MODELS OF MOLECULAR OUTFLOWS

S. CABRIT*
DEMIRM, Observatoire de Paris
61 Avenue de l’Observatoire
75014 Paris, FRANCE
e-mail: Sylvie.Cabrit @ obspm.fr

Abstract. In this contribution, I present a broad "historical" review of the various hydrodynamical models that have been considered for explaining molecular outflows, and of their merits and failures when compared with observations. Wind-driven bubbles, viscous jet mixing-layers, and jet bowshocks, are discussed in turn. Most general properties of outflows can be understood in terms of a simple bowshock model. However, the detailed structure of outflows is more complex and not yet fully understood, given the presence of time variability in the jet velocity and/or direction. Finally, I discuss constraints on wind properties (momentum, mass-loss rate, radius) that can be derived from molecular outflows driven by jet bowshocks.

Key words: Outflows – Jets – Interstellar Shocks

1. Introduction

The large amount of mass in molecular flows from young stellar objects (YSOs) shows that they are mostly made of ambient material entrained by an underlying "primary wind" from the central source. Modelling outflows basically aims at understanding this dynamical entrainment process.

Molecular outflows share several observational characteristics that must be reproduced. Recent reviews are given, e.g., by Bachiller & Gómez-González (1992), and Masson & Chernin (1993). Before discussing specific hydrodynamical models, I will recall here two important "model-independent" constraints set by observations.

First, the small number of outflows with superimposed blueshifted and redshifted emission in their lobes, like e.g. B335 and RNO 43, has shown that, at least in the bulk of most flows, the transverse component of velocity must be small, \( \sim 5 \) km s\(^{-1}\), compared with the axial component (Cabrit et al. 1988; Meyers-Rice & Lada 1991). Second, the broad emission line wings indicate that most of the mass is moving at low velocities, and that large intrinsic velocity gradients must be present in the swept-up gas (Masson & Chernin 1992). In particular a velocity that decreases with increasing polar angle \( \theta \) could reproduce both the apparent linear acceleration ("Hubble-law") seen in edge-on flows and the apparent deceleration seen in pole-on flows (Moriarty-Schieven & Snell 1988; Cabrit 1989; Shu et al. 1991).

* On leave from Observatoire de Grenoble

Two classes of dynamical models have been considered to explain these features in a coherent way. The first one (chronologically) involves the interaction of a loosely collimated wind with ambient material, giving rise to wind-driven bubbles, while the second, recently supported by observations, assumes the flow is driven by a highly-collimated jet. As a large body of work has been done on this subject over more than a decade, I will not give an exhaustive review, but rather try to discuss the basic flow properties for each of these two classes of models, and see how they compare with observations.

2. Models of Wind-Driven Bubbles

This first class of model was motivated by the fact that (1) outflows were initially thought to be only moderately collimated (e.g. Lada 1985), (2) the ionized component of YSO jets fails by 1 to 2 orders of magnitude to provide sufficient momentum for driving molecular flows (e.g. Mundt et al. 1987; Cabrit & Bertout 1992 and references therein). A natural possibility was that outflows were driven by a loosely collimated neutral wind, physically distinct from the jets. Detection of extremely high-velocity (EHV; \( \bar{V} \sim 150 \) \( \text{km s}^{-1} \)) HI and CO emission in several flows further lent support to this atomic wind hypothesis (e.g. Lizano et al. 1988), although spatial resolution was insufficient at the time to assess its collimation.

The expansion of spherical wind-bubbles, investigated in the context of OB star winds by Weaver et al. (1977), was generalized to the case of molecular outflows by Dyson (1984) and Kwok & Volk (1985). A dense shell of swept-up gas is formed, with two possible expansion regimes: a momentum-conserving regime, where the wind cools rapidly after impacting the shell and imparts only its momentum, and an energy-conserving regime, where the shocked wind remains hot and further pushes the shell with its thermal pressure. The latter is more efficient at accelerating the bubble, by a typical ratio \( V_{\text{wind}}/V_{\text{shell}} \sim 10 \). As YSO winds could be in either regime (e.g. Dyson 1984), both cases have been investigated.

Wind-driven bubbles possess two interesting features. First, they are naturally collimated by the anisotropic pressure distribution around YSOs. As this distribution should have a minimum along the polar axis — e.g., in a rotationally flattened dense core, or in a structure supported by a dipolar magnetic field — prolate outflow lobes will result, as observed (Königl 1982). Second, the shell will expand faster toward the poles, in the direction of least resistance, and more slowly toward the equator, where it is confined. This type of latitude gradient is exactly what is needed to explain the differing velocity gradients in pole-on and edge-on flows (see Sect. 1). However, other