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Angular Momentum Transport in Lopsided Galaxies

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Abstract. About 30% of spiral galaxies in the local universe are lopsided (e.g., the well-known M101). In a typical lopsided galaxy, the spatial distribution of stars and gas are elongated in one direction than the other and the asymmetry is often prominent in the out-skirts of the disk. Such a lopsided asymmetry is also evident in the kinematics. However, despite being common and a large-scale asymmetry, its role in the angular momentum (AM) transfer remained unexplored. Recently, Saha & Jog (2014) showed that like bars and spirals, lopsidedness also takes part in the outward AM transport in a galaxy, provided *it is leading in nature*. It was shown that a combination of trailing spiral and leading lopsidedness is necessary for a galaxy to transport AM outward - facilitating smooth in-flow of cold gas along the galactic plane from cosmic filaments. Using N-body simulations of off-centered disk and dark matter halo, we first generate lopsidedness in the outer part of the disk and demonstrate that indeed lopsidedness is leading in nature.

Keywords. galaxies: structure, galaxies: evolution, galaxies: kinematics and dynamics

1. Introduction

An important physical process that drives evolution of spiral galaxies, especially in the secular evolution phase, is the transport of angular momentum within various components in the disk and between the disk and its surrounding dark matter halo. Strong non-axisymmetric features such as a bar, and spiral arms that are abundant in local disk galaxies, are also the two commonly recognized drivers of this process as shown theoretically and via numerical simulations (Lynden-Bell & Kalnajs 1972; Tremaine & Weinberg 1984; Weinberg & Katz 2002; Athanassoula & Misiriotis 2002; Sellwood & Debattista 2006; Dubinski et al. 2009; Saha & Naab 2013). As a result of this physical process, the disk tends to reach a state of minimum energy configuration and may continue to do so. Concurrently, the disk grows central concentration or form a pseudo-bulge in the central region (Combes & Sanders 1981; Pfenniger & Norman 1990; Raha et al. 1991; Kormendy & Kennicutt 2004; Saha et al. 2010). The process of outward AM transport is also intimately linked to the accretion of gas along the cosmic filaments (Kereš et al. 2005; Dekel et al. 2009; Combes et al. 2014). In an isolated disk galaxy, gas can flow inward due to positive torque exerted by the bars and spirals that dominate the optical disk. However, to bring gas from cosmic filaments to the central region of a stellar disk along the galactic plane, removal of angular momentum is a must and direction of angular momentum flow must be outward. Lopsided asymmetry (Baldwin et al. 1980) which is often prominent in the outer disk (Fig.1a shows the classic example of M101 in which lopsidedness is prominent in the outer parts as can be seen from far-UV to optical to 21 cm observation) is shown to bridge the gap between the filaments and the inner optical disk (see Saha & Jog 2014). In addition, it is shown that lopsidedness has to be leading in order to transport angular momentum outward (as shown by Saha & Jog

2014) whereas spirals need to be trailing (shown by Lynden-Bell & Kalnajs 1972). Using N-body simulations (as presented below), we show that lopsidedness is indeed leading in nature (Saha, Combes and Jog, in prep).

2. AM transport

In a pioneering work, Lynden-Bell & Kalnajs (1972) showed that spiral structure can transport angular momentum outward provided it is trailing. Redistribution of this angular momentum is associated with the build up of central concentration and gas inflow along the galactic plane. This transport of angular momentum is primarily due to the gravity torque exerted by the spiral structure. However, there is another physical process that adds to the angular momentum transport known as the Lorry transport or advective transport (see appendix of Lynden-Bell & Kalnajs (1972)). In general, the lorry transport may add on to the effect of gravity torque or oppose it, and this depends on a number of parameters such as the physical properties of the non-axisymmetric perturbation, the underlying mass distribution etc.. So the net sign of the angular momentum flow (gravity torque plus advective torque) is not clear a priori in a galactic disk. Saha

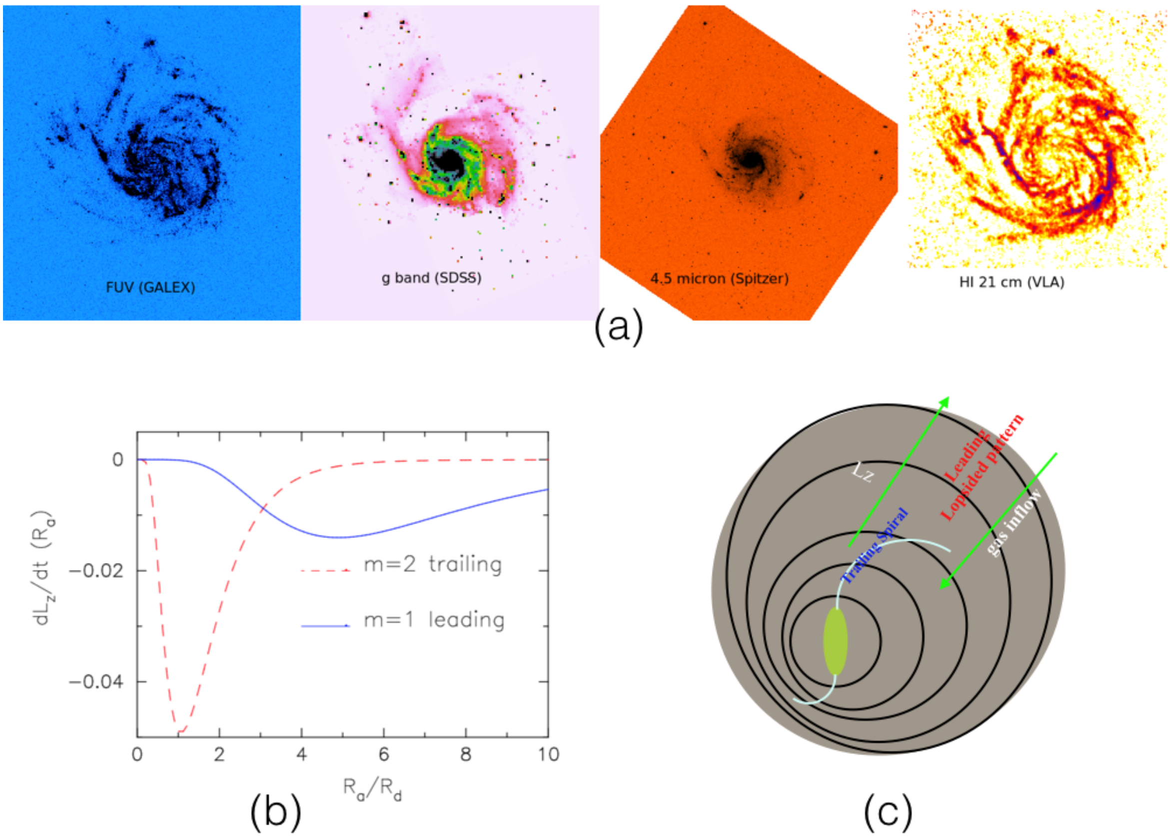

Figure 1. Lopsidedness and gravitational torque: Figure (a)- shows that prevalence of lopsidedness across the electro-magnetic spectrum starting far-ultraviolet (from GALEX) to optical (SDSS), IR (from Spitzer) and 21cm (VLA). The Figure (b) (from Saha & Jog 2014) shows that the rate of change of angular momentum within a given radius is negative when the $m = 2$ spiral is trailing and $m = 1$ lopsidedness is leading in nature and this combination allows the disk to transfer angular momentum outward. The Figure (c) shows a cartoon of net outward flow of AM in the galaxy and inflow of gas - in which leading lopsidedness and trailing spirals are shown to work in tandem.

& Jog (2014) have shown that lopsidedness which is predominantly seen in the outer part of a galactic disk (Zaritsky et al. 2013) can take part in the angular momentum transfer and the angular momentum flow is outward if lopsidedness is leading in nature. Since the presence of lopsidedness is positively correlated with spiral structure (Reichard et al. 2008; Jog & Combes 2009), the net outward flow of angular momentum demands that a combination of trailing spiral structure and leading lopsidedness be present in a lopsided spiral galaxy (see Fig. 1b). Such a combination of spiral and lopsidedness may be at work in accreting cold gas (see Zaritsky & Rix 1997) along the galactic plane from cosmic filaments (schematic diagram in Fig. 1c). However, we lack observational evidence in favour of leading lopsidedness; in fact, observationally it is not clear whether lopsidedness is leading or trailing. In Fig. (2), we show a time sequence of simulated surface density maps which show clear lopsidedness in the outer stellar disk. Such lopsidedness has been created by off-centered dark matter halo (details will be presented in forthcoming paper by Saha, Combes and Jog (2018) in prep). The bulk of the stars in the disk rotates anti-clockwise. The time sequence starting from 200 Myr to 480 Myr, reveals that lopsidedness is a slowly rotating pattern and is leading in nature. However, this is one of the several ways to generate lopsidedness (see review by Jog & Combes 2009) in a galactic disk and it remains to be verified whether lopsidedness is leading in every case.

3. Discussion

In a typical lopsided spiral galaxy, while the inner optical disk is dominated by $m = 2$ modes such as a bar and/or spiral structure, the outer part is dominated by $m = 1$ lopsidedness. It is intriguing why a spiral galaxy would prefer such an arrangement. Of course, following Lindblad's original kinematic argument it can be said that in a typical disk galaxy with flat rotation curve, the free precession frequency of an $m = 2$ mode i.e., $\Omega - \kappa/2$ varies slowly or even remains constant (depending on the mass model) in the inner part - making it susceptible for the m=2 mode. On the other hand, $\Omega - \kappa$ for an $m = 1$ mode has a steep gradient in the inner part compared to the outer - implying strong differential precession and hence harder for an $m = 1$ mode to survive there. Such an arrangement of modes become advantageous for regulating the flow of

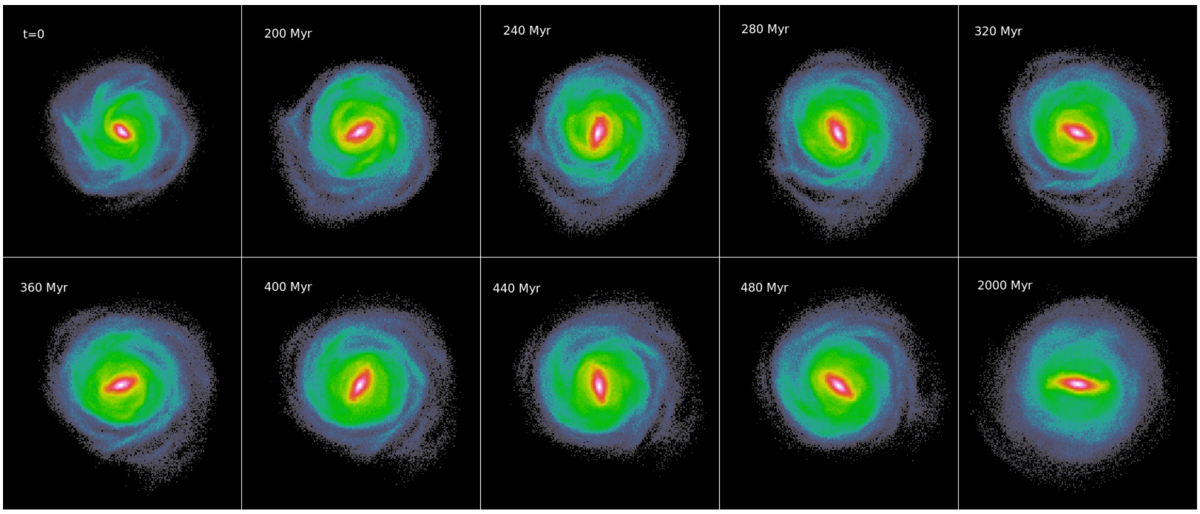

Figure 2. N-body simulations of an off-centred disk and dark matter halo system: the time sequence from t = 200 Myr to t = 480 Myr reveals that the outer lopsidedness is leading in nature (details will appear in a forthcoming paper by Saha, Combes and Jog, in prep). Note that the rotation of the stars in the galaxy is anti-clockwise.

angular momentum in the galaxy - as shown by Saha & Jog (2014), that a combination of trailing spiral plus leading lopsidedness is required for the net angular momentum flow to be outward. Being a large-scale perturbation, lopsidedness can effectively link the inner optical disk to outer cosmic filaments and let the cold gas flow (Bournaud et al. 2005) inward along the galactic plane. However, the other possibility in which lopsidedness could be trailing, would make the angular momentum flow inward and perhaps outflows of gas from the disk. The author acknowledges Anvar Shukurov (who was present in this meeting) for pointing out this possibility and enlightening discussion. The author thanks Chanda Jog for a careful reading of the manuscript.

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