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Corentin Schreiber

A Statistical and Multi-wavelength Study of Star Formation in Galaxies

Doctoral Thesis accepted by
Paris-Sud University, France

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Supervisor's Foreword

Our understanding of the processes ruling the formation and evolution of galaxies substantially progressed over the last years mostly due to new generations of observatories on the ground and in space. Yet we are still lacking a clear picture of the reasons why galaxies experienced a peak activity of star formation about ten billion years ago and why an increasing fraction of galaxies stopped forming new generations of stars since that epoch.

The astronomical community globally expected this behavior to be driven by environment effects through galaxy interactions or mergers and over the course of large-scale structure formation such as groups and clusters of galaxies. The morphology of galaxies would shift from flat rotating disks to dispersion-dominated galaxies with elliptical shapes.

Such expectation was driven not only by past observations but also by the commonly accepted hierarchical galaxy formation paradigm in which galaxies acquired their mass through successive mergers over cosmic time.

Instead, the main picture that is coming out of these new observations shows a surprising universality of galaxy properties and in particular of their growth rate with cosmic time. Despite their different morphologies, rotation, and local environment, galaxies of the same stellar mass appear to be forming stars with the same rate at a given distance from us. If confirmed over most of the cosmic history and with reliable tracers of galaxy properties, such behavior would favor a paradigm in which galaxies grow secularly rather than by episodic bursts.

In his thesis work, Corentin Schreiber addressed this issue using the deepest available data over a wide range in wavelength for galaxies out to 12.3 billion years ago, thus covering 90 % of the cosmic history since the Big Bang. The European Space Agency's cornerstone space observatory, Herschel, is central to this work. It carried the largest mirror ever launched in space offering the possibility to image the deep far-infrared Universe with a unique precision. Because massive stars are formed in giant molecular clouds, their ultraviolet radiation is absorbed by interstellar dust and reemitted in the far infrared. To reliably trace back the star formation history of galaxies, astronomers therefore look after the far-infrared light radiated by dust grains heated at temperatures of typically 30 K.

Despite its large telescope and great sensitivity, the diffraction pattern of the distant galaxies observed at wavelengths ranging from 100 to 500 μ limited Herschel's view on the distant Universe to the most extreme objects—not representative of the main growth path of galaxies, or to the last 8–10 billion years just after the peak of the cosmic star formation history.

Corentin Schreiber proposed a new approach that made a major difference in our ability to probe the distant Universe. Starting by selecting galaxies in intervals of stellar masses, he developed a new method to determine how strongly did galaxies differ in their star formation rate even below the Herschel detection limit, which he called "scatter stacking." Based on his new approach, he was able to show that more than 70 % of galaxy star formation did not happen in merger-driven starbursts over 90 % of the Universe. Instead, galaxies largely grew in mass through this secular mode of star formation. To validate his method, he designed a tool now publicly available to simulate a realistic Universe with galaxies representing accurately their observed colors, shapes, and environment over the whole cosmic history of the Universe. This tool called the Empirical Galaxy Generator (EGG), turned out to be powerful to calibrate not only his method but also source detection algorithms and is now even used in the preparation of the next-generation space mission of ESA, Euclid.

Then turning to the most massive galaxies in the Universe, Corentin Schreiber was able to show that about half of these galaxies, which stop forming stars before the others, happen to do so in a slow manner—through what he calls a "slow downfall"—as opposed to the classical "quenching" of star formation that is commonly advocated but still resisting a robust observational validation. If this process is confirmed, it suggests that all galaxies did die not from violent events but also from a natural exhaustion of their gas reservoirs. How this slow downfall and the more classical quenching of star formation can be reconciled with the paradigm in which galaxies are continuously fed by infalling intergalactic matter remains an open issue.

France
June 2016

Prof. David Elbaz

Publications Related to This Thesis

First-author publications

C. Schreiber, et al. 2016, The mid- to far-infrared spectral energy distribution of star-forming galaxies from $z = 3$ to $z = 0.5$, to be submitted to A&A.

C. Schreiber, M. Pannella, R. Leiton, et al. 2016, The ALMA Redshift 4 Survey (AR4S): I. The massive end of the $z = 4$ main sequence of galaxies, submitted to A&A. http://adsabs.harvard.edu/abs/2016arXiv160606252S

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Other publications related to this thesis

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My thanks will now go to the two referees, Alberto Franceschini and David Alexander, who had to read the present thesis and validate its correctness. I was very touched by your reports, and I am very happy that you found my work worth a Ph.D. degree. On the day of the public defense, Guillaume Pineau des Forêts, Véronique Buat, and Ivo Labbé were added to the jury. I was very honored by your presence, and I would like to thank all for coming and laying a critical eye on my results. I would also like to thank Springer Nature for awarding me the Springer Thesis Prize.

[1]The Comissariat à l'Energie Atomique et aux Energies Alternative.

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Leiden, The Netherlands
June 2016 Corentin Schreiber

Contents

Abbreviations

AGN	Active Galactic Nucleus
ALMA	Atacama Large Millimeter Array
AOT	ALMA Observing Tool
CANDELS	Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey
CIRB	Cosmic InfraRed Background
CMB	Cosmic Microwave Background
COSMOS	Cosmic Evolution Survey
ECDFS	Extended Chandra Deep Field South
FIR	Far InfraRed
GOODS	Great Observatory Origins Deep Survey
HerMES	*Herschel* Multi-tiered Extragalactic Survey
HST	*Hubble* Space Telescope
IGL	Integrated Galaxy Light
IGM	InterGalactic Medium
IMF	Initial Mass Function
IR	InfraRed
IRS	InfraRed Spectrograph
ISM	InterStellar Medium
ISO	Infrared Space Observatory
JCMT	James Clerk Maxwell Telescope
LIRG	Luminous InfraRed Galaxy
MAD	Median Absolute Deviation
MIPS	Multiband Imaging Photometer for *Spitzer*
MIR	Mid InfraRed
MS	Main Sequence
NIR	Near InfraRed
PACS	Photodetector Array Camera and Spectrometer
PAH	Polycyclic Aromatic Hydrocarbon
PEP	PACS Evolutionary Probe
PSF	Point Spread Function

QSO	Quasi-Stellar Object
SDSS	Sloan Digital Sky Survey
SED	Spectral Energy Distribution
SFE	Star Formation Efficiency
SFH	Star Formation History
SFR	Star Formation Rate
SLED	Spectral Line Energy Distribution
SMBH	SuperMassive Black Hole
SMC	Small Magellanic Cloud
SPIRE	Spectral and Photometric Imaging Receiver
sSFR	Specific Star Formation Rate
UDS	Ultra-Deep Survey
ULIRG	Ultra Luminous InfraRed Galaxy
UV	UltraViolet
ΛCDM	Cosmological constant (Λ) and Cold Dark Matter

Symbols

b	Birthrate parameter (–)
β	UV spectral slope (–)
f_{gas}	Fraction of the baryonic mass found in the form of hydrogen gas in the ISM (–)
f_{PAH}	Fraction of the dust mass found in PAH molecules (–)
Gyr	Billion years (time)
IR8	Ratio of total IR luminosity to 8-μm luminosity (–)
IRX	InfraRed eXcess (–)
kpc	Kiloparsec (length)
$L_\odot$	Solar luminosity, or bolometric luminosity of the Sun, 3.846×10^{26} W (energy/time)
M_{disk}	Stellar mass in the galactic disk (mass)
M_{dust}	Mass of dust particles in the ISM (mass)
M_{gas}	Mass of hydrogen gas in the ISM (mass)
Mpc	Megaparsec (length)
M_*	Stellar mass, or mass of stars (mass)
$M_\odot$	Solar mass, or mass of the Sun, 1.989×10^{30} kg (mass)
Myr	Million years (time)
$12 + \log_{10}(O/H)$	Oxygen abundance (–)
pc	Parsec, 3.087×10^{16} m (length)
SFR	Star formation rate (mass/time)
sSFR	Specific star formation rate (1/time)
t_{dep}	Depletion timescale (time)
T_{dust}	Dust temperature (temperature)
U	Intensity of the interstellar radiation field (energy/time/surface)
yr	Year (time)
Z	Metallicity (–)