FORMATION OF BIPOLAR FLOWS IN STAR FORMING REGIONS BY STELLAR WINDS

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1. INTRODUCTION

It is observed that a number of large-scale supersonic bipolar flows exist in star forming regions. Infrared sources which seem to excite active motions are usually found in the center of these objects (cf. the recent surveys by Bally and Lada 1983, Torrelles *et al.* 1983, Snell *et al.* 1984, Goldsmith *et al.* 1984). From the observation of the high density gas, the bipolar flow seems to originate from the interaction of the isotropic stellar wind with a large scale flattened interstellar cloud from which the protostars are formed.

2. OUR MODEL AND METHOD OF CALCULATION

The cloud is assumed to be isothermal and surrounded by a tenuous gas of uniform density ρ_d. A young star producing the wind is located in the middle plane of the cloud. The density distribution of the cloud surrounding the star is represented as

$$\rho(r_0,\theta) = \rho_B \mathrm{sech}^2(r_0\cos\theta/\Delta) + \rho_d \quad , \qquad (1)$$

with $\Delta = (kT/2\pi G\mu\rho_B)^{\frac{1}{2}}$, which is the scale height of the cloud. For the anisotropic density distribution, such as given in equation (1), the flow pattern induced by an isotropic stellar wind will not be spherical but elongated in the direction of the density gradient as schematically shown in Figure 1.

The motion and the structure of the expanding shell strongly depend on whether the shell is energy driven or momentum driven (Königl 1982, Dyson 1984). If the shocked wind cools slowly (well), the swept-up interstellar matter is driven by the pressure of shocked wind (the ram pressure of the wind). To investigate the motion and the structure of the expanding shell, we have utilized the generalized Laumbach-Probstein method (Laumbach and Probstein 1969, Sakashita, Hanami and Umemura 1985).

3. RESULTS

As shown in Figure 2, the envelope of the shock front elongates in the direction of the density gradient and, after the shock front propagates a few scale heights, the envelope forms a bipolar shape.

4. IMPLICATIONS AND DISCUSSION

4.1 Density Scale Height of the Cloud

Larson (1981) and Torrelles *et al.* (1983) have suggested that the dense core of the molecular cloud in star forming regions is probably supported by the turbulent motion in the cloud and then the scale height of the turbulence supported cloud becomes

$$\Delta = 0.39\times10^{-1}(\sigma/1 \text{ km s}^{-1})\ (10^6/n_B)^{1/2} \text{ pc}, \qquad (2)$$

where σ is the velocity dispersion in the cloud. If $\Delta = 0.39$ pc, the swept-up mass in the shell, M_{swept} is equal to 14 $M_\odot$ in fair agreement with the observed mass of the bipolar flow (10 $M_\odot$).

4.2 Flow Velocity

The flow velocity immediately behind the shock front can be represented as

$$V_{se} = 8.24 \cos^{2/3}\theta\,(n_{B.6}/0.5\ \dot{M}_6 V_{w.6}{}^2)^{-1/3}(\Delta/0.39\times10^{-1} \text{ pc})^{-2/3}$$
$$dy/dx\ 1/x\ (\text{km/s}), \qquad (3)$$

for the energy driven shell and as

$$V_{sm} = 1.71 \cos\theta\,(n_{B.6}/\dot{M}_6 V_{w.6})^{-1/2}\ (\Delta/0.39\times10^{-1} \text{ pc})^{-1}$$
$$dy/dx\ 1/x\ (\text{km/s}), \qquad (4)$$

for the momentum driven shell, where $n_{B.6}$, $\dot{M}_6$ and $V_{w.6}$ are expressed in units of 10^6 cm^{-3}, 5×10^{-6} $M_\odot$ y^{-1} and 500 km/s respectively. The observed values of flow velocities are 10 km/s. Then, the energy driven shell is in better agreement with the observations than the momentum driven shell.

4.3 Momentum Efficiency

Observations have shown that the radiation of the central star cannot explain the observed ratio of linear momentum transport $(MV_{se})/t/L_*/c) > 100$ (Goldsmith *et al.* 1984, Bally and Lada 1983).For the energy driven case, we examine the ratios of the kinetic energy and the thermal energy of the expanding shell between R and R_c to the energy supplied by the stellar wind $1/2\dot{M}\, V_w{}^2 t$, and they are plotted in Figure 3. Increasing the fraction of the kinetic energy means that momentum transport becomes effective in later phases. The momentum efficiency for the energy driven case is,

$$\text{Eff}_m = M_{swept} V_{se}/\dot{M}\, V_w t = 13.2\ dy/dx\ 1/x$$
$$n_{B.6}{}^{1/3}(\Delta/0.39\times10^{-1} \text{ pc})^{2/3}\ M_6{}^{-1/3}\ V_{w.6}{}^{1/3} \quad .$$

If the stellar wind is driven by the single photon scattering process, $\dot{M}\, V_w t$ is roughly L_*/c. Then we can estimate that $M_{swept} V_{se}/t(L_*/c)$ is

https://doi.org/10.1017/S0074180900096042 Published online by Cambridge University Press

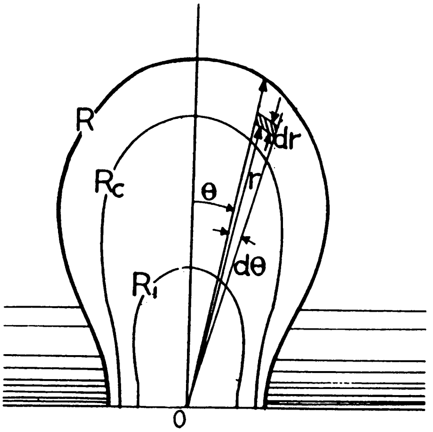

Fig. 1

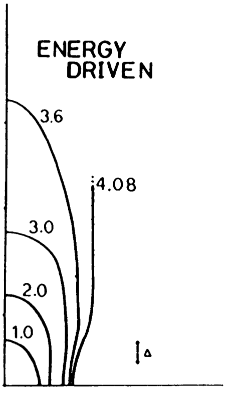

Fig. 2

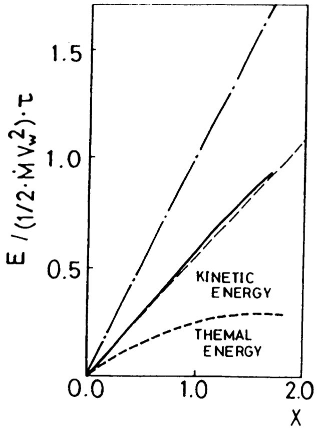

Fig. 3

greater than 13.2. It is possible that the rate can be comparable to the observed value since the factor dy/dx 1/x can be a large value in a later phase.

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https://doi.org/10.1017/S0074180900096042 Published online by Cambridge University Press