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Transformation of the energy of a supernova into the mechanical energy of a galactic disk

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A gravitational mechanism for converting the energy of the expanding shells of a supernova into the mechanical energy of galactic disk stars is proposed.

Keywords: Supernova shells; Supershells; Galactic disk dynamics

1 Efficiency of energy conversion

As we have shown earlier, there is a gravitational mechanism for converting the energy of the expanding shell of a supernova (likewise of the supershell around a star-formation region) into the mechanical energy of a star cluster [1, 2]. It was assumed that as long as the shell continues to expand, it does not go beyond the cluster, and once its expansion has completely stopped, the shell material gets mixed with the interstellar material of the cluster. Thus, the gas does not leave the limits of the cluster, but the "bubbles" pulsating in it convert some of the supernova energy into the mechanical energy of the stars. It is demonstrated that frequent supernova bursts in a dense cluster rich in gas (for example, in a galactic nucleus) provide for a substantial inflow of mechanical energy and can perceptibly affect the evolution of the cluster as a whole [3]. Now, we will demonstrate the significant importance of the mechanism for evolution of the galactic disk as a whole.

To estimate the coefficient of conversion of the kinetic energy of the supernova shell into the energy of a cluster, we considered the simple model:

• volume density of stars (ρ_s) and interstellar matter (ρ_g) are homogeneous at the initial moment;

• supernova remnant is an infinitely thin shell immediately expanding to a maximum radius of R_m. The entire interstellar medium of the shell covered by the volume transferred to the surface of a sphere R_m, and then in a dynamic time scale back to a place again uniformly filled sphere.

Assuming that all the initial kinetic energy of the shell is to overcome gravity, we have [3] coefficient of energy conversion η_0 with $\rho_g \leq \rho_s$:

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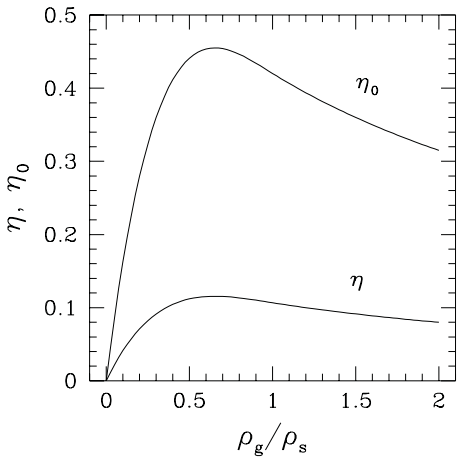


Figure 1 Coefficient η of conversion of the supernova shell energy into the cluster energy versus the relative gas density (ρ_g/ρ_s): η_0 – without allowance for radiative energy losses; η – with due regard for the loss of the shell energy by radiation.

$$\eta_0 = 0.63 \cdot \frac{3k - 3k^2 + k^3}{1 + 0.5k}, \tag{1}$$

and with $\rho_g > \rho_s$:

$$\eta_0 = \frac{0.63}{1 + 0.5k}, \tag{2}$$

where $k \equiv \rho_g/\rho_s$. The function $\eta_0(k)$ is shown in Fig. 1.

Since this dependence was obtained under the assumption of full conversion of the kinetic energy of the shell into its potential energy in the gravitational field of stars and gas, it overestimates the efficiency of the process. Some of the energy of the shell, of course, is thermalized and irradiated. We assessed the contribution of this process and found [3] that under conditions typical of star clusters and galactic disks the emission of the expanding shell loses about 75% of its initial energy. With this in mind, we obtain the final estimate for the coefficient of energy transformation:

$$\eta \approx 0.25\eta_0. \tag{3}$$

This formula can be considered quite suitable for astrophysical estimation purposes. The function $\eta(k)$ is also shown in Figure 1.

2 Energy contribution of supernovae in the evolution of the stellar disk of the Galaxy

As we know, the youngest population of the galactic disk form the most subtle of its subsystem with the characteristic height above the equatorial plane of about 100 pc, and the corresponding velocity dispersion of 10 km/s. With increasing age of

the stars the dispersion of their velocities increases, and the half-thickness of stellar disk increases too. Different mechanisms of the disk evolution were considered (e.g., gravitational perturbations from giant molecular clouds or spiral arms), but no definite opinion about the relative roles of these processes still exists [4].

Consider an infinite homogeneous disk with half-thickness H and a surface density σ. Gravitational acceleration above the disk is $g = 4\pi G\sigma$, and energy to increase the disk half-thickness up to $2H$ is equal to $E = 4\pi G\sigma^2 H/3$. To estimate how much the mechanism described above can change the structure of the galactic disk, we take into account only those supernovae whose specific energy (per unit mass of formed stars) is $\epsilon = 10^{51}$ erg$/100M_\odot$. Stellar population receives a portion η of this energy. Hence, we find a characteristic change in the thickness of the galactic disk:

$$H = \frac{3\epsilon\eta}{4\pi G\sigma}. \tag{4}$$

The surface density of the galactic disk is of the order of $\sigma \approx 10^2 M_\odot/\mathrm{pc}^2$ [4]. Given that the average density of interstellar matter in the thin disk of the Galaxy is close to the average density of stars, and with transition to a thick disc ratio $\rho_\mathrm{g}/\rho_\mathrm{s}$ it is significantly reduced, we can taken as an average $\eta = 0.01$. Then the estimate for the change in thickness of the disc will be $H \approx 3$ kpc. This value is more than enough to take seriously the proposed mechanism of energy conversion of supernova energy into the motion of field stars. Even if we have somewhat overestimated its effectiveness (for example, have not considered the possibility of "galactic fountains" that reduce the energy of supernova remnants [5]), this mechanism should, anyway, have a strong influence on the evolution of the vertical structure of the stellar disk of the galaxy.

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