# Scientific Highlights for IAU Symposium 373, "Resolving the Rise and Fall of Star Formation in Galaxies"

# Dates and Location: 9-11 August 2022, Busan, Republic of Korea (IAU GA XXXI)

The three talks in the plenary session (recorded and placed on the IAU YouTube channel) provide a snapshot of the themes of the Symposium. Adam Leroy (United States) reviewed recent advances in resolving the baryon cycle between gas and stars in nearby galaxies. He stressed the sensitivity of molecular cloud properties to galactic environment, the short lifetimes of molecular clouds (relative to the gas consumption timescale) and the consequent low efficiency of star formation. Annalisa Pillepich (Germany) detailed advances in large-volume cosmological simulations that model the coupled evolution of dark matter, stars, gas, and massive black holes. While still limited to resolutions of >100 pc and thus unable to resolve the full multiphase structure of the interstellar medium, these simulations reproduce the broad characteristics of the galaxy population and predict the existence of large, hot bipolar cavities blown by active galactic nuclei (AGN)—predictions which are now starting to be confirmed. Yingjie Peng (China) addressed the comparison of observations and theory from an evolutionary perspective, and sounded a note of caution about current simulations. He noted that while these simulations have been tuned to reproduce the evolution of the stellar mass function, they have mixed success in matching observations of quenching, star formation rate per stellar mass, and merger rate—yet the latter quantities are what ultimately determine the stellar mass function.

The oral sessions over three days surveyed a broad range of results, with ALMA observations playing a prominent role. Much of the discussion centered on three classic diagrams. First, the rise and fall of cosmic star formation with time, which is now well-established, albeit with considerable uncertainty at the highest redshifts because the fraction of optically obscured star formation is still poorly constrained and may be higher than previously thought. The decline of star formation in recent epochs is often attributed to AGN feedback, though clear evidence of feedback removing the gas reservoir remains scant. Second, the star formation rate - stellar mass diagram, on which the "star-forming main sequence" is located. The properties of main sequence galaxies are now well characterized and well reproduced in simulations, but what causes galaxies to leave the main sequence remains an important unsolved problem, and simulations still have difficulty reproducing the guiescent galaxy population. Finally, the star formation rate - gas mass diagram, commonly referred to as the Kennicutt-Schmidt relation. While this relation is remarkably invariant with cosmic time, variations among galaxies and across redshift do seem to occur, although possibly arising from differences in the type of gas being probed (dense vs. diffuse) and the systematics involved in accurately measuring both quantities.

## **Executive Summary for IAU Symposium 373**

Star formation is relevant to nearly every area in astrophysics, from planetary science to galaxy evolution. Yet the physical processes that determine the rate of star formation and its spatial and

temporal distribution are still poorly understood. IAU Symposium 373 focused on the impact that resolved studies of galaxies, both observational and theoretical, are having on the understanding of star formation on all scales. The goal of the meeting was to highlight the latest advances in understanding star formation in its galactic context (via resolved studies) and how it drives galaxy evolution.

The general picture of galaxy evolution is one of steady, inside-out growth and maturation of galaxy disks accompanied by rapid aging of the highest mass galaxies due to internal and/or external processes that inhibit star formation. Yet the roles of various factors in the aging process - e.g., galaxy mergers, gas consumption, environmental refueling (or lack thereof), and nuclear activity - remain poorly understood. Integrated over the galaxy population, the effect of galactic aging can be seen as a dramatic decline in the cosmic star formation rate since the epoch of "cosmic noon" at a redshift z~2. This is the "rise and fall of star formation" as measured across the galaxy population.

For galaxies that are still forming stars today, the star formation rate is strongly correlated with the stellar mass and the supply of molecular gas. However, the exact form of these star formation (scaling) relations, their universality, and the role of additional physical parameters (including galaxy conditions and environment) remain important topics of discussion. Moreover, these relations have provided limited insight into the cessation of star formation, commonly termed "quenching", which can occur locally well before the star formation of an entire galaxy shuts down. This is the "rise and fall of star formation" as measured within individual galaxies.

Until fairly recently, the communities that studied star formation in galaxies were divided into those who studied small scale processes at high resolution in very nearby galaxies (including our own), and those who treated star formation as a galaxy-scale process, studied out to high redshifts. In the last decade, the study of star formation has been undergoing a revolution that has connected these communities – thanks to a combination of new interferometric facilities in the radio and sub-mm (e.g., ALMA, NOEMA, SMA) and integral field units (IFUs) in the optical (VLT MUSE and surveys such as CALIFA, MaNGA, and SAMI), as well as advances in computational models that are starting to connect sub-galactic and cosmological domains. A key advance has been the ability to spatially resolve the sub-kiloparsec scales on which star formation relations are established, bridging the gap between resolved studies in the local neighborhood and large-scale galaxy surveys. Helping to interpret these new data are a new generation of simulations and new techniques for confronting them with observations.

IAU Symposium 373, running from 9-11 August 2022 at the XXXI General Assembly meeting in Busan, Republic of Korea, provided an opportunity to share the latest findings in the field of star formation on sub-galactic scales. It was divided into the following topical sessions:

- 1. Scales of Star Formation: From Molecular Cores to Galaxies
- 2. Sustaining Star Formation: Gas Conditions & Environment
- 3. The Decline of Star Formation: Feedback, Fuel Shortage or Inefficiency?
- 4. The Rise and Fall of Star Formation Across Cosmic Time
- 5. Regulation of Star Formation and the Evolution of Galaxies

A key objective for the meeting was to synthesize our knowledge of how star formation is regulated within individual galaxies and leverage it to understand the rise and fall of the star formation rate on cosmological timescales. To this end, the organizers solicited talks from experts in different methodologies, addressing star formation at both low and high redshift. The resulting program of talks highlighted the youth and diversity of the field, and hopefully facilitated many new collaborations, despite the ongoing challenges to conference participation imposed by international conditions at the time. The symposium was particularly well-suited for a General Assembly because many astronomers are interested in aspects of star formation (e.g., in relation to galaxy evolution) but may not consider themselves star formation specialists.

The scientific program included 21 invited talks (11 by female speakers) and 36 contributed talks (20 by female speakers). The geographic distribution of speakers was 18 (31%) from East Asia, 15 (26%) from North America, 14 (25%) from Europe, 7 (12%) from Australia, 2 (4%) from South America, and 1 (2%) from Africa. Owing to the COVID-19 pandemic, 20 (35%) of the talks were given remotely.

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Division J, Galaxies and Cosmology

#### Other Supporting Divisions and Commissions:

- Division H, Interstellar Matter and Local Universe
- Commission J1, Galaxy Spectral Energy Distributions
- Commission B4, Radio Astronomy

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SESSION 4	8:15-8:45	Adam Leroy (invited)	USA	Star Forming Galaxies Resolved into their Fundamental Units
SESSION 4  The Decline of Star Formation: Feedback, Fuel shortage or Inefficiency?  Wed 10 Aug  S373 - 4  Chair: Karen Masters  10:30-10:50  Bianca Poggianti (invited; remote)  Italy  Star forming clumps, rates and histories: the spatially resolved view in dense galaxy environments  10:50-11:10  Ji-Hoon Kim (invited)  Korea  How Feedback Affects Stellar and Galactic Evolution: Perspectives in the Era of High-resolution  Simulations  Simulations  The SAMI Galaxy Survey: Using concentrated star formation and stellar population ages to  understand environmental quenching  11:30-11:40  Camila De Sá Freitas  Germany  Quenching, bursting and galaxy shapes: colour transformation as a function of morphology  11:40-11:50  Vuri Oku  Japan  Osaka feedback modell it. Modeling supernovae based on high-resolution simulations  Wed 10 Aug  S373 - 5  Chair: Bruce Elmegreen  13:30-13:50  14:10-14:20  Gingzheng Yu (remote)  China  On the HI Content of MaNGA Major Merger Pairs  Lihwai Lin (invited; remote)  China  UK  MISDOM: Molecular cloud perite and a sar function general and external quenching mechanisms on various timescales.  SESSION 5  The Rise and Fall of Star Formation Across Cosmic Time  Wed 10 Aug  S373 - 6  Chair: Karrin Menéndez-Delmestre  Chair: Karrin Menéndez-Delmestre  Wed 10 Aug  S373 - 6  Chair: Karrin Menéndez-Delmestre  Chair: Karrin Menéndez-	8:45-9:15	Annalisa Pillepich (invited)	Germany	Star formation and its decline across the bodies of galaxies and cosmic environments
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16:25-16:35 Po-Feng Wu (remote) Taiwan Understanding quenching at high redshifts from local IFU surveys	13:30-13:50 13:50-14:10 14:10-14:20 14:20-14:30 14:30-14:40 14:40-14:50  SESSION 5 Wed 10 Aug 15:15-15:35 15:35-15:55 15:55-16:05	Alberto Bolatto (invited) Lihwai Lin (invited; remote) Qingzheng Yu (remote) Yang Sun Martin Bureau Cressida Cleland  The Rise and Fall of Star Formation A \$373 - 6 Miroslava Dessauges-Zavadsky (invited; remote)  Itziar Aretxaga (invited)  Marcie Mun (remote)  Chelsea Sharon	Taiwan China USA UK UK Seross Cosmic Time Switzerland Mexico Australia Singapore	Chair: Bruce Elmegreen Using Observables to Test Models What drives galaxies from the main sequence to the green valley? On the HI Content of MaNGA Major Merger Pairs Evolution of Bulk Gas Flows from Starburst to Quiescent Galaxies WISDOM: Molecular cloud properties and star-formation quenching Investigating internal and external quenching mechanisms on various timescales.  Chair: Karín Menéndez-Delmestre Dissecting the star formation process at molecular cloud scale 8 billion years ago  (Sub-)mm continuum surveys: mapping the dusty galaxy contribution to the star formation history  Spatially resolving the star formation activity of galaxies at 3 - 4 Gyrs of lookback time with MAGPI Characterizing the Resolved Schmidt-Kennicutt Relation Using Different SFR Tracers at Cosmic Noon
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Thu 11 Aug	S373 - 7		Chair: Ena Choi	
10:30-10:50	Elisabete da Cunha (invited; remote)	Australia	The properties of star-forming galaxies in the first 5 billion years of cosmic history	
10:50-11:10	Manuel Aravena (invited)	Chile	The supply of gas through cosmic time: insights on the galaxy assembly at early epochs	
11:10-11:20	Kathryn Grasha	Australia	The Chemical Evolution of Spiral Galaxies from Start of Cosmic Dawn to Today	
11:20-11:30	Ana Carolina Posses Nascimento	Chile	Resolving the ISM structure and kinematics in two star forming galaxies at z ~ 6	
11:30-11:40	Massissilia Hamadouche	UK	The evolution of quiescent galaxies from z = 0.6 to z = 1.3	
11:40-11:50	Tjitske Starkenburg (remote)	USA	The evolutionary path of quenching galaxies and comparisons between theoretical and observational samples	
SESSION 6	Regulation of Star Formation and the Evolution of Galaxies			
Thu 11 Aug	\$373 - 8		Chair: Martin Bureau	
13:30-13:50	Vincenzo Mainieri (invited; remote)	Germany	The role of AGN outflows and jets in regulating star formation	
13:50-14:10	Kentaro Nagamine (invited)	Japan	Feedback models in galaxy simulations and probing their impact using cosmological hydrodynamic simulations	
14:10-14:20	Hannah Stacey	Germany	How dusty quasars shape the inner regions of galaxies at cosmic noon	
14:20-14:30	Boris Sindhu Kalita (remote)	France	Direct glimpse at accretion-driven galaxy evolution in the protocluster-era	
14:30-14:40	Kohei Ichikawa (remote)	Japan	Rapidly growing supermassive black holes in extremely radio-loud galaxies	
14:40-14:50	Нао Не	Canada	Analysis of giant molecular cloud properties on FIRE-2 Mergers	
Thu 11 Aug	S373 - 9		Chair: Daniel Dale	
15:15-15:35	Eve Ostriker (invited)	USA	Feedback and the Emergence of Star Formation Scaling Relations	
15:35-15:45	Chang-Goo Kim	USA	How are Galactic Star Formation Rates Regulated? Role of Supernovae, UV Radiation, and Magnetic fields	
15:45-16:05	Rachel Somerville (invited)	USA	Modeling star formation across a vast range of spatial scales	
16:05-16:15	Dandan Xu (remote)	China	Linking the rise and fall of star formation with the large-scale angular-momentum environment through circumgalactic medium	
16:15-16:25	Jaeyeon Kim	Germany	Environmental dependences of molecular cloud lifecycle in 60 main sequence galaxies	
16:25-16:35	Juan Espejo	Australia	What drives disk instabilities and star-forming clumps in galaxies at Cosmic Noon?	