A MODEL OF WHITE DWARF PULSAR AR SCORPII

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ABSTRACT

A 3.56 hr white dwarf (WD)–M dwarf (MD) close binary system, AR Scorpii, was recently reported to show pulsating emission in radio, IR, optical, and UV, with a 1.97 minute period, which suggests the existence of a WD with a rotation period of 1.95 minutes. We propose a model to explain the temporal and spectral characteristics of the system. The WD is a nearly perpendicular rotator, with both open field line beams sweeping the MD stellar wind periodically. A bow shock propagating into the stellar wind accelerates electrons in the wind. Synchrotron radiation of these shocked electrons can naturally account for the broadband (from radio to X-rays) spectral energy distribution of the system.

Key words: binaries: general – pulsars: general – radiation mechanisms: non-thermal – white dwarfs

1. INTRODUCTION

A white dwarf (WD)–M dwarf (MD) binary, AR Scorpii (henceforth AR Sco), was recently reported to emit pulsed broadband (radio, IR, optical, and UV) emission (Marsh et al. 2016). The brightness of the system varies in long timescales with the orbital period of 3.56 hr and shows pulsation in short timescales with a period of 1.97 minutes. Interpreting the high pulsating frequency as the “beat” frequency of the system, the inferred rotation period of the WD is 1.95 minutes. The spectral energy distribution (SED) of the pulsed emission supports a synchrotron origin for the radiation (Marsh et al. 2016). These peculiar observational properties make AR Sco a unique system. Although AR Sco could be in the evolutionary stage of the so-called intermediate polar (Bookbinder & Lamb 1987; Patterson 1994; Oruço & Meintjes 2012), of which accretion is the main power source, the absence of accretion features in AR Sco demands another mechanism to explain the observations.

It has been suggested that if the dipole magnetic field of a WD is strong enough, it would behave like a WD radio pulsar (Zhang & Gil 2005). The unique pulsating properties of AR Sco suggest that such WD pulsars indeed exist. Here, we propose a WD–MD interaction model for the system. We show that the interaction between the WD pulsar open field line beams with the stellar wind of MD naturally accounts for all the observational properties of the system.

2. WD PULSAR

WDs are the final evolutionary state of stars whose masses are not large enough to become a neutron star (Heger et al. 2003). A group of WDs have a surface magnetic field ranging from $10^5$–$10^8$ G (Wickramasinghe & Ferrario 2000). Some of them spin with periods around one hour, possibly caused by the mass transfer from a companion star (Ferrario et al. 1997). These rapidly rotating magnetized WDs would mimic neutron star pulsars in many ways, e.g., a co-rotating magnetosphere (Goldreich & Julian 1969), and possible pair production processes (Zhang & Gil 2005).

The mass and radius of the WD in AR Sco are derived as $M_{\text{WD}} = 0.8M_\odot$, $R_{\text{WD}} = 7 \times 10^8$ cm, respectively (Marsh et al. 2016). With the measured period $P = 1.95$ minutes and period derivative $\dot{P} = 3.9 \times 10^{-13}$ s$^{-1}$, the spin-down luminosity of the WD pulsar in AR Sco is $L_{\text{rot}} = -4\pi^2I_{\text{PP}}\dot{P} = 3 \times 10^{31}$ erg s$^{-1}$, where $I = \frac{2}{3}M_{\text{WD}}R_{\text{WD}}^2$ is the moment of inertia of the WD. The mean luminosity of AR Sco is $\xi 1.7 \times 10^{33}$ erg s$^{-1}$ including the emission from the MD and is $\xi 1.6 \times 10^{33}$ erg s$^{-1}$ for the non-thermal emission only. Therefore, the spin-down power of the WD can comfortably power the non-thermal radiation of AR Sco.

Assuming a magnetic dipole for the WD and considering a wind outflow from the magnetosphere, the magnetic spin-down power can be written as (e.g., Shapiro & Teukolsky 1983; Xu & Qiao 2001; Contopoulos & Spitkovsky 2006)

$$\dot{E}_{\text{mag}} \simeq \frac{(2\pi)^4B_p^2R_{\text{WD}}^6}{6c^3P^4},$$

where $B_p$ is the surface magnetic field and $c$ is the speed of light. The total spin-down torque of the WD should be exerted from this dipole-wind component and a propeller torque exerted from MD (corresponding to a spin-down power of $\dot{E}_{\text{MD}}$). In the following, we assume $\dot{E}_{\text{mag}} \gg \dot{E}_{\text{MD}}$. One can then derive the surface magnetic field at the polar cap:

$$B_p \simeq \left( \frac{3M_{\text{WD}}c^3}{5\pi^2R_{\text{WD}}^4PP} \right)^{1/2} = 7.1 \times 10^8 G \left( \frac{P}{1.95 \text{ minutes}} \right)^{1/2} \left( \frac{\dot{P}}{3.9 \times 10^{-13} \text{s}^{-1}} \right)^{1/2}.$$  

The light cylinder radius is $R_L = cP/2\pi = 5.6 \times 10^{11}$ (P/1.95 minutes) cm, which is greater than the distance between the WD and the MD, $d \sim 7.6 \times 10^{10}$ cm. This suggests that the MD sits inside the magnetosphere of the optical emission.
WD, and significant interaction between the WD wind and MD is expected. The polar cap opening angle of the last open field line is (Ruderman & Sutherland 1975)

$$\theta_{\text{open}} = \left( \frac{R_{\text{WD}}}{R_c} \right)^{1/2} = 2^6 \left( \frac{P}{1.95 \text{ minutes}} \right)^{-1/2},$$

and the corresponding polar cap radius is

$$R_{pc} = R_{\text{WD}} \left( \frac{R_{\text{WD}}}{R_c} \right)^{1/2} = 2.5 \times 10^7 \left( \frac{P}{1.95 \text{ minutes}} \right)^{-1/2} \text{ cm.}$$

The maximum available unipolar potential drop across the polar cap is

$$\Phi_{\text{max}} = \frac{2\pi^2 B_p R_{\text{WD}}}{c^2 P^2} \approx 3.9 \times 10^{11} \text{statV} \times \left( \frac{P}{1.95 \text{ minutes}} \right)^{-3/2} \left( \frac{3.9 \times 10^{-13} \text{s}^{-1}}{\right)^{1/2},$$

which can accelerate electrons to a Lorentz factor of

$$\gamma_e = q_e \Phi_{\text{max}}/m_e c^2 \approx 2.3 \times 10^8,$$

where $q_e$ is the electron charge and $m_e$ is the electron mass. Pair production through $\gamma - B$ and $\gamma - \gamma$ mechanisms is possible, so that the WD can act as an active pulsar (Zhang & Gil 2005; Kashiwayama et al. 2011).

### 3. GEOMETRY

Before performing calculations on the radiation properties, we first infer the geometry of AR Sco by analyzing the temporal characteristics of the pulses. Unlike radio pulsars that typically show a small duty cycle <10%, AR Sco shows a large duty cycle of about 50% in the light curves in broadband. The emission likely comes from the MD rather than the WD itself (Marsh et al. 2016). More interestingly, there are two peaks in each period, and each peak has exactly the same period. A natural explanation is that the WD is a nearly perpendicular rotator (the angle between the spin and magnetic axes is close to $\alpha \approx 90^\circ$) with both open field line beams sweeping the MD in each rotation period. The orbital brightness modulation implies that the inclination of the orbital plane to the line of sight is small. A deviation of the line of sight from the orbital plane would naturally produce the uneven brightness of the two peaks in each spin cycle. All these clues lead to a special geometric configuration as shown in Figure 1. The spin axis of the WD points into the plane of the page, while the line of sight and the orbital plane are roughly on the page plane for the specific configuration in Figure 1.

The ratio between the durations of the active pulse and the quiescent time is $\sim 1:1$ (duty cycle $\sim 50\%$). This suggests that the opening angle of the entire eclipse site seen from the WD should be $\sim 90^\circ$. Since the MD only opens a $2\alpha_{\text{MD}}/d \sim 38^\circ$ angle from the WD, the actual location of the emission site should be at a larger radius from the MD center. The interaction between the particle beam streaming out from the open field line regions and the MD wind would lead to the formation of a bow shock, where the electrons can be accelerated to give radiation. In Figure 1, when the open field lines of the WD are approaching the atmosphere of the MD, there exists a position at which the ram pressure of the stellar wind balances the magnetic pressure. We note this position as point "A" (its position will be calculated in Section 4.2) and assume that radiation rises from this point. In the realistic 3D case, this position should be a part of a ring-like region. According to the duty cycle of the pulsation, the angle from the WD between point A and the MD center should be $\theta_{A} \sim 90^\circ/2 = 45^\circ$.

### 4. RADIATION

#### 4.1. Synchrotron Radiation

An outflow of relativistic particles from the open field line regions of the WD would impact the MD wind and drive a bow shock into it. Since the magnetization of the WD wind is not known, there may or may not be a reverse shock. In any case, since the accelerated particles are still within the magnetosphere of the WD, they would give rise to synchrotron radiation in the magnetic field of the magnetosphere.

The open field lines of the WD would be extruded by the ram pressure of the stellar wind during the period when they sweep the MD wind. When the polar cap faces the center of the MD, the effective opening angle of the open field lines reaches the maximum value (Figure 1), and the luminosity also reaches the peak value. We define the head position of the bow shock at this epoch as point "B." Since the magnetic pressure at B is larger than that at A, the magnetic pressure would push point B to be near the surface of the MD. Its distance to the center of the WD is $x \sim d - R_{\text{MD}} \approx 5.1 \times 10^{10}$ cm ($R_{\text{MD}} = 2.5 \times 10^{10}$ cm is the radius of the MD) and the corresponding magnetic field is $B_B = B_p (x/R_{\text{WD}})^{-2} \approx 1860$ G. Since the synchrotron emission SED we model is an average one across different phases, we use an average magnetic field $\bar{B} = (B_A + B_B)/2 \approx 1200$ G ($B_A$ is the magnetic field at A and is obtained according to its position; see Section 4.2) in our calculations.

For a relativistic electron of Lorentz factor $\gamma_e$, its radiation power is (Rybicki & Lightman 1979)

$$\dot{\epsilon} = \gamma_e^2 \sigma_T \bar{B}^2 c / 6\pi = 1.5 \times 10^{-9} \gamma_e^2 \text{ erg s}^{-1},$$

where $\sigma_T$ is the Thomson cross section. Hereafter, the convention $Q_e = (Q/10^4)$ is adopted in cgs units. Its cooling timescale can be calculated as $t_{\text{cool}} = (\gamma_m c^2/\dot{\epsilon})$. It is reasonable to assume that the relativistic electrons that give rise to synchrotron radiation obey a broken-power-law distribution, i.e.,

$$\frac{dN_e}{d\gamma_e} = \begin{cases} C \gamma_e^{-p}, & \gamma_m \leq \gamma_e \leq \gamma_{\text{max}}, \\ C \gamma_e^{-p-1}, & \gamma_e < \gamma_m \leq \gamma_{\text{max}}, \end{cases}$$

where $C \propto (p - 1) \gamma_m^{-p-1} n_e$, $\gamma_m$ is the typical Lorentz factor, $\gamma_e$ is the cooling Lorentz factor, $\gamma_{\text{max}}$ is the maximum Lorentz factor, and $n_e$ is the number density of the electrons. Then, the peak frequency of the corresponding synchrotron spectrum is

$$v_m = \frac{3 \times 0.9 \bar{B}_{10}^2}{4\pi n_e c} = 2.5 \times 10^{10} \gamma_m^2 \text{ Hz},$$
where $n_p \simeq 0.5$ (Wijers & Galama 1999). Inspecting the SED (Marsh et al. 2016, Figure 2), we find $\nu_m \simeq 5 \times 10^{12}$ Hz, which gives $\gamma_m = 45$. The cooling Lorentz factor $\gamma_c$ can be estimated by equating $t_{\text{cool}}(\gamma_c)$ with the mean dynamical time of the shock $t_{\text{dyn}} \simeq \frac{45}{360} \nu_p$, where $45^\circ$ is the angle for the WD beam to sweep through before reaching the peak, and the half value reflects the mean angle, which defines the mean dynamical timescale. We then obtain $\gamma_c = 73 (P/1.95 \text{ minutes})^{-1}$. The Lamor radius of a relativistic electron is $R_L = \gamma_c m_e c^2 / q_e B$, and its acceleration timescale can be calculated as $t_{\text{acc}} \simeq R_L/c$. Equating $t_{\text{acc}}(\gamma_{\text{max}})$ with $t_{\text{cool}}(\gamma_{\text{max}})$, one can obtain the maximum Lorentz factor of the shocked electrons as $\gamma_{\text{max}} = (6\pi q_e / q_e^2 B)^{1/2} = 3.4 \times 10^6$. The corresponding maximum Lamor radius is $R_{L,\text{max}} = 4.8 \times 10^6$ cm.

Assuming that the width of the emission shell is $\eta R_{\text{MD}}$, the shell volume $V$ is $2\pi (1 - \cos(\theta_B)) \eta R_{\text{MD}}^3$, where $\theta_B$ is the half opening angle of the shell seen from the MD, and $\theta_B \simeq 90^\circ - \arcsin(R_{\text{MD}}/d) = 71^\circ$ (Figure 1). The value of $\eta$ may be inferred from the Lamor radius of the most energetic electron, i.e., $\eta \simeq 2R_{L,\text{max}}/R_{\text{MD}} = 4 \times 10^{-4}$. Since $\nu_m < \nu_c$, the synchrotron emission is in the slow cooling regime, and the peak flux density is at $\nu_m$, which reads

$$F_{\nu,\text{peak}} = \frac{\sqrt{3} q_e B}{m_e c^2} \frac{\eta \nu_m V}{4\pi D_L^2},$$

where $D_L = 116$ pc is the distance of AR Sco to the observer. Observationally, the spectrum of AR Sco shows a peak flux density $\simeq 1.6 \times 10^{-24}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ (Marsh et al. 2016).
We therefore obtain

\[
\frac{4 \pi R_{\text{MD}} v_{\text{esc}} m_p}{\zeta} = 4.1 \times 10^{-11} (\zeta/0.2)^{-1} M_\odot \text{ yr}^{-1},
\]

where \( \zeta \) denotes the fraction of electrons that are accelerated and \( n_e \) has been taken as \( 3.5 \times 10^8 \) cm\(^{-3} \) as required in Equation (10). This value is within the range of mass-loss rate of MDs in the literature, \( 10^{-15} \sim 10^{-10} M_\odot \text{ yr}^{-1} \) (e.g., Mullan et al. 1992; Wood et al. 2001; Vidotto et al. 2014). It indicates that the wind from the WD could be a reasonable source for electrons.

The position of the balance point \( A \) (see Figure 1 and Section 3) can be found using the balance between the ram pressure of the wind and the magnetic pressure. We define the distance between \( A \) and the MD center as \( r_A \). The distance between \( A \) and the WD center may be roughly estimated as \( d \). The relative velocity between the wind and the magnetic field lines is thus \( v_{\text{rel}} = \frac{2 \pi}{P} d \). The condition that the magnetic pressure balances the wind ram pressure gives

\[
\frac{B_A^2}{8 \pi} = \left( \frac{r_A}{R_{\text{MD}}} \right)^{-2} \frac{1}{\zeta} n_e m_p v_{\text{rel}}^2,
\]

where \( B_A = B_p (d/R_{\text{MD}})^{-3} \) is the magnetic field strength at point \( A \), \( m_p \) is the proton mass, and the factor \( (\zeta/0.2)^{-1} \) takes into account the correction of the electron density \( n_e \) from point B to point A due to the radial expansion of the wind. Using Equations (10) and (13), one obtains

\[
r_A = 5.0 \times 10^{10} \left( \frac{F_{\nu, \text{peak}}}{1.6 \times 10^{-24} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}} \right)^{1/2} \times \left( \frac{\eta}{4 \times 10^{-4}} \right)^{-1/2} \left( \frac{\zeta}{0.2} \right)^{-1/2} \text{ cm}.
\]

Another way to derive \( r_A \) is from the geometric relation in Figure 1. For the isosceles triangle defined by point \( A \) and the centers of the two stars, one has \( \sin \theta_A/r_A = \sin (90^\circ - \theta_A/2)/d \), which gives \( r_A = 5.8 \times 10^{10} \) cm for \( \theta_A \sim 45^\circ \). One can see that the values of \( r_A \) are consistent with each other using two methods, suggesting that the emitting electrons are indeed from the MD wind.

4.3. The Spectrum

Using the electron distribution in Equation (7), one can calculate the synchrotron spectrum. The spectrum is characterized by a broken power law separated by three frequencies, the self-absorption frequency \( \nu_a \), the injection frequency \( \nu_m \), and the cooling frequency \( \nu_c \) (Sari et al. 1998). The characteristic frequencies \( \nu_m \) and \( \nu_c \) are derived from \( \gamma_m \) and \( \gamma_c \), respectively. The spectrum in the spectral regime \( \nu_m < \nu < \nu_c \) has \( \nu F_{\nu} \propto \nu^{-(p-3)/2} \). According to the observed SED of AR Sco (Marsh et al. 2016), the source was also detected in the X-ray band by Swift X-Ray Telescope (even though not pulsed). The X-ray data constrain the value of \( p \) to be around 2.4. The self-absorption coefficient at frequency \( \nu \) can be calculated as (e.g., Rybicki & Lightman 1979; Wu et al. 2003)

\[
\kappa_\nu \simeq \frac{q_\nu}{B} n_e \gamma_m \left( \frac{\nu}{\nu_m} \right)^{-5/3},
\]

where \( q_\nu = \frac{8 \pi^2}{9 \Gamma(1/3)} \frac{p+2}{p+1} (p-1) \simeq 5.2 \), and \( \Gamma(1/3) \) is the Gamma function of argument 1/3. The self-absorption frequency can be solved when the optical depth \( \kappa_\nu n_e R_{\text{MD}} \)
One gets $\nu_B \simeq 2.4 \times 10^{-3} \nu_m$ for AR Sco. Figure 2 displays the comparison between our analytical model SED and the observed SED (Marsh et al. 2016). One can see that the model can well interpret the data. One interesting feature is that the observed flux at the thermal peak exceeds the model spectrum of the MD thermal emission. However, adding the contribution of the non-thermal synchrotron component (which extends all the way to the X-ray band), the total model flux matches the observations very well.

5. SUMMARY AND DISCUSSION

We have shown that the peculiar observations of the pulsating AR Sco system can be understood with the framework of interaction between the WD pulsar’s open field line beams and the wind of the MD. The observational data demand a nearly perpendicular rotator for the WD pulsar and a nearly edge-on orbital configuration for the observer on Earth. In order to interpret the observed SED, the required electron number density is too high for a WD wind. Rather, electrons accelerated by a bow shock into the MD wind can produce the right amount of electrons to interpret both the shape and the normalization of the SED.

In our model, although the magnetic field lines of the WD are likely ordered, an observer sees a hemisphere where magnetic field lines have different directions so that on average the directional information cancels out (e.g., in Figure 2, the field lines above and below point B have opposite orientations). One would therefore not expect significant circular polarization (Matsumiya & Ioka 2003), which is consistent with the observations (Marsh et al. 2016).

Our model suggests that rapidly rotating, highly magnetized WDs can indeed behave like radio pulsars, as has been speculated in the past (Zhang & Gil 2005). The rarity of these WD pulsars (Kepler et al. 2013) may be due to the conditions that produce an active magnetosphere via pair production being much more stringent for WDs than NSs. The peculiarity of AR Sco lies in its extremely short period and its close proximity with its MD companion. According to our modeling, the observed emission is from the shocked MD wind rather than from the WD pulsar itself. However, if some WDs indeed behave as pulsars, one would expect to directly detect emission from WD pulsars in the future. GCRT J1745-3009 might be another, less energetic, transient WD pulsar (Zhang & Gil 2005) at a distance beyond 1 kpc from the Earth (Kaplan et al. 2008).

We thank the anonymous referee for valuable suggestions and Yuan-Pei Yang for helpful discussion on this Letter. This work is partially supported by the National Basic Research Program of China with grant No. 2014CB845800 and by the National Natural Science Foundation of China (grant Nos. 11473012 and 11303013). J.J.G. acknowledges the China Scholarship Program to conduct research at UNLV.

Note added in proof. After this Letter was posted, we noticed an alternative suggestion by Katz (2016), who suggested a WD–MD synchronization model to interpret the source. Without introducing a strong MD wind, it is unclear whether that model can have enough electrons to satisfy the observational constraints.

REFERENCES

Arons, J. 2009, in Neutron Stars and Pulsars, Astrophysics and Space Science Library, Vol. 357, ed. W. Becker (Berlin: Springer), 373
Bookbinder, J. A., & Lamb, D. Q. 1987, ApJL, 323, L131
Contopoulos, I., & Spitkovsky, A. 2006, ApJ, 643, 1139
Duncan, R. C., & Thompson, C. 1992, ApJL, 392, L9
Ferrario, L., Vennes, S., Wickramasinghe, D. T., Bailey, J. A., & Christian, D. J. 1997, MNRS, 292, 205
Goldreich, P., & Julian, W. H. 1969, ApJ, 157, 869
Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, ApJ, 591, 288
Kaplan, D. L., Hyman, S. D., Roy, S., et al. 2008, ApJ, 687, 262
Kashiya, K., Ioka, K., & Kawanaaka, N. 2011, PhRvD, 83, 023002
Katz, J. I. 2016, arXiv:1609.07712
Kepler, S. O., Pelisoli, I., Jordan, S., et al. 2013, MNRAS, 429, 2934
Lobato, R. V., Malheiro, M., & Coelho, J. G. 2016, IJMPD, 25, 1641025
Malheiro, M., Rueda, J. A., & Ruffini, R. 2012, PASJ, 64, 56
Marsh, T. R., Gänsicke, B. T., Hümmerich, S., et al. 2016, Natur, 537, 374
Matsumiya, M., & Ioka, K. 2003, ApJL, 595, L25
Mukhopadhyay, B., & Rao, A. R. 2016, JCAP, 5, 007
Mullan, D. J., Doyle, J. G., Redman, R. O., & Mathioudakis, M. 1992, ApJ, 397, 225
Orubu, B., & Meintjes, P. J. 2012, MNRS, 421, 1557
Paczynski, B. 1990, ApJL, 365, L9
Patterson, J. 1994, PASP, 106, 209
Ruderman, M. A., & Sutherland, P. G. 1975, ApJ, 196, 51
Rybicki, G. B., & Lightman, A. P. 1979, Radiative Processes in Astrophysics (New York: Wiley-Interscience)
Sari, R., Piran, T., & Narayan, R. 1998, ApJL, 497, L17
Shapiro, S. L., & Teukolsky, S. A. 1983, Research Supported by the National Science Foundation (New York: Interscience)
Thompson, C., & Duncan, R. C. 1996, ApJ, 473, 322
Usoskin, I. G. 2002, ApJ, 578, 1009
Vidotto, A. A., Jardine, M., Morin, J., et al. 2014, MNRAS, 438, 1162
Wickramasinghe, D. T., & Ferrario, L. 2000, PASP, 112, 873
Wijers, R. A. M. J., & Galama, T. J. 1999, ApJ, 523, 177
Wood, B. E. 2004, LRSP, 1, 2
Wood, B. E., Linsky, J. L., Müller, H.-R., & Zank, G. P. 2001, ApJL, 547, L49
Wu, X. F., Dai, Z. G., Huang, Y. F., & Lu, T. 2001, ApJL, 561, L85
Zhang, B., & Gil, J. 2005, ApJL, 631, L143
Zhang, B., & Harding, A. K. 2000, ApJ, 532, 1150