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Effect of dark matter halo on global spiral modes in a collisionless galactic disk

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HIGHLIGHTS

- Dominant dark matter halos shown to prevent spiral features in LSBs.
- Stellar disks are modeled as realistic collisionless system.
- UGC 7321, a LSB galaxy, considered where dark matter dominates from inner region.
- No global spiral mode found in UGC 7321.

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ABSTRACT

Low surface brightness (LSB) galaxies are dominated by dark matter halo from the innermost radii; hence they are ideal candidates to investigate the influence of dark matter on different dynamical aspects of spiral galaxies. Here, we study the effect of dark matter halo on grand-design, $m = 2$, spiral modes in a galactic disk, treated as a collisionless system, by carrying out a global modal analysis within the WKB approximation. First, we study a superthin, LSB galaxy UGC 7321 and show that it does not support discrete global spiral modes when modeled as a disk-alone system or as a disk plus dark matter system. Even a moderate increase in the stellar central surface density does not yield any global spiral modes. This naturally explains the observed lack of strong large-scale spiral structure in LSBs. An earlier work (Ghosh et al., 2016) where the galactic disk was treated as a fluid system for simplicity had shown that the dominant halo could not arrest global modes. We found that this difference arises due to the different dispersion relation used in the two cases and which plays a crucial role in the search for global spiral modes. Thus the correct treatment of stars as a collisionless system as done here results in the suppression of global spiral modes, in agreement with the observations. We performed a similar modal analysis for the Galaxy, and found that the dark matter halo has a negligible effect on large-scale spiral structure.

1. Introduction

Low Surface Brightness (LSB) galaxies are characterized by low star formation rate (Impey and Bothun, 1997) and low disk surface density (de Blok and McGaugh, 1996; de Blok et al., 2001). The spiral structure in LSBs is often incipient or fragmentary and usually faint and difficult to trace (Schombert et al., 1990; McGaugh et al., 1995; Schombert et al., 2011), and they generally do not host any strong large-scale spiral structure, the kind we see in case of normal high surface brightness (HSB) galaxies like our Milky Way. We note that, we are interested only in small LSBs, which are more abundant, and do not include the giant LSBs like Malin 1. Some of the giant LSBs show fairly strong, large-scale spiral structure as in UGC 6614 (Das, 2013) and in the inner regions they are dynamically similar to their HSB counterparts (Lelli et al., 2010). Fuchs (2002) has applied the technique of density-wave theory to put constraint on the decomposition of the rotation curve in LSBs. However we note that in the sample considered by Fuchs (2002) contains giant LSB (e.g., UGC 6614) which often show large-scale spiral structure (e.g., see Das, 2013).

The LSBs are dark matter dominated from the very inner regions (Bothun et al., 1997; de Blok and McGaugh, 1997; de Blok et al., 2001). Within the optical disk, the dark matter constitutes about 90 per cent of the total mass of LSBs, whereas for the HSBs the contributions of the dark matter halo mass and stellar mass are comparable (de Blok et al., 2001; Jog, 2012). Thus, the LSBs constitute a natural laboratory to study the effect of dark matter halo on different aspects of galactic dynamics.

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Several past studies have shown the effect of dominant dark matter halo in the suppression of global non-axisymmetric bar modes (Mihos et al., 1997), in making the galactic disks superthin (Banerjee and Jog, 2013) and in prohibiting the swing amplification mechanism from operating, thus explaining the lack of small-scale spiral structure as noted observationally (Ghosh and Jog, 2014).

According to the density wave theory, the grand-design spiral arms are the high density regions of a rigidly rotating spiral density wave, with a well defined pattern speed, that are self-consistently generated by the combined gravity of the unperturbed disk and the density wave (Lin and Shu, 1964; 1966). For a recent review on this see Dobbs and Baba (2014).

In a recent work Ghosh et al. (2016) (hereafter Paper 1) investigated the role of a dominant dark matter halo on the global spiral modes within the framework of the density wave theory by treating the galactic disk as a fluid. Using the input parameters of a superthin LSB galaxy UGC 7321 and the Galaxy, they found that for UGC 7321, the dark matter halo has a negligible effect on arresting the global spiral modes when the disk is modeled as a fluid. This is in contrast to the results for small-scale spiral features where the dark matter was shown to suppress the small-scale, swing-amplified spiral structures almost completely (Ghosh and Jog, 2014). Ghosh et al. (2016) (Paper 1) argued that that since LSBs are relatively isolated, tidal interactions are less likely to occur compared to those for the HSB galaxies. Thus even though the global spiral modes are formally permitted in the fluid disk plus dark matter halo model, it was argued that it is the lack of tidal interaction that makes it difficult for the global spiral structure to develop in these galaxies.

In this paper we address the effect of dark matter halo on global $m = 2$ modes by modeling the galactic disk more realistically as a collisionless system. A tidal encounter is likely to give rise to global modes, as has been seen in simulations, as in M51 (see e.g., Toomre and Toomre, 1972).

We use the dispersion relation for a *collisionless* disk to construct global standing-wave like solutions by invoking the Bohr-Sommerfeld quantization condition (for details see Paper 1). Note that fluid disks allow wavelike solutions at small wavelengths, since fluid pressure provides the restoring force; but collisionless disks suppress wavelike modes for very small wavelengths (e.g. see Binney and Tremaine, 1987).

§2 contains formulation of the problem and the input parameters. In §3 we present the WKB analysis and the relevant quantization rule. §4 and §5 contain the results and discussion, respectively while §6 contains the conclusions.

2. Formulation of the problem

We model the galactic disk as a collisionless system characterized by an exponential surface density Σ_s, and one-dimensional velocity dispersion σ_s. For simplicity, the galactic disk is taken to be infinitesimally thin. In other words, we are interested in perturbations that are confined to the mid-plane ($z = 0$). The dark matter halo is assumed to be non-responsive to the gravitational perturbations of the disk. We have used cylindrical coordinates (R, ϕ, z) in our analysis.

2.1. Details of models

In this subsection, we describe the models that we have used for the study of effect of dark matter halo on the global spiral modes.

The dynamics of the disk is calculated first only under the gravity of the disk (referred to as disk-alone case) and then under the joint gravity of disk and the dark matter halo (referred to as disk plus halo case). We took an exponential stellar disk with central surface density Σ_0 and the disk scalelength R_d, which is embedded in a concentric dark matter halo whose density follows a pseudo-isothermal profile characterized by core density ρ_0 and core radius R_c.

The net angular frequency, Ω and the net epicyclic frequency, κ for a galactic disk embedded in a dark matter halo, concentric to the galactic disk, are given as:

$$\kappa^2 = \kappa^2_{\mathrm{disk}} + \kappa^2_{\mathrm{DM}}\,; \quad \Omega^2 = \Omega^2_{\mathrm{disk}} + \Omega^2_{\mathrm{DM}}\,. \tag{1}$$

The expressions for κ^2_{disk}, Ω^2_{disk} in the mid-plane ($z = 0$) for an exponential disk and κ^2_{DM}, Ω^2_{DM} for a pseudo-isothermal halo in the mid-plane ($z = 0$) have been calculated earlier (see Paper 1 for details).

In the early-type galaxies, the bulge component dominates in the inner regions, and hence exclusion of the bulge component from the models for early-type galaxies will underestimate the rotation curve in the inner regions. In Paper 1, it was shown that for the Galaxy, inclusion of bulge yielded more realistic results (for details see §5.1 in Paper 1). Also note that UGC 7321 has no discernible bulge (Matthews et al., 1999; Matthews and Wood, 2003). Therefore, only for our Galaxy we have included bulge in both the disk-alone and disk plus dark matter halo models. We adopt a Plummer–Kuzmin bulge model for our Galaxy which is charac-cterized by total bulge mass M_b and bulge scalelength R_b.

The expressions for $\kappa^2_{\mathrm{bulge}}$, $\Omega^2_{\mathrm{bulge}}$ in the mid-plane ($z = 0$) for such a bulge having a Plummer–Kuzmin profile are given in Paper 1. Therefore, for the Galaxy, these $\kappa^2_{\mathrm{bulge}}$ and $\Omega^2_{\mathrm{bulge}}$ terms will be added in quadrature to the corresponding terms due to disk and dark matter halo.

2.2. Input parameters

The input parameters for different components of UGC 7321 (Banerjee et al., 2010) and the Galaxy (Mera et al., 1998; Blum, 1995) are summarized in Table 1.

For UGC 7321, the stellar velocity dispersion in the radial direction is taken to be: $\sigma_\mathrm{s} = (\sigma_{\mathrm{s}0})_R \exp(-R/2R_d)$, where $(\sigma_{\mathrm{s}0})_R$ is the central velocity dispersion in the radial direction. The observed central velocity dispersion in the z direction ($(\sigma_{\mathrm{s}0})_z$) is 14.3 km sec^{-1} (Banerjee et al., 2010). In the solar neighborhood, it is observationally found that $(\sigma_\mathrm{s})_z/(\sigma_\mathrm{s})_R \sim 0.5$ (e.g., Binney and Tremaine, 1987). Here we assume the same conversion factor for all radii.

For the Galaxy, the observed stellar velocity dispersion in the radial direction is : $\sigma_\mathrm{s} = (\sigma_{\mathrm{s}0})_R \exp(-R/8.7)$, where $(\sigma_{\mathrm{s}0})_R =$ 95 km sec^{-1} (Lewis and Freeman, 1989).

3. WKB analysis

The dispersion relation for an infinitesimally thin galactic disk, modeled as a collisionless system, in the WKB limit, is given by (Binney and Tremaine, 1987):

$$(\omega - m\Omega)^2 = \kappa^2 - 2\pi G\Sigma_s|k|\mathcal{F}(s,\chi), \tag{2}$$

where $s(= (\omega - m\Omega)/\kappa)$ and $\chi\,(= k^2\sigma_s^2/\kappa^2)$ are the dimensionless frequencies. $\mathcal{F}(s,\chi)$ is the reduction factor which physically takes into account the reduction in self-gravity due to the velocity dispersion of stars. The form for $\mathcal{F}(s,\chi)$ for a razor-thin disk whose stellar equilibrium state can be described by the Schwarzchild distribution function is given by (Binney and Tremaine, 1987):

$$\mathcal{F}(s,\chi) = \frac{2}{\chi}\exp(-\chi)(1-s^2)\sum_{n=1}^{\infty}\frac{I_n(\chi)}{1-s^2/n^2}\,. \tag{3}$$

Since we are interested in $m = 2$ grand spiral modes, a rearrangement of Eq. (2) yields

$$4(\Omega_\mathrm{p} - \Omega)^2 = \kappa^2 - 2\pi G\Sigma_s|k|\mathcal{F}(s,\chi)\,, \tag{4}$$