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DEVELOPMENT OF GRAVITATIONAL INSTABILITY UNDER MATTER-ANTIMATTER ANNIHILATION CONDITIONS

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Goal: To study antimatter objects that can form in domains. Within the framework of this work, the development of gravitational instability under conditions of matter and antimatter annihilation is investigated.

Task: To find the relationship between Jeans instability and the effect of annihilation product pressure.

Annihilation at Domain Boundaries

The main reaction determining the evolution of the boundary between baryonic and antibaryonic domains is proton-antiproton annihilation:

$$p + \bar{p} \to \text{мезоны} \to \gamma, e^{\pm}, \nu.$$

Total energy released in a single annihilation event:

$$E_{\text{ann}} = 2m_p c^2 = 2 \times 938,27 \text{ МэВ} = 1,877 \text{ ГэВ}.$$

For an antimatter domain to survive long enough, its mass must satisfy certain constraints:

$$10^3 M_{\odot} \leq M \leq 10^5 M_{\odot}$$

Gravitational pressure at the center:

$$p_{\text{grav}} \sim \frac{GM^2}{R^4}$$

Pressure of ultrarelativistic plasma:

$$p_{\text{rad}} = \frac{1}{3} a T^4 \sim \frac{1}{3} n_a E_{\text{ann}}.$$

Gravitational instability under annihilation conditions

Dispersion relation for sound waves taking into account gravity:

$$\omega^2 = c_s^2 k^2 - 4\pi G\rho$$

Jeans mass — the minimum mass of a fluctuation capable of collapse:

$$M_J = \frac{4\pi}{3}\rho\left(\frac{\lambda_J}{2}\right)^3 = \frac{\pi^{5/2}c_s^3}{6G^{3/2}\rho^{1/2}}$$

$$M_J \propto c_s^3 \propto T^{3/2}$$

Finding the optimal Jeans mass

The temperature in the annihilation zone reaches $T \sim 10^7 \sim 10^8$ K.
The speed of sound in the heated medium:

$$c_s = \sqrt{\frac{k_B T}{m_p}} \sim 300 \text{ км/c}$$

Substituting the numerical values ($\rho = n_b m_p$, $n_b \sim 10^{40}$ m^{-3}, $c_s \sim 3 \times 10^5$ m/s) into the formula for the Jeans mass, we obtain:

$$M_J \sim 2000 M_\odot$$

Only clumps with a mass greater than 2000 $M_\odot$ can collapse.

Estimation of the pressure ratio

If we substitute $M \sim n_b m_p R^3$ (where n_b is the baryon density) into the formula for gravitational pressure and set $n_a = n_b$, then we obtain the ratio:

$$\frac{p_{\text{rad}}}{p_{\text{grav}}} \sim \frac{n_b E_{\text{ann}}/3}{G n_b^2 m_p^2 R^2} = \frac{E_{\text{ann}}}{3 G n_b m_p^2 R^2}$$

Let us consider the case for the Jeans mass. $M_\odot = 2 \times 10^{30}$ kg is the solar mass. Then:

$$M = 2 \times 10^3 \times 2 \times 10^{30} = 4 \times 10^{33} \text{ кг}$$

The characteristic radius of the domain is taken to be equal to the radius of a typical globular cluster or a compact dwarf galaxy:

$$R \sim 1 \text{ пк} = 3 \times 10^{16} \text{ м}$$

Estimation of the pressure ratio

From the relation $M \sim n_b m_p R^3$ (up to a numerical coefficient of order unity), we obtain:

$$n_b \sim \frac{M}{R^3 m_p}$$

Substituting the numerical values:

$$n_b = \frac{4 \times 10^{33}}{(3 \times 10^{16})^3 \times 1,67 \times 10^{-27}} \sim 8,7 \times 10^{10}\ \text{м}^{-3}$$

$$E_{\text{ann}} = 2m_p c^2 = 3,01 \times 10^{-10}\ \text{Дж},$$
$$G = 6,67 \times 10^{-11}\ \text{м}^3 \cdot \text{кг}^{-1} \cdot \text{с}^{-2},$$
$$m_p = 1,67 \times 10^{-27}\ \text{кг}.$$

Estimation of the pressure ratio

Let us substitute the values into the formula for the ratio of annihilation pressure to gravitational pressure:

$$\frac{p_{\mathrm{rad}}}{p_{\mathrm{grav}}} \sim \frac{3,01 \times 10^{-10}}{3 \times 6,67 \times 10^{-11} \times 8,7 \times 10^{10} \times (1,67 \times 10^{-27})^2 \times (3 \times 10^{16})^2} \sim 6,89 \times 10^{9}$$

The obtained value is >> 1. Thus, the annihilation pressure always dominates over the gravitational pressure, and the cloud expands rather than contracts.

Conclusion

- An analysis of the energy release during proton-antiproton annihilation has been carried out. It is shown that in a single annihilation event, an energy of $E_{ann} = 1.877$ GeV is released, and the annihilation products are ultrarelativistic.
- A comparison of the annihilation product pressure with the gravitational pressure has been performed. The obtained ratio $p_{rad}/p_{grav} \sim 6.89 \times 10^9 \gg 1$ shows that the annihilation pressure dominates over the gravitational pressure. This pressure is precisely the main obstacle to gravitational contraction.
- The modification of the Jeans mass under conditions of annihilation heating has been considered. Annihilation heating of the medium to $T \sim 10^7$–10^8 K increases the sound speed to $c_s \sim 300$ km/s, which yields an estimate of the Jeans mass $M_J \sim 2000\ M_\odot$. This value satisfies the domain existence condition $10^3\ M_\odot \leq M \leq 10^5\ M_\odot$.
- The main problem for the development of gravitational instability in antimatter domains is the pressure of annihilation products, which exceeds the gravitational pressure. To overcome it, additional mechanisms are required, for example, the presence of internal subdomains of matter inside the antimatter domain, which can locally change the pressure balance and create conditions for gravitational collapse.