THE FORMATION OF CRYSTALLINE DUST IN AGB WINDS FROM BINARY-INDUCED SPIRAL SHOCKS

RICHARD G. EDGAR, JASON NORDHAUS, ERIC G. BLACKMAN, AND ADAM FRANK

Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627; rge21@pas.rochester.edu

Received 2007 September 14; accepted 2008 January 22; 2008 February 11

ABSTRACT

As stars evolve along the asymptotic giant branch (AGB), strong winds are driven from the outer envelope. These winds form a shell, which may ultimately become a planetary nebula. Many planetary nebulae are highly asymmetric, hinting at the presence of a binary companion. Some post-AGB objects are surrounded by tori of crystalline dust, but there is no generally accepted mechanism for annealing the amorphous grains in the wind to crystals. Here, we show that the shaping of an AGB wind by a binary companion provides a possible mechanism for forming crystalline dust in the orbital plane.

Subject headings: hydrodynamics — planetary nebulae: general

1. INTRODUCTION

During the asymptotic giant branch (AGB) phase, strong winds are driven from the outer envelope. After ~107 yr, the AGB envelope is expelled, resulting in a proto–white dwarf surrounded by a circumstellar nebula. As the hotter core of the star is unveiled, the nebula ionizes and becomes a planetary nebula (PN). Most PNe are highly asymmetric, displaying complex morphological structures such as disks and bipolar jets (e.g., Balick & Frank 2002 and references therein). The engine driving the asymmetry is thought to begin during the AGB phase or shortly thereafter in the post-AGB phase. A binary companion may be responsible for shaping the nebula. Recent work suggests that a binary interaction may be required to form a PN (Soker 2006; Moe & De Marco 2006; Nordhaus et al. 2007).

The formation of equatorial tori, collimated bipolar jets, and circumstellar disks may be a consequence of additional energy and angular momentum supplied by the binary companion, either through a common envelope phase or by directly shaping the AGB wind (Nordhaus & Blackman 2006; Nordhaus et al. 2007; Blackman et al. 2001). A binary can also process the wide variety of dust species present in AGB winds (Waters 2004). Most of the grains are amorphous, with crystalline silicates also seen at 10%–20% abundance from stars with particularly high mass-loss rates (Kemper et al. 2001; Suh 2002). Observations of a number of post-AGB systems reveal spectral energy distributions consistent with a torus of crystalline dust at large radius. A number of papers have suggested that this dust lies in a Keplerian circumbinary disk (Molster et al. 1999; de Ruyter et al. 2006; Van Winckel et al. 2006; Gielen & Van Winckel 2007; Deroo et al. 2007). However, a velocity curve has only been obtained for one system, the “Red Rectangle” (Bujarrabal et al. 2005), and this system still contains features that are difficult to interpret. Soker (2000) noted that there are serious difficulties in transforming a spherical AGB wind into a circumbinary disk, in terms of both the angular momentum supply and the transfer mechanism. The origin of the crystallinity is not yet clear. Molster et al. (1999) suggest that some form of low-temperature annealing might occur, whereas Tielens et al. (1998) contend that preexisting crystalline grains are amorphized by iron diffusion.

Here, we discuss an alternative means of reproducing observed dust tori: annealing in shocks induced by a binary companion. We will show that the shock temperatures can be sufficient to anneal the grains with the shock lying in the orbital plane. Shock heating has been proposed before (Nakamoto & Miura 2003), but without an astrophysical scenario in which the shock would naturally form.

2. NUMERICAL STUDY

Our code is based on the FLASH code of Fryxell et al. (2000), which is an adaptive mesh refinement code based on a piecewise parabolic method hydrodynamics solver.1 For this work, we use FLASH in Cartesian coordinates. We have added a simple NBODY solver, to model the binary. The wind is modeled by resetting all grid cells within a distance rwind of the primary to a density ρwind, a temperature Twind, and a radial velocity of vwind with respect to the primary. This does not model the full physics driving the wind. However, so long as all the driving occurs within the orbit of the secondary, the details cannot affect our results. The gravitational effect of the bodies is subject to softening. The softening length for the primary is less than rwind; that of the secondary is chosen to be smaller than the expected Hoyle-Lyttleton radius (see, e.g., Edgar 2004). We do not include a jet (cf. García-Arredondo & Frank 2004), because it is not relevant to the present study. Close to each boundary, there is a damping region, where the gas density and temperature are reduced to their ambient values. We do this to ensure that waves cannot reflect from the boundaries.

We performed two sets of runs. In the first, we used a 1 M⊙ primary, with ρwind = 10−14 g cm−3, Twind = 105 K, vwind = 3.8 × 104 cm s−1, and rwind = 2 × 1015 cm. In second set of runs, we used a 3 M⊙ primary, with Twind = 2 × 105 K, vwind = 6.5 × 106 cm s−1, and ρwind and rwind unchanged. This choice of parameters ensures that the wind can escape from the system (velocities fall to <106 cm s−1 for material leaving the computational domain). We refine the grid to ensure that rwind is always covered by 8 grid cells, while the secondary’s Hoyle-Lyttleton radius is always covered by 4 grid cells. The gas is assumed to be adiabatic, with γ = 4/3, a reasonable intermediate value.

3. RESULTS

We first consider a 1 M⊙ primary, a 0.25 M⊙ secondary, and an orbital semimajor axis of 6 AU. Most observed post-AGB binary orbits are smaller. However, we are modeling the

1 The source code is available at http://flash.uchicago.edu/.
early AGB phase, and Theuns et al. (1996) showed that the outflowing wind offers an excellent mechanism for shrinking the binary’s orbit (although we do not permit this in the current runs). The Hoyle-Lyttleton radius of the secondary is approximately \(4.5 \times 10^{12}\) cm. Because we require at least 4 grid cells across the Hoyle-Lyttleton radius, our grid resolution is just over \(10^{13}\) cm near the planet’s orbit.

In Figure 1, we show the gas density of the system along two axes. The spiral structure along the \(z\)-axis is remarkably similar to that noted by Mauron & Huggins (2006) in AFGL 3068, albeit on a different scale. The structure is also similar to that noted by Theuns & Jorissen (1993) and Mastrodemos & Morris (1999). Figure 2 shows the temperature structure of the spiral. Temperatures exceeding 1000 K are generated in a region \(\sim 10^{13}\) cm thick. This region is well resolved by our grid.

We ran a second numerical experiment that was identical to the first, except that we increased the softening length of the secondary to a value substantially larger than the Hoyle-Lyttleton radius. This increase isolated the effect of the secondary from the orbital motion of the binary. The overall density structure changed very little, but the temperatures in the spiral dropped dramatically. Therefore, the orbital “recoil” of the primary is responsible for the macroscopic density structures, in support of the “piston” model of He (2007). However, the local deflection of the flow by the secondary drives the shock formation and the associated increase in temperature.

In a third numerical experiment, we increased the binary separation to 10 AU but kept all the other parameters the same as in the first numerical experiment. The flow was similar to the first numerical experiment, with a slightly reduced peak temperature in the shock. We also performed a fourth numerical experiment that was identical to the first, except for a 100 \(M_\odot\) secondary (making a \(q = 0.095\) binary). The spiral density structure was retained, but we found that the peak temperature was slightly lower and spread over a smaller volume. Finally, we performed a set of runs for a system with a 3 \(M_\odot\) primary and found a similar peak temperature. When \(v_{\text{wind}}\) was increased to ensure that the wind could escape, the shock temperatures were higher.

4. DISCUSSION

Our numerical experiments suggest a mechanism for producing a torus of crystalline dust around an AGB binary: amorphous dust grains are annealed in the gas shocked by the secondary. As the outward motion of the spiral shock slows, the arms will merge and appear as a torus.

---

2 Compare especially their Fig. 4 to our Fig. 1.
4.1. Grain Annealing

There are a number of important timescales that must be assessed to determine whether such annealing can occur. The first has to do with the shock velocities. Examining the output of our FLASH runs, we find that the velocities are always $\sim 10^8$ cm s$^{-1}$. Before the shock, the velocities can be a factor of a few higher. After the shock, the velocities can be a factor of a few lower. In our calculations, the velocity is mainly radial, so the crossing time of the high-temperature region (10$^{12}$ cm or so in radial extent in the midplane) is $\sim 10^8$ s.

The next timescale is the stopping distance of grains by gas. Calculating the distance required for a grain to sweep up its own mass of gas, we find $l_{\text{stop}} = (4p_{\text{dust}}a_{\text{dust}})/(3\rho)$. For expected gas densities and dust sizes, $l_{\text{stop}} \sim 1.3 \times 10^{11}$ cm, which is sufficiently small to ensure that gas and dust are dynamically coupled; dust grains will not be blown out by radiation pressure. Note that $l_{\text{stop}}$ is somewhat smaller than the numerical resolution. The stopping timescale will be similar to the time required to heat the dust grains by collisions. This is given by $t_{\text{heat}} = l_{\text{stop}}/v \approx 1.3 \times 10^8$ s. In making the above argument, we have assumed that the frictional heating of the grains can overcome their radiative cooling. Since the radiative loss rate can be quite high, this might not be a valid assumption.

Hollenbach et al. (2000) studied the annealing of silicate grains as a function of temperature. The process is controlled by the Boltzmann equation, with the rate $\propto \exp \{-E/k_B T\}$. If temperatures exceeding 1067 K were reached, the amorphous grains would anneal to crystals on times $t_{\text{anneal}} \approx 280$ s. At lower temperatures, annealing stalled for around 35 h, after an initial burst of crystallization. Harker & Desch (2002) applied this to spiral shocks in protoplanetary disks induced by gravitational instabilities, concluding that annealing would be possible.

The final timescale is that of cooling. We have used a simple adiabatic equation of state for the gas. In reality, the gas will be able to cool through a forest of molecular line transitions. Computing these accurately is complicated. To make an estimate, we use the cooling curves of Schirrmacher et al. (2003), who considered the wind of a pulsating star. Using Figure 4 of their work, we find $t_{\text{cool}} = (3k_B T)/(2m_r Q_{\text{rad}}).$ Using the value of the cooling function for a temperature of 1100 K and a density of $10^{-15}$ g cm$^{-3}$, we find $t_{\text{cool}} \approx 1.4 \times 10^8$ s.

What are the implications for grain annealing? First, $t_{\text{anneal}}$ is so short compared to the other timescales that, so long as temperatures in excess of 1067 K are reached, we can assume that annealing is instantaneous. If we could neglect postshock cooling of the gas, then the crossing time for the whole shock is so long that annealing should occur even if the shock temperature is only 1067 K. However, cooling is likely to be significant, so successful annealing requires $t_{\text{heat}} < t_{\text{cool}}$. Specifically, we require

$$\frac{t_{\text{heat}}}{t_{\text{cool}}} = 0.9 \left( \frac{a_{\text{dust}}}{1 \, \mu m} \right) \left( \frac{\dot{Q}_{\text{rad}}}{10^6 \text{ ergs g}^{-1} \text{s}^{-1}} \right) \left( \frac{\rho}{10^{-15} \text{ g cm}^{-3}} \right)^{-1} \times \left( \frac{T}{1100 \text{ K}} \right)^{-1} \left( \frac{v}{10^6 \text{ cm s}^{-1}} \right)^{-1} < 1. \quad (1)$$

Note that $\dot{Q}_{\text{rad}}$ is approximately proportional to density, so this ratio is fairly insensitive to $\rho$. Smaller grains will heat (and hence anneal) faster. We calculated $t_{\text{heat}}$ for 1 $\mu$m grains, and we expect the actual grains to be smaller, perhaps as small as 0.1 $\mu$m, making the heating time an order of magnitude shorter. Such grains would anneal easily, particularly since each grain trajectory will encounter the spiral shock multiple times.

4.2. Shock Temperature Scaling

We now estimate how the shock temperature of the gas scales with the system parameters. The problem may be split into two parts: The wind from the primary may be modeled as a spherical Bondi wind (see, e.g., pp. 14–22 of Frank et al. 2002). A shock is then induced in this wind by the secondary.

An important parameter in a Bondi wind is the sonic radius. This occurs at $r_s = GM/2c_s^2(r)$. In our winds, $T \sim 1000$ K or less, implying that the sonic radius will be outside the orbit of the secondary. Since we construct our initial conditions to be escaping and supersonic, our wind solution should always be supersonic (the type 4 solutions of Frank et al. 2002).

Because the Bondi solution itself is not analytically available, we shall assume that the Mach number of the flow remains constant and that the wind velocity remains close to the escape velocity. Both assumptions are correct for highly supersonic Bondi flows. The flow then shocks as it passes the secondary. However, the Mach number of the shock is not $M_{\text{launch}}$ because we must add in the orbital motion of the companion to obtain the total relative velocity of the gas. This is comparatively straightforward, because the velocity of a body in a circular orbit is a factor $\sqrt{2}$ smaller than the escape velocity. This implies that $M^2 \approx 1.5M_{\text{launch}}^2$. Combining these, we find

$$T_{\text{post shock}} \approx 1200 \left( \frac{M}{M_\odot} \right)^2 \left( \frac{r_{\text{wind}}}{2 \times 10^{16} \text{ cm}} \right)^{-1} \left( \frac{r_{\text{orb}}}{10^{14} \text{ cm}} \right)^{-1}. \quad (2)$$

This assumes that the wind velocity is always equal to the local escape velocity. Our numerical experiments had $v_{\text{wind}}$ slightly larger than the escape velocity, leaving some “excess” velocity that equation (2) does not take into account. Consequently, equation (2) is rather more sensitive to $r_{\text{orb}}$ than the temperatures of our numerical experiments. We emphasize that this calculation is only a rough estimate of the temperatures reached and that we saw a wide range of temperatures in our numerical experiments. At the tip of the bow shock, the temperature was much higher (this material would probably be accreted by the secondary anyway). All along the spiral arms, we found that the temperatures rapidly dropped to values similar to those predicted by equation (2).

Our numerical simulations indicate that the shock temperatures depend weakly on the secondary mass—2 orders of magnitude in secondary mass leads to an $\sim 20\%$ change in temperature. This is not included in equation (2), but the simulations are consistent with the much stronger predicted dependence on the primary mass. There are also two important scales for the secondary in addition to its own radius, namely, the Hoyle-Lyttleton radius and the Roche radius. In our simulations and in the analytic scaling above, we implicitly assume that the Hoyle-Lyttleton radius is smaller than the Roche radius. In cases for which the reverse applies, we would expect an accretion disk to form close to the secondary. The shock structure and temperature may depend somewhat on the ratio of these two radii, which we have not pursued in the present work.

What limits are appropriate for $T_{\text{post shock}}$? As we have already mentioned, we require $T_{\text{post shock}} > 1067$ K for annealing to occur. However, it must not be too high, or the grains will vaporize—2000K is a good upper limit. Equation (2) then provides rough
constrains on the systems that can produce crystalline dust tori. For a 1 $M_\odot$ star, we would require $0.6 \times 10^{15} \text{ cm} < r_{\text{orb}} < 1.1 \times 10^{15} \text{ cm}$ (assuming $r_{\text{wind}} = 2 \times 10^{13} \text{ cm}$). If the primary were a 3 $M_\odot$ star, the limits become $5.4 \times 10^{15} \text{ cm} < r_{\text{orb}} < 1 \times 10^{15} \text{ cm}$ (assuming the same $r_{\text{wind}}$ value).

4.3. Dust Formation

The dust has to form before it encounters the shock, which implies a minimum binary separation for this mechanism. De Ruyter et al. (2006) found $n_{\text{max}} < 10 \text{ AU}$ for all their systems, which is comparable to the orbital distances that we have used. In lower mass systems, the dust formation constraint is smaller, but so is the binary separation implied by equation (2). Furthermore, in Figure 2, we see that annealing temperatures are reached on at least the second passage of the spiral arm. This means that it might even be possible for annealing to occur even if the secondary is within the dust formation radius.

5. CONCLUSION

We have demonstrated that a binary companion to an AGB star can create a torus of crystalline dust. The crystalline dust is formed by the annealing of amorphous grains in the spiral shock induced by the companion. Such a torus is likely to be expanding and not in Keplerian orbit around the system. Peretto et al. (2007) found that NGC 6302 contained an expanding torus of gas. Molster & Kemper (2005) noted that high degrees of crystallinity in post–main-sequence stars appear to be associated with binarity (see also Molster et al. 2001). Our model addresses only the formation of crystalline dust, not the growth of very large dust grains. We have put forth a model with the understanding that it may not be complete; it is a paradigm in need of further study. However, our model offers a simple, physically consistent explanation for expanding tori of crystalline dust in young AGB binary systems.

We have only made rough estimates of cooling and heating. We have demonstrated that the relevant timescales should permit annealing, but more work is needed. Future calculations should incorporate gas cooling. This is not straightforward, because the relevant temperatures and timescales imply nonequilibrium chemistry. There are a number of cooling curves available for a variety of gas mixtures, and care must be taken to select an appropriate one. A more careful study of the physics of dust in shocks will also be necessary (see, e.g., Slavin et al. 2004 for calculations of the shock processing of grains in the interstellar medium). Ideally, the dust should also be incorporated into the code as a separate, coupled component. This will permit a better estimate of the heating times of the grains.

We acknowledge support from NSF grants AST-0406799 and AST-0406823 and NASA grants ATP04-0000-0016 (NGO5GH61G) and NGO4GM12G. This work is supported in part by the US Department of Energy under grant B523820 to the Center for Astrophysical Thermonuclear Flashes at the University of Chicago. The computations presented here were performed using time granted through TeraGrid under project TG-AST070018T. We are grateful to Garrelt Mellema for helpful comments about gas cooling.

REFERENCES

Balick, B., & Frank, A. 2002, ARA&A, 40, 439
Blackman, E. G., Frank, A., & Welch, C. 2001, ApJ, 546, 288
Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Neri, R. 2005, A&A, 441, 1031
Deroo, P., van Winckel, H., Verhoeest, T., Min, M., Reyniers, M., & Waters, L. B. F. M. 2007, A&A, 467, 1093
de Ruyter, S., van Winckel, H., Maas, T., Lloyd Evans, T., Waters, L. B. F. M., & Depojhge, H. 2006, A&A, 448, 641
Edgar, R. 2004, NewA Rev., 48, 843
Frank, J., King, A., & Raine, D. J. 2002, Accretion Power in Astrophysics (3rd.; Cambridge: Cambridge Univ. Press)
Fryxell, B., et al. 2000, ApJS, 131, 273
Garcia-Arredondo, F., & Frank, A. 2004, ApJ, 600, 992
Giel, C., & Van Winckel, H. 2007, Baltic Astron., 16, 148
Hallenbeck, S. L., Nuth, J. A., III, & Nelson, R. N. 2000, ApJ, 535, 247
Harker, D. E., & Desch, S. J. 2002, ApJ, 565, L109
He, J. H. 2007, A&A, 467, 1081
Kemper, F., Waters, L. B. F. M., de Koter, A., & Tielens, A. G. G. M. 2001, A&A, 369, 132
Mastrodemos, N., & Morris, M. 1999, ApJ, 523, 357
Maurom, N., & Huggins, P. J. 2006, A&A, 452, 257
Moe, M., & De Marco, O. 2006, ApJ, 650, 916
Molster, F., & Kemper, C. 2005, Space Sci. Rev., 119, 3
Molster, F. J., Yamamura, I., Waters, L. B. F., Nyman, L.-Å., Käufl, H.-U., de Jong, T., & Loup, C. 2001, A&A, 366, 923
Molster, F. J., et al. 1999, Nature, 401, 563
Nakamoto, T., & Miura, H. 2003, in Astrophysics of Dust, ed. A. N. Witt (San Francisco: ASP), 63
Nordhaus, J., & Blackman, E. G. 2006, MNRAS, 370, 2004
Nordhaus, J., Blackman, E. G., & Frank, A. 2007, MNRAS, 376, 599
Peretto, N., Fuller, G., Zijlstra, A., & Patel, N. 2007, A&A, 473, 207
Scharf, M., & Schmieder, B. 2003, A&A, 404, 267
Slavin, J. D., Jones, A. P., & Tielens, A. G. G. M. 2004, ApJ, 614, 796
Soker, N. 2000, MNRAS, 312, 217
Soker, N. 2006, ApJ, 645, 157
Suh, K.-W. 2002, MNRAS, 332, 513
Theuns, T., & Jorisissen, A. 1997, MNRAS, 280, 1264
Tielens, A. G. G. M., Waters, L. B. F. M., Molster, F. J., & Jastrowon, K. 1998, Ap&SS, 255, 415
Van Winckel, H., Lloyd Evans, T., Reyniers, M., Deroo, P., & Giel, C. 2006, Mem. Soc. Astron. Italiana, 77, 943
Waters, L. B. F. M. 2004, in ASP Conf. Ser. 309, Astrophysics of Dust, ed. A. N. Witt, G. C. Clayton, & B. T. Draine (San Francisco: ASP), 229