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Density Wave Theory with Co-Rotation May Have a Critical Problem

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Abstract: The Density Wave Theory, which aims to explain the formation of spiral arms in disc galaxies, has been subject to discussion. According to this theory, at the co-rotation circle, the rotational velocity of the density waves or spiral arms matches that of the galactic matter. Consequently, this alignment should impede the formation of new stars within this co-rotation circle, leading to the presence of dark or dim gaps within the spiral arms. Additionally, the theory predicts the occurrence of the front side trail effect in the inner region of the co-rotation circle and the rear side trail effect in the outer region. However, despite these expectations, no such spiral patterns have been observed, prompting the need for revision or reconsideration of the Density Wave Theory.

Keywords: Density Wave Theory; co-rotation; spiral arms; spiral arm dark gaps; trail effects.

Introduction

Spiral galaxies have captivated human curiosity since Lord Rosse's observation of the first spiral galaxy, M51, in 1845, where it was initially described as a spiral nebula [1]. Understanding the mechanisms behind the formation of these stunning and intricate spiral patterns has remained an enduring mystery in the field of astronomy. Over the years, several models have been proposed to shed light on the formation of spiral arms in disk galaxies. These models include the Density Wave Theory (DWT) [2-3], the Swing Amplification theory [4], the Manifold theory [5-9], and the author's own proposal, the Rotating Two Arm Sprinkler Emission (ROTASE) theory [10]. Currently, the DWT stands as the leading model, introducing the concept of a co-rotation circle within disk galaxies. This circle represents a region where the rotational velocity of the spiral arms matches that of the galactic matter. Notably, Mishurov & Zenina [11] and Dias and Lépine [12] independently reported the Sun's location within the co-rotation area of the Milky Way. However, the author has identified a critical issue with this model: the predicted spiral arm pattern does not align with observational evidence. This discrepancy will be thoroughly discussed and analyzed in this paper.

A problem in the Density Wave Theory with co-rotation

According to the DWT, long-lived quasi-stationary density waves exist within disc galaxies, although the origin of these waves remains unclear. These density waves consist of galactic matter, including stars, interstellar dust, and gases. However, the composition of matter within the density waves is constantly changing as galactic components dynamically move in and out. Importantly, the rotation of the density waves and the rotation of the galactic matter are decoupled, meaning they rotate independently of each other.

In the disc of the galaxy beyond the rotation area of the galactic bar, the galactic matter rotates around the galactic center with a flat rotation velocity. Meanwhile, the density waves rotate as a "rigid body" with a constant angular velocity. Within the disc galaxy, a co-rotation circle can be identified, where the density waves and the galactic matter have the same rotation velocity. Inside the co-rotation circle, the galactic matter rotates faster than the density waves, entering the density waves from the rear side and exiting at the front side. Conversely, in the outer region of the co-rotation circle, the galactic matter rotates slower than the density waves, entering from the front side

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and exiting at the rear side of the density waves. The velocity of entering and exiting galactic matter varies and is proportional to the distance from the co-rotation circle.

To illustrate this process, Figure 1 on the left side depicts the entering and exiting dynamics of the galactic matter, adapted from Figure 1 in reference [13]. The red dashed line represents the co-rotation circle, the purple arrows indicate the entering directions, and the white arrows show the exiting directions. The length of the arrows corresponds to the velocity, with longer arrows representing higher velocities. From the end of the galactic bar (marked as A) to the co-rotation circle (marked as B), the entering/exiting velocity gradually decreases to zero. From the co-rotation circle (marked as B) to the galactic edge (marked as D), the velocity gradually increases. ***It is crucial to note that at the co-rotation circle (marked as B to B1), the entering and exiting velocity is zero, indicating no movement of galactic matter in and out. This observation forms the basis of the argument presented in this paper.***

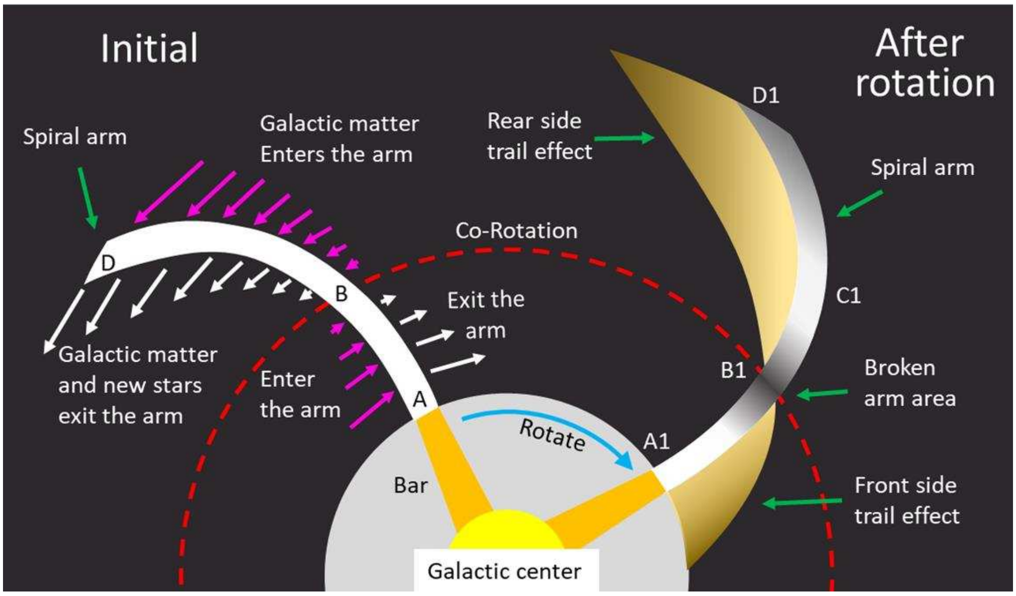

Figure 1. illustration of the density wave theory and the predicted spiral arm.

When galactic matter enters the density waves, it undergoes compression, triggering the formation of stars of various sizes and lifetimes. The number of newly born stars is directly proportional to the amount of galactic matter entering the density waves. These newly formed stars, which are part of the galactic matter, continue to orbit the galaxy's center, subject to the flat differential rotation. The most luminous and massive stars, with short lifetimes, are primarily found within or in close proximity to the density waves or spiral arms where they were formed. As a result, these regions exhibit intense brightness and luminosity, contributing to the visually observed spiral arm structures.

The smaller, longer-lived newborn stars gradually exit the spiral arms, their velocities represented by the white arrows in the diagram. As they age and rotate around the galactic center, their luminosity gradually diminishes due to the gradual depletion of hydrogen. This fading luminosity produces a trail effect after the stars leave the spiral arms. The length of the trail effect is directly related to the exiting velocity, as illustrated in Figure 1 on the right side. This figure predicted the observed spiral pattern after a certain rotation, where point A has rotated to A1, co-rotation point B has rotated to B1, and spiral edge point D has rotated to D1.

In the inner region of the co-rotation circle, the trail effect should be observed at the front side, while in the outer regions, it should be observed at the rear side. At the co-rotation region marked by B, where the galactic matter and the density waves have the same rotation velocity, no galactic matter moves in or out. Therefore, no new stars can form and no trail effect can be observed in this region.

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Even if we assume that new stars were initially formed at the beginning of the density waves at point B, their luminosity would be significantly reduced by the time they reach point B1 due to rotation, resulting in a dark gap at the co-rotation circle of the spiral arm in the B1 area, as depicted in Figure 1 on the right side. The expected change in luminosity along the spiral arm line based on this aspect is illustrated in Figure 2.

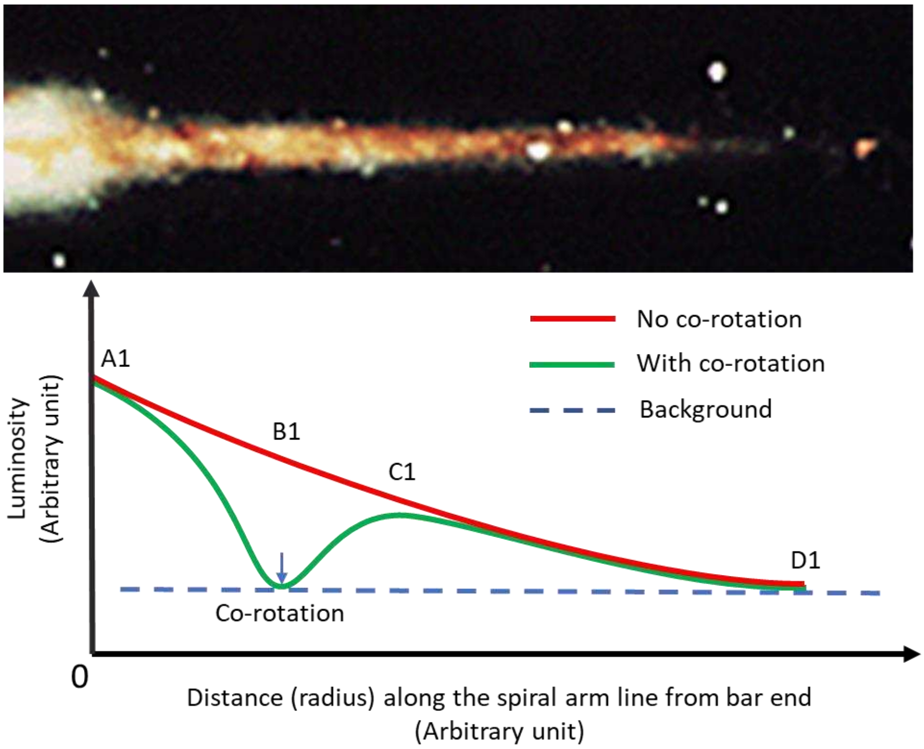

Figure 2. the luminosity of the spiral arms changes with the distance from the bar end. The top image is the half image of side view of Milky Way galaxy showing the thickness of galaxy decreases with the galactic radius.

The distribution of galactic matter in a spiral galaxy resembles a thick and dense disc, with the center being the thickest and most dense. As we move towards the edge of the galaxy, the thickness and density of galactic matter gradually decrease. This can be observed in the half side-view image of the Milky Way shown on the top of the Figure 2.

In Figure 2, the red line represents the luminosity changes of the spiral arms with respect to the distance from the end of the galactic bar in the absence of a co-rotation circle. The green line represents the luminosity changes with respect to the distance from the end of the galactic bar when a co-rotation circle is present. The blue dashed line represents the luminosity of the galactic background or the area between the spiral arms.

Without the presence of a co-rotation circle, the luminosity smoothly decreases as we move away from the end of the galactic bar. However, the situation becomes more complex when a co-rotation circle exists in the galaxy, as depicted by the green line in Figure 2. At this special circle, where the rotation velocities of the spiral arms and the galactic matter are equal, no galactic matter moves in or out of the spiral arms. Consequently, no new stars are formed, and the luminosity should be the same as the background or the area between the spiral arms.

Therefore, the luminosity of the inner part of the spiral arms should gradually decrease from the bar end (A1) to the co-rotation circle (B1) due to the gradual decrease in the amount of entering galactic matter, ultimately resulting in zero newly born stars at B1. Beyond the co-rotation circle, the velocity of galactic matter moving in and out of the spiral arms increases with the radius. This leads to an increase in the amount of galactic matter entering the spiral arms and, consequently, an increase in the number of newly born stars. As a result, the luminosity of the spiral arms gradually increases

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until reaching the peak point (C1), after which it decreases. This decline occurs because the thickness and density of the galactic matter gradually decrease, causing the amount of entering galactic matter to decrease despite the increasing entering velocity. The luminosity gradually decreases to the background level at the galactic edge (D1).

It is important to note that the spiral pattern illustrated in Figure 1 on the right side has not been observed to date, based on the author's limited knowledge. To further illustrate this point, the galaxy J101652.52-004630.0 (referred to as J101652 for brevity) is presented as an example in Figure 3. The left side of Figure 3 shows the original image of the galaxy, exhibiting a grand design pattern with luminous, loosely open, clean, and well-constructed spiral arms characterized by perfect central symmetry. This galaxy serves as an ideal testing model for any theory concerning spiral arm formation. On the right side of Figure 3, the spiral arm pattern is fitted using the galactic spiral equations developed from the ROTASE model, with the parameter $\varrho = 2.5$ and Euler rotation (-14, 15, 0).

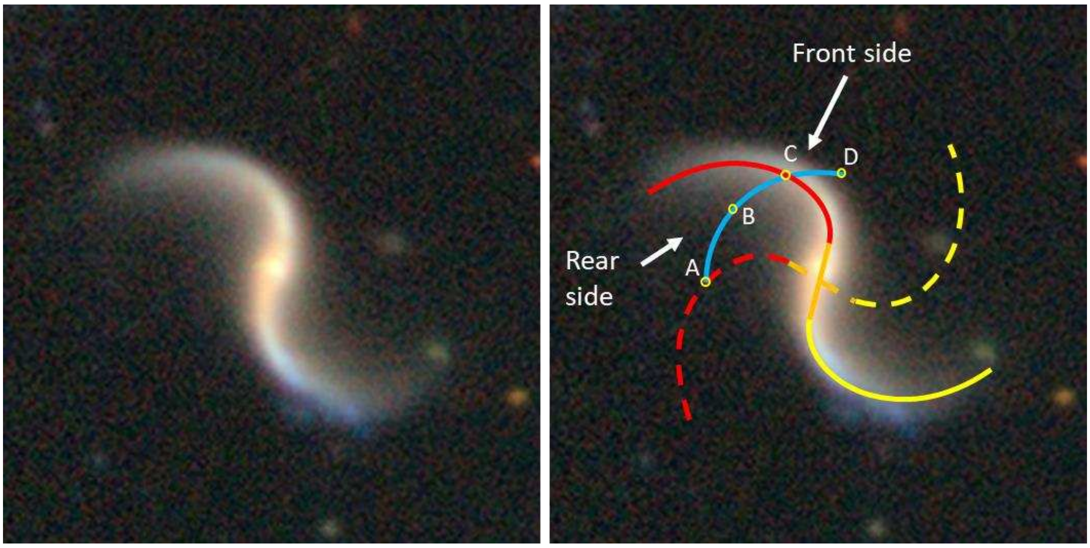

Figure 3. Galaxy J101652, left is the original image; right, the pattern fitting for current (solid line) and 75-degree bar rotation time ago (dashed line) by ROTASE model.

In Figure 3 on the right side, the solid red and yellow lines represent the fitted lines for the spiral arms, while the orange line represents the galactic bar. The dashed red and yellow lines correspond to the fitted lines of the spiral arms rotated counterclockwise by 75 degrees, showcasing the possible past positions of the spiral arms millions of years ago. The blue arc denotes the circle line representing the rotation of galactic matter around the galactic center.

Observing the spiral arms, the front side of rotation appears clean with a sharp edge, and the luminosity decreases rapidly. However, the rear side exhibits a strong trail effect, characterized by a gradual decrease in luminosity. The luminosity of the spiral arm represented by the red line has been extracted previously [10] and is displayed in Figure 4. It shows a smooth decrease along the spiral arm, without any dips or flattened patterns as predicted by the green line in Figure 2 based on the DWT.

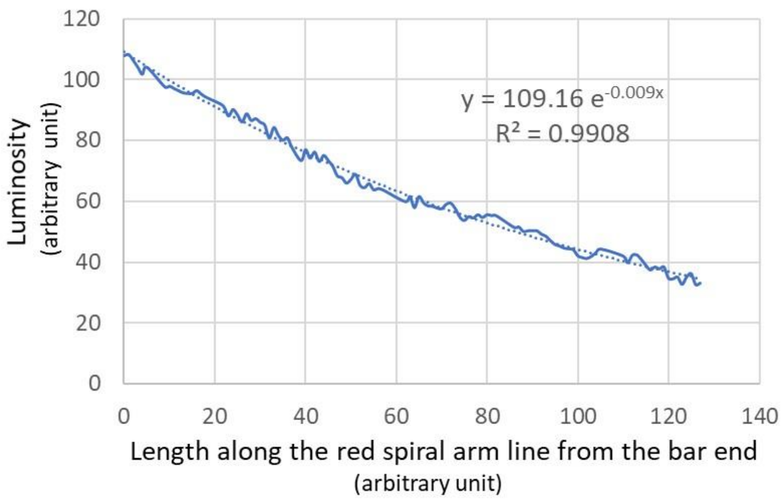

Figure 4. The surface luminosity changes along the spiral arm line in galaxy J101652.

In Figure 3 on the right side, the blue arc represents the rotation line of the galactic matter at that particular radius. It also serves as the trajectory along which newly born stars formed inside the spiral arm, located at point A and C, when they exit the arm. As these newborn stars exit, they generate a luminosity gradient along this trajectory, resulting in a slow decrease in luminosity.

On the other hand, newborn stars do not exit from the front side of the spiral arm. Therefore, no trail effect should be observed at the front side, and the luminosity within the width of the spiral arm should decrease quickly.

The luminosity along the blue arc has been extracted previously [10] and is displayed in Figure 5. The blue line in Figure 5 represents the luminosity change with distance from the maximum point C (inside the spiral arm) to the background level at point A on the rear side. The orange line in Figure 5 represents the luminosity change with distance from the maximum point C to the background level at point D on the front side. The pattern displayed in Figure 5 corresponds to the expected luminosity changes when the newborn stars exit from the rear side of the spiral arms.

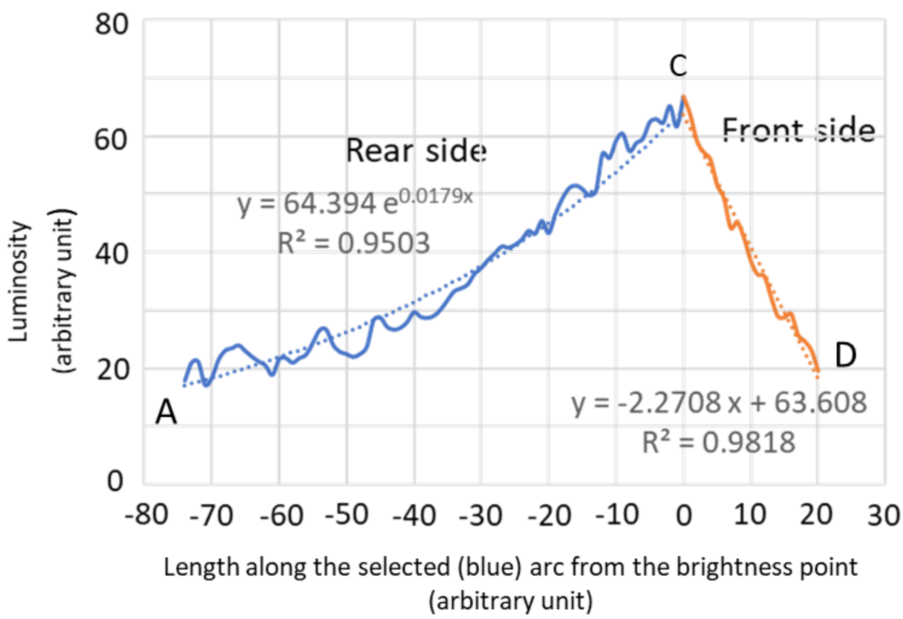

Figure 5. the surface luminosity changes along the selected blue arc in the Figure 3 right.

The time required for the 75-degrees rotation of the spiral arm located at dashed line position in the past in Figure 3 to the its current position represented with the solid lines (i.e., rotate from A to C) can be roughly viewed as the lifetimes of all new born stars as whole in the entire spiral arms, therefore, in this time span, the luminosity of the all new born stars formed at the moment inside of the spiral arms will decrease to the background level. If we assume that the density waves were just fresh established at the dashed line location in Figure 3 right, although it takes great amount of time to develop the whole density waves and the spiral arms may have been formed long time ago before the dashed line location. For simplicity, let's say, the blue arc is the co-rotation circle, all new born stars at the co-rotation circle at point A will rotate with the same velocity as the density waves/spiral arms. When the spiral arms rotate to their current location shown in solid red and yellow lines, the stars and galactic matter at the point C are the same stars and galactic matter at point A, all those stars at the point C be dead, i.e., their luminosity will be the background level, a dark gap should occur at the point C. However, such dark gaps do not occur in this galaxy which means no co-rotation circle in this galaxy, and furthermore, no such dark gaps observed in all available galaxies so far. Therefore, it can be concluded that the DWT is not applicable in this case.

The galaxy J101652 shows only rear side trail effect which clearly indicates that the new born stars formed inside of spiral arms exit at the rear side of the arms and the rotation velocity of the entire spiral arms is faster than the rotation velocity of the galactic matter. If the formation of the Milky Way follows Density Wave Theory, then, if we take a picture of the whole Milky Way from above the galactic disc, we should see a dim ring near the Sun's circulation orbit.

Conclusion

The existing images of spiral galaxies do not exhibit the anticipated dark gaps and trail effects in the spiral arms as predicted by the Density Wave Theory with co-rotation. Consequently, it becomes necessary to revise or reconsider this theory.

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