Global collapses and expansions in star-forming clouds

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ABSTRACT
Spectral observations of star-forming molecular clouds sometimes reveal distinct red asymmetric double-peaked molecular line profiles with weaker blue peaks and stronger red peaks. For some star-forming molecular clouds, molecular line transitions with red asymmetric line profiles coexist with those with blue asymmetric line profiles (i.e. blue asymmetric double-peaked molecular line profiles with weaker red peaks and stronger blue peaks) in spatially resolved spectral observations from different lines of sight, whereas for others molecular transitions with red asymmetric line profiles dominate. Blue asymmetric line profiles are usually interpreted as signals of central core collapses, whereas red asymmetric line profiles remain unexplained. In this paper, we advance a spherically symmetric self-similar hydrodynamic model framework for envelope expansions with core collapses (EECCs) of a general polytropic molecular gas cloud under self-gravity. Based on such EECC hydrodynamic cloud models, we perform tracer molecular line profile calculations using the publicly available RATRAN code for star-forming clouds with spectroscopic signatures of red asymmetric line profiles. The observation of red asymmetric line profiles in molecular cloud cores indicates that EECC processes are probably essential hydrodynamic processes in star formation. Using spatial distributions, we explore various profiles of molecular lines for several tracer molecules in various settings of EECC dynamic models with and without shocks.

Key words: hydrodynamics – line: profiles – radiative transfer – stars: formation – stars: winds, outflows – ISM: clouds.

1 INTRODUCTION
Collapses, expansions, shocks and turbulence are important dynamic features of star formation processes in molecular clouds. Such molecular cloud dynamic characteristics may be revealed by several pertinent diagnostics and comprehensive analysis of molecular spectral emission line profiles. An extensively discussed theoretical framework for the formation of low-mass stars is the ‘inside-out collapse’ scenario (Shu 1977; Shu, Adams & Lizano 1987). This model describes an isothermal self-similar dynamic solution that has a collapsing core surrounded by a static envelope with an expanding boundary that envelops more and more mass in the collapsed region. By adopting empirically inferred temperature variations to replace the constant temperature, this dynamic collapse structure may lead to double-peak molecular line profiles with blue peaks stronger than red peaks (i.e. blue profiles), as revealed by spectral line observations of some molecular globules in early stages of star formation (e.g. Zhou et al. 1993; Saito et al. 1999; Hogerheijde & Sandell 2000). A collapse solution based on the dynamics of a general polytropic gas sphere can also lead to blue profiles, but with a temperature variation involved in the dynamic model in a self-consistent manner (Gao, Lou & Wu 2009).

Clearly, a collapse model is not the full story of star formation, as there exist observational signatures that cannot be accounted for in the collapse scenario (e.g. Wilner et al. 2000; Belloche et al. 2002; van der Tak, Caselli & Ceccarelli 2005). One important signature is the detection of molecular emission lines with red asymmetry, that is, when optically thick emission lines are red-shifted relative to optically thin lines from the same source. A statistical survey of the observed optically thick molecular lines shows that ~25 per cent up to ~30 per cent of all sources show red asymmetry (e.g. Mardones et al. 1997; Evans 2003; Fuller, Williams & Sridharan 2005). Among sources of red asymmetry, double-peak molecular line profiles with red peaks stronger than blue peaks (i.e. red profiles) are also identified (e.g. Park, Lee & Myers 2004; Tafalla et al. 2006; Velusamy et al. 2008). More specifically, for a number of known cloud sources, both red and blue asymmetries are observed towards the same transitions of the same molecules but at different beam offsets from the centre (e.g. Tafalla et al. 1998; Matthews et al. 2006). Whereas blue profiles are recognized as the signature of radial inflows or core collapses, it is not yet clear what these red profiles imply.

Earlier radiative transfer calculations with parametrized flow structures indicated that rotation and radial outflows in molecular...
clouds may produce red profiles (e.g. Adelson & Leung 1988). The dynamics of bipolar outflows have been studied extensively (e.g. Shu et al. 1991, 1994; Fiege &Henriksen 1996a; Ostrikov 1997; Matzner & McKee 1999; Shang et al. 2006), and their spectroscopic signatures (e.g. molecular line profiles and radio maps) have also been explored (e.g. Fiege & Henriksen 1996b). Many of these molecular bipolar outflows have velocities ≳10 km s⁻¹ (e.g. Wu et al. 2005; Su et al. 2007), which are larger than the widely observed typical gas flow velocities of ~1 km s⁻¹ indicated by red asymmetry signatures (e.g. Mardones et al. 1997; Fuller et al. 2005). Of course, for special cases in which bipolar outflows are oriented close to the plane of the sky, molecular line splittings can be smaller. Line profiles (as well as millimetre continuum maps) in a molecular cloud with bipolar outflow show an asymmetric spatial distribution according to the axis direction of the outflow (e.g. Di Francesco et al. 2001; Matthews et al. 2006; Jørgensen et al. 2007). Red profiles caused by rotation around the central core have a systematic displacement in the velocity of the local standard of rest (VLSR) (Di Francesco et al. 2001; Redman et al. 2004). The spatial distribution of red profiles is also asymmetric according to the direction of the rotation axis (Park et al. 1992; Zhou 1995). Although generally considered to be part of the contribution to the line broadening, turbulence in clouds is sometimes invoked to explain line profiles with red or blue asymmetries, especially the more violent turbulence in the outer layers of clouds (e.g. Ossenkopf 2002; Lee & Kim 2009). The contraction and expansion motions caused by large-scale thermal pulsations (with a typical oscillation period of ~10³ yr) in starless cores can also cause asymmetric molecular line profiles in molecular clouds in their early stages of star formation (Lada et al. 2003; Keto et al. 2006; Redman, Keto & Rawlings 2006; Aguti et al. 2007).

Theoretical models of envelope expansion with core collapse (EECC) for star formation represent a significant recent development (Lou & Shen 2004; Shen & Lou 2004; Yu & Lou 2005; Lou & Gao 2006; Yu et al. 2006; Hu & Lou 2008; Wang & Lou 2008). Such an EECC dynamic process might affect the initial mass function of stars (e.g. Nakano et al. 1995) and the environment of star formation (e.g. Matzner & McKee 2000; Moraghan, Smith & Rosen 2008). The crucial question is whether such global dynamic structures actually exist in star-forming clouds with detectable observational diagnostics, such as characteristic features in molecular line profiles. The main thrust of this paper is to show that theoretical molecular line profiles based on the general polytropic EECC solutions with collapses, expansions and shocks are able to explain observations of red profiles and can further provide plausible inferences regarding the star-forming region.

This paper is structured as follows. We first present possible self-similar dynamic structures of collapse and expansion solutions for general polytropic molecular clouds (Wang & Lou 2008) in Section 2. Molecular spectral line profiles are then obtained from radiative transfer calculations in Section 3. Exploration of the EECC cloud conditions that generate red asymmetric line profiles and our perspective of model applications are also presented therein. We summarize and conclude in Section 4.

2 COLLAPSE AND EXPANSION DYNAMICS

2.1 General polytropic hydrodynamic models

To describe star-forming molecular clouds, we adopt the general polytropic self-similar model framework of Wang & Lou (2008) but without the random magnetic field. In spherical polar coordinates (r, θ, φ), the non-linear hydrodynamic partial differential equations (PDEs) for spherically symmetric molecular cloud dynamics are

\[
\frac{\partial \rho}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \rho u) = 0, \tag{1}
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} = - \frac{1}{\rho} \frac{\partial p}{\partial r} - \frac{GM}{r^2}, \tag{2}
\]

\[
\frac{\partial M}{\partial t} + u \frac{\partial M}{\partial r} = 0, \quad \frac{\partial M}{\partial r} = 4\pi r^2 \rho, \tag{3}
\]

\[
\left( \frac{\partial}{\partial t} + u \frac{\partial}{\partial r} \right) \ln \left( \frac{p}{\rho^c} \right) = 0, \tag{4}
\]

where the mass density ρ, the radial flow velocity u, the thermal gas pressure p and the enclosed mass M depend on the radius r and time t; G = 6.67 × 10⁻¹¹ dyn cm²g⁻² is the gravitational constant and γ is the polytropic index. Equations (1) and (2) are mass and radial momentum conservations, respectively; equation (3) is another form of mass conservation. Equation (4) is the conservation of specific entropy along streamlines, which implies a general polytropic equation of state (EoS) \( p = K(r, t) \rho^\gamma \), with \( K(r, t) \) being a coefficient that varies with both time t and radius r in general. These non-linear PDEs allow self-similar solutions, and the pertinent self-similar transformation is given below:

\[
r = k^{1/2} t^{a}, \tag{5}
\]

\[
u = k^{1/2} t^{-1} v(x), \quad \rho = \frac{\alpha(x)}{4\pi G t^2}. \tag{6}
\]

\[
M = k^{3/2} t^{5/2} m(x) \frac{(3n - 2)G}{2}, \quad p = k^{2n-4} \alpha(x) \gamma m(x)^{\gamma}, \tag{7}
\]

where x is the self-similar independent variable combining r and t in a special manner, and \( \alpha(x) \), m(x) and v(x) are the dimensionless reduced mass density, enclosed mass and radial flow velocity, respectively. According to mass conservation, equation (3), the reduced enclosed mass can be expressed as \( m(x) = \alpha(x) x^2 \left[ \pi x - v(x) \right] \). Being an important thermodynamic variable, the gas temperature T is given by the ideal gas law

\[
T = \frac{p}{k_B \rho / (\mu m_H)} = \frac{\mu m_H}{k_B} k^{2n-2} \alpha(x) \gamma^{-1} m(x)^{\gamma}, \tag{8}
\]

where \( k_B \), \( \mu \) and \( m_H \) are Boltzmann’s constant, the mean molecular weight and the hydrogen mass, respectively. We adopt \( \mu \equiv 1 \) for typical star-forming clouds. For a finite \( dm(x)/dx \) as \( x \to 0 \), equation (7) gives a central mass accretion rate of

\[
M_0 = k^{3/2} \pi^{n-1} m_0 / G, \tag{9}
\]

with \( m_0 \) being the central reduced point mass enclosed. For \( n = 1 \), the central mass accretion rate \( M_0 \) remains constant; for \( n > 1 \) and \( n < 1 \), this \( M_0 \) increases and decreases with increasing time, respectively. The indices \( \gamma, n \) and \( q \) are related by the general polytropic EoS (4) with \( q = 2(n + \gamma - 2)/(3n - 2) \) for self-similar dynamics. The case \( n + \gamma = 2 \) features an EoS for a conventional polytropic gas, and \( \gamma = n = 1 \) describes an isothermal gas. Self-similar transformation equations (5)–(7) make it possible to cast non-linear PDEs (1)–(4) into non-linear ordinary differential equations (ODEs) in terms of \( x \), which can then be solved numerically with analytical asymptotic conditions and by taking care of the sonic critical curve (see Wang & Lou 2008 for details).
Table 1. Parameters of self-similar EECC dynamic solutions without and with shocks for the five Models I–V, labelled by roman numerals in the leftmost column. Among the three scaling indices $\gamma$, $n$, and $q$, only two are independent, and all three are related by the general polytropic equation of state (4) with $q = 2(n + \gamma - 2)/(3n - 2)$. The three parameters $x_{\text{inf}}, m_0$, and $m_{\text{tot}}$ are the dimensionless infall radius separating the inner collapse and outer expansion regions, the reduced central point mass, and the reduced total enclosed mass for a model cloud, respectively. The two coefficients $A$ and $B$ are the mass and velocity parameters in asymptotic solutions (11) as $x \to +\infty$ which are ‘boundary’ conditions in constructing corresponding self-similar solutions. The parameters $x_1$, $x_2$, $v_1$, and $v_2$ are the upstream and downstream locations and velocities for solutions across an outgoing shock front (i.e. Models IV and V).

| No. | $\gamma$ | $n$ | $q$ | $x_{\text{inf}}$ | $m_0$ | $m_{\text{tot}}$ | $A$ | $B$ | $x_1$ | $v_1$ | $x_2$ | $v_2$ |
|-----|-----|-----|-----|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| I   | 1.1 | 0.8 | $-1/2$ | 1.50 | 1.49 | 5.0 | 3.5 | 2.2 | - | - | - | - |
| II  | 1.2 | 0.8 | 0    | 1.77 | 3.72 | 10.0 | 5.0 | 2.4 | - | - | - | - |
| III | 1.2 | 0.9 | 2/7  | 1.80 | 3.74 | 20.8 | 10.0 | 2.4 | - | - | - | - |
| IV  | 1.2 | 0.8 | 0    | 0.51 | 0.207 | 4.6 | 2.68 | 0.47 | 2.77 | 0.01 | 2.57 | 1.54 |
| V   | 1.2 | 0.8 | 0    | 0.10 | 0.0254 | 9.2 | 7.72 | 3.70 | 1.70 | $-0.30$ | 1.68 | 0.58 |

Analytically, we have a static equilibrium solution for a spherical cloud, namely, a singular polytropic sphere (SPS):

$$v = 0, \quad \alpha = \left[ \frac{n^2-q}{2(2-n)(3n-2)} \right]^{-1/(n-3n/2)} x^{-2/n},$$

$$m = n \left[ \frac{n^2-q}{2(2-n)(3n-2)} \right]^{-1/(n-3n/2)} x^{(3n-2)/n},$$

(e.g. Lou & Hu 2010). This static SPS solution may be helpful for speculating on the origin of the self-similar collapse and expansion solutions (see below).

In the limit of $x \to +\infty$, we have an asymptotic similarity solution to the leading orders, namely

$$\alpha = A x^{-2/n},$$

$$v = \left( -nA + 2(2-n) m_0^{q-1} A^{1-n+3n/2} x^{(n-2)/n} \right) n y^{(n-1)/n} + B x^{(n-1)/n},$$

where $A$ and $B$ are two constants of integration, referred to as the mass and velocity parameters, respectively. In the other limit of $x \to 0^+$, the asymptotic central free-fall solution is

$$v = \left[ \frac{2m_0}{(3n-2)x} \right]^{1/2}, \quad \alpha = \left[ \frac{(3n-2)m_0}{2x^3} \right]^{1/2},$$

where $m = m_0$ is the reduced enclosed mass $m(x) = \alpha x^2 (n x - v)$ as $x \to 0^+$ for a point mass at the very centre.

2.2 General polytropic EECC solutions

We focus mainly on self-similar dynamic solutions for envelope expansions with core collapse in the form of free-fall towards the cloud centre (i.e. EECC solutions; Lou & Shen 2004; Shen & Lou 2004). The relevant parameters of five such selected self-similar solutions are listed in Table 1, where $x_{\text{inf}}$ is the outgoing boundary separating the collapse and expansion regions; $m_0$ is the dimensionless central reduced point mass; and $m_{\text{tot}}$ is the total reduced enclosed mass of a spherical star-forming cloud with an expanding outer edge at $x = 5$. We also list in Table 1 the two important mass and velocity parameters $A$ and $B$, which characterize asymptotic dynamic behaviours for $x \to +\infty$ and serve as asymptotic ‘boundary’ conditions in constructing general polytropic EECC solutions (see equations 26 and 27 of Wang & Lou 2008 for details). Solutions IV and V are two EECC shock solutions with $\gamma = 1.2$ and $n = 0.8$; the upstream point $x_1$ and downstream point $x_2$ correspond to the same shock radius $R_{sh}$; $v_1$ and $v_2$ are the upstream and downstream reduced radial flow velocities, with negative values being infall and positive values being expansion, respectively.

Each of these selected EECC solutions has a central collapsed core and an outer expansion envelope with an outgoing interface at $x_{\text{inf}}$ separating the two zones. At the beginning of evolution ($t \to 0^+$), this boundary radius is approximately zero according to self-similar transformation (5), which indicates that collapse begins at the very centre of the cloud. As time goes on, this boundary radius increases with a constant $x_{\text{inf}}$ at a variable speed of $u_0 = n k^{1/2} x^{1-n} x_{\text{inf}}$ according to equation (5), which means that more and more mass is enclosed within the collapse region (see expression 7). At a given time $t$, the mass densities and gas temperatures of all these EECC solutions increase towards the cloud centre. Shock solutions involve discontinuities of flow velocity, density and temperature across the shock radius $R_{sh}$. Their dynamic structures are shown in Figs 1 and 2, adopting the estimated physical scalings described below.

In constructing self-similar hydrodynamic solutions, we have presumed a priori the possible existence of such a form of similarity solutions under plausible asymptotic conditions and actually derive them analytically and/or numerically from non-linear hydrodynamic equations satisfying relevant physical constraints. Meanwhile, it is of considerable interest to figure out even qualitatively how a molecular cloud system can sensibly evolve into such a self-similar phase given a certain class of initial and boundary conditions. This is a challenge particularly in view of the existence of several possible asymptotic self-similar solutions and requires a deeper theoretical understanding than we have at present (e.g. Wang & Lou 2008). At this stage, we tentatively offer speculations on possible scenarios leading to self-similar EECC dynamic evolution invoked in this paper for modelling the dynamics of certain star-forming molecular clouds.

Analogous to the stellar oscillations widely studied observationally and theoretically, molecular clouds in SPS equilibrium (10) when somehow perturbed may give rise to acoustic pulsations on much larger spatial and temporal scales (e.g. Lada et al. 2003; Keto et al. 2006; Redman et al. 2006; Aguti et al. 2007). For simplicity, we envision purely radial acoustic pulsations with possible radial nodes in spherical molecular clouds; for example, such radial pulsations might be induced or excited by a sufficiently massive companion or transient object. In an idealized conceptual scenario, such acoustic pulsations might persist periodically for a long time in molecular clouds. Realistically, such acoustic pulsations might
be ‘damped’ in one or two ‘periods’ as a result of radiative losses as well as non-linear effects. Among the various pulsation phases, it would be possible to have a phase characterized by core contractions with envelope expansions. With such ‘initial’ conditions in molecular clouds, the non-linear evolution may eventually lead to core collapse under self-gravity while the envelope expands into the surrounding interstellar medium (ISM). It is emphasized that no pulsations are necessarily persistent in this scenario. We speculate that this might evolve into the self-similar EECC dynamic phase advanced in this paper. Following this scenario, pulsations of molecular clouds with different phases may evolve non-linearly into a variety of dynamic states.

The EECC solution is necessarily consistent with energy conservation. For most low-mass star formation scenarios, the Kelvin–Helmholtz time-scale $t_{KH} = GM_{	ext{tot}}^2/(RL)$ is longer than the dynamic time-scale $(\rho G)^{-1/2}$, because of the lower radiative efficiency (see e.g. McKee & Ostriker 2007). Here $M_{\text{tot}}$, $R$ and $L$ are the total mass, the outer radius and the luminosity of the cloud, respectively. Because of radiative inefficiency, most low-mass star-forming clouds need to divert part of the continuously released gravitational energy during the central accretion. Global envelope expansion, which is a plausible dynamic solution as already shown, serves as the extra gravitational energy release. From the consideration of energy conservation, the EECC shock solutions may offer valuable insights regarding the problem that accretion rates derived from observed luminosity are much smaller than those expected according to their dynamic evolution (i.e. the luminosity problem) in low-mass star formation (e.g. Kenyon et al. 1990; McKee & Ostriker 2007). For the physical scenario of a variable central mass accretion rate and thus variable luminosity for the formation of low-mass stars in molecular clouds, it is possible to provide a general polytropic model explaining the ‘luminosity problem’ (Lou & Dong, in preparation).

### 2.3 Physical properties of molecular clouds

The reduced dynamic variables should be converted to physical variables as applicable to realistic astrophysical cloud systems.

The typical infall radius of a molecular cloud is $\sim 0.01$–$0.03$ pc (e.g. Myers 2005), or $\sim 10^{-3}$–$10^{-4}$ au. As the reduced infall radius is at $x \sim 1$, we may choose the length-scale as

$$L^{1/2} \sim 4 \times 10^3 \text{au}$$  \hspace{1cm} (13)

in the self-similar transformations (5)–(7). The outer cloud radius is set at $R \sim 2 \times 10^4$ au. The number density at the infall radius is estimated as $\sim 10^4$–$10^5$ cm$^{-3}$ (e.g. Harvey, Wilner & Myers 2003; Evans et al. 2009). A reduced number density of unity implies

$$4\pi G\mu nH_2 r^{-1} \approx 9 \times 10^6 \text{cm}^{-3},$$  \hspace{1cm} (14)

leading to an estimated dynamic time-scale. With parameter scalings (13) and (14) for clouds, the physical variables of a cloud can be expressed according to equations (5)–(9):

$$r = 4 \times 10^3 x \text{ au},$$  \hspace{1cm} (15)

$$u = 0.213 v(x) \text{ km s}^{-1},$$  \hspace{1cm} (16)

$$N = 9 \times 10^4 \alpha(x) \text{ cm}^{-3},$$  \hspace{1cm} (17)

$$M = 0.204 m(x)/(3n-2) M_\odot,$$  \hspace{1cm} (18)

$$T = 5.33 \alpha(x) r^{-1} m(x) \text{ K},$$  \hspace{1cm} (19)
Table 2. Physical parameters of cloud Models I–V, with \( \gamma \) and \( n \) the polytropic and scaling indices, respectively. The two physical masses \( M_0 \) and \( M_{\text{tot}} \) are the central point mass and the total cloud mass inside \( R = 2 \times 10^4 \) au, and \( \dot{M}_0 \) denotes the central mass accretion rate. The infall radius, \( R_{\text{inf}} \), is the boundary between the infall and outflow regions. The parameter \( R_{\text{sh}} \) is the outgoing shock radius for shock solutions in Models IV and V, and \( u_1 \) and \( u_2 \) are the upstream and downstream radial flow velocities, with negative values denoting inflows.

| No. | \( \gamma \) | \( n \) | \( M_0 \) \( 10^5 \) M\(_\odot \) | \( M_{\text{tot}} \) \( 10^5 \) M\(_\odot \) | \( \dot{M}_0 \) (M\(_\odot\) yr\(^{-1} \)) | \( R_{\text{inf}} \) (au) | \( R_{\text{sh}} \) (au) | \( u_1 \) | \( u_2 \) |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| I   | 1.1 | 0.8 | 0.75 | 2.52 | 3.38 \times 10^{-6} | 6.0 \times 10^3 | − | − | − |
| II  | 1.2 | 0.8 | 1.18 | 5.10 | 5.30 \times 10^{-6} | 7.1 \times 10^3 | − | − | − |
| III | 1.2 | 0.9 | 1.91 | 11.00 | 8.41 \times 10^{-6} | 7.2 \times 10^3 | − | − | − |
| IV  | 1.2 | 0.8 | 0.106 | 2.54 | 4.73 \times 10^{-7} | 2.04 \times 10^3 | 11.1 \times 10^3 | 0.002 km s\(^{-1} \) | 0.34 km s\(^{-1} \) |
| V   | 1.2 | 0.8 | 0.012 | 4.68 | 5.77 \times 10^{-8} | 0.40 \times 10^3 | 6.8 \times 10^3 | −0.07 km s\(^{-1} \) | 0.13 km s\(^{-1} \) |

\[ \dot{M}_0 = 2.26 \times 10^{-6} m_0 M_\odot \text{yr}^{-1}, \quad (20) \]

where \( N = \rho/(\mu m_p) \) is the particle number density. We note that the dynamic time-scale of a cloud is also automatically fixed; that is, \( t_d \sim 2.2 \times 10^2 \) yr according to scaling estimate (14). From scaling estimates (13) and (14), the sound parameter \( k \) is estimated by \( k^{1/2} = 3.76 \text{ km s}^{-0.9} \) for solution III and by \( k^{1/2} = 65.7 \text{ km s}^{-0.8} \) for solutions I, II, IV and V, while the upstream \( k^{1/2} \) jumps up to \( k^{1/2} = 70.8 \text{ km s}^{-0.8} \) and \( k^{1/2} = 66.5 \text{ km s}^{-0.8} \) on the downstream side of shock solutions IV and V, respectively.

With scaling expressions (13) and (14), we estimate the physical properties of star-forming clouds as exemplified by Models I to V tabulated in Table 2. Figs 1 and 2 illustrate the radial profiles for the physical variables of these model clouds in two sets.

For those models without shocks (i.e., I, II and III), the infall radii \( R_{\text{inf}} \) are similar to each other, and their central core masses \( M_0 \) and total masses \( M_{\text{tot}} \) are also comparable. Here, the infall radius \( R_{\text{inf}} \) may be fairly small at the onset of a cloud core collapse and expands to encompass more gas and dust particles within the collapsed region as time goes on. We note in Fig. 1 that the overall number density and temperature values increase from Model I to Model III, and the temperature of Model III increases slightly outwards at large radii (~10^4 au). We note in Table 2 a gradual increase of the two masses \( M_0 \) and \( M_{\text{tot}} \) from Model I to Model III, caused by the increasing mass parameter \( A \) as shown in Table 1 [see equation (26) in Wang & Lou (2008)]. Our numerical explorations reveal that as \( n + \gamma \) increases, the presence of EECC solutions calls for increasing values of \( A \). Another difference is that the ratio of the central mass point to the total mass \( M_0/M_{\text{tot}} \) decreases from ~29.9 per cent in Model I to ~23.2 per cent in Model II to ~17.4 per cent in Model III. This phenomenon may be explained by reference to the general polytropic SPS solution (10), in which smaller \( \gamma \) and \( n \) values lead to mass distributions with a higher central concentration.

By comparing Models II, IV and V, we can infer the effects of shocks in self-similar EECC dynamic solutions. From Fig. 2, we see that the central infall velocities for EECC solutions with shocks (i.e., Models IV and V) are greatly suppressed, and their infall radii \( R_{\text{inf}} \) are smaller than that in Model II without a shock (Table 2). As a consequence, the central mass accretion rate \( \dot{M}_0 \) and the central mass \( M_0 \) for Models IV and V are smaller, taking only 10 per cent and 1 per cent of the values of Model II, respectively. The low values of mass accretion rates and central masses make these shock solutions potentially applicable for the formation of brown dwarfs. We should also note from Table 2 that the total masses \( M_{\text{tot}} \) for these three models are comparable, which suggests the possibility that under certain conditions protostars with different masses may form from molecular clouds with similar masses. In other words, molecular clouds of comparable masses have the additional freedoms to give rise to central protostars of different masses. The very low masses and mass accretion rates of EECC shock solutions are caused by efficient envelope expansions with a small inner boundary radius (Table 2). Inside the shock radius \( R_{\text{sh}} \), the particle number density \( N \) and gas temperature \( T \) of Models IV and V are higher than or close to those of Model II (see Fig. 2).

From Table 2, it can be seen that the central mass of a cloud (i.e. the protostellar mass) is not tightly or directly related to the total cloud mass for different model solutions, especially for EECC dynamic solutions with shocks. This conclusion agrees with the result that the mass function \( M_0/M_{\text{tot}} \) is determined mainly by the relative sizes of the mass accretion and outflow rates (e.g. bipolar outflows therein), and is weakly dependent on the core mass \( M_0 \) and number density \( N \) (e.g. Nakano, Hasegawa & Norman 1995; Matzner & McKee 2000). However, a constant ratio between mass outflow and accretion rates is always presumed for a given multistar-forming cloud, and the assumption that the initial mass function (IMF) of protostars should be closely connected with the cloud mass function (CMF) is usually made (e.g. Hennebelle & Chabrier 2008; Myers 2008). There is no obvious reason, however, why protostars forming in the same cloud should have the same ratio of mass outflow to accretion. Based on our analysis and results, we strongly suggest that solutions with different ratios between outflow and accretion exist in the same molecular cloud, and the IMF of protostars can differ from the CMF significantly, especially for those protostars with extremely low masses (i.e. brown dwarfs).

### 3 SPECTRAL LINE PROFILE SIGNATURES

We perform radiative transfer calculations for molecular spectral line profiles using the publicly available numerical code RATRAN (Hogerheijde & Sandell 2000) under spherical symmetry. The RATRAN code has been benchmarked among seven other radiative transfer codes by Van Zadelhoff et al. (2002) against examples of star-forming clouds such as B335. Based on the Monte Carlo method (e.g. Hammersley & Handscomb 1964; Shreider 1966; Bernes 1979), the RATRAN code deals with both radiative transfer and non-local thermal equilibrium (non-LTE) excitations of atomic and molecular lines, making it readily adaptable to realistic astrophysical cloud systems. We adopt dynamic cloud models for line

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1 We use the two terms ‘core mass’ and ‘cloud mass’ interchangeably in the loose sense.

2 For the purpose of testing and checking, our simple model radiative transfer calculations (Gao et al. 2009) are also performed by adjusting optical depths in parallel to the RATRAN code calculations for samples of red profiles. The relevant results are comparable.
Figure 3. Computed molecular line profiles of HCO\(^+\)(1–0) at 89.19 GHz (solid curves) and HCO\(^+\)(3–2) at 267.56 GHz (dashed curves) from individual pixels of spatially resolved emission lines for five EECC dynamic models, namely Models I–V. The ordinate is the brightness temperature in kelvin, and the abscissa is the projected velocity component along the LOS in the local standard of rest (LSR) in units of km s\(^{-1}\). Rows from top to bottom show molecular line profiles for dynamic Models I–V, respectively. Panels from left to right present the LOS with seven values of the impact parameter \(b\) (i.e. 0.27 \times 10\(^3\), 0.54 \times 10\(^3\), 0.81 \times 10\(^3\), 1.08 \times 10\(^3\), 1.35 \times 10\(^3\), 3.24 \times 10\(^3\) and 5.94 \times 10\(^3\) au). Impact parameters for pointings are not uniformly spaced on purpose, so that the transitions between blue profiles and red profiles can be clearly identified for Models I, II and III; however, the spatial coverage is sufficiently large to show variations of molecular line profiles. Involving both turbulence and thermal effects, the intrinsic line broadening is chosen as \(\Delta u = 0.17\) km s\(^{-1}\).

profile calculations. The dynamic and thermal parameters, namely radial flow velocity \(u\), number density \(N\) and gas kinetic temperature \(T\), are obtained consistently from the general polytropic EECC dynamic Models I–V. The temperature of dust in a cloud is assumed to follow the gas kinetic temperature \(T\). From the cloud centre to its outer radius \(R = 20000\) au, a molecular cloud is divided into 12 shells with high enough accuracy for calculations (8 and 10 shells were also tested separately, but displayed little variance in line profiles). However, the physical properties of these shells are not uniform, in order to show the transition between infall and outflow for all the dynamic models.

In Figs 3, 4 and 5, we show a sample of computed molecular line profiles, namely HCO\(^+\) \(J=1–0\) at 89.19 GHz and HCO\(^+\) \(J=3–2\) at 267.56 GHz, for the five dynamic EECC solution Models I–V. Molecular line profiles for transitions CO \(J = 2–1\) at 230.54 GHz, C\(^{18}\)O \(J = 1–0\) at 109.78 GHz, CS \(J = 2–1\) at 97.98 GHz and N\(_2\)H\(^+\) \(J = 1–0\) at 93.13 GHz are shown in Figs 6 and 7. All molecular data were obtained from the Leiden Atomic and Molecular Database (Schöier et al. 2005). Emission-line profiles with different impact parameters \(b\) [i.e. distance of line of sight (LOS) from the cloud centre] and under different conditions of micro-turbulence are shown in these figures. More compressed separations between impact parameters for pointings are chosen for the LOS passing through the innermost regions of clouds, in order to show clearly the transitions between blue profiles and red profiles for Models I–III. The number density of HCO\(^+\) molecules is assumed to be proportional to the overall molecular number density with a constant ratio, namely \(N_{\text{HCO}^+} = 2 \times 10^{-6} N\). Molecules in Figs 6 and 7 are also assumed to be of constant abundance ratios, namely \(N_{\text{CO}} = 5 \times 10^{-3} N\), \(N_{\text{C}^{18}\text{O}} = 1 \times 10^{-3} N\), \(N_{\text{CS}} = 3 \times 10^{-9} N\) and \(N_{\text{N}_2\text{H}^+} = 1.5 \times 10^{-10} N\), respectively. All these molecular abundances were chosen according to Tafalla et al. (2006), but the central abundance hole derived from the fitting procedure therein is not assumed in our model calculations. Strictly speaking, for all molecules, the variation of the abundance ratio should be taken into account (Rawlings & Yates 2001; Tsamis et al. 2008): the constant abundance ratio adopted here is just a first-order approximation.

3.1 Red profiles from EECC dynamic models

The most distinct spectroscopic signature of EECC dynamic models with core collapses and envelope expansions is the double-peak molecular line profile with the red peak being stronger than the blue.
peak, referred to as the red profile. We readily see such red profiles from cloud models described by each EECC solution in Figs 3–5. A more generic type of red profile has no obvious central dip but shows a stronger red shoulder, which exists over a larger range of the impact parameter $b$ for the LOS. In Figs 6 and 7, red profiles exist in many grids, except for CO and C$^{18}$O transitions in Model III (Fig. 6).

We demonstrate two types of self-similar EECC dynamic solutions according to the appearance of red profiles for molecular spectral lines from star-forming clouds. For Models I, II and III, red profiles exist only for a fairly large impact parameter $b$; that is, in Fig. 3, $b \gtrsim 1.08 \times 10^3$ au for Models I and III, and $b \gtrsim 1.35 \times 10^3$ au for Model II. Inside these radii (i.e. impact parameter), blue profiles for molecular lines emerge because of the more dominant role of core collapse towards the centre. This type of spatial transition from blue profiles to red profiles can be seen in some molecular clouds with spatially resolved observations (e.g. Tafalla et al. 2000; Ward-Thompson & Buckley 2001), although the appearance of such signatures in clouds may not be sufficiently spherically symmetric. For Models IV and V, whose infall radii are very small at the chosen epochs, red profiles for molecular lines exist throughout pixels with a range of impact parameter $b$; this can also be seen in some recent observations (Thompson & White 2004; Aguti et al. 2007). These results of our numerical exploration clearly indicate that the broad existence of red profiles is a characteristic signature of global envelope expansion; in contrast, the blue profiles are a characteristic feature of core collapse (e.g. Zhou et al. 1993; Gao et al. 2009). For all these EECC dynamic models without or with shocks, molecular emission line profiles decrease in overall magnitude as the LOS departs from the core centre and gradually disappear as the cloud density and temperature decrease further.

By comparing molecular line profiles among Models I, II and III, we find slight differences caused by different EECC dynamic profiles. The higher spectral amplitude in Model III appears to be caused by the higher number density and gas kinetic temperature involved (Fig. 1). The central dips for line profiles of Model III are shallower than those from Models I and II; this is probably because of the gradual temperature rise at outer radii of Model III (Fig. 1). However, we cannot immediately claim that these differences in molecular line profiles are caused by different values of the polytropic index $\gamma$ and scaling index $n$ in dynamic models, because, for the same set of indices, different asymptotic boundary conditions will lead to considerable variations in dynamic profiles (see e.g. Lou & Gao 2006; Hu & Lou 2008; Wang & Lou 2008). For Models IV and V, molecular emission lines with red profiles are present for all values of the impact parameter $b$. How, then, can we understand the role of expanding shocks in these self-similar EECC dynamic solutions? Dynamically, in gas clouds with a relatively smooth or less drastic mass density profile, shocks are more likely to happen, which pushes more mass outwards and leads to a more effective envelope expansion. The widespread existence of red profiles just represents a small infall radius at the epoch.

Figure 4. RATRAN computations for molecular spectral line profiles for the five EECC dynamic Models I–V as in Fig. 3, but with intrinsic line broadening $\Delta u = 0.5$ km s$^{-1}$. This intrinsic line broadening involves both turbulence and thermal effects.

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and highly efficient envelope expansion. Therefore by referring to underlying dynamic models, the presence of red profiles for nearly all impact parameters $b$ indicates that the central protostellar mass is very small (i.e. $\sim 0.106 \, M_\odot$ in Model IV and $\sim 0.012 \, M_\odot$ in Model V) and the molecular cloud may form a brown dwarf at the centre.

3.2 Effects of optical depth and turbulence

Optically thick conditions (i.e. absorption and scattering) in star-forming molecular clouds are responsible for asymmetric spectroscopic signatures such as those shown in Figs 3–5. Both HCO$^+$ $J = 1$–$0$ and $J = 3$–$2$ transitions are deeply self-absorbed (e.g. Tafalla et al. 2006), whereas the $J=3$–$2$ line transition has a lower optical depth and source function because of lower populations of relevant energy levels on $J = 3$ and $J = 2$ in such a cold environment with $T \sim 10 \, K$. This contrast has two effects on molecular line profiles: first, the intensities of $J = 3$–$2$ lines are weaker; and secondly, asymmetries of molecular line profiles are less apparent for $J=3$–$2$ transitions. This leads to the widely tested conclusion that in reference to optically thin lines, optically thick asymmetric molecular transition lines offer an important diagnosis of examining the large-scale thermal and dynamic structures of molecular clouds. The CO and CS transitions in Figs 6 and 7 are also examples of optically thick transitions that show distinct red profiles. In contrast, C$^{18}$O and N$_2$H$^+$ transitions are examples of optically thin transitions, which simply show single-peak line profiles.

Turbulence in molecular clouds also affects molecular line profiles in a significant manner (e.g. Arons & Max 1975; Larson 1981; Lou & Rosner 1986; Zweibel & McKee 1995; MacLow 1999). In this paper, the effect of turbulence is subsumed in the form of the intrinsic line broadening $\Delta v$; another contribution to the intrinsic line broadening is the thermal broadening of $\Delta v_{\text{th}} \sim 0.1 \, \text{km s}^{-1}$ for clouds with a temperature of $\sim 10 \, K$. We show radiative transfer results for a smaller or comparable turbulent broadening in Figs 3 and 4, and molecular line profiles for clouds under stronger turbulence are shown in Fig. 5. Besides the increase in line width, line profile asymmetry decreases as a result of the enhanced turbulence.

3.3 Star-forming molecular clouds

By fitting spatially resolved spectral line profiles to real molecular clouds, we may infer their underlying dynamic structures, and further estimate the physical parameters (e.g. protostellar mass, central mass accretion rate and dynamic age etc.) of star-forming molecular cloud cores. There are several steps to the data fitting: (1) selection of self-similar EECC dynamic solutions, (2) adoption of proper physical scalings derived from empirical information, and (3) choice of suitable turbulent broadening. Furthermore, submillimetre continuum observations can serve as a constraint on the radial profiles of density and temperature (e.g. Adams 1991; Shirley et al. 2000; Harvey et al. 2003) before fitting to molecular spectral emission line

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Figure 5. RATRAN computations for molecular spectral line profiles for the five EECC dynamic Models I–V as in Fig. 3, but with intrinsic line broadening $\Delta v = 1.5 \, \text{km s}^{-1}$. This intrinsic line broadening involves both turbulence and thermal effects.
profiles. In order to describe more realistic cloud situations, variations of the molecular abundance ratio should be taken into account. Star-forming molecular clouds L1517B (e.g. Tafalla et al. 2006), L1544 (e.g. van der Tak et al. 2005), L1551NE (e.g. Moriarty-Schieven, Butner & Wannier 1995) and L483 (e.g. Park et al. 2000; Tafalla et al. 2000; Carolan et al. 2008), among others, are strong candidates for being molecular clouds that probably involve EECC dynamic motions.

In addition to red profiles for molecular lines, there are several other clues for applying EECC dynamic models to molecular clouds. Global cloud systems have an estimated speed range of ~0.1–1 km s\(^{-1}\) for flows, which is smaller than the typical speeds of bipolar outflows of \(\gtrsim 10\) km s\(^{-1}\). Observed with sufficient spatial resolution, molecular line profiles from clouds with EECC dynamics will manifest a circular symmetry, whereas bipolar outflows have line emissions with a bipolar asymmetry in spatial distributions, as mentioned in Section 1. A frequency resolution of about 0.1 km s\(^{-1}\) is needed to resolve spectroscopic signatures, as shown in Figs 3 to 5. High spatial resolution (e.g. 2 arcsec or smaller for molecular clouds at ~200 pc) is also very important for detecting variations of molecular line profiles as a function of radius in the cloud core, which helps to distinguish between different underlying dynamic structures.

**4 SUMMARY AND CONCLUSIONS**

We invoked self-similar general polytropic EECC dynamic solutions without or with shocks to model the global evolution of a certain class of molecular clouds. By specifying relevant parameters plausibly estimated for molecular clouds, we illustrated several examples of general polytropic EECC cloud solutions. On the basis of these cloud solutions, we performed radiative transfer calculations to produce molecular line profiles to confirm the viability of the EECC model framework.

Through extensive numerical explorations, we demonstrated that the widely observed ‘red profiles’ in molecular emission spectral lines from star-forming clouds may well serve as important diagnostics for revealing the underlying EECC self-similar hydrodynamics in molecular clouds (Lou & Shen 2004; Shen & Lou 2004; Lou & Gao 2006; Wang & Lou 2008). From the point of view of general polytropic hydrodynamics and radiative transfer, our explanation for the mystery of ‘red profiles’ in emission spectral lines appears natural and physically plausible. In particular, a molecular cloud characterized by an envelope expansion with a simultaneous central core collapse represents a novel scenario. Based on EECC solutions with or without shocks, optically thick molecular emission lines from gas clouds can show red profiles for all values of the impact parameter \(b\) of the LOS from...
the cloud centre, or just outside a certain large enough $b$ value (with the inner region showing blue profiles). The optical depth of transition lines and turbulent broadening caused by micro gas motions will affect the appearance of red profiles. Different from those of bipolar outflows, emission lines from clouds under EECC dynamics will grossly show circular spatial symmetry, and the flow speed is typically smaller (e.g. $\sim$0.1–1 km s$^{-1}$). By fitting spectral emission line profiles of certain dynamic models with observed emission lines from star-forming clouds, it is possible to resolve the dynamic structures of these molecular clouds. These processes will also give rise to more physical parameters for the formation of protostars and their cloud environment.

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REFERENCES

Adams F. C., 1991, ApJ, 382, 544
Adelson L. M., Leung C. M., 1988, MNRAS, 235, 349
Aguti E. D., Lada C. J., Bergin E. A., Alves J. F., Birkinshaw M., 2007, ApJ, 665, 457
Arons J., Max C. E., 1975, ApJ, 196, L77
Belloche A., André P., Despois D., Blinder S., 2002, A&A, 393, 927
Berner C., 1979, A&A, 73, 67
Bian F. Y., Lou Y.-Q., 2005, MNRAS, 363, 1315
Carolan P. B., Redman M. P., Keto E., Rawlings J. M. C., 2008, MNRAS, 383, 705
Di Francesco J., Myers P. C., Wilner D. J., Ohashi N., Mardones D., 2001, ApJ, 562, 770
Evans N. J., 2003, in Curry C. L., Fich M., eds, Proc. Conf., Chemistry as a Diagnostic of Star Formation. NRC Research Press, Ottawa, Canada, p. 157
Evans N. J., II, et al., 2009, ApJS, 181, 321
Fiege J. D., Henriksen R. N., 1996a, MNRAS, 281, 1038
Fiege J. D., Henriksen R. N., 1996b, MNRAS, 281, 1055
Fuller G. A., Williams S. J., Sridharan T. K., 2005, A&A, 424, 949
Gao Y., Lou Y.-Q., Wu K., 2009, MNRAS, 400, 887
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Hammersley J. M., Handscomb D. C., 1964, Monte Carlo Methods. Methuen Press, London

Harvey D. W. A., Wilner D. J., Myers P. C., 2003, ApJ, 583, 809

Hennebelle P., Chaubier D., 2008, ApJ, 684, 395

Hogerheijde M. R., Sandell G., 2000, ApJ, 534, 880

Hu R. Y., Lou Y.-Q., 2008, MNRAS, 390, 1619

Jørgensen J. K. et al., 2007, ApJ, 659, 479

Kenyon S. J., Hartmann L. W., Strom K. M., Strom S. E., 1990, AJ, 99, 869

Keto E., Broderick A. E., Lada C. J., Narayan R., 2006, ApJ, 652, 1366

Lada C. J., Bergin E. A., Alves J. F., Huard T. L., 2003, ApJ, 586, 286

Larson R. B., 1981, MNRAS, 194, 809

Lee J.-E., Kim J., 2009, ApJ, 699, L108

Lou Y.-Q., Gao Y., 2006, MNRAS, 373, 1610

Lou Y.-Q., Hu R.-Y., 2010, New Astron., 15, 198

Lou Y.-Q., Rosner R., 1986, ApJ, 309, 874

Lou Y.-Q., Shen Y., 2004, MNRAS, 348, 717

McKee C. F., Ostriker E. C., 2007, ARA&A, 45, 565

MacLow M.-M., 1999, ApJ, 526, 169

Mardones D., Myers P. C., Tafalla M., Wilner D. J., 1997, ApJ, 489, 719

Matthews B. C., Hogerheijde M. R., Jørgensen J. K., Bergen E. A., 2006, ApJ, 652, 1374

Matzner C. D., McKee C. F., 1999, ApJ, 526, L109

Matzner C. D., McKee C. F., 2000, ApJ, 545, 364

Moraghan A., Smith M. D., Rosen A., 2008, MNRAS, 386, 2091

Moriarty-Schieven G. H., Butner H. M., Wannier P. G., 1995, ApJ, 445, L55

Myers P. C., 2005, ApJ, 623, 280

Myers P. C., 2008, ApJ, 687, 340

Nakano T., Hasegawa T., Norman C., 1995, ApJ, 450, 183

Ossenkopf V., 2002, A&A, 391, 295

Ostriker E. C., 1997, ApJ, 486, 291

Park Y.-S., Yun H. S., Hong S. S., Lee H. M., 1992, J. Korean Astron. Soc., 65, 25

Park Y.-S., Panis J.-F., Ohashi N., Choi M., Minh V. C., 2000, ApJ, 542, 344

Park Y.-S., Lee C. W., Myers P. C., 2004, ApJS, 152, 81

Rawlings J. M. C., Yates J. A., 2001, MNRAS, 326, 1423

Redman M. P., Keto E., Rawlings J. M. C., Williams D. A., 2004, MNRAS, 352, 1365

Redman M. P., Keto E., Rawlings J. M. C., 2006, MNRAS, 370, L1

Saito M., Sunada K., Kawabe R., Kitamura Y., Hirano N., 1999, ApJ, 518, 334

Schöier F. L., van der Tak F. F. S., van Dishoeck E. F., Black J. H., 2005, A&A, 432, 369

Shang H., Allen A., Li Z.-Y., Liu C.-F., Chou M.-Y., Anderson J., 2006, ApJ, 649, 845

Shen Y., Lou Y.-Q., 2004, ApJ, 611, L117

Shirley Y. L., Evans N. J. E., Rawlings J. M. C., Gregersen E. M., 2000, ApJS, 131, 249

Shreider Yu. A., ed., 1966, The Monte Carlo Method. Pergamon Press, Oxford

Shu F. H., 1977, ApJ, 214, 488

Shu F. H., Adams F. C., Lizano S., 1987, ARA&A, 25, 23

Shu F. H., Ruden S. P., Lada C. J., Lizano S., 1991, ApJ, 370, L31

Shu F., Najita J., Ostriker E., Wilkin F., Ruden S., Lizano S., 1994, ApJ, 429, 781

Shu Y.-N., Liu S.-Y., Chen H.-R., Zhang Q., Cesaroni R., 2007, ApJ, 671, 571

Tafalla M., Myers P. C., Mardones D., Caselli P., Bachiller R., Benson P. J., 1998, ApJ, 504, 900

Tafalla M., Mardones D., Myers P. C., Bachiller R., 2000, A&A, 359, 967

Tafalla M., Santiago J., Myers P. C., Caselli P., Walmsley C. M., Crapsi A., 2006, A&A, 455, 577

Thompson M. A., White G. J., 2004, A&A, 419, 599

Tsamis Y. G., Rawlings J. M. C., Yates J. A., Viti S., 2008, MNRAS, 388, 898

van der Tak F. F. S., Caselli P., Ceccarelli C., 2005, A&A, 439, 195

Van Zadelhoff G.-J. et al., 2002, A&A, 395, 373

Velusamy T., Peng R., Li D., Goldsmith P. F., Langer W. D., 2008, ApJ, 688, L87

Wang W.-G., Lou Y.-Q., 2008, Ap&SS, 315, 135

Ward-Thompson D., Buckley H. D., 2001, MNRAS, 327, 955

Wilner D. J., Myers P. C., Mardones D., Tafalla M., 2000, ApJ, 544, L69

Wu Y., Zhang Q., Chen H., Yang C., Wei Y., Hu P. T. P., 2005, AJ, 129, 330

Yu C., Lou Y.-Q., 2005, MNRAS, 364, 1168

Yu C., Lou Y.-Q., Bian F. Y., Wu Y., 2006, MNRAS, 370, 121

Zhou S., 1995, ApJ, 442, 685

Zhou S., Evans N. J. II, Kömpe C., Walmsley C. M., 1993, ApJ, 404, 232

Zweibel E. G., McKee C. F., 1995, ApJ, 439, 779

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