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Dynamical imprint of interstellar gas on persistence of spiral structure in galaxies

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Abstract. The persistence of the spiral structure in disk galaxies has long been debated. In this work, we investigate the dynamical influence of interstellar gas on the persistence of the spiral arms in disk galaxies. We show that the gas helps the spiral arms to survive for longer time-scale ($\sim$ a few Gyr). Also, we show that the addition of gas in calculation is necessary for getting a stable density wave corresponding to the observed pattern speed of the spiral arms.

Keywords. galaxies: spiral – galaxies: ISM – galaxies: kinematics and dynamics

1. Introduction

According to the density wave theory, the large-scale spiral arms are *stationary* density waves in a disk galaxy which rotate with a constant pattern speed ($\Omega_{\rm p}$) (Lin & Shu 1964). However, Toomre (1969) showed that a wavepacket of such density waves will be destroyed within a few rotation time-scales which poses a serious problem to the *stationary* nature of density waves. Also, any late-type disk galaxy contains a finite amount of interstellar gas. Several earlier studies have shown that the gas plays a significant role in various dynamical contexts (e.g. see Jog & Solomon 1984).

Here, we consider gas on an equal footing with the stars, and investigate how gas could influence the origin and persistence of large-scale spiral structure in disk galaxies.

2. Two-component model of galactic disk

The WKB dispersion relation for an infinitesimally thin, gravitationally bound two-component galactic disk consisting of stars (treated as *collisionless*) and gas (treated as a *fluid*) is (for the particular form see Ghosh & Jog 2015)

$$s^2 = s^2(x; Q_{\rm s}, Q_{\rm g}, \epsilon) \tag{2.1}$$

where $|s|$ ($=m(|\Omega - \Omega_{\rm p}|)/\kappa$) and $|x|$ ($=k/k_{\rm crit}$) are the dimensionless frequency and wavenumber of the perturbation. $Q_{\rm s}$, $Q_{\rm g}$ are Toomre Q values for stars and gas, respectively, and ϵ is gas fraction. Ghosh & Jog (2015) showed how equation (2.1) varies for different gas fraction values (for details see fig. 1 there).

2.1. *Effect of gas on group velocity*

A wavepacket of such a density wave travels radially with its corresponding group velocity given by (e.g. see Toomre 1969) : $c_g(R) = sgn(ks)(\kappa/k_{\rm crit})\frac{ds}{dx}$, where $sgn(ks) = \pm 1$ depending on whether $ks > 0$, or is < 0.

We found that with the inclusion of more gas in the system, the slope (ds/dx) decreases monotonically by a factor of 2–3 (for details see fig. 1 in Ghosh & Jog 2015). This in turn means that the group velocity of such a wavepacket will decrease (by a factor of 2–3), and

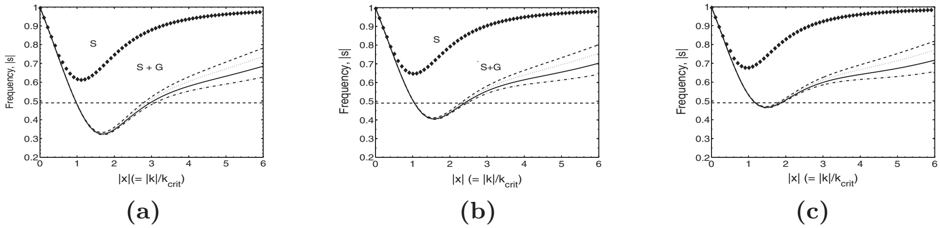

Figure 1. The Galaxy : dispersion relations for stars-alone (S) and stars plus gas (S + G) cases, plotted in a dimensionless form, for a range of Q_{s} and Q_{g} values, at $\mathrm{R} = 2\mathrm{R_d}$. Panel (a) for $Q_{\mathrm{s}} = 1.5$, panel (b) for $Q_{\mathrm{s}} = 1.6$, and panel (c) for $Q_{\mathrm{s}} = 1.7$. In each panel, Q_{g} is taken to be 1.4, 1.5, 1.6, and 1.7, successively. The horizontal line denotes the $|s|_{\mathrm{obs}}$ at that radius.

subsequently the wavepacket will take more time to reach the center of the galaxy before it gets destroyed. This clearly shows that the interstellar gas helps the density waves and hence the large-scale spiral arms to survive for longer time-scale ($\sim$ a few Gyr).

2.2. *Stability of density wave : Role of interstellar gas*

Also, for a disk galaxy with observationally measured rotation curve and the pattern speed for the spiral arms, one can define $|s|_{\mathrm{obs}} = m|\Omega_{\mathrm{p}} - \Omega|/\kappa$.
Now, to get a *stable* density wave corresponding to the observed pattern speed, one has to satisfy $|s|_{obs} \geqslant |s|_{\mathrm{cut-off}}$ where, $|s|_{\mathrm{cut-off}}$ is the lowest possible value of $|s|$ for which one is able to get a stable wave solution from the dispersion relation (equation 2.1) at a given radius R (for details see Ghosh & Jog 2016).

Using the mass model of our Galaxy given by (Mera *et al.* 1998), and for a observed $\Omega_{\mathrm{p}} = 18$ km s^{-1}kpc^{-1} (Siebert *et al.* 2012), we calculated $|s|_{\mathrm{obs}}$, and for a range of Q_{s} (= 1.5–1.7) and Q_{g} (= 1.4–1.7) values, we showed that when the disk is modeled as only comprised of stars, it cannot produce a stable density wave; instead one needs to include the interstellar gas along with stars in order to get a stable density wave corresponding to the observed pattern speed of the spiral arms (see Fig. 1). Ghosh & Jog (2016) showed a similar finding for three other galaxies, NGC 6946, NGC 2997 and M 51.

3. Conclusions

In summary, we show that the inclusion of gas steadily decreases the group velocity of wavepacket of density waves, and hence it helps the spiral arms to survive for a longer time-scale ($\sim$ a few Gyr). Ghosh & Jog (2016) showed for NGC 6946, NGC 2997 and M 51 that inclusion of gas in the calculation is necessary in order to get a *stable* density wave corresponding to the observed pattern of spiral arms. Here, we show that a similar trend also holds for our Galaxy.

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