
157. Many more Gaia sources in ω Cen

GAIA DATA RELEASE 3 was issued in June 2022, and the next major release, DR4, is not scheduled until 2025. But on 10 October 2023, the Gaia Data Processing and Analysis Consortium (DPAC) published five papers forming part of a special ‘[Focused Product Release](#)’. I will look at each of these in my next five essays.

The first, which I will describe here, relates to the globular cluster ω Cen. The key point is that a special observing mode, implemented to overcome some of the limitations of the extreme spatial crowding in the cluster’s core, has resulted in an additional *half a million new stars* observed by Gaia in its central region!

I LOOKED at some of the first Gaia results on ω Cen in essay #40 (October 2021). As I explained there, at a distance of about 5200 pc, it is the largest and most massive globular cluster in the Milky Way. With a diameter of 50 pc, it contains some 10 million stars, has a total mass of $4 \times 10^6 M_{\odot}$, and is thought to be the core remnant of a disrupted dwarf galaxy. But it is too distant, too crowded, and just too faint, for *any* of its stars to have been observed by Gaia’s predecessor, Hipparcos!

In essay #40, I also gave some of the key results on the numbers of cluster stars included in EDR3, and the resulting estimates of its distance and proper motion. Specifically, Soltis et al. (2021) selected 178 548 stars from EDR3 within 45 arcmin of the cluster centre. They estimated a mean cluster proper motion of $\mu_{\alpha} = -3.25 \mu\text{as}$, $\mu_{\delta} = -6.76 \mu\text{as}$, in good agreement with the value found for DR2 (Baumgardt et al., 2019).

Selecting stars participating in this common space motion then resulted in 108 054 candidate members. Further restriction according to their location in the colour–magnitude diagram resulted in 66 467 members with good Gaia astrometry and two-colour photometry.

Their mean cluster parallax was 0.191 ± 0.001 mas, corresponding to a distance of 5236 ± 28 pc, a value in good agreement, for example, with the classical photometric distance of 5.2 kpc from Harris (1996).

I also described the calibration of the luminosity of the tip of the cluster’s red giant branch, and the implications for the distance scale, and the value for H_0 .

HOWEVER, the DR3 catalogue for ω Cen, along with a handful of other high-density stellar regions on the sky, shows a striking absence of detected sources in its most crowded central region. To understand how a dedicated observing mode, and the associated ‘Focused Product Release’, has now allowed the detection of many more stars in the central regions of ω Cen, let me outline the principles and limitations of Gaia’s normal observational mode, and explain how these ‘holes’ arise.

In Gaia’s normal mode of operation, the images of sources entering each of the two fields of view are detected by the instrument’s ‘sky mapper’. Information on detected and confirmed sources (their magnitude, as well as their 2-d coordinates and trajectory in the focal plane) is passed in real time to the subsequent CCDs of the Astrometric Field (AF), the Blue and Red Photometer (BP/RP), and the Radial Velocity Spectrograph (RVS).

In normal mode, accurate astrometry is obtained from the astrometric field. These observations preserve the full CCD pixel resolution *along* scan, so yielding the most accurate astrometry along-scan. But for sources fainter than 13 mag, and in order to limit the volume of data sent to the ground, a number of across-scan pixels are ‘collapsed’ (on-board) into a single data sample.

Gaia’s resulting astrometric crowding limit is around 1.05 million objects deg^{-2} , or about one object per 12 arcsec^{-2} . The completeness of the Gaia catalogue is, accordingly, generally very high. But for a small number of very densely populated regions on the sky, this standard ‘windowing’ and readout strategy for the astrometric field observations becomes saturated: multiple sources begin to overlap, leading to conflicting readout windows, to windows containing multiple sources, or to no readout at all.

In a program of dedicated ‘Service Interface Function’ scans, an alternative approach to the on-board observations of a number of such high stellar density regions has been implemented. These special observations of crowded fields have been obtained for the globular clusters ω Cen, 47 Tuc, M4, M22, and NGC 4372, as well as Baade’s Window in the Galactic bulge, the LMC and SMC, and the Sagittarius I galaxy.

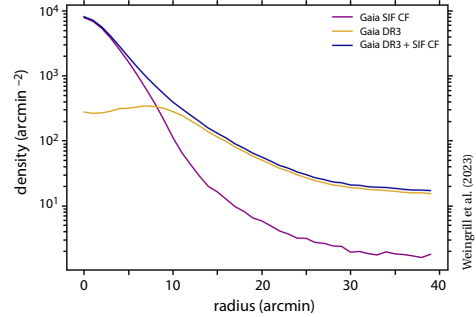
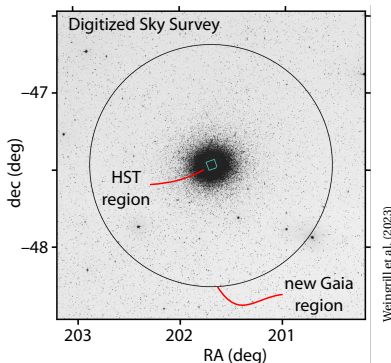
IN THIS SPECIAL MODE of operation, the satellite's 'scanning law' and spin rate are not modified. But sources, and their associated astrometric data, are instead derived from the binned (2×2) pixels of the sky mapper. This has the advantage of preserving much more of the *across-scan* spatial information, and thereby significantly reducing source confusion. A further improvement in the effect of crowding results from the fact that the sky mappers are only illuminated by a *single* field-of-view, while the astrometry field observations result from the superposition of the two fields of view (in order to provide relative astrometry over widely separated regions of the sky).

Disadvantages of these dedicated sky mapper observations are twofold. First is the lower astrometric accuracy compared with the astrometric field data, the latter resulting from nine along-scan CCDs, each exploiting the full along-scan pixel resolution. The second is the absence of colour and spectral information for the sources which, for the nominal mode of operation, is obtained from the Blue and Red Photometer (BP/RP), and the Radial Velocity Spectrograph (RVS) fields.

AS I MENTIONED at the start, results for ω Cen were made available (as part of program of five 'Focused Product Releases', supplementing DR3), in October 2023. As described in detail by Weingrill et al. (2023), these new results were derived from special scans obtained between 1 January 2015 and 8 January 2020, and a dedicated processing pipeline. Incidentally, further such crowded fields observations are still ongoing.

As a result, the previous 'hole' in the core of the ω Cen cluster, evident in Data Release 3, is now 'filled' with 526 587 additional sources, compared with the 321 698 already present in Gaia DR3. Their fidelity, and their associated astrometry, was validated by comparing the results to a dedicated Hubble Space Telescope dataset covering the cluster core.

Magnitude uncertainties are in the range 1–10 mmag over $G = 15 - 20$ mag. Astrometric standard errors are significantly higher than for Gaia DR3, with median uncertainties of ~ 3 mas in RA/Dec, ~ 2 mas in both components of proper motion, and ~ 4 mas in parallax.



PRE-DATING THESE latest data on the core region, many studies of ω Cen have been published exploiting the Gaia data. These include:

- calibration of the luminosity of the tip of the red giant branch, and the cluster's 3-d structure and Galactic orbit (Soltis et al., 2021; Li et al., 2023);
- kinematics and orbital anisotropy of the various stellar sub-populations as a function of metallicity (Jindal et al., 2019; Cordoni et al., 2020; Sanna et al., 2020), including retrograde substructures (Myeong et al., 2018), and internal rotation as a function of stellar mass (Scalco et al., 2023);
- identification of stellar streams (tidal debris) torn off the cluster as it orbits the Galaxy (Ibata et al., 2019a; Ibata et al., 2019b; Kuzma et al., 2021; Canducci et al., 2022), and confirmation of its disrupted dwarf galaxy origin (Youakim et al., 2023);
- chemical tagging (including s-process elements) of the Fimbulthul tidal stream (Simpson et al., 2020);
- confirmation of the cluster's relationship to the Gaia-Sausage/Enceladus stream (Limberg et al., 2022);
- the distribution of dark and luminous mass, with evidence that the dark-mass component is more centrally concentrated (Evans et al., 2022);
- studies of its metal-poor stars (Johnson et al., 2020), the distribution of hot subdwarfs (Luo et al., 2021), and of far ultraviolet sources (Prabhu et al., 2022a; Prabhu et al., 2022b);
- distortion mapping of the HST instruments ACS, UVIS and WFC2 (Kozhurina-Platais et al., 2018; Casetti-Dinescu et al., 2021), and proper motions from HST (Libralato et al., 2018; Scalco et al., 2021);
- axion and neutrino bounds, from the TRGB (Capozzi & Raffelt, 2020), and constraints on the monopole-dipole potential (Poddar & Pachhar, 2023).

I AM WRITING THIS at a time when this wealth of new observations has only just been made available, and before its scientific exploitation has begun. Given the range of scientific results that have been obtained on ω Cen so far, we can look forward to many deeper insights based on this new source catalogue in the future.