Is a spontaneous contraction of the universe thermodynamically possible?

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Abstract

In this work, we study the expansion and contraction of the cosmic fluid from a thermodynamic perspective. We make general considerations about both processes by calculating their Gibbs free energy function and analyzing its sign. The sign determines whether the process is spontaneous or non-spontaneous. The result is that, while the expansion of the universe is a spontaneous process at any temperature, the contraction process is not. To carry out this study, we derive an equation that relates the entropy generated by these processes to the redshift and the adiabatic index. Using this equation, we calculate the Gibbs free energy function, studying the spontaneity of the expansion and contraction processes. The result is that, while the expansion process is always spontaneous, the contraction process is never spontaneous, requiring external energy to make it possible.

Keywords: large-scale structure of Universe, cosmology: theory, cosmology: miscellaneous

1. Introduction

11- Thermodynamic study of the expansion process of the universe

We will conduct a simple thermodynamic study of the universe's expansion process. First, we must define the model we will use: we will consider an ideal gas expanding adiabatically in a piston, that is, without heat exchange, and we will thermodynamically study its expansion. Starting with the thermodynamic variables Pressure (P), Volume (V), and Temperature (T), we associate pressure with the pressure of the cosmic fluid, volume with the volume of the universe, and temperature with the temperature of the cosmic microwave background (CMB) at each time. In the pressure of the cosmic fluid, according to (Melia F, 2026), we include the pressure due to gravitational forces and dark energy forces. The former are attractive forces that contribute to compressing the universe, while the latter contribute to expanding it.

Furthermore, to carry out our study, we will need to calculate the enthalpy change ΔH and the entropy change ΔS due to the expansion. Using an ideal gas model, the enthalpy H is a function only of the temperature, resulting in:

$$\Delta H = \frac{d+2}{2}.\ R\ \Delta T;$$ d = degrees of freedom of its molecule of ideal gas

The entropy of the universe is divided into two main categories: the entropy generated by the formation of stars, planets, other cosmic matter, and life; and the entropy due to the expansion of the universe. The first has already been calculated (Egan C.A., Lineweaver C. H., 2010) and constitutes the most significant contribution to the entropy of the universe. The second is the one that interests us in this work, and we develop it here according to our model.

1.2- Entropy of the universe due to expansion and contraction

For an ideal gas process, the change in entropy is calculated using the following equation

$$\Delta S = n\,(c_v \ln(T_2/T_1) + R \ln(V_2/V_1))$$

where n is the number of moles, c_v is the molar heat at constant volume, which in the case of a monatomic ideal gas is $c_v = \frac{d}{2}$ R, where R is the ideal gas constant.

Since we are only studying the expansion process of the universe, in this work we refer its temperature to the CMB temperature at each moment and we will do so as a function of the redshift.

To calculate the temperature of the cosmic microwave background (CMB) at each time point, we will use the equation obtained in the work referenced here (Tatsuya Kotani et al. 2025) and apply it to our calculations. According to this work, the equation is consistent with the predictions of the Standard Cosmological Model. The equation gives CMB temperature values as a function of redshift.

The equation is as follows:

$$T_{CBM} = T_0\,(1+z)$$

$$T_0 = 2{,}72548 \mp 0{,}00057$$

According to our equation for entropy

$$\Delta S = S_2 - S_1 = n\,(c_v \ln(T_2/T_1) + R \ln(V_2/V_1))$$

$T_2/T_1 = T_0/T_{CBM} = 1/(1+z)$

$V_2/V_1 = a_2^3/a_0^3 = (a(t_o)/a(t_e))^3 = ((1+z))^3$

V_1, T_1, the volume and temperature of the universe at time t_e; V_2, T_2 the volume and temperature of the universe at time t_o. and being "a" the scale factor of the universe.

$$\Delta S = S(t_0) - S(t) = n\,(c_v \ln(T_0/T_t) + R \ln(V_0/V_t)) = n\,(-c_v + 3R) \ln(1+z)$$

For a ideal gas with d degrees of freedoms: $c_v = \frac{d}{2}$ R

The adiabatic index ʹϒ of the ideal gas (cosmic fluid) as a function of the number of degrees of freedom of its molecule d;

$$\Upsilon = 1 + \frac{2}{d}$$

result:

$$\mathbf{0 < \Delta S = n\,\left(\frac{3\Upsilon - 4}{\Upsilon - 1}\right) R \ln(1+z)}$$

2. Study of the Gibbs free function in processes of expansion and contraction of the universe

In the work we present here, we will study the behavior of the universe in an expansion phase and a contraction phase, examining whether these are spontaneous or not from a thermodynamic point of view within the cosmic fluid model we are studying. To do this, we will determine the sign of the change in the Gibbs free energy function, G, in both processes, thus determining whether the process is spontaneous or non-spontaneous, depending on the sign of the ΔG, Gibbs free energy function.

The variation of the Gibbs free energy function ΔG is expressed by:

$$\mathbf{\Delta G = (\Delta H - T\,\Delta S)}$$

ΔG < 0 spontaneous process

ΔG > 0 non-spontaneous process

The expansion and contraction of the universe are irreversible adiabatic processes, characterized by a decrease in temperature during expansion, and an increase in temperature during contraction, and in both cases, an increase in entropy. We will calculate the Gibbs free energy function for both, determining its sign.

In expansion universe

The temperature decreases; therefore, according to the formula for calculating enthalpy in ideal gases.

$$\Delta H = \frac{d+2}{2}. R\, \Delta T = \frac{\Upsilon}{\Upsilon - 1}\ R\, \Delta T < 0$$

The enthalpy change has a negative sign $\Delta H < 0$. Entropy, as in any irreversible adiabatic process, will increase; therefore, the entropy change has a positive sign $\Delta S > 0$.

The Gibbs free energy function will be:

$\Delta G = (\Delta H - T\, \Delta S)$

<u>In expansion universe,</u>

$(\Delta H - T\, \Delta S) < 0$; $\Delta G<0$

the expansion process is spontaneous at any temperature.

<u>In contraction universe</u>

In every adiabatic contraction process of an ideal gas, the temperature increases., thus, according to the formula for calculating enthalpy in ideal gases.

$$\Delta H = n \frac{d+2}{2}. R\, \Delta T = n\ \frac{\Upsilon}{\Upsilon - 1}\ R\, \Delta T > 0$$

The enthalpy change has a positive sign $\Delta H > 0$. Entropy, as in any irreversible adiabatic process, will increase; therefore, the entropy change has a positive sign $\Delta S > 0$.

The Gibbs free energy function will be:

$$\Delta G = (\Delta H - T\, \Delta S)$$

Since it is a contraction of the universe $z < 0$, then:

$$\Delta S = n\ (\frac{3\Upsilon-4}{\Upsilon-1}\ )\ R\ \ln(1+z) = (\frac{3\Upsilon-4}{\Upsilon-1}\ )\ R\ \ln (T_1/T_2) = (\frac{3\Upsilon-4}{\Upsilon-1}\ )\ R\ \ln (((T_0 - \Delta T)/T_0) =$$

$$= (\frac{3\Upsilon-4}{\Upsilon-1}\ )\ R\ \ln\ (1 - (\Delta T/T_0)) = (\frac{3\Upsilon-4}{\Upsilon-1})\ \ R\ (-\Delta T/T - (\Delta T/T)^2/2 - \ldots.) \cong\ (\frac{3\Upsilon-4}{\Upsilon-1})\ \ R\ (-\Delta T/T)$$

$$T.\ \Delta S = -\ (\frac{3\Upsilon-4}{\Upsilon-1})\ \ R\ \Delta T$$

$$\Delta H = \frac{\Upsilon}{\Upsilon-1}\ \ R\ \Delta T$$

The adiabatic compression of a gas causes a temperature increase; therefore, the compression of the universe, according to the model we are studying, will cause a temperature increase. Consequently, the enthalpy change will be positive.

$\Delta G = (\Delta H - T\, \Delta S)$

$\Delta H > 0$; $\Delta S > 0$

$$\Delta H - T.\ \Delta S = (\ \frac{\Upsilon}{\Upsilon-1}\ \ R\ \Delta T) + (\frac{3\Upsilon-4}{\Upsilon-1}\ \ R\ \Delta T) =$$

$$\frac{4\Upsilon-4}{\Upsilon-1}\ \ R\ \Delta T = 4R\ \Delta T > 0$$

<u>In contraction universe</u>,

$(\Delta H - T\, \Delta S) > 0$; $\Delta G > 0$

the contraction process is non-spontaneous at any temperature.

3. Conclusions

Through a thermodynamic study of a gaseous model for our universe, we have analyzed the expansion and contraction of universe. To do this, we calculated the Gibbs free energy function of the process to determine its potential spontaneity. To calculate the Gibbs free energy function, we developed an equation for the entropy of the expansion-contraction process, relating it to the redshift and the adiabatic index of the cosmic fluid. The calculation of the Gibbs free energy function indicates that the expansion process is always spontaneous, while the contraction process is non spontaneous, only occurring with an additional external energy.

Therefore, we can deduce that a bouncing universe of expansion and contraction does not seem to be a realistic possibility for our universe. Rather, we expect uncontrolled expansion as its end, not a return to the beginning.

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