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Research Article

Deriving the Average Change in Kinetic Energy of a Galaxy in Non-Relativistic Motion

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Abstract

This study presents a novel approach to calculating the average change in kinetic energy of galaxies exhibiting non-relativistic motion. The methodology integrates the dynamics of total observed motion, which encompasses both peculiar and recessive motion, with the gravitational influence of neighboring galaxies. The peculiar motion is quantified through peculiar redshift, while recessive motion is described by Hubble's Law. The total observed velocity is the sum of these two components. The research derives an expression for the average acceleration of a galaxy based on the change in its total observed redshift wavelength over time. Utilizing Newton's Second Law of Motion, the average observed force and subsequent work done by this force is calculated. The work done by conservative forces, primarily gravitational forces exerted by neighboring galaxies, is also considered to determine the total work done on the galaxy. Results indicate that the average total observed force causing the motion of a galaxy is a non-conservative force, resulting from the combined effects of non-conservative forces responsible for peculiar and recessive motion. The change in potential energy due to gravitational interactions with neighboring galaxies is accounted for, leading to the formulation of the average change in kinetic energy. The conclusion of the paper provides a comprehensive expression for the average change in kinetic energy of a galaxy, factoring in the mass of the galaxy, the speed of light, the total observed redshift, the change in distance with respect to Earth, and the gravitational constant. This expression is significant for understanding the dynamics of galactic motion and the forces at play in a non-relativistic context.

More Information

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Introduction

In non-relativistic motion, the velocity of a moving particle is assumed to be much smaller than the speed of light. Here, Newtonian Mechanics holds good. But if the velocity approaches or becomes comparable to the speed of light (the speed of a particle can never reach the speed of light), Newtonian Mechanics does not hold good and so, Einstein's Special Relativity comes into play.

Before coming to the methodology, it's important to know the basics of galactic motion.

Quantification of recessive and peculiar velocities

Every galaxy in the universe is separating away from each other due to the continuous expansion of the universe. Such a recessive motion of a galaxy is described by its recessive velocity v_r, which is directly proportional to the proper distance D, as given by Hubble's Law:

$$v_r = H_0 D \tag{1}$$

Where H_0 is the Hubble's constant [1].

Apart from this recessive velocity due to expansion, a galaxy possesses its own velocity, relative to the expansion, with which it is moving. This is called the peculiar velocity, v_p. This is given by the equation:

$$v_p = cz_p \tag{2}$$

Where c is the speed of light and z_p is the peculiar redshift, based on the Doppler Effect. Peculiar redshift refers to the change in wavelength of the light emitted by a galaxy due to its peculiar motion, with respect to the actually emitted wavelength of light from the galaxy. This peculiar redshift happens when a galaxy is moving away from us (observer). However, if a galaxy tends to move towards us, a peculiar blueshift happens. Even the recessive velocity can be expressed as

$$v_r = cz_r \tag{3}$$

Where z_r is the cosmological redshift. The sum of the recessive and peculiar velocity of a galaxy is known as the total observed velocity,

$$v = cz \tag{4}$$

Where

$$z = \frac{\lambda o - \lambda e}{\lambda_e} \tag{5}$$

Is the total observed redshift. λ_o is the total observed wavelength due to both the recessive and peculiar motion of the galaxy, and λ_e is the emitted light from the galaxy due to both its recessive and peculiar motion [1].

These three velocities are hence, approximately related as:

$$v = v_r + v_p \tag{6}$$

Or

$$cz = cz_r + cz_p \tag{7}$$

For galaxies not very distant from us showing non-relativistic motion. Therefore, such galaxies possess much smaller redshifts, which can be approximately related as [1]:

$$z = z_r + z_p \tag{8}$$

Apart from the recessive and peculiar motion of a galaxy which must be due to non-conservative or external forces, the actual motion of a galaxy will also be affected by conservative forces. The major conservative force on a galaxy will be the gravitational force exerted by the neighboring galaxies.

Methodologies

Several studies have examined the interplay between peculiar and recessive motions. For instance, Tamara and Morag [1] explored the impact of neighboring galaxies on peculiar velocities, finding that gravitational interactions significantly influence these velocities. This study's results align with their findings, demonstrating that the average total observed force incorporates both peculiar and recessive motions and highlighting the role of non-conservative forces in galactic dynamics. Iannuzzi [2] investigated the initial orbits of galaxies and the resulting impact on their velocities, emphasizing the importance of considering both recessive motion and peculiar velocities for accurate simulations. This aligns with our methodology of incorporating both components to derive the total observed force. Paulino-Afonso [3] examined structural evolution across cosmic time, noting the significance of peculiar velocities in the transformation of galaxies. This study supports the need to account for both peculiar and recessive motions in understanding galactic dynamics. Leconte-Chevillard [4] provided historical context on the methodologies used to study galactic motions, confirming that the combination of peculiar and recessive velocities has long been recognized as crucial for understanding the expansion of the universe. Rebhan [5] focused on the implications of cosmic inflation and its effects on galaxy velocities, emphasizing the complex interactions between different forces acting on galaxies. This further justifies the need to incorporate both conservative and non-conservative forces in our analysis.

Now let's see the methodology of this article in deriving the dynamics of total observed motion of a galaxy, which includes the combined effect of peculiar and recessive motion. From Equation (4) and Equation (5), we have:

$$v = cz \tag{9}$$

$$v = c\frac{\lambda o - \lambda e}{\lambda_e} \tag{10}$$

Let's consider a change in the total observed velocity of the galaxy due to the change in its total observed redshift wavelength:

$$\Delta v = c\frac{\Delta\lambda}{\lambda_e} \tag{11}$$

Divide both sides by change in time Δt, from a certain point of time t_1 to a time t_2:

$$\frac{\Delta v}{\left(t_2 - t_1\right)} = \frac{c}{\lambda_e}\cdot\frac{\Delta\lambda}{\left(t_2 - t_1\right)} \tag{12}$$

This gives the average acceleration of the galaxy, a, due to its total observed motion:

$$\mathrm{a} = \frac{c}{\lambda_e}\cdot\frac{\Delta\lambda}{\Delta \mathrm{t}} \tag{13}$$

If we know the mass m of the galaxy, then from Newton's Second Law of Motion, we can get the average observed force of the galaxy, F, that causes its total observed motion as:

$$F = m\frac{c}{\lambda_e}\cdot\frac{\Delta\lambda}{\Delta \mathrm{t}} \tag{14}$$

Let this force cause a displacement Δs from a displacement vector s_1 (at time t_1, as measured from the Earth) to a certain displacement vector in space, s_2 (at time t_2). Here we approximate that the direction of displacement is in the direction of force. Then, the average work done by the average observed force of the galaxy, for this displacement, will be:

$$W = F\cdot(s_2 - s_1) \tag{15}$$

$$W = m\frac{c}{\lambda_e}\cdot\frac{\Delta\lambda}{\Delta \mathrm{t}}\cdot\Delta s \tag{16}$$

Following the discussion in "Introduction" and the aforementioned methodologies used by various scholars, the work done by conservative forces also needs to be incorporated to get the total work done on the galaxy. These conservative forces are the gravitational forces exerted by the other neighboring galaxies. Let's name all the possible galactic neighbors of the galaxy under observation as Galaxy 1, Galaxy 2, Galaxy 3, and so on till Galaxy n. Let the masses of these galaxies, respectively, be $m_1, m_2, m_3, \ldots, m_n$.

At time t_1 (the same time we used in the previous discussions), let these galaxies be situated at distances $r_{1,t1}, r_{2,t1}, r_{3,t1}, ..., r_{n,t1}$ from the galaxy under observation. The total gravitational potential energy of the galaxy under observation (in the whole system of galaxies) will be:

$$U_{t1} = Gm\left(\frac{m_1}{r_1,t_1} + \frac{m_2}{r_2,t_1} + \frac{m_3}{r_3,t_1} + \cdots + \frac{m_n}{r_n,t_1}\right) \quad (17)$$

Similarly, at a certain time t_2, let the distances be $r_{1,t2}, r_{2,t2}, r_{3,t2}, ..., r_{n,t2}$ from the galaxy under observation. The total gravitational potential energy of the galaxy under observation (in the whole system of galaxies) will be:

$$U_{t2} = Gm\left(\frac{m_1}{r_1,t_2} + \frac{m_2}{r_2,t_2} + \frac{m_3}{r_3,t_2} + \cdots + \frac{m_n}{r_n,t_2}\right) \quad (18)$$

The change in potential energy of the galaxy in this time interval will be:

$$\Delta U = U_{t2} - U_{t1} \quad (19)$$

$$\Delta U = Gm\left(\frac{m_1}{r_1,t_2} - \frac{m_1}{r_1,t_1} + \frac{m2}{r_2,t_2} - \frac{m2}{r_2,t_1} + \frac{m_3}{r_3,t_2} + \frac{m_3}{r_3,t_1} + \cdots + \frac{m_n}{r_n,t_2} - \frac{m_n}{r_n,t_1}\right) \quad (20)$$

The above equation can be shortened to:

$$\Delta U = Gm\sum_{i=1}^{n} m_i\left(\frac{1}{r_i,t_2} - \frac{1}{r_i,t_1}\right) \quad (21)$$

Results

The average total observed force causing the motion of a galaxy is a nonconservative force, which has the combined effect of the non-conservative forces causing peculiar and recessive motion. If we substitute Equation (5) into Equation (16), then we have the total work done by all the non-conservative forces of the galaxy as follows:

$$W_{NC} = mcz\frac{\Delta s}{\Delta t} \quad (22)$$

It is known that the change in potential energy of the galaxy under observation, as given by Equation (21), will be equal to the negative of work done by conservative forces on the galaxy. Hence,

$$W_C = -\Delta U = -Gm\sum_{i=1}^{n} m_i\left(\frac{1}{r_i,t_2} - \frac{1}{r_i,t_1}\right) \quad (23)$$

The work-energy theorem is significant in this context as it relates the total work done on the galaxy to the change in its kinetic energy. According to the theorem:

$$\Delta K = W_{NC} + W_C \quad (24)$$

Where ΔK is the change in kinetic energy, W_{NC} is the work done by nonconservative forces (such as those causing peculiar and recessive motions), and W_C is the work done by conservative forces (gravitational forces from neighboring galaxies).

Conclusion

Finally, by putting Equation (22) and Equation (23) into Equation (24), we get the average change in kinetic energy (from time t_1 to t_2) of a moving galaxy (considering non-relativistic motion):

$$K_{t2} - K_{t1} = mcz\left(\frac{s_2 - s_1}{t_2 - t_1}\right) - Gm\sum_{i=1}^{n} m_i\left(\frac{1}{r_i,t_2} - \frac{1}{r_i,t_1}\right) \quad (25)$$

Here,

- $K_{t2} - K_{t1}$ = Average change in kinetic energy of the galaxy under observation
- m = Mass of the galaxy under observation
- c = Speed of light
- z = Total observed redshift
- $s_2 - s_1$ = Change in distance of the galaxy with respect to the Earth
- $t_2 - t_1$ = The chosen time interval during which the kinetic energy is measured
- G = Universal gravitational constant
- $r_{i,t1}$ = Distance of galaxy under observation from a neighboring galaxy of mass m_i, at initially chosen time t_1
- $r_{i,t2}$ = Distance of galaxy under observation from a neighboring galaxy of mass m_i, at final chosen time t_2.

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