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THE INTERACTION OF PROTOSTELLAR WINDS WITH THEIR ENVIRONMENT

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RESUMEN

El instante en que el viento estelar puede escapar de la superficie de una protoestrella puede estar determinado por la dependencia temporal del material de la nube que cae hacia la estrella más que por algun cambio abrupto en el viento mismo. Examino la transición de un flujo de caída pura (acreción) a caída y salida simultáneas (acreción y viento), o salida pura (viento), en el contexto de un colapso de adentro hacia afuera con rotación. Suponiendo un viento protoestelar lanzado de la superficie estelar, el tiempo de escape se determina como una función de la tasa de pérdida de masa del viento y de su velocidad, además de las tasas de caída y rotación del núcleo de la nube en colapso. La fase atrapada consta de un viento lo suficientemente fuerte para hacer retroceder el material de la superficie estelar pero demasiado débil para empujar el flujo de acreción chocado (pesado) fuera del potencial gravitacional de la estrella. A menos que el viento se encienda impulsivamente, una fracción significativa de la vida de la protoestrella antes del escape del viento puede pasar en esta fase de viento atrapado en donde el gas es lanzado de la protoestrella pero no escapa y termina estrellándose contra las superficies de la protoestrella y del disco. Podría ser que algunos "núcleos sin estrellas" contengan protoestrellas muy jóvenes todavía no detectadas en la fase de acreción y que las fluctuaciones episódicas de la luminosidad asociadas a este viento atrapado pudieran observarse.

ABSTRACT

The time of protostellar wind breakout may be determined by the time-dependence of the infalling flow, rather than any sudden change in the driving wind. I examine the transition from pure infall to simultaneous infall and outflow, or pure outflow, in the context of rotating, inside-out collapse. Assuming a protostellar wind launched from the stellar surface, the breakout time is determined as a function of the wind's mass-loss rate and speed, as well as the infall and rotation rate of the collapsing cloud core. The trapped 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. Unless the wind turns on impulsively, a significant fraction of the pre-breakout life of the protostar may be spent in this trapped wind phase in which gas is launched from the protostar but is pulled back, crashing onto the protostellar and disk surfaces. It may be that some "starless cores" contain as-yet undetected, very young accreting protostars, and that episodic luminosity fluctuations associated with this trapped wind could be observed.

Key Words: **ISM: JETS AND OUTFLOWS — STARS: MASS LOSS — STARS: PRE-MAIN SEQUENCE**

1. INTRODUCTION

The current paradigm for low-mass star formation in isolation (Shu, Adams, & Lizano 1987) envisions an early period of pure accretion, in which infalling gas directly strikes the protostellar surface, prior to wind breakout. No such purely accreting protostars are known. In fact, all well-studied pre-main sequence stars and protostars show evidence of mass outflow, which is generally assumed to occur simultaneously with infall and accretion through a circumstellar disk. Among candidate protostars, the Class 0 sources (André, Ward-Thompson, & Barsony 1993) are the most deeply embedded and are therefore interpreted to be the youngest. Yet evidence of outflow is one of the defining characteristics of Class 0 sources, and searches for outflows in molecular lines and for free-free emission from stellar winds (Harvey et al. 2002) alone may fail to identify, if it exists, an earlier stage of pure accretion. Unbiased mm and sub-mm searches (e.g., Motte, André, & Neri 1998; Visser, Richer, & Chandler 2002) have the potential to detect protostars lacking winds, or to put tight limits on the possible duration of a pure accretion phase. 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 assumption of quasi-stationarity to permit full time dependence.

2. DESCRIPTION OF INFALL, WIND, AND PROTOSTAR

The inside-out collapse of a singular, isothermal sphere yields a mass accretion rate $\dot{M}_{\rm i} = 0.975\, a_\circ^3/G$ at the center (Shu 1977). Here $a_\circ \sim 0.2\,{\rm km\,s^{-1}}$ is the isothermal sound speed in the cloud core, resulting in an accretion rate $\sim 2\times 10^{-6}\,M_\odot\,{\rm yr}^{-1}$. At the center is a protostar whose mass grows linearly in time $M_* = \dot{M}_{\rm i}\,t$, 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 (Cassen & Moosman 1981; Terebey, Shu, & Cassen 1984). The adopted initial angular frequency, $\Omega \sim 2\times 10^{-14}\,{\rm s}^{-1}$, is consistent with observed velocity gradients of cloud cores (Goodman et al. 1993). The natural length scale of the distortion is the centrifugal radius $R_{\rm cen}$, which grows as t^3. At a given time t, the initial conditions assume that the infall directly strikes the protostar. I then turn on a wind at the stellar surface, of radius $R_* \sim 3\,R_\odot$, and numerically determine whether it can reverse the infall and escape. At early times, $R_{\rm cen} \ll R_*$, and the accretion is nearly isotropic, making breakout of the wind difficult. At late times, when $R_{\rm cen} \gg R_*$, escape becomes easy along the poles.

For simplicity, the wind is assumed isotropic and of constant speed $V_{\rm w}$, and mass-loss rate $\dot{M}_{\rm w}$. As discussed below, the assumption of isotropy of the wind may be relaxed. The wind and infall collide supersonically, and a shocked shell forms. Low speeds ($< 300\,{\rm km\,s^{-1}}$) imply rapid cooling and a geometrically thin shell. I include the inputs of mass and momentum from infall, the wind, as well as rotation and the gravitational force due to the protostar.

3. THE TRAPPED WIND STAGE

I solved the problem in dimensionless form, which reduces the parameter space from six (R_*, $\dot{M}_{\rm w}$, $V_{\rm w}$, $a_\circ$, Ω, t) to three dimensions (nondimensional time τ, wind speed ν, and $\alpha \equiv \dot{M}_{\rm w}/\dot{M}_{\rm i}$). As a result, the parameter space has been fully explored. 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 wind speed is less than the critical speed $\nu_{\rm crit}$, the shell stalls and falls back. This is the trapped wind stage. Figure 1 shows the critical wind speed for breakout, in units of the escape speed at the stellar surface. The trapped wind

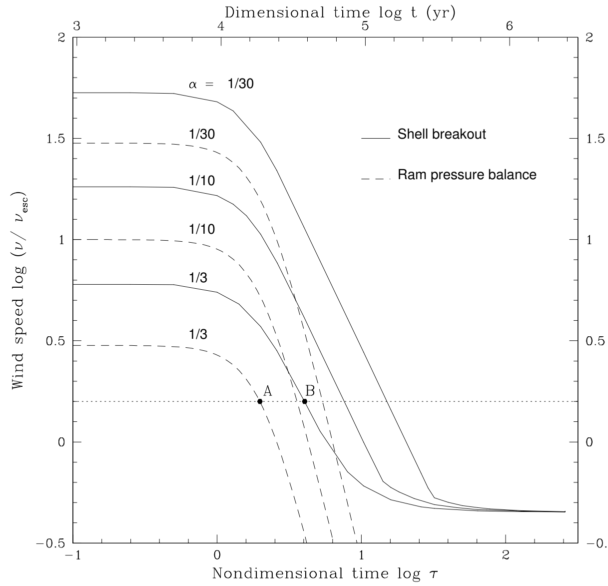

Fig. 1. Critical wind speed for breakout (solid curves), in units of the free-fall (escape) speed, as a function of evolutionary time. The corresponding α-values are shown, as well as the wind speed necessary for ram pressure balance at the stellar surface (dashed curves). Assuming wind launch conditions $V_{\rm w}/V_{\rm esc} = $ constant (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 $V_{\rm w}/V_{\rm esc} = 1.6$, we follow a horizontal line at $\log(V_{\rm w}/V_{\rm esc}) = 0.2$. The trapped wind phase begins at $t \approx 19,000\,{\rm yr}$, while breakout occurs only at $t \approx 38,000\,{\rm yr}$.

phase lies between the dashed (ram pressure balance at R_*) curve and the solid one (critical wind speed) for a given ratio $\alpha \equiv \dot{M}_{\rm w}/\dot{M}_{\rm i}$. There are two equivalent ways to view these results. Firstly, given an evolutionary time and a value of α, the results state the necessary wind speed for breakout. Alternately, given a wind speed and a value of α, these results state at what time such a wind can break out of the infalling flow.

The results of Fig. 1 may be rescaled to apply to *anisotropic* winds, by comparing to an equivalent, isotropic wind having the same mass- and momentum-loss rates along the z-axis. In this manner, a wind that is stronger towards the z-axis acts like a wind of greater α, with smaller $\nu_{\rm crit}$ and correspondingly earlier breakout time. At early times, the evolution is primarily determined by the momentum-loss rate of the wind in the z-direction. Because protostellar winds are not expected to be isotropic (e.g., launched by a magneto-centrifugal mechanism), realistic breakout times should be significantly earlier than those predicted for an isotropic wind, so these results should be interpreted as upper limits. Additionally, a more flattened distribution of infalling matter will also make breakout of the wind toward the poles easier, and result in an earlier breakout time. Although a more highly focused wind will break out at an earlier time, the fraction of the time spent in the trapped wind phase should be similar, because a more focused wind shifts not only the $\nu_{\rm crit}$ curves, but also those of ram pressure balance, to the left (earlier time) in Fig. 1.

Although these calculations deduce a trapped wind phase, no such phase is known observationally, and the youngest known protostellar sources appear to have outflows at $t \sim 10^4$ yr (André & Montmerle 1994). On the other hand, at breakout our protostar has mass near the hydrogen burning limit, consistent with the mass limit of typical continuum surveys for protostars of $\sim 0.1\,M_\odot$. Thus, part of the discrepancy may be that the mass accretion rate could be higher than we have assumed, or may be a declining function of time. The current model may be rescaled by adjusting the values of the dimensional parameters ($a_\circ$, Ω, $V_{\rm w}$, R_*, etc.). The scaling of the breakout time with input parameters, holding (α, ν, τ) constant, is in fact $t_{\rm break} \propto R_*^{1/3} a_\circ^{-1/3} \Omega^{-2/3}$. The reason for the weak dependence on $a_\circ$ is that the breakout time is primarily detemined by the anisotropy of the infall i.e., on the rotation rate of the initial cloud core. It does not seem reasonable to change these parameters on average by such a large factor so as to shorten the breakout time by ~ 4 to 10. Instead, either the wind or the infall (or both) needs to be significantly more anisotropic than assumed here. Because magnetocentrifugal launch mechanisms typically do not have initially high collimation, but become more focused as they propagate, it remains to be seen whether such collimation is sufficient to shorten the breakout time to be in agreement with the lack of observed protostellar sources without outflows. It seems likely that it is important to also have a more anisotropic infalling flow. The current calculations will be extended in the near future to consider such additional sources of anisotropy.

It is hoped that these semi-analytic models will inspire more detailed exploration of this problem with 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 (1981). 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. I note that numerical simulations demonstrating strong collimation due to the circumstellar density asymmetry (e.g., Delamarter, Frank, & Hartmann 2000) have assumed a much more asymmetric density field than that used here.

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