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A Lagrangian View on the Relation between Galaxy and Halo Angular Momentum

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Abstract. Observations combined with basic theoretical considerations suggest that disk galaxies have approximately the same specific angular momentum (sAM) as a typical dark matter halo with the corresponding host mass. The most simplistic interpretation of this newly established result is that the baryons that make up the disks have retained the sAM they obtained from cosmological tidal torques throughout their evolution from the intergalactic medium down to the present-day stars within the galaxy. There is evidence, however, that reality may be substantially more complex than this simplistic picture. Here is a theoretical discussion of the sAM of such baryons through various stages in their evolution. It is argued that the sAM evolution during many of these stages is still not well known, is expected to be substantial, and is probably interrelated despite the diversity of scales and physical processes involved. A strong interplay is necessary to obtain a result that mimics the simplistic 'retention' picture.

Keywords. methods: numerical, galaxies: evolution, galaxies: formation, galaxies: fundamental parameters, galaxies: kinematics and dynamics, galaxies: spiral, galaxies: structure

1. Introduction

Increasingly accurate measurements of the angular momentum content of galaxies have led in recent years to a picture of the scaling relation between galaxy mass, type, and specific angular momentum (sAM) that is generally accepted, even if some important details are still debated. When this picture is extended using simple yet robust theoretical relations between galaxy mass and host dark matter halo mass, the observed angular momenta of galaxies can be directly related to theories of the emergence of angular momentum by cosmological tidal torques. It is then found that the sAM magnitudes of late-type galaxies (and more generally, galactic disks) are approximately equal to the typical sAM magnitudes of dark matter halos that have the assumed host masses. This is often loosely referred to as galactic angular momentum 'retention' or 'conservation', to be contrasted with the galactic angular momentum 'catastrophe' in early cosmological simulations, whereby the sAM magnitudes of galaxies were substantially smaller than those of their halos. This empirical approximate equality demands an explanation.

2. The Lagrangian bookkeeping of angular momentum

The Lagrangian approach adopted here traces the changes over time of the sAM of the individual baryonic particles that eventually constitute disk galaxies. The angular momentum of these particles, with respect to the center of the galaxy in which they eventually end up, changes under the influence of torques, generally both before and after they are incorporated into the galaxy, and both at early times when they are part of the gas phase and at late times when they are already locked into stars.

The quantity of focus here is the ratio between the sAM $\langle j_* \rangle$ of the stars in a typical disk galaxy of a certain mass and the sAM $\langle j_{\mathrm{DM-halo}} \rangle$ of a typical halo that has the mass of these galaxies' typical host halo mass. This ratio, Equation (2.1*a*), is estimated empirically to be very close to unity (e.g. Fall & Romanowsky 2013; see Section 1). This ratio is expanded in two steps, starting with Equation (2.1):

$$\begin{aligned}
\langle j_* \rangle / \langle j_{\mathrm{DM-halo}} \rangle = [& \qquad (2.1a)\\
& f_{\mathrm{in-situ-stars}} \times \\
& j_{\mathrm{in-situ-stars}} \\
& + \qquad (2.1b)\\
& f_{\mathrm{ex-situ-stars}} \times \\
& j_{\mathrm{ex-situ-stars}} \\
& \qquad] / \langle j_{\mathrm{DM-halo,disks}} \rangle \times \qquad (2.1c)\\
& \qquad (\langle j_{\mathrm{DM-halo,disks}} \rangle / \langle j_{\mathrm{DM-halo}} \rangle). \qquad (2.1d)
\end{aligned}$$

This equation describes two distinct ideas. First, the sAM of the stars is broken in Equation (2.1*b*) down to a mass-weighted average of that of the stars formed in-situ (in the main progenitor of the galaxy) and that of the stars formed ex-situ (in galaxies that will later merge onto the main progenitor). Second, the factor $\langle j_{\mathrm{DM-halo,disks}} \rangle$ is added both in the denominator (Equation (2.1*c*)) and the numerator (Equation (2.1*d*)). This factor represents the typical sAM of dark matter halos that are the actual hosts of disk galaxies (in contrast to $\langle j_{\mathrm{DM-halo}} \rangle$ that is the sAM of a typical halo of that same mass). Therefore, Equation (2.1*d*) represents the ratio between the typical spin of dark matter halos that host disk galaxies and the typical spin of all dark matter halos of the same mass. If disk galaxies reside preferentially in dark matter halos with higher spins, as suggested by some simulations (Rodriguez-Gomez et al. 2017), this ratio is larger than unity, possibly on a similar scale to the scatter in the halo spin parameter, $\approx 0.2\,$dex.

The ratio $\langle j_* \rangle / \langle j_{\mathrm{DM-halo}} \rangle$ is expanded further in Equation (2.2) by adding to Equation (2.1) several steps of division and multiplication by identical factors, which result in ratios that represent specific stages in the Lagrangian evolution of baryonic particles.

Equation (2.2*b*) introduces the factor $j_{\mathrm{in-situ-stars@form}}$, which is the sAM of in-situ stars at their birth time. The ratio $(j_{\mathrm{in-situ-stars}}/j_{\mathrm{in-situ-stars@form}})$ then represents the ratio between the final angular momentum content of the in-situ stars (e.g. at $z = 0$) and that at the time of their formation.

Equation (2.2*c*) introduces the factor $j_{\mathrm{in-situ-gas@gal-acc,last}}$, which is the sAM of the baryons that will eventually turn to in-situ stars, but at the last time that they are accreted onto the galaxy, still in the form of gas (what exactly constitutes the 'galaxy' for this purpose is left here unspecified). A similar factor, $j_{\mathrm{in-situ-gas@gal-acc,1st}}$, which is introduced in Equation (2.2*d*), is the sAM of those same baryons, but at the *first* time that they are accreted onto the galaxy. Any given gas parcel may accrete onto the galaxy and then be ejected from it, e.g. under the influence of some sort of feedback, only to then re-accrete onto the galaxy. This can happen several times, and the ratio $(j_{\mathrm{in-situ-gas@gal-acc,last}}/j_{\mathrm{in-situ-gas@gal-acc,1st}})$ in Equation (2.2*d*) represents the angular momentum change between the last and first accretion events, namely during the 'galaxy/halo fountain' (e.g. Oppenheimer et al. 2010). Several independent numerical studies of galactic winds indicate that this is likely to be a gain rather than a loss, perhaps by $\sim 0.2\,$dex (e.g. Brook et al. 2012; Übler et al. 2014; DeFelippis et al. 2017). The factor $(j_{\mathrm{in-situ-stars@form}}/j_{\mathrm{in-situ-gas@gal-acc,last}})$ in Equation (2.2*c*), on the other hand, represents the sAM change of the gas phase within the disk before star-formation.

$$
\begin{aligned}
\langle j_*\rangle/\langle\, j_{\mathrm{DM-halo}}\,\rangle = [\quad & && (2.2a)\\
& f_{\mathrm{in-situ-stars}} \times && \\
& (j_{\mathrm{in-situ-stars}}/j_{\mathrm{in-situ-stars@form}}) \times && (2.2b)\\
& (j_{\mathrm{in-situ-stars@form}}/j_{\mathrm{in-situ-gas@gal-acc,last}}) \times && (2.2c)\\
& (j_{\mathrm{in-situ-gas@gal-acc,last}}/j_{\mathrm{in-situ-gas@gal-acc,1st}}) \times && (2.2d)\\
& (j_{\mathrm{in-situ-gas@gal-acc,1st}}/j_{\mathrm{in-situ-gas@halo-acc}}) \times && (2.2e)\\
& (j_{\mathrm{in-situ-gas@halo-acc}}/j_{\mathrm{in-situ-DM@halo-acc}}) \times && (2.2f)\\
& (j_{\mathrm{in-situ-DM@halo-acc}}/j_{\mathrm{allDM@halo-acc}}) && (2.2g)\\
& + && \\
& f_{\mathrm{ex-situ-stars}} \times && \\
& (j_{\mathrm{ex-situ-stars}}/j_{\mathrm{ex-situ-stars@gal-acc}}) \times && (2.2h)\\
& (j_{\mathrm{ex-situ-stars@gal-acc}}/j_{\mathrm{ex-situ-stars@halo-acc}}) \times && (2.2i)\\
& (j_{\mathrm{ex-situ-stars@halo-acc}}/j_{\mathrm{ex-situ-DM@halo-acc}}) \times && (2.2j)\\
& (j_{\mathrm{ex-situ-DM@halo-acc}}/j_{\mathrm{allDM@halo-acc}}) && (2.2k)\\
& \qquad] \times (j_{\mathrm{allDM@halo-acc}}/\langle j_{\mathrm{DM-halo,disks}}\rangle) \times && (2.2l)\\
& \qquad\quad (\langle j_{\mathrm{DM-halo,disks}}\rangle/\langle j_{\mathrm{DM-halo}}\rangle) && (2.2m)
\end{aligned}
$$

Further, Equation (2.2*e*) introduces $j_{\mathrm{in-situ-gas@halo-acc}}$, the sAM of those same baryons (that eventually form in-situ stars) but at the time of their accretion onto the host halo. Hence, the ratio $(j_{\mathrm{in-situ-gas@gal-acc,1st}}/j_{\mathrm{in-situ-gas@halo-acc}})$ in Equation (2.2*e*) represents the angular momentum change that occurs during the first infall phase from the halo boundary to the galaxy boundary. DeFelippis et al. (2017) found this phase to involve a significant loss of sAM in Illustris, $\approx 0.4\,\mathrm{dex}$ for Milky-Way-mass galaxies.

Equation (2.2*f*) and Equation (2.2*g*) do not represent evolutionary stages like the ones discussed so far, but rather contrast the sAM of different components, all at the time of accretion onto the halo. First, Equation (2.2*f*) introduces $j_{\mathrm{in-situ-DM@halo-acc}}$, which is the sAM of the dark matter that originates in the same Lagrangian region (at very high redshift) as the gas that will eventually become in-situ stars, at the time of its accretion onto the halo. Hence, the ratio $(j_{\mathrm{in-situ-gas@halo-acc}}/j_{\mathrm{in-situ-DM@halo-acc}})$ in Equation (2.2*f*) represents the ratio between the sAM values (at halo accretion time) of the gas (that will become in-situ stars) and its associated dark matter. In the standard picture, this ratio is unity as both are subject to the same large-scale tidal field, but recent work suggests otherwise due to the larger quadrupole moment of the gas, resulting is a ratio that is larger than unity, possibly $\approx 0.2\,\mathrm{dex}$ (Danovich et al. 2015).

Second, Equation (2.2*g*) represents the ratio between the sAM (at halo accretion time) of the dark matter component that is associated with the 'in-situ gas' and that of the total dark matter that accreted onto the halo. This ratio is different from unity if the baryons that eventually form in-situ stars are 'special' in a way that the dark matter associated with them in the Lagrangian sense does not fairly sample the sAM of the entirety of the accreted dark matter. This could be the case due to preferential wind ejection of low angular momentum gas (Brook et al. 2011) or due to preferential accretion from an inside-out cooling flow (Kassin et al. 2012) or from gas filaments (Stewart et al. 2013).

The ex-situ component has a few analogs with the in-situ component: Equation (2.2*k*) with Equation (2.2*g*), Equation (2.2*j*) with Equation (2.2*f*) and Equation (2.2*i*) with Equation (2.2*e*). It is worth noting that DeFelippis et al. (2017) found that in the Illustris simulation the product of Equations (2.2*k*) and (2.2*j*) is ≈ 0.5 dex larger than the product of the analogous Equations (2.2*g*) and (2.2*f*). Further, since no star-formation or ejections are involved, Equation (2.2*h*) consolidates the few steps analogous to those in Equations (2.2*b*) through (2.2*d*), and represents the ratio between the sAM of the ex-situ stars in the final galaxy and the sAM those stars had at the time they were accreted (or merged) into the galaxy. Clearly, merger dynamics can drive this ratio away from unity. Finally, Equation (2.2*l*) could deviate from unity due to merger dynamics of dark matter halos.

3. Discussion

From a Lagrangian point of view, the stellar sAM of a galaxy can be described as the product of some 'initial' sAM of the baryonic particles locked up in the galaxy's stars and a series of changes in their sAM over time. This is described by Equation (2.2), where the 'initial' sAM for each particle is chosen as that at the time of its accretion onto the main progenitor halo of the final galaxy. In addition to these differences between the sAM at different times, a few factors in Equation (2.2) describe relations that connect the sAM of these baryons at accretion to the typical sAM of relevant dark matter halos.

When applied to $z = 0$ disk galaxies, these combined factors relate the stellar sAM of a typical disk galaxy to that of a typical dark matter halo of the appropriate mass, which are constrained empirically to be very similar to one another (Fall & Romanowsky 2013). A ratio so close to unity immediately suggests a simple picture where stars are made of baryons that acquired the same sAM as dark matter before accreting into the halo, that are representative in sAM space to the entirety of baryons that ever accreted onto the halo, and that do not experience angular momentum gains or losses during their evolution inside the halo. This simple, popular picture of 'angular momentum retention' essentially implies that all of the factors in Equation (2.2) are very close to unity.

There is, however, substantial evidence from a diverse set of numerical work that this is not the case. Instead, simulations suggest that many of the ratios in Equation (2.2) are of order $0.1 - 0.5$ dex, as briefly mentioned throughout Section 2. These ratios operate on a large range of scales and under the influence of a diverse set of physical processes. If they were largely independent as might be a expected as a result of this diversity, they would result in a large scatter of $j_*/\langle j_{\rm DM-halo}\rangle$, contrary to empirical results. Explaining the proximity of their overall product to unity would constitute an even bigger challenge.

The conclusion therefore is that the dozen different ratios in Equations (2.2*b*) through (2.2*m*) must be tightly interrelated. Studying the interplay between the diversity of scales and processes contributing to the evolution of baryonic angular momentum is a promising avenue towards understanding the origin of disk galaxies in our Universe.

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