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Swing amplification in stars and gas : origin of local spiral structure in galaxies

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Abstract. We present a study of the growth of local, non-axisymmetric perturbations in gravitationally coupled stars and gas in differentially rotating galactic disk. The amplified perturbations in stars and gas constitute trailing, material spiral features which may be identified with the local spiral features seen in all spiral galaxies. The local, linearized perturbation equations in the sheared frame are derived, and solved to obtain the results for a temporary growth via swing amplification. Due to the lower gas velocity dispersion, the resulting growth in gas is higher, and also the amplified gas features are more tightly wound, as observed. Due to the coupling between stars and gas, the stellar amplification and the range of pitch angles over which it can occur are both increased. Our two-component study can therefore naturally explain the origin of the broad spiral arms in the underlying old stellar populations of galaxies, and the radially increasing arm contrasts—as observed in the pioneering work by Schweizer (1976), and later by Elmegreen & Elmegreen (1984). The arms are predicted to be broader in gas-rich galaxies, as is indeed observed for example in M33. These new results arise directly due to the inclusion of gas in the problem.

Key words : galactic structure—stellar populations

1. Introduction

A non-axisymmetric perturbation in a galactic disk may show strong though temporary growth even when the disk is stable to the growth of axisymmetric perturbations, as was shown for the one-component case by Goldreich & Lynden-Bell (1965), and Julian & Toomre (1966). The epicyclic motion of a disk particle and the unperturbed shear flow in a sheared galactic disk share a similar sense of motion. This, plus the self-gravity of the component, results in the above behaviour. Toomre (1981) has called this phenomenon 'swing amplification' since the maximum growth occurs as a mode swings from a radial to a trailing position.

An inclusion of even a small mass fraction ($\leq 10\%$) of a low dispersion component (gas) makes the entire star-gas galactic disk system significantly more unstable to the growth of axisymmetric perturbations, as shown by Jog & Solomon (1984a, b).

Here we present a study of the growth of local, non-axisymmetric perturbations leading to swing amplification in the gravitationally coupled stars and gas in a sheared galactic disk. The aim is to study the physical effects of inclusion of gas on the growth of perturbations in both stars and gas in a galaxy. The amplified perturbations in stars and gas constitute trailing, material spiral features which may be identified with the local spiral features seen in all spiral galaxies. Our analysis is particularly applicable to galaxies which exhibit a messy, or a patchy spiral structure with many, fragmented spiral arms, such as M33 (NGC 598), or NGC 2841. Such galaxies are more common than the grand-design spiral galaxies, such as M51. For the details of this work, see Jog (1992).

2. Formulation of equations and results

The stars and gas in a galactic disk are treated as two isothermal fluids of different velocity dispersions, with the stellar velocity dispersion being much greater than that in the gas. The two fluids interact gravitationally with each other. The formulation of the equations for this two-fluid system closely follows the one-fluid treatment by Goldreich & Lynden-Bell (1965). The local, linearized, coupled perturbation equations in the sheared frame are obtained. These are solved numerically as an initial value problem to obtain the results for a temporary growth in stars and gas via swing amplification.

The problem is formulated in terms of five dimensionless parameters—namely, the Q-factors for local stability for stars and gas, respectively; the gas mass fraction; the shearing rate in the galactic disk; and the lengthscale of perturbation. By using the observed values for these parameters, we obtain amplification parameters and the pitch angles for features in stars and gas for dynamically distinct cases, as applicable for different regions of spiral galaxies.

The swing amplification in each fluid occurs as a perturbation swings past the radial position. The amplification is higher in the colder fluid, that is gas, and the amplified gas feature is more tightly wound than the stellar feature. The high resolution CO observations and the optical CCD images of M51 by Rand & Kulkarni (1990) confirm this. In their study the CO features do indeed lie inside the I-band images, the latter indicating the old stellar population.

When the gas contribution is high, the stellar amplification and the range of pitch angles over which it can occur are both increased, due to the gravitational coupling between the two fluids. This results in the broad stellar spiral arms in the underlying old stellar populations. Thus our two-component analysis can naturally explain the origin of the broad spiral arms in old stars, which were discovered by Schweizer (1976) in his pioneering study of photometry of galaxies, and later confirmed in a study of a larger sample by Elmegreen & Elmegreen (1984). Also, we predict the arms to be broader in gas-rich galaxies. This is in fact observed for example in M33, NGC 6946, and NGC 2403 (see the I-band images in Elmegreen 1981).

The arm contrast increases with radius in both old stars and gas in the inner Galaxy, in agreement with the observations of Schweizer (1976) for external galaxies.

A real galaxy consisting of stars and gas may display growth of non-axisymmetric perturbations even when it is stable against axisymmetric perturbations and/or when either fluid is stable against non-axisymmetric perturbations.

3. Discussion

The above results follow directly due to the inclusion of gas in the problem. The above results are expected to be of even greater significance in future as the high spatial and spectral resolution photometric data from large single-dish telescopes and from optical and infrared interferometry become available for a large number of galaxies.

For the input parameters typical of various regions in the Galaxy, the resulting pitch angles are in the range of ~ 70°-80°. These are in a much better agreement with the observed pitch angles for external galaxies than the larger values (~ 90°) assumed in the standard density wave theory. We are currently studying this in detail.

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