In the Mira A/B system, we therefore appear to have a bipolar outflow from Mira B which first interacts with the wind from Mira A and at larger distances emerges from the wind into the streaming ISM region. However, in the present paper we consider the simpler problem of an aligned (bi-conical) bipolar outflow/streaming environment interaction (i.e., we neglect the presence of the wind from Mira A). This is a first step to modeling the high velocity outflow observed by Meaburn et al. (2009).

We present an analytic, stationary, thin shell model of the interaction of a bi-conical outflow and an aligned, streaming environment in § 2. Time-dependent, axisymmetric numerical simulations of this problem are described in § 3, and their results presented in § 4. With the simulations we show the characteristics of the flow in greater detail, and evaluate the level of agreement with the analytic, thin shell solution. Finally, the implications of this model for the interpretation of Mira's outflow are discussed in § 5.

2. THE ANALYTIC MODEL

Let us consider a source that ejects a bipolar, conical outflow (with a half-opening angle θ_j, velocity v_j and mass loss rate $\dot{M}_j$ for each outflow lobe), immersed in a uniform, streaming environment of density ρ_a, which travels parallel to the outflow axis at a velocity v_a. The situation is shown in the schematic diagram of Figure 1. We assume that, as the material from the outflow encounters the streaming environment, a thin shell of well mixed material is formed (the thick solid line shown in Figure 1). This layer has a bow shock shape $R(\theta)$, where R is the spherical radius and θ the angle measured from the z-axis, see Figure 1).

At a position θ along the bow shock, the material flowing along the thin shell has a mass rate:

$$\dot{M}(\theta) = \int_0^\theta d\dot{M}_j + \pi r^2 \rho_a v_a \,, \tag{1}$$

where the first term on the right represents the mass fed into the shell by the conical jet, and the second term is the mass from the streaming environment (with $r = R\sin\theta$ being the cylindrical radius, see Figure 1).

The radial momentum rate of the material in the shell is:

$$\dot{\Pi}_r(\theta) = \dot{M}(\theta)\, v_r(\theta) = \int_0^\theta v_j \sin\theta \, d\dot{M}_j \,, \tag{2}$$

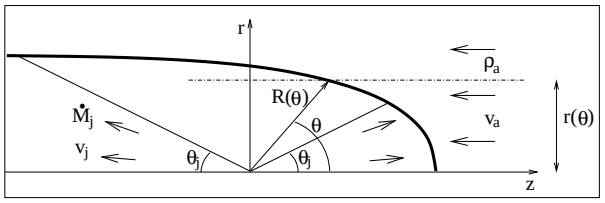

Fig. 1. Schematic diagram showing the interaction between a bi-conical outflow (of half-opening angle θ_j, velocity v_j and total mass loss rate $2\dot{M}_j$) with a streaming environment of density ρ_a and velocity v_a (aligned with the outflow axis).

with a contribution only from the jet. The axial momentum (along the z-direction) flowing along the shell is:

$$\dot{\Pi}_z(\theta) = \dot{M}(\theta)\, v_z(\theta) = \int_0^\theta v_j \cos\theta \, d\dot{M}_j - \pi r^2 \rho_a v_a^2 \,. \tag{3}$$

In equations (2) and (3), v_r and v_z are the r- and z-components of the velocity of the (well mixed) material flowing along the thin shell. One can also write an expression for the angular momentum rate of the material flowing along the shell:

$$\dot{J}(\theta) = \dot{M}(\theta)\, v_\theta(\theta) R(\theta) = \int_0^r r' v_a (2\pi 4' \rho_a v_a) dr'$$

$$= \frac{2}{3}\pi \rho_a v_a^2 R^3 \sin^3\theta \,, \tag{4}$$

where v_θ is the velocity in the θ-direction (of the material flowing along the thin shell), which is given by:

$$v_\theta = v_r \cos\theta - v_z \sin\theta \,. \tag{5}$$

Now, we consider a conical, bipolar outflow with a mass loss rate given by:

$$d\dot{M}_j = \begin{cases} \frac{\dot{M}_j}{1-\cos\theta_j}\sin\theta\, d\theta & \theta \le \theta_j \text{ or } \theta \ge \pi - \theta_j \,, \\ 0 & \theta_j < \theta < \pi - \theta_j \,. \end{cases} \tag{6}$$

With this form for $d\dot{M}_j$, it is possible to carry out the integrals in equations (1–3), allowing us to obtain the shape of the bow shock:

$$R(\theta) = R_0 \,\mathrm{cosec}\,\theta \times \sqrt{3\,(1 - \theta\,\mathrm{cotan}\,\theta)}\,; \;\; \theta \le \theta_j \,, \tag{7}$$

$$R(\theta) = R_0 \,\mathrm{cosec}\,\theta$$
$$\times \sqrt{3\,[\cos(\theta-\theta_j)\sin\theta_j \,\mathrm{cosec}\,\theta - \theta_j \,\mathrm{cotan}\,\theta]}\,;$$
$$\theta_j < \theta < \pi - \theta_j \,, \tag{8}$$
$$R(\theta) = R_0 \,\mathrm{cosec}\,\theta$$