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COMMISSION H4 STELLAR CLUSTERS

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TRIENNIAL REPORT 2021-2024

1. Introduction

The research of Commission H4 concerns star clusters, of any size, at any distance, and of any age. It includes the observation and theory of stellar groupings as they form and evolve, cluster disruption, stellar interactions inside clusters, and star formation in dense environments.

From the beginning of modern astrophysics, the field of research on star clusters has always been important, since it grants astronomers the unique opportunity to study systems of coeval stars. Studies of clusters allow us to easily determines ages of galactic structures using HR diagrams and the location of the main sequence turnoff; to determine distances within the Milky Way Galaxy; along with the study and understanding of variable star. Clusters also provide constraints on star formation and the origin of the field population. They offer critical tests of stellar evolution models, and provide important constraints for stellar nucleosynthesis and Galactic chemical evolution. Thanks to improvements in observational techniques and new theoretical tools, this research field is witnessing a great transformation. The Commission H4 has an official newsletter: The Stellar Clusters Young and Old Newsletter (SCYON), edited by A. Adamo, M. Netopil and E. Paunzen, gathering information on job offers, conferences, and recently published papers in the field.

We highlight here the main research fields, the review papers that have appeared, and provide a list of the international meetings devoted to or related to star clusters.

2. Research topics and new advances

The research covered by the commission H4 addresses the formation and dynamical evolution of star clusters; stellar evolution and ages; star clusters as tracers of stellar populations; not-so-simple stellar populations in star clusters; studies of specific types of objects within clusters; nuclear clusters; extragalactic cluster systems; structure of star clusters. An increasing portion of the electromagnetic spectrum, ranging from X-rays to the far-infrared is used in the anaysis, as well as advanced N-body simulations.

Interconnections between the different topics (Associations and Young clusters; Old Clusters and Globular Clusters; Dynamics) continues to be dominant in the study of this field. The astrometric Gaia "revolution" played a further role, in particular enabling the discovery of thousands of new open clusters (Gaia DR3). The accuracy on distances

within the nearest $\sim$ 4 kpc now allows to remove distance from the equation, providing a much more accurate and robust determination of the other cluster parameters. The full exploitation of this power is yet to come!

Gaia has also led to the discovery of many new stellar streams around the Milky Way, which constitute unique probes of the assembly history of our Galaxy, and of the nature of its dark matter halo. In the era when physics experiments struggle to identify the particle(s) that account toward a quarter of the energy content of the Universe, new astrophysical constraints like that from stellar streams and clusters in galactic haloes are likely showing the way forward.

The community continues the joint exploitation of Gaia data together with spectroscopic surveys (APOGEE, GALAH, Gaia-ESO), while we prepare for the next generations with 4MOST, WEAVE, MOONS etc. Asteroseismology is being exploited also for cluster stars, with Kepler-K2 and TESS, in combination with spectroscopic information.

JWST has opened a new window on the formation of the globular clusters in the early Universe. Combined with gravitational lensing, new census of clusters from cosmic dawn to cosmic noon are underway. One of the main challenge in this domain is to connect the star clusters to their environments, to understand in which physical conditions they form, and how in-turn they affect their surroundings. In particular, the role of massive clusters in the re-ionization of the Universe has been highlighted, but conclusions still suffer from large uncertainties and incompleteness.

Accompanying the observational campaigns, the theoretical efforts are also moving toward a more seamless integration of the context of clusters. The first simulations of galaxies with a star-by-star description has recently been proposed. Although still restricted to small systems and specific conditions, these pioneer work pave the way for a whole new generation of models, which will bridge the gap between galaxies and their clusters.

The technological barrier of the 1 million bodies star-by-star simulations of globular clusters is now routinely broken, thanks to GPU acceleration. Our community has also started to develop and adopt new tools using the power of artificial intelligence. Machine learning techniques began to be applied to massive spectroscopic databases and will be crucial for next generation surveys. Tremendous progress are expected, thanks to the new ways to extract information from complex and rich data, and to test many models.

The field is moving toward accurate and close to holistic models which will finally develop a predictive power. This upcoming revolution will certainly guide the preparation and design of the new observational instruments.

3. Publications within the past triennium

Peer-reviewed publications in the period from March 2021 to January 2024 as follows (from NASAs Astrophysics Data Service):

- Globular clusters: $\sim$ 1110 papers,
- Young massive clusters: $\sim$ 80 papers,
- Open clusters: $\sim$ 750 papers,
- Stellar associations: $\sim$ 160 papers,
- Star clusters and gravitational waves: $\sim$ 290 papers.

The number of publications in the field is stable and remains comparable to that during the previous triennium.

4. International conferences within the past triennium

- Cool Stars, Stellar Systems, and the Sun (Cool Stars 20.5), 2-4 March 2021, online
- EAS symposia on star clusters, 28 June 2 July 2021, online
- Star Clusters: the Gaia revolution, 5-7 October 2021, Barcelona
- Dynamical Formation of Gravitational Wave Sources, 2-7 January 2022, Aspen
- Illuminating Galaxy Formation with Ancient Globular Star Clusters and their Progenitors, 13-18 March 2022, Aspen
- The Renaissance of Open Cluster Science with Gaia, EAS Valencia, 29 June 2022
- UV Insights to Massive Stars and Young Clusters, IAU Busan, 1-19 August 2022
- Cool Stars, Stellar Systems and the Sun 21, 4-9 July 2022, Toulouse
- Wheel of Star Formation: A conference dedicated to Prof. Jan Palous, 12-16 September 2022, Prague
- MODEST-23: Star Clusters in the Post-Pandemic Era, 28 August - 1 September 2023, Evanston
- Two in a million: The interplay between binaries and star clusters, 11-15 September 2023, Garching
- From star clusters to field populations: survived, destroyed and migrated clusters, 20-23 Novemver 2023, Florence
- Globular Clusters and Their Tidal Tails: From the Milky Way to the Local Group, 28-31 May 2024, Toronto
- Young Star Clusters, EAS Padova, 4 July 2024
- MODEST-24: Exploring Dense Stellar Systems Across Cosmic Time, 19-23 August 2024, Warsaw

This triennium has seen the revival of the MODEST series of conferences (Modeling and Observing Dense Stellar Systems) initiated in the early 2000's, but interrupted by the pandemic. A first event hosted by Northwestern University in Evanston, USA in August 2023 has revived the series, and a second opus is being organized by the Copernicus Institute in Warsaw, Poland next August.

5. Conclusion and future plans

This triennium has witnessed major developments in the observational side of our field, from the Milky Way with the latest data releases from Gaia, up to cosmic dawn and the very first clusters in the Universe revealed by JWST. Results from Euclid covering a wide range of galactic and intergalactic environments are extremely promising to provide more constraints on the formation and evolution of star clusters, and their roles in the evolution of the Universe and its structures. The most recent advances on the theoretical side accompany these progresses, with the improvement of well-tested methods (e.g. N-body star-by-star simulations of clusters), and the still timid but rapidly growing development of new tools (e.g. using AI).

The next triennium promises a lot of progresses, in particular with the acceleration of the observational-theoretical collaborations, and the exploitation of state-of-the-art new tools. Now, the next frontier is probably to connect the first clusters from the distant Universe, with their counterparts in the local Universe, in the Milky Way and its neighbors. The emerging synergy between large surveys, precise and targeted measurements, and multi-scale and multi-physics cosmological simulations prepares for the exciting upcoming revolution in the field.

Francesca DAntona & Florent Renaud
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