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The COSMIC-DANCE project: Unravelling the origin of the mass function

H. Bouy[1], E. Bertin[2], L. M. Sarro[3], D. Barrado[4], A. Berihuete[5], J. Olivares[3,6], E. Moraux[6], J. Bouvier[6], M. Tamura[7], J.-C. Cuillandre[8], Y. Beletsky[9], N. Wright[10], N. Huelamo[4], L. Allen[11], E. Solano[4], and W. Brandner[12]

[1] University of Bordeaux, France
[2] Institut d'Astrophysique de Paris, France
[3] UNED, Madrid, Spain
[4] Centro de Astrobiologia, Madrid, Spain
[5] University of Cadiz, Spain
[6] Institut de Planetologie d'Astrophysique de Grenoble
[7] National Astronomical Observatory of Japan, Tokyo
[8] Comissariat a l'Energie Atomique, Saclay, France
[9] Las Campanas Observatory, Chile
[10] Keele University, UK
[11] National Optical Astronomical Observatory, USA
[12] Max Planck Institute for Astrophysics, Heidelberg, Germany

Abstract

The COSMIC-DANCE project is an observational program aiming at understanding the origin and evolution of ultracool objects by measuring the mass function and internal dynamics of young nearby associations down to the fragmentation limit. The least massive members of young nearby associations are identified using modern statistical methods in a multi-dimensional space made of optical and infrared luminosities and colors and proper motions. The photometry and astrometry are obtained by combining ground and in some case space based archival observations with new observations, covering between one and two decades.

1 Introduction

In spite of the vast observational efforts of the past decade, the shape of the initial mass function at the very low mass end is still uncertain and often dominated by small number statistics or significant contamination rates. Additionally, the minimum mass for star formation has still not been measured. The initial mass function is one of the most important output of star formation, and as such, one of the prime tools to study and uncerstand star formation. An accurate knowledge of the initial mass function has important consequences in many fields of astrophysics and well beyond local star formation, from the study of exoplanets to the structure and evolution of galaxies. Having an accurate knowledge of the initial mass function in the solar neighborhood, where we can actually resolve entire populations, is the first step towards a better understanding of star formation on galactic and cosmological scales. COSMIC-DANCE aims at delivering complete samples of members of nearby young associations down to the (currently predicted) fragmentation limit. To achieve this ambitious objective, COSMIC-DANCE will rely on a strategy based on two main ingredients: a novel selection method based on modern statistical methods that takes advantage of all the photometric and astrometric information available, and precise astrometric (proper motion) measurements well beyond Gaia sensitivity and in the infrared using new astrometric tools and a new methodology taking advantage of archival wide field images.

2 Finding the least massive members of young nearby associations

Deriving a complete mass function over the entire mass spectrum is a challenging task. Brown dwarfs and planetary mass objects are extremely faint, even in the youngest and closest associations. Their luminosities and colors are additionally similar to a large variety of exotic extragalactic sources, making their photometric identification difficult and leading to significant contamination rates. Spectroscopic confirmation is expensive, because it is possible only with long exposures on the largest telescopes. In practice, only small (a few tens) sub-samples of ultracool candidate members are usually confirmed spectroscopically, leading to large statistical uncertainties on the derived mass functions that prevent any conclusive comparison with the predictions of theories and numerical simulations. To overcome this problem, proper motions have since long been used to infer the membership to an association. The co-eval members of an association indeed share the same kinematics, inherited in most parts from their parent molecular cloud. Finding members of a "moving group" therefore consists in finding all the sources having the same velocity in the proper motion diagram. With the advent of wide field cameras, measuring proper motions has become much more efficient than spectroscopic confirmation. Provided that one has multiple epochs over a sufficiently long time baseline, the proper motion of thousands of sources can be computed and used to identify co-moving members of an association. In that context, Gaia will lead to a small revolution in the field of star formation as it will make the identification of co-moving group members trivial.

Gaia will nevertheless suffer from two major limitations for the specific study of the initial mass function. First, it will be limited to G ~20mag. Even though it represents a tremendous improvement with respect to Hipparcos, it is still not enough to detect the least massive members of even the closest and youngest associations [4]. Second, Gaia is operating in the visible and will therefore be strongly affected by the bright nebolisity and heavy extinction ubiquitous in the core of young nearby clusters. These two limitations are extremely unfortunate for the study of the initial mass function, first because the ultra-low mass regime is where the differences between inborn and evolutionary effects are expected to be the largest and easiest to detect, and second because the embedded cores of young nearby clusters are the place where the present mass function is the closest to the initial mass function.

The COSMIC-DANCE project aims a complementing Gaia beyond its limit of sensitivity to derive the best possible mass function over the entire mass range.

3 The need for new methods

3.1 Ground-based astrometry

Measuring proper motions for millions of very faint sources with an accuracy sufficient to evaluate their membership and study the internal dynamics of the group is a major technical challenge and required the development of new methods and tools. The key to reach a sufficient precision using ground based data is to span a long time baseline. COSMIC-DANCE therefore takes advantage of the numerous overlapping archival images available at various international facilities and obtained up to 20yr ago. These facilities include wide field optical and near-infrared cameras that were/are installed at the CFHT, Subaru, UKIRT, La Silla, Paranal, CTIO, Roque de Los Muchachos, AAO, and KPNO observatories. Second, a new methodology and suite of tools was necessary to deal with such a variety of instruments and sites, efficiently process the thousands of images, and derive a precise astrometric solution. Most astrometric softwares available to date were indeed tuned to a single camera and required a lot of human inputs. As such they were not capable of dealing with a large number of files in an efficient, robust and unsupervised way.

In [2], we described the methods and tools developped in the context of the COSMIC-DANCE project, their performances and their limitations. Briefly, the long time baseline and the detailed knowledge of more than 10 wide field cameras combined with the new capabilities of the AstrOmatic software suite allow us to reach a precision well below the mas/yr on the proper motions and to depth 4 to 5 mag (equivalent) deeper than Gaia's limit of sensitivity. Fig. 2 shows the results obtained in our first study for the Pleiades cluster. We routinely achieved a sub-millarcsecond per year precision up to i $\sim$23mag, depending on the time baseline and number of individual epochs. While such a precision has been achieved by many authors in the past, we believe that it was never achieved on such large scales (more than 80 deg^2 and almost 3 million sources in this case).

3.2 Membership

Identifying the few hundreds members of a young associations within the millions of stars and galaxies present in the survey is another challenging task. Finding all the members, and only the member, is the first step required to derived an accurate mass function and study

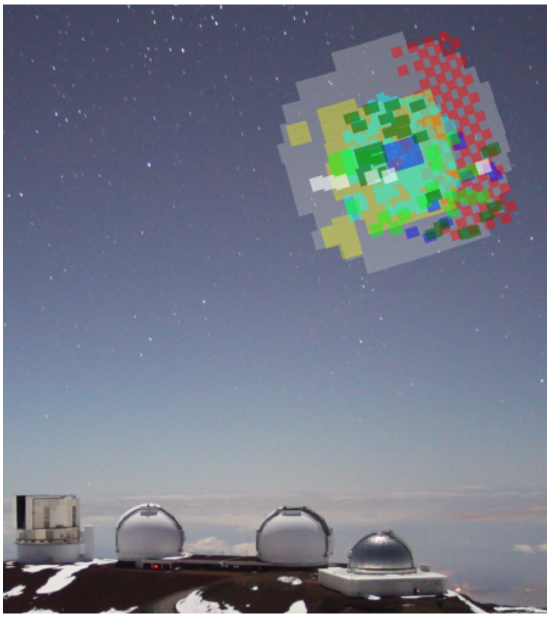

Figure 1: Footprints of the various archival images used for the Pleiades study overplotted on the sky over Mauna Kea observatory. Each color represents a different camera. A total of 7 cameras have been used. Background photograph credit: J. C. Cuillandre.

the internal dynamics. We therefore embarked on the development of a new method designed to take advantage of all the information available in the multi-wavelength photometric and astrometric COSMIC DANCE database.

Because our analysis is done with archival images, we cannot control the coverage and depth of the survey. As a result, the database contains a large number of missing values (when no observations was obtained in a given band in a given area, or these observations were too shallow), and the astrometric and photometric precisions depend very much on the observational history in a given area of the sky. The membership selection was therefore designed to deal properly (from a statistical point of view) with censored data and deliver self-consistent membership probabilities for all the sources, and to include a rigourous treatment of error propagation all along the chain.

The first method used for the analysis of the Pleiades dataset was using a bayesian approach with a curvilinear forward model for the likelihood of the measurements of cluster members in the astrometric + photometric space to infer posterior membership probabilities. The method and algorithms, described in details in [5], was very succesful and discovered 812 high probability members in both the COSMIC DANCE and Tycho-2 catalogues (Fig. 3 with contamination rates estimated to be as low as a few percents, leading to significant improvements in the luminosity and mass function measurements.

While these methods proved to be significantly more robust and efficient at identifying members than previous methods found in the literature, they suffer from several limitations. In particular they did not incorporating the cluster properties in the membership analysis.

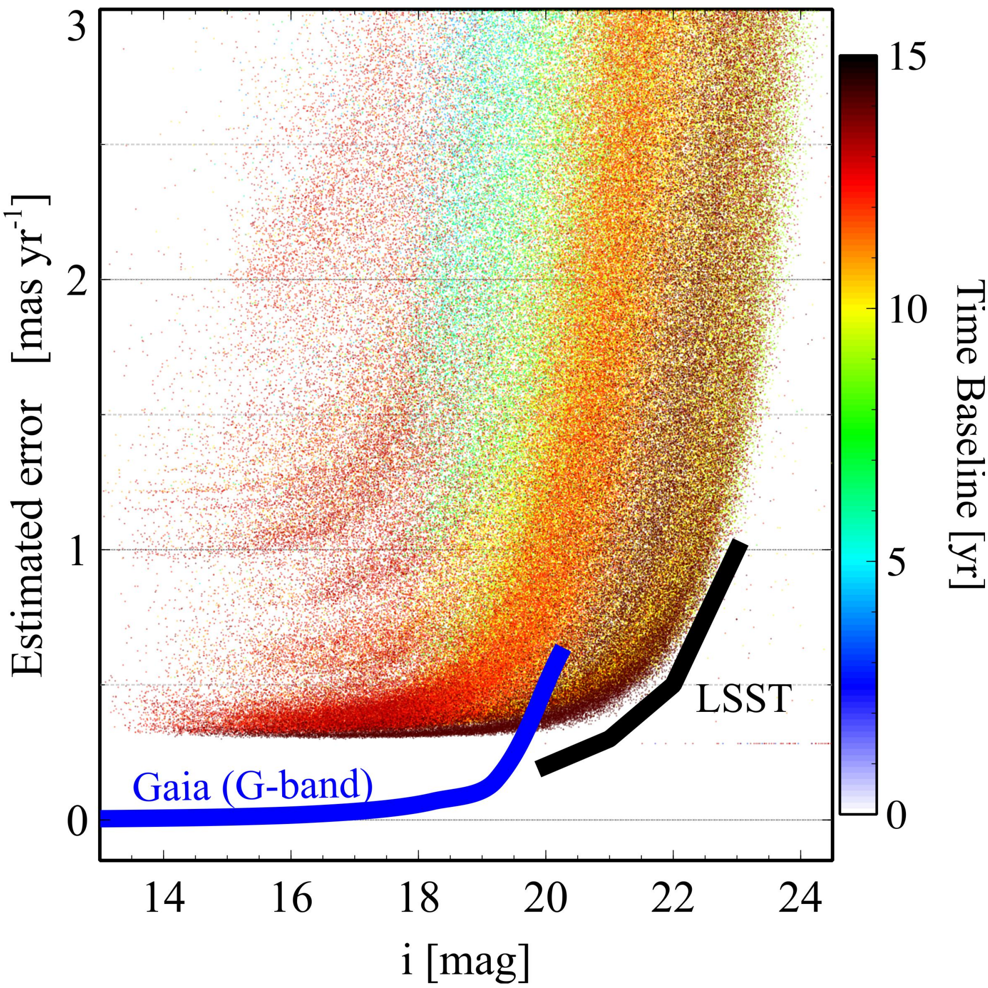

Figure 2: Estimated errors on the proper motion as a function of *i*-band luminosity and time baseline. The predictions for Gaia and LSST are overplotted for comparison (note that Gaia will operate in the G-band). Adapted from [2]

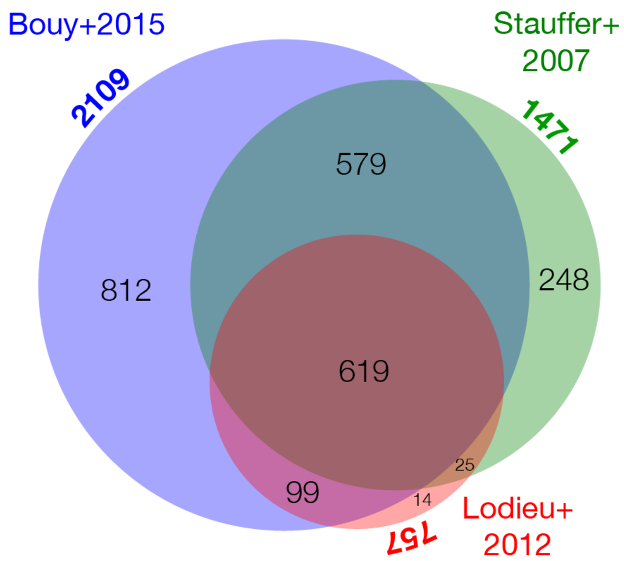

Figure 3: Venn diagram of the Pleiades candidates members presented in our study (blue) and in [3] (red) and [6] (green) studies.

A number of important cluster parameters are very informative for the membership analysis. For example, the spatial distribution, or the mass function itself, tell us about the membership probability of any given source. As a simple example, let us consider the spatial distribution. A source located near the core of the cluster is more likely to be a member than a source located far from the core, simply because the members density is much higher around the core. Including that precious information (distance to the core) in the membership analysis therefore allows to optimize the completeness and minimize the contamination. But to know the position of the cluster core and to know the spatial distribution of members, one first need to know the members. Hierarchical models are designed to solve this kind of problems with nested parameters. They are designed to derive at the same time the membership probability of any source, and the clusters properties and in particular the luminosity function. Given the large number of free parameters required to describe a young nearby cluster (over 70 at the time of writing this article), we decided to develop the hierarchical models in a bayesian framework (Olivares et al., in prep.). These tools shall allow us to derive the best possible luminosity functions with the associated uncertainties. These uncertainties will be realistic and include all major sources of bias and error, and allow quantitative comparisons with the predictions of theories and numerical simulations of star formation.

4 Perspectives and conclusions

The successful exploratory work made in the Pleiades cluster will now be repeated in a number of nearby young associations. We select as high priority targets various associations younger than 5Myr, as the present day mass function of these groups will be the closest to the initial mass function. We select the closest associations to ensure that the archival and new observations reach the fragmentation limit, but also to ensure that they have a sufficiently large mean proper motion to allow an efficient membership analysis. They include in particular the Taurus star forming region, but also stellar groups and associations of the Sco-CMa and Vela blue streams [1].

New observations are continuously being obtained at various facilities around the world with the best wide field cameras, ensuring that we will have the required long time baseline and a large number of individual epochs required to derive precise proper motions and have a more homogeneous photometric coverage between the u and K-band. This unique astrometric and photometric database, complemented with Gaia at the bright end, will allow us to derive the best luminosity functions for a sample of nearby young associations probing a broad range of environements and initial conditions.

The samples of young stellar objects to be discovered by COSMIC DANCE will be priviliged targets for upcoming missions and facilities such as JWST or the ELTs.

Finally, the methods and techniques developped in the framework of the COSMIC DANCE project have numerous applications in other fields of astrophysics, and are already used to search for solar system objects, white dwarfs, field ultracool dwarfs, wide binaries, but also to the study time domain astrophysics over periods of one to two decades.

Acknowledgments

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