Action of Winds
Inside and Outside of Star Clusters

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Abstract. The feedback form pre-main sequence and young stars influences their vicinity. The stars are formed in clusters, which implies that the winds of individual stars collide with each other. Inside of a star cluster, winds thermalize a fraction of their kinetic energy, forming a very hot medium able to escape from the cluster in the form of a large-scale wind. Outside of the cluster, the cluster wind forms a shock front as it interacts with the ambient medium which is accreted onto the expanding shell. A variety of instabilities may develop in such shells, and in some cases they fragment, triggering second generation of star formation. However, if the cluster surpasses a certain mass (depending on the radius and other parameters) the hot medium starts to be thermally unstable even inside of the cluster, forming dense warm clumps. The formation of next generations of stars may start if the clumps are big enough to self-shield against stellar radiation creating cold dense cores.

Keywords. stars: formation, ISM: structure, globular clusters: general, open clusters and associations: general

1. Introduction

The star formation in galaxies transforms ISM to stars, which at the same time return a fraction of their mass to the ISM. The gas recycling redistributes the yield of stellar evolution causing the chemical evolution of galaxies. Star formation is an important process of internal galactic evolution, however, in some cases, it may be triggered by galaxy external agents.

Stars are formed in groups in cold, dense cores of molecular clouds. The feedback of young and massive stars influences their vicinity by radiation, stellar winds and by supernova explosions. In this contribution we shall separately discuss the actions of winds, and of other contributors to the feedback, outside and inside of stellar clusters. The feedback in star forming regions drives turbulence, and it may trigger the next generation of star formation in the compressed shells of the ISM outside of star clusters, or it may initiate star formation in warm clumps inside massive and sufficiently compact young stellar clusters.

2. Outside of a star cluster

The combined feedback of many stars in clusters forms expanding dissociation, ionization and shock fronts creating bubbles and expanding shells in the ISM. The shells are observed in HI in the Milky Way and many nearby galaxies. Radio surveys of the Northern (Hartmann & Burton, 1997) and Southern (McClure-Griffiths *et al.*, 2002) skies discovered hundreds of shells and shell-like structures on the size scales 10 pc - 1 kpc. Ehlerová & Palouš (2005) have used an automated search algorithm to find more than 600 shells in the outer Milky Way. Observation of HI shells in external galaxies are summarized by Walter & Brinks (1999), many more discoveries are expected in THINGS: the HI nearby galaxy survey (Walter *et al.*, 2008). In the infrared, Churchwell *et al.* (2006) and Churchwell *et al.* (2007) found many 0.1 - 10 pc size shells in the GLIMPSE survey covering only a part of the plane of the Milky Way. Deharveng *et al.* (2003), Zavagno *et al.* (2006), Sidorin (2008), and Deharveng *et al.* (2009) identified shells observationally in optical, infrared, radio and other wavebands, some of them appear to have triggered star formation at their borders. Watson *et al.* (2009) analyzed some of the shells from the GLIMPSE survey to determine properties of YSOs related to them.

The observed shells seem to be created by the feedback from young and massive stars in clusters, following the "collect and collapse" scenario proposed by Elmegreen & Lada (1977). It assumes that the massive stars of a star cluster supply energy into the interstellar medium as stellar winds and radiation creating an expanding bubble filled with a high temperature gas. The bubble expands due to its internal overpressure, sweeping the ambient medium into a dense shell. When the shell cools down it becomes gravitationally unstable forming fragments that are seeds of a new stellar generation.

Gravitational fragmentation of expanding shells has been studied under the assumption that their thickness is infinitesimally small. Vishniac (1983) derived the dispersion relation using a decomposition into spherical harmonics. With the linear analysis of hydrodynamical and Poisson equations in 2 dimensions Elmegreen (1994) and Whitworth *et al.* (1994) derived very similar dispersion relations composed of two stretching terms depending on the general expansion velocity of the shell V_{sh} and on its radius R_{sh} plus a term due to shell internal pressure depending on the speed of sound inside of the shell c_{sh}, which are opposed by the gravity term depending on the shell surface density Σ_{sh}.

$$\omega(l) = -\frac{AV_{sh}}{R_{sh}} + \sqrt{\frac{BV_{sh}^2}{R_{sh}^2} - \frac{c_{sh}^2 l^2}{R_{sh}^2} + \frac{2\pi G\Sigma_{sh} l}{R_{sh}}}, \tag{2.1}$$

where G is the gravitational constant and $(A, B) = (\frac{3}{2}, \frac{1}{4})$ or $(3, 1)$ for non-accreting or accreting shells, l is the wave number and ω gives the growth rate of a perturbation. From this dispersion relation it is visible that initially, when the radius of the shell is small and its expansion velocity is large, the first term dominates and the shell is stable; we may say that it is stabilized by expansion. Later, when the shell radius becomes large and its expansion is decelerated, the first two terms are negligible. The time t_b, when it becomes unstable for the first time can be derived provided the functions $R_{sh}(t), V_{sh}(t)$ and $\Sigma_{sh}(t)$ are known. Then, there is a certain range of wave numbers given by the dispersion relation, that are unstable, and we may ask how quickly they grow, and try to construct the mass spectrum of fragments.

A shell expanding due to internal overpressure into a higher density medium is subjected to instabilities: initially, when the expansion velocity is large, the expansion driven by high internal thermal pressure is opposed by ram pressure decelerating the shell. However, the thermal pressure acts isotropically and the ram pressure is always directed

against expansion, which creates, in the case of a small deviation from sphericity, a pressure component parallel to the shell surface leading to growth of perturbations, which is described as the Vishniac instability (Vishniac, 1983). Another instability appears when a low-density gas accelerates the high-density gas. This Rayleigh-Taylor instability, which forms long 'fingers' of high-density fluid extending to the low-density medium, is particularly important for large density differences. Later, when Vishniac and Rayleigh-Taylor instabilities combine with the Jeans gravitational instability, the shell breaks into fragments.

In order to see the effect of individual instabilities, in a series of papers (Dale *et al.*, 2009; Wünsch *et al.*, 2010; and Dale *et al.*, 2010) we try to isolate the gravitational instability. Therefore, we analyze the shells expanding into a medium of very low density and set the internal pressure equal to the external one. The lack of effective gravitational/inertial force (the shell evolves ballistically) eliminates the Rayleigh-Taylor instability. At the same time, the negligible ram pressure eliminates the Vishniac instability. We explore with 3 dimensional hydrodynamical simulations the gravitational instability during the ballistic motion of expanding shells.

The value of external and internal pressures is essential, since it influences the shell thickness: at low pressures the shell thickness increases during its ballistic motion, which makes the short wavelengths more stable, compared to dispersion relation 2.1, the low mass fragments do not form in this case. On the other hand, at high pressures, when the shell thickness decreases, even shorter wavelengths become unstable, compared to dispersion relation 2.1, producing an excess of low mass fragments. We also give the thick shell dispersion relation and propose a new Pressure Assisted Gravitational Instability (PAGI), which involves the external pressures and explains the above described behavior. Finally, we follow the evolution of individual fragments: their mass distribution corresponds to the PAGI dispersion relation only at the beginning of fragmentation during its linear phase. Later, they accumulate the remaining mass of the shell in a strongly non-linear process, which we call oligarchic accretion: the old fragments that were created initially accrete most of the mass and they leave only a small portion for others that were formed later.

As a next step, we shall also include the mass accumulation during its expansion, thus we shall be able to study other instabilities and explore the PAGI dispersion relation and oligarchic accretion in more general situations.

3. Inside of a star cluster

The young and massive stars in clusters deposit energy and mass into the intracluster medium. It happens in the form of radiation, winds and supernovae composing the stellar feedback in star clusters. They range from open clusters (OCl) of $10^4 M_\odot$ to globular clusters (GC) and super star clusters (SSC) of $10^6 M_\odot$. We also consider the compact dwarf galaxies (CDG), which may be the most massive compact stellar groups, of mass up to $10^8 M_\odot$. The energy deposited by individual young stars thermalizes in wind - wind collisions causing a large overpressure inside of the cluster driving the large-scale star cluster wind. In the adiabatic solution of Chevalier & Clegg (1985) the overpressure results in the wind blowing from the center to the periphery of the cluster where it reaches the sound speed c_s. Outside of the cluster, the adiabatic wind accelerates up to a velocity of $2c_s$.

In a series of papers Tenorio-Tagle *et al.* (2007), Wunsch *et al.* (2007), Wunsch *et al.* (2008), Tenorio-Tagle *et al.* (2010), Silich *et al.* (2010), and Hueyotl-Zahuantitla *et al.* (2010) we describe a model where the stellar wind's mechanical energy is thermalized
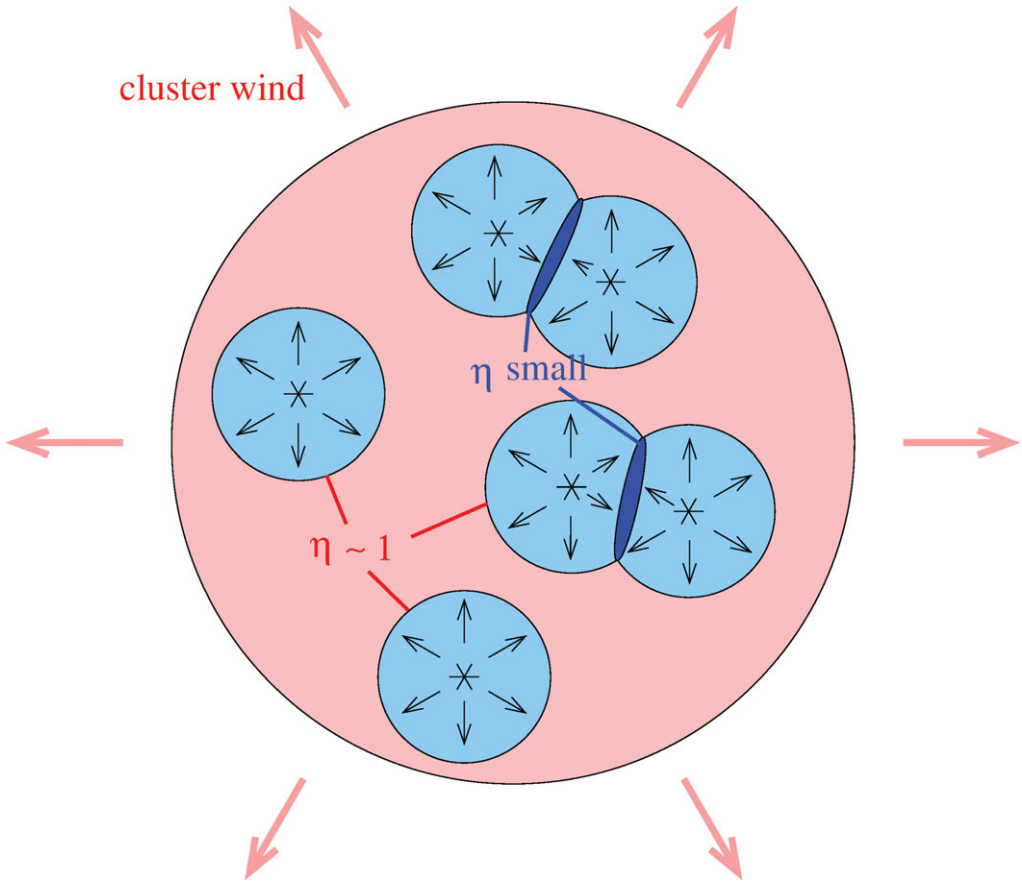
Figure 1. A model of the star cluster. Stars are homogeneously distributed in the cluster volume. The individual stellar winds collide and thermalize a fraction η of their mechanical energy in shocks.

with an efficiency η. The value of η is unknown; however, we try to estimate it from observations and also from numerical simulations. A schematic view of the modelled cluster is shown in Fig. 1.

In our model we give the solution of the hydrodynamical equations (3.1 - 3.3). In some cases the external gravitational force is included:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = q_m \tag{3.1}$$

$$\frac{\partial u}{\partial t} + (u \cdot \nabla)u + \nabla P / \rho = -\nabla \phi_{\mathrm{BH+NSB}} \tag{3.2}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot (eu) + P\nabla u = q_e - Q \tag{3.3}$$

where q_m and q_e are the mass and energy deposition rates per unit of volume, ρ is the density, u is the velocity, and e is the internal energy of the medium, $Q = n_i n_e \Lambda(T, Z)$ is the cooling rate, n_i and n_e are the ion and electron number densities, and $\Lambda(T, Z)$ is the Raymond and Cox (Plewa, 1995) cooling function, which depends on the thermalized gas temperature, T, and metalicity, Z. The right hand side of the equation (3.2) represents
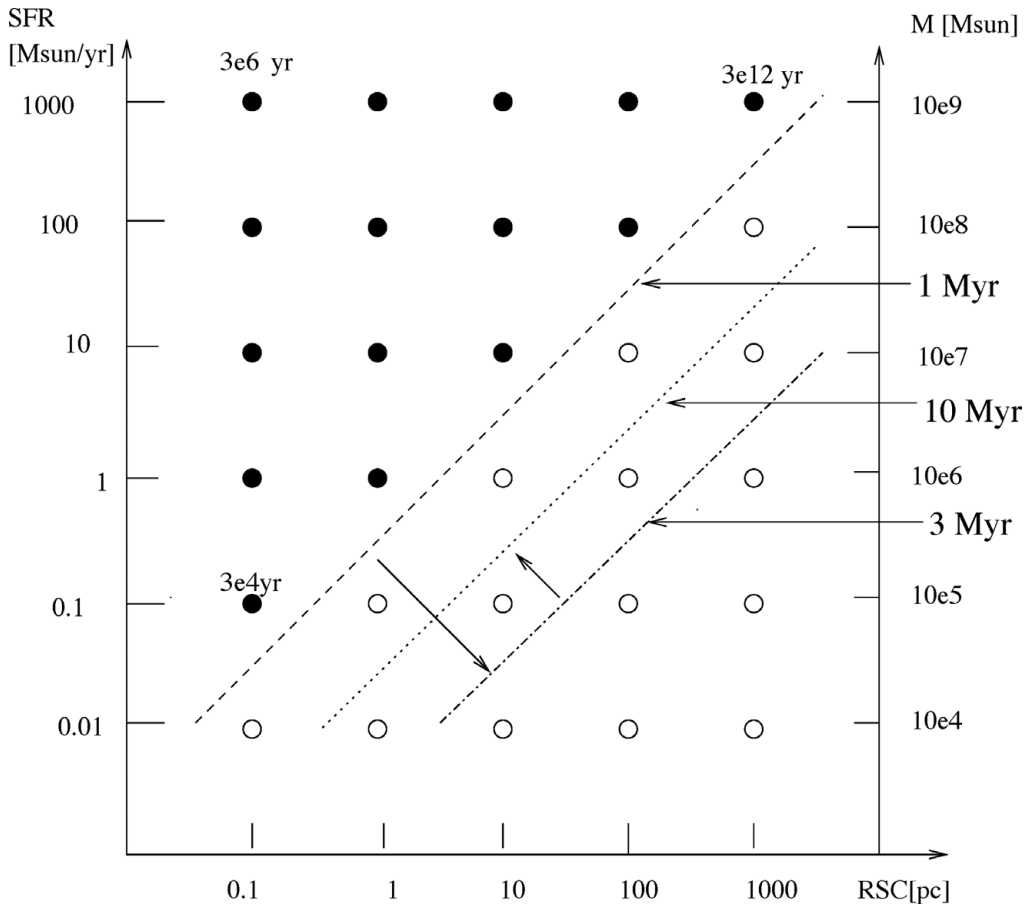
Figure 2. SFR versus R_{SC} plane for $\eta = 0.01$. The positions of clusters at the age of 1 Myr with the pure wind solutions (open circles) and bimodal solutions (filled circles) are given. The dashed line is the critical line dividing the pure wind area from the bimodal solution area. It changes its position with the age of the cluster as shown by arrows. The self-shielding time for a 10 Myr old cluster is given for bimodal solutions at the extreme positions in the SFR - R_{SC} plane.

the external gravitational force of the central black hole and of the gravitating mass of the starburst itself. This external gravitational term has been considered in some cases only.

The adiabatic solution of hydrodynamical equations by Chevalier & Clegg (1985) is valid when for certain cluster radii the mechanical wind energy is low enough. When we increase it above a certain critical value, the wind solution applies to the outer part of the cluster volume only. Inside of a stagnation radius R_{st}, the intracluster medium is thermally unstable, forming warm clumps. The position of the critical line in the cluster mass versus cluster radius plane is very sensitive to the value of η: small η moves the critical line to smaller masses.

In Fig. 2 we show how the position of the critical line, in the case of $\eta = 0.01$, changes its position during the first 10 Myr of the cluster life. We assume that a cluster is formed during the first 1 Myr, and that its final mass is given by the star formation rate (SFR).
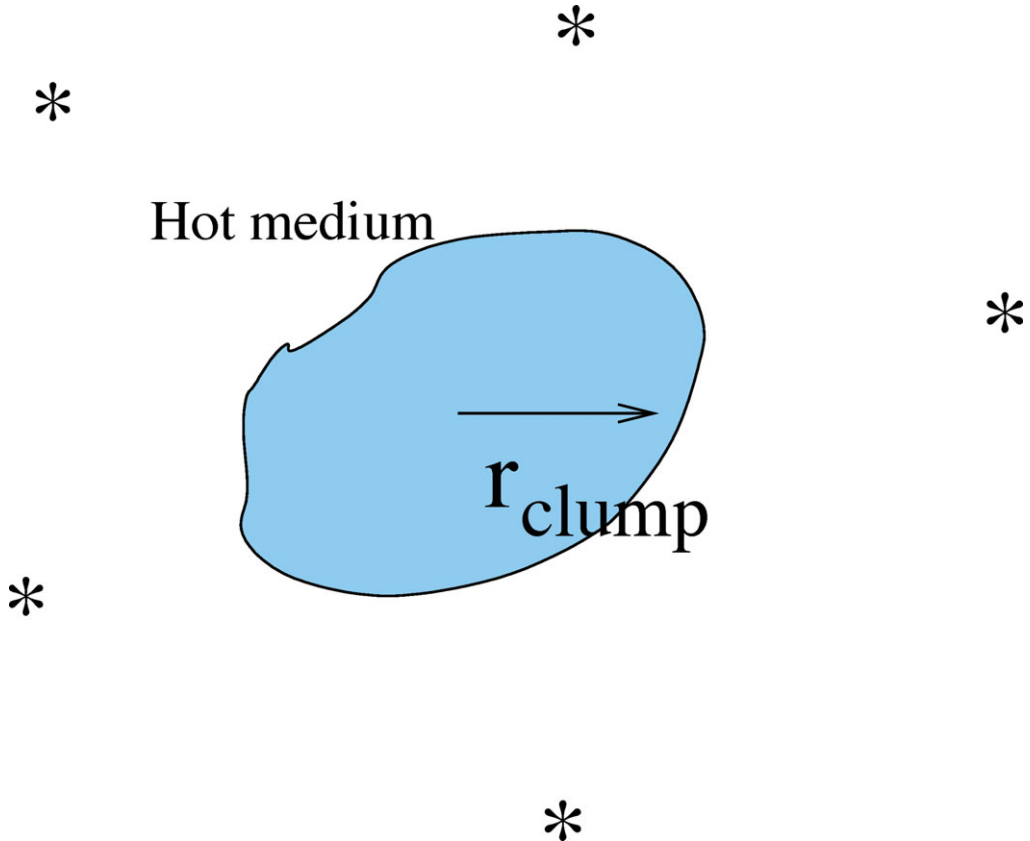
Figure 3. A warm clump inside of the thermally unstable central part of a forming cluster.

However, for larger values of η the critical line shifts to the left upper corner of the SFR versus R plane. When η is close to 1, almost all the clusters are described by the single mode wind solution.

We are interested if such clumps (see Fig. 3) may be Jeans unstable. We assume that a warm clump is in pressure equilibrium in the hot medium, $n_{clump} = \frac{P_{hot}}{kT}$, where $T = 10^4 K$ is the clump temperature. Thus the Jeans mass, $M_{Jeans} = 2.5 \times 10^5 M_\odot \left(\frac{n_{clump}}{10^3\,cm^{-3}}\right)^{-3/2}$, depends sensitively on the pressure of the hot medium P_{hot}. However, P_{hot} is very sensitive to the thermalization efficiency η. Low values of η produce low values of P_{hot}, which implies large M_{Jeans}. We conclude that if the value of η is small, masses of warm clumps with the temperatures $10^4 K$ have, after 10 Myr of mass accumulation in the thermally unstable region of a young star cluster, masses much smaller than M_{Jeans}, and therefore they are gravitationally stable.

Another question is whether the thermally unstable clumps are able to self-shield against the UV photon field of the young star cluster. The time t_{SS} of the clump growth needed to build clumps able to self-shield may be estimated with the following formula

$$t_{SS} = \frac{3}{4}\mu m_H \left(\frac{kT}{P_{hot}}\right)^5 \left(\frac{3\dot{N}_{UV,SC}}{4\pi R_{SC}\alpha_*}\right)^3 \left(\frac{N_{OB}}{\dot{M}_{SC}}\right), \tag{3.4}$$

where $\alpha_* = 1.58 \times 10^{-13} cm^3 s^{-1}$, $\dot{N}_{UV,SC}$ is the number of UV photons produced by the star cluster, $\dot{M}_{SC}$ is the mass flux inserted by all the stars of the cluster and N_{OB} is the

number of OB stars. We assume that N_{OB} also gives the number of warm clumps. A more detailed derivation of this will be given elsewhere (Palouš *et al.*(2010)).

The self-shielding times for 10 Myr old clusters are given in Fig. 2. t_{SS} is less than 1 Myr for small clusters with radius less that 1 pc. There, the clumps are able to self-shield, which may enable the decrease of temperature in their central parts, and trigger secondary star formation there. On the other hand, in star forming regions larger that 10 pc, t_{SS} is larger that 100 Myr, which probably eliminates the warm clumps as seeds of secondary star formation.

4. Conclusions

Outside of star clusters, the common action of the feedback of many stars forms shells, which may become gravitationally unstable, forming second generations of stars. We discuss the analytical and numerical models of expanding shells and analyze the mass spectra of fragments.

Inside of star clusters the bimodal wind solution applies above the critical line in the cluster mass versus radius plane. For small values of the thermalization efficiency, the warm clumps seem to be gravitationally stable, however, for clusters less that 1 pc in radius the self-shielding time is short. The cores of warm clumps may further decrease their temperature, becoming seeds of secondary star formation.

Acknowledgements

References

Chevalier, R. A. & Clegg, A. W. 1985, *Nature*, 317, 44
Dale, J., Wünsch, R., Whitworth, A., & Palouš, J. 2009, *MNRAS*, 398, 1537
Dale, J. Wünsch, R. Smith, R. J., Whitworth, A., & Palouš, J 2010, *MNRAS*, submitted
Deharveng, L., Lefloch, B., Zavagno, A., Caplan, J., Whitworth, A. P., Nadeau, D., & Martín, S. *A&A*, 408, L25
Deharveng, L., Zavagno, A., Schuller, F., Caplan, J., Pomarès, M., & De Breuck, C. 2009, *A&A*, 496, 177
Ehlerová, S., Palouš, J. 2005, *A&A*, 437, 101
Elmegreen, B. G. & Lada, C. J. 1977, *ApJ*, 214, 725
Elmegreen, B. G. 1994 *ApJ*, 427, 384
Hartmann, D. & Burton, W. B. 1997, *Atlas of Galactic Neutral Hydrogen*, Cambridge University Press
Hueyotl-Zahuantitla, F., Tenorio-Tagle, G., Wünsch, R., Silich, S., & Palouš, J. 2010, *ApJ*, 716, 324
McClure-Griffiths, N. M., Dickey, J. M., Gaensler, B.M., & Green, A., J. 2002, *ApJ*, 578, 176
Palouš, J., Wünsch, R., Silich, S., & Tenorio-Tagle, G. 2010 *in preparation*
Plewa, T. 1995, *MNRAS*, 275, 143
Sidorin, V. 2008 *IR, optical and X-ray counterparts of HI shells in the Milky Way*, Diploma Thesis, Charles University, Prague

Silich, S., Tenorio-Tagle, G., Muñoz-Tuñon, C., Hueyotl-Zahuantiutla, F., Wünsch, R., & Palouš, J. 2010, *ApJ*, 711, 25

Tenorio-Tagle, G., Wünsch, R., Silich, S., & Palouš, J. 2007, *ApJ*, 658, 1196

Tenorio-Tagle, G., Wünsch, R., Silich, S., Muñoz-Tuñon, C., & Palouš, J. 2010, *ApJ*, 708, 1621

Vishniac, E. T. 1983 *ApJ*, 274, 152

Walter, F. & Brinks, E. 1999, *AJ*, 118, 273

Walter, F., Brinks, E., de Blok, W. J. G., Bigiel, F., Kennicutt, R. C. Jr., Thornley, M. D., & Leroy, A. 2008, *AJ*, 136, 2563

Watson, C., Corn, T., Churchwell, E. B., Babler, B. L., Povich, M. S., Meade, M. R., & Whitney, B. A. 2009 *ApJ*, 694, 546

Whitworth, A.P., Bhattal, A. S., Chapman, S. J., Disney, M. J., & Turner, J. A. 1994 *MNRAS*, 268, 1341

Wünsch, R., Silich, S., Palouš, J., & Tenorio-Tagle, G. 2007, *A&A*, 471, 579

Wunsch, R., Tenorio-Tagle, G., Palouš, J., & Silich, S. 2008, *ApJ*, 683, 683

Wünsch, R., Dale, J., Palouš, J., & Whitworth, A. P. 2010, *MNRAS*, in press

Zavagno, A., Deharveng, L., Comerón, F., Brand, J., Massi, F., Caplan, J., & Russeil, D. 2008 *A&A*, 446, 171