Formation of the Asymmetric Accretion Disk from Stellar Wind Accretion in an S-type Symbiotic Star

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Abstract

The accretion process in a typical S-type symbiotic star, targeting AG Draconis, is investigated through 3D hydrodynamical simulations using the FLASH code. Regardless of the wind velocity of the giant star, an accretion disk surrounding the white dwarf is always formed. In models where the wind is faster than the orbital velocity of the white dwarf, the disk size and accretion rate are consistent with the predictions under Bondi–Hoyle–Lyttleton (BHL) conditions. In slower-wind models, unlike the BHL predictions, the disk size does not grow, and the accretion rate increases to a considerably higher level, up to >20% of the mass-loss rate of the giant star. The accretion disk in our fiducial model is characterized by a flared disk with a radius of 0.16 au and a scale height of 0.03 au. The disk mass of \(5 \times 10^{-3} M_\odot\) is asymmetrically distributed, with the density peak toward the giant star being about 50% higher than the density minimum in the disk. Two inflowing spiral features are clearly identified, and their relevance to the azimuthal asymmetry of the disk is pointed out. The flow in the accretion disk is found to be sub-Keplerian, at about 90% of the Keplerian speed, which indicates a caveat of overestimating the O VI emission region from the spectroscopy of Raman-scattered O VI features at 6825 and 7082 \(\AA\).

Unified Astronomy Thesaurus concepts: Symbiotic binary stars (1674); Hydrodynamical simulations (767); Stellar accretion disks (1579)

1. Introduction

Binary systems involving an accreting white dwarf (WD) are mainly classified into cataclysmic variables and symbiotic stars. Cataclysmic variables are semidetached binary systems of an accreting WD and a late-type main-sequence star. In these stellar systems, the formation of an accretion disk through Roche lobe overflow has been well established. The main features characterizing cataclysmic variables are dwarf nova outbursts, which are attributed to significant changes in viscosity relating to the surface mass density of the disk (e.g., Warner 1995).

In contrast, a symbiotic star is a wide binary system consisting of a late-type evolved star with a large mass-loss rate, ranging \(10^{-8} \text{ to } 10^{-6} M_\odot \text{ yr}^{-1}\) (Dupree 1986; Seaquist et al. 1993; Höfner & Olofsson 2018), and a hot accreting star, usually a WD (Kenyon 1986). Symbiotic stars are classified as S-type or D-type, based on their spectral energy distributions. D-type symbiotic stars exhibit infrared (IR) excess, indicative of the presence of a warm dust component with \(T \sim 10^3 \text{ K}\), whereas no such IR excess appears in S-type objects. The orbital periods of S-type symbiotic stars are typically a few years, whereas those of D-type symbiotics are poorly known and have been suggested to be in the range of several decades (Belczyński et al. 2000).

The large binary separation of most symbiotic stars implies that the Roche lobe of the giant component is underfilled, so that accretion onto the WD component occurs through gravitational capture of the slow stellar wind from the giant component. Mürset & Schmid (1999) suggested that, at least in most symbiotic systems, the radius of the giant star is only half the distance to the inner Lagrangian point, which was empirically found from the strong correlation between the spectral types of cool giants and their orbital periods. However, in some cases with short orbital period systems, mass transfer through the inner Lagrangian point may not be completely excluded (e.g., Boffin et al. 2014).

The luminosity of the hot component in symbiotic stars during the quiescent phase is found to be in the range \(10^8 \text{ to } 10^9 L_\odot\), which is mostly contributed by stable thermonuclear reaction on the surface of the WD, with an accretion rate of a few times \(10^{-8} \text{ to } 10^{-7} M_\odot \text{ yr}^{-1}\), depending on the mass of the WD (see, e.g., Figure 2 of Shen & Bildsten 2007). Major outbursts with luminosity of the order \(10^4 L_\odot\) are often attributed to thermonuclear burning, as a result of a substantially increased accretion rate of \(\sim 10^{-6} M_\odot \text{ yr}^{-1}\) (Sokoloski et al. 2006; Mikolajewska 2012). The variability exhibited by symbiotic stars is apparently influenced by many factors, including the pulsations of the giant star, the instability associated with the accretion flow, and nonsteady thermonuclear burning on the surface of the WD (Sokoloski et al. 2006).

A highly interesting spectroscopic tool for probing the accretion processes in symbiotic stars is provided by the broad emission features at 6830 and 7088 \(\AA\) that are known to be present in about half of the symbiotic stars (Allen 1980; Akras et al. 2019). These spectral features are formed through the inelastic scattering of O VI \(\lambda\lambda 1032\) and 1038 with atomic hydrogen (Schmid 1989). They exhibit double- or triple-peak profiles, with an enhanced red peak, and the peak separation is about 20–40 km s\(^{-1}\). Schmid (1996) carried out a pioneering radiative transfer study, using the Monte Carlo technique, to investigate the basic properties of Raman-scattered O VI
features, including the Raman scattering efficiency and polarization structures.

Lee & Kang (2007) proposed that multiple-peak profiles can be explained by invoking a Keplerian accretion disk, with a peak separation of \( \sim 50 \text{ km s}^{-1} \), an asymmetric density distribution augmented by the modulation of the stellar wind terminal velocity \( \sim 20 \text{ km s}^{-1} \), and the presence of receding bipolar components with respect to the binary orbital plane. The geometry of the neutral medium is complex, and the accretion flow around the WD tends to be asymmetric, based on previous Raman O VI spectroscopic investigations (see Lee & Lee 1997; Heo & Lee 2015; Lee et al. 2019).

Lee et al. (2019), however, pointed out that the line profile analysis of Raman-scattered O VI has its limitations, as the adopted model for the O VI emission region is purely kinematical, with no proper dynamical considerations. Therefore, hydrodynamical studies of the stellar wind accretion in symbiotic stars will allow a quantitative estimation of the asymmetric distribution of the O VI emitters, leading to a more reliable description of mass transfer through Raman spectroscopy than the purely kinematical model.

The stellar wind accretion processes in relatively close binary systems, corresponding to typical S-type symbiotic stars, have been investigated by Chen et al. (2017) and Saladino et al. (2018, 2019). Their hydrodynamic simulations for a variety of orbital and wind parameters, including a binary separation of 3–20 au, have clarified that the comparable speeds between the wind flow of the giant star and the orbital motion of the accretor (the companion star; the secondary star; the WD in a symbiotic star system) provide favorable conditions for disk formation. These studies focused on showing the effects of the orbital and wind parameters on the overall morphology of the matter surrounding the binary, the mass-accretion efficiency onto the accretor, the angular momentum loss of the binary orbit, and the change in the mass-loss rate of the giant star. Less focused issues in these previous investigations include the physical structures of accretion disks—for example, the density and velocity distributions, which constitute the main scope of this paper.

Some details of the disk formation resulting from the capturing of wind material in binaries, albeit only for relatively wide systems with separations of 10–20 au, are explored by Huarte-Espinosa et al. (2013). Based on the Bondi–Hoyle–Lyttleton (BHL) accretion theory (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944), Huarte-Espinosa et al. (2013) derived the upper limit for the radius of the wind-captured disk surrounding the accretor as a function of the masses of the component stars, the orbital separation, and the wind velocity. This formula plays an important role in yielding the minimum resolution criteria for numerical simulations to properly resolve the wind capture timescale that is associated with the simulated grid resolution. In this earlier work, the disks occupied more than \( \sim 50 \) cells within the radii for the different models. Besides such an analytic treatment of the disk formation, the major results from these numerical simulations included the discovery of the vortex tube–like accretion stream and the measurement of the temporal changes of the accretion disk in terms of mass and eccentricity. They also provided new insights into BHL accretion and a comprehensive analysis of the accretion streams in binary systems. The formation process and the physical structure of a disk in a closer binary would be different, however; for instance, as noted by Huarte-Espinosa et al. (2013), the stripping of the disk material, due to the powerful ram pressure of the stellar wind, and much higher accretion rates would be expected in closer binaries.

In this work, we carry out 3D hydrodynamic simulations of stellar wind accretion processes in relatively close binaries that mimic typical S-type symbiotic stars. To understand the formation and evolution of accretion disks in close binaries, we present a quantitative analysis of the flows toward, and within, the accretion disks. In Section 2, we introduce the numerical methods adopted in this work. In Section 3, our fiducial model presents the gas flows that form a large-scale spiral structure surrounding the binary stars, where the head interacts with the flows, building an accretion disk around the WD. Several models that adopt different wind parameters are also exhibited in order to describe the formation criteria and time evolutions of the accretion disks in this section. The observational ramifications for the S-type symbiotic star AG Dra are briefly described in Section 4. Finally, we discuss the effects of the accretion and the structure of the disks in Section 5.

2. Simulation Setup

2.1. Equations of Hydrodynamics

In order to simulate the wind accretion processes in S-type symbiotic stars, we adopt the adaptive mesh refinement code FLASH (Fryxell et al. 2000) in version 4.5, with modifications similar to those in the works carried out by Kim & Taam (2012b) and Kim et al. (2013, 2017, 2019). In this work, the fluid is assumed to be inviscid and non-self-gravitating. The Eulerian hydrodynamic equations are used in the center-of-mass frame, with the Cartesian coordinates.

Based on the continuity equation

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \tag{1}
\]

the initial density distribution is set by

\[
\rho_0(r) = \frac{M_G}{4\pi |r - r_G|^2 V_G}, \tag{2}
\]

assuming a steady-state stellar wind originating from the intrinsically spherical symmetric mass loss of a nonpulsating and nonrotating giant star situated at \( r = r_G \). The initial density distribution of the background is relaxed within an orbit of the binary in the simulation. Here, the parameter \( V_G \) indicates the stellar wind velocity at \( |r - r_G| = r_s \), which we define as the surface of the giant star. The radius \( r_s \), at which the wind density and velocity conditions are reset for every simulation step, is set to 0.25 au, similar to the photospheric radius of an evolved giant star of an S-type symbiotic system (Skopal 2005; see also Dumm & Schild 1998). Because the radius of the giant star is much less than the distance to the inner Lagrangian point (~1 au) in the binary system employed in our simulations, mass transfer through the Roche lobe overflow does not occur. The adopted mass-loss rate of the giant star is \( \dot{M}_G = 10^{-7} M_\odot \text{ yr}^{-1} \). Because the mass loss of the giant star during the total simulation time is negligible, in terms of the orbital evolution of the binary system, a simplification is made, by fixing the stellar masses and their orbits throughout the simulation.
The masses of the two stars are fixed to $M_\star = 1.5 \, M_\odot$ and $M_{\text{WD}} = 0.6 \, M_\odot$. The two stars orbit the center of mass of the binary system, following the assumed circular trajectories with a fixed separation of 2 au ($= |\mathbf{r}_G - \mathbf{r}_{\text{WD}}|$). The corresponding orbital period is $\sim 2$ yr. The orbital velocity of the WD is $V_{\text{WD}} = 21.8$ km s$^{-1}$, with respect to the center of mass of the binary, and the relative velocity between the stars is $V_{\text{rel}} = 30.5$ km s$^{-1}$. In Table 1, we summarize the fixed parameters adopted for the models exhibited in this paper.

The acceleration force on the wind material is determined by the equation of motion:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla P - \nabla \Phi_{\text{eff}}^{\star} - \nabla \Phi_{\text{WD}}. \quad (3)$$

An adiabatic equation of state with a specific heat ratio, $\gamma = 5/3$, for a monatomic ideal gas is used to update the pressure $P$. We also set the effective temperature of the giant star, $T_{\text{eff}} = 4000$ K, which is proper for the giant star of S-type symbiotic stars, as presented by Skopal (2005).

The specific gravitational forces $-\nabla \Phi_{\text{eff}}^{\star}$ and $-\nabla \Phi_{\text{WD}}$ due to the presence of the giant star and the WD, are defined by the Plummer models with the softening radii $r_{\text{soft,G}}$ and $r_{\text{soft,WD}}$, respectively (Binney & Tremaine 2008):

$$-\nabla \Phi_{\text{eff}}^{\star} = -\frac{GM_\star(1-f)}{|\mathbf{r} - \mathbf{r}_{\text{G}}|^3 + r_{\text{soft,G}}^2},$$

$$-\nabla \Phi_{\text{WD}} = -\frac{GM_{\text{WD}}}{|\mathbf{r} - \mathbf{r}_{\text{WD}}|^3 + r_{\text{soft,WD}}^2}.$$ 

Here, $G$, $M_{\text{G,WD}}$, and $r_{\text{G,WD}}$ are the gravitational constant, the individual masses of the giant star and the WD, and the position vectors of the stars at the center-of-mass coordinates, respectively. The softening radius $r_{\text{soft,G}}$ for the giant star is set to 0.25 au, being comparable to the expected photospheric radius of the giant star (see above). The size of the WD (on the order of $10^{-5}$ au) cannot be resolved in our simulations, due to the limitations on computation time; therefore, we set the softening radius $r_{\text{soft,WD}}$ as the smallest length scale at a given resolution of the simulation model, within which we require more than a minimum of four grid cells (see Table 2). The acceleration factor $f$ of unity is assumed in all of our simulations (see Section 2.1 of Kim & Taam 2012a for details of the wind model).

The orbital velocity of the WD relative to the wind velocity in situ is an important factor regulating the detailed properties of the accretion disk. The simulations are carried out by varying the intrinsic wind velocity, $V_w$, defined as the velocity at the distance to the WD (i.e., 2 au) in the corresponding single-star simulation, in which the WD is intentionally absent. Alternatively speaking, $V_w$ is determined merely by the balance between the gas pressure and the effective gravitational potential of the giant star with an inclusion of the acceleration factor, mimicking the radiation pressure onto the hypothetical dust particles. The velocity $V_w$ for each model is listed in Table 2.

### Table 1

| Parameter | Value | Description |
|-----------|-------|-------------|
| $M_\star$ | $1.5 \, M_\odot$ | Mass of the giant star |
| $M_{\text{WD}}$ | $10^{-7} \, M_\odot$ yr$^{-1}$ | Mass-loss rate of the giant star |
| $M_{\text{WD}}$ | $0.6 \, M_\odot$ | Mass of the WD |
| $a$ | 2 au | Binary separation |
| $r_{\text{G}}$ & $r_{\text{soft,G}}$ | 0.25 au | Photospheric and gravitational softening radii of the giant star |
| $T_{\text{eff}}$ | 4000 K | Effective temperature of the giant star |
| $f$ | 1 | Acceleration factor |

2.2. Treatment for Cooling

In the energy equation, we include the radiative cooling as two separate terms, following Saladin et al. (2018):

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P)\mathbf{v}] = -\rho \left[ \frac{3k}{2\mu m_p} \left( T - T_{\text{eq}} \right) \rho \right] + Q_{\text{sh}}. \quad (4)$$

Here, $E$, $T$, $P$, $\mathbf{v}$, and $\rho$ are the basic quantities that describe the fluid, representing the total energy, temperature, pressure, velocity vector, and mass density, respectively. The constants $k$ and $m_p$ are the Boltzmann constant and proton mass, respectively, and $\mu = 1.29$ is the mean molecular weight appropriate to the solar metallicity (e.g., Anders & Grevesse 1989).

The first cooling term on the right-hand side of Equation (4) regulates the gas temperature, being balanced with the equilibrium temperature (Chandrasekhar 1934),

$$T_{\text{eq}} = T_{\text{eff}}(W + 3/4\tau^4)^{1/4}, \quad (5)$$

within the equilibrium timescale, $C/\rho$, where the constant $C = 10^{-5}$ g s$^{-3}$ is derived from an approximate density-dependent expression of the radiative cooling rate in the atmosphere of giant stars (Bowen 1988). The effective temperature $T_{\text{eff}}$ represents the temperature at the photosphere of the giant star. The parameter $W = (1/2)[1 - (1 - r_{\text{G}}^2/s^2)^{1/2}]$ indicates the geometrical dilution factor at a distance $s = |\mathbf{r} - \mathbf{r}_{\text{G}}|$ from the giant star, while the optical depth $\tau_i = \int_0^s \left( \kappa_g + \kappa_d \right) \rho \, r^2 \, ds$ and the factor $3/4$ in Equation (5) are determined by assuming a plane-parallel atmosphere. The opacities for gas and dust, $\kappa_g$ and $\kappa_d$, are $2 \times 10^{-4}$ and 5 cm$^2$ g$^{-1}$, respectively. Notice that when the gas temperature drops below $T_{\text{eq}}$, this first cooling term behaves like a heating source with regard to the radiation of the giant star, preventing unrealistic reductions in the gas temperature.

The second term on the right-hand side of Equation (4) describes the radiative cooling, taking into account neutral hydrogen and heavier chemical elements in a gaseous medium with solar abundance. The cooling rate is defined as

$$Q_{\text{sh}} = \frac{\Lambda_{\text{bd}} n_{\text{H}} T_{\text{eq}}^4}{\rho} , \quad (6)$$

with the cooling function $\Lambda_{\text{bd}}$ provided by Schure et al. (2009) in their Table 2. The hydrogen number density $n_{\text{H}} = X \rho / m_p$ is calculated with a fixed mass fraction of hydrogen in the gas ($X = 0.707$). When the gas temperature rapidly increases at the shock fronts that are established at the spiral’s arms or in the vicinity of the WD, under the strong gravitational potential well, the second cooling term plays an important role in efficiently reducing the internal energy of the gas. It therefore provides a favorable condition for disk formation surrounding...
The intrinsic wind velocity $V_w$ is measured at a distance of 2 au in the corresponding single-star simulation, with an ejection of the stellar wind of velocity $V_{ej}$ at the photospheric radius $r_*$ of the giant star. The radius of the accretion sink sphere is denoted by $r_{sink}$, and the softening radius $r_{soft,WD}$ is set to be the same as $r_{sink}$. By $\Delta r_{\text{finest}}$, we denote the length of the finest grid cell in the adaptive mesh refinement scheme. For the seven cases in which the accretion disk is defined (i.e., all but Sim6; see Section 3.2), we list the radius $<R_{\text{disk}}>$, the height $<H_{\text{disk}}>$, and the mass $<M_{\text{disk}}>$, which are obtained by averaging over the period at the last orbit of the binary. The standard deviations of the lengths and masses are less than 10% of the values.

The WD is treated as an accretion sink, with the sink radius $r_{sink}$ in order to prevent the unrealistic penetration of flows through the WD and to obtain legitimate values for the accretion rate. In our simulation, the radius $r_{sink}$, within which the accretion sink occurs, is set to be the same as the gravitational softening radius $r_{soft,WD}$. When the flow approaches the WD within the radius $r_{sink}$ and its energy condition satisfies the gravitational bound state, the flow is regarded as having entered the sink, and no further trace is made. Instead, the density within the sink radius is replaced by an arbitrary small value, the sink density $\rho_{sink}$ which is predefined to be much smaller than the background density, practically as the in situ density in the absence of the WD. The velocity within the sink radius is replaced by the orbital velocity of the WD. The accretion rate, $\dot{M}_{\text{acc}} = \sum \rho_i dU_i/dt$, is recorded at the end of each simulation time step, of the time duration $dt$, where the density and volume elements of the $i$th grid cell within the accretion sink, satisfying the sink condition, are denoted by $\rho_i$ and $dU_i$. Several tests have been performed to verify that our choice for $\rho_{sink}$ does not affect the overall morphology of the accretion flows and their physical properties. We have also performed tests to confirm the sufficiency of the numerical resolution in assigning at least four layers within the accretion sink radius (see also Truelove et al. 1997). In tests for the sink radius reduced by half (and accompanied by proper grid resolution), negligible changes are observed in the disk radius and height measurements, and in the density and temperature ranges within the accretion disk.

### 2.4. System Coordinates

The computational domain is set to be a rectangular cube, with the dimensions $12.8 \times 12.8 \times 6.4$ au$^3$, and with the center of mass of the binary stars ($x=y=z=0$) at the center of the first and second coordinates, but on the boundary of the third coordinate, assuming a symmetry about the equatorial plane ($z=0$). The boundary condition for the plane coinciding with the equatorial plane reflects all quantities in the $z>0$ space to the $z<0$ space through the mirror at the $z=0$ plane. The boundary conditions for the other five boundary planes are set to diode, defined in the FLASH code, which allows the outflow but prohibits the inflow of fluid. At each simulation time step, the meshes for the high-density regions are refined through the adaptive mesh refinement technique, with a predefined maximum refinement level of 6 (or a level of 7 in one model, for the resolution test) and $64 \times 64 \times 32$ cells being included in each level of refinement. To interpolate the physical quantities of each grid cell, the Piecewise Parabolic Method is adopted in this work.

In the analyses for the accretion disk of the WD, we introduce the coordinates $(x', y', z')$, defined in the rest frame of the WD. We also note that the notations $r$ and $R$ indicate the radii in spherical and cylindrical coordinates, respectively. The angle $\Theta$ is defined about the WD in the counterclockwise direction, starting from the opposite side to the location of the giant star.

### 3. Results

#### 3.1. Simulation Models and Overall Morphology

We have carried out eight simulations, Sim1–Sim8, with different wind conditions, and their input parameters and the resulting properties of the accretion disks are tabulated in Table 2. Our experiments are designed to investigate the physical properties of the outflows and the accretion disks surrounding the WD, according to the increase in $V_w$ from Sim1 to Sim6. The intrinsic wind velocity of Sim1, measured from an unperturbed single-star simulation, starts from $V_{ej}=6$ km s$^{-1}$ at the surface of the giant star (i.e., at radius $r_*$) and reaches $V_w=13.7$ km s$^{-1}$ at the distance corresponding to the binary separation. This wind model mimics a transonic wind, as the sound speed at the surface of the giant star is $\sim 7.4$ km s$^{-1}$. The winds of the giant star in the other seven models are intrinsically supersonic. A slow wind with $V_w$ smaller than the orbital velocity $V_{\text{WD}}=21.8$ km s$^{-1}$ (Sim1–Sim5) facilitates the capture of stellar wind material, resulting in favorable conditions for the formation of an accretion disk surrounding the WD.

A fast wind with the velocity $V_w$ exceeding the orbital velocity $V_{\text{WD}}$ tends to pass over the WD, instead of effectively building a disk around it. Under such unfavorable conditions
for disk formation, the Sim6 model failed to create a disk. With reduced sink radii, the Sim7 and Sim8 models were computed in order to assess the effects of the sink radius and the grid resolution on the formation of the accretion disk. We assured our minimum grid criterion, four cells within radius $r_{\text{sink}}$, for these models by increasing the maximum refinement level.

In the comparison of all the simulated models, the Sim5 model exhibits a transitional morphology (see Figure 1). The

![Figure 1](image_url)

**Figure 1.** The density distributions obtained from the eight simulations, Sim1–Sim8. For each simulation, the upper panel covers the entire simulation domain, displaying the outflowing wind morphology in the orbital plane, while the lower panel is the zoomed-in version, to clearly show the accretion flows around the WD. Each simulation model is labeled in the top left corner of each upper panel. For each model, a snapshot from the last orbit is chosen. In the coordinate system, where the center of mass of the binary system coincides with the center of the coordinates and the WD is on the $+x$-axis at $x = 1.43$ au, the giant is located at $x = -0.57$ au. The outer rims of the accretion disks are denoted by the blue circles. The black filled circles toward the center of the WD indicate the accretion sinks in the simulations.
Figure 2. Snapshots of the density and temperature distributions of the Sim2 model when the binary stars have completed their four orbital motions. The top panels, from (a) to (d), exhibit the distributions in the equatorial x–y plane, while the bottom panels, from (e) to (h), display the vertical structures in the x–z plane. Panels (a), (b), (e), and (f) present the entire simulation domain, including the spiral structure, with its head at the WD, while panels (c), (d), (g), and (h) are the corresponding zoomed-in images, targeting the accretion disk surrounding the WD. The outer boundary of the accretion disk, indicated by the blue lines, is characterized by a radius of 0.15 au and a height of 0.03 au, with a flared shape in the vertical direction. The snapshot images are centered at the center of mass of the binary star system.

The accretion disk is well developed in the forward direction of the orbital motion of the WD in the slower Sim1–Sim4 models, while the material above the disk radius and beneath the bow shock is stripped out in the faster Sim5–Sim8 models. As a result, the accretion disks in the Sim5–Sim8 models are exposed to winds, and the accretion tails (or accretion columns) are revealed in the manner that is demonstrated in the BHL theory (Bondi & Hoyle 1944). Notice that morphological transition occurs with the in situ intrinsic wind velocity being similar to the orbital velocity of the WD ($V_{\infty} \sim V_{\text{WD}}$).

Figure 2 presents, as an example, the detailed structures of the Sim2 model at large and small scales at the time when the stars have completed their four orbits. The first and second columns of the figure exhibit the density and temperature distributions, respectively, viewed face-on (upper panels) and edge-on (lower panels). The third and fourth columns show zoomed-in images of the same distributions near the WD. The binary stars are rotating in the counterclockwise direction around their center of mass, at $(x, y, z) = (0, 0, 0)$. The giant star and the WD are located at $(x_G, y_G) = (-0.57 \text{ au}, -0.01 \text{ au})$ and $(x_{\text{WD}}, y_{\text{WD}}) = (1.42 \text{ au}, 0.02 \text{ au})$, respectively, at the current epoch.

It is clearly identified that a spiral structure attached to the WD coils around the central stars (see also Theuns & Jorissen 1993; Kim & Taam 2012b; Huarte-Espinosa et al. 2013; Saladino et al. 2018, 2019). The inner and outer edges of the spiral structure are well defined by the narrow regions showing high temperatures ($T > 8000 \text{ K}$; see Figure 2(b)). The outer edge is extremely turbulent, and it creates a thick wall filled with high-temperature substructures. The inner edge is relatively smoothly distributed, in both density and temperature. This inner edge is tightly wound around the giant star, terminating at the meeting point with the outer edge of the spiral, $(x, y) \sim (1.8 \text{ au}, 0.2 \text{ au})$, as seen in Figures 2(a) and (c). Toward this position, the temperature of the inner edge is no longer high (see Figure 2(b)). The region around the giant star confined by the inner spiral edge is relatively low in density.

Most of the wind material entering into the spiral structure eventually escapes from the binary potential, while some fraction of the material remains gravitationally captured by the WD, forming an accretion disk. The blue lines in the third and fourth columns of Figure 2 demonstrate the 3D morphology of the accretion disk (as defined in Section 3.3.2). Interestingly, the accretion disk is vertically not razor-thin, but has a flare shape (Figures 2(g)–(h)).

3.2. Formation of Accretion Disk

The formation criterion for an accretion disk adopted in this work is the presence of circularized accretion flows around the WD that last longer than an orbital period. If formed, the shape and mass of the accretion disk are computed as follows.

1. Disk height $H_{\text{disk}}$. We first draw 10 density profiles along vertical lines passing the points of intersection with the equatorial plane at an arbitrary radius $R$ from the WD, starting from $r_{\text{sink}}$ and increasing with intervals of $\Delta R$. The gas density decreases, following an exponential function up to a certain height, and beyond this height the density drops abruptly. We define the scale height $H(R)$ at radius $R$ as the average of the 10 values for these heights that characterize the exponential density declines. The
disk height $H(R_{\text{disk}})$, or simply $H_{\text{disk}}$, is the scale height at the radius of the disk, $R = R_{\text{disk}}$, defined as below.

2. **Disk mass** $M_{\text{disk}}$. We estimate the mass $M(R)$ within the volume of the flare-shaped disk, bounded by a cylinder with an arbitrary radius $R$ and scale height $H(R)$, with its inner boundary at the sphere of the radius $r_{\text{sink}}$. We repeat this mass estimation by gradually raising the radius of the outer boundary by $\Delta R$, until the mass increment is negligible (less than 1%), i.e., $M(R + \Delta R) - M(R) < 0.01M(R + \Delta R)$, and the final value is defined as the disk mass $M_{\text{disk}}$, or $M(R_{\text{disk}})$.

3. **Disk radius** $R_{\text{disk}}$. This is correspondingly defined as the radius at which the above mass condition is satisfied.

We estimate these three quantities at each simulation time step. The values show some fluctuations in the early orbits, and become stabilized in the later orbits. In Figure 3, the $R_{\text{disk}}$, $H_{\text{disk}}$, and $M_{\text{disk}}$ of, for example, the Sim2 model are displayed as a function of time. The disk radius $R_{\text{disk}}$ increases slightly beyond the noise level of variation, until it eventually reaches a near-constant value of $\sim 0.15$ au at $t > 4$ orbit. The disk height $H_{\text{disk}}$ shows a $\sim 40\%$ increase in the early evolution ($t < 4$ orbit) and attains a near-constant value of $\sim 0.03$ au. The disk mass reaches up to $M_{\text{disk}} \sim 4.6 \times 10^{-8} M_\odot$ at $t \sim 5.4$ orbit, and stops increasing afterward. The final disk mass corresponds to $\sim 3\%$ of the mass expelled from the giant star over 14 yr (seven orbits). We note that the growth of the disk mass within the
nearly stationary volume of the disk at \( t = 4 - 5.4 \) orbit enhances the density of the disk (see the change in the minima of the density profiles with time in Section 4.1). The mean values of these quantities over the last orbit of the simulation are listed in Table 2.

Disks are always formed, regardless of the initial parameter sets, if the simulation mesh resolution and the accretion sink radius are properly assigned. Under the same spatial conditions as the Sim1–Sim5 models, the Sim6 model fails to create an accretion disk (see Figure 1). It turns out to be a numerical artifact, as the Sim7 model with a sink radius \( r_{\text{sink}}(=r_{\text{soft,WD}}) \) reduced by half successfully forms an accretion disk with the radius of 0.1 au. From these experiments, we note that a sink radius greater than \( \sim 25\% \) of the (potential) disk radius causes the artificial destruction of the disk. Here, we did not change the resolution of the simulation grids, as they satisfied the minimum requirements for resolving \( r_{\text{sink}} \) (i.e., four cells within \( r_{\text{sink}} \)). The Sim8 model is for the disk formation in an environment where the adjacent wind velocity is faster than the orbital velocity of the WD. In this model, by reducing \( r_{\text{sink}} \) and \( r_{\text{soft,WD}} \) to 0.0125 au, we successfully produced the accretion disk with its radius of 0.058 au.

As noted in Table 2, the representative disk radius (i.e., the average disk radius over the temporal oscillation during the last simulation orbit) does not change with wind velocity in the Sim1–Sim4 models, but starts to decrease with faster winds in the Sim5–Sim8 models. The disk radius \( <R_{\text{disk}}> \), tabulated in Table 2 and indicated by the filled circles in Figure 4, is smaller than the accretion-line impact parameter \( b \) (the black solid line in Figure 4) derived by Huarte-Espinosa et al. (2013) for the BHL flow toward the retarded position of the WD:

\[
b = 2 q^2 (1 + q)^3 \left( \frac{1}{a} \right)^{5/2} \left( \frac{1}{a} + \frac{1}{a_w} \right)^{-7/2},
\]

where \( q = \frac{M_{\text{WD}}}{M_G} \) is the stellar-mass ratio, \( a \) is the binary separation, and \( a_w = GM_G/((1 + q) V_w^3) \) is a specific length scale indicating the binary separation when the wind velocity \( V_w \) equals the orbital velocity of the WD about the center of mass of binary stars, i.e., \( V_w = V_{\text{WD}}(a = a_w) \). The disk radii of the Sim1–Sim4 models are almost the same, and significantly smaller than the \( b \) parameter, while the disk radii of the Sim5–Sim8 models decrease, following the decreasing trend of the \( b \) line with wind velocity. On the other hand, the bars above the filled circles in Figure 4 present the distances to the outermost rotating component of the material around the WD, measured along the line toward the giant star; in most cases, it represents the stand-off distance of the bow shock. Figure 4 indicates that the \( b \) parameter actually limits this distance, which, by definition, is larger than the disk radius. For reference, the Hill radius and the sink radius of each model are also drawn in

---

**Figure 4.** Radii of the accretion disks (filled circles) and stand-off distances of the bow shocks (horizontal bars) obtained from the simulations. The solid line shows the accretion column impact parameter \( b \) proposed as an upper limit for the disk radius by Huarte-Espinosa et al. (2013). For comparison, the Hill radius of the simulated binary system is marked by the horizontal long-dashed line, and the sink radii for Sim1–Sim5, Sim7, and Sim8 are shown by the three horizontal short-dashed lines.
3.3. Accretion Rate

The mass-accretion rate $M_{\text{acc}}$ is measured by integrating the mass entering into the sink sphere with its energy condition that forbids its escape from the sink. For comparison, we also measure the mass transfer rate $M_{\text{inflow}}$, by integrating the mass fluxes inflowing through the surface of the flared disk (defined in Section 3.2). The disk mass $M_{\text{disk}}$ is independently measured in Section 3.2, by integrating the density distribution within the flared disk, excluding the sink sphere. In our fiducial Sim2 model, the averaged rates over the entire simulation time are $M_{\text{acc}} \approx 4.8 \times 10^{-8} M_\odot$ yr$^{-1}$ and $M_{\text{inflow}} \approx 2.3 \times 10^{-8} M_\odot$ yr$^{-1}$, implying that the inflowing matter to the disk is twice the matter swallowed by the WD. Because $M_{\text{inflow}}$ exceeds $M_{\text{acc}}$, the inflowing matter is gradually accumulated within the disk, and therefore the disk mass increases with the evolution, which is consistent with Figure 3(c).

Figure 5 presents the time-averaged value of the mass-accretion efficiency $\beta$, which is defined as the ratio of the rate of mass entering the accretion sink and the mass-loss rate of the giant star. The filled circles are our model results, and the dashed curve shows the efficiency $\beta_{\text{BHL}}$ from the BHL theory (see the text).

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\[
\beta_{\text{BHL}} = \frac{\alpha_{\text{BHL}}}{2} \left( \frac{q}{1 + q} \right)^2 \left( \frac{V_{\text{infl}}}{V_{\text{w}}} \right)^2 \left[ 1 + \left( \frac{V_{\text{rel}}}{V_{\text{w}}} \right)^2 \right]^{-3/2},
\]

where $V_{\text{rel}} = (1 + q)V_{\text{WD}}$ is the orbital velocity of the WD in the rest frame of the giant star, and the efficiency coefficient $\alpha_{\text{BHL}} = 1$ is adopted. It is found that the accretion efficiencies in the slow-wind models (Sim1–Sim3) are considerably larger than $\beta_{\text{BHL}}$, while those in the faster-wind models (Sim4–Sim8) are similar to the BHL prediction.

Espey & Crowley (2008) pointed out the poor understanding of the mass-loss processes in cool giants, quoting the wind terminal velocities $< 100$ km s$^{-1}$ (see also, e.g., Dupree & Reimers 1987). In the case of S-type symbiotic stars with wind velocity exceeding 20 km s$^{-1}$, our simulations imply that the accretion efficiency will be a few percent, comparable with that of the BHL accretion. However, a higher accretion efficiency of $\sim 10\%$ or more is expected for S-type symbiotic systems with a lower wind velocity than the orbital velocity of the WD. The orbital parameters for most D-type symbiotic stars are only...
poorly known, so that a reliable estimate of the accretion efficiency based on the current work is not obvious (e.g., Schmid & Schild 2002; Matthews & Karovska 2006; Hinkle et al. 2013).

3.4. Disk Spirals

Of particular interest is the presence of two inflowing spirals within the accretion disk (see, e.g., Figure 2(c)). In cataclysmic variables, the disk spirals are excited by tidal interaction, as has been confirmed by many observations through indirect imaging techniques, such as Doppler tomography, and by inviscid hydrodynamic calculations at several nonadiabatic equations of state (Matsuda et al. 2000, and references therein). In symbiotic stars, however, an observational confirmation of the disk spirals has not been made, and a theoretical approach to the disk spirals has only been performed by Bisikalo et al. (1997). In this work, we stress that disk spirals can be formed even in symbiotic stars through the 3D wind accretion calculation for the first time.

We present, for example, maps from the Sim2 model in Figure 6, with panel (a) showing the density in linear color scale, panel (b) showing the radial velocity $V_R$, and panel (c) showing the rotational velocity $V_\phi$ of the matter. The magnitudes of the directional velocities in the maps in panels (b) and (c), and the fluid velocity vectors denoted by the gray arrows, are all recalculated in the rest frame of the WD at the current time $t = 4$ orbit. One spiral entering into the disk radius at $\Theta \sim 30^\circ$, i.e., from the forward direction of the orbital motion of the WD (hereafter, the front spiral), is winding the WD for more than one lap, before reaching the sink radius (see the black solid curve in Figures 6(a)–(c)). The other spiral presents a shorter trajectory, starting from $R = R_{\text{disk}}$ at $\Theta \sim -40^\circ$ (hereafter, the rear spiral; see the solid gray curve). In order to measure the physical quantities along the spirals, we first define the shapes of the disk spirals in a functional form of the logarithmic spiral: $R/R_{\text{disk}} = \exp[-(\Theta - \Theta_0)/\Theta_\phi]$, where the $\Theta_\phi$ parameter satisfies $\Theta_\phi = \Theta(R = R_{\text{disk}})$ and the polar slope of the spiral is a constant $-\Theta_\phi^{-1}$. After unrolling the density map of the accretion disk in the polar coordinates, we
find the positions of the local density maxima along the radius axis, within a 5 pixel margin from the test function of the logarithmic spiral. The $\chi^2$ goodness-of-fit test provides the coefficients $(\Theta_a, \Theta_b) = (33^\circ \pm 4^\circ, 500^\circ \pm 10^\circ)$ for the front spiral and $(\Theta_a, \Theta_b) = (-41^\circ \pm 3^\circ, 332^\circ \pm 8^\circ)$ for the rear spiral, where the radial distance $R$ from the WD is defined from the disk radius $R_{\text{disk}} = 0.15$ au to the sink radius $r_{\text{sink}} = 0.05$ au.

Figure 6(d) shows that the densities along these spirals are $\sim 5 \times 10^{-12}$ g cm$^{-3}$ at $R \sim R_{\text{disk}}$ (marked by the open circles), which are similar to each other. The density along the rear spiral increases up to $\sim 2 \times 10^{-11}$ g cm$^{-3}$ at $\Theta \sim 180^\circ$, and then steeply decreases until the spiral reaches $R = r_{\text{sink}}$. On the other hand, the density along the front spiral increases up to $\sim 2.5 \times 10^{-11}$ g cm$^{-3}$ at $\Theta \sim 220^\circ$–$250^\circ$, and then decreases until the spiral reaches the sink radius.

It is noticeable that the density along the front spiral ceases the decreasing trend at $\Theta \sim 300^\circ$–$360^\circ$ (see Figure 6(d)). Interestingly, in a similar range of $\Theta$, the radial velocity of the matter along the front spiral becomes positive at $\Theta \sim 220^\circ$–$370^\circ$ (see Figure 6(e)), and the rotational velocity ceases its increasing trend by staying at $V_a \sim 60$ km s$^{-1}$ at $\Theta = 200^\circ$–$360^\circ$ (see Figure 6(f)).

For a streamline analysis, we trace the streamlines, starting from 400 random points far from the disk. When the flows arrive at the disk radius with negative (i.e., incoming) radial velocities, we record those entering spots at the disk radius $R_{\text{disk}}$ in Figure 7(a). The arrows in this figure show the magnitudes and directions of the fluid velocities in the rest frame of the WD.

We find that the flows do not enter the disk through the entire outer rim of the disk, but that the entering spots are instead limited to the two arc segments marked by the blue and red colors in Figure 7(a). The angular extent of the blue arc segment ranges from $36^\circ$ to $216^\circ$, spanning a half circle, whereas the red arc segment has a small angular extent of $\Delta \Theta \sim 3^\circ$, limited to the range between $336^\circ$ and $339^\circ$.

Figure 7(b) shows six representative accretion streamlines that arrive at the outer rim of the disk. It is apparent that the three red streamlines converge at the red arc segment shown in Figure 7(a). The three blue streamlines represent wind components originating directly from the giant star, which subsequently get deflected as they pass through the bow shock. The entering spots of this blue group of flows are spread over $\Delta \Theta \sim 180^\circ$, as marked by the blue arc segment in Figure 7(a). The inflows from the rear side amount to $\sim 50\%$ of the total incoming mass, which means that a similar amount of mass enters the disk from the front side through the bow shock.

The two groups of inflows appear to be assimilated into the two spiral features after entering the disk. The rear spiral is likely composed of the inflowing matter entering through the small arc segment, marked by the red spots in Figure 7(a), whose angular position is similar to $\Theta_a$ of the rear spiral. The inflows from the front side through the large arc segment (the blue spots) would compose the front spiral, and the incessant injection of matter throughout a large fraction of the spiral would be responsible for the abnormal behavior of the front spiral described in the previous subsection.

3.5. Accretion Streamlines

A close inspection of the streamlines reveals that there are two major streams acting as the origin of the disk material.

![Figure 7](image_url)
4. Observational Ramifications for AG Dra

One important goal of this work is to obtain the matter distribution and the kinematics of the accretion flow, which will be used as the input parameters for future line profile analyses of Raman-scattered O VI features. In particular, our Sim2 simulation is carried out with a view to finding the physical properties of the accretion disk in the S-type symbiotic star AG Dra in the quiescent phase.

4.1. Asymmetric Disk Distribution

One of the notable features in the disk shape is the asymmetric density distribution. Figure 8 presents the time evolutions of the density maps of the Sim2 disk model in the equatorial plane. We find that the overall density distribution in the disk is conspicuously asymmetric and that the highest density is always achieved near the direction toward the giant star. In addition, the entering spots of the accretion streamlines...
the accretion flows composing the front spiral. The maximum densities are \(\sim 50\%\) higher than the minima on the opposite sides of the disk. This implies that, if the emissivity depends only on the squares of density, the emissivity ratio between the maximum and the minimum in a disk exceeds \(\sim 2\), which is consistent with the best-fitting result for the accretion disk of AG Dra hypothesized by Lee et al. (2019).

We investigate the model dependence of the degree of asymmetry, defined as the ratio between the maximum and the minimum of the radially averaged density profile along the azimuthal angle of the disk, \(\rho_{\text{Max}}/\rho_{\text{Min}}\). In the upper panel of Figure 10, the filled circle presents the mean value of the time variation of this quantity during the last orbit of the simulation, and the error bar shows its standard deviation. The resulting density ratio is nearly independent of the wind models, being \(\sim 1.5\) on average.

The large temporal variations in the degree of density asymmetry, as indicated by the error bars, have an implication for an observation at a marginal spatial resolution: the time variation of the emissivity from the dominant part of the disk may be a natural consequence and contribute to the variability, in addition to the pulsation of the giant star, the oscillation during the binary orbital period, and the intrinsic variation in the stellar wind (e.g., Galis et al. 2015; Richie et al. 2020).

The bottom panel of Figure 10 shows that the angular direction of \(\rho_{\text{Max}}\) tends to be toward the giant star (\(\Theta \sim 180^\circ\)) in the relatively slow-wind models (Sim1–Sim4), in which relatively large disks are formed. The deviation from \(\Theta \sim 180^\circ\) with time is, however, quite large, probably due to the turbulent motions of the inflowing matter, as expected from the fluctuations in the outer outflowing spiral enveloping the two stars. For the faster-wind models (Sim5–Sim8), a more refined numerical approach, substantiated with increased computing power, should be adopted in order to clarify the physical origin of the large uncertainties.

### 4.2. Kinematics of the Accretion Flow

In addition to the matter distribution around the WD component, the kinematic property of the accretion flow is essential to properly model the spectroscopic observations. Lee et al. (2019) investigated the line profile of Raman-scattered O VI features at 6825 and 7082 Å, based on the assumption that the O VI emission region of AG Dra is characterized by Keplerian motion around the WD component (e.g., Heo et al. 2016, 2021). However, one would naturally expect the real accretion flow to be much more complicated than a simple Keplerian motion, due to the presence of the giant component and the contributions from the thermal and turbulent motions.

An analysis of Sim2 reveals that the azimuthal velocity component \(V_\phi\) of the accretion stream is about 90% of the Keplerian velocity \(V_K\). More specifically, at \(R = 0.135\) au, the azimuthal speed of the accretion flow \(V_\phi\) is measured to be \(53\) km s\(^{-1}\), where the expected Keplerian speed is \(V_K = 61\) km s\(^{-1}\) (see Figure 6(f)). The sub-Keplerian rotation is probably attained as a result of the combined effect of the turbulent component and the pressure gradients associated with the adiabatic equation of state, which act against the gravity of the WD. The sub-Keplerian accretion flow highlights an important caveat in interpreting the spectroscopic observations of symbiotic stars, including AG Dra. That is, one may overestimate the size of the Raman O VI emission region when...
it is deduced under the simple assumption that the flow is Keplerian.

For example, in the spectrum of AG Dra investigated by Lee et al. (2019), the separation of the peaks in the double-peak profile of Raman-scattered O VI at 6825 Å was observed to be ≃8.2 Å, which was translated to a Keplerian velocity $V_K \approx 27$ km s$^{-1}$ of the main O VI emission region around the WD. With the adopted value of $M_{\text{WD}} = 0.6 M_\odot$, the distance to the O VI emission region from the WD is 0.7 au, assuming that the flow is Keplerian. If the accretion flow is sub-Keplerian, as the result of the Sim2 model indicates, then the O VI emission region would be located at a distance of $r_{\text{OVII}} = 0.5$ au from the WD, which is smaller by a factor of ≃70% than the value deduced under the Keplerian flow assumption.

However, the disk radius for the Sim2 model is $<R_{\text{disk}}>_K = 0.16$ au, which is only one-third of the above estimate of $r_{\text{OVII}}$. This substantial discrepancy may indicate other possibilities for radiative transfer modeling, with O VI emission regions and neutral regions more sophisticated than those of Lee et al. (2019). For example, based on the spectra obtained with the Far Ultraviolet Spectroscopic Explorer, Young et al. (2005) proposed that the O VI emission-line region is located in the illuminated part of the giant atmosphere. It has also been proposed that the O VI emission region may be found in a slowly expanding region from the hot WD (Schmid et al. 1999). It should be noted that the radiative transfer of Raman-scattered O VI by Lee et al. (2019) was based on an additional assumption, that all the neutral matter was present near the giant star. Furthermore, Schmid (1996) proposed that the kinematics of the neutral wind from the giant component in symbiotic stars is very important in the line formation of Raman-scattered O VI features, pointing out that the receding part of the neutral wind contributes to the red-enhanced line profile exhibited in Raman O VI features.

5. Summary and Discussion

In this work, we have carried out a hydrodynamical study of the stellar wind accretion process in a representative S-type symbiotic star in order to investigate the physical properties of the accretion disk. The FLASH code was used, incorporating radiative cooling and an accretion sink. The binary model considered in this work consists of a WD with $M_{\text{WD}} = 0.6 M_\odot$ and a mass-losing giant of $M_G = 1.5 M_\odot$, with a mass-loss rate of $\dot{M}_G = 10^{-7} M_\odot$ yr$^{-1}$. The binary separation is assumed to be 2 au, for which the orbital period is 1.96 yr. These binary parameters are chosen in order to obtain detailed physical properties of the S-type symbiotic star AG Dra, in which Raman-scattered O VI lines exhibit double-peak profiles indicative of an accretion flow around the WD component.

In our fiducial Sim2 model, the accretion disk has a flared shape, characterized by the physical dimensions of $<R_{\text{disk}}> = 0.16$ au and $<H_{\text{disk}}> = 0.03$ au, and the accretion flow is sub-Keplerian, with a speed about 90% of the Keplerian speed. The disk mass reaches $M_{\text{disk}} \sim 5 \times 10^{-8} M_\odot$, with a temperature of $\sim 6300$ K. The accretion rate is $\dot{M}_{\text{acc}} \sim 1.1 \times 10^{-8} M_\odot$ yr$^{-1}$. This accretion rate is comparable to the rate of $3.2 \times 10^{-8} M_\odot$ yr$^{-1}$, suggested by Greiner et al. (1997) as a source for hydrogen burning on the surface of the WD, satisfying the observed X-ray emission flux of AG Dra in its quiescent state.

In our fast-wind models (Sim5–Sim8), with the wind velocity $V_w$ being faster than the orbital velocity $V_{\text{WD}}$ of the WD, the accretion efficiency $\beta$, the disk radius $R_{\text{disk}}$, and the shape of the accretion column attached to the WD as part of the outflowing spiral are in accordance with the BHL theory. The relatively slower Sim1–Sim3 models, however, have accretion efficiencies that are considerably higher than the BHL prediction, which are likely related to the presence of a detached bow shock preserving the still rotating material above the disk radius from ram pressure stripping due to the stellar wind.

The physical properties of accretion disks formed through the capture of slow stellar wind from the giant donor are quite different from those of the geometrically thin and optically thick accretion disks found in cataclysmic variables resulting from Roche lobe overflow, in which, for example, the accretion flow is almost Keplerian. Perets & Kenyon (2013) pointed out the similarities in surface density and temperature profiles between wind-fed disks and low-mass protoplanetary disks. A detailed discussion of the hydrodynamical nature of wind-fed disks can be found in the works of, e.g., de Val-Borro et al. (2017) and Huarte-Espinosa et al. (2013), whereas in this work, we focus on the kinematics and density distribution found in the accretion flow. The temperature distribution in the disk will be affected by the nature of the coolants, as well as the radiation from the hot WD, which will be the scope of our future work.

The matter distribution in the accretion flow is azimuthally asymmetric, which is possibly related to the behaviors of the streamlines constituting the two inflowing spiral features within the disk. The asymmetric density distribution of the disk matter is sustained over a few orbital periods, until the end of the numerical simulations. It is found that one side is denser than the opposite side, by a factor of ≃1.5, implying that the local emissivity can be twice as strong as that on the opposite side.

In our future work, we will apply photoionization computation to the current hydrodynamical results, in order to obtain the local emissivities of O VI $\lambda\lambda 1032$ and 1038 and the distribution of neutral hydrogen. The emissivities of O VI will be used as input information for an investigation into the line formation of Raman-scattered O VI features, using the Monte Carlo technique adopted by Chang & Lee (2020). It remains to be seen whether an asymmetric density distribution in the accretion flow is responsible for the multiple-peak profiles that are often displayed by Raman-scattered O VI features at around 6825 and 7082 Å.

The density affects the flux ratio of O VI $\lambda\lambda 1032$ and 1038 in such a way that the flux ratio $F_{1032}/F_{1038}$ decreases from 2 to 1 as the density increases. Therefore, the local variations in O VI density lead to a varying flux ratio $F_{1032}/F_{1038}$. In particular, the flux ratio $F_{1032}/F_{1038}$ is lower on the side with high density than on the opposite side, which may give rise to the disparity between the line profiles of Raman O VI features at 6825 Å and 7082 Å. One important difficulty in obtaining the flux ratio $F_{1032}/F_{1038}$ is the possible interstellar extinction of O VI $\lambda 1038$ by molecular hydrogen (e.g., Schmid et al. 1999; Birriel et al. 2000). It is hoped that useful insights into the complex nature of Raman O VI features can be provided through combined studies of hydrodynamics and photoionization modeling.

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References
Akras, S., Guzman-Ramirez, L., Leal-Ferreira, M. L., et al. 2019, ApJS, 240, 21
Allen, D. A. 1980, MNRAS, 190, 75
Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Belczynski, K., Mikolajewska, J., Munari, U., et al. 2000, A&AS, 146, 407
Binney, J., & Tremaine, S. 2008, Galactic Dynamics (2nd edn.; Princeton, NJ: Princeton Univ. Press)
Birriel, J. J., Espey, B. R., & Schulte-Ladbeck, R. E. 2000, ApJ, 545, 1020
Bisikalo, D. V., Boyarchuk, A. A., Chechetkin, V. M., et al. 1997, Ap&SS, 252, 389
Boffin, H. M. J., Hillen, M., Berger, J. P., et al. 2014, A&A, 564, A1
Boffin, H. M. J., & Jorissen, A. 1988, A&A, 205, 155
Bondi, H., & Hoyle, F. 1944, MNRAS, 104, 273
Bowen, G. H. 1988, ApJ, 329, 299
Chandrasekhar, S. 1934, MNRAS, 94, 444
Chang, S.-J., & Lee, H.-W. 2020, JKAS, 53, 169
Chen, Z., Frank, A., Blackman, E. G., et al. 2017, MNRAS, 468, 4465
de Val-Borro, M., Karovska, M., Sasselov, D. D., et al. 2017, MNRAS, 468, 3408
Dunm, T., & Schild, H. 1998, NewA, 3, 137
Dupree, A. K. 1986, ARA&A, 24, 377
Dupree, A. K., & Reimers, D. 1987, in Exploring the Universe with the IUE Satellite, Vol. 129 ed. Y. Kondo & W. Wamsteker (Dordrecht: Reidel), 321
Espey, B. R., & Crowley, C. 2008, in ASP Conf. Ser. 401, RS Ophiuchi (2006) and the Recurrent Nova Phenomenon, ed. A. Evans et al. (San Francisco, CA: ASP), 166
Fryxell, B., Olson, K., Ricker, P., et al. 2000, ApJS, 131, 273
Gális, R., Hric, L., & Smelcker, L. 2015, OEJV, 169, 4
Greiner, J., Bickert, K., Lauthardt, R., et al. 1997, A&A, 322, 576
Heo, J.-E., Angeloni, R., Di Mille, F., et al. 2016, ApJ, 833, 286
Heo, J.-E., & Lee, H.-W. 2015, JKAS, 48, 105
Heo, J.-E., Lee, H.-W., Angeloni, R., et al. 2021, ApJ, 915, 105
Hinkle, K. H., Fekel, F. C., Joyce, R. R., & Wood, P. 2013, ApJ, 770, 28
Höfner, S., & Olofsson, H. 2018, A&ARv, 26, 1
Hoyle, F., & Lyttleton, R. A. 1939, PCPS, 35, 405
Huarte-Espinosa, M., Carroll-Nellenback, J., Nordhaus, J., et al. 2013, MNRAS, 433, 295
Kenyon, S. J. 1986, The Symbiotic Stars (Cambridge: Cambridge Univ. Press)
Kim, H., Hsieh, I.-T., Liu, S.-Y., et al. 2013, ApJ, 776, 86
Kim, H., Liu, S.-Y., & Taam, R. E. 2019, ApJS, 243, 35
Kim, H., & Taam, R. E. 2012a, ApJ, 744, 136
Kim, H., & Taam, R. E. 2012b, ApJ, 759, 59
Kim, H., Trejo, A., Liu, S.-Y., et al. 2017, NatAs, 1, 0060
Lee, H.-W., & Kang, S. 2007, ApJ, 669, 1156
Lee, K. W., & Lee, H.-W. 1997, MNRAS, 292, 573
Lee, Y.-M., Lee, H.-W., Lee, H.-G., et al. 2019, MNRAS, 487, 2166
Matsuda, T., Makita, M., Fujimura, H., et al. 2000, Ap&SS, 274, 259
Matthews, L. D., & Karovska, M. 2006, ApJL, 637, L49
Mikolajewska, J. 2012, BaltA, 21, 5
Mürset, U., & Schmid, H. M. 1999, A&AS, 137, 473
Perets, H. B., & Kenyon, S. J. 2013, ApJ, 764, 169
Richie, H. M., Wood-Vasey, W. M., & Coban, L. 2020, JAAVSO, 48, 21
Saladino, M. I., Pols, O. R., & Abate, C. 2019, A&A, 626, A68
Saladino, M. I., Pols, O. R., van der Helm, E., et al. 2018, A&A, 618, A50
Schmid, H. M. 1989, A&A, 211, L31
Schmid, H. M. 1996, MNRAS, 282, 511
Schmid, H. M., Krautter, J., Appenzeller, I., et al. 1999, A&A, 348, 950
Schmid, H. M., & Schild, H. 2002, A&A, 395, 117
Schure, K. M., Kosenko, D., Kaastra, J. S., et al. 2009, A&A, 508, 751
Seaquist, E. R., Krogulec, M., & Taylor, A. R. 1993, ApJ, 410, 260
Shen, K. J., & Bildsten, L. 2007, ApJ, 660, 1444
Skopal, A. 2005, A&A, 440, 995
Sokoloski, J. L., Kenyon, S. J., Espey, B. R., et al. 2006, ApJ, 636, 1002
Theuns, T., & Jorissen, A. 1993, MNRAS, 265, 946
Truelove, J. K., Klein, R. I., McKee, C. F., et al. 1997, ApJ, 489, 179
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge: Cambridge Univ. Press)
Young, P. R., Dupree, A. K., Espey, B. R., et al. 2005, ApJ, 618, 891

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