



# The Gaia view on massive stars: EDR3 and what to expect from DR3

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**Abstract.** At the time of this meeting, the latest *Gaia* data release is EDR3, published on 3 December 2020, but the next one, DR3, will appear soon, on 13 June 2022. This contribution describes, on the one hand, *Gaia* EDR3 results on massive stars and young stellar clusters, placing special emphasis on how a correct treatment of the astrometric and photometric calibration yields results that are simultaneously precise and accurate. On the other hand, it gives a brief description of the exciting results we can expect from *Gaia* DR3.

**Keywords.** astrometry — catalogs — Galaxy: structure — open clusters and associations: general — stars: kinematics and dynamics — stars: early-type

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## 1. Introduction

The early third *Gaia* data release (EDR3, [Brown et al. 2021](#)) provides astrometry and *G*-band photometry for 1 467 744 819 and 1 806 254 432 sources, respectively. For the astrometry, 40% of the sources are “five-parameter solutions” in which the (pseudo-)color<sup>‡</sup> of the source is known independently and is of higher quality than the remaining 60% of “six-parameter solutions” in which the (pseudo-)color has to be simultaneously calculated ([Lindegren et al. 2021b](#)). For the photometry, in addition to the *G*-band information, 86% of the sources also have  $G_{BP}$  and/or  $G_{RP}$  magnitudes extracted from the spectrophotometric detectors ([Riello et al. 2021](#)), whose wavelength-dependent information will not be available until the full third data release (DR3).

This contribution has four parts. First, we describe our calibration efforts to ensure the precision and accuracy of the astrometry and photometry for all sources, massive

† Deceased.

‡ See the [Gaia documentation](#) for its definition.

or not. Second, we present the integration between *Gaia* data and the Galactic OB stars of the Alma Luminous Star (ALS) catalog (Reed 2003), started with the previous *Gaia* data release (DR2, see Pantaleoni González et al. 2021) and which we have now updated with EDR3 data to produce the largest catalog of massive Galactic OB stars with accurate distances ever. Third, we discuss the Villafranca project of Galactic young stellar groups, which is cataloguing all stellar groups with OB stars in the solar neighborhood (Maíz Apellániz 2019; Maíz Apellániz et al. 2020, 2022a). Finally, we briefly comment on what to expect from the new data products that will become available in DR3.

## 2. Astrometric and photometric calibration

Lindgren et al. (2021a) describe that the catalog EDR3 parallaxes  $\varpi$  have a zero point  $Z_{\text{EDR3}}$  that depends on magnitude, color, and ecliptic latitude and that to minimize systematic effects one should use a corrected parallax  $\varpi_c = \varpi - Z_{\text{EDR3}}$ . In two papers (Maíz Apellániz et al. 2021a; Maíz Apellániz 2022) we have built on that work to produce a methodology that yields accurate and precise EDR3 parallaxes:

- Maíz Apellániz (2022) provides an alternative  $Z_{\text{EDR3}}$  with the same functional form as Lindgren et al. (2021a). The parameters are very similar for  $G > 13$  but differ significantly for brighter stars.

- As described in Maíz Apellániz et al. (2021a) and elsewhere (e.g. Fabricius et al. 2021), EDR3 parallax uncertainties  $\sigma_{\text{int}}$  are too low and, if used directly, yield distances with underestimated uncertainties. Following the analysis of Maíz Apellániz (2022), calculating external uncertainties  $\sigma_{\text{ext}}$  as  $\sigma_{\text{ext}} = \sqrt{k^2 \sigma_{\text{int}}^2 + \sigma_s^2}$ , where  $k$  is a magnitude-dependent multiplicative constant and  $\sigma_s$  is described below, provides more realistic uncertainty estimates.  $k$  is close to 1 for the fainter stars, increases to values close to 2 around  $G = 12$ , decreases again to  $\sim 1.3$  around  $G = 10$ , and can become as large as 3.0 for the brightest stars, where the original  $Z_{\text{EDR3}}$  was based on a small number of sources.

- EDR3 parallaxes are correlated as a result of the presence of a residual angular covariance (Lindgren et al. 2021b). This has two consequences. [1] The existence of an uncorrected systematic uncertainty for individual parallaxes ( $\sigma_s$  in the previous formula) that is the square root of the angular covariance at zero separation. It has an estimated value of  $10.3 \mu\text{as}$  and can be interpreted as the minimum uncertainty of any single EDR3 parallax (Maíz Apellániz et al. 2021a). [2] The need to add covariance terms when combining parallax uncertainties of objects assumed to be at the same distance (e.g. stellar clusters). As a corollary, stellar clusters that span a small angle in the sky have combined parallax uncertainties that approach  $\sigma_s$  asymptotically, leading to minimum distance uncertainties of  $\sim 1\%$  at 1 kpc and  $\sim 3\%$  at 3 kpc (Maíz Apellániz et al. 2022a).

- Parallaxes for objects with six-parameter solutions or large RUWE (Renormalized Unit Weight Error) are, in general, of worse quality but it is possible to use them correctly with an increased value of  $k$  (Maíz Apellániz 2022).

With respect to photometry, *Gaia* holds the promise of providing the first high dynamic range (17 mag), simultaneously accurate and precise (better than 10 mmag), whole-sky multiband optical photometric survey. However, as we discovered for *Gaia* DR1 (Maíz Apellániz 2017) and DR2 (Maíz Apellániz & Weiler 2018), eliminating the residual systematic offsets requires tweaking the filter passbands and applying small corrections. We have produced a similar analysis for EDR3 that will be submitted soon (Weiler et al. in preparation).

## 3. The ALS catalog and distances to OB stars

Finding OB stars via photometry alone, though possible (Maíz Apellániz & Sota 2008; Maíz Apellániz et al. 2014), is difficult due to the combined effects of extinction and

photometric calibration of ground-based surveys. Two decades ago, [Reed \(2003\)](#) used a combination of photometric and (preferably) spectroscopic data to compile the ALS catalog of Galactic OB stars, which by 2005 contained 18 693 objects. However, the diverse quality of the data (which in many cases lacked even good-quality coordinates) hampered the use of the catalog without including a significant number of contaminants.

In [Pantaleoni González et al. \(2021\)](#), from now on ALS II, we undertook the task of cross-matching the ALS catalog with *Gaia* DR2, painstakingly comparing star by star between the existing data and the *Gaia* catalog. After eliminating duplicates, unmatched objects, and stars with bad astrometry or photometry, we were left with 15 662, of which 13 762 are suspected of truly being Galactic OB massive stars. Among the results from that paper, we point out the following:

- Neither Apsis ([Bailer-Jones et al. 2013](#)) nor StarHorse ([Anders et al. 2019](#)) provide good extinction measurements for OB stars based on *Gaia* DR2 data. Apsis apparently mistakes high-extinction OB stars for cooler, lower-extinction objects while StarHorse allows for some objects to have large negative extinctions and others to follow an anomalous relationship between color excess and amount of extinction.

- In order to convert parallaxes into distances one needs to use priors. Commonly used with *Gaia* DR2 data are those of [Bailer-Jones et al. \(2018\)](#) and [Anders et al. \(2019\)](#), which assume spatial distributions different from the one for OB stars. For that reason, we compared their distances with the ones derived from the prior of [Maíz Apellániz \(2001, 2005\)](#) and the updated parameters of [Maíz Apellániz et al. \(2008\)](#). We found good agreement among the distances derived from the three priors for values below 3 kpc but some differences thereafter.

- We produced a map of the location of the OB stars in the solar neighborhood. The most significant result is the discovery of a structure that extends from the Orion-Cygnus (or Local) and Perseus arms that we dub the Cepheus spur. It is located 50-100 pc above the Galactic plane and appears to be a 2-D extension of the 1-D Radcliffe wave ([Dixon 1967](#); [Alves et al. 2020](#)).

After our work with ALS II, *Gaia* EDR3 yielded significantly improved astrometry and photometry. We continued our analysis of the data by attempting to cross-match the ALS stars that were not in the 15 662 sample above and reprocessing the whole sample to better differentiate between massive and non-massive stars. We have also expanded the sample by including stars with GOSSS [Maíz Apellániz et al. \(2011\)](#) and LiLiMaRlin ([Maíz Apellániz et al. 2019](#)) spectral classifications (a new paper of the GOSSS series, GOSSS IV, will be submitted soon) and from the Cygnus OB2 ([Berlanas et al. 2020](#)) and Carina OB1 ([Berlanas et al. in preparation](#)) associations. The new sample includes several thousand more stars and will be submitted as ALS III later this year.

The information that will be made available in DR3 (see below) and that from ground-based surveys such as GALANTE ([Maíz Apellániz et al. 2021b](#)) will allow us to significantly expand the ALS sample in the near future. Our estimate is that as many as  $10^5$  Galactic OB stars may be identified using those data.

#### 4. The Villafranca project

The Villafranca catalog of Galactic OB stellar groups combines *Gaia* astrometry and photometry with spectroscopy from ground-based surveys to derive information about the young stellar clusters and associations in the solar neighborhood and beyond. A zeroth paper ([Maíz Apellániz 2019](#)) describes the method used to determine group membership, Villafranca I ([Maíz Apellániz et al. 2020](#)) analyzes 16 groups with O2-O3.5 stars using *Gaia* DR2 data, and Villafranca II ([Maíz Apellániz et al. 2022a](#)) revises those results with *Gaia* EDR3 data and adds ten new stellar groups with O stars.

With the Villafranca project we have been able to provide precise distances ( $\sim 1\%$  at 1 kpc,  $\sim 3\%$  at 3 kpc) whose accuracy has been verified for some examples using alternative geometric distances. We have also published detailed analyses of each cluster, describing the massive stars with accurate spectral types that belong to them and finding runaway candidates. For four nearby low-extinction clusters we have used the PMS seen in the cleaned *Gaia* CMDs to estimate their ages. Such CMD analyses will be extended in the future with the help of complementary ground-based surveys such as GALANTE (Maíz Apellániz et al. 2021b).

The most interesting result that has come out of the Villafranca project is the discovery of orphan clusters, very young stellar groups that have been disrupted as the consequence of multiple stellar interactions among their massive stars. The prototype object is the Bermuda cluster (Villafranca O-014 NW) at the North America nebula (Maíz Apellániz et al. 2022b), which through three ejection events expelled a total of at least nine stellar systems (twelve individual stars) between 1.9 and 1.5 Ma ago, including its three most massive stars (one of which, the primary of the Bajamar system, is the earliest-type O star within 1 kpc of the Sun). As a result, the cluster has lost over  $200 M_{\odot}$  in stars and has altered its mass function from one that was top-heavy to one that is compatible with a Kroupa-like function. Moreover, the cluster has lost so much mass that it is now expanding (Kuhn et al. 2020) and will likely dissolve several million years from now.

We are currently working on the third paper of the Villafranca series, which will concentrate on the region of the sky where Carina OB1<sup>†</sup> is located. Three stellar groups in Carina OB1 (Villafranca O-002, Villafranca O-003, and Villafranca O-025) and one in its background (Villafranca O-004) were already analyzed in previous papers and here we will add several more, some with O and early-B stars and some with just the latter. Future papers will expand the sample of Villafranca groups.

## 5. A peek into what the future holds in store

By the time this contribution is published, *Gaia* DR3 will be out in the wild but at the time of this writing access to the data is restricted to DPAC members (and their lips are sealed). What can we say about it without making fools of ourselves in the eyes of you, dear (future) reader, who may know more than us?

We can divide the DR3 results into two types: *raw* and *processed*. By *raw* we mean the direct output of the *Gaia* instruments without significant assumptions about the nature of the source and/or comparisons with models and by *processed* those results that imply an additional treatment such as measuring velocities, equivalent widths, or time series of the raw data. There will be three types of raw results: low-resolution BP+RP spectrophotometry for 219 197 643 objects, high-resolution *z*-band spectroscopy for 999 645 objects, and *z*-band photometry for 32 232 187 objects, in all cases averaged over time. The list of processed results is significantly longer and includes radial velocity and  $v \sin i$  measurements, variable-star identifications and classifications, astrometric and spectroscopic orbit determinations, astrophysical parameters estimations, and H $\alpha$  and DIB  $\lambda 8621$  equivalent widths, among others.

The information content resulting from *Gaia* DR3 will surpass that of previous data releases, as two dimensions will be added to a large number of objects: wavelength in the form of the two types of spectroscopy and time in the form of the analysis of variable stars. It is true that, as it was before, most of the information will not be for massive stars but this time there has been a concerted effort by DPAC to find hot stars (mostly of intermediate mass but some massive) in the sample through a combination of the

<sup>†</sup> Which, despite its name, should not be considered the Keel Kenobi association, something that was instead a result of Darth Vader's actions.

low-resolution spectrophotometry and the high-resolution spectroscopy. Furthermore, the added information will surely help finding new massive needles in the Galactic haystack.

Further down the road we will have *Gaia* DR4. While EDR3 and DR3 are based on 34 months of data, DR4 will use almost double that amount, 66 months. Such a longer baseline will undoubtedly improve the precision of most data products, especially proper motions. However, an even better improvement is likely to take place in the accuracy, that is, the reduction of systematic errors, as the experience from previous data releases will be used to characterize and correct them (for example, the comparison between DR2 and EDR3 was the base for the work of Lindegren *et al.* 2021a, see section 3 in that paper). And then there will be the data deluge in the form of the full astrometric, photometric, and radial-velocity catalogs: all data, all epochs, enough to maintain a generation of Galactic astronomers busy.

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† <https://www.cosmos.esa.int/gaia>

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## Discussion

NATHAN SMITH: For the case of the North America cluster, some gas must have also been ejected in addition to the stars. Does that mean that the cluster was initially bound?

JESÚS MAÍZ APELLÁNIZ: Most likely. We estimate (making reasonable assumptions about the IMF) that the cluster formed 400-500  $M_{\odot}$  in stars and that it has ejected  $\sim 200 M_{\odot}$  of those. If you add the gas that must have been ejected, chances are that the cluster has retained significantly less than half of its initial total mass, which would be sufficient to unbound it.

ALEX DE KOTER: What is the origin of the ejections from the North America cluster? Dynamical interactions or supernova explosions?

JESÚS MAÍZ APELLÁNIZ: Dynamical interactions. The cluster is very young and there are no signs of supernovae at all. Indeed, the three ejections events can be dated quite accurately (to within a few tens of ka) to 1.5, 1.6, and 1.9 Ma ago and they serve as estimates of the age of the cluster ( $\sim 2$  Ma) if we assume that such events take place preferentially very early in the cluster's life. Those values are also consistent with the expansion rate observed in what remains of the cluster.