Angular Momentum – Conference Summary

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Abstract. Angular momentum (AM) is a key parameter to understand galaxy formation and evolution. AM originates in tidal torques between proto-structures at turn around, and from this the specific AM is expected to scale as a power-law of slope 2/3 with mass. However, subsequent evolution re-shuffles this through matter accretion from filaments, mergers, star formation and feedback, secular evolution and AM exchange between baryons and dark matter. Outer parts of galaxies are essential to study since they retain most of the AM and the diagnostics of the evolution. Galaxy IFU surveys have recently provided a wealth of kinematical information in the local universe. In the future, we can expect more statistics in the outer parts, and evolution at high z, including atomic gas with SKA.

Keywords. galaxies: bulges – galaxies: dwarf – galaxies: evolution – galaxies: formation – galaxies: general – galaxies: halos

This focus meeting has emphazised the high importance of angular momentum, to understand the formation and evolution of galaxies. It is now used extensively, given the progress of IFU instruments and large galaxy surveys.

Given these recent developments, it is difficult to imagine the debate that was occurring only 60 years ago, about the origin of the angular momentum of galaxies. The theory was first proposed by C. von Weizsäcker that galaxies were originating in large eddies of cosmic turbulence. This theory was followed by many people like G. Gamow, V. Rubin, his student or J. Oort.

Jim Peebles convinced Jan Oort that turbulence was irrelevant, that gravity and tidal torques could create the right amount of angular momentum (AM). For that he computed the torques with N-body simulations (N=90) and showed that the un-dimensional value of the AM $\lambda = \frac{J|E|^{1/2}}{GM^{5/2}} \sim 0.1$, in agreement from analytical estimations.

Since then, dark matter has been introduced, the problem is more complex, since we observe only the angular momentum of the baryons, which has to be related to the dark matter one. How are these acquired, how do they exchange?

The first cosmological simulations with baryons and dark matter, pointed out a serious problem, called the AM catastrophy: the baryons were losing their angular momentum through dynamical friction in mergers in favor of the dark matter, and were accumulating in very small disks at the bottom of the potential wells. Thanks to the feedback, and also the increase in spatial resolution of the simulations (lowering the effects of friction), the AM catastrophy is now limited (e.g. Obreja, Pedrosa and others, this meeting).

1. The "Fall" relation

In their pioneering study, Fall & Efstathiou (1980) take into account baryons and dark matter, which was only made of old stars at this epoch. Fall (1983) considers several scenarios of AM, mass or energy conservation, and concludes that the best scenario

fitting the observations is that of baryonic mass M and AM conserved, while energy is dissipated. In this case, the specific angular momentum, i.e. j= J/M is a power-law function of mass, with slope 2/3. Several parallel lines can be traced, with the same slope in the logj-logM diagram, the highest one is for very late disk galaxies (Sc), while the early-type galaxies (ETG) fall below, due to their high velocity dispersion and low rotation (low V/σ). When only dark matter halos are concerned, the Virial relation combined with the hypothesis that all halos at any mass are formed out of a constant volumic density, leads to the power-law relation with slope 2/3.

Thirty years later Romanowsky & Fall (2012), and Fall & Romanowsky (2013) follow up using the much better determined AM and the much larger statistics provided by modern galaxy surveys. They show that the specific j can be used as a new classification scheme for galaxies, since all the Hubble sequence can be retrieved through parallel lines of 2/3 slopes in the logj-logM baryonic diagram. Many other versions of this diagram and classification were published (Obreschkow & Glazebrook 2014; Cortese *et al.*, 2016; Posti *et al.*, 2018; Sweet *et al.*, 2018).

All these studies led to consider a third parameter in the AM scaling relation: the relation can be viewed in a 3-dimension space, where the third axis is the bulge to total mass ratio B/T (Fall & Romanowsky 2018, also Obreschkow & Glazebrook 2014). The scaling relation M-j-B/T can then be retrieved from the well known Tully-Fisher relation for spirals, and fundamental plane for early-type galaxies. together with a structure relation (for instance the Freeman's relation M $\propto$ R^2 for high-surface brightness spirals).

2. ΛCDM hydro numerical simulations

In the recent years, there has been a burst of simulation papers, interested in following angular momentum, as described by Susana Pedrosa in her review (Pedrosa & Tissera 2015; Genel *et al.* 2015; Teklu *et al.* 2015; Obreja *et al.* 2016, 2018; Lagos *et al.* 2018). Although the most realistic simulations, including star formation and feedback, have solved the AM catastrophy (through the effect of feedback and higher spatial resolution), they have revealed that the scaling relations of specific AM (j) versus baryonic mass are flatter than those observed. The various galaxies follow parallel lines in the logj-logM baryonic diagram, with the B/T parameter increasing towards the bottom right, but the slope of the lines are nearly 1/3.

Although the stellar feedback helps to solve the AM catastrophy, it also excessively thickens galaxy disks. Simulations still predict too massive bulges, and feedback is not sufficient to produce the large number of observed bulgeless galaxies.

James Bullock remarked that very different results (especially in density and temperature) can be obtained in general in cosmological simulations when using different codes, different algorithms (Eulerian, Lagrangian), different resolutions, different recipes for star formation and feedback. However, the results on angular momentum, either of stars (j_*) or gas (j_{gas}) are converging!

Due to dissipation, gaseous filaments are much thinner than dark matter filaments. This means that even before matter enters into galaxies, the specific AM of baryons is 3 times higher than the specific AM of dark matter. This changes the initial conditions in general adopted in semi-analytical models, where baryons and dark matter are assumed to have gained the same specific j through tidal torques. The virial radius R_V changes a lot with time, it increases by a factor ~ 3 from z=1 to z=0. Since j $\propto \lambda$ R_V, it is still possible that the size of baryonic disks are the same at the end. The final j will depend on the AM of the gas accreted in the mean time.

The size ratio between the stellar and dark matter components decreases with time for low M, this was not reproduced before by the semi-analytical models. Now abundance matching is considering sizes, as Rachel Somerville showed in her talk.
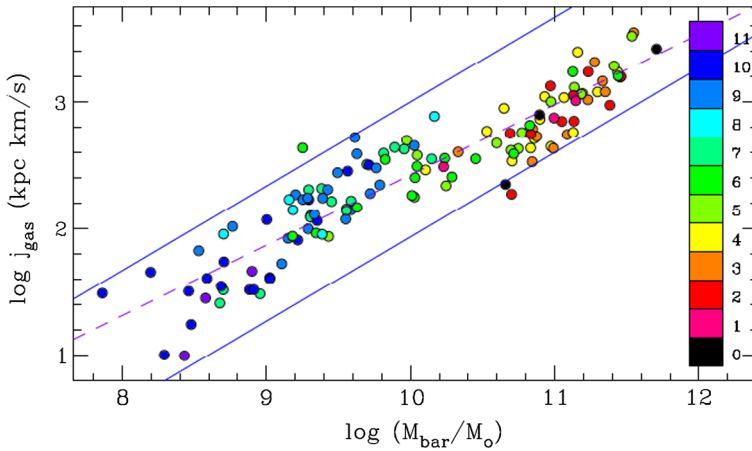
Figure 1. The specific gas angular momentum $j_{gas} \propto R_d \, V_[flat$, versus the baryonic mass $M_{bar} = M_* + M(HI)$, from the 175 spiral galaxies of the SPARC sample of Lelli *et al.* (2016). The atomic gas is rotating maximally (negligible velocity dispersion), and the diagram should follow the upper envelope with a slope 2/3. In fact, the best fit has a slope of 0.55. The colour indicates the galaxy type, 0 being a lenticular, then Sa, Sab .. 9 is Sm, 10 Im and 11 BCD.

3. Why such a scaling relation?

The observation of the $\log j_*$ - $\log M_*$ scaling relations in parallel lines with a slope 2/3 is not straightforward to interpret. The first predictions were done with the total matter, and can be applied essentialy to the dark matter, but it is not obvious why the stars would follow the same relation.

Posti *et al.* (2018a,b) have proposed some biased collapse scenario, to explain why the baryons do not retain all their initial angular momentum. However, the scenario must be rather contrived. Indeed, to derive from the dark matter relation $j_{DM} = J_{DM} / M_{DM} \propto M_{DM}^{2/3}$, the equivalent relation for stars, $j_* \propto f_j \, f_*^{-2/3} \, M_*^{2/3}$, we must assume that the product $f_j \, f_*^{-2/3} = cst$, with $f_j = j_*/j_{DM}$ and $f_* = M_*/M_{DM}$. This last ratio is the well known fraction of stellar mass in a galaxy, which is much below the universal baryon fraction $f_b = 17\%$. From abundance matching, this function peaks for halos of the Milky Way mass, and then falls steeply on each side by 2 orders of magnitude (e.g. Behroozi *et al.* 2010). To interpret the AM observations, we should explain why the f_j ratio has the same behaviour, more exactly $f_j \propto f_*^{2/3}$. the biased collapse scenario proposed by Posti *et al.* (2018b) requires that the outer parts of halos, rich in AM, fail to accrete on the galaxy to form stars. This requirement looks like a conspiracy!

May be the specific AM of baryons does not always follow the scaling relation with slope 2/3. When dwarfs dominated by dark matter and gas are considered, the slope is more near 0.5, as shown in Figure 1.

4. Exchanges of AM – Secular evolution

During galaxy evolution, angular momentum is not frozen either in the baryons or dark matter, but their fraction may vary. AM can be exchanged through spiral arms within the disk, which produces radial migration. Some density breaks in the radial distribution of stars can be attributed to these processes (Athanassoula 2014, Peschken *et al.* 2017). Bars exchange AM with the dark halo, enhancing the formation of bars, which are waves of negative angular momentum. Bars can also be destroyed through torquing the gas, which is driven to the center.

It is interesting to follow AM along cosmic filaments. Galaxies have special orientations with respect to filaments: spirals have their spin parallel to them, while ellipticals, coming from mergers of spirals, have their spin perpendicular to them. The fraction of fast rotators (at least faster than the average) is increasing with the distance to the filaments. Galaxy surveys begin to be able to check all these predictions. (Welker *et al.* 2014, Xiaohu Yang *et al.* 2018)

5. Large complexity in AM evolution

Shy Genel described a long long equation, supposed to control the evolution of the angular momentum, and follow its evolution along a galaxy life, with matter accretion and major mergers. All parameters have to be taken into account, such as the stars formed in situ, or ex-situ, the gas forming stars, and what happens during the feedback, the new star formation from the gas lost, the gas accretion, the minor mergers, the radial migration, the AM exchange with DM. All this is far from the AM prediction from torques at turn-around, and the scaling relation of j $\propto$ M$^{2/3}$.

How can we explain this miracle?

First the envelope at high j applies to pure disks, with 100% efficiency to retain AM. This is relatively obvious if material is almost in circular orbits: this plays the role of an attractor (see the talk from Francesca Rizzo, and Rizzo *et al.* 2018). Then you depart progressively from this attractor, as soon as you form bulges, spheroids, heating the stellar component, without the possibility of gas cooling.

6. Apparent contradictions

AM is a proxy for morphological types, as Fall & Romanowsky (2013) proposed. It is also well known that morphological types are segregated by the densiy of environment (Dressler *et al.*, 1980). Spirals are dominating in the field, while their abundance decreases at high galaxy density in favor of lenticulars and ellipticals. Michele Capellari (2016) in his review article proposes to apply this segregation with density to fast and slow rotators, to replace the spiral/elliptical classification. And indeed, slow rotators are found at density peaks in clusters and groups.

But in her talk, Jenny Greene claimed that there is no evidence of environment effect on the AM of early-type galaxies (Greene *et al.*, 2018). This is obtained from many surveys (MASSIVE, SAMI, MANGA), and the AM depends only on mass.

Another issue when considering AM, is to know whether studies are extending enough in radius. As described beautifully by Matthew Colless, we are witnessing a golden age for kinematical studies of galaxies, with integral field units (IFU) large surveys (Atlas3D, SAMI, CALIFA, MANGA etc.). However, large numbers (thousands) of galaxies are observed only to Re, and hundreds to 2Re. In general you need HI surveys to reach the flat portion of rotation curves, richer in AM.

In the optical, the kinematics of Globular Clusters (GC) show that the spin and ellipticity increase in S0, while they drop in Ellipticals with radius, as described with the SLUGGS survey by Jean Brodie (Brodie & Romanowsky 2016). With Planetary Nebulae (PNe) Pulsoni *et al.* (2018) go much further in radius, to 15-20 Re, where all the AM and signatures of the galaxy formation subsist. There is a large diversity of situations for ETG. Some slow rotators begin to rotate in the outer parts, and among fast rotators, 70% slowly rotate in the outer parts.

The transition radius between in-situ and ex-situ material is $\propto 1/M_*$: i.e. there is more ex-situ material in massive galaxies, formed through mergers. This is perfectly compatible with Illustris simulations (Rodriguez-Gomez *et al.* 2016).

Lagos *et al.* (2018) have measured in detail through simulations how galaxies gain and lose AM by matter accretion and mergers. Dry mergers reduce specific j by 30%, while wet mergers inscrease j by 10%.

7. Atomic gas and dwarfs

As shown in Obreschkow *et al.* (2016) and in Murugeshan's talk, the angular momentum has a large influence in the stability of spiral galaxies and their HI gas fraction. The stability criterion can be written as q = j σ_v/GM $\propto$M$^{-1/3}$, and the HI gas fraction f$_{atm}$ is AM-regulated and also $\propto$M$^{-1/3}$. A related study by Romeo & Mogotsi (2018) on stability and AM regulation includes the thickness of the stellar disk T$_*$, i.e. Q$_* \sim \sigma_v$ T$_*$.

In Chengalur's talk, another discrepancy between simulations and observations was revealed for dwarf galaxies: the specific AM of baryons j$_b$ increases below a baryonic mass of $10^{9.1}$M$_\odot$, with respect to the M$^{2/3}$ expected scaling relation (Kurapati *et al.* 2018). For these dwarfs, disks become thicker due to star formation feedback, and to the shallow potential well. There is no dependency on large-scale environment, so this is not due to possible accretion. Another explanation is that such dwarfs are dominated by dark matter, therefore their observed rotational velocity is much higher with respect to their visible mass (M$_{bar}$) than for spiral of larger masses.

In FIRE simulations, dwarfs have very low rotational support: the large SF feedback gives them a rounder shape (El-Badry *et al.* 2018), and their specific j falls below the M$^{2/3}$ scaling relation.

8. Perspectives

May be all diagnostics of galaxy evolution are retained in the outer parts: accretion, ex-situ star formation, etc. In that case PNe are the best tracers of AM and evolution. It is of prime importance to acquire more statistics, for instance in the Hector IFS survey, 10^5 galaxies will be obtained. Also other parameters must be followed, metallicity, stellar populations (see Kassin's talk).

With ELT and JWST, it will be possible to track the evolution with redshift. We know already that galaxies become clumpy at $z > 2$ and have much lower j$_*$. While it is predicted that j$_* \sim (1+z)^{-1/2}$ (Obreschkow *et al.* 2015), F. Fraternali in his talk found no evolution with z. [*Remark by the co-editor, Danail Obreschkow: It seems important to bear in mind that the approximation $j \propto (1+z)^{-1/2}$ for dark haloes of fixed mass only applies to the matter-dominated era ($z \gtrsim 1$). Explicitly, neglecting the weak evolution of j expected from the cosmic evolution of the virial over-density $\Delta_{\rm vir}$, we find $\langle j/M^{2/3} \rangle \propto E^{-1/3}(z) = (\Omega_m(1+z)^3 + \Omega_\Lambda)^{-1/6}$, which asymptotes to $\Omega_m^{-1/6}(1+z)^{-1/2}$ for $z \to \infty$, but Taylor-expands to $(1+z)^{-\Omega_m/2} \approx (1+z)^{-0.15}$ around $z = 0$.*]

It is also paramount to study external accretion of gas, which contains a lot of AM, is at the origin of warps, etc. HI maps are badly needed at intermediate and high z; in the future SKA will provide a large number of these gas maps.

References

Athanassoula, E.: 2014, *MNRAS*, 438, L81
Behroozi, P. S., Conroy, C., Wechsler, R. H.: 2010, *ApJ*, 717, 379
Brodie, J., Romanowsky, A. J.: 2016, *IAUS*, 317, 190
Bullock, J. S., Boylan-Kolchin, M.: 2017, *ARA&A*, 55, 343
Capellari, M.: 2016, *ARA&A*, 54, 597
Cortese, L., Fogarty, L. M. R., Bekki, K. *et al.*: 2016 *MNRAS*, 463, 170
Dressler, A.: 1980 *ApJ*, 236, 351
El-Badry, K., Quataert, E., Wetzel, A. *et al.*: 2018, *MNRAS*, 473, 1930
Fall, S. M., Efstathiou, G.: 1980, *MNRAS*, 193, 189
Fall, S. M.: 1983, *IAUS*, 100, 391
Fall, S. M., Romanowsky, A. J.: 2013, *ApJ*, 769, L26
Fall, S. M., Romanowsky, A. J.: 2018, *ApJ*, in press, arXiv180802525
Genel, S., Fall, S. M., Hernquist, L. *et al.*: 2015, *ApJ*, 804, 40L

Greene, J. E., Leauthaud, A., Emsellem, E. *et al.*: 2018, *ApJ*, 852, 36

Kurapati, S., Chengalur, J. N., Pustilnik, S., Kamphuis, P.: 2018, *MNRAS*, 479, 228

Lagos, C., Stevens, A. R. H., Bower, R. G. *et al.*: 2018, *MNRAS*, 473, 4956

Lelli, F., McGaugh, S. S., Schombert, J. M.: 2016, *AJ*, 152, 157

Obreja, A., Stinson, G. S., Dutton, A. A. *et al.*: 2016, *MNRAS*, 459, 467

Obreja, A., Dutton, A. A., Maccio, A. V. *et al.*: 2018, *MNRAS*, in press, arXiv180406635

Obreschkow, D., Glazebrook, K.: 2014, *ApJ*, 784, 26

Obreschkow, D., Glazebrook, K., Bassett, R. *et al.*: 2015, *ApJ*, 815, 97

Obreschkow, D., Glazebrook, K., Kilborn, V., Lutz, K.: 2016 *ApJ*, 824, L26

Pedrosa, S. E., Tissera, P. B.: 2015, *A&A*, 584, A43

Peschken, N., Athanassoula, E., Rodionov, S. A.: 2017, *MNRAS*, 468, 994

Posti, L., Fraternali, F., Di Teodoro, E. M., Pezzulli, G.: 2018a, *A&A*, 612, L6

Posti, L., Pezzulli, G., Fraternali, F., Di Teodoro, E. M.: 2018b, *MNRAS*, 475, 232

Pulsoni, C., Gerhard, O., Arnaboldi, M. *et al.*: 2018, *A&A*, in press, arXiv171205833

Rizzo, F., Fraternali, F., Iorio, G.: 2018, *MNRAS*, 476, 2137

Rodriguez-Gomez, V., Pillepich, A., Sales, L. V. *et al.*: 2016, *MNRAS*, 458, 2371

Romanowsky, A. J., Fall, S.M: 2012, *ApJS*, 203, 17

Romeo, A. B., Mogotsi, K. M.: 2018, *MNRAS*, 480, L23

Somerville, R. S., Behroozi, P., Pandya, V. *et al.*: 2018, *MNRAS*, 473, 2714

Sweet, S. M., Fisher, D., Glazebrook, K. *et al.*: 2018, *ApJ*, 860, 37

Teklu, A. F., Remus, R.-S., Dolag, K. *et al.*: 2015, *ApJ*, 812, 29

Welker, C., Devriendt, J., Dubois, Y.; Pichon, C., Peirani, S.: 2014, *MNRAS*, 445, L46

Yang, X., Zhang, Y., Wang, H. *et al.*: 2018, *ApJ*, 860, 30