FRONTIERA: HIGH-RESOLUTION SPECTROSCOPY OF STELLAR POPULATIONS IN THE ERA OF EXTREME LARGE TELESCOPES

PH.D. REPORT

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December 2021

1 The research project

1.1 Scientific context

This PhD program is entirely funded by the FRONTIERA project, (Fostering high-resolution Technology and Innovation for Exoplanets and Research in Astrophysics, PI I. Pagano), an INAF strategic project financed by the Italian Ministry of Education, Universities and Research (MIUR), and aimed at maintaining and consolidating the Italian scientific and technological excellence in the domain of high spectral and spatial resolution, in collaboration with national and international universities, including the DIFA of Bologna, as well as in training students and young researchers to be the key players in the use of new instrumentation and its scientific exploitation.

In recent years, a new generation of high-resolution spectrographs working in the near-infrared (NIR) spectral range has been developed by consortia involving Italian researchers. Some of these instruments are already available (e.g. TNG-GIANO, VLT-CRIRES+), other facilities will be available in the next years (e.g. VLT-MOONS, ELT-HIRES). These new IR spectrographs are ideal to study the physics, chemistry and kinematics of intrinsically red (i.e. cool) and/or reddened (by dust extinction) giant and supergiant stars in galaxy fields as well as in star clusters. Indeed, these stars are among the brightest populations in any stellar system and easily observable out to large distances and also in heavily reddened environments. However, the systematic exploration and calibration of the NIR spectral diagnostics to study these cool stellar populations based on high-resolution spectroscopy is still in its pioneering stage. Any effort to make progress in the field is innovative and of impact for stellar archaeology and stellar evolution.

This PhD project takes the challenge of exploring this new parameter space and characterizing the physical properties, the chemical content and the kinematics of cool giants and supergiants in selected disc fields and clusters of our Galaxy, with the ultimate goal of tracing their past and recent star formation and chemical enrichment history. This PhD project makes use of high-resolution NIR spectra acquired with GIANO-B at the TNG in the context of the large program SPA - Stellar Population Astrophysics: the detailed, age-resolved chemistry of the Milky Way disk (PI: Origlia).

1.2 First year activity

From a combined optical and NIR high-resolution study of the Arcturus standard star, a suitable identification and calibration of the main atomic and molecular lines to be used for the determination of the photospheric parameters (temperature, gravity, microturbulence and other velocity broadening) and chemical abundances have been performed. Within this activity, all the necessary software tools for data reduction, spectral synthesis and chemical analysis have been implemented, and different codes and model atmospheres for the spectral synthesis, have been widely tested. The most striking diagnostic tool defined and calibrated in this PhD work is the so-called C-Thermometer, which uses C I and molecular CO lines in the H band to derive the temperature of cool giants and supergiants. Another interesting tool is the O-Gravitometer, which compares the oxygen forbidden line (in optical) and the OH molecular lines, thus allowing us to derive the stellar surface gravity (i.e., the mass).

From June, 28 to July 7 2019, C. Fanelli has been also visiting astronomer at the Telescopio Nazionale Galileo (TNG) for an observing run of 8 nights in July 2019 within the SPA large program, during which GIANO-B high-resolution YJHK spectra of red supergiants, metal-poor giants and magnetic Ap stars have been acquired.

1.3 Second year activity

The result of this work on Arcturus has been published in the refereed paper: *Stellar population astrophysics (SPA) with the TNG. The Arcturus Lab*, by C. Fanelli, L. Origlia, E. Oliva, A. Mucciarelli, N. Sanna, E. Dalessandro, and D. Romano, 2020, A&A, 645, 19. By using the tools described in the Arcturus paper, a selection of unblended and unsaturated NIR lines for the chemical analysis of red giant stars with the near future VLT-MOONS multi-object spectrograph has been also performed. This contribution has allowed C. Fanelli to be involved in the MOONS Galactic Survey Guarantee Time Observation (GTO) Program.

Then a detailed data reduction and spectral analysis to get radial velocities, stellar parameters and abundances of iron and iron-peak elements, CNO and other light elements and neutron-capture elements has been performed on the following targets. i) 27 young red supergiants (RSGs) in the Perseus Complex to characterize the recent chemical enrichment in the outer disc; ii) 14 RGB stars in the galactic globular cluster M71 in order to disentangle pristine enrichment from evolutionary effects and the impact on the multiple stellar populations problem; iii) 7 very metal-poor stars to test the power of NIR spectroscopy to constrain the pristine chemical enrichment of the Galaxy.

For an additional sample of 18, young main-sequence stars of the Perseus complex accurate radial and rotational velocities have been obtained by analysing in the Fourier space the profile of suitable, unblended atomic lines.

1.4   Third year activity

The results of the kinematics analysis of the Perseus complex young stellar populations (by combining Gaia parallaxes and proper motions and the radial velocities from the present PhD spectroscopic work) have been published in the refereed paper: *First Phase Space Portrait of a Hierarchical Stellar Structure in the Milky Way*, by E. Dalessandro1 , A. L. Varri, M. Tiongco, E. Vesperini, C. Fanelli, A. Mucciarelli, L. Origlia, M. Bellazzini, S. Saracino, E. Oliva, N. Sanna, M. Fabrizio, and A. Livernois. ApJ, 909, 90D

The results of the detailed chemical analysis of the 27 observed RSGs in the Perseus complex have been advertised at the online EWASS 2021 conference in the session "Star clusters to the next scale: reading the Local and high-z Universe with new giant eyes", through the ePoster titled *High-resolution NIR spectroscopy of red supergiants: tracing Galactic young cluster formation and early evolution* by C. Fanelli. Then they have been detailed in the paper *Stellar Population Astrophysics (SPA) with the TNG - The chemical content of the red supergiant population in the Perseus complex* submitted for publication to A&A.

The present study on the Perseus complex has shown the effectiveness of RSGs of K and M spectral types in tracing the detailed chemistry and recent enrichment of their host. Coupled with kinematic information (line-of-sight radial velocities and proper motions). The resulting chemical homogeneity and co-moving kinematics within the Perseus complex suggest that we may have caught an ongoing process of hierarchical cluster assembly. Such a detailed kinematic and chemical screening also set the observational framework for future self-consistent chemo-dynamical modelling for a comprehensive description of modes and timescales of star formation, dynamical interactions and chemical enrichment of the region.

This study also represents a formidable observational test bench to probe models of stellar evolution, nucleosynthesis and internal mixing in the still poorly constrained RSG evolutionary phase for stars at half-solar metallicity. An ApJ Letter reporting the unexpected, striking result of Li detection and its dependence on the stellar mixing in a sub-sample of these RSGs is almost ready for submission.

This PhD project has been also granted a *Marco Polo* fellowship and two months (October and November 2021) has been spent by C. Fanelli at the Observatoire de la Cote d'Azur in Nice, under the supervision of Prof. M. Schultheis. During that period some preparatory work for an optimal selection of targets for the VLT-MOONS GTO in the Galactic center region has been performed.

1.5   Final remarks

This PhD work has allowed C. Fanelli to gain first insights on several aspects of stellar astrophysics research, namely: i) kinematics and chemistry of red stellar populations for constraining the formation and evolution of their hosts; ii) evolution and nucleosynthesis of red supergiants; iii) spectral and stellar atmosphere modelling.

This PhD work has also allowed C. Fanelli i) to be visiting observer at the TNG telescope and operating high resolution GIANO-B and HARPS-N spectrographs in the optical and NIR, thus gaining some direct experience in stellar spectroscopic observations; ii) to exchange information and tools with foreign researchers in Nice, Edinburgh and Santiago (Chile), who are members of the VLT-MOONS Consortium, thus starting to be actively involved in the GTO program preparation and in the design of the chemical analysis pipeline; iii) to interact with the Galactic archaelogy group of the Observatoire de la Cote d'Azur in Nice and to start talking about possible scientific collaborations and Postdoc opportunities.

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2   Workshops, conferences & seminars

May, 27-31 2019, Bologna, Italy: IAU 351 - MODEST19 - Star Clusters: From the Milky Way to the Early Universe, participant

2019, Bologna, Weekly PhD seminars, contributed talk: *Space Policy: from the OST up today*;

2020, Bologna, Weekly PhD seminars, contributed talk: *Stellar chemical abundances and how to find them*;

EAS 2021: online European Astronomical Society Annual Meeting 2021, participant and ePoster on *High-resolution IR spectroscopy of red supergiants: tracing Galactic young cluster formation and early evolution*

November, 18 2021, Nice, 45 min seminar on *High-resolution NIR Spectroscopy of cool Stars: The Giant, the Supergiant and the Galactic Center*

3   PhD schools & internal courses

February, 25-27, 2019, Bologna, PhD school on *Alma Science Proposal Workshop / PhD School*;

Webinar series June-July PhD school on *Neutrinos and Dark Matter in Astro- and Particle Physics*;

June, 17-25, 2019, Bologna, Internal course on *Statistics for Astrophysics*;

September, 17-18-21-22, 2020, Bologna, Internal course on *GAIA: Great Advances In Astrophysics*;

November, 30 – December 2, 2020, Bologna, Internal course on *The interstellar medium*;

April, 19-23 2021, Bologna, Internal course on – *Gamma Ray Bursts: from observations to physical properties*;

May, 5-14, 2021, Bologna, Internal course on – *Writing, talking and presenting science*.

4   Attendance at ISA lectures and other seminars

November 13, 2018, Bologna: *A heart attack: can we re-wire the heart?*, Lecture by Damia Mawad, University of New South Wales, Sidney, Australia;

May 18, 2019, participant at *Bertinoro: V Meeting Nazionale Gruppo Italiano di Paleopatologia*;

November 12, 2019, Bologna: *This turbolent, turbulent world*, Lecture by Alexandre Lazarian, University of Wisconsin - Madison, USA;

November 18, 2019, Bologna: chair at the 1 day conference *Per un guado, una terra, una nuvola, un canto: relazione tra cambiamenti climatici e migrazioni globali*;

November 19, 2019, Bologna: *Rigour and aesthetics: Japanese traditional mathematics*, Lecture by Emanuele Delucchi, University of Fribourg, Switzerland;

December 7, 2021 - *Energy generation in organic solar cells through the lens of multiscale simulations*, Lecture by Gabriele D'Avino, CNRS & Université Grenoble Alpes, France;

December 14, 2021 - *New frontiers of Planetary Science in Africa: African quest for space exploration*, Lecture by Fulvio Franchi, Botswana International University of Science and Technology (BIUST), Botswana.

5   Teaching activity

Teaching assistant for the course "Ottica Astronomica", Laurea Triennale in Astronomia at DIFA, Bologna during A.A. 2019/20, A.A. 2020/21 and A.A. 2021/22.

6 Research period abroad

June, 28 - July 7, 2019, La Palma, Canary Islands, Spain : 8 nights of observations with the GIANO-B spectrograph at the TNG, within the large program "SPA - Stellar Population Astrophysics: the detailed, age-resolved chemistry of the Milky Way disk (PI: Origlia);

October – December 2021, Nice, France: Marco Polo fellowship at the Laboratory Lagrange, Observatoire de la Cote d'Azur, under the supervision of Prof. Mathias Schultheis.

7 Third mission & Outreach

Founder & coordinator of *Dottorato et al. - Uno sguardo sulla vita del dottorando quadratico medio. Racconti di ricerca e vita quotidiana di aspiranti astrofisici*, with a grant of 700 euro from the Bologna University under the "Bando per l'attribuzione di contributi alle associazioni/cooperative studentesche universitare accreditate, per la realizzazione di iniziative ed attività culturali, sportive e ricreative nell'anno 2019";

Founder & coordinator of *AstroVersi*, the official group of DIFA "Augusto Righi" for scientific podcast production, project approved by DIFA and granted 2700 euro by Prof. F. Ferraro, DIFA, Bologna.

8 Other relevant activities

2019-2022: PhD Student Representative in the Department Council;

2019-2022: PhD Student Representative in the Department Giunta;

May, 27-31, 2019, Bologna: LOC member for the international conference *IAU 351 - MODEST19 - Star Clusters: From the Milky Way to the Early Universe*;

January, 21-26, 2020, Loiano: 5 nights of observations with BFOSC at the CASSINI telescope under the program *A pilot project to explore the potential use of the Cassini telescope for Galactic Archeology* (PI:Mucciarelli);

April, 20, 2021, Bologna: organizational support to the *Alma Orienta* day

9 Pubblications

Stellar Population Astrophysics (SPA) with the TNG - The Arcturus Lab
C. Fanelli, L. Origlia, E. Oliva, A. Mucciarelli, N. Sanna, E. Dalessandro, and D. Romano, 2021, A&A, 645, 19 ;

Lo scienziato giacobino - Analisi di un'opera scientifica del XVIII secolo mai diventata tale
C. Fanelli & S. Bordignon (Giornale di Astronomia, 2021);

First Phase Space Portrait of a Hierarchical Stellar Structure in the Milky Way
E. Dalessandro , A. L. Varri, M. Tiongco, E. Vesperini, **C. Fanelli**, A. Mucciarelli, L. Origlia, M. Bellazzini, S. Saracino, E. Oliva, N. Sanna, M. Fabrizio, and A. Livernois, 2021, ApJ, 909, 90D;

Stellar Population Astrophysics (SPA) with the TNG - The chemical content of the red supergiant population in the Perseus complex
C. Fanelli, L. Origlia, E. Oliva, E. Dalessandro, A. Mucciarelli, and N. Sanna, 2021, submitted to A&A, under review (AA/2021/42492);

Lithium in red supergiants of the Perseus complex
C. Fanelli, L. Origlia, E. Oliva, A. Mucciarelli, E. Dalessandro, and N. Sanna, 2021, to be submitted to ApJL;

Pristine vs self-enrichment chemical scenarios in the metal-rich globular cluster M71
C. Fanelli et al., 2022, in prep.