IAU Symposium
352
3–7 June 2019
Viana do Castelo, Portugal

Proceedings of the International Astronomical Union

Uncovering Early Galaxy Evolution in the ALMA and JWST Era

Edited by

Elisabete da Cunha
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ISSN 1743-9213

International Astronomical Union

CAMBRIDGE
UNIVERSITY PRESS

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IAU SYMPOSIUM 352

COVER ILLUSTRATION:

A multi-wavelength view of the deep Universe in the Hubble Ultra Deep Field. In blue, the optical/near-infrared emission of galaxies imaged using the Hubble Space Telescope is shown. Orange shows the carbon monoxide emission (indicating molecular gas out of which new stars can form) imaged by ALMA. This is an example of multi-wavelength images that will be obtained in the future by combining deep JWST and ALMA observations. This image is based on the very deep ALMA survey by the ALMA Spectroscopic Survey in the HUDF (ASPECS) collaboration (see also ESO Science Release #1633).

Image credit: B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO); NASA/ESA Hubble

Over the image we show an outline of the 16th-century Portuguese fortress that served as the venue for this IAU Symposium, the Fort of Santiago da Barra in Viana do Castelo.

https://doi.org/10.1017/S1743921320000940 Published online by Cambridge University Press

https://doi.org/10.1017/S1743921320000940 Published online by Cambridge University Press

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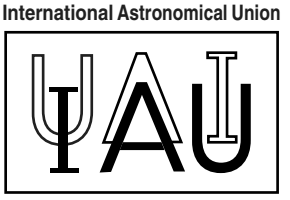

UNCOVERING EARLY GALAXY EVOLUTION IN THE ALMA AND JWST ERA

PROCEEDINGS OF THE 352nd SYMPOSIUM OF THE INTERNATIONAL ASTRONOMICAL UNION HELD IN VIANA DO CASTELO, PORTUGAL 3–7 JUNE, 2019

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https://doi.org/10.1017/S1743921320000940 Published online by Cambridge University Press

CAMBRIDGE UNIVERSITY PRESS
University Printing House, Cambridge CB2 8BS, United Kingdom
1 Liberty Plaza, Floor 20, New York, NY 10006, USA
10 Stamford Road, Oakleigh, Melbourne 3166, Australia

First published 2020

Printed in the UK by Bell & Bain, Glasgow, UK

Typeset in System LaTeX 2ε

A catalogue record for this book is available from the British Library Library of Congress Cataloguing in Publication data

This journal issue has been printed on FSC™-certified paper and cover board. FSC is an independent, non-governmental, not-for-profit organization established to promote the responsible management of the world's forests. Please see www.fsc.org for information.

ISBN 9781108492133 hardback
ISSN 1743-9213

Table of Contents

SESSION 1: Epoch of reionization

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SESSION 2: Theoretical models and simulations

SESSION 3: Spectral energy distribution models

https://doi.org/10.1017/S1743921320000940 Published online by Cambridge University Press

https://doi.org/10.1017/S1743921320000940 Published online by Cambridge University Press

https://doi.org/10.1017/S1743921320000940 Published online by Cambridge University Press

https://doi.org/10.1017/S1743921320000940 Published online by Cambridge University Press

SESSION 7: Lessons from local galaxies and high-z analogues

https://doi.org/10.1017/S1743921320000940 Published online by Cambridge University Press

SESSION 8: Synergies with other facilities & future outlook

https://doi.org/10.1017/S1743921320000940 Published online by Cambridge University Press

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Preface

The 352nd Symposium of the International Astronomical Union, on *Uncovering early galaxy evolution in the ALMA and JWST era,* happened in the Portuguese coastal town of Viana do Castelo from June 2nd to 7th, 2019. It is noteworthy that this was only the second IAU symposium ever hosted in Portugal. The main goal of this IAU Symposium was to bring together the international community of observational and theoretical astronomers in the field of early galaxy evolution, with a special focus on new results from the Atacama Large Millimetre Array (ALMA) and preparation for new research and synergies with the soon-to-be-launched James Webb Space Telescope (JWST). We consider this symposium to have been a big success! The symposium brought together 172 participants from 24 countries in a week of very high quality science talks and discussions, as well as some important collateral activities that had the goal of involving the local community through various teaching and outreach events.

Thanks to deep observations in the last few decades with the Hubble Space Telescope, the Spitzer Space Telescope, and ground-based 8-10-metre class telescopes, we know more about the young Universe than ever before, having reached tantalisingly close to the dark ages and the formation of the first stars and galaxies. It is now well established that the rate of cosmic star formation rose rapidly from the epoch of reionization to a maximum at $z \sim 2$. The first three billion years of cosmic time were therefore the prime epoch of galaxy formation. Characterising galaxies at this epoch, both observationally and theoretically, is thus crucial to achieve a major goal of modern astrophysics: to understand how galaxies such as our Milky Way emerged from the primordial density fluctuations in the early Universe and evolved through cosmic time.

Many questions have to be addressed with the next generation of observing facilities and theoretical models. For example, what physical processes drove the rise in star formation rate in the first three billion years? How is the formation and evolution of galaxies determined by their dark matter haloes and large-scale environment? How did black hole growth follow this rise, and how important is the galaxy-AGN connection at early cosmic times? Which star-forming galaxies are responsible for re-ionising the Universe (a major event in cosmic history), and how important is the contribution by early quasars? How do the gas, metals and dust in the interstellar medium of early galaxies evolve? What regulates star formation in galaxies, and what are the physical drivers behind the close correlation between stellar mass and star formation rate (the so-called 'star-forming main sequence')? Are there different star formation modes associated with secular and interaction-driven starbursts, and how important were those processes in shaping the general galaxy population? What dynamical processes established the morphologies of galaxies we observe today? Recent major international investments in two major facilities, the Atacama Large Millimetre Array (ALMA) and the James Webb Space Telescope (JWST), promise to shed light on these questions and uncover the rise of galaxies from the cosmic dark ages. ALMA has been operating since 2011 and has already started changing our view of the distant Universe by detecting dust heated by young star formation and cold molecular gas i.e. the fuel for new star formation, with unprecedented sensitivity and spatial resolution, reaching all the way to the epoch of reionization ($z > 6$). ALMA gives us an exquisite view into the physical state of the dense interstellar medium in the young Universe, which is determinant in understanding star formation and feedback processes. The soon-to-be-launched JWST will bring a necessary and complementary view of the stellar populations and ionised interstellar medium in galaxies at those epochs. It will directly observe young stars radiating in the rest-frame ultraviolet as well as more evolved stars emitting mostly in the optical and near-infrared (which

https://doi.org/10.1017/S1743921320000940 Published online by Cambridge University Press

comprise most of the total stellar mass), and it will access the nebular emission from gas Ionised by the young stars, AGN, and shocks. Combining ALMA and JWST will be crucial to go beyond simply detecting large samples of galaxies in the young Universe, but also characterising in detail the physical processes governing their evolution.

The main science driver of the symposium was the need for the extragalactic community to be prepared to maximise what we can learn from having those facilities simultaneously available during the lifetime of JWST. We brought together the community of theoretical and observational experts to discuss and strategise on how we can make the most of ALMA and JWST synergies in advancing our understanding of galaxy evolution in the young Universe during the next decade. The goal was to formulate the key questions that will be answered with ALMA+JWST, and discuss what observations, diagnostics, and theoretical models/simulations will need to be developed to address them. To achieve this goal, the symposium included an overview of the state-of-the-art in observations and theoretical models of high-redshift galaxies, identifying strategic areas where the overlap between ALMA and JWST will be crucial, and fostering exchanges and international collaboration between theorists and observers, as well as astronomers traditionally observing in different spectral regions.

A major challenge in the JWST era will be how to optimally and reliably measure the physical properties of galaxies from observations in order to compare with theoretical predictions and build a more robust physical understanding of galaxy evolution at early cosmic times. To do this, we need spectral models of galaxies that reliably account for the evolution of young stellar populations, as well as the transfer of starlight through gas and dust in their interstellar medium. For example, the evolution of low-metallicity massive stars is a key ingredient to characterising galaxy spectra in the rest-frame ultraviolet, and importantly the production of ionising photons in galaxies, and has recently arisen as a major source of discrepancy between current models, especially when accounting for the effects of stellar rotation and binaries. Another major source of uncertainty is the potential evolution of the properties of interstellar dust towards early cosmic epochs, which will have to be addressed observationally by combining JWST and ALMA observations to fully characterise both dust attenuation and emission. As spectral models are becoming increasingly complex, we must use advanced statistical techniques to compare models and observations. The symposium also addressed how to put the wealth of new observational information in the context of theoretical models and the variety of increasingly more detailed numerical simulations of galaxy formation. As observations improve in spatial resolution and sensitivity, they present a further challenge to simulations that aim to reproduce both the statistical properties of the galaxy population and the detailed physical processes occurring in galaxies, such as star formation and AGN feedback, or gas accretion and outflows. Only by bringing together the observers and simulators can we as a community build a framework where observations can be optimally used to test and further develop our theoretical physical understanding of the processes that affect galaxy evolution. We also made important links to the local/low-redshift galaxy community to understand what can be learnt from detailed observations of nearby galaxies at resolutions that cannot be achieved in the high-redshift Universe even with ALMA and JWST. For example, studies of resolved stellar populations in nearby dwarf galaxies and other analogues can reveal the star formation history of these objects far into the past, all the way to the epoch of reionization when they might have played a major role as a source of ionizing photons. Also, studies of resolved star clusters and star-forming regions in nearby galaxies give us a detailed insight into the physics of star formation, as well as providing calibrations for diagnostics of, e.g., the star formation rate and gas-phase metallicity. Finally, detailed, high-resolution studies of the interstellar medium of local

galaxies give us a detailed picture of the physical processes happening between stars and the surrounding gas and dust.

Bringing together these and other science topics under a common theme, and with the particular focus on synergies between ALMA and JWST for studies of high-redshift galaxy evolution made this symposium unique and very timely. The field was ripe for a meeting that brought together both users of ALMA and JWST as well as theorists, to strategise for the next decade when both these facilities will be available. This will be a transformative time when not only we will detect the first galaxies, but we will start to understand the underlying physics of early galaxy evolution and the sources that drove one of the most important events in cosmic history, the reionization of the Universe.

We would like to emphasize the lively, collegial, and inclusive atmosphere of the symposium, which we believe was a major factor in the fruitful scientific interactions and discussions. The science organizing committee was very active in diversity and equity efforts, from ensuring gender, seniority, and geographical balance of invited and contributed speakers, as well as session chairs, to ensuring poster presenters (especially early-career researchers) had a high visibility throughout the symposium (through poster sparkler sessions, poster viewing sessions, as well as a 'best poster' competition and a 'poster quiz' for participants). We also actively encouraged family caregivers to attend the symposium (who are still women in the majority of cases), by providing an on-site babysitter service free of charge to the participants. This was a very successful initiative in the sense that the participants who used the service were very positively impacted. We view this as a constructive initiative, and encourage future conference and symposium organizers to consider offering this service.

Along with the scientific programme, we also had various collateral for the local community of Viana do Castelo, which had a very positive impact in the community's engagement with astronomy in general, and in the visibility of the IAU in particular. This was achieved thanks to the excellent collaboration with the local authorities, in particular the Viana do Castelo City Council and Mayor, and the important activities co-organized between the LOC and the University of Porto. The connection with the local community and sense of contributing to the local scientific culture were no doubt one of the most rewarding parts of organizing this symposium. We strongly encourage future IAU symposium organizers to think about how they can use the opportunity of organizing a symposium to not only produce a stimulating meeting for professional astronomers and astronomy students, but also to enrich and build ties with local communities that do not always have access to science events. We included a fully accredited teacher training workshop, co-organized by the University of Porto and the 'Ciencia Viva' organization, with the topic *New tools for Astronomy in secondary school.* This workshop was taught by two professors of the University of Porto, Prof Carlos Martins (LOC co-chair) and Prof Paulo Mauricio, for a total of 25 hours between March and June, 2019. This was a unique opportunity for local high-school teachers to obtain fully accredited training in astronomy, free of charge and without having to travel outside of Viana do Castelo.

We also had two events organized with the Viana do Castelo City Council: a welcome reception and a press conference. The welcome reception was a chance for the conference participants to get to know each other and also to interact with the local authorities, including the Mayor. The press conference increased the visibility of the symposium (and of the IAU) in the local press, and was a valuable opportunity to talk about the science topics of the symposium to a broad audience, and to advertise the public events that happened later in the week. One of these events was a free evening of public talks (in Portuguese) in the beautiful Sá de Miranda Municipal Theatre. The event was presented by Miguel Gonçalves, a well-known Portuguese science communicator, and included talks about the IAU (by pioneer Portuguese astronomer and IAU General Secretary Prof Teresa

Lago), the European Space Agency and the JWST (by symposium participant and Viana native Dr Catarina Alves de Oliveira), and early galaxies (by SOC member Dr David Sobral). The talks were followed by a panel Q&A including all the speakers and also Dr Elisabete da Cunha, symposium organizer. This event was a success, very well attended by the locals, and with great visibility in the press. The symposium week ended with a stargazing night for the public at the city beach, organized in collaboration with the Planetarium of Porto and City Council. The attendance exceeded expectations, with about 300 locals of all ages coming to the beach despite the windy evening. The main attractions were the Moon craters and Jupiter. This event was such a success that it motivated City Council to organize more regular stargazing events in Viana do Castelo in the future. We believe this has a lot of potential to become a lasting positive impact of the symposium in the local community.

As a final note we would like to thank the IAU for the support in organizing this conference, and specifically the support of Division J (Galaxies and Cosmology), our co-ordinating division, as well as Division H (Interstellar Matter and Local Universe), Division G (Stars and Stellar Physics), and Division D (Education, Outreach, and Heritage). We are also immensely grateful to all the members of the scientific and local organizing committees without whom this symposium could not have happened (in particular the Leiden members for their tireless support with registration and finances). Many thanks as well to our invited speakers, discussion leads, contributed speakers, and poster presenters for contributing to the high level of scientific talks and discussions, as well as all participants who enthusiastically asked questions, engaged in discussions, and contributed to the overall excellent atmosphere of the symposium, inside and outside of the seminar room. We thank Richard Ellis and Gabriella de Lucia in particular for having accepted the challenge of giving the summary talks. We also thank Carlos Martins and Paulo Mauricio for their efforts in leading the teacher training workshop, and Planetário do Porto for their major contribution to the stargazing event. A huge thanks to Prof Teresa Lago, Miguel Gonçalves, Catarina Alves de Oliveira, and David Sobral, for having accepted our invitation to be the stars of our public talk event, and for making it such an exciting success. Also, additional thanks to Catarina for organizing to send the JWST promotional materials for the participants through ESA. Finally, a very special thanks to the Camara Municipal de Viana do Castelo, in particular Ms Manuela Passos Silva, Dr Ricardo Carvalhido, and Mayor Jose Maria Costa, for their enthusiastic and invaluable support in all aspects of the symposium, from providing gifts for the participants, to buses, to the welcome reception and press conference, and venues for the collateral events, as well as Mr Vítor Ramalhete for his prompt help in dealing with technical difficulties. The city truly embraced the event and welcomed everyone with open arms in true northern Portuguese fashion.

Organizing this symposium was a truly rewarding experience for both of us, scientifically and personally, and we hope everyone who was involved has as many great memories of the event as we do.

Elisabete da Cunha and Jacqueline Hodge, SOC co-chairs
January 2020

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Participants of the symposium. *Credit*: Paulo Carmo

Participants chatting with Viana do Castelo Mayor José Maria Costa and his assessor Ms Manuela Passos at the welcome reception. *Credit*: Armando Belo

Press conference with the local press, including SOC co-chair Dr Elisabete da Cunha and Viana Councilman for Science Dr Ricardo Carvalhido. *Credit*: Armando Belo

Session 4 discussion session, including Xiaohui Fan, Stacey Alberts, Takuma Izumi, Hideki Umehata, Bram Venemans, Chelsea Sharon, and Stephanie Juneau. *Credit*: Elisabete da Cunha

SOC co-chairs Prof Jacqueline Hodge and Dr Elisabete da Cunha. *Credit:* Elisabete da Cunha

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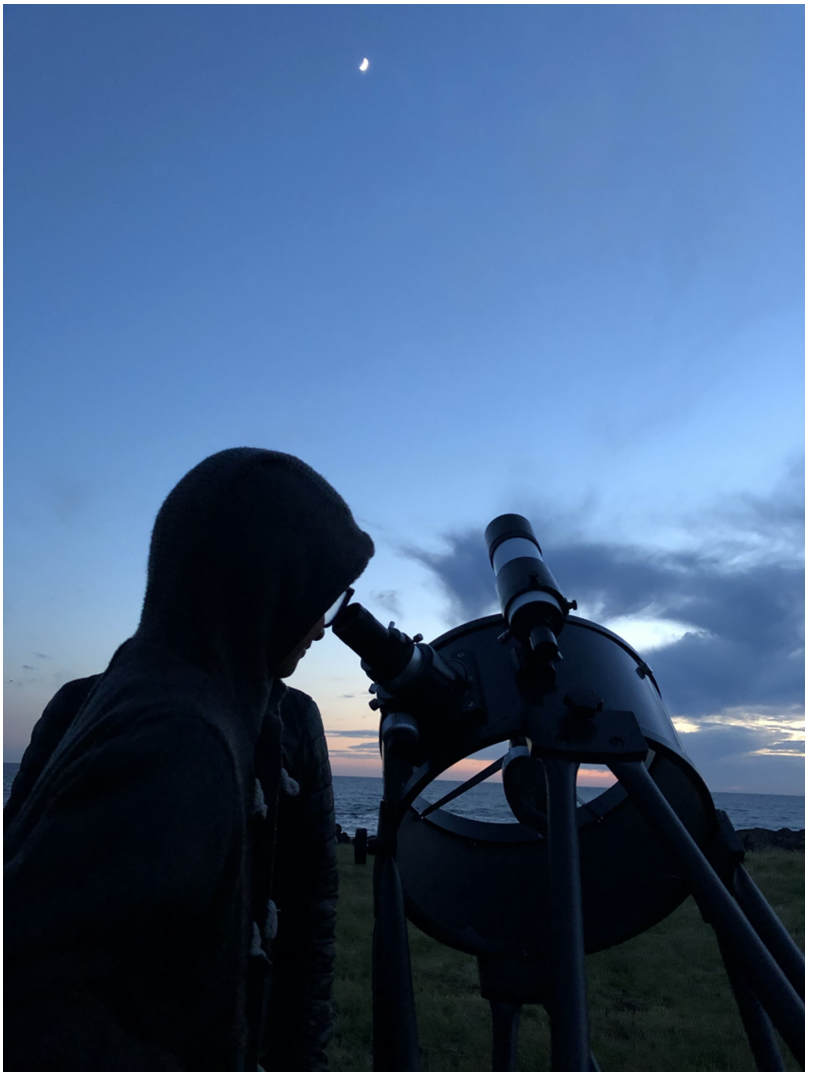
Q&A session with the public at the Municipal Theatre. Left to right: Dr David Sobral, Dr Elisabete da Cunha, Mr Miguel Gonçalves, Dr Catarina Alves de Oliveira, Prof Teresa Lago. *Credit*: Armando Belo



Local boy looking through telescope at the public stargazing event.
Credit: Elisabete da Cunha

https://doi.org/10.1017/S1743921320000940 Published online by Cambridge University Press

Science highlights

The science programme started with several interesting talks about the current state of the art of detections of the faintest, most distant early galaxies (Smit, Finkelstein, Bouwens, Oesch, Atek). Thanks to HST and Spitzer, often aided by gravitational lensing, we can go deep into the low end of luminosity (and mass) functions of early galaxies, getting close to recovering all the sources responsible for reionization. However in order to really get there, we will need JWST (Oesch, Bouwens, Renzini talks). Efforts are now focusing on not only detecting the faintest, most distant galaxies, but also characterizing their physical properties. ALMA is providing exciting new results in this area, as shown by Smit, Hashimoto, Bowler, Carniani. Mostly [CII] and [OIII] line detections at $z > 6$ with ALMA are providing spectroscopic redshifts for the sources, as well as in some cases dynamical masses and information on the ionized gas. To measure the dust continuum in these sources remains challenging, with some tantalizing observations suggesting that dust grains might be very different than what we observe in the local Universe. A current open question is what is the dust temperature and luminosity in these sources. Answering this will require multi-band ALMA measurement.

In the theory session we had many interesting updates on the state of theoretical early galaxy formation models (Dayal, Arata, Ceverino, Ma, Hutter, Naidu). These models are making predictions on the properties of galaxies in the epoch of reionization that will be directly in the future tested by JWST observations of those galaxies, and also by Square Kilometre Array observations of the 21cm neutral hydrogen signal at reionization. We also highlight the talk by Narayanan, who presented a new model for interstellar dust formation, growth, and destruction that takes into account all known physical processes affecting the evolution of dust grains, and is included in a large-scale cosmological simulation, allowing us to follow the total dust content of galaxies in a way that can be compared with future ALMA and JWST observations.

Spectral energy distribution (SED) models of galaxies are needed to translate our multi-wavelength observations into physical parameters that can be compared to theoretical simulations and models. Currently SED model developers are getting ready to interpret the future vast amount of data on high-redshift sources that will be enabled by the JWST (e.g., talks by Leja, Gomes). A critical step is to produce realistic spectra, including both stellar continuum and nebular emission, especially in the rest-frame UV and optical (talks by Charlot, Hirschmann). In order to do that new stellar evolution ingredients that are still uncertain are needed (for example, stellar binaries and rotation; Nanayakkara, Schaerer, Stanway), as well as robust photoionization models. We had an interesting discussion session about the challenges in producing SED models for the future, when many of their ingredients (stellar evolution, stellar spectra, initial mass function) are very uncertain at the early evolutionary stages when the metallicity was low.

We had several talks about the detection of quasars at high-redshift (Bañados, Venemans, Fan), which trace high density environments at high redshift ($z > 6$) where galaxies and massive central black holes are rapidly growing. These are ideal environments to test the galaxy-AGN connection (e.g., Alberts, Bischetti, Juneau, Humehata talks). ALMA is enabling great strides in this kind of science by observing the interstellar medium of these objects, both in dust continuum, [CII], and CO (e.g., Venemans, Izumi, Sharon talks).

In the session dedicated to the interstellar medium, we had updates on the ALMA large programmes ASPECS (Aravena), and ALPINE (Le Fevre), as well as additional contributed talks reporting on ALMA studies of the molecular gas content of high- redshift star-forming galaxies with ALMA (Williams, Suess, Magdis, Liu). These studies

https://doi.org/10.1017/S1743921320000940 Published online by Cambridge University Press

are unlocking a key component in our understanding of how star formation is fuelled at cosmic dawn and beyond. Another avenue worth highlighting are detailed studies of strongly lensed, bright dusty star-forming galaxies, which allow us to dissect the interstellar medium down to molecular cloud scales and study small-scale physics effects (such as turbulence) on star formation (Spilker, Falgarone, and the talks by Rujopakarn, Dessauges, and Tadaki in the following session). Another highlight is the use of CO isotopes in the ISM, which can be observed with ALMA at high-redshift, to trace variations of the stellar initial mass function (Romano talk).

Another approach that holds a lot of promise for future combined studies with ALMA and JWST is to obtain resolved, multi-wavelength observations of star-forming galaxies so we can trace both their stellar component (past and current star formation), and their interstellar medium (fuel for future star formation), at similar scales. ALMA and ground-/space-based large telescopes (VLT, Keck and HST now, ELT and JWST in the future) are ideally matched for this purpose (talks by Shivaei, Wuyts, Bezanson, James, Lang, Ritondale, Cochrane). A common result from current studies seems to be that there is often a mismatch between the extent and/or location of the rest-frame UV/optical emission produced by stars, and the infrared emission produced by dust. This can tell us something about the morphology and structure of early galaxies, and how the stellar component is growing, but highlights that caution must be taken when correcting the stellar emission for dust attenuation. Some ambiguities remain due to the fact that high spatial resolutions cannot be achieved in the rest-frame near-infrared with current facilities, which would be closer to a pure stellar distribution (i.e., unaffected by dust); JWST will help resolve this issue.

We had a very interesting session on what can be learnt from local analogues to high-z galaxies; this demonstrated that there is indeed a lot of potential for the two communities of local and distant Universe studies to collaborate. A promising approach is to select low-mass, low-metallicity, high star formation galaxies locally that presumably resemble the first galaxies that contributed to reionization, and study them in the exquisite detail enabled by their relative closeness (e.g., talks by Amorin, Gonalves, Senchyna, Fisher). Such studies focus, for example, how calibrating observational diagnostics for star formation and metallicity, or measuring quantities like the escape fraction of ionizing photons. The main challenges are still how to define exactly what constitutes a low-redshift analogue, and whether true analogues of young galaxies can be found in our evolved Universe.

In our last session, we had several talks about new observations with the MUSE integral field spectrograph on the ELT (Bacon, Maseda, Boogaard), which give us a preview of the potential of combining this type of observations with ALMA. We highlight the discovery enabled by MUSE of ultra-faint Lyman-alpha emitters at high-redshift, which are very young primeval galaxies with very low metallicities and high star-formation rates, and presumably would contribute significantly to reionization (Maseda); these will be prime targets for JWST in the future. We also had exciting previews of the capabilities of the JWST instruments for high-redshift galaxy evolution science, and descriptions of the planned GTO programmes (Alves de Oliveira, Rieke, Bunker).

https://doi.org/10.1017/S1743921320000940 Published online by Cambridge University Press