THE ASTROPHYSICAL JOURNAL, 543:L53–L56, 2000 November 1

COLLIDING STELLAR WINDS: "ASYMMETRIC" THERMAL CONDUCTION

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Received 2000 May 19; accepted 2000 September 8; published 2000 October 18

ABSTRACT

We present the first results from modeling asymmetric thermal conduction in colliding stellar winds. This effect is important even when a weak magnetic field is present in windblown bubbles and planetary nebulae. Using a simplified model of this complicated physical situation, we demonstrate that asymmetric conduction may cause asymmetric structures even if the colliding winds were initially spherically symmetric. We also find that the interior of such hot bubbles becomes convective. The objects that this model represents will show higher asymmetry if observed in X-rays rather than in the optical.

Subject headings: hydrodynamics — ISM: bubbles — ISM: individual (NGC 6888) — X-rays: ISM

1. INTRODUCTION

Colliding stellar winds (CSWs) have an important role in the physics of various astrophysical objects. They may be responsible for the increased X-ray emission from binaries consisting of massive luminous stars (e.g., Pollock 1987; Prilutskii & Usov 1976; Lebedev & Myasnikov 1990; Luo, McCray, & Mac Low 1990; Stevens, Blondin, & Pollock 1992; Myasnikov & Zhekov 1991, 1993) as well as for the X-ray emission from windblown bubbles (WBBs; e.g., Bochkarev 1988; Wrigge, Wendker, & Wisotzki 1994; Wrigge 1999; Weaver et al. 1977; Bochkarev & Zhekov 1990; Garcia-Segura & MacLow 1995a, 1995b; Strickland & Stevens 1998) and from planetary nebulae (PNs; e.g., Kreysing et al. 1992; Zhekov & Perinotto 1996, 1998). CSWs are assumed to be responsible for shaping PNs and WBBs. This is why the CSW phenomenon can be defined in a broader context that includes not only the case of the collision of two stellar winds emitted simultaneously (CSWs in binary systems) but also the case of winds being blown consecutively in time (PNs and WBBs). The interaction of a stellar wind with uniform interstellar matter can also be considered along these lines.

It is interesting to note that since relatively cold and hot gases coexist in the above-mentioned cases of CSWs, we expect that electron thermal conduction (THC) may also play an important role for the physics of CSWs (WBBs: Weaver et al. 1977; Zhekov & Myasnikov 1997; PNs: Bedogni & D'Ercole 1986; Soker 1994; Zhekov & Perinotto 1996; CSWs in binaries: Myasnikov & Zhekov 1998). It is well known (Braginskii 1958; Spitzer 1962) that a magnetic field (MF) highly reduces electron THC in directions perpendicular to the MF lines. Thus, even the presence of a weak MF will result in very asymmetric heating effective only along MF lines. This asymmetric heating may cause the evaporation of cold gas along only the MF lines, and this will result in a very interesting macroscopic picture of CSWs. The presence of an MF in hot luminous stars is always an issue, but since some of these stars are sources of nonthermal radio emission, it is reasonable to assume that an MF is present, although it may not be dynamically important for the stellar winds in these objects.

We note that the mechanism proposed here is different from the magnetic shaping of PNs as described by Chevalier & Luo (1994; see also Garcia-Segura 1997 and Garcia-Segura et al. 1999). The basic idea of magnetic shaping is that the MF becomes dynamically important (magnetic pressure is larger than the thermal pressure) at large distances from the central star. Our mechanism, on the other hand, assumes that the MF has no influence on the gasdynamics at all. The MF's sole role is to redirect the thermal flux, which results from the temperature gradients in the gas. The role of asymmetric heating was also discussed by Soker (1994), who made a qualitative prediction that a higher conduction efficiency in the MF pole directions can lead to asymmetry in X-rays and line emission intensities in PNs.

Unfortunately, the hydrodynamics of the MF-THC interaction is quite a difficult task if one likes to study it numerically. First of all, we need to have a very good idea about the stellar MF configuration. However, if we start our studies with the simplest possible model for an MF in stars with stellar winds (Parker 1958), i.e., one suggesting that only the toroidal MF component is important at large distances from the star, then the numerical model will require that three-dimensional calculations be performed even in the axially symmetric case of CSWs in binaries. Therefore, we need a simple example of the MF-THC interaction that, even if not complete with regard to the background physics, will allow us to "catch" the gross, qualitative characteristics of this phenomenon. Namely, we would like to answer the following question: can asymmetric heating affect/change the global structure of CSWs? We think that this question is fundamental for hydrodynamics since asymmetric heating is an internal process for the structure under consideration and does not introduce any external forces. From this point, even a very simplified treatment of the MF-THC interaction is justified, and WBBs and PNs seem to be good targets for these preliminary studies. In § 2, we describe the main model assumptions. Our results and a discussion are given in § 3. Our conclusions are given in §4.

2. MODEL AND NUMERICAL METHOD

The physical picture, which we believe is realistic in the case of CSWs in WBBs and PNs, could be as follows. The central

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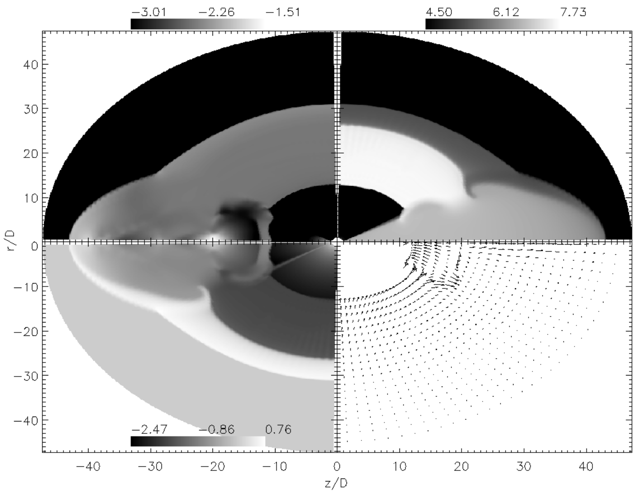

FIG. 1.—Standard WBB for the case of circumstellar matter with constant density. The age of the WBB is 5000 yr, and ATHC was taken into account. From left to right, the distributions of pressure, temperature, density (all of them in log scale), and velocity field are shown (for graphical clarity, the velocity field of the free wind is not shown). The pressure, density, and velocity are given in units of 5.16×10^{-8} ergs cm^{-3}, 1.29×10^{-24} g cm^{-3}, and 2000 km s^{-1}, respectively, while temperature is in kelvins. The WBB elongation is along the MF axis. All distances are normalized to $D = 1.4 \times 10^{17}$ cm. Due to the symmetry of the gasdynamics problem, the calculations are performed in only one quadrant.

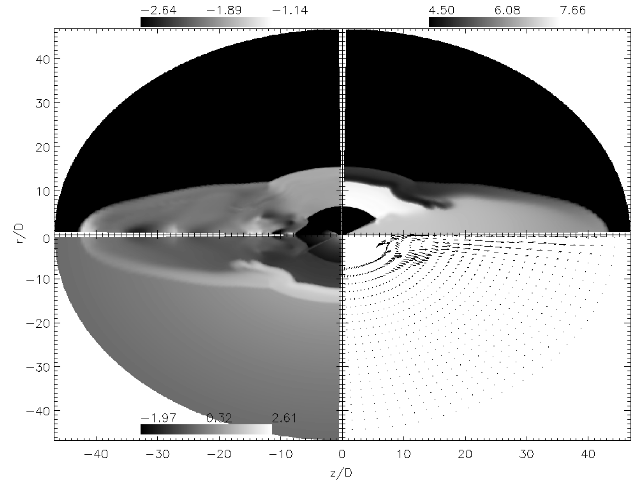

FIG. 2.—Same as in Fig. 1, but the circumstellar matter has a $1/r^2$ density profile. All normalizations are the same.

star has a relatively strong wind whose parameters may vary during the stellar evolution, and depending on the mass of the central star, the interaction of different winds will form either a WBB or a PN. The wind of the central star has a constant wind velocity and mass-loss rate within each evolutionary stage. When an interaction of the stellar wind with circumstellar matter is considered, a constant density is assumed for the latter. Also, the central star possesses a weak MF, and the wind is not magnetically driven; i.e., the field has no influence on the wind's dynamics. This is why we assume that the MF geometry is in accord with the Parker model (Parker 1958) and that only the toroidal component is important at distances far from the stellar surface. We recall that the Parker model suggests that the gas outflow (the wind) is radially symmetric and that its velocity is considerably larger than the stellar rotational velocity; i.e., we have a slow magnetic rotator.

In such a case, CSWs form a spherically symmetric structure (a WBB or a PN), presented by the standard hydrodynamic picture of two shocks and contact discontinuity. However, the heat transfer will be allowed only in a region of space near the MF axis. Therefore, the evaporation from the "cold" outer shell will be asymmetric, and a deviation from sphericity might be expected for the whole structure. We note that since the MF is toroidal far from the star, it will be parallel to the shock front(s) (*perpendicular* to the radial gas flow) and will gradually approach zero near the MF axis. In the frame of this model, the exact heat-transport coefficients (Braginskii 1958) suggest that the presence of even a weak stellar MF ($B_s \leq 1$ G on the star surface) will considerably suppress THC across the field lines and cause asymmetric heating in CSWs.

Since the exact dependence of the THC coefficient on the MF strength is quite awkward and not easy to use in numerical simulations, we "mimic" the MF effect instead. For the sake of technical simplicity in numerical modeling, we assume that the conductivity coefficient is a function of only the polar angle, $\kappa \simeq \kappa_{\rm classical} (\cos\theta)^N$, where $\kappa_{\rm classical}$ is the standard electron conductivity coefficient and N is a free parameter ($\theta = 0$ is the direction of the MF axis). Qualitatively, larger values of N correspond to a stronger MF and vice versa. This functional dependence on the polar angle is smooth and satisfies the strategy of these preliminary studies, namely, to check what the global response of the CSW structure will be if energy exchange is restricted within a given part of the structure. This dependence also allows us to study the MF effect on the thermal conduction by varying N. Most importantly, such an approach requires that only two-dimensional calculations be carried out.

Our numerical method for calculating THC was previously tested in the one-dimensional modeling of WBBs and the two-dimensional modeling of CSWs in binaries. We only recall that the soft-fitting technique is basic for our model; it permits the same number of grid points between the shock surfaces for all evolutionary times. Further details are found in Zhekov & Myasnikov (1997) and Myasnikov & Zhekov (1998).

3. RESULTS AND DISCUSSION

In order to study the asymmetric heat transfer in CSWs, we explored the purely conductive "standard" WBB (Zhekov & Myasnikov 1997), which is formed when a stellar wind with a mass loss of 10^{-6} $M_\odot$ yr^{-1} and a wind velocity of 2000 km s^{-1} interacts with circumstellar matter. Two cases were considered: (1) the circumstellar matter has a constant number density of 1 cm^{-3}, and (2) it has a $1/r^2$ density profile that is due to a previously blown wind with a mass-loss rate of 10^{-5} $M_\odot$ yr^{-1} and a wind velocity of 10 km s^{-1} . All calculations were performed in a two-dimensional spherical coordinate system with 256 grid points in the r-direction and 64 points in the θ-direction ($0 \leq \theta \leq \pi/2$). The free parameter $N = 100$ was used in these calculations in order to give about the same reduction of the thermal conduction at $\theta = 10°$–$30°$ as the exact Braginskii's formula would give for $B_s = 1$ G and a WBB age of a few thousands years. Although a much more sophisticated treatment of this effect is needed, we note that even these simplified numerical calculations show that asymmetric heating results in the asymmetric shaping of the CSW structures (Figs. 1 and 2).

Figures 1 and 2 demonstrate another interesting feature of asymmetric thermal heat conduction (ATHC). Thermal convection is taking place in the boundary region between the conductive (near the MF axis) and adiabatic parts of the hot bubble. This convection is well seen in the velocity field that clearly demonstrates some inflow and outflow motions present at all evolutionary times. Our grid studies confirm that the asymmetric CSW structures are reproducible and that their characteristics converge on finer grids. We are then confident that the ATHC effects do not have a numerical origin.

Despite the numerical confirmation of the expected ATHC effects, it is worth trying to understand qualitatively the physical reasons for them. With this regard, we first recall the meaning of "evaporation" in the case of two neighboring gases with very different temperatures. As already mentioned, such a situation exists in WBBs and PNs or in CSWs in binaries (in the latter case, if the velocities of the stellar winds are quite different). In these cases, THC simply transfers energy from the hotter gas to the colder one. The pressure of the previously colder gas increases, and the pressure balance on the contact discontinuity is violated. Finally, the contact discontinuity moves into the hotter gas, looking for a new equilibrium position. This effect was well demonstrated by the numerical modeling of THC in WBBs (Zhekov & Myasnikov 1997). We note that in this case, the *temperature* and *pressure gradients* have *opposite directions*. The temperature gradients are always directed outward, while the pressure gradients are directed inward; i.e., these gradients are in some sense acting to compensate each other.

Let us now turn to ATHC in WBBs and PNs. In this case, the effects of THC are limited to only some region near the MF axis, which we define as the ATHC "cone." The role of THC is again to transfer energy from the hotter gas to the colder one, and this indeed happens in the ATHC cone. Once some energy has been transferred, a pressure gradient appears on the contact discontinuity. On the boundary between the ATHC cone and the adiabatic part of the hot bubble, both a pressure gradient and a temperature gradient appear in the previously hotter gas. Now the physical picture is more complicated, and it is interesting to note that the *pressure* and *temperature gradients* in the hot bubble have the *same direction*, from the adiabatic part of the hot bubble to the ATHC cone. Due to this, a "temperature-pressure pump" is established; this pump continuously transfers energy toward the gas near the MF axis, and because of the high THC efficiency in this region, from there it moves further on into the cold outer shell. In the cold shell, the pressure and temperature gradients also appear in all directions, and the highest pressure and temperature values are near the MF axis. This explains why the asymmetry effects are more pronounced near the axis of symmetry. The pressure gradients cause some global gas flows to occur within the bubble interior that result in the observed thermal convection.

As already stated, our primary goal was to check whether ATHC can affect the global structure of CSWs, and a positive answer to this question was given by our simplified model. It is interesting to see how the global asymmetry correlates with the ATHC cone size (determined by the free parameter N). Figure 3 demonstrates what can be expected qualitatively. The larger the size of the ATHC cone (smaller N-values), the smaller the global asymmetry of CSW structures. One can extrapolate this qualitative result and claim that the ATHC mechanism might even be capable of producing jetlike structures.

We note that our calculations do not take into account radiative energy losses. If they are considered, we may expect to see quite a complex flow pattern in the interior of the CSW structure since various timescales (dynamic, cooling, and conduction) will interfere. The resulting conditions may also be favorable for the development of various instabilities such as thermal, Rayleigh-Taylor, or Kelvin-Helmholtz.

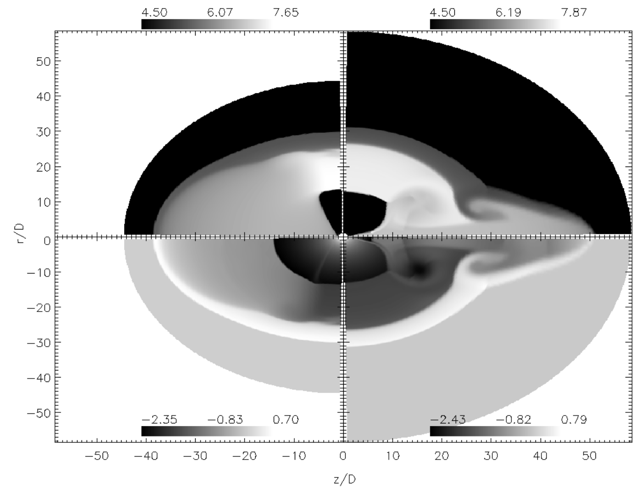

FIG. 3.—Standard WBB and all normalizations same as in Fig. 1, except that $N = 10$ (*left panels*) and $N = 1000$ (*right panels*). Temperature and density distributions are shown in the upper and lower panels, respectively.

An interesting consequence of ATHC is that the global asymmetry of the CSW structure will be much more pronounced in X-rays than in the optical. As Figures 1 and 2 demonstrate, there is a density contrast in the hot bubble interior with the denser plasma located in the vicinity of the MF axis. Therefore, only the gas in that region will be easily detectable in X-rays, while the optical observations will reveal the geometry of the outer cold shell. Although projection effects are important, this may explain qualitatively why the X-ray emission from NGC 6888 was found mainly in the northern and southern filaments of that WBB (Wrigge et al. 1994), i.e., along its major axis. On the other hand, if the global asymmetry of WBBs and PNs were a result of a density contrast in the outer wind, a higher surface brightness in X-rays would be expected along the minor axis of the WBB structures (because the density of the hot bubble is larger there). Thus, there are distinctive predictions from these two different models that allow a decisive observational test to be made by comparing high spatial resolution observations in X-rays and in the optical.

Moreover, the global asymmetry of WBBs and PNs will be established only in regions where THC can operate, i.e., in regions with hot gas and large temperature gradients. Therefore, the "halos" of WBBs and PNs, if detectable, will be spherically symmetric, and a departure from sphericity will be apparent only in the region where stellar winds collide. Finally, the ATHC physical picture might be even more interesting if the weak MF is the result of an oblique magnetic rotator or if the "magnetized" star is a component of a binary system. Then some MF axis "precession" effects will be expected that will definitely require three-dimensional modeling to be performed.

4. CONCLUSIONS

In this work, we presented the first results from a simplified numerical model that considers asymmetric thermal conduction in CSWs in WBBs and PNs. Such a physical situation may exist when a weak MF field is present. Then thermal conduction will be efficient only along the MF lines. Our two-dimensional numerical simulations show that asymmetric thermal conduction will cause evaporation in a region near the MF axis, and this will result in a global asymmetric expansion of the CSW structure. This picture is in accord with the qualitative predictions by Soker (1994). Thus, a new mechanism for the asymmetric shaping of WBBs and PNs is proposed. In addition, the hot bubble interior becomes convective, and more realistic calculations are needed in order to study the development of various instabilities. These improved models must take into account radiative losses as well as the self-consistent treatment of the MF.

We anticipate that, since the realistic ATHC cone will be narrower than that considered in our preliminary studies, the exact solution of the problem may show that even jetlike structures are formed by asymmetric heating. This increases the technical difficulties for the numerical modeling and such studies are postponed for a future work. Nevertheless, this work cannot be postponed for too long since the initial boost was provided by the encouraging results presented in this Letter. Finally, from an observational standpoint, the most interesting consequence is that CSW structures where asymmetric conduction is taking place will appear more asymmetric in X-rays than in the optical. Future X-ray observations with high spatial resolution (e.g., *Chandra* and *XMM*) will help discriminate between different models.

This work was supported by NASA grant NAG5-8236 (S. A. Z.) and by the RFBR grant N 99-01-00756 (A. V. M.). We thank Eli Michael for the careful reading of the manuscript. The authors appreciate the valuable comments by an anonymous referee.

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