Mixing and Angular Momentum tranSport of massIvE stars

Reporting

Project Information

MAMSIE

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Periodic Reporting for period 4 - MAMSIE (Mixing and Angular Momentum tranSport of massIvE stars)

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Summary of the context and overall objectives of the project

Computations of the chemical enrichment of galaxies and of the Universe as a whole, rely heavily on the outcome of stellar evolutionary theory of massive stars (e.g. Maeder 2009, Langer 2012). Essentially all heavy elements are delivered by stars that get born with several to tens of times the mass of the Sun (hereafter termed massive stars). Theoretical predictions for the evolutionary properties of such massive stars depend strongly on poorly known phenomena like convective overshooting, internal differential rotation, internal magnetic elds, the stellar wind, etc. The joint consequences of these processes for the mixing of chemical species and for the transport and loss of angular momentum throughout the stellar lifetime remain largely unknown. Furthermore, the inclusion of angular momentum transport and turbulent entrainment from the convective core regions are currently still lacking in stellar evolution theory while they hold the potential to explain various recently observed phenomena that have hitherto no explanation in terms of current models (e.g. Tkachenko et al. 2014).

With MAMSIE, we have taken a unique and new approach with the aim to estimate the phenomena of internal rotation, magnetism, and mixing in massive stars via the detection and interpretation of stellar oscillations. This has been achieved thanks to the development and application of novel asteroseismic modelling methods based on detected and identied gravity-mode oscillations. In contrast to well-established method relying on pressure-mode oscillations propagating through the envelopes of stars, gravity modes probe the entire stellar interior, all the way from the surface to the core. The exploitation of such gravity modes in young massive stars was not available prior to the AdG. Within the AdG MAMSIE, we discovered a large number of such gravity modes in tens of massive stars observed with the NASA Kepler space telescope.

Work performed from the beginning of the project to the end of the period covered by the report and main results achieved so far

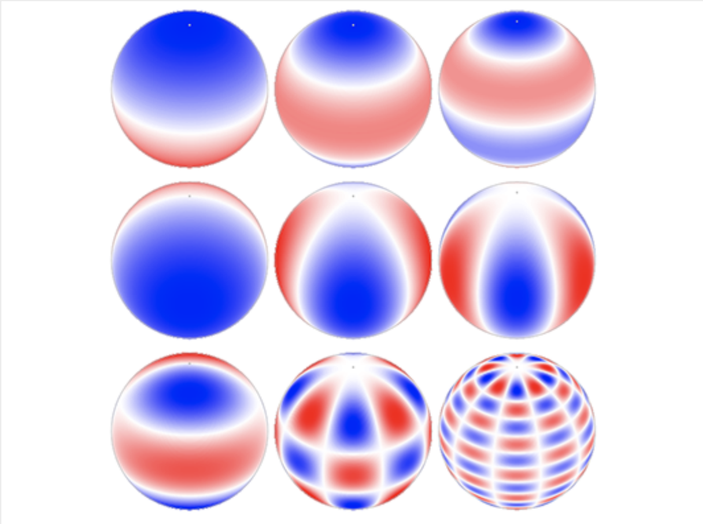
A critical result MAMSIE is our proof that most of these detected and identified modes actually occur in the gravito-inertial regime. These are modes restored by the joint effect of buoyancy and the Coriolis force. They were shown to offer the optimal observational diagnostics to perform the envisioned modelling of the stars, resulting in high-precision estimation of the mass, evolutionary stage, and convective core mass, in addition to the near-core rotation rate. Our identification of the gravito-inertial modes laid the foundation of new modelling methods developed to estimate the physical properties in the deep interior of stars, notably their rotation, mixing and core hydrogen fraction.

More specifically, WP1 revealed better progress than anticipated on the front of mode identification and capacity to estimate internal rotation. The MAMSIE method developed by Van Reeth et al. (2016) saw follow-up research in various worldwide teams, confirming our findings to within our error estimation of this quantity. This key 2016 MAMSIE paper made us re-orient Work Package 2 towards a novel integrated forward mathematical modelling tool for stellar parameter estimation and astrophysical model selection based on gravito-inertial modes rather than gravity modes. This new methodological and computational framework was developed by relying on state-of-the-art statistical theory suitable for high-dimensional grid-based parameter estimation in the presence of strong parameter correlations and theoretical uncertainties. This novel methodology in WP2 constituted a major milestone in our project and was subsequently applied to tens of massive stars with identified gravito-inertial modes.
The observational diagnostic input came from carefully developed statistical time-series analysis

algorithms applied to the space photometric data assembled for WP1. Our computer algorithms delivered the frequencies of nonradial oscillation modes, giving rise to the new observational diagnostic of tilted period spacing patterns influenced by the internal rotation frequency of the stars. As a by-product of our time-series analysis to hunt for period spacing patterns, the MAMSIE team discovered the ubiquitous occurrence of stochastic internal gravity waves buried underneath the signal due to the stronger gravito-inertial modes. This detection of such internal gravity waves originating in the deep core of the stars was a high-risk aspect of MAMSIE and implied an observational breakthrough. It led to several MAMSIE discovery publications, among which the high-profile paper by Bowman et al. (2019). This achievement occurred thanks to the bridging of the interdisciplinary high-risk Work Packages 3 and 4 on the topic of hydrodynamical simulations with the space photometry data analysis developed for WP1. This bridging of research themes led to the discovery result, unanticipated in the sense that all stars seem to reveal such low-amplitude low-frequency signal due to internal gravity waves. These detections offered us at once an observational proof for the astrophysical interpretation of the far more efficient angular momentum transport in massive stars than anticipated prior to MAMSIE, as included in the review paper Aerts et al. (2019).The software used for all our published MAMSIE modelling results led to new stellar evolution models according to Work Package 5, whose ingredients were made publicly available to the worldwide community. This is also the case for our observational diagnostics deduced in WP1. The delivery of our methods and tools developed for WP5 in open access guarantees the option of reproducibility of our science results by independent teams. Ultimately, the full integration of the five work packages was achieved in the application of gravito-inertial asteroseismology to stars in the mass range from 3 to 9 solar masses, as published in Pedersen et al. (2021). This major publication offers a good summary of our overall MAMSIE goals set out at the start of the grant.

Progress beyond the state of the art and expected potential impact (including the socio-economic impact and the wider societal implications of the project so far)

Gravito-inertial mode asteroseismology did not exist as a research field prior to our MAMSIE grant, so we indeed went far beyond the state of the art. Its birth followed from our achievement to identify the wavenumbers of gravito- inertial modes, along with estimation of the rotation frequency in the region near the convective core of stars by Van Reeth et al. (2016). After this new method to deduce the internal rotation frequency of stars of intermediate mass, it took a dedicated two-year development to come up with a novel mathematical stellar modelling approach. Our method is developed to perform stellar modelling based on detected and identified gravito-inertial modes, along with the near-core rotation frequency. This methodology published in Aerts et al. (2018) and its application by Pedersen et al. (2021) are considered a breakthrough, in a beautiful synergy of a new theory and its application in stellar astrophysics. Indeed, there was no capacity to estimate internal mixing in the radiative envelope of intermediate-mass stars observationally. We achieved that and along with it MAMSIE brought the title of the grant, i.e. asteroseismic estimation of mixing and angular momentum inside massive stars, to a reality.



Example of different pulsation regions in a star: red = moving inwards, blue = moving outwards

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