

Focus Meeting: Galactic Angular Momentum

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Abstract. The 6th Focus Meeting (FM6) at the XXXth IAU GA 2018 aimed at overviewing the rise in angular momentum (AM) science seen in the last 10 years and debating new emerging views on galaxy evolution. The foundational works on galaxy formation of the 1970s and 80s clearly exposed the fundamental role of AM, suspected since the time of Kant. However, quantitative progress on galactic AM remained hampered by observational and theoretical obstacles. Only in the last 10 years, numerical simulations began to produce galactic disks with realistic AM. Simultaneously, the fast rise of Integral Field Spectroscopy (IFS) and millimetre/radio interferometry have opened the door for systematic AM measurements, across representative samples and cosmic volumes. The FM bridged between cutting-edge observational programs and leading simulations in order to review, debate and resolve core issues on AM science, ranging from galactic substructure (e.g. gas fraction, turbulence, clumps) to global properties (e.g. size evolution, morphologies) and cosmology (spin alignment, cosmic origin of AM). The co-chairs and SOC members strived to assemble a representative selection of leading scientists in the field, while adhering to principles of equal opportunity and inclusivity.

Keywords. Galaxies: general – Galaxies: formation – Galaxies: evolution – Galaxies: galaxies: fundamental parameters – Galaxies: halos – Galaxies: bulges – Cosmology: theory.

1. Rationale: state of affairs motivating this meeting

In the standard model of galaxy formation, cold dark matter (CDM) haloes grow from primordial density fluctuations while acquiring AM through tidal torques. Galactic disks then condense at the halo centres by radiative dissipation of energy. The cooling baryons naturally exchange AM with their haloes, but the mass-size relation of local star-forming galaxies suggests that, on average, the specific AM of the baryons must remain approximately conserved. Explaining this apparent conservation has been a long-standing problem for theory: until recently (early 2010), hydro-gravitational simulations (using both particle-based and grid-based techniques) systematically failed at reproducing disks as large and thin as normal late-type galaxies, such as the Milky Way. The simulated galaxies were deficient in AM, making them too small and too bulgy – a problem so severe that it became known as the ‘AM catastrophe’. Overcoming this catastrophe via increased computing power and refined feedback physics has been one of the major recent success stories of galaxy simulations. However, there is still debate about exactly how this is achieved: is outflowing gas torqued so that re-accreted gas has higher AM, is low AM material preferentially removed from galaxies, or do the winds prevent loss of AM by making inflows smoother?

A certain result from the AM catastrophe is that AM is one of the most critical quantities for explaining galaxy morphologies, opening a new bridge between theory and observation. The recent fast rise of IFS has enabled simultaneous measurements of the composition and Doppler velocity at every position in a 2D galaxy image, hence enabling

a pixel-by-pixel integration of the AM. Such measurements of AM in early-type galaxies (ATLAS^{3D} survey, 2011) led to the surprising discovery that most of these seemingly featureless objects exhibit a rotational structure akin to that of normal spiral galaxies, thus containing more AM than previously suspected. The fewer actual ‘slow-rotators’ host up to ten times less AM at a fixed mass. AM thus offers a more fundamental, albeit harder to measure, classification of galaxy types than the classical Hubble sequence. This conclusion was cemented by recent AM measurements in spiral galaxies, again suggesting that the Hubble morphology sequence might be substituted for a more physical classification by AM. The precise form of this new AM-based classification scheme remains nonetheless a source of much argument. Many recent hydro-gravitational simulations (e.g. Illustris, EAGLE, Horizon, Magneticum, MAGICC, CLUES, NIHAO) contribute to this discussion, as do most major kinematic observing programs. Prominent examples include optical IFS/IFS-like surveys (e.g. ATLAS^{3D}, CALIFA, MaNGA, SLUGGS, P.N.S, KROSS, SAMI Survey), interferometric radio surveys (e.g. THINGS on the VLA) and many other kinematic observations on modern and future instruments (e.g. KMOS, MUSE, SINFONI, HECTOR, ALMA, NOEMA, JWST, SKA and precursors).

The strong correlations between morphology and AM of local galaxies raises the question as to whether the cosmic evolution of morphologies is paralleled, or even driven, by the evolution of AM. Observationally, the Hubble Space Telescope’s (HST) exquisite spatial resolution showed that star-forming galaxies at redshift $z > 1$ had very different structures to local grand-design spirals: The rapidly star-forming early galaxies showed a predominance of ‘clumpy’ and ‘irregular’ morphologies caused by super-giant (300 to 1000 pc) star-forming complexes. The physical origin of these clumpy morphologies and the processes that drive the large star formation rates are currently heavily debated. High- z IFS observations surprised with the finding that most of the clumpy star-forming galaxies have a regular, rotating disk structure. Interestingly, the emission line velocity dispersions appear to be about five times larger than in mass-matched local disks, which presents a major puzzle, because high velocity dispersions are predicted to stabilise the disks, preventing them from fragmenting into star-forming clumps. While high gas fractions could explain instabilities in spite of high dispersion, deep IFS studies (on Keck-OSIRIS, Gemini-GMOS) in rare nearby clumpy disks suggest that low AM is the dominant driver of instabilities. This motivates the arguable conjecture that the cosmic evolution of AM plays indeed a major role in the morphological transformation of the star-forming population – a hypothesis that was debated at this FM.

Answers to key questions regarding the cosmic evolution of AM are about to emerge from new high- z IFS observations on 8m-class telescopes (e.g. KMOS and MUSE on the VLT), as well as from an array of cosmological hydro-gravitational simulations (see above). Meanwhile multi-wavelength surveys are about to pile up evidence for strong correlations between AM and various baryonic processes (e.g. star formation rates, the transition from atomic to molecular gas and the growth of black holes). Moreover, ongoing and near-future surveys (see above) are about to expand AM science to smaller and larger scales: for the first time, enough spatially resolved velocity maps are available to systematically study the spatial distribution of the baryon AM in galaxies, which offers a nuanced test of different evolution models. On large scales, the number and spatial completeness of galaxies mapped using IFS are about to become sufficient to test the weak correlations between AM and cosmic large scale structure predicted by simulations.

In summary, observational and computational studies of AM have induced major progress in galaxy evolution theory over the last decade. The rich and fast evolving diversity of AM-related topics and the need for bringing observers and theoreticians together were the primary drivers for this FM at the XXXth IAU GA 2018.

2. Contributions: proceedings, talks, posters

2.1. Proceedings

All our proceedings are published and indexed online on Zenodo. A subset of forty pages of substantial reviews and summaries are additionally printed in *Focus in Astronomy* by Cambridge University Press.

Proceedings of oral presentations published on Zenodo and in Focus in Astronomy

- Danail Obreschkow, “Focus Meeting: Galactic Angular Momentum”.
- Françoise Combes, “Angular Momentum – Conference Summary”.
- P. J. E. Peebles, “On the History and Present Situation”.
- Claudia del P. Lagos, “Angular Momentum Evolution of Galaxies: the Perspective of Hydrodynamical Simulations”.
- Matthew Colless, “Emerging Angular Momentum Physics from Kinematic Surveys”.
- Susana Pedrosa, “The Fundamental Physics of Angular Momentum Evolution in a Λ CDM Scenario”.
- Filippo Fraternali and Gabriele Pezzulli, “Angular Momentum Accretion onto Disc Galaxies”.

Proceedings of oral presentations published online on Zenodo

- Daniel DeFelippis, et al., “Baryonic Angular Momentum in Simulated Disks: The CGM”.
- Kareem El-Badry, “The Interplay between Galactic Angular Momentum and Morphology”.
- Michael Fall & Aaron Romanowsky, “New Perspectives on Galactic Angular Momentum, Galaxy Formation, and the Hubble Sequence”.
- Shy Genel, “A Lagrangian View on the Relation between Galaxy and Halo Angular Momentum”.
- Chandrashekar Murugesan, et al., “Does Angular Momentum Regulate the Atomic Gas Content in H I-deficient Spirals?”.
- Aura Obreja, “Galaxy Simulations after the Angular Momentum Catastrophe”.
- Lorenzo Posti, “Angular Momentum-Mass Law for Discs in the Nearby Universe”.
- Claudia Pulsoni, et al., “The extended Planetary Nebula Spectrograph (ePN.S) Early Type Galaxy Survey: the Kinematic Diversity of Stellar Halos”.
- Rhea-Silvia Remus, et al., “Connecting Angular Momentum, Mass and Morphology: Insights from the Magneticum Simulations”.
- Francesca Rizzo, “S0 Galaxies Are Faded Spirals: Clues from their Angular Momentum Content”.
- Kanak Saha, “Angular Momentum Transport in Lopsided Galaxies”.
- Sarah M. Sweet, et al., “Spatially Resolved Galaxy Angular Momentum”.
- Charlotte Welker, “Stellar Kinematics in the Cosmic Web: Lessons from the SAMI Survey and the Horizon-AGN Simulation”.

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2.2. *Oral presentations*

All oral presentations are available online at <http://gam18.icrar.org>. The abstracts of all oral presentations, other than summaries and addresses, are available online at <https://astronomy2018.univie.ac.at/abstractsFM06>.

Each proceeding listed in §2.1 corresponds to an oral presentation. The titles of the additional oral presentations are:

- Jenny Greene, “The role of AM in central and satellite ETGs”.
- Xiaohu Yang, “Observing various alignment signals of galaxies”.
- James Bullock, “From halos to disks: the physics of AM profiles”.
- Rhea-Silvia Remus, “Connecting AM, mass and morphology: insights from the Magneticum simulations”.
- Michele Cappellari, “Surprises in kinematic observations of ETGs”.
- Jean Brodie (presented by presented by R.-S. Remus, “Understanding the assembly histories of ETGs from the kinematics of stars and globular clusters”.
- Jayaram Chengalur, “Expanding AM measurements to dwarf galaxies”.
- Sarah Blyth, “Future high-redshift observations of H I kinematics”.
- Lia Athanassoula, “AM and the evolution of disc galaxies”.
- Susan Kassin, “The Assembly of Disk Galaxies: From Keck to JWST”.
- Caroline Foster, “Spinning galaxies into shape”.
- Rachel Somerville, “On the relationship between galaxy and halo size and spin”.
- Martha Tabor, “Untangling galaxy components: the AM of bulges and disks in the MaNGA survey”.
- Hoseung Choi, “Spin evolution of Horizon-AGN ETGs”.
- Anelise Audibert, “Morphology and kinematics of the cold gas inside the central kiloparsec of nearby AGN with ALMA”.
- Arianna Di Cintio, “Poster overview session”.

2.3. *Posters*

The titles and abstracts of all posters are available online at <https://astronomy2018.univie.ac.at/PosterAbstracts/posterFM06>

Posters were presented by Valentina Abril Melgarejo, Sung-Ho An, Aleksandra Antipova, Joan Font (for John Beckman), Sebastian Bustamante, Bernardo Cervantes Sodi, Horacio Dottori, Joan Font, Shy Genel, Jesus A. Gomez-Lopez, Katherine Harborne, Ivan Kacala, Eunbin Kim, Keiichi Kodaira, Baerbel Koribalski, Andrea Lapi, Jie Li, Katharina Lutz, Brisa Mancillas-Vaquera, Kyoko Onishi, Sol Rosito, Luis Enrique Prez Montao, Nicolas Peschken, Antonio J. Porras, Christoph Saulder, Felix Schulze, Yun-Kyeong Sheen, Shraavan Shetty, Olga Silchenko, Matthias Steinmetz and Jolanta Zjupa.

3. **People: organisers, presenters, attendees**

The Scientific Organising Committee (SOC) consisted of 16 members assembled from 12 countries and 5 continents, including senior astronomers as well as earlier career researchers. Collectively, the SOC members led and won the original proposal to host this FM at the XXXth IAU GA, put forward the list of invited speakers, selected the contributed talks and posters, chaired most of the sessions during the meeting and edited the proceedings. The organisation of the local logistics of the entire General Assembly

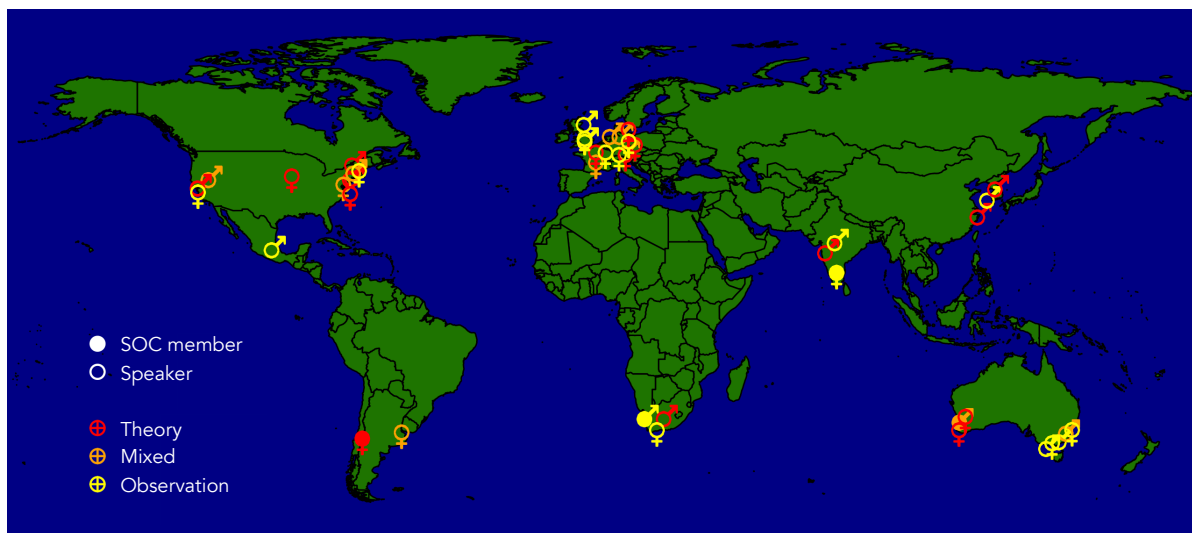


Figure 1. The geographical distribution of the SOC members and selected speakers, as well as their expertise, was fairly balanced, apart from a natural European clustering.

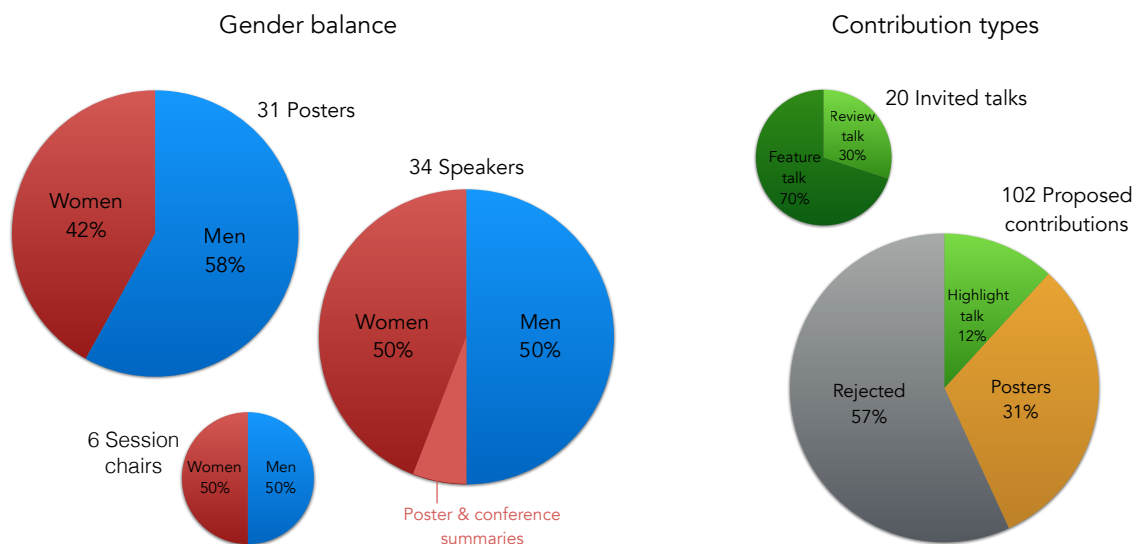


Figure 2. LEFT: An almost 50-50 gender balance was achieved for presenters and session chairs during the meeting. RIGHT: In addition to 20 invited talks, 102 proposal for additional talks and posters were received. Of those submissions, 31 were assigned a poster and 14 a short talk.

was handled by a dedicated LOC, headed by Gerhard Hensler, in conjunction with the IAU secretary and a national organising committee.

The SOC invited 20 high-level speakers for 20-min “review talks” and 14-min “feature talks” and selected 14 submitted proposals for 9-min “highlight talks”. These talks were paralleled by a poster exhibition featuring the 31 highest-ranked additional submissions, out of 102 submissions in total (see Figure 2, right). According to NASA ADS, 10 of the 15 highest cited researchers on “Galactic AM” (and similar) of the last 20 years were present among the speakers and SOC members, making this meeting representative of the state-of-the-art.

Figures 1 and 2 (left) show a balanced mix of speakers in terms of gender and geographical distribution, bar a natural over-density in Europe, the site of many world-leading academic institutions and the location of the meeting. Figure 1 also reveals a fairly balanced mix of theoretical and observational expertise among the SOC members and

speakers. Furthermore, the list of presenters included a wide range of seniority, spanning from early-career researchers, even first-time presenters, to very senior astronomers, most notably Prof James Peebles, one of the most influential theoretical cosmologists of the last 50 years and a key player in early AM science. Many PhD students and several Master students were selected for poster presentations.

In total, 374 participants of the General Assembly signed up for this meeting, but other participants were free to walk in. We estimate that 400–500 people attended parts of the meeting, with an average of 150 present at any one time.

4. Acknowledgements

On behalf of the whole SOC, I sincerely thank all our speakers and poster presenters for the high standard of their contributions. Many invited speakers, especially those presenting a review, made a respectable effort to paint a holistic picture of recent results and persisting questions. These presentations, which extended well beyond the presenters' personal research, were particularly important and deserve a special acknowledgement. I extend this gratitude to all those, whose proposal was not selected for a presentation. Undoubtedly, most rejected submissions would have been on par with the high standard of the meeting and would have enriched the scientific discussion. Those submissions helped us gauge the collective interest of our attendees and optimise the program. I also wish to thank the estimated 400–500 people who attended (parts of) this meeting and who contributed through challenging and interesting questions.

On behalf of all attendees and SOC members, I would like to send a warm thank you to the local organisers in Vienna, especially to Gerhard Hensler and his team, to the excellent technical crew at the convention centre, and to the overall coordination by the IAU, in particular to the then General Secretary Piero Benvenuti and his successor Teresa Lago, who is the chief editor of the proceedings published in *Focus in Astronomy*.

As the chair of the SOC, I would like to express my fullest gratitude to all SOC members for their enormous help from the early vision (mid 2016) to successful completion (late 2018) of this meeting – a two-year long process, which I would walk again with this driven team of brilliant scientists and reliable organisers.