Galactic Morphology

Victoria Song

Although the scientific field of astronomy has been around since ancient times, galactic morphology is a newer area of study, emerging as a centerpiece of the astronomical community during the 1900s. Galactic morphology studies the origins and evolution of galaxies in the Hubble Sequence with a particular emphasis on spiral galaxies since they are the most pervasive type in the universe. Several theories on spiral structure have been proposed, and this paper aims to summarize another approach. Scientists in the past have treated spiral arms as semi-permanent wave patterns on the galactic disk, but with the discovery of giant molecular clouds, gravitational hydrodynamics are likely a key piece of the puzzle.

1. Introduction

The study of galactic morphology is at the frontier of modern astronomy. In the Hubble sequence, galaxies are classified into four main categories based on shape: elliptical, spiral, lenticular, and irregular. Spiral galaxies, making up about 60% of all the galaxies in the universe, are not only by far the most common type but also the least understood in the Hubble sequence. During the 1920s, Edwin Hubble resolved celestial bodies outside the Milky Way into individual spiral galaxies, and scientists sought to understand the origins and morphologies of their characteristic arms ever since. Toomre compiled an assortment of spiral morphology theories in his 1977 review paper [1]. Most notably, Lindblad devoted a great portion of his career in attempt to explain such phenomena. From the 1920s to the 1960s, Lindblad devised a theory on the role of stellar dispersion orbitals in a spiral galaxy's structure. Because most galaxies are too isolated to influence their neighbors, Lindblad believed that spiral structure was driven by internal dynamics rather than external forces. In particular, he believed that stellar orbits, when their smaller epicycles were superimposed onto the rotation of the galaxy, would produce the stunning spiral pattern observations we see today [2]. Epicycles in a galaxy are analogous to higher harmonics superimposed on a wave. They describe smaller orbits whose centers rotate about a larger circumference. The epicyclic frequency of each star would coincide with other stars such that their orbits would show compression, thus forming an arm pattern along the galactic disk's denser ridges. Furthermore, Lindblad noticed that the angular velocity of the spiral pattern can be described as a function of distance from the galactic center:

$$\Omega_p(r) = \Omega(r) - \kappa(r)/m \qquad (1)$$

Where Ω_p is pattern's angular velocity, Ω is the angular velocity of the star's main orbit, κ is the star's epicyclic angular velocity, and m is the epicyclic wave number [3]. (m describes the number of arms the galaxy would have.) The minus sign in the function indicates that pattern speed can be nearly constant for certain epicyclic frequencies. To maintain a constant pattern speed, the epicyclic number needs to be an integer value. For example, $m = 2$ would signify bisymmetric arms. From our perspective, we would see the stars in the galaxy act as one cohesive body. It is essential that the pattern speed remains constant, or the spiral pattern would disperse too quickly [4].

This is best exemplified by Kalnajs, who formulated spiral structure through the superimposition of kinematic rings, as shown in Figure 1.

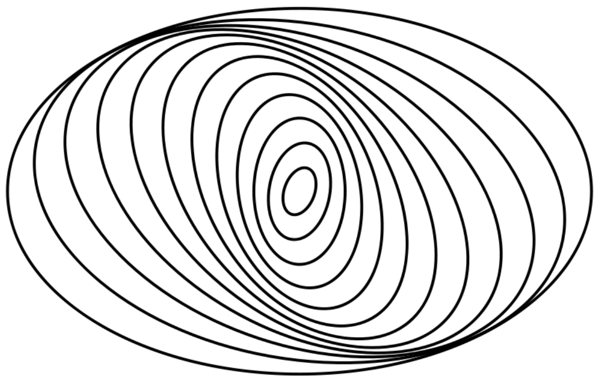

Figure 1. A diagram of Kalnajs's kinematic rings. Kinematic rings represent the trajectory of individual stars around the center. Adapted from [5].

For this shape to be maintained, the ellipses need to rotate at more or less equal speeds of $\Omega(r) - \kappa(r)/2$, at the same rate, and without any change in diameter [6]. Under this condition, a set of stable stellar orbits would be generated. These orbits would follow solid-body rotation on the plane of the disk galaxy. Thus, even though the stellar disk is differentially rotating, the kinematic rings will create a solidly rotating spiral pattern. Yet, even this mechanism would not guarantee a spiral pattern. Kalnajs made the clever assumption that the semi-major axis of each stellar orbit would align in such a way to form spiral arms from denser regions of the disk [7]. The flaw in Kalnajs's theory is that it is too perfect to be true. With the self-gravity of other stars, it is improbable that each individual star could move perfectly in line with an elliptical path to form spiral arms [8].

A dramatic improvement to Kalnajs's kinematic rings came in 1964, when Lin and Shu proposed the Density Wave Theory. The Density Wave Theory appeared to resolve the long-standing Winding Problem. Because galaxies are observed to be differentially rotating (see Rubin's flat rotation curve in Figure 2), stars closer to the center would complete orbits faster than stars on the outer rims of the galaxy. As seen in Figure 3, the galaxy's spiral arms would then wind up and lose its striking pattern.

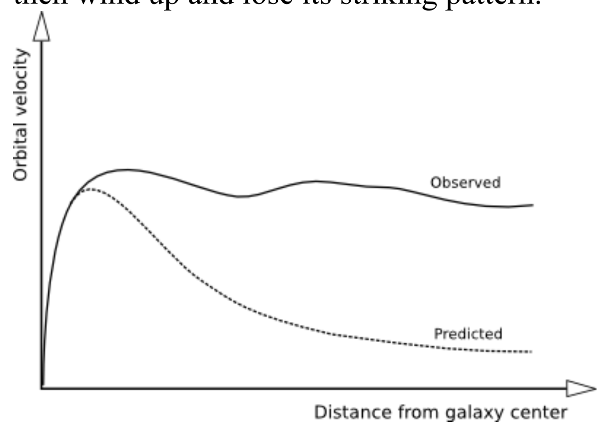

Figure 2. Rubin's flat rotation curve. Keplerian motion predicts that orbital velocity would decay as radius increases, but this graph clearly shows differential rotation. The linear speed at each point is constant. Thus, angular velocity is inversely proportion to radius. Adapted from [9].

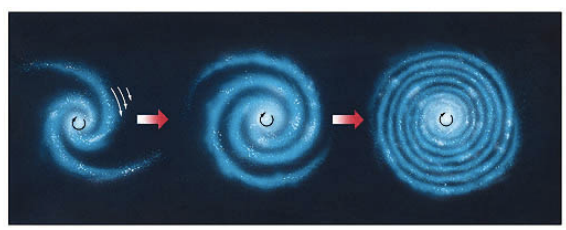

Figure 3. The Winding Problem visualized. The lagging of objects farther from the center due to differential rotation causes the spiral to wind up tighter and eventually disappear, thus earning its name as the Winding Problem. Adapted from [10].

Lin and Shu approached the Winding Problem differently from Kalnajs and Lindblad. Instead of basing their theory on the motion of stellar orbits, they focused on the behavior of wave patterns on the galactic disk. Once these wave patterns are generated, they can be maintained semipermanently due to gravity-driven wave mechanics. In his review paper, Toomre pointed out that "Lin and Shu—with their QSSS (Quasi-Stationary Spiral Structure) hypothesis that a wavelike spiral force field somehow exists and keeps on rotating—jumped deliberately into the *middle* of a difficult problem [11]." In other words, Lin and Shu's density waves lacked origin and were likely unstable. Yet, even with these shortcomings, the Density Wave Theory is the most commonly accepted explanation for spiral structure in the astronomy community.

2. Density Wave Theory

Density Wave Theory rests on the premise that gravitational instabilities govern galactic structure. Spiral arms are assumed to be wave patterns created by denser concentrations of matter at special locations. The spiral pattern remains either stationary or at least quasi-stationary in a frame of reference rotating around the center of the galaxy at a proper angular speed (possibly zero) [12]. Lin and Shu treat the galactic disk as an ideal model, with all the mass of stars and interstellar gases all laying on a 2D disk and the surface density equal to the projected density on the galactic plane [13].

While Lindblad's theory concerns individual stellar orbits, the interaction of stars over the galactic disk as a whole is directly considered in Lin and Shu's theory through the use of a mass distribution function. The galactic system is described with a set of differential equations:

$$\mu_t + \frac{1}{r}[(r\mu u)_r + (\mu v)_\theta] = 0 \tag{2a}$$

$$u_t + uu_r + \frac{vu_\theta}{r} - \frac{v^2}{r} = \phi_r \tag{2b}$$

$$v_t + uv_r + \frac{vv_\theta}{r} + \frac{uv}{r} = \frac{\phi_\theta}{r} \tag{2c}$$

$$\phi_{rr} + \frac{\phi_r}{r} + \frac{\phi_{\theta\theta}}{r^2} + \phi_{zz} = -4\pi G\mu(r,\theta)\delta(z) \tag{2d}$$

Lin and Shu used the system of differential equations 2a-2b to describe the velocity field of the galactic disk in relation to mass density, where μ represents mass density, u and v are velocities, and ϕ is the gravity potential [14].

Here, Lin and Shu provide the solution in spiral form using a cylindrical system of coordinates [15]:

$$\mu'^{(r,\theta,t)} = S(r)e^{-\omega_i t}\cos\left[\omega_r t - n\theta + \Phi(r)\right] \tag{3}$$

$$\theta = \frac{1}{n}[\Phi(r) + const.] \tag{4}$$

Equation 4 shows a spiral with n arms. If such a solution exists and persists, axis-symmetric spiral patterns would indeed be maintained on the galactic plane. In this scenario, stars and gas are deemed to enter and exit spiral arms as cars going in and out of a traffic jam in a highway. Again, this theory does not address the generation of spiral arms, only their possibility of existence.

3. Giant Molecular Clouds

To understand galactic morphology, it is necessary to study the galactic system by its parts. Thus, analyzing the properties and behaviors of giant molecular clouds (GMCs) become of critical importance since they are the entities that fuel star formation. Molecular clouds of diatomic hydrogen gas, which have a density of 100 molecules/cm^3, make up the densest parts of interstellar media (ISM). (In comparison, neutral atomic hydrogen has a density of 100 times less that value in interstellar media.) GMCs were discovered in the 1970s, first in the Milky Way and then in nearby galaxies such as M51 and M33. Because GMCs were not discovered until recently, earlier theories could not have benefitted from this knowledge.

In the paper written by Koda et. al., observations of GMCs were obtained using CARMA, an interferometer whose cutting-edge design guarantees the highest-fidelity imaging ever achieved at millimeter wavelengths. CARMA detects GMCs at 4σ significance. Its angular resolution corresponds of 4” corresponds with 160 pc wide molecular clouds, which is high enough to isolate but not resolve GMCs since the typical GMC separation is about 100 pc (Scoville & Sanders 1987; Koda et al. 2006) [16]. The distribution of CO(J = 1-0) emission was mapped over the entirety of the M51 disk, as shown in Figure 4. The emission line of CO(J=1-0) refers to the electron jumping from an excited energy level of J=1 to ground state by emitting photons, where J represents the azimuthal orbital number. The regions of M51 that contain carbon monoxide should also contain molecular hydrogen, given that the temperature, pressure, and other necessary conditions are similar for the formation of different types of molecular gases. From an empirical point of view, carbon monoxide is easier to detect than diatomic hydrogen because it is a polar molecule, which means it emits radio waves for telescopes to detect.

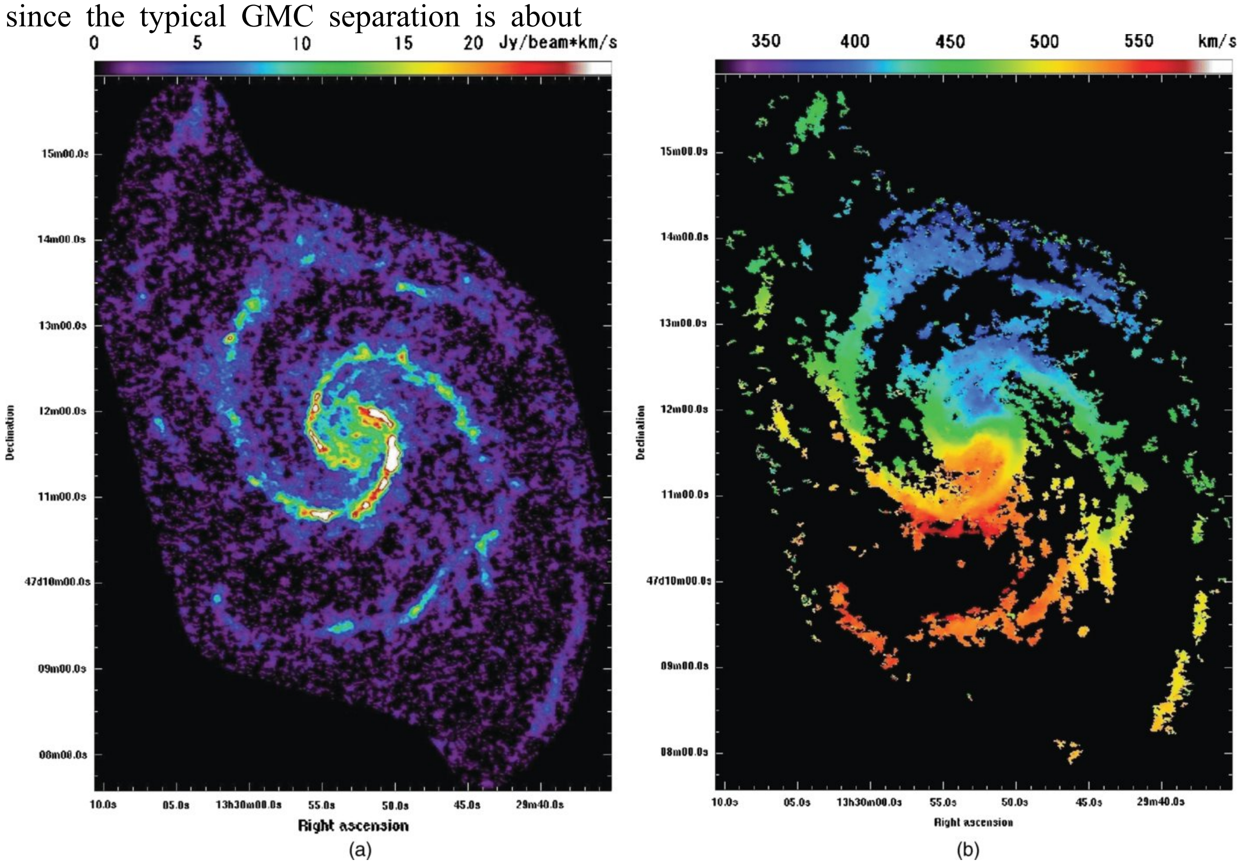

*Figure 4. (a) This is an integrated intensity map of CO(J=1-0) on the galactic disk. (b) The CO velocity field. For both graphs, the x-axis represents Right ascension of the galaxy in Jy/beam*km/s, and the y-axis represents declination in s. Adapted from [17].*

The map of carbon dioxide is significant because it shows that spiral arms are made primarily of GMCs [18]. In other words, spiral arms appear to be material structures, not compression patterns described by Density Wave Theory.

Another observation by Koda et. al. also seems to be at odds with the Density Wave Theory: GMCs were not only located on spiral arms, but also observed to be in the inter-arm regions of M51. CLUMPFIND identifies GMCs down to 4σ significance, indicating that GMCs of 4 x 10^5 solar masses lay in the inter-arm regions [19]. On the other hand, Giant Molecular Associations (GMAs), which are GMCs spanning more than 500 pc across are only found on the spiral arms. Figure 5 shows the distribution of GMCs both on the arms and in the inter-arm regions, with each individual cloud represented by a circle.

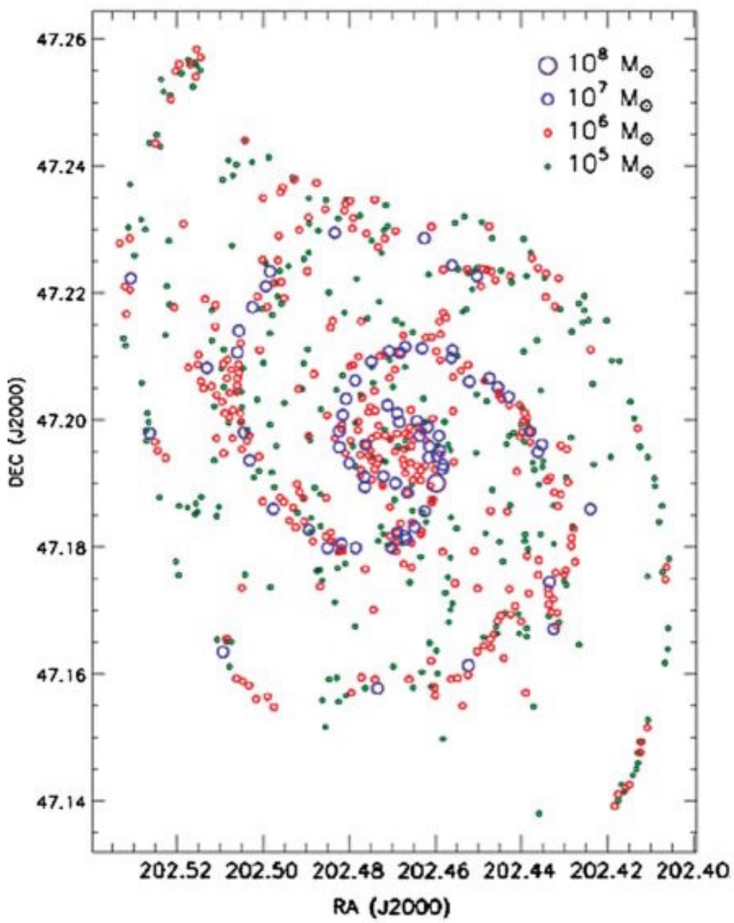

Figure 5. A graph mapping out the distribution of GMCs and GMAs in M51 as points, with x-axis representing right ascension and y-axis representing declination. GMAs are seen only on the spiral arms, but GMCs can be found on the inter-arm regions. Adapted from [20].

This observation also brings up the lifetime controversy of GMCs. Whether GMCs are short-lived or semi-permanent structures are still disputed. On one hand, Larson believes that GMCs are transient because young stars only stay in them fro about 10-20 Myr [21]. It is true that few older stars are found in molecular clouds. In addition, Density Wave Theory also predicts short lifetimes for GMCs because GMCs would only take 10-

20 Myr to traverse the spiral arm by wave motion. ISM would compress at certain regions of the galactic disk to form molecular gas along a spiral arm and would quickly be destroyed upon leaving the arm. According to this notion, there would be few to none GMCs in the inter-arm region, which directly contradicts observations of Koda et. al. On the other hand, some scientists argue that GMCs are long-lived. Scoville and Hersh, for example, estimate that GMCs live around 10^8 years (Scoville & Hersh 2004) [22]. The presence of GMCs in the inter-arm regions would indeed demand a much longer lifespan than Larson predicts. If GMCs lived long enough to last through the inter-arm crossing period, their presence in the inter-arm regions is naturally explained. GMAs found on the spiral arms can potentially more efficiently drive star formation since their large mass (10^7-10^8 solar masses) could more likely achieve the jeans instability, a state of hydrostatic equilibrium where internal gas pressure is too weak to prevent gravitational collapse. Larson posits that stellar feedback, like photo-disassociation by OB stars and ultraviolet radiation by supernova explosions, can blow apart GMAs, but these mechanisms could not be powerful enough to cause significant destruction of GMAs given the GMAs' large mass [23]. Still, the lack of old stars in GMCs and GMAs make this a plausible theory. However, the lack of old stars in GMCs could be explained by the fact that old stars must leave GMCs since they follow solid-body dynamics instead of hydrodynamics [24]. Naturally, compact objects like stars would diverge from the hydrodynamic path of GMCs. Thus, experimental facts are against Larson and other supporters of short GMC lifetimes.

Whether GMCs are long-lasting or transient, it is clear that Density Wave Theory cannot reconcile the discrepancies between prediction and observation alone. Some other forces must be at play. GMCs typically span 10-100 pc in diameter, but Rosolowsky presents the resolution of GMCs down to 20 pc in M33 using the BIMA array [25].

For GMCs big and small, Rosolowsky et. al. discovered that these molecular clouds are rotating objects because GMCs have velocity gradients. Figures 6 and 7 show that GMCs are rotate as solid bodies in the ISM, as measured by the gradient.

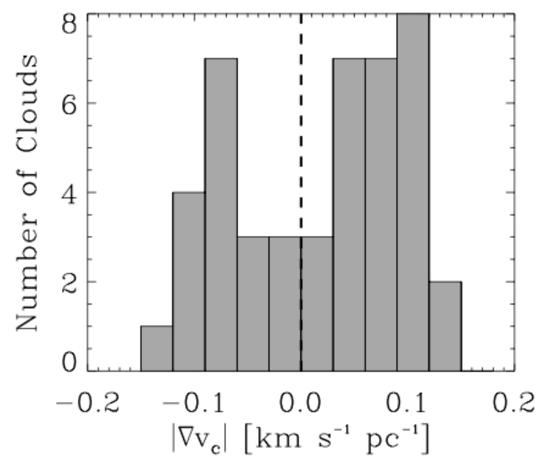

*Figure 6. The x-axis shows the magnitude of the velocity gradient in km/s*pc how velocity changes with respect to radius from the GMC center. The y-axis shows the number of clouds. It shows how many clouds have what kind of gradient. The significance of this graph shows that clouds are solidly rotating objects because they have a per cloud gradient. Adapted from [26].*

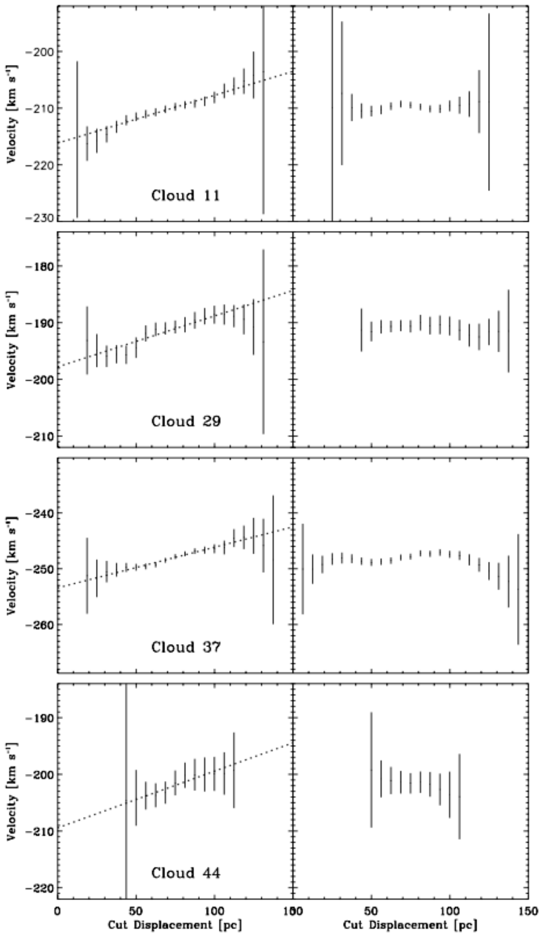

Figure 7. Velocity vs. displacement graphs for various clouds shows relatively constant gradients. This indicates solid rotation of the clouds. Adapted from [27].

The galaxy follows differential rotation while GMCs follow solid-body rotation, so GMCs would go towards the center if they are rotating in the prograde direction. Moreover, it is found that the direction of GMC rotation seems to align with the galaxy's rotation. This phenomenon is also explained by the Coriolis effect. Rosolowsky et. al. found that 60% of GMCs are prograde while 40% of GMCs are retrograde [28]. If prograde and retrograde GMCs were divided evenly, the center bulge of the galaxy would not be able to grow because half the material would flow in and the other half would flow out.

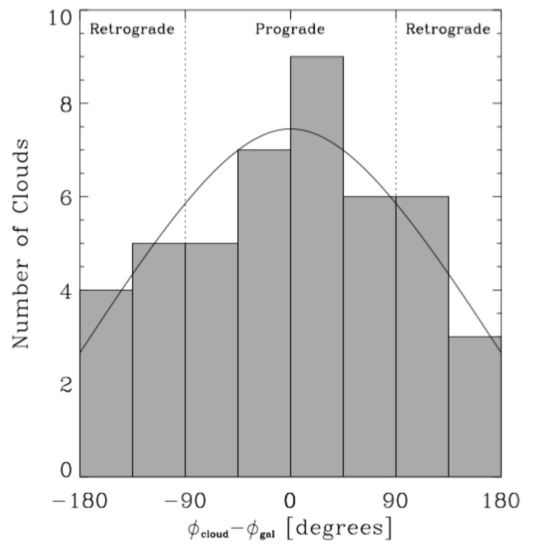

Figure 8. This graph shows the correlation between the difference in angle of the GMC's rotation and the galactic disk's rotation versus the number of clouds at that angle. As shown by the bars, there are more prograde GMCs than retrograde GMCs. It doesn't peak at zero, it peaks above zero and shows more prograde. Adapted from [29].

Another facet of GMC rotation is the Angular Momentum Problem, which will be discussed in Section 5.

4. The Center of a Galaxy: Super Massive Black Holes

Most spiral galaxies host Super Massive Black Holes (SMBHs) at their center. Theory predicts that SMBHs co-evolve with their galaxies. Typically, an SMBH would achieve up to 0.2-0.5% of its galaxy's mass at present day (equivalent to about 1 million solar masses), but recently Trakhtenbrot et al. discovered an SMBH that has 10% the mass of its galaxy [30]. The SMBH is called CID-947 and is located in a galaxy at redshift z = 3.328, which signifies the early cosmological epoch [30]. Given its M_{BH}/M_* ratio, CID-947 must have been efficient at accreting material compared to other SMBH.

The rapid growth of CID-947 and other similar SMBH could be attributed to the accretion of GMCs. In 2016, Tremblay et al. found that GMCs are accreting within 100 pc of the SMBH at the galactic center.

Tremblay et al. write that “Cold accretion onto black holes has long been predicted by both theory and simulations, but it has not been definitively observed in a manner so stripped of ambiguity regarding the clouds’ proximity to a black hole [31].” The notion that an SMBH consumes material from its galaxy to grow is affirmed by these observations, which were taken using ALMA and VLBA dataset for the Abell 2597 Brightest Cluster Galaxy. ALMA tracked the CO(2-1) emission as an indicator of molecular hydrogen. In fact, the total measured CO(2-1) line flux indicates molecular hydrogen gas of mass $M_{H2} = (1.8 \pm 0.2) \times 10^9$ solar masses [32]. Several photographs taken at different wavelengths are overlaid in Figure 9 to show the trajectory of molecular clouds accreting onto the SMBH.

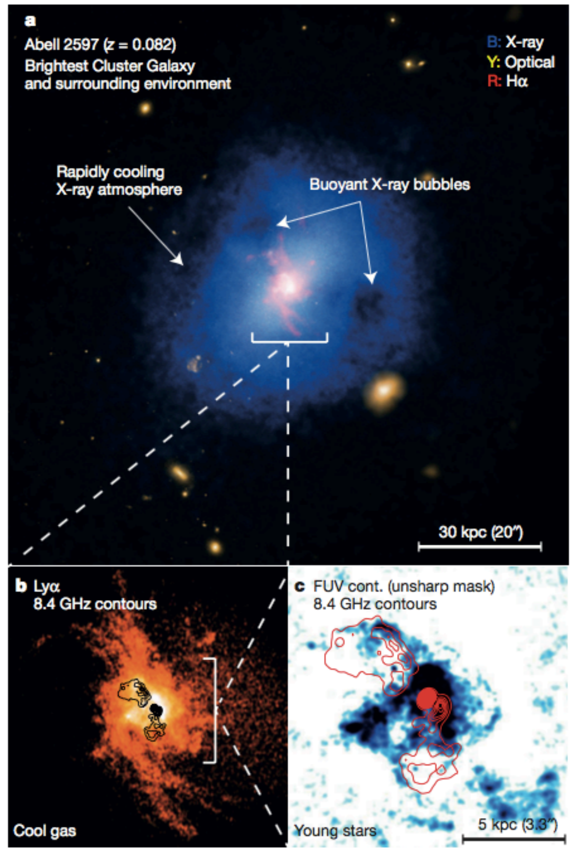

Figure 9. (a) The Hα[N ii] emission line from Chandra X-ray, HST, and DSS optical is shown in colors blue, red, and yellow, respectively. The arrows indicate thermally unstable hot atmosphere and buoyant X-ray bubbles in the region. (b) HST image of Lyα emission of ionized gas in nebula 13 (the red region shown in (a)). VLA radio contours (8.4 GHz) are outlined in black. (c) FUV emission of the HST continuum is mapped out, which should indicate the locations of young stars within nebula 15. The same VLA radio contours, in red, once again outline the source. Adapted from [33].

Figure 10 zooms into the molecular clouds seen in Figure 9 and shows that the clouds' ionized gas is perhaps just a thin shell surrounding colder and more massive molecular cores. The exterior may have been heated by intense radiation by environmental factors.

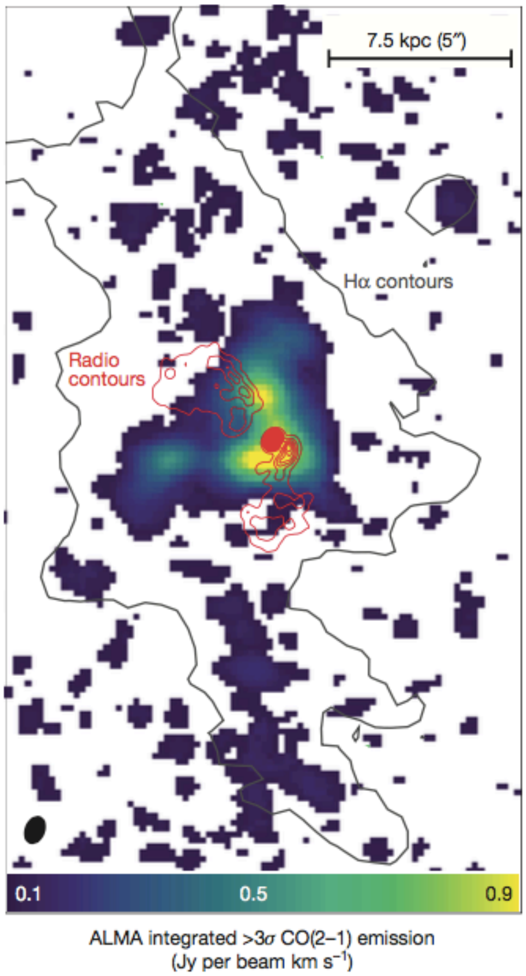

Figure 10 [Explain axis.] This image of continuum-subtracted CO(2-1) shows that the nebula is a shell of hot ionized gas with a core of cold molecular gas. This nebula is located in the innermost 30 kpc (also seen in Figure 1b) of the galaxy. Adapted from [34].

Instead of a single kpc-scale of molecular gas, it is likely that Tremblay et. al. observed a conglomeration of smaller, distinct clouds [35]. Nonetheless, the data clearly shows that cold molecular gas is falling inward towards the galactic center through radial or in-spiraling paths.

If GMCs are falling directly into the SMBH rather than in highly eccentric elliptical orbits, an accretion rate of around 0.1 to a few solar masses per year may be obtained [36]. Of course, this range could also be affected by the three-dimensional distribution of the accreting clouds. On the other hand, if GMCs follow elliptical orbits around the SMBH, the growth rate of the SMBH would depend more on external torques that might lessen the GMCs' angular momentum. However, such torques should be in abundant supply since simulations predict a stochastic "rain" of thermal instabilities that occur from all directions around the black hole, which would bolster angular momentum cancellation through tidal stress or cloud-to-cloud collisions [37].

GMCs, which are responsible for star formation, may be able to form stars near the SMBH which the SMBH will then take in to grow. When the orbit of a star passes close enough to the SMBH's event horizon, the star is sheared apart by tidal forces produced by the imbalance of gravity on its opposite ends in phenomena known as a Tidal Disruption Event (TDE). Although a high density of stars is located at the galactic bulge near the SMBH, it is unlikely that TDE is the main mechanism responsible for SMBH growth because TDEs happen rarely, only about once a year. The accretion of ISM gas, however, remains a plausible factor to SMBH growth.

That an SMBH consumes material from its host galaxy to grow is affirmed by these observations, but the question remains on how GMCs arrive so close to the galactic bulge in the first place. Far away from the SMBH, the influence of external torques are lesser in magnitude. The ISM needs to shed its angular momentum by several orders of magnitude in order to arrive at the destination observed by Tremblay et. al.

5. Angular Momentum Problem

The Winding Problem plaguing spiral arm theories results from our belief that matter cannot fall towards the center of the galaxy due to the conservation of angular momentum. If GMCs were viewed as isolated, massive objects, their angular momentum will increase their speed when they get closer to the center of the galaxy. In order to fall in, GMCs must reduce their initial angular momentum. Such angular momentum discrepancies exist at many orders of magnitude in the galaxy. For example, the angular momentum of a star-forming cloud is 3 orders of magnitude greater than the maximum angular momentum in a star rotating at breakup speed [38]. The discrepancy is even greater SMBHs, where the angular momentum of matter in the galactic bulge is 4-5 orders of magnitude greater than theory predicts for a maximally rotating black hole [39]. Additionally, Rosolowsky et. al. measures that GMCs have angular momentums 5 orders of magnitude greater in observation than in theory [40]. In summary, the initial angular momentum of the diffuse material appears to be much higher than the final angular momentum of the compact object. This fact is true for stars, black holes, and GMCs. Moreover, the massiveness of these objects limit the efficiency at which angular momentum could be transported from the system to the surrounding environment.

It is important to discuss the Angular Momentum Problem because the basic components of the galaxy (stars, spiral arms, etc.) need to be formed without violating the fundamental scientific principle of angular momentum conservation. The ubiquitous nature of this issue warrants closer examination in the context of studying galactic morphology. The source of the Angular Momentum Problem comes from the axiomatic fact that most diffused media undergo some type of rotation, as produced by the general rotation of the galactic disk itself. Most if not all components of the disk, like stars, black holes, and GMCs, are found rotating. GMCs are believed to come from the collapse of neutral atomic hydrogen gas. Stars come from collapsed molecular gas from the GMC core, and black holes grow by accreting surrounding material. These objects are formed within a rotating media.

GMCs could shed their angular momentum to nearby media, and gravitational forces should dominate the process of transporting angular momentum. After all, magnetic forces would not have as significant an effect on neutral hydrogen molecules. Therefore, GMCs should not be viewed as isolated objects but instead seen as part of a continuous media, which can be described by hydrodynamic processes.

Lin and Shu did not use hydrodynamics, but they did consider the galactic disk as a thin, continuous media. What they were trying to solve was the mass density distribution. A similar model could be used in hydrodynamics. If the galactic disk is modeled as a 2D differentially-rotating gas media following Rubin's flat rotation curve, the GMCs can be modelled as vortices following a Gaussian vorticity distribution to simulate their observed solid rotation (where the vorticity value decreases with radius in the manner of a normal distribution). Such a hydrodynamic system can be solved using the vortex method discussed in Section 6.

6. Galactic Hydrodynamics: Vortex Theory of GMCs

Hydrodynamics may give insight as to how and where angular momentum is transported, possibly providing a "solution" to the Angular Momentum Problem. Specifically, vortices moving in a vorticity gradient shows that mass can be transported among a rotating media. Observations of electron plasma by Driscoll et. al.

demonstrates that vortices tend to move to the extrema of the vortex gradient. Before moving onto the details of the electron plasma experiment, a brief review of the vorticity method in hydrodynamics is warranted.

The generic hydrodynamic process in gravitational field of earth is governed by the Navier-Stokes equation, as follows:

$$\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} = -\left(\frac{\nabla p}{\rho} + \vec{g}\right) + \nu \nabla^2 \vec{v}$$

Where velocity field $\vec{v}$ is described by the pressure p, density ρ, and gravity acceleration $\vec{g}$, ν is viscosity.

If we take the "curl" (∇×) operator of the above equation, like so:

$$\nabla \times \frac{\partial \vec{v}}{\partial t} + \nabla \times (\vec{v} \cdot \nabla \vec{v}) = -\nabla \times \left(\frac{\nabla p}{\rho} + \vec{g}\right) + \nabla \times (\nu \nabla^2 \vec{v}) \quad (5)$$

We get vorticity equation:

$$\frac{D\vec{\omega}}{Dt} = (\vec{\omega} \cdot \nabla)\vec{v} + \upsilon \nabla^2 \vec{\omega} \quad (6)$$

Where the definition of vorticity is as follows:

$$\vec{\omega} = \nabla \times \vec{v} \quad (7)$$

In 2D, the first term on the right side vanishes. Because the vector $\vec{v}$ stays in the plane which is perpendicular to vorticity. So the equation simplifies, seen below:

$$\frac{D\vec{\omega}}{Dt} = \upsilon \nabla^2 \vec{\omega} \quad (8)$$

For inviscid fluids ν = 0 in the above equation. Thus, we get:

$$\frac{D\vec{\omega}}{Dt} = 0 \ (9)$$

Where $\frac{D}{Dt} = \frac{\partial}{\partial t} + \vec{v} \cdot \nabla$ is the material derivative operator.

In the electron plasma study, the electron density in a uniform magnetic field has dynamic equations isomorphic to the 2D Euler equation above for incompressible, inviscid fluids' vorticity $\vec{\omega}$. Therefore, measuring the electron density (which is easily done using electron accelerator like in an old television) is equivalent to measuring vorticity in a 2D inviscid fluid. A diagram of the experimental setup is shown in Figure 11.

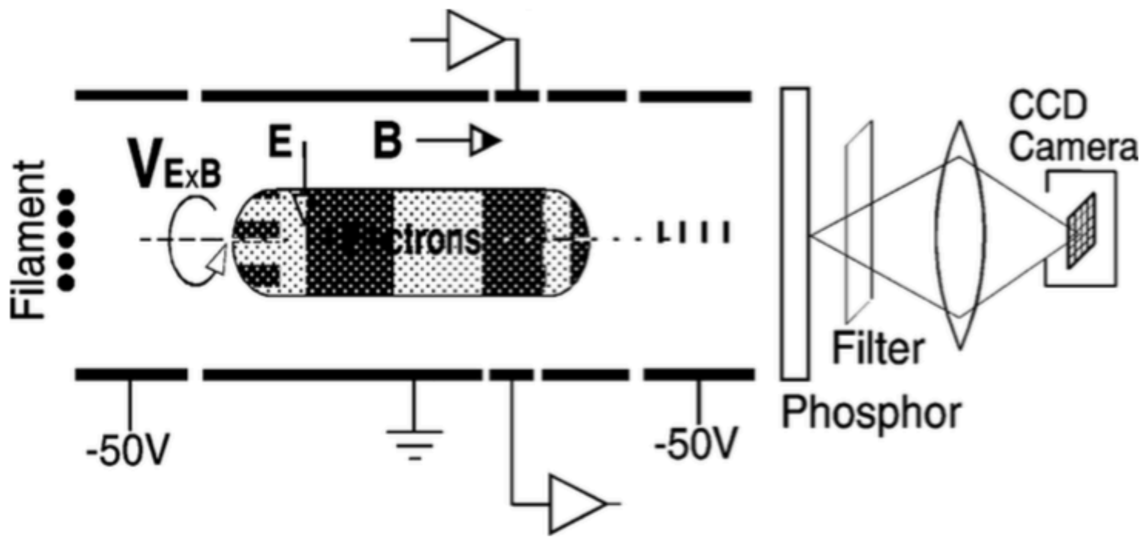

Figure 11. The apparatus used for the electron plasma experiment. Adapted from [41].

The same vorticity equation should also govern galactic hydrodynamics because there is negligible viscosity in ISM (Reynolds number Re ~ 10^9). The galactic disk can be viewed as a thin, 2D inviscid, incompressible fluid. This model essentially changes Lin and Shu's wave approach to a vorticity approach with a similar galactic disk model.

Driscoll et. al. found that prograde electron vortices move towards the center of the background vorticity, where vorticity is at its maximum. On the other hand, retrograde electron vortices receded to the edge of the background vorticity, where vorticity is at its minimum [42].

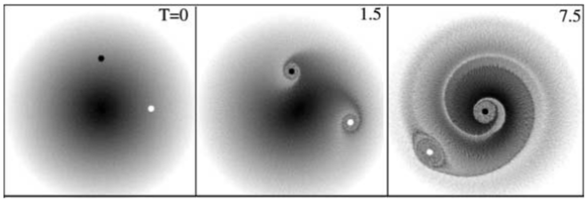

Figure 12. The time-lapse of electron vortices evolving in the experiment. The black dot represents a prograde electron vortex, and the white dot represents a retrograde electron vortex. The background vortex lays behind the two. This is a computer simulation. Adapted from [43].

A similar phenomenon is observed on the macroscopic level. For example, hurricanes in the northern hemisphere tend to move towards the north pole while hurricanes in the southern hemisphere go towards the south pole. GMCs likely follow this trend as well. If we model the galactic disk as a 2D, inviscid differentially rotating medium with vorticity distribution inversely proportional to radius derived from the flat rotation curve, GMCs on the galactic disk would be modeled as Gaussians for their vorticity distributions. 60% of GMCs would be prograde, and 40% would be retrograde, as Rosolowsky et. al. measured in M33 [44]. Like electron vortices, we should expect prograde GMCs falling to the center without suffering the Angular Momentum Problem. Thus, spiral arms could be viewed as rivers of GMCs flowing towards the center bulge and out to the galaxy's edge instead of wave patterns described by Density Wave Theory.

7. Conclusion

If the Angular Momentum Problem were solved using vortex theory, several implications would emerge. First, arms are material and made primarily of GMCs. Prograde GMCs stream towards the center to feed the SMBH and the galactic bulge, and the Winding Problem would be solved because the radial motion of GMCs mimic that of water in a whirlpool. Meanwhile, retrograde GMCs would go move towards the edge of the galaxy along the spiral arms like water droplets in a garden sprinkler. This easily generates spiral arms in many forms, including bi-symmetric, grand design, as well as flocculent types, which is much more generic than Density Wave Theory can create. Second, GMCs are potentially long-lived structures because they complete orbits many times that of the galactic year before dissolving in the galactic center. The lack of older stars (other than young OB stars) in GMCs does not conflict with long lifetimes of GMCs since stars, as solid bodies, would no longer be subjected to hydrodynamic forces within the GMCs. Stars move out of the GMCs as the GMCs move radially along the spiral arms. Tremblay's et. al. observations may be possible because GMCs are transported within the rotating media towards the SMBH. As stars form in proto-stellar disk, one can imagine gas vortices generated in such a disk which can transfer material to the center without being affected by the Angular Momentum Problem. As for GMC formation, collisions between smaller molecular clouds is more likely the cause because GMCs are long-lived and rotating. Vortex merging happens more often than solid-body collisions. In conclusion, vortex theory can describe the galaxy system as a whole and its individual parts because it has the potential to solve the Angular Momentum Problem.

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