The triggered star formation in rotating disks

J. Palouš (palous@ig.cas.cz) and S. Ehlerová (sona@ig.cas.cz)
Astronomical Institute, Academy of Sciences of the Czech Republic

B. G. Elmegreen (bge@watson.ibm.com)
IBM Research Division, T. J. Watson Research Center

Abstract. The gravitational instability of expanding shells triggering the formation of clouds and stars is analyzed. Disks with different scale-heights, ambient and shell velocity dispersions, mid-plane densities, rotation rates and shear rates are explored with three dimensional numerical simulations in the thin shell approximation. Three conditions for the shell collapse are specified: the first is that it happens before a significant blow-out, the second requires that the shell collapses before it is distorted by Coriolis forces and shear, and the third requires that the internal pressure in the accumulated gas is small and the fragmentation is achieved within the expansion time. The gas-rich and slowly rotating galaxies are the best sites of the triggered star formation, concluding that its importance has been much larger at the times of galaxy formation compared to the present epoch.

Keywords: Stars: formation; ISM: bubbles; Galaxies: ISM

1. Introduction

The gravitational instability divides the ISM to fragments, from which the molecular clouds originate. Their subsequent subdivision leads to the formation of stellar clusters. The question whether this chain of processes initiates spontaneously or whether it is triggered by an external push remains open. Probably both the spontaneous and the triggered star formation operate in galaxies and it is difficult to decide which is more important. Various kinds of triggering such as a compression of pre-existing clouds, accumulation of gas into a shell, cloud-cloud or shell-shell collisions have been discussed by Elmegreen (1998) and Chernin et al. (1995). In this contribution we discuss the constrains for the gravitational fragmentation of expanding shells and we try to specify when and where it operates.

2. Model

We use a model of a shell approximated by an infinitesimally thin surface expanding into a stratified, non-magnetic gaseous disk with a Gaussian density profile of thickness $H$, mid-plane density $\rho$, velocity dispersion $c_{\text{ext}}$, local rotation curve $V(R) \propto R^\alpha$, and local angular
rotation rate $\Omega$. The shell expansion is driven by an energy injection rate $L$ over the time $\tau$, after which the energy source fades out. At time $t$ the shell reaches the distance from the expansion center $r$, it has the surface density $\sigma$, the local expansion speed $v$ and the internal velocity dispersion in the swept-up matter $c_{sh}$.

From the linear approximation of hydrodynamical and Poisson equations on the surface of an expanding shell Elmegreen (1994) and Wünsch & Palouš (2001) derived the condition for the time $t_b$ after the beginning of expansion, when the instability starts

$$\omega(t_b) = -\frac{3v}{r} + \left(\frac{v^2}{2r^2} + \left[\frac{\pi G \sigma}{c_{sh}}\right]^2\right)^{1/2} = 0. \quad (1)$$

For $t > t_b$ and $\omega(t) > 0$, a fragmentation integral determines the time of significant collapse $t_f$:

$$I_f(t_f) = \int_{t_b}^{t_f} \omega(t')dt' = 1. \quad (2)$$

Using the three-dimensional numerical simulations, the condition (1) and the integral (2) are evaluated for any part of the shell up to the time when $v \leq c_{ext}$ everywhere in the galaxy symmetry plane.

3. Results

From many ($\sim 10000$) models when all the above parameters were varied over an extended grid of values we derive the conditions of the gravitational instability of expanding shells:

1. the disk gas surface density $\Sigma$ has to exceed some critical value

$$\Sigma_{crit} = 0.27 \left(\frac{E_{tot}}{10^{51} erg}\right)^{-1.1} \left(\frac{c_{ext}}{kms}^{-1}\right)^{4.1} 10^{20} cm^{-2}, \quad (3)$$

where $E_{tot} = L \times \tau$. The value of $\Sigma_{crit}$ depends strongly on $c_{ext}$, for higher values of $c_{ext}$ fragmentation starts at higher values of $\Sigma$.

2. the ratio of the mid-plane gas density $\rho$ to the total mass density $\rho_{tot}$ has to be close to 1;

3. the instability parameter $Q = \kappa c_{ext}/\pi G \Sigma$ or analogical shear parameter $Q_A = 8^{1/2} c_{ext} A/\pi G \Sigma$ have to be small ($Q, Q_A \leq 1 - 1.4$);

4. the ratio of the $c_{sh}^5/(GL)$ has to be small;
5. the value $c_{sh}/c_{ext}$ has to be small. It may be interpreted with the help of the analytical solution where the critical value $L_{crit}$ of the energy injection rate can be derived (Ehlerová & Palouš, 2001)

$$L_{crit} = \left( \frac{c_{ext}}{8.13 \, \text{km/s}} \right)^4 \left( \frac{c_{sh}}{\text{km/s}} \right) 10^{51} \, \text{erg} \, \text{Myr}^{-1}. \quad (4)$$

If the energy injection rate $L$ is greater than $L_{crit}$ the shell fragments. $L > L_{crit}$ transforms condition 4 into 5.

Note that the above conditions are interconnected: both 1 and 2 express that the fragmentation happens before a significant blow out to large $z-$distances from the galactic plane. 4 and 5 require that $L$ has to be large and $c_{sh}/c_{ext}$ has to be small. A more detailed description of the simulations and results is given by Ehlerová & Palouš (2001) and Elmegreen et al. (2001).

## 4. Conclusions

The gravitational instability and star formation triggered by the collapse of an expanding shell requires the following conditions to be fulfilled:

- The gas surface density has to surpass a critical value $\Sigma_{crit}$ given by eq. (3) and the gas mid-plane volume density can not be much less than the total mass mid-plane density. This means that if the gas represents only a small fraction of the total mass in the disk, the other components have to be distributed in disks of much larger thickness, producing the $K_z$ force that restricts the possibility of blow-out. With a gaseous and stellar disk of similar thickness, the shells are gravitationally unstable if the stellar disk is comparable to or less massive than the gaseous one.

- The disk should not rotate too fast and the shear should not be too large. High values of $A$ and $\kappa$ increase the values of $Q_A$ and $Q$ to the point where the shells are stable. Fast rotation and high shear distort the shell making large parts of it stable.

- The ISM should be able to cool sufficiently fast to decrease the random velocities from $c_{ext}$ in the undisturbed medium to $c_{sh}$ in the swept-up matter, for instability $c_{sh}/c_{ext} < 0.1$ within the expansion time. The influence of ISM metallicity on this condition should be explored in the future.
Steep dependence of $\Sigma_{\text{crit}}$ on $c_{\text{ext}}$ indicates the importance of the self-regulating feedback: for certain $c_{\text{ext}}$ the star formation is triggered if $\Sigma$ surpasses certain critical value $\Sigma_{\text{crit}}$. Star formation is accompanied by heating of the ISM, increase of $c_{\text{ext}}$ increasing the value of $\Sigma_{\text{crit}}$ and subsequent reduction of triggered SFR. The $\Sigma_{\text{crit}}$ for spontaneous star formation may be less steeply dependent on $c_{\text{ext}}$. Consequently, at the sites where the $c_{\text{ext}}$ has been increased, the triggered mode of star formation may have been suppressed and the spontaneous mode of star formation may still be effective at the same time.

The best place for triggered star formation are early gas rich galaxies, where only a small part of the gas has been transformed to stars and where the rotation is still quite slow. In the present epoch the triggering is rather exceptional restricted to high $L$ regions with enough gas and low shear. This may be the situation of galaxy versus galaxy collision, when the external gas is squeezed to the central part of a galaxy. There, during the star formation burst, the triggered star formation may operate for some time.

Acknowledgements

The authors gratefully acknowledge financial support by the Grant Agency of the Academy of Sciences of the Czech Republic under the grant No. A 3003705/1997 and the support by the grant project of the Academy of Sciences of the Czech Republic No. K1048102. BGE was supported by NSF grant AST-9870112.

References

Chernin A.D., Efremov Yu. N., Voinovich P. A. 1995, MNRAS 275, 313.
Ehlerová S., Palouš J. 2001, MNRAS, in press, astro-ph/0111495
Elmegreen B. G. 1994, ApJ 427, 384
Elmegreen B. G. 1998 *Origins of Galaxies, Stars, Planets and Life*, ed. C. E. Woodward, H. A.Q. Thronson, M. Shull, ASP Conf. Ser. 148, p. 150.
Elmegreen B. G., Palouš J., Ehlerová S. 2001, MNRAS, submitted
Wünsch R., Palouš J. 2001 A&A 374, 746

Address for Offprints: Jan Palouš
Astronomical Institute
Academy of Sciences of the Czech Republic
Boční II 1401, 1401 Prague 4
Czech Republic