: V1432 Aql - cataclysmic variables: asynchronous polars

1 INTRODUCTION

Polars (also called AM Herculis stars), a sub-type of magnetic cataclysmic variables (CVs), consist of a highly magnetic (~ 10-200 MG) white dwarf (WD) and a red dwarf overflowing its Roche lobe. The accreted material from the secondary follows a free trajectory until it is channeled by the magnetic field, then falls onto WD leading to a shock, which converts the kinetic energy into the thermal energy, and forming an accretion column. The cooling of the post-shock plasma is dominated by the multi-temperature bremsstrahlung emission in hard X-rays, and the cyclotron radiation in optical and infrared (see Cropper 1990). Thus, information on the accretion geometry is encoded in the intrinsic emission.

However, the observed radiation in polars has a significant contribution from the X-rays that interact with the environment, including the surface of WD, the pre-shock material, accretion stream and any circumstellar medium that might exit. The X-rays reflected by the stellar surface produces the 10-30 keV Compton reflection hump and the Fe Kα fluorescent line at 6.4 keV, while the latter can also originate from intrinsic absorbers. And the emitted X-rays may be viewed through the complex absorbing material, which causes an absorption effect in additional to that of the Galactic interstellar medium (ISM, Mukai 2017).

Normally the magnetic torque forces the WD to spin synchronously with its orbital rotation, but several polars well confirmed to be slightly asynchronous, with the WD’s spin period P_{spin} more or less than their orbital one P_{orb} by ~ 1% or less (Wang et al. 2020). As the only eclipsing asynchronous polar (AP), V1432 Aql has raised several important and still unresolved questions. One is the very nature of its accretion configuration. In APs, the WD rotates differently with respect to its companion, so as the orientation of WD magnetic field and it repeats on the longer beat period (P_{beat} = |1/P_{spin} - 1/P_{orb}|^{-1}) during which the accretion flow is channeled by different magnetic field lines and impacts nearest poles (Wynn & King 1992). This pole-switching effect was detected from the analysis of the light curves, spread through a beat cycle, in V1500 Cyg (Pavlenko et al. 2018), CD Ind (Littlefield et al. 2019; Hakala et al. 2019), BY Cam (Mason et al. 1998) and 1RXS J083842.1-282723 (Halpern et al. 2017), while no such effect was detected in V1432 Aql from its long-term light curves (Littlefield et al. 2015). Geckeler & Staubert (1997) and Staubert et al. (2003) interpreted that the gas stream is captured by different lines of a dipole field and falls on to the WD surface near the same magnetic pole, but this accretion geometry requires more energy to lift the gas stream above the orbital plane so is less realistic. In fact, no efficient threading is seen in APs, as indicated by Doppler tomography (Schwope 2001) and X-ray observations (Mukai et al. 2003), for example, V1432 Aql showed an azimuthally extended accretion curtain and maybe the accretion stream travels most of the way around the WD before it is fully threaded by the field lines (Littlefield et al. 2015). This kind of accretion from belt-like structure is suggested by many authors (Patterson et al. 1995; Schmidt & Stockman 2001; Mukai et al. 2003) and explains why only one accretion pole is active all the time, no
matter what the relative orientation between the WD’s magnetic field and the secondary is.

The other major unresolved question is how an eclipsing system can produce so peculiar optical radiation, such as no sharp ingress/egress profiles (Littlefield et al. 2015), and the presence of residual emission lines (Watson et al. 1995; Schmidt & Stockman 2001). While the X-ray observation proved beyond doubt that the eclipse is caused by the secondary (Mukai et al. 2003), other radiation components are invoked to explain its optical radiation during the eclipse. This can be resolved by the existence of the belt-like structure around the WD if it is not fully occulted by the secondary.

As the mass stream punches into the magnetosphere, it is stripped over a range of radii by the field lines and feeds accretion over a much larger range of azimuth on the surface of the WD. In order to study the characteristics of the accretion region, in this paper, we present the analysis of archival contemporaneous NuSTAR and Swift observations of V1432 Aql. In Section 2, we detail the reduction of the data, while Section 3 presents the results from the spectral analysis. Finally, Section 4 presents a discussion about the implications of the spectral results and describes the accretion geometry in V1432 Aql.

2 OBSERVATIONS AND DATA REDUCTION

V1432 Aql was observed during 2012-2014 through a V filter (Littlefield et al. 2015). Here we retrieved these data from the American Association of Variable Star Observers (AAVSO)\(^1\) database and compared them with the X-ray data.

The NuSTAR satellite observed V1432 Aql on 2018 April 05 for 27.1 ks from 05:00 to 21:39 (ObsID 3046004002). The data were reduced using the NuSTAR Data Analysis Software as part of HEASoft 6.21 and latest CALDB files following standard procedures. We extracted source X-ray events from different circular regions with a radius of 30 arcsec centered on the source for the NuSTAR modules, FPMA and FPMB. For the background, we chose a 50 arcsec radius, circular and source-free region on the same detector. We generated the spectra and the corresponding response files using nuproducts.

A Swift observation was obtained simultaneously with NuSTAR for 6.2 ks from 04:43 to 10:56 (ObsID 00088611001). We extracted source X-ray spectrum from a circular region of radius 20 arcsec centered on the source. The background was obtained from a nearby source-free region of radius 40 arcsec. We built the ancillary matrix using the tool xrtmkarf and used the response matrix provided by the Swift calibration team. We grouped all spectra using grappha to have at least 25 counts per bin. Spectral fits were done with Xspec v12.10c (Arnaud 1996) by using the $\chi^2$ statistic.

3 RESULTS

3.1 Light Curves

The asynchronous rotation of a WD with respect to its orbital revolution causes a pole-switching modulation with each accretion region active for a half beat cycle (Wynn & King 1992). However, no evidences of such modulation were observed for V1432 Aql. In order to verify whether only one accretion region is active all the time, we need to study the spin phase variation of the emission region along the beat phase. We present the average spin modulation of V1432 Aql observed with NuSTAR in energy bands of medium (3-10 keV) and hard (10-78 keV) X-rays in 200s time bins (the upper panel of Figure 1) using the ephemeris of Andronov et al. (2006). The X-ray light curves show pulse maximum over spin phase ~ 0.3 – 0.45 and minimum over ~ 0.45 – 1.1, while their hardness ratios stay at the same level ~ 0.5 over phase ~ 0.3 – 1.1, which indicate that the dim phase is due to the changing aspect of the WD rather than the absorption effect from the accretion stream. Then we fold the optical data to the spin period along the beat phase using an arbitrary beat epoch (the low panel of Figure 1). The eclipse profiles of X-ray data at spin phase ~ 0.6 implies that the X-ray observation is at beat phase ~ 0.13, where the optical bright hump at spin phase ~ 0.35 is coincident with the X-ray maximum. The bright humps in the optical light curves are over spin phase ~ 0.3 – 0.7 along the whole beat phase, which suggests they origin from the emission regions near almost the same longitude of the WD. Thus Figure 1, in contrast to that of the other APs (Wang et al. 2020), indicates that the accretion regions are along almost the same longitude of the WD.

3.2 X-ray Spectral Model

The X-ray absorption and reflection effects are degenerate, thus it is very important to use broad-band data to determine the characteristics of the emission regions. For this, we fitted the contemporaneous Swift/XRT (0.3-10 keV) and NuSTAR (FPMA + FPMB; 3-78 keV) spectra simultaneously, but first excluded the Fe K region (5.5-7 keV). Given the weak cyclotron and low polarization (≤ 2%) (Rana et al. 2005), the X-ray radiation can be approximated by the multi-temperature thermal emission model cemekl (Done & Osborne 1997) based on a thermal plasma code apec (switch = 2).

We chose that each temperature component is weighted by its cool-temperature component is weighted by its cool-

\(^{1}\) https://www.aavso.org/
(\(n_H = 10 \text{ cm}^{-3}\)). Since polars are strong soft X-ray emitters, we also added a blackbody component to model the low energy data.

The interaction of the radiation with matter was accounted for by the following models. Since the radiation may be viewed through complex absorbers, we used the usual partial-covering absorber model (PCfabs) in addition to a single absorber (PHABS) where the neutral hydrogen column density is \(\sim 1.3 \times 10^{21} \text{ cm}^{-2}\) estimated from a visual extinction of HST UV spectrum (Schmidt & Stockman 2001). When investigating the reflection of the WD’s surface, we applied the reflect model (Magdziarz & Zdziarski 1995) with the same abundances as the X-ray emitting plasma assuming freshly accreted matter covers its surface. We fixed the inclination angle of the reflecting surface at the default value of \(\cos \mu = 0.45\). Then we fitted the data once with the reflection model included, and once with it excluded.

We allowed the cross-normalization factor relative to NuSTAR/FPMA to vary for to allow for the cross-calibration between these instruments. In Table 1, we report the best-fit results with their 90\% confidence error ranges in the 3rd column. The difference in \(\chi^2\) (\(\Delta \chi^2\)) compared to the no-reflection case and the reflection amplitude of \(\sim 3\) show that the reflection effect is highly significant, which implies a low height of shock front and a high specific accretion rate. In V1432 Aql (Mukai et al. 2015) Next we modeled all data in the 0.3-78 keV range, and introduced a Gaussian emission model to represent fluorescent Fe Kα line at 6.4 keV. The low accretion column means that half of radiation of the post-shock plasma will be intercepted and reprocessed by the surface, so we fixed the reflection amplitude to its maximum value (\(ref_{eff} = 1\)) while allowed \(cos \mu\) to vary, also we fixed the abundance to the value from the previous fit because the Gaussian line could severely affect it. We summarized the best-fitting results in the last column of Table 1, and shown the spectra in Figure 2. The low spin-averaged \(\mu \sim 0\) suggests a face-on viewing geometry, which implies that the latitude \(\beta\) of the accretion regions is roughly equal to the inclination \(i\) of the system. Also the NuSTAR spectra suggest a pronounced fluorescent iron line at 6.4 keV with an equivalent width (EW) estimated at 196+44 eV. The reflection can contribute EW as much as \(\sim 100\) eV, and the partial absorber with \(N_{H,eff} \sim 9 \times 10^{22} \text{ cm}^{-2}\), defined as the sum of \(C_F \times N_H\) for each partial absorber, could account for the rest \(\sim 90\) eV \((= N_{H,eff}/10^{23} \text{ cm}^{-2}\) eV; Ezuka & Ishida 1999). We conclude that the shock-front has to form immediately above the WD’s surface in order to explain the significant reflection and the strong Fe Kα 6.4 keV line.

### 3.3 The Characteristics of the X-Ray Radiation

The spectral fitting results imply that a substantial fraction (up to a half) of the radiation from the post-shock plasma must be intercepted by the WD’s surface, where the soft and medium energy X-rays are largely absorbed and reprocessed, while hard X-rays are reflected (Mukai 2017). Therefore, in theory, the unabsorbed emission directly from the accretion column should account for a half of the total unabsorbed emission. In order to study the energy balance, we need to calculate the total X-ray luminosity from each part. We extrapolated the best-fitting model up to 100 keV and down to 0.01 keV, the unabsorbed flux \(F_{\text{zemax}}\) from the accretion column is derived as \(4.93^{+0.36}_{-0.11} \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}\) which is converted to the total luminosity \(L_{\text{zemax}}\) corresponding to isotropic emission into the half sphere at a distance \(d\) of \(6.30^{+0.33}_{-0.14} \times 10^{32} \text{ erg s}^{-1}\). The blackbody emission comes from surface elements and its bolometric luminosity is given by \(L_{bb}^{0.01-100} = \pi d^2 F_{bb}^{0.01-100} \text{ sec} \theta\), where \(\theta\) is the mean viewing angle to the emission region (Ramsay & Cropper 2004). Assuming that the blackbody emission region is same as the reflecting surface, we have sec \(\theta = 1/\cos \mu \approx 1\), so the total blackbody luminosity \(L_{bb}\) can be estimated from its time-averaged flux \(6.30^{+0.36}_{-0.11} \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}\). Following the same procedure above, the reflection luminosity \(L_{\text{reflec}}\) is calculated as \(1.39^{+0.11}_{-0.09} \times 10^{32} \text{ erg s}^{-1}\). We estimate that the luminosity outside of 0.01-100 keV is about 1% less than the total one, so the sum of these emission components can be used to estimate the total X-ray luminosity as \(L_{0.01-100} = 1.22^{+0.13}_{-0.10} \times 10^{32} \text{ erg s}^{-1}\), and \(L_{\text{zemax}}\) occupies \(52^{+22}_{-25}\%\) share of the total radiation. We find that V1432 Aql is consistent with the model which includes radiative heating only.

### 3.4 The parameters of the system

A small height of shock column implies that the highest temperature \(T_s\) just below the shock is proportional to the gravitational potential of the WD (Aizu 1973) as \(k T_s = \frac{3}{2} \mu m_p G M_1/R_1\), where \(\mu \approx 0.62\) is the mean molecular weight, \(k\) is Boltzmann constant, \(m_p\) is the proton mass, \(M_1\) is the WD mass, and \(R_1\) is its radius. Therefore, by combining the measured \(T_{max}\) with the Nauenberg (1972) mass-radius relation of WDs, we can calculate \(M_1 = 0.80 \pm 0.03 M_\odot\) and \(R_1 = 0.01 \pm 0.0003 R_\odot\). Adopting the mass–radius relation for CV donor stars (McAllister et al. 2015) and assuming that its volume is equal to that of its Roche lobe (Eggleton 1983), we estimate the mass of the secondary as \(M_2 = 0.22 \pm 0.02 M_\odot\). The X-ray eclipsing analysis (Mukai et al. 2003) gave the eclipse width of 700 s, which implies the inclination of the system as \(i = \frac{78}{0.3} = 260\). The accretion rate \(\dot{M}\) can be estimated assuming that the accretion luminosity is emitted mostly in X-rays and is given by \(\dot{M} = \dot{L}_{0.01-100}/GM_1\). In view of the energy balance of V1432 Aql, the total accretion luminosity is estimated at \(1.26^{+0.06}_{-0.02} \times 10^{33} \text{ erg s}^{-1}\) from \(L_{\text{zemax}}\) to reduce the uncertainty. Substituting these values in equation above gives an accretion rate of \(1.32^{+0.10}_{-0.07} \times 10^{-10} M_\odot\text{yr}^{-1}\). We note that this low accretion rate makes less possible for the postnova classification.
Table 1. Spectral Fit Results.

| Components | Parameters | REFLECT*CEMEKI+BBODY | REFLECT*CEMEKI+BBODY+GAUSS |
|------------|------------|----------------------|-----------------------------|
|            | Bandpass (keV) | 0.3-5.5; 7.5-78 | 0.3-78 |
| PHABS      | $N_H$ (10^{22} cm^{-2}) | 0.13a | 0.13a |
| PCFABS     | $N_H$ (10^{22} cm^{-2}) | 9.28±3.38 0.67±0.06 | 12.65±2.31 0.72±0.04 |
| REFLECT    | $r_e l_e f_{r f}$ | 3.11±2.60 1.15 | 1a |
|            | cos $\mu$ | 0.485 | 0.95 ±0.16 |
|            | Flux$^b$ | ... | 2.18±0.18 ±0.13 |
| CEMEKL     | $\alpha$ | 1a | 1a |
|            | $kT_{\text{max}}$ (keV) | 32.56±6.92 521 | 36.39±2.93 102 |
|            | $n_H$ (cm^{-3}) | 10^4±5.21 | 10^2 |
|            | $Z$ ($Z_\odot$) | 0.25±0.20 | 0.25a |
|            | Redshift | $1.1 \times 10^{-4}$ | $1.1 \times 10^{-3}$a |
|            | Flux$^b$ | ... | 4.93±0.26 ±0.11 |
| BBODY      | $kT$ (eV) | 53±16 12 | 52±15 42 |
|            | Flux$^b$ | ... | 6.73±1.18 ±4.32 |
| GAUSS      | LineE | ... | 6.4a |
|            | $\alpha$ | ... | 0.15±0.08 ±0.09 |
| $\Delta \chi^2$/d.o.f. | ... | 1.01/437 | 1.03/541 |

Note: $^a$ fixed parameter (see text); $^b$ in units of 10^{-11} erg s^{-1} cm^{-2} in the range of 0.01-100 keV.

of V1432 Aql given the short synchronization time-scale for APs (Littlefield et al. 2015; Schmidt & Stockman 1991).

3.5 Comparison with previous results

The past X-ray data obtained with RXTE and XMM-Newton were studied in detail by Rana et al. (2005). They derived a much large blackbody temperature of soft X-rays $88 \pm 2$ eV by adopting a rather low neutral hydrogen column density $4.5 \times 10^{20}$ cm^{-2}. With the $N_H$ of PHABS fixed at this value, Swift data gave a blackbody temperature of 72 ± 24 eV in agreement with their value within errors. We deduce that $T_{\text{bb}} = 52$ eV is much accurate due to the reliable estimation of $N_H$ from the absorption dip at 2200 Å. The best-fit spectral model from the NuSTAR + Swift data yielded a balance in accretion energy, consistent with both predicted by the standard model and the results of Ramsay & Cropper (2004). Rana et al. (2005) quoted a comparatively lower soft-to-hard X-ray ratio of 0.16. Considering that they overestimated the absorption from ISM, their analysis about the energy balance is less convincing.

The most obvious difference between their results and ours is the estimation of the WD mass $M_1$, which may attribute to the reflection effect involved in our model and the different specific accretion rates (Section 4). Our results imply the shock height of the accretion column $H_{sh} \sim 0.001R_1$ using the equation (1) in Rana et al. (2005). The low height is consistent with the strong reflection effect $r_{\text{refl}} \approx 1$. If we ignore the reflection effect in spectral model, the NuSTAR + Swift data give $M_1 \sim 0.9 M_\odot$ that is closer to the estimation $M_1$ of Rana et al. (2005). Also the velocity of narrow Hα lines support our $M_1$ determination. The narrow emission lines arises from the heated hemisphere of the secondary (Patterson et al. 1995) and its radial velocities have an amplitude $\sim 170$ km s^{-1} (Staubert et al. 1994; Watson et al. 1995; Patterson et al. 1995). This velocity is same as that of the inner Lagrangian L1 point if the system has $M_1 = 0.8 M_\odot$ and other parameters in Section 3.4, as the case in AM Her, where the narrow emission component Origins from the L1 point (Mukai 1988). While a radial velocity of $\sim 170$ km s^{-1} will depart from the secondary, on which the material has the minimal velocity of $235$ km s^{-1}, if the system has $M_1 = 1.2 M_\odot$ and other parameters calculated following the method in Section 3.4. From the observed egress duration in V1432 Aql, Mukai et al. (2003) estimated for $M_1$ an upper limit of 0.67 $M_\odot$. We speculate that the radiation from the disk-like structure around the WD maybe contaminate the flux and lower their estimation of $M_1$.

4 DISCUSSION AND CONCLUSIONS

The significant reflection component, and the large Fe Kα equivalent width of $\sim 196$ eV imply that the height of the shock is not significant. The low height of the accretion shock justifies the validity of the post-shock model, where each bremsstrahlung component cools at a constant pressure and gravity, and indicates that the multi-temperature characteristic stems from a range of specific accretion rates over the accretion region. As it approaches the WD, the accretion stream travels most of the way around it, and the gas in the stream is threaded gradually and channeled onto different magnetic field lines, which stretches the accretion region near the WD’s equator and causes the local accretion rate redistribution. Although we fit the soft X-ray component with a single temperature due to the low quality of data, the heated area of the WD may be characterized using a distribution of temperatures, because the area around the accretion region is heated by the multi-temperature shock and the emitting area presents a soft X-ray spectrum with a temperature distribution. Beuermann et al. (2012) explained the soft X-ray spectral energy distribution in AM Her using an exponential distribution of the emitting area vs. blackbody temperature $a(T) = a_0 \exp (-T/T_0)$, where $a_0$...
is the emitting area per eV and $T_0$ is the characteristic temperature. Assuming the same distribution of the heated area with respect to the temperature, we can estimate, from $L^{bb}$ and $T^{bb}$, the fractional region of the heated region as $\sim 0.024\%$ on the WD’s surface, and the mean specific mass accretion rate of $\sim 5.6 \, g \, cm^{-2} \, s^{-1}$, a typical accretion rate in high state for polars. We find that a distribution of the temperatures for the heated region can circumvent the obstacle set by the high blackbody temperature detected (Rana et al. 2005; Staubert et al. 1994).

In this paper, based on reliable estimations of the neutral hydrogen column density and the distance to V1432 Aql, we employed the reasonable models to the broad-band X-ray emission and obtained self-consistent results from the spectral fits. We have unambiguously detected the continuum reflection component in V1432 Aql due to the low height of the accretion column. We estimated the WD’s mass $M_1 = 0.8 M_\odot$ from the maximal temperature of the post-shock column and concluded that this estimation is more accurate than that in the previous works. Then we described the accretion geometry of V1432 Aql, and found that a heated region near the WD’s equator with a distribution of temperatures, the result of the belt-like structure fed accretion, can explain the high soft X-ray temperature. We plan to continue our analysis using the optical data, and performing the arrival time analysis to investigate the effects of the variable location of the threading region on that of the accretion region in order to learn better the interaction between the magnetic field and the matter.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (No. 11933008 and No. 11922306) and Chinese Academy of Sciences Interdisciplinary Innovation Team. We acknowledge with thanks the variable star observations from the AAVSO International Database contributed by observers worldwide and used in this research. The work is also based on observations obtained with the NuSTAR mission, a project led by the California Institute of Technology (Caltech), managed by the Jet Propulsion Laboratory and funded by NASA. We thank the NuSTAR Operations, Software and Calibration teams and the Swift Operations team for support with the execution and analysis of these observations.

DATA AVAILABILITY STATEMENT

All AAVSO data used in the preparation of this manuscript is available from https://www.aavso.org/. NuSTAR and Swift data can be acquired from https://heasarc.gsfc.nasa.gov/db-perl/W3Browse/w3browse.pl using the object names.

Facilities: Swift, NuSTAR.

REFERENCES

Aizu K., 1973, Progress of Theoretical Physics, 49, 1184
Andronov I. L., Baklanov A. V., Burwitz V., 2006, A&A, 452, 941
Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, Astronomical Society of the Pacific Conference Series Vol. 101, Astronomical Data Analysis Software and Systems V. p. 17
Asplund M., Grevesse N., Sauval A. J., Scott P., 2009, ARA&A, 47, 481
Beuermann K., Burwitz V., Reinsch K., 2012, A&A, 543, A41
Cropper M., 1990, Space Sci. Rev., 54, 195
Done C., Osborne J. P., 1997, MNRAS, 288, 649
Eggleton P. P., 1983, ApJ, 268, 368
Ezuka H., Ishida M., 1999, ApJS, 120, 277
Gaia Collaboration et al., 2018, A&A, 616, A1
Geckeler R. D., Staubert R., 1997, A&A, 325, 1070
Hakala P., Ramsay G., Potter S. B., Beardo M., Buckley D. A. H., Wynn G., 2019, MNRAS, 486, 2549
Halpern J. P., Bogdanov S., Thorstensen J. R., 2017, The Astrophysical Journal, 838, 124
Littlefield C., et al., 2015, MNRAS, 449, 3107
Littlefield C., Garnavich P., Mukai K., Mason P. A., Szkyd P., Kennedy M., Myers G., Schwar R., 2019, ApJ, 881, 141
Magdziarz P., Zdziarski A. A., 1995, MNRAS, 273, 837
Mason P. A., Ramsay G., Andronov I., Kolesnikov S., Shakhovskoy N., Pavlenko E., 1998, MNRAS, 295, 511
McAllister M., et al., 2019, MNRAS, 486, 5535
Mukai K., 1988, MNRAS, 232, 175
Mukai K., 2017, PASP, 129, 062001
Mukai K., Hellier C., Madejski G., Patterson J., Skillman D. R., 2003, ApJ, 597, 479
Mukai K., Rana V., Bernardini F., de Martino D., 2015, ApJ, 807, L30
Nauenberg M., 1972, Astrophysical Journal, 175, 417
Patterson J., Skillman D. R., Thorstensen J., Hellier C., 2019, PASP, 107, 307
Pavlenko E. P., et al., 2018, MNRAS, 479, 341
Ramsay G., Cropper M., 2004, MNRAS, 347, 497
Rana V. R., Singh K. P., Barrett P. E., Buckley D. A. H., 2005, ApJ, 625, 351
Schmidt G. D., Stockman H. S., 1991, ApJ, 371, 749
Schmidt G. D., Stockman H. S., 2001, The Astrophysical Journal, 548, 410
Schwope A., 2001, Tomography of Polars. p. 127
Staabert R., Koenig M., Friedrich S., Lamer G., Sood R. K., James S. D., Sharma D. P., 1994, A&A, 288, 513
Staubert R., Friedrich S., Potschmidt K., Benlloch S., Schuh S. L., Kroll P., Splittergerber E., Rothschild R., 2003, A&A, 407, 987
Wang Q., Qian S., Han Z., Fang X., Zang L., Liu W., 2020, ApJ, 892, 38
Watson M. G., et al., 1995, MNRAS, 273, 681
Wynn G. A., King A. R., 1992, MNRAS, 255, 83

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