Richiesta: Massive stars as cosmic clocks: shaping the evolution of infant galaxies FINAL

Richiesta convalidata, con Checksum d29da5ddc42fb353e1162a908a86468892fcd6ce787123f3f672d502d210df55

Richiesta collegata alle seguenti Schede

Titolo Scheda	Acronimo	Coordinatore	Azione
The Final Fate of Super-AGB and Massive Stars: Remnants and Nucleosynthesis	FIFA	marco.limongi	Visualizza Scheda
Birth, evolution and final destiny of the stars, the architects of the chemical and biological evolution of the universe.	BIDSTAR	alessandro.chieffi	Visualizza Scheda
Black holes archaeology with electromagnetic and gravitational wave signals. A cosmic archaeology tool (CAT)	CAT	rosa.valiante	Visualizza Scheda

Commenti

Proposer CV

File allegato: CVfile_europasscv_it.pdf

General Info

Request Title

Massive stars as cosmic clocks: shaping the evolution of infant galaxies

Type of Grant

Theory Grant

Declaration that the activities covered by the present request do not have any funding already available

True

Declaration that the proposed project satisfies the requirements described in the INAF Call

True

Primary RSN

RSN2

Request Author's Name and Email

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Short Abstract

The James Webb Space Telescope (JWST) has started to unveil the physical properties of z > 10 galaxies in their first few Myr of evolution, when their growth is shaped by their massive stars. This offers the unprecedented opportunity to test the nature of massive stellar populations at these extreme redshifts. In this grant proposal, we plan to exploit a unique set of state-of-the-art theoretical tools to develop an extended database of models of massive stars in a wide range of initial mass, metallicity and rotation rate and to explore their impact on the assembly history and chemical properties of z > 10 galaxies. Using a combination of semi-analytical models and numerical simulations, we aim at providing new insights to interpret the stunning discoveries of JWST.

Description

Massive stars play a pivotal role in the evolution of galaxies: their light dominates the emitted spectrum, their explosions inject energy in the interstellar medium (ISM) and enrich it with metals and dust grains. Finally, they leave behind black hole (BH) remnants which, depending on their mass, may provide the lightest initial seeds to grow high-redshift supermassive black holes (SMBHs). These processes contribute to regulating the evolution of star forming galaxies throughout their cosmic history, but in their infancy, within the first 30 Myr since the onset of star formation, massive stars can be considered to be their cosmic clocks.

Observing galaxies in these early phases of their evolution provide a unique opportunity to decipher the properties of their massive stellar population. These observations are now possible thanks to the unparalleled sensitivity of JWST. Indeed, as of today, more than 10 galaxies with spectroscopic redshifts z > 10 have been detected, the most distant of which at z≈13.2 (Curtis-Lake+23). A swarm of z > 10-20 candidates has been photometrically identified, providing the first constraints on the cosmic star formation rate out to z≈16.5 (Harikane+23). Their physical properties, in terms of stellar mass, star formation history, chemical enrichment, stellar populations, have revealed unexpected findings, even sparking speculations that these observations might be in tension with the LCDM model (Labbè+2023). Early results have reported a trend of decreasing metallicity and increasing gas excitation and ionization efficiency with increasing redshift (Trump+2023; Nakajima+2023; Curti+2023). For a relatively small number of objects, peculiar elemental abundance ratios have been reported, such as high nitrogen enrichment (Bunker+2023, Cameron+2023, Jones+2023, Pascale+2023, Isobe+2023, Topping+2024, Castellano+2024) or high C/O ratio (D'Eugenio+2023) which may be due to the physical properties of massive stars forming in these systems.

It is important to stress that at z>10, spectroscopically confirmed galaxies are found to host ≈10^(7.2)-10^9 Msun in stars (Robertson+2023; Roberts-Borsani+2023), with stellar populations having formed half of their mass on timescales 16-70 Myr, and sub-solar metallicity (< 0.1– 0.6 Zsun). As such, ***these galaxies are massive stars-dominated systems***. In addition, stellar winds are believed to be weak at low metallicity (Limongi+18), providing less kinetic energy input to stellar environments. Metallicity also affects the stellar progenitor mass above which massive stars fail to explode and quietly collapse to BHs, with important implications for the timescales on which mechanical feedback and chemical enrichment due to supernova explosions operate (Dekel+23; Renzini+23). Clearly, the evolution of these systems is very sensitive to the peculiar nature of the stars that populate the high-mass end of the stellar initial mass function (IMF).

At these high redshifts, the shape and normalization of the stellar IMF may deviate from the standard (Salpeter-like or Kroupa-like) power-law that is generally assumed to be universal, i.e. a good approximation at all redshifts and metallicities. In fact, high-resolution hydrodynamical simulations have recently shown that a gradual transition in the stellar IMF occurs, with a relative fraction of massive stars increasing with decreasing metallicity at Z≤ 10^(-2) Zsun (Chon+2021) and with increasing redshift at z≥10 (Chon+2022). As a result, we expect stellar populations in infant galaxies at very high redshifts to exhibit a mass spectrum characterized by a non-universal IMF, with far reaching implications for their evolution (Yung+2024; Trinca+2024).

With the aim of providing new insights to interpret the stunning discoveries made by JWST, in this grant proposal we plan to

exploit a unique set of state-of-the-art theoretical tools to describe the evolution properties of massive stars varying in mass, metallicity, and rotation speed, and explore the impact on the evolution of infant galaxies at high-redshift.

In particular, our main objectives are to:

OB1: assess which stars can explode and enrich the ISM in the first galaxies, what types of elemental abundances we expect and the relationship between the initial stellar mass and final BH mass;

OB2: understand the mechanical and chemical feedback timescales in the first galaxies;

OB3: explore the statistical properties of the first galaxies and AGNs;

OB4: explore early dust enrichment in the first galaxies.

To address these goals, we have identified 4 work packages (WP) that we briefly describe below. A detailed description of milestones and deliverables is provided in the corresponding section.

WP1: massive stellar models (led by Limongi, Chieffi, Roberti & Ugolini)
We plan to expand and consolidate a grid of presupernova models of stars with initial masses in the range [13 - 120] Msun, initial metallicities in the range [0 - 2] Zsun and rotation rates vrot = 0, 150, 300 km/s. Following Limongi & Chieffi (2018), we will use the FRANEC stellar evolution code (Chieffi & Limongi 2013, Limongi & Chieffi 2018) to compute the pre-supernova evolution of these stars and the HYPERION code (Limongi & Chieffi 2020) to simulate their explosion and to compute the explosive nucleosynthesis and remnant masses. In particular, we plan to explore the dependence of the nucleosynthetic yields and final remnant mass (black hole or neutron star) on the initial mass, metallicity and rotation velocity.

WP2: infant galaxies toy models (led by Schneider, Valiante)
Starting from a redshift and metallicity-dependent stellar IMF(z, Z), we plan to implement massive star models (WP1) into simple galaxy toy models (see Valiante+2008 and Schneider & Maiolino 2024 for similar implementations) to understand their effects on the star formation history and compute self-consistently: (1) the time evolution of galaxy UV luminosity; (2) the time evolution of the elemental abundance ratios, including C, N, O and other chemical species and accounting for dust depletion factors (WP4); (3) the resulting BH mass function. These simple massive stellar feedback-regulated evolutionary tracks can be used as input to CLOUDY photoionization code (Chatzikos+2023; Ferland+2017) to simulate the resulting spectral energy distribution including nebular emission lines to be compared with JWST observations.

WP3: statistical properties of the first galaxies and AGNs (led by Trinca, Valiante)
The state-of-the-art semi-analytical model CAT (Cosmic Archaeology Tool; Trinca+2022) has been successfully used to explore the statistical properties of high-redshift galaxies and AGNs, and how these compare with JWST observations (Schneider+2023, Trinca+2023, 2024) at $z < 10$. Using the new grids of massive star models and associated feedback schemes developed in WP1 and WP2 based on a non-universal IMF, CAT will enable us to extend our exploration at $z > 10$ comparing the statistical properties of simulated galaxies and AGNs to new JWST observations. We will explore the redshift evolution of cosmic star formation rate, and birth rate of different BH seed populations (light, medium-weight and heavy seeds, Sassano+2023). This, in turn, will have an impact on the BH accretion histories in connection to their host galaxy evolution, therefore shaping the UV luminosity functions of both galaxies and AGNs.

WP4: zoom-in simulations of the first galaxies (led by Angeloni, Graziani, and Venditti)
We plan to use the new massive stellar models developed in WP1 to expand our grid of supernova dust yields (Marassi+2019) and implement the new metal/dust yields and mechanical feedback scheme (WP2) in our dustyGadget cosmological hydrodynamical model (Graziani+2020), which has been successfully used to predict galaxy properties at $4 < z < 10$ that well reproduce JWST observations (Di Cesare+2023, Venditti+2023).
The code is currently being adapted to run high-resolution zoom-in simulations (Graziani+2024) to resolve the first star forming galaxies at $z > 10$. We plan to use the initial conditions of previous runs to re-run the zoom-in simulations with updated chemical yields and feedback schemes, exploring the implications on their dust enrichment timescales.

References
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Yung et al. 2024, MNRAS, 527, 5929

Participants

Participants list

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Description of the roles inside the team

Marco Limongi, Alessandro Chieffi, Lorenzo Roberti: computation of the presupernova of massive star models and their associated nucleosynthesis by means of the FRANEC code

Marco Limongi, Cristiano Ugolini: computation of the explosions of massive stars and their associated nucleosynthesis and remnant masses by means of the HYPERION code

Raffaella Schneider: development of toy models, exploration of consequences for high-z galaxy evolution with CAT and dustyGadget

Rosa Valiante, Alessandro Trinca: implementation in the semi-analytical model CAT and consequences for the UV luminosity function of galaxies and AGNs

Luca Graziani: implementation in hydrodynamical models of galaxy formation and consequences on cosmic metal enrichment. Computation of dust yields

Each non staff participant will be exposed with a total number of about 0.2 FTE

Total number of FTEs associated to the request

1.4

Deliverables and Milestones

We present below the main milestones and deliverables for each work package. We stress that - while ambitious - the work plan is realistic as most of the theoretical tools that we intend to use have been already developed and need only to be upgraded or re-run on new grids of models. The key team members responsible for each milestone are also identified.

First year of the project:

In the first 6 months we plan to

WP1:

- Extend the database of models and yields to very low and zero metallicity. In particular we will compute a set of pre-supernova evolutions of stars in the mass range between 13 and 120 Msun having primordial initial metallicity and initial rotation velocities v=0, 150 and 300 km/sm, using the same version of the FRANEC code adopted in Limongi & Chieffi 2018 (LC18) (Chieffi, Limongi, Roberti)
- Compute the explosions and the yields of the zero metallicity models by means of the HYPERION code under the same assumptions of LC18 (Ugolini, Roberti, Limongi, Chieffi)

WP2:

- Develop a simple toymodel to compute the radiative, mechanical, and chemical feedback of massive stars and supernova explosions on the evolution of young galaxies varying the star formation history and stellar IMF (Schneider, Valiante)
- Apply the toymodel to the existing database of massive stellar models and supernova explosions for rotating/non rotating stars with very low and zero metallicity developed by team members (Schneider)

WP3:

- Implement within the chemical evolution model of dustyGadget cosmological hydrodynamics code the separate evolution of grain species and new metal/dust yields (Angeloni, Graziani, Venditti)
- Implement a redshift/metallicity dependent stellar IMF in the semi-analytical model CAT (Trinca, Valiante)

In the following 6 months we plan to

WP1:
- write 1 first paper presenting the pre-supernova evolution, explosion and nucleosynthesis of zero metallicity models of massive stars in the range 13-120 Msun, with initial rotation velocities v=0, 150, 300 km/s. We will also provide table of stellar yields of isotopes from H to Bi for all the computed models (lead authors Limongi, Roberti, Chieffi)

WP2:
- Apply the toymodel on the new extended grid of massive stars and supernova explosion developed within the first 6 months.
- Explore chemical and spectral diagnostics to disentangle star formation histories and stellar IMF properties from time-dependent spectral energy distributions and comparison with existing data (Graziani, Schneider, Valiante)
- write 1 paper presenting the results of the toymodels: 1 paper on the radiative imprints, chemical abundances, metal/dust yields (including dust depletion corrections) (Lead authors: Graziani, Schneider, Valiante)

WP4:
- Run supernova dust production/survival on the new extended grid of zero metallicity models and prepare the database to be used by dustyGadget and CAT (Graziani, Venditti)

Second year of the project:

In the first 6 months we plan to

WP1:
- Compute the explosions of the extended grid of models by means of the HYPERION code under different assumptions of the injected energy and, as a consequence, determine the yields and the initial mass-remnant mass relation according to the various assumptions (Ugolini, Roberti, Limongi, Chieffi)

WP3
- Run CAT using a metallicity/redshift dependent stellar IMF to explore the statistical properties of galaxies and AGNs at $4 < z < 30$ (Schneider, Trinca, Valiante)

WP4:
- Run a set of hydrodynamics simulations with the updated dustyGADGET dust chemical evolution including the new metals/dust yields with volume and resolution suitable to resolve young galaxies at $8 < z < 15$ (Angeloni, Graziani, Venditti)

In the following 6 months we plan to

WP1:
- write 1 paper presenting the effect of the various assumptions on the explosions on the yields and the remnant masses of the extended grid of presupernova models (lead authors Roberti, Ugolini, Limongi, Chieffi)

WP3:
- write 1 paper to present the result of dustyGadget simulations (Lead authors: Angelini, Graziani, Schneider, Venditti)

WP4:
- write 1 paper to present the result of CAT simulations (Lead authors: Schneider, Trinca, Valiante)

Total monetary request (in kEuro)

50

Budget

Analytic budget description (numbers in Euro)

Item	Year 2025	Year 2026
Hardware	20000 Euro	0 Euro
Travels	10000 Euro	20000 Euro

Description of how the budget will be used

The project involves intensive and diversified computational activity. Hence we require a substantial fraction of the budget (40%) to increase the computational resources and storage capability of the team. We also foresee to dedicate 3000 € to each team member to participate in international conferences and disseminate project results.

Hardware:

In order to perform within the schedule all the calculations planned in the proposal, we need the following hardware:

- 8 HD NAS type WD RED PRO 20TB SATA 3.5 7200RPM: 4000 euro
- 7 HD NAS type WD RED PRO 14 TB 3.5 5200 RPM : 3500
- 2 HD NAS type WD RED PRO 6 TB 3.5 5200 RPM : 500
- 3 Notebooks : 6000
- 1 Workstation: 6000

Declaration that the applicant is at most 35 years old (must be true at the deadline for the application)

False

PI name for the main project the proposer is working for