

Star formation in expanding shells

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Abstract

The star formation induced in dense walls of expanding shells is discussed. The fragmentation process is studied using the linear perturbation theory. The influence of the energy input, the ISM distribution and the ISM speed of sound is examined analytically and numerically. The universal condition for the gravitational fragmentation of expanding shells is formulated: if the total surface density of the disk is higher than a certain critical value, shells are unstable. The critical density depends on the energy of the shell and the sound speed in the ISM.

1 Introduction

HI shells (and holes) are structures found in the distribution of neutral hydrogen of many nearby galaxies. The density of the gas in their walls is higher than the average density of the unperturbed ambient medium; the star formation in rims of HI shells is observed, e.g. in LMC (Kim et al. 1999), SMC (Stanimirovic et al. 1999), IC 2574 (Walter & Brinks 1999), etc. Its significance for the evolution of galaxies was studied by Palouš, Tenorio-Tagle & Franco (1994) and others.

The gravitational instability of the shell may lead to the formation of a cloud and then to the star formation. This instability is discussed in this contribution. The density perturbation on the shell surface is stretched by the expansion, while its self-gravity supports its growth. The instantaneous maximum growth rate of the perturbation in the linear approximation is (Elmegreen 1994)

$$\omega = -\frac{3v_{exp}}{R} + \sqrt{\frac{v_{exp}^2}{R^2} + \left(\frac{\pi G \Sigma_{sh}}{c_{sh}}\right)^2}, \quad (1)$$

where R is the radius of the shell, v_{exp} is its expansion speed, Σ_{sh} is its column density and c_{sh} is the speed of sound within the shell. The perturbation grows only if $\omega > 0$.

During the evolution, R , v_{exp} and Σ_{sh} change. We may ask, which conditions ensure $\omega > 0$ so that the gravitational instability may develop. One possibility is

studied by Elmegreen (1994). Shells in galaxies with thin disks are not spherical but elongated and even cylindrical. With the assumption that the diameter of the cylinder and its height are equal to the height of the galactic disk, the parameter of the gravitational instability of expanding shells may be derived:

$$Q_{trigg} = \frac{\kappa c_{ext}}{\pi G \Sigma_{gas}} \quad (2)$$

where c_{ext} is the speed of sound in the unperturbed medium and Σ_{gas} is the surface density of the gaseous component of the galactic disk. This relation shows, that the star formation in expanding rings may be triggered, if the gas surface density Σ_{gas} is sufficiently high.

In this paper we are interested in studying the fragmentation properties of HI shells without any assumptions on shapes and dimensions of the structures. For another application of the fragmentation of expanding shells see the contribution of G. Parmentier in this book.

2 Shells in the static homogeneous medium

During a majority of the evolution the thickness of the blastwave propagating into the ISM is much smaller than its radius. This is used by the thin shell approximation, in which the blastwave is described as the cold infinitesimally thin layer surrounding the hot medium and expanding. In case of the static homogeneous medium the blastwave is spherically symmetric and the analytical self-similar solution can be found (Sedov 1959; Weaver, Castor & McCray 1977).

The formula (1) for the instantaneous maximum growth rate of perturbations shows, that at early stages of the evolution the shell is stable, as the fast expansion stretches all perturbations which might appear. Only later, when v_{exp} is small, R large and Σ_{sh} high, the self-gravity begins to play a role and fragments may form. At the time t_b the growth rate ω becomes positive. This is the first moment, when the shell starts to be unstable and the fragmentation process begins.

Using the analytical solution we can get relations for the radius $R(t_b)$, the expansion velocity $v_{exp}(t_b)$ and $\Sigma_{sh}(t_b)$ at the time t_b , see Ehlerová et al (1997); or Ehlerová 2000. The radius $R(t_b)$ is a lower limit to the distance on which the fragmentation (and the triggered star formation) may take place; the expansion velocity $v_{exp}(t_b)$ is an upper limit to the random component of the velocity of newly created clouds (or stars).

So far we have assumed the supersonic motion, i.e. $v_{exp}(t) > c_{ext}$. If the shell becomes a sound wave before it starts to be unstable (i.e. before the time t_b), it will always remain stable. It is possible to derive the expression for the minimum energy input, which is able to trigger the fragmentation process. The condition, that v_{exp} at t_b is equal to the sound speed in the ambient medium c_{ext} , gives the critical luminosity L_{crit} (the energy flux L of the source is constant

with time):

$$L_{crit} = \left(\frac{c_{ext}}{8.13 \text{ km s}^{-1}} \right)^4 \left(\frac{c_{sh}}{\text{km s}^{-1}} \right) 10^{51} \text{ erg Myr}^{-1} \quad (3)$$

If the energy input is greater than L_{crit} , the shell starts to fragment; if the input is smaller, the shell is always stable. L_{crit} does not depend on the density of the ambient medium but it is a strong function of its speed of sound.

3 Shells in galactic disks

Numerical simulations must be used to describe the evolution of shells in z -stratified galactic disks with the gravitational field. The thin shell approximation has been applied in numerical simulations by many authors (see Ikeuchi 1998, for a review on this subject). The code, which we use in this paper, is an improved and extended successor to the code of Palouš (1990) described in Ehlerová et al (1997) and in Efremov, Ehlerová & Palouš (1999). The thin shell is divided into a number of elements; a system of equations of motion, mass and energy for each element is solved and the fragmentation condition (1) is evaluated.

Numerical simulations include some effects, which are neglected in the analytical solution. The most important are: 1) the pressure of the ambient medium and radiative cooling; 2) the finite, time-limited energy input from an OB association (life-time of the source is τ); and perhaps the most obvious one 3) the stratification of the ISM in galaxies. In this contribution we do not take into account the gravitational field of the galaxy (see Ehlerová 2000, for the discussion of this subject).

Due to the disk-like ISM density distribution, shapes of expanding shells are not spherical, but elongated in the direction of the density gradient. For higher input energies and thin disks, large lobes extending to high z -distances form. A fraction of the energy supplied by the hot stars escapes to the galactic halo. This phenomenon, called the blow-out, decreases the effect of the OB association on the most dense parts of shells in the galactic plane.

Fragmentation properties vary with the position on the shell. Typically, for shells growing in a smooth distribution of gas with the z -gradient, a dense ring is created in the region of the maximum density, which is the most unstable part of the shell, while large lobes in low-density regions are stable. In the following we present results for the most unstable part of shells.

The ISM in galaxies is far from being smooth, it is turbulent (see a great deal of contributions in these proceedings). However, coherent shells and bubbles are observed even in a rather turbulent ISM. Our numerical experiments in a medium with a hierarchy of density fluctuations show, that shells are mostly influenced by the large-scale gradients in the ISM (with the possible exception of the very perturbed regions, where the coherent shock does not form). Therefore

we think, that the discussion of shell properties in the smooth medium does not lose its relevance to the real situation.

4 The critical surface density

To study the influence of the z -stratification, we simulated shells in different types of the ISM distribution and different disk thicknesses $n(z) = n_0 \times f(\frac{z}{H})$, where f describes the profile of the disk and H is its thickness. We do not assume any relation between H , n_0 and c_{ext} ; we fix the velocity dispersion in the shell c_{sh} to a constant value, $c_{sh} = 1 \text{ km s}^{-1}$. Results of calculations are as follows:

1. For a given total energy E_{tot} and the sound speed c_{ext} shells are unstable, if the surface density of the gaseous disk exceeds a certain value.
2. The minimum gas surface density of the disk needed for the onset of the fragmentation does not depend on the z -profile of the disk.
3. The value of this critical surface density depends on the E_{tot} and c_{ext} .
4. Exceptions to these three rules appear for i) very small shells, which are to a high degree spherical, and therefore does not feel the influence of the disk z -stratification; and ii) shells with a very profound blow-out, which enables an escape of a substantial part of the energy to the halo.

From simulations we derive the fit for the critical surface density of the gaseous disk:

$$\Sigma_{crit} = 0.27 \left(\frac{E_{tot}}{10^{51} \text{ erg}} \right)^{-1.1} \left(\frac{c_{ext}}{\text{km s}^{-1}} \right)^{4.1} 10^{20} \text{ cm}^{-2}. \quad (4)$$

5 Conclusions

There exist a critical value of the disk gas surface density Σ_{crit} , shells expanding in disks with the lower gas surface density are stable, shells expanding in disks with the higher density are unstable, can fragment and form gaseous clouds and stars. The value of Σ_{crit} depends on the E_{tot} and c_{ext} . How does it agree with other criteria for spontaneous or triggered star formation?

The Q criterion for the radial instability of the gaseous disk

$$Q_{sp} = \frac{\kappa c_{ext}}{\pi G \Sigma} \quad (5)$$

(Safronov 1960), or similar criterion for stellar particles by Toomre (1964), predicts, that the critical surface density is linearly dependent on the sound speed. Similarly, the Elmegreen criterion (2) for the fragmentation of expanding shells

shows the same behavior. The critical surface density (eq. 4) derived by us depends on a fourth power of the sound speed in the ISM. The main difference is, that we do not study effects of the gravitational field of the galaxy (which leads to the dependence on the epicyclic frequency κ), but instead we ask, that the expansion of the shell must be supersonic, otherwise the evolution of instabilities is not described well by the equation (1), and moreover (and more importantly) the accumulation of mass by the blastwave is stopped and the growth of density perturbations is significantly slower or inhibited.

Values of Σ_{crit} for reasonable values of E_{tot} and c_{ext} are of the order of $(10^{20} - 10^{21}) \text{ cm}^{-2}$, which coincides with the value of observed threshold surface densities for the star formation in galaxies (Kennicutt 1997; Hunter, Elmegreen & Baker 1998). The agreement of these two quantities may indicate, that the contribution of the star formation induced by shells to the total star formation may be important.

The very steep dependence of Σ_{crit} on c_{ext} , as given by the equation (4), indicates the importance of the self-regulating feedback for the triggered star formation mode. Young stars in OB associations release the energy and compress the ambient ISM, creating shells. In dense walls of shells, the star formation may be triggered, if the disk surface density surpasses a critical value Σ_{crit} . The star formation is accompanied by the heating of the ISM, i.e. increasing c_{ext} . This leads to the increase of Σ_{crit} and a subsequent reduction of the star formation rate. The energy dissipation and cooling of the ISM decreases c_{ext} and Σ_{crit} and increases the star formation, closing the self-regulating cycle of the triggered mode of the star formation.

The Q criterion (5) describes the spontaneous mode of the star formation. Our condition (4) describes the triggered star formation (and even more precisely, the self-propagating star formation). Then the less steep dependence of Σ_{crit} on c_{ext} for the spontaneous star formation means, that this mode may keep its effectivity in regions, where c_{ext} has been increased and the triggered mode of star formation has been stopped.

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