THE BREAKOUT OF PROTOSTELLAR WINDS IN THE INFALLING ENVIRONMENT

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Abstract

The time of protostellar wind breakout may be determined by the evolution of the infalling flow, rather than any sudden change in the central engine. I examine the transition from pure infall to outflow, in the context of the inside-out collapse of a rotating molecular cloud core. I have followed numerically the motion of the shocked shell created by the impact of a stellar wind and infalling gas. These fully time-dependent calculations include cases both where the shell falls back to the stellar surface, and where it breaks out as a true outflow. Assuming a wind launched from the protostellar surface, the breakout time is determined in terms of the parameters describing the wind ($\dot{M}_w$, V_w) and collapsing cloud core ($a_\circ$, Ω). The trapped wind phase consists of a wind sufficiently strong to push material back from the stellar surface, but too weak to carry the heavy, shocked infall out of the star's gravitational potential. To produce a large-scale outflow, the shocked material must be able to climb out of the star's gravitational potential well, carrying with it the dense, swept-up infall.

KEYWORDS: *circumstellar material–ISM: jets and outflows–stars: mass-loss–stars: pre-main-sequence*

1. Introduction

Because essentially all known protostellar or pre-main sequence objects show evidence of winds, jets, or outflows, the current thinking is concentrated on a picture of simultaneous infall and outflow, in which infall and accretion occur towards the protostellar equatorial regions, and a wind breaks out along the poles (e.g. André et al., 1993). Yet early thinking on the stages of young stellar evolution identified a phase in which infall directly strikes the protostellar surface, with no outflow present (Shu et al., 1987), no clear examples are known of such protostars. In this contribution I consider limits on the timescale for purely-accreting objects in the context of the standard model of inside-out collapse from a molecular cloud core. The mathematical formulation is a generalization of Wilkin & Stahler (1998), dropping the assumptions of normal force balance and quasi-stationarity to permit full time-dependence and dynamical expansion (or collapse).

2. Description of the Infall, Wind, and Protostar

The inside-out collapse of a singular, isothermal sphere yields a mass accretion rate $\dot{M}_i = 0.975\, a_\circ^3/G$ at the center (Shu, 1977). Here $a_\circ$ is the isothermal sound speed in the cloud core. At the origin is a protostar whose mass grows linearly in time $M_* = \dot{M}_i\, t$, where t is the time since the start of collapse. In the presence of initial, solid-body rotation, the infall is distorted, and accretion occurs preferentially onto the circumstellar disk (Ulrich, 1976; Cassen & Moosman, 1981; Terebey et al., 1984). The natural length scale of the distortion is the centrifugal radius R_{cen}, which grows as t^3. I turn on a wind at the stellar surface, of radius R_*, and numerically determine whether it can halt infall and escape. At early times, $R_{cen} \ll R_*$ and the accretion is nearly isotropic, making breakout of the wind difficult. At late times, when $R_{cen} \gg R_*$, escape becomes easy along the poles.

For simplicity, the wind is assumed isotropic and of constant speed V_w, and mass-loss rate $\dot{M}_w$. The wind and infall collide supersonically, and a shocked shell forms. Low speeds imply rapid cooling and a geometrically thin shell. The dynamics of such time-dependent, thin shells has been discussed in detail by Giuliani (1982). I include the inputs of mass and momentum from infall, the wind, and the gravitational force due to the protostar.

3. The Trapped Wind Stage

For a given evolutionary time and ratio $\alpha \equiv \dot{M}_w/\dot{M}_i$, I determine the minimum wind speed necessary to break out of the infalling flow. Fig. 1 shows an example calculation of a shell that fails to escape and falls back to the star. In this case, a modest increase in wind speed dramatically changes the outcome, permitting breakout of the shell from the infall region. I solved the problem in dimensionless form, which reduces the parameter space from six (R_*, $\dot{M}_w$, V_w, $a_\circ$, Ω, t) to three dimensions (nondimensional time τ, wind speed ν, and α). As a result, the parameter space has been fully explored. Fig. 2 shows the critical wind speed for breakout. When the wind ram pressure exceeds the infall ram pressure at the stellar surface, the wind may initially push the shell upwards. But if the

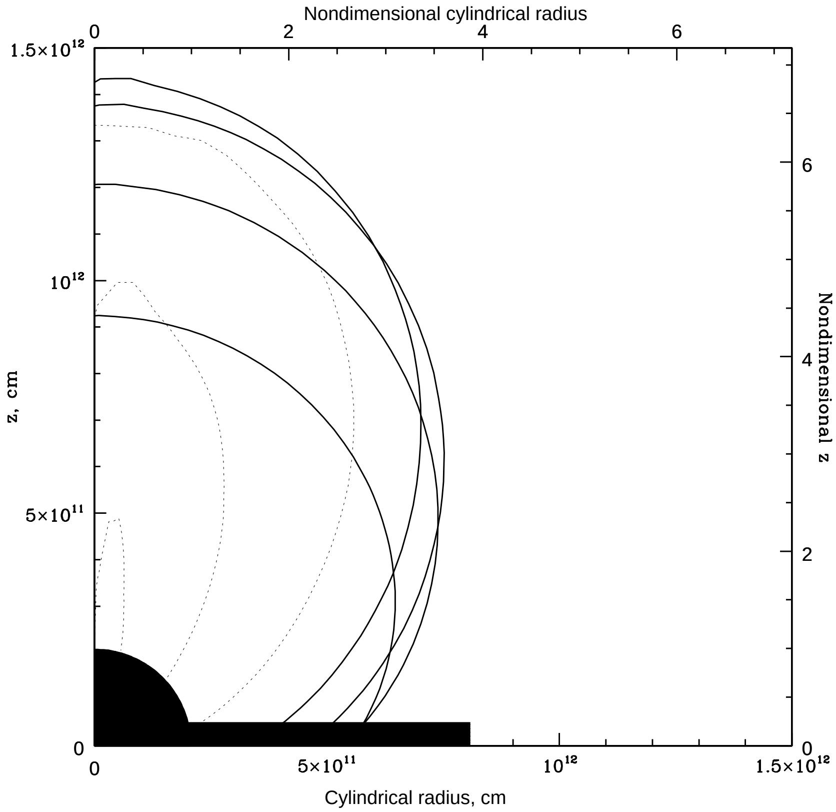

Figure 1: Time-evolution of a failed outflow. The solid curves show the initial rise, while dotted curves show the subsequent recollapse. The protostellar age since core formation is 3.8×10^4 years. The shapes correspond to equal time intervals of 0.016 years. The size of the centrifugal radius is indicated by the disk. Lengths are in cm on the left and bottom axes, and in units of the stellar radius on the remaining axes.

wind speed is less than the critical speed, the shell stalls and falls back. This is the trapped wind stage. In Fig. 3, its duration is the time between the dashed (ram pressure balance) curve and the solid one (critical wind speed) for a given ratio $\alpha \equiv \dot{M}_w/\dot{M}_i$.

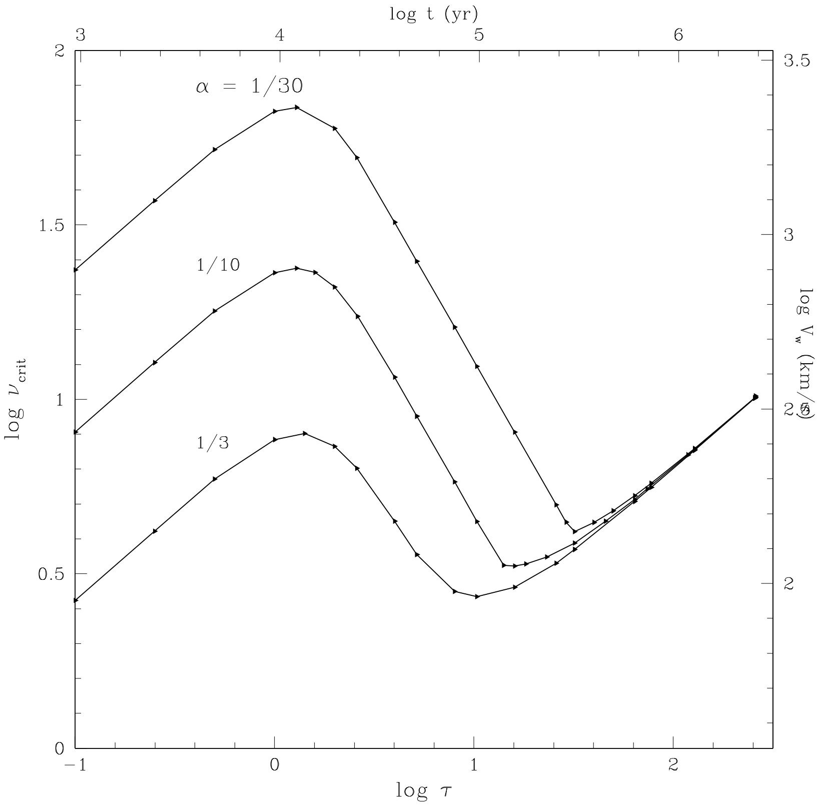

Figure 2: Minimum breakout wind speed versus evolutionary time. The three loci correspond to three ratios, α, of the wind mass loss to infall accretion rate. For a given α, the region above the curve corresponds to breakout, while that below the curve corresponds to recollapse. The power-law increase in ν_{crit} at early and late times is associated with the increasing gravitating mass of the protostar.

4. Discussion

The results of Figs. 2 and 3 may be easily scaled to apply to *anisotropic* winds, by comparing to an equivalent, isotropic wind having the same mass and momentum loss rates along the z-axis. Indeed, at early times, the evolution is

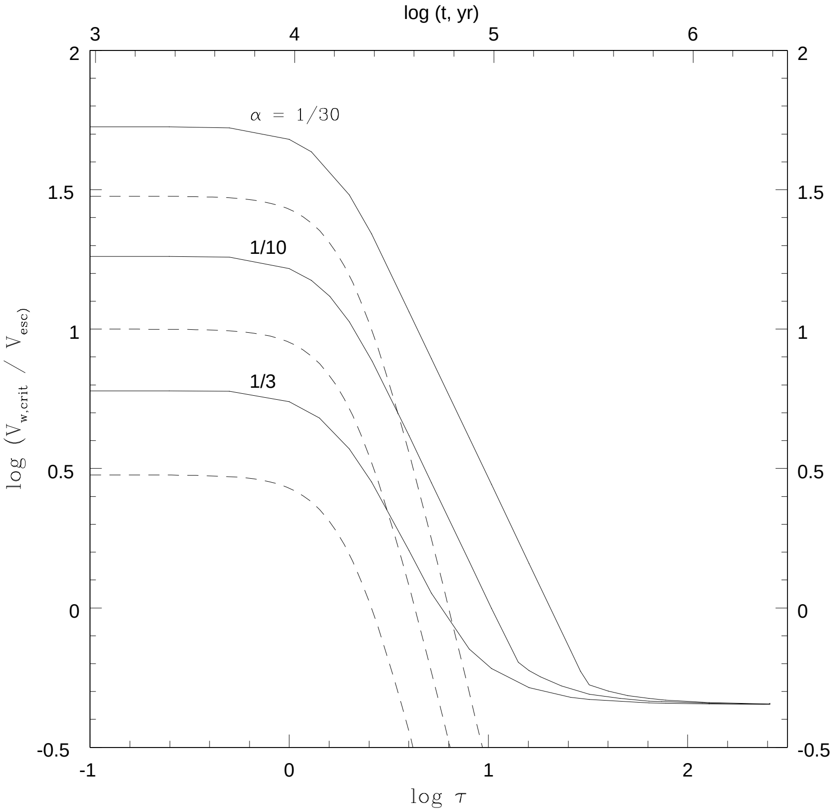

Figure 3: Critical wind speed for breakout (solid curves), in units of the free-fall (escape) speed, as a function of evolutionary time. The corresponding α-values are shown, as well as the wind speed necessary for ram pressure balance at the stellar surface (dashed curves). Assuming wind launch conditions $V_w/V_{esc} = const.$ (i.e. following a horizontal line in this figure), evolution begins at the left edge of the plot with the wind unable to advance beyond the stellar surface until the line intersects the appropriate dashed curve. Then the "trapped wind" phase lasts until the line intersects the corresponding solid curve for breakout. For example, for $V_w/V_{esc} = 1.6$, we follow a horizontal line at $\log(V_w/V_{esc}) = 0.2$. The trapped wind phase begins at $t \approx 19\,000\,yr$, while breakout occurs only at $t \approx 38\,000\,yr$, indicating a substantial duration for the trapped wind stage.

primarily determined by the momentum loss rate of the wind in this direction. At late times, it is the wind speed rather than momentum loss rate that determines breakout. It is hoped that these semi-analytic results will inspire more detailed exploration of this problem with fully radiative hydrodynamic simulations. The existing literature (e.g. Frank & Noriega-Crespo, 1994) on this is not immediately comparable because they have used a different density law which is self-similar, unlike that of Cassen & Moosman. Moreover, I argue that initial conditions with wind velocity much greater than the critical velocity are unphysical, as such a strong wind would have broken out at an earlier time, unless the wind itself evolves strongly with time.

Strong collimation of wind by anisotropic infall is not seen in the current calculations, although further exploration of this issue is forthcoming. I note that numerical simulations demonstrating strong collimation due to the circumstellar density asymmetry (e.g. Delamarter et al., 2000) have assumed a much more asymmetric density field than that used here.

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