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HYDRODYNAMIC SIMULATIONS OF CIRCUMSTELLAR ENVELOPES UNDER THE GRAVITATIONAL INFLUENCE OF A WIDE BINARY COMPANION: COMPARISON BETWEEN CIRCULAR AND ELLIPTICAL ORBITS

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Abstract. *Shapes of circumstellar envelopes around mass losing stars contain information of the very inner region of the envelope where mass loss process takes place. It's well known that the presence of a binary companion leads to strong influence on the structure of the envelope through orbital motion of the mass losing star and the gravitational interaction of the companion with the stellar wind. To investigate this effect and structures of envelopes, we have performed high resolution hydrodynamic simulations of a wide binary system in a number of orbital configurations. Our simulations clearly show the importance of the equation of state of the gas because in isothermal case the width of the spiral arm is significantly broadened with respect to the ideal gas case, therefore resulting in unrealistic spiral patterns. As the orbital geometry changes from circular to elliptical, our simulation results show that the spiral becomes bifurcated and increasingly asymmetric as indicated in previously published results. In the polar direction, the prominent alternating arcs associated with circular orbital configuration morph into almost continuous circular rings. The physical condition of the gas in the envelope is shown to vary strongly between the spiral arm and inter-arm regions. Our hydrodynamic simulations will be useful to interpret high angular resolution observations of circumstellar envelopes.*

Keywords: circumsteller envelope.

Classification numbers: 79.10.Fy.

I. INTRODUCTION

Intermediate mass stars with mass in the range from 1 to 8 solar masses evolve through a brief but important phase called Asympotic Giant Branch (AGB) or the second Red giant phase. During this phase the stars are characterized by large mass loss rate through slow and dusty stellar wind [1]. As a result, the AGB stars are enshrouded in an expanding and thick envelope of gas and dust. The envelope is commonly assumed to be spherically symmetric with gas density and temperature decrease smoothly from the inner region to the outer region of the envelope. Such view provided a framework to interpret the observations and to understand the physics and chemistry of circumstellar envelopes. However, with new observations coming from more advanced and more capable instruments available recently such as millimeter and sub-millimeter radio interferometers, or space observatories, the circumstellar envelopes have been shown to exhibit a wide variety of morphologies and features such as bipolar, quadrapolar shapes, rings and arcs or clumpy structures. Interestingly, spiral patterns have been observed in a number of circumstellar envelopes such as CIT 6 [2, 3, 5, 6]. These spiral patterns have been interpreted as the direct evidence for the presence of a binary system at the center of these circumstellar envelopes. These observations also imply that our view of the AGB stars evolving in isolation is likely too simplistic and clearly needs revision. Numerical hydrodynamic simulations been been undertaken by some groups to investigate influence of the binary companion on the structure and physical properties of the circumstellar envelopes [3–5, 7]. They show that the spiral structure originates mainly from the reflex motion of the primary star and the spacing of the spiral pattern could be related to the orbital period and the expansion velocity of the gas. The effect of the companion is mainly due to its gravitational attraction and tends to focus the wind toward the orbital plane leading to enhanced equatorial density distribution. In addition, the spiral pattern is found to be a truly three dimensional structure extending high above the orbital plane toward the polar axis [7]. Therefore when viewing from directions close to the orbital plane of the system the envelope would appear to contain a series of alternating but nearly concentric arcs. We note that in previous work only binary systems in circular orbits are considered. Only recently that highly elliptical orbits (with eccentricity of ~0.8) are considered in hydrodynamic simulations by Kim *et al.* [8] in order to match the spiral pattern seen in high angular resolution observations of molecular line emissions from CRL 3068.

In this paper we report the initial results of our program to study the structure of circumstellar envelope around an AGB star in the presence of a binary companion in circular and elliptical orbits. We will emphasize the difference in the properties of the circumstellar envelope as the orbital geometry changes and possible implication for future astronomical observations.

II. METHODOLOGY

We simulate the circumstellar envelope as an uncompressible, non-cooling and non-self-gravitating gaseous environment. We use the hydrodynamic module of the PLUTO code [9] to solve the Euler's equations of classical fluid dynamics:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = 0,$$

$$\partial\vec{v}\partial t + (\vec{v}\cdot\nabla)\vec{v} = \frac{-\nabla p}{\rho} - \nabla\phi,$$
$$\frac{\partial p}{\partial t} + \vec{v}\cdot\nabla p + \rho c_s^2 \nabla\cdot\vec{v} = 0,$$

where $c_s = \sqrt{\dfrac{\partial p}{\partial \rho}}$ is the sound speed in the gas. The binary system consists of two stars interacting with each other by gravitational force which keeps them moving on circular or elliptical orbits. The mass losing star is called the primary star, which is normally heavier than the companion star. The gas is expelled from the primary star with a wind velocity $V\prime_w$ relating to the mass lost rate as follows:

$$\dot{M}_p = 4\pi r_p^2 \rho_0 V_w'$$

where, r_p is the inner radius of the envelope around the primary star and ρ is the gas density at the inner boundary. Because the primary star moves with an orbital velocity of V_p, the wind velocity as seen in the center of mass frame is $\vec{V}_w = \vec{V}_w' + \vec{V}_p$.

The gravitational potential φ in the source term on the right of the momentum equation is due to the companion star. The gravitational potential is expressed as:

$$\phi = (-GM_c om)/r$$

where M_{com} is the mass of the companion. We assume that the radiation pressure causing outward expansion of the circumstellar envelope (stellar wind) is exactly balanced by the gravitational attraction of the primary, therefore, the potential of the primary star is not include in the source term.

The thermodynamic state of the gas is an important factor effecting on the results of our simulations. A simple assumption often used is the isothermal condition of the gas, where the temperature is a constant throughout the envelope. In this case the thermal equation of state (EOS) is simple as follows:

$$p = \frac{\rho}{m_u \mu} k_b T,$$

where m_u is the atomic mass unit, μ is the mean molecular weight, ρ is the density, k_b is the Boltzmann constant and T is the gas temperature. In an isothermal gas, the gas pressure is directly related to density as follows:

$$p = \rho c_s^2$$

where, c_s is the isothermal sound speed. In this isothermal case the Euler's equation for energy is not needed, so it is neglected. Alternatively, we also consider the adiabatic case where the EOS is as follows:

$$p = (\gamma - 1)\rho e$$

where e is the internal energy, γ is the adiabatic index or the ratio of specific heats capacities. In our simulations we use a value of 1.4 for the adiabatic index γ.

Our simulations are carried in a three dimensional domain $\sim$4800 AU (astronomical unit) in size. We use 800 grid points in each direction to reach a spatial resolution of $\sim$1.3 Au near the primary star. The binary system includes the primary star with a mass of 2.2 times the solar mass

(M_s) and the secondary star with a mass of 0.8 times the solar mass. The primary star has the mass loss rate of about 10^{-5} M_s/yr, typical for AGB stars with known spiral pattern such as CIT 6, CRL 3068 or CW Leo [2,3,10]. The orbital period of the binary system is set at 325 years, well in the range of the expected orbital periods of envelopes with spiral pattern. The orbital period corresponds to the distance between binary components of about 68 AU. The wind velocity V'_w is set at 15.7 km/s, also typical for the above systems such as CIT 6 (wind velocity of 18 km/s, [2]) or CW Leo (wind velocity of 14 km/s, [10]). The sound speed at the inner boundary is set to 2 km/s, which corresponds to a gas temperature of about 700 K, also a typical value for the inner region near the mass losing AGB star.

III. RESULTS AND DISCUSSION

Isothermal and ideal gas

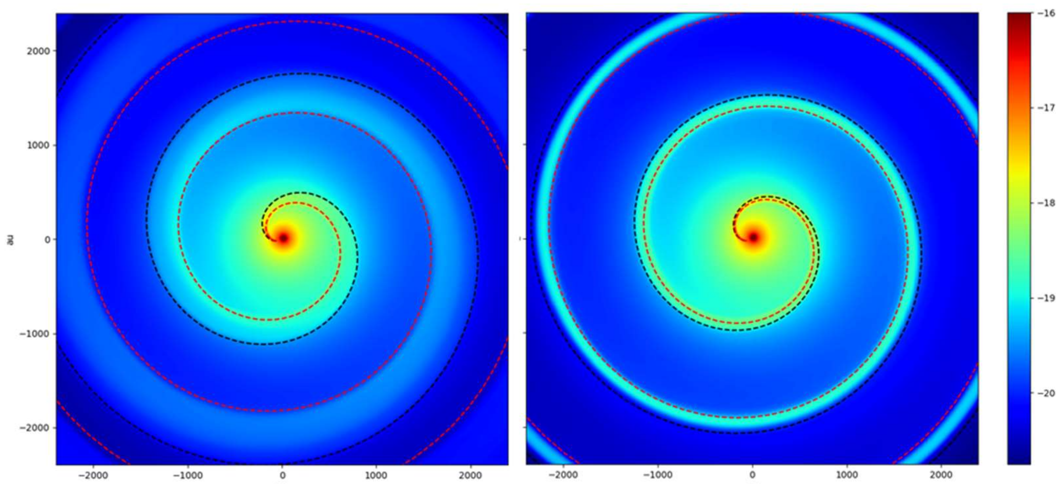

Fig. 1. Density distributions in the logarithmic scale of the gas in the orbital plane from the two cases of isothermal EOS (left panel) and adiabatic EOS (right panel) in circular orbits. The dashed curves are the *Archimedean* spiral matched to the density distribution. The red curves correspond to the inner side and the black curves correspond outer surface of the spiral pattern.

In Fig. 1 we show the results of our simulations in the two cases of isothermal and adiabatic EOS and the binary system moving in a circular orbit. The spiral patterns show significant differences between the two cases (i) the width of the spiral arm in the isothermal case is much larger than that in the adiabatic case; (ii) the density contrast is noticeably higher in the adiabatic case. These differences are directly related to the expanding speeds of the inner and outer surface of the spiral pattern. To determine these speeds, we fit these boundaries to the Archimedean spirals using procedure similar to that of Kim & Taam [3]. These spirals are described as follows:

$$\frac{dr}{d(\phi)} = \frac{V_{pattern}}{V_p} r_p$$

where, r_p and V_p are the radius and the orbital velocity of the primary star, respectively. $V_{pattern}$ is the expanding speed of the spiral pattern. In our model, the primary star moves on the circular orbit around the center of mass of the system with an orbital radius r_p of 18 AU and an orbital velocity V_p of 1.7 km/s. These input parameters give the following results: the radial velocities of the inner and outer surface of the spiral are 14.6 km/s and 19.4 km/s for isothermal gas and 15.0 km/s and 16.5 km/s for ideal gas. Therefore, the inner boundaries of two spiral patterns expand similarly, but the outer boundary of the spiral in the isothermal case moves faster than the one in the adiabatic case. Kim & Taam [3] explored different wind velocities and orbital velocities of the primary star in their simulations. From fitting of the simulation results to the Archimedes's spirals, they found that inner and outer speeds of the spiral follow approximately:

$$V_{out} = V'_w + \frac{2}{3}V_p \tag{1}$$

$$V_i = \left(V'_w - 2c_s\right) + \left(\frac{2}{3}V_p - \frac{1}{2}c_s\right). \tag{2}$$

These equations show that the inner speeds are smaller by as much as 2.5c$_s$ ($\sim$ 5 km/s) than the outer speeds. This only coincides with the isothermal case in our model with the larger arms. However, in circumstellar envelopes the gas temperature is known to decrease quickly with radial distance and observationally the spiral patterns are often narrow as the adiabatic EOS case. Therefore, we conclude that hydrodynamic simulations of circumstellar envelopes should not use the isothermal assumption.

Circular and elliptic orbits

In this section we compare the properties of the envelope under the influence of binary companion in circular and elliptical orbits. The adiabatic EOS is used in both cases and the elliptical orbit has an eccentricity of e=0.5. In figures 2 and 3 we show the density distributions for the circular and elliptical orbit configuration on the orbital plane and in the plane containing the polar axis of the envelope. When the binary is in a circular configuration, the spiral pattern is smooth and can match satisfactorily to the Archimedean spiral as shown in Fig. 1. The cut along the polar axis reveals that the spiral pattern extends highly above the orbital plane and almost approaches the polar axis forming a series of alternating arcs. In addition, the gravitational influence of the binary companion shows up in a strong enhancement of gas density near the orbital plane as can be seen in the right frame of Fig. 2. Our results are therefore consistent with that published earlier in Refs. [3, 7]. In Fig. 3, it can be seen easily that new features appear as the orbital configuration changes from circular to elliptical. The spiral pattern becomes asymmetric and elongated in the same direction as the major axis of the orbit. In addition to the main arm, there is a faint bridge (or bifurcation) of material connecting the inner and outer part of the spiral arm (left frame of Fig. 3). This effect can be qualitatively explained by eccentric motion of the primary mass losing star. When the star is near the closest approach of the elliptic orbit, it moves faster. Then the wind ejected from this part of orbit moves faster and overtakes the slower wind ejected earlier leading to the bifurcation in the spiral pattern. More interestingly, the cut along the polar axis reveals that the alternating arcs now morph into almost circular and concentric rings. Because binary systems might generally exist in elliptical orbit configurations, our new result might explain why concentric arcs or rings are often observed toward circumstellar envelopes.

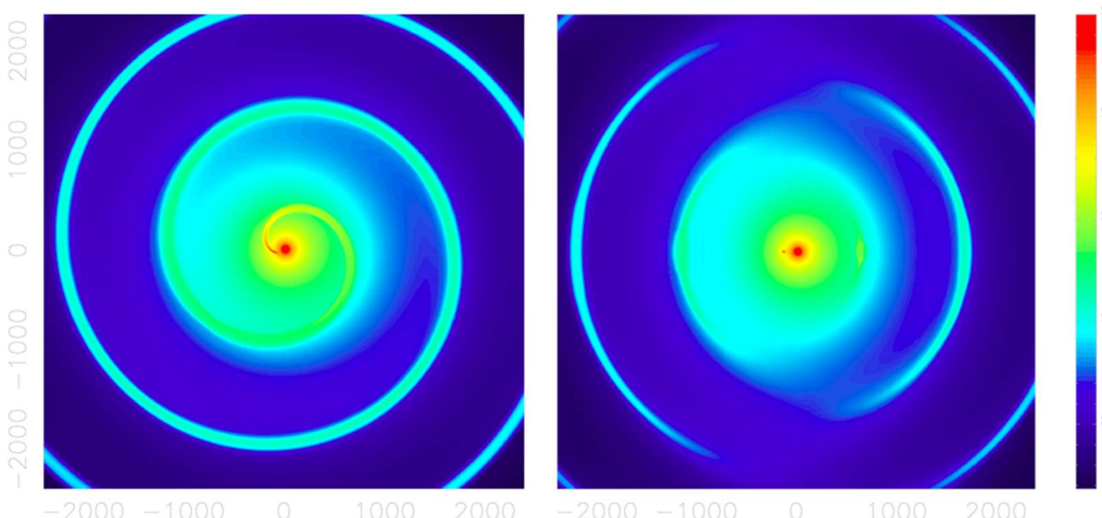

Fig. 2. Density distributions in the circular orbit case shown in logarithmic scale. Left panel shows gas density distribution in the orbital plane; right panel shows gas density in a the plane containing polar axis and perpendicular to the orbital plane.

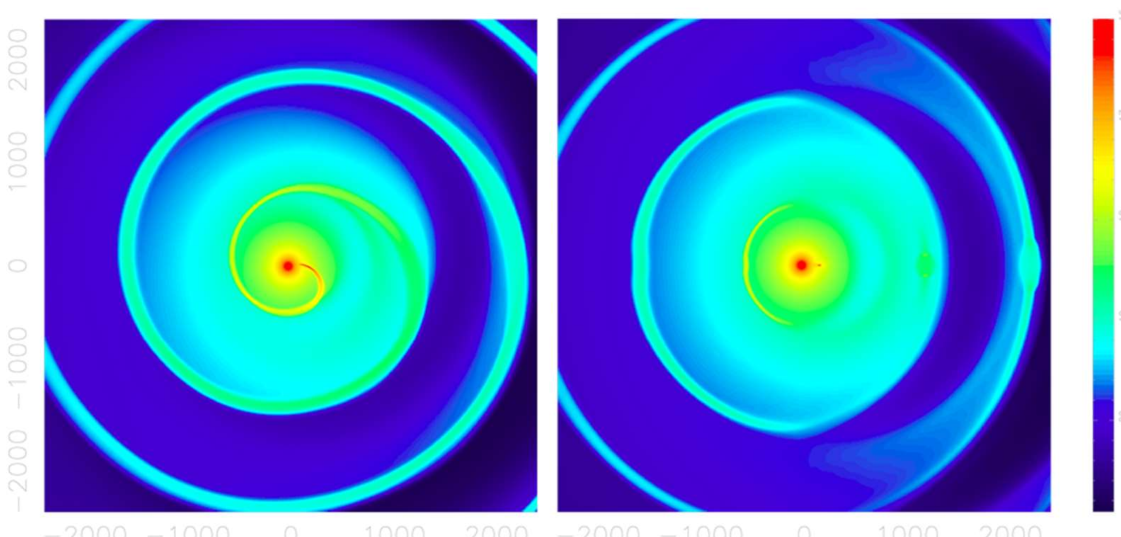

Fig. 3. Same as Fig. 2 but for the elliptical orbit case.

Temperature profiles

As the gas moves radially outward, it expands and cools adiabatically. In Figure 4 we show the gas temperature along two radial directions, one along the X axis and the other along the Y axis for the circular orbit case. The gas temperature in the inter-arm region in both directions decreases monotonically with radial distance as expected. However, across the spiral arm the gas is strongly compressed due to the collision between gas moving at different velocities, leading to elevated gas temperature. From Figure 4 we can estimate the jump in temperature due to shock compression is about 2 to 3 times the in comparison to temperature of the upstream gas. To evaluate our results, we analyze kinetic temperature obtained from the model and compare with one of AFGL 3068 [11]. From the CO excitation analysis, they found that kinetic temperature declines with radius as a function $r^{-0.83}$. As can be seen in Figure 4 the temperature profiles of the inter-arm gas along two perpendicular directions when plotted in logarithmic scale match quite closely with a straight line having the same slope of -0.83. Therefore, our choice is of the adiabatic index produces results consistent with observations. With the available gas density and temperature we will be able to carry out molecular excitation and radiative transfer to predict the intensity distribution of molecular line emission from the envelope and make comparison with high angular resolution observations in a similar fashion as in [5]. That will be the topics of a future publication.

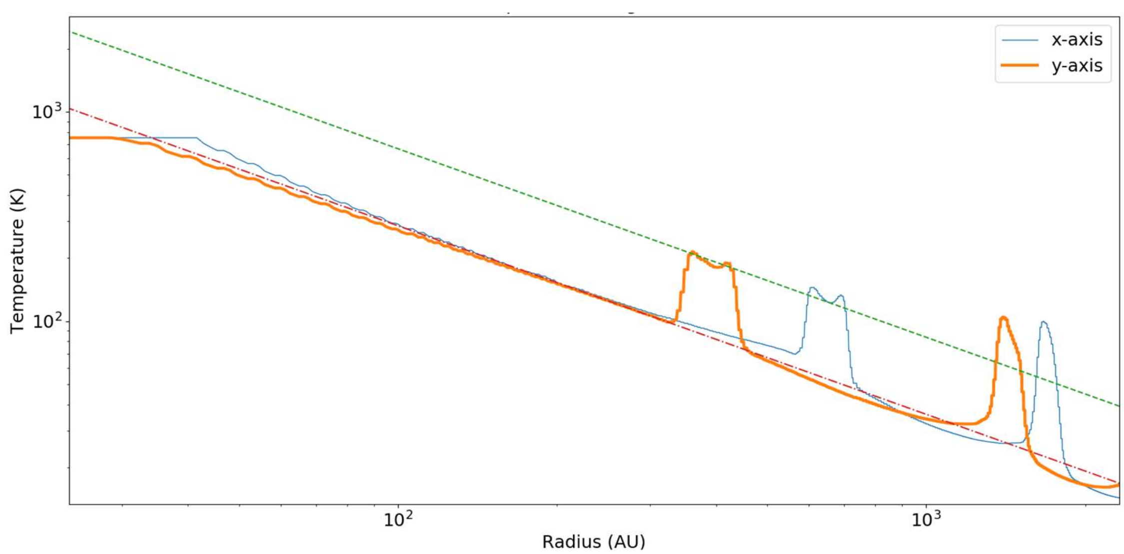

Fig. 4. Temperature profiles in logarithmic scale along two perpendicular directions in the orbital plane. The dash-dotted straight line has a slope of -0.83 and provides a close match to the temperature of inter-arm gas.

IV. CONCLUSION

We have carried out hydrodynamic simulations of circumstellar envelopes under the gravitational influence of a widely separated binary companion in circular and elliptical orbital configurations. Our simulation results clearly show that isothermal assumption for the envelope results in highly broadened and unrealistic spiral pattern. We show further the change in morphology of the envelope imprinted by the orbital geometry of the binary system with the appearance of bifurcation and asymmetry in the spiral pattern as the binary orbit becomes more elliptical. In the future we hope to compare our simulation results with high angular resolution observations of molecular line emissions obtained from advanced millimeter and sub-millimeter interferometric arrays.

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