

## 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 quiescent 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  $z \sim 2$ . 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.

#### **Scientific Organizing Committee**

- Tony Wong (U. Illinois, USA): co-chair
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- Karin Menéndez-Delmestre (UFRJ, Brazil)
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- Amelie Saintonge (UCL, UK)

#### **Editors of the Proceedings**

- Woong-Tae Kim (Seoul National U., Korea)
- Tony Wong (U. Illinois, USA)

#### **Coordinating Division**

- 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

<b>SESSION 1</b>	<b>Scales of Star Formation: From Molecular Cores to Galaxies</b>		
Tue 9 Aug	<b>S373 - 1</b>		<b>Chair: Tony Wong</b>
10:30-10:50	Sebastián Sánchez (invited; remote)	Mexico	The local and global relations between $\Sigma_*$ , $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{mol}}$ that regulate star-formation
10:50-11:10	Catherine Zucker (invited; remote)	USA	Supernova-Driven Star Formation in the Milky Way
11:10-11:20	Kazuki Tokuda	Japan	ALMA resolved views of molecular filaments/clumps in the Large Magellanic Cloud: A possible gas flow penetrating one of the most massive protocluster systems in the Local Group
11:20-11:30	Amy Miller	Australia	Turbulence-Controlled Hierarchical Star Formation in the Large Magellanic Cloud
11:30-11:40	Jin Koda	USA	Abundant Molecular Cloud Cores with Photo-Dissociated Envelopes Discovered in the XUV Disk of M83 with ALMA
11:40-11:50	Sarah Jeffreson (remote)	USA	A sub-grid model for the molecular cloud lifecycle
<b>SESSION 2</b>	<b>Sustaining Star Formation: Gas Conditions &amp; Environment</b>		
Tue 9 Aug	<b>S373 - 2</b>		<b>Chair: Monica Rubio</b>
13:30-13:50	Kazuo Sorai (invited; remote)	Japan	Molecular Gas Contents and Star Formation Efficiency in Local Galaxies
13:50-14:10	Barbara Catinella (invited; remote)	Australia	The link between cold gas global reservoirs and star-formation activity in galaxies
14:10-14:20	Erwin De Blok	Netherlands	First results from the MHONGOOSE ultra-deep MeerKAT HI survey of nearby galaxies
14:20-14:30	Gyueun Park	Korea	Probing the Conditions for the Atomic-to-Molecular Transition in the Interstellar Medium
14:30-14:40	Zara Randriamanakoto	South Africa	The SUNBIRD Survey: insights into small-scale star formation mechanisms through the NIR study of young massive clusters
14:40-14:50	Bruce Elmegreen	USA	A Search for correlations between turbulence and star formation in LITTLE THINGS and THINGS galaxies
Tue 9 Aug	<b>S373 - 3</b>		<b>Chair: Katie Grasha</b>
15:15-15:35	Zhiyu Zhang (invited; remote)	China	Dense molecular gas tracers in nearby galaxies
15:35-15:55	Aeree Chung (invited)	Korea	The impact of ICM ram pressure on the cool gas content and SF activity of galaxies
15:55-16:05	Jiayi Sun	Canada	Molecular Cloud Populations in the Context of Their Host Galaxies: Insights from PHANGS-ALMA
16:05-16:15	Ayu Konishi	Japan	Exploring the evolution of giant molecular clouds in one of the nearest spiral galaxies M33
16:15-16:25	Gerhard Hensler	Austria	Conditioning star formation in intergalactic clouds
16:25-16:35	Hsi-An Pan (remote)	Taiwan	Gas-Star Formation Cycle in Nearby Galaxies
<b>SESSION 3</b>	<b>Plenary Session</b>		
Wed 10 Aug	<b>S373 - Plenary</b>		<b>Chair: Eva Schinnerer</b>
8:15-8:45	Adam Leroy (invited)	USA	Star Forming Galaxies Resolved into their Fundamental Units
8:45-9:15	Annalisa Pillepich (invited)	Germany	Star formation and its decline across the bodies of galaxies and cosmic environments
9:15-9:45	Yingjie Peng (invited; remote)	China	Exploring star formation and quenching via observations, simulations and synergies
<b>SESSION 4</b>	<b>The Decline of Star Formation: Feedback, Fuel shortage or Inefficiency?</b>		
Wed 10 Aug	<b>S373 - 4</b>		<b>Chair: Karen Masters</b>
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
11:10-11:20	Jeong-Gyu Kim	Korea	Star Formation Efficiency and Destruction of Giant Molecular Clouds with UV Radiation Feedback
11:20-11:30	Di Wang	Australia	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	Yuri Oku	Japan	Osaka feedback model II: Modeling supernovae based on high-resolution simulations
Wed 10 Aug	<b>S373 - 5</b>		<b>Chair: Bruce Elmegreen</b>
13:30-13:50	Alberto Bolatto (invited)	USA	Using Observables to Test Models
13:50-14:10	Lihwai Lin (invited; remote)	Taiwan	What drives galaxies from the main sequence to the green valley?
14:10-14:20	Qingzheng Yu (remote)	China	On the HI Content of MaNGA Major Merger Pairs
14:20-14:30	Yang Sun	USA	Evolution of Bulk Gas Flows from Starburst to Quiescent Galaxies
14:30-14:40	Martin Bureau	UK	WISDOM: Molecular cloud properties and star-formation quenching
14:40-14:50	Cressida Cleland	UK	Investigating internal and external quenching mechanisms on various timescales.
<b>SESSION 5</b>	<b>The Rise and Fall of Star Formation Across Cosmic Time</b>		
Wed 10 Aug	<b>S373 - 6</b>		<b>Chair: Karín Menéndez-Delmestre</b>
15:15-15:35	Miroslava Dessauges-Zavadsky (invited; remote)	Switzerland	Dissecting the star formation process at molecular cloud scale 8 billion years ago
15:35-15:55	Itziar Aretxaga (invited)	Mexico	(Sub-)mm continuum surveys: mapping the dusty galaxy contribution to the star formation history
15:55-16:05	Marcie Mun (remote)	Australia	Spatially resolving the star formation activity of galaxies at 3 - 4 Gyrs of lookback time with MAGPI
16:05-16:15	Chelsea Sharon	Singapore	Characterizing the Resolved Schmidt-Kennicutt Relation Using Different SFR Tracers at Cosmic Noon
16:15-16:25	Melanie Kaasinen	Germany	Resolving Star-forming Gas at the Peak Epoch of Star Formation
16:25-16:35	Po-Feng Wu (remote)	Taiwan	Understanding quenching at high redshifts from local IFU surveys

Thu 11 Aug	<b>S373 - 7</b>		<b>Chair: Ena Choi</b>
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 $z \sim 6$
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
<b>SESSION 6</b>	<b>Regulation of Star Formation and the Evolution of Galaxies</b>		
Thu 11 Aug	<b>S373 - 8</b>		<b>Chair: Martin Bureau</b>
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	Hao He	Canada	Analysis of giant molecular cloud properties on FIRE-2 Mergers
Thu 11 Aug	<b>S373 - 9</b>		<b>Chair: Daniel Dale</b>
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?