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Morphological analysis of the spiral structure of interacting galaxies

Análisis morfológico de la estructura espiral de galaxias en interacción

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ABSTRACT

This research focused on the study of multiple spiral structures in galaxies undergoing various types of interactions, with a specific emphasis on galaxies NGC 4254 and NGC 5985. Using the two-dimensional Fourier transform, the study provides insights into the complex morphological features of these galaxies. NGC 4254, classified as SA(s)c, reveals prominent $m = 1$ and $m = 2$ modes in the Fourier analysis, indicating continuous spiral structures extending from the nucleus to the outer regions. In the case of NGC 5985, classified as SAB(r)b, the dominant Fourier modes are $m = 1$ and $m = 2$. The study measured the length of the bar to be 3.9 kpc and a ring with a radius of 10.9 kpc. The presence of discontinuous spiral structures is attributed to numerous bifurcations in the spiral arms. In summary, this research provides valuable insights into the nature of multiple spiral structures in interacting galaxies. The two-dimensional Fourier transform proves to be a valuable tool for uncovering morphological details, offering key insights into the evolutionary histories and environmental influences of NGC 4254 and NGC 5985.

Keywords: Morphology, spiral galaxies, spiral structure, interaction, Fourier transform.

RESUMEN

Esta investigacion se centró en el estudio de las estructuras espirales multiples en galaxias que experimentan diversos tipos de interacciones, con un enfoque específico en las galaxias NGC 4254 y NGC 5985. Utilizando la transformada de Fourier bidimensional, la investigación proporciona infomacion sobre las complejas características morfológicas de estas galaxias. NGC 4254, clasificada como SA(s)c, revela modos $m = 1$ y $m = 2$ prominentes en el análisis de Fourier, lo que indica estructuras espirales continuas que se extienden desde el núcleo hasta las regiones exteriores. En el caso de NGC 5985, clasificada como SAB(r)b, los modos de Fourier dominantes son $m = 1$ y $m = 2$. El estudio midió la longitud de la barra hasta los 3.9 kpc y un anillo con un radio de 10.9 kpc. La presencia de estructuras espirales discontinuas, atribuidas a las numerosas bifurcaciones en los brazos espirales, En resumen, esta investigación arroja valiosa informacion sobre la naturaleza de las estructuras espirales múltiples en galaxias que estan en interacción. La transformada de Fourier bidimensional se presenta como una herramienta valiosa para descubrir detalles morfológicos, proporcionando información clave sobre las historias evolutivas e influencias ambientales de NGC 4254 y NGC 5985.

Palabras Clave: Morfologia, galaxias espirales, estructura espiral, interacción, transforada de Fourier.

1 INTRODUCTION

In the universe, it is possible to observe clusters and groups of galaxies with different morphological types. Among these structures, spiral galaxies have been of interest due to the effects of interactions on their morphology and dynamics. These galaxies present an opportunity to understand evolutionary effects in the universe.

Spiral galaxies are the most frequently observed type of galaxy. They are interesting to study because their spiral structure exhibits various forms and serves as a starting point for studying galaxy evolution. The presence of spiral arms in disk galaxies is usually associated with their gas content and star formation. The presence of a spiral structure is important because it helps us understand star formation in the local universe. Galaxy interactions are a dynamic phenomenon that impacts their morphologies [1], during interactions, gravitational forces can create galactic tides that distort spiral patterns, generating unique and asymmetrical shapes. Moreover, these interactions can trigger bursts of star formation, enriching galaxies with young and massive stars.

Since there are more galaxies in groups than isolated ones in the universe, it is crucial to understand that morphological properties can vary depending on the type of interaction and the type of galaxy involved. This implies that the interaction between a spiral galaxy and an elliptical galaxy differs from the interaction between two spiral galaxies. To support the proposed hypothesis, it is essential to have images of several interacting spiral galaxies, regardless of their morphological type, and compare them with images of a set of isolated spiral galaxies. This will help establish morphological differences and validate our premise.

The morphological study of interacting spiral galaxies is a useful mechanism for identifying properties associated with specific morphological patterns in each galaxy, such as tidal bridges, tidal tails, and star-forming rings. Additionally, this research can help distinguish different stages of interaction, from initial approaches to close encounters, or the point of interaction, and the long-term consequences of such interactions on the evolution of the galaxies involved.

On the other hand, establishing a theory to explain the formation of the spiral structure remains a challenge because there is no model capable of fitting the diversity of appearances of spiral structures that can be observed. Initially, studies focused on the idea that spiral structure was generated by density waves in their disks [2].

In this work, an analysis of spiral galaxies under some form of interaction is performed, with a focus on their morphologies and the underlying physical processes. This analysis is carried out using images from the Sloan Digital Sky Survey project, which was chosen for its excellent image resolution. Specifically, we focus on studying images in the G band because the spiral structure is better resolved in this band.

2 METHODOLOGY

When working with galaxy images for morphological studies, it is necessary to perform a cleaning process due to the noise they contain. This noise can originate from distant objects (stars, gas clouds, etc.) and the physical conditions of the capturing instruments (telescopes). These instruments' sensitivity can lead to additional light contributions in the images, attenuation due to photometric reactions in the atmosphere, and the presence of light from nearby objects that affect the captures.

The image cleaning is carried out in **IRAF** (Image Reduction and Analysis Facility), which provides a comprehensive set of tools for the analysis and processing of astronomical data, including images. The first step to enhance galaxy images is to remove field stars that interfere with the analysis. This is done using the **IMEDIT** routine of **IRAF**. The second step to improve the images is related to the inclination of the observed galaxy. Galaxies are randomly inclined in our line of sight. The work of [3] calculates the ratio of semimajor axes for 23.000 galaxies. Knowing this value allows deprojecting the image, turning the galaxy into a "Face-on" orientation, regardless of its inclination angle. When this process is performed, the Fourier method can be implemented to identify the morphological properties of the spiral structure.

The Fourier transform has been widely used for morphological analysis of spiral galaxies [4, 5, 6, 7]. This method is very useful for identifying the number of arms a galaxy may have, their distribution in the disk, the extent of the bar, and the degree of winding, among other characteristics. The Fourier analysis is implemented using the **2DFFT** (Two-Dimensional Fast Fourier Transform) program, and for it to work correctly, the images must be noise-free and deprojected, as explained earlier. Additionally, this method can provide a radial density function $S_m(r)$ that allows for obtaining a radial intensity distribution for any component. By analyzing this function, the dominant position of a particular component in the galaxy can be determined.

On the other hand, spiral galaxies exhibit different brightness values between the core and the outer regions. The brightness in the central region is much higher than in the regions where the spiral structure is located. This can result in overexposure in the bulge of the galaxy, causing the details of the spiral structure to be lost. These regions are vital for determining the extent of the arms, so an additional process is needed to correct this brightness difference. This process involves eliminating the core brightness.

It has been observed that the nuclei of spiral galaxies have a surface brightness similar in shape to that of an elliptical galaxy [8]. This brightness is described by $\log(\Sigma/\Sigma_\circ) \propto r^{-1/4}$. In the regions outside the bulge, brightness decreases exponentially as $\Sigma(r) = \Sigma_\circ \exp(-r/r_s)$. The value of $\Sigma_\circ$ corresponds to the surface brightness of the center, and r_s is a value known as the scale length. The definition of this value is associated with the distance where the light decreases as $1/e$ [8]. The spiral structure is enhanced by removing the azimuthal radial profile, which is explained as the average brightness over all azimuthal angles at each radius. Each radial position is normalized to a constant root-mean-square value `RMS`, significantly improving the qualities in the core and spiral structure regions. The average azimuthal radial profile is determined from the following relationship:

$$\bar{I}_\theta = \frac{\Sigma_\theta I(r,\theta)}{N}, \tag{1}$$

$I(r,\theta)$ are the brightness intensity values at each pixel (r,θ), and N is the number of pixels contributing to the mean calculation at each radius. In order to remove the average azimuthal radial profile, it is necessary to subtract the mean intensity value from the intensity values at each radius in the following way:

$$I_{pr}(r,\theta) = I(r,\theta) - \bar{I}_\theta(r). \tag{2}$$

2.1 General features and analysis of the images.

The interacting galaxies studied to identify morphological features are NGC 4254 and NGC 5985. These galaxies were selected because of their unique and visually striking morphology, and because it is possible to visually identify morphological patterns that have been affected by several gravitational interaction processes forming tidal tails.

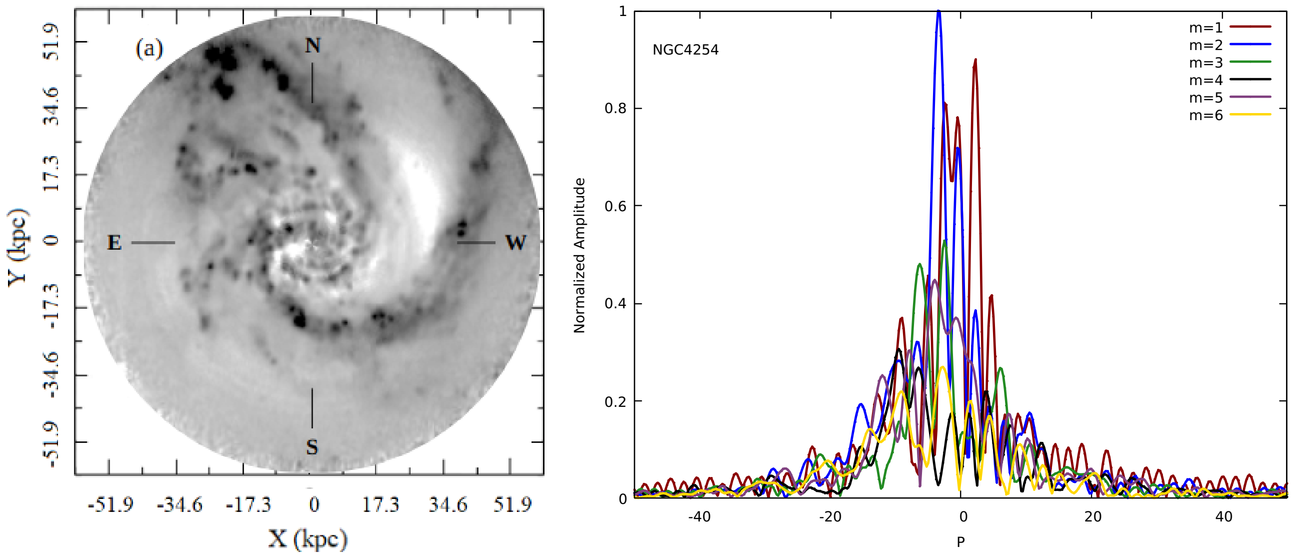

Fig. 1. Spiral galaxy NGC 4254 in the g band (inverted color). The image on the left is the result of noise cleaning, deprojection, core extraction, and spiral structure enhancement. The image on the right corresponds to the Fourier spectra.

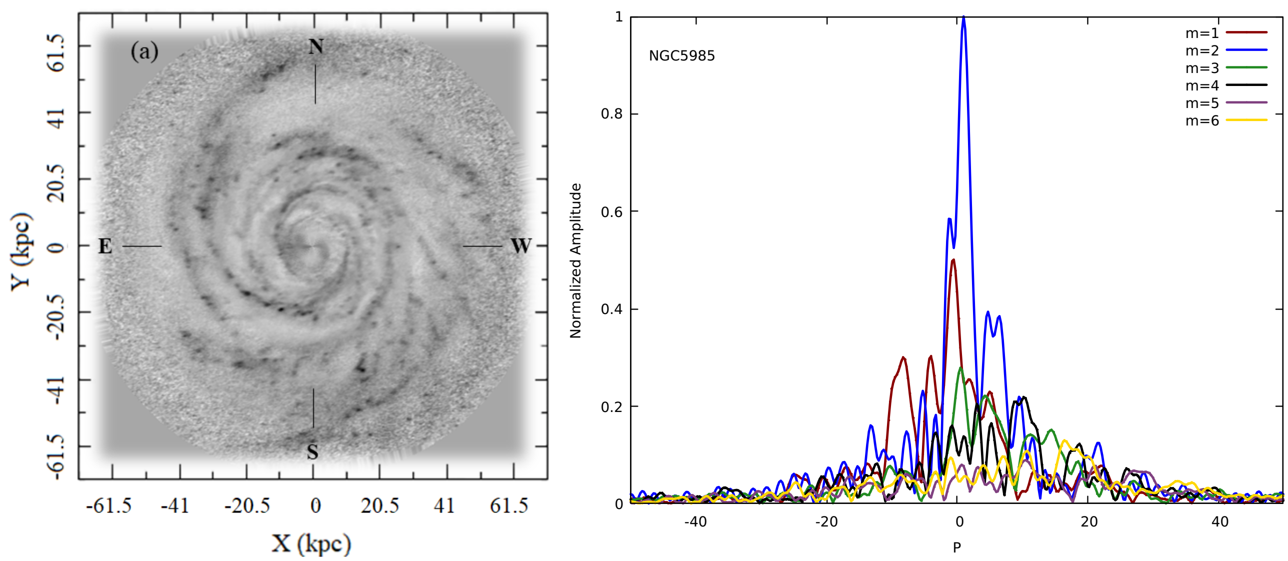

Fig. 2. Spiral galaxy NGC 5985 in the g band (inverted color). The image on the left is the result of noise cleaning, deprojection, core extraction, and spiral structure enhancement. The image on the right corresponds to the Fourier spectra.

Galaxy NGC 4254, also known as M99 (Messier 99), is located in the Coma Berenices constellation. Its coordinates are 12h 18m 49s (right ascension) and +14d 25m 9s (declination). Its morphological type is SAc [9], classifying it as a spiral galaxy with open arms, a central bar, and a ringed structure. Figure 1 presents the deprojected, noise-free image of galaxy NGC 4254 along with the enhancement of the spiral structure and the Fourier spectra. The Fourier transform shows that the galaxy has two dominant modes, which are $m = 1$ and $m = 2$. Therefore, it is necessary to observe the behavior of these modes through density functions.

On the other hand, among the most important characteristics of spiral galaxy NGC 5985 is its gravitational connection with another pair of galaxies, known as the Draco Triplet, and under certain criteria, this triplet is considered gravitationally isolated [10]. Its coordinates are 15h 39m 37.09s (right ascension) and +59h 19m 55.0s (declination), and its morphological type is SAB(r)b [9], classifying it as an intermediate spiral with a ring. Figure 2 presents the images of galaxy NGC 5985 after the normalization process and the calculation of the Fourier spectra. In the enhancement applied to the image, it is evident that the galaxy exhibits bifurcations and discontinuities in the spiral arms of the galactic disk. It was also identified that the bar is not dominant and terminates at approximately 3.9 kpc. Initially, the segments of the spiral arms are indicated by the Fourier spectra (figure 2), showing that the dominant mode is $m = 2$, and the second most relevant component is $m = 1$.

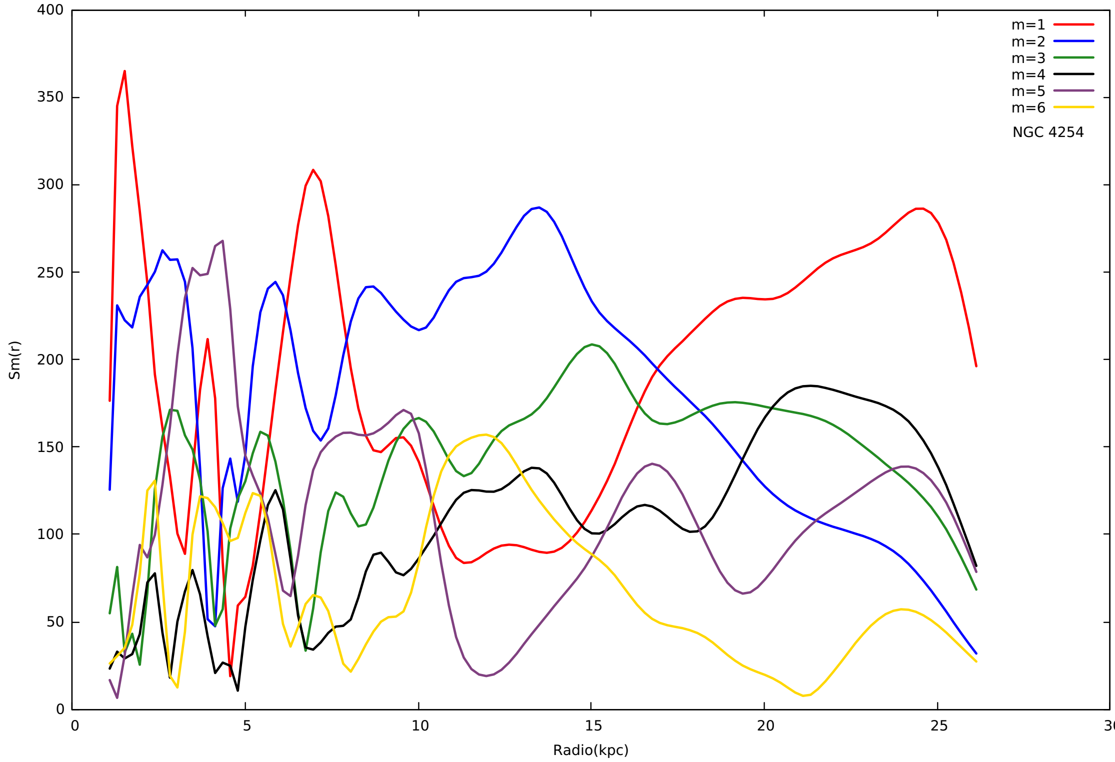

Fig. 3. Density functions of spiral galaxy NGC 4254 obtained from the Fourier spectra.

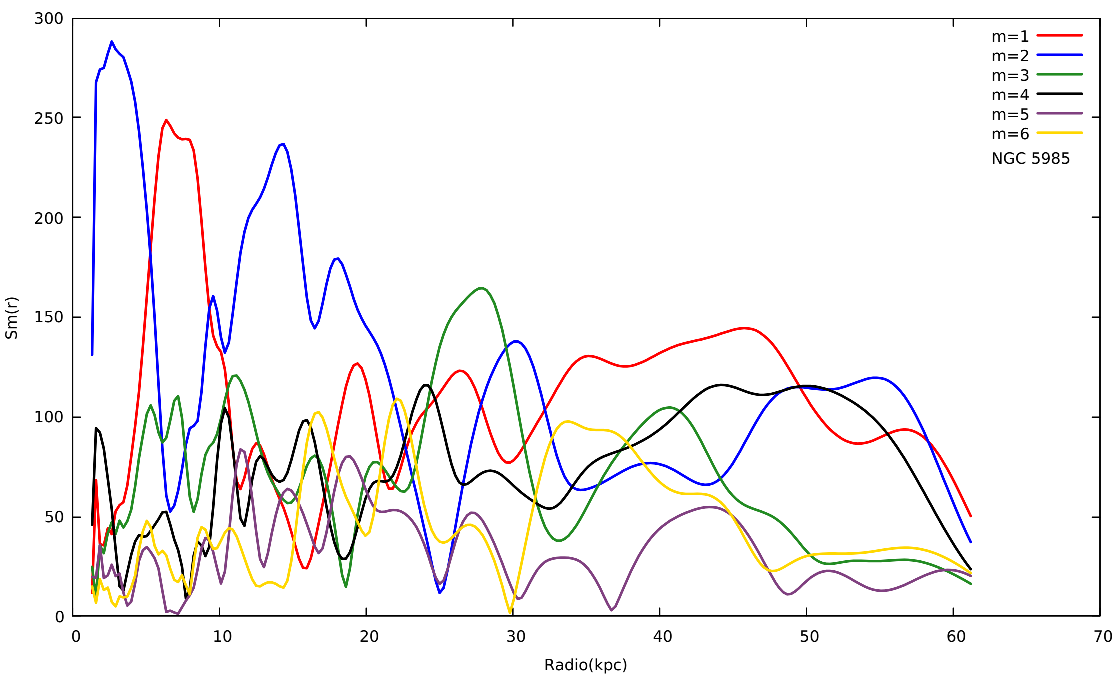

Fig. 4. Density functions of spiral galaxy NGC 5985 obtained from the Fourier spectra.

Density Functions

The density function of galaxy NGC 4254 shown in figure 3 show that the most important component is $m = 1$, indicating that this galaxy has a more extensive spiral arm. In the intermediate region, from approximately ~ 9.5 to approximately ~ 16.1 kpc, $m = 2$ is the mode of greater relevance, revealing the presence of a two-armed spiral symmetry in this region, similar to a grand design galaxy. This mode becomes less relevant at around ~ 17 kpc, as the main mode, $m = 1$, regains dominance, indicating the presence of the more extensive arm from this region onward.

The density functions of galaxy NGC 5985, shown in figure 4, reveal that the modes $m = 1$ and $m = 2$ are dominant up to approximately 23 kpc. From this point, the intensity of mode $m = 2$ decreases, allowing modes $m = 6$ and, especially, $m = 4$ to dominate in a relatively narrow region of 24 kpc. As we move away from this region, component $m = 3$ starts to become relevant up to about 30 kpc. In the outer regions, modes $m = 1$ and $m = 2$ oscillate while maintaining their significance up to the farthest point. This feature suggests that the galaxy does not exhibit multiple arms in both the outer and inner regions.

In NGC 5985, it is possible to observe symmetry in the central region up to approximately 10 kpc, extending in the north and south directions of the disk. The presence of an outer arm in the southwestern part of the nuclear region is also evident, along with segmentations of the spiral structure in the southeast direction. Furthermore, it is demonstrated that the $m = 1$ component is the most important due to the detection of a possible more extensive spiral arm.

3 CONCLUSIONS.

In this work, it was possible to identify important morphological features present in the galaxies NGC 4254 and NGC 5985 through the use of the Fourier transform. When analyzing the results of the two-dimensional Fourier transform for the spiral galaxy NGC 4254, which is morphologically classified as SA(s)c in the Hubble scheme, it becomes evident that in this morphological analysis conducted in the G-band, the most significant components are $m = 1$ and $m = 2$. It is observed that the spiral structure exhibits continuity from the galaxy's nucleus to its outer regions in both components. In the nuclear region for $m = 2$, two overlapping structures are apparent, which, at first glance, appear to be perpendicular and emerge from the galaxy's nucleus. In the G-band image, the structure towards the east is almost nonexistent. On the other hand, in the $m = 1$ component, a single-armed spiral structure emerging from the nucleus is evident. For $m = 2$, the spiral arms extend from the galaxy's nucleus to the outer region but are interrupted at approximately a radius of 4 kpc. Conversely, for $m = 1$, the one-armed spiral structure is observed in the density functions as a less intense component compared to $m = 2$, but from 9 kpc onward, it becomes more significant than the two-armed component.

Analyzing the results of galaxy NGC 5985, which has a morphological classification of SAB(r)b, in addition to the Fourier spectra, it becomes evident that the dominant modes in the galaxy are $m = 1$ and $m = 2$. The presence of a bar with an extension of 3.9 kpc was measured, as well as the radius of the ring at 10.9 kpc. Discontinuous spiral structures were also measured due to the bifurcations present in the galaxy. It was observed that in the outer regions, a mode $m = 3$ is relevant, along with discontinuous structures known as filaments.

It is interesting to note that arm bifurcations are present in both galaxies we analyzed, and their most dominant components are $m = 1$ and $m = 2$. From the density functions, it is evident that galaxy NGC 4254 likely experienced a rapid interaction at some point in its life, which would explain its strong $m = 1$ component. As for NGC 5985, its numerous discontinuities and bifurcations in the spiral arms can be attributed to being in an interactive environment.

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