A&A 650, A201 (2021)
https://doi.org/10.1051/0004-6361/202140985

Astronomy & Astrophysics

The 10 parsec sample in the *Gaia* era⋆,⋆⋆

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Received 2 April 2021 / Accepted 23 April 2021

ABSTRACT

Context. The nearest stars provide a fundamental constraint for our understanding of stellar physics and the Galaxy. The nearby sample serves as an anchor where all objects can be seen and understood with precise data. This work is triggered by the most recent data release of the astrometric space mission *Gaia* and uses its unprecedented high precision parallax measurements to review the census of objects within 10 pc.

Aims. The first aim of this work was to compile all stars and brown dwarfs within 10 pc observable by *Gaia* and compare it with the *Gaia* Catalogue of Nearby Stars as a quality assurance test. We complement the list to get a full 10 pc census, including bright stars, brown dwarfs, and exoplanets.

Methods. We started our compilation from a query on all objects with a parallax larger than 100 mas using the Set of Identifications, Measurements, and Bibliography for Astronomical Data database (SIMBAD). We completed the census by adding companions, brown dwarfs with recent parallax measurements not in SIMBAD yet, and vetted exoplanets. The compilation combines astrometry and photometry from the recent *Gaia* Early Data Release 3 with literature magnitudes, spectral types, and line-of-sight velocities.

Results. We give a description of the astrophysical content of the 10 pc sample. We find a multiplicity frequency of around 27%. Among the stars and brown dwarfs, we estimate that around 61% are M stars and more than half of the M stars are within the range from M3.0 V to M5.0 V. We give an overview of the brown dwarfs and exoplanets that should be detected in the next *Gaia* data releases along with future developments.

Conclusions. We provide a catalogue of 540 stars, brown dwarfs, and exoplanets in 339 systems, within 10 pc from the Sun. This list is as volume-complete as possible from current knowledge and it provides benchmark stars that can be used, for instance, to define calibration samples and to test the quality of the forthcoming *Gaia* releases. It also has a strong outreach potential.

Key words. parallaxes – stars: late-type – planetary systems – solar neighborhood – galaxies: stellar content – catalogs

1. Introduction

Determining the number of stars in the sky must have been in the minds of many people since the dawn of humanity. Ancient astronomers, such as Timocharis of Alexandria and Hipparchus of Nicaea, started to count and catalogue stars visible to the naked eye and built the first magnitude-limited catalogues. Modern astronomers prefer using volume-limited catalogues, with different maximum distance limits (e.g., Jenkins 1937; van Biesbroeck 1961; Reid et al. 2004; Gliese & Jahreiss 2015; Henry et al. 2018), because any magnitude-limited sample is biased against intrinsically faint (and single) objects (Malmquist 1925). A good example concerns the low-mass stars ($M \lesssim 0.5\,M_{\odot}$). We now know that they constitute an important part of the objects in our Galaxy, while even the brightest of them (AX Mic) is invisible to the naked eye. Astronomers such as Max Wolf and Frank E. Ross catalogued stars with a large proper motion to try discovering faint, but nearby stars (Wolf 1917; Ross 1926). Willem J. Luyten produced many catalogues (e.g., Luyten 1979) with different cuts in proper motion and corresponding names (i.e., LFT for five-tenths of an arcsec limit, LTT for two-tenths, and LHS for half a second).

Ever since the first stellar parallaxes were measured (Bessel 1838; Henderson 1839; von Struve 1840, see Reid & Menten 2020 for a review), astronomers have tried to map out our nearest neighbours. Individual measurements have been followed by increasingly larger trigonometric parallax catalogues across the 20th century, providing fundamental data for volume-limited catalogues: 72 stars by Newcomb (1904), 1870 stars in the First General Catalogue of trigonometric parallaxes computed by Frank Schlesinger and edited by the Yale University Observatory in 1924, 6399 stars in the Yale Parallax Catalogue (Jenkins 1963), 7879 stars in the Fourth General Catalogue of trigonometric parallaxes (van Altena et al. 1995), etc. The end of the 20th century was marked by the first astrometric space mission, HIPPARCOS (HIgh Precision PARallax COllecting Satellite, Perryman et al. 1997) providing a catalogue of 117 955 relatively bright stars ($V \lesssim 12.4$ mag). The second astrometric space mission, *Gaia* (Gaia Collaboration 2016), provides another dramatic increase, both qualitatively and quantitatively,

⋆ The animation and a zoomable version of Fig. B.1 are available at https://www.aanda.org
⋆⋆ Table A.1 is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/650/A201, at https://gruze.org/10pc/, and at https://gucds.inaf.it/

with all sky parallax measurements for about 1.5 billion objects. It offers the means to complete volume-limited samples with larger distance limits. The *Gaia* Catalogue of Nearby Stars (GCNS), based on the *Gaia* Early Data Release 3 (*Gaia* EDR3, Gaia Collaboration 2021a), pushes the limit to 100 pc (Gaia Collaboration 2021b, GSS21).

Our first motivation to compile the 10 pc sample was to use it as a quality assurance test of the GCNS and, therefore, to verify the *Gaia* EDR3 before its publication. Such information could be derived from the work of the REsearch Consortium On Nearby Stars (RECONS[1]), who have focused on the detection and characterisation of nearby star systems for several decades. They have published their results in a large series of papers. Part of them, as well as statistics, are listed in the RECONS webpage. Yet the compilation of a 10 pc catalogue from this resource is not straightforward.

According to RECONS, the 10 pc sample as of 12 April 2018 included 462 objects in 317 systems (Henry et al. 2018). The publication of the second *Gaia* data release (*Gaia* DR2, Gaia Collaboration 2018) a few days later provided new, more precise parallaxes that moved some objects inside or outside of the 10 pc limit. It also provided individual parallaxes for components in systems. It resulted in 418 objects in 305 systems, with eight systems added by *Gaia* (Henry et al. 2019).

However, *Gaia* DR2 also contained a large number of spurious objects: a simple cut at a parallax ≥100 mas in *Gaia* DR2 returns 1722 objects. Using a random forest classifier to disentangle between good and bad astrometric solutions, GSS21 found that 15 sources, although classified as good from the classifier, lie closer than Proxima Centauri (see their Fig. 12). On the contrary, with one more year of observations, better reduction and calibration procedures of the *Gaia* EDR3, a parallax ≥100 mas selection returns only 315 objects with a very high and improved precision, of which three had an obvious spurious solution and were rejected from the random forest classifier. The GCNS essentially offered a reasonably clean sample, with no new discoveries, but with higher precision astrometry and the first individual parallaxes for five objects in systems.

In the framework of the GCNS, the 10 pc compilation was not exhaustive but restricted to objects that should have been visible to *Gaia*, given its magnitude limits at the bright ($G \simeq 2.5$ mag) and faint ($G \simeq 21$ mag) ends. In the present work, we give a more complete census of the 10 pc sample using our knowledge of the nearby objects, including stars and their companions, brown dwarfs, and planets. For many of the objects, it also benefits from the exquisite parallaxes obtained from the last data release based on 34 months of operation of *Gaia*. This list will be used for further *Gaia* quality assurance. It includes all objects (i.e., planets and unresolved components) as separate entries as many of these will be detected in future *Gaia* releases. We also believe that it could be of general use to the community as it provides a complete list of benchmark and vetted objects and we are making it publicly available. For the foreseeable future, the 10 pc sphere is the only volume that it will be possible to find and characterise all objects. Finally, the 10 pc sample has significant outreach potential.

Following in the steps of Louise F. Jenkins, who published a list of 127 stars with their known companions and gathered the knowledge at that time on the neighbours whose distance is less than 10 pc from the Sun (Jenkins 1937), we give here the current snapshot of the nearby sample within 10 pc. In Sect. 2, we describe the catalogue and how we constructed it. In Sect. 3 we explore the content of the catalogue and give a few statistics. Sect. 4 places the catalogue in the context of ongoing and future observational programmes that will impact the sample. Sect. 4 also illustrates the potential of this catalogue for outreach. Finally, conclusions are given in Sect. 5.

2. The 10 pc catalogue

2.1. Catalogue compilation

We started our compilation using the Set of Identifications, Measurements, and Bibliography for Astronomical Data (SIMBAD) database[2] (Wenger et al. 2000). This database provides information on astronomical objects of interest beyond the Solar System that have been studied and reported in scientific publications. We retrieved 378 stars and brown dwarfs with a parallax greater or equal than 100 mas through the SIMBAD table access protocol (TAP) service[3] with the following query, `SELECT * FROM basic LEFT JOIN allfluxes on oid=oidref WHERE plx_value > = 100`, which returns the information on the object type, its astrometry, its photometry in U, B, V, R, I, J, H, and K_s bands, and, when available, its spectral type. To the SIMBAD list we added 21 cool brown dwarfs from recent parallax programmes, but they are not yet included in the database (Sect. 3.3).

Since the query is based on the parallax, SIMBAD sometimes returns only one object while the literature papers refer to separate components (e.g., very close astrometric binaries and spectroscopic binaries), so we added these components as explained in Sect. 3.1. We removed objects whose binarity has been refuted by *Gaia* parallaxes, from confusion with activity, or, on the contrary, confirmation by high-contrast imaging studies. We finally completed the list by adding confirmed exoplanets, starting from existing exoplanet databases and reviewing their status to add only confirmed discoveries (Sect. 3.4).

We discarded five objects that initially passed our TAP SIMBAD criterion. Three of them were the brown dwarfs WISE J053516.80–750024.9, WISE J035934.06–540154.6, and WISE J154214.00+223005.2, with published parallaxes of 250 ± 79 mas, 145 ± 39 mas (Marsh et al. 2013), and 96 ± 41 mas (Tinney et al. 2014), respectively, which now have higher-precision parallax measurements from Kirkpatrick et al. (2021) that move them outside the 10 pc limit. The other two objects were also low-mass stars: LP 388–55, an M7.5 V + L0 binary that had its parallax re-estimated from 110.7 ± 5.8 mas (Dittmann et al. 2014) to 64.3 ± 0.7 mas in *Gaia* EDR3 and the binary G 19–15 had a dynamical parallax measured of 74.0 ± 0.99 mas from Docobo et al. (2019).

This compilation resulted in 540 objects in 339 systems that are listed in Table A.1 (available at the CDS). It contains 375 stars from F to early-L spectral type, including 20 white dwarfs (plus one candidates in a system). It also lists 85 brown dwarfs (plus three candidates) and 77 confirmed exoplanets. We also tabulated, numbered from 1001 and higher in the catalogue, two low-mass star systems, namely G 100-28 (GJ 1083) and Ross 440 (GJ 352), 13 ultra-cool T and Y brown dwarfs whose 1σ parallax uncertainties will allow them to be located within 10 pc, and the two components of a brown dwarf binary with a photometric parallax estimate larger than 100 mas.

The sample was constructed by setting a strict parallax limit of 100 mas. However, the parallax measurements carry uncertainties, and objects located within 3-sigma of this limit may

[1] http://www.recons.org

[2] http://SIMBAD.u-strasbg.fr

[3] https://simbad.u-strasbg.fr/simbad/sim-tap

Table 1. Example of content of the 10 pc catalogue (the first object, Proxima Centauri).

Parameter	Unit	Description	Example
NB_OBJ	...	Running number for object, ordered by increasing distance	1
NB_SYS	...	Running number for system, ordered by increasing distance	1
SYSTEM_NAME	...	Name of the system	alf Cen
OBJ_CAT	...	Star (*), LM (low mass star), BD (brown dwarf), WD (white dwarf), or Planet	LM
OBJ_NAME	...	Name of the object	Proxima Cen
RA	deg	Right ascension (ICRS)	217.392321472009
Dec	deg	Declination (ICRS)	−62.6760751167667
EPOCH	a	Epoch for position	2016.0
PARALLAX	mas	Trigonometric parallax	768.066539187357
PARALLAX_ERROR	mas	Parallax uncertainty	0.049872905
PARALLAX_BIBCODE	...	Reference for the parallax	2020yCat.1350....0G
PMRA	mas a^{-1}	Proper motion in right ascension	−3781.74100826516
PMRA_ERROR	mas a^{-1}	Proper motion uncertainty in right ascension	0.031386077
PMDEC	mas a^{-1}	Proper motion in declination	769.465014647862
PMDEC_ERROR	mas a^{-1}	Proper motion uncertainty in declination	0.050524533
PM_BIBCODE	...	Reference for the proper motion	2020yCat.1350....0G
RV	km s^{-1}	Line-of-sight velocity	−22.345
RV_ERROR	km s^{-1}	Line-of-sight velocity uncertainty	0.006
RV_BIBCODE	...	Reference for the line-of-sight velocity	2014MNRAS.439.3094B
SP_TYPE	...	Spectral type	M5.5
SP_BIBCODE	...	Reference for spectral type	1995AJ....110.1838R
SP_METHOD	...	Method used to derive the spectral type (see text)	Opt Spec
G_CODE	...	Reference code for the G magnitude (see text)	3
G	mag	*Gaia* G band magnitude measured, given only if G_CODE is 2 or 3	8.984749
G_ESTIMATE	mag	*Gaia* G band magnitude estimated, given only if G_CODE is 10 or 20	...
GBP	mag	*Gaia* B_P band magnitude, given only if G_CODE is 2 or 3	11.373116
GRP	mag	*Gaia* R_P band magnitude, given only if G_CODE is 2 or 3	7.5685353
U	mag	U magnitude	14.21
B	mag	B magnitude	12.95
V	mag	V magnitude	11.13
R	mag	R magnitude	9.45
I	mag	I magnitude	7.41
J	mag	J magnitude	5.357
H	mag	H magnitude	4.835
K	mag	K_s magnitude	4.384
SYSTEM_BIBCODE	...	Reference for multiplicity or exoplanets	2018A&A...615A.172M
EXOPLANET_COUNT	...	Number of confirmed exoplanets	1
GAIA_DR2	...	*Gaia* DR2 identifier	5853498713160606720
GAIA_EDR3	...	*Gaia* EDR3 identifier	5853498713190525696
SIMBAD_NAME	...	Name resolved by SIMBAD	alf Cen C
COMMON_NAME	...	Common name	Proxima Cen
GJ	...	Gliese & Jahreiß catalogue identifier	GJ 551
HD	...	Henry Draper catalogue identifier	...
HIP	...	HIPPARCOS catalogue identifier	HIP 70890
COMMENT	...	Additional comments on exoplanets, multiplicity, etc.	Proxima Cen c: candidate planet 2019ESS.....410203D

not belong to the 10 pc sample when their measured parallax is larger than this limit or when the value is smaller. We used a SIMBAD query with a 20 mas parallax cut and replaced the SIMBAD parallax by the more accurate *Gaia* EDR3 value when available. We find 16 objects with parallaxes within 3-sigma from our 100 mas parallax limit. This number does not include the 15 brown dwarfs already identified at a 1-sigma level. However, in general we expect the true distance of an object to be larger than the inversion of the measured parallax so we expect to lose more objects than we gain due to errors at this border zone. Indeed, considering the bayesian distances computed in the GCNS, the number of objects with parallaxes > 100 mas is 312 while the number of objects with median distances < 10 pc is 310.

The description of the catalogue is reported in Table 1, with the first object of the list, Proxima Centauri, shown as an example. The references in the catalogue are given with the bibcode assigned by the SAO/NASA Astrophysics Data System[4]. The full references are given in the appendix.

2.2. The 10 pc sample and Gaia

The ability to fully catalogue and characterise the 10 pc sample renders it a fundamental dataset to test the quality of upcoming *Gaia* releases. Some example quality checks for *Gaia* using this dataset are as follows: (i) Catalogue completeness: To check the completeness of the overall stellar sample and white dwarf population, one can extrapolate from the local stellar density as was done by GSS21. (ii) Exoplanet detections: While the bulk of the expected large catalogue of exoplanets detected from *Gaia*

[4] https://ui.adsabs.harvard.edu/

Table 2. G_CODE values for retrieved or estimated G magnitudes.

G_CODE	G magnitude	N_{obj}
2	Retrieved from *Gaia* DR2	3
3	Retrieved from *Gaia* EDR3	342
10	Estimated from spectral type [(a)], $\sigma \approx 0.6$ mag	37
20	Estimated from $M_G = 25$ mag [(b)], lower limit	49

Notes. [(a)] G magnitude estimated from the absolute magnitude versus spectral type calibration computed as part of the GCNS. [(b)] G magnitude of late T and Y brown dwarfs too faint for *Gaia* computed assuming an arbitrarily absolute G magnitude set to 25 mag.

astrometry will only appear in the fourth data release, the first sample of exoplanet detections might already be announced in the third data release. It will likely include a subset of those planetary companions within 10 pc with detectable astrometric signatures (see Sect. 3.4). (iii) Magnitude limits: The 10 pc sample has stars that are too bright for *Gaia* and brown dwarfs that are too faint. It provides an empirical estimate of the magnitude limits. (iv) Binarity detection: there are at least 94 multiple systems in our 10 pc sample. They cover a wide parameter space in mass ratios, magnitude differences, angular separations, inclinations, and orientations. Binary systems for which we do not find solutions in the *Gaia* pipeline should be understood.

By comparing the *Gaia* EDR3 to our 10 pc sample, we found that there are eight nearby stars too bright to be observed by *Gaia* and 54 brown dwarfs that are probably too faint. Of the 401 remaining objects, 89 do not have a full astrometric solution in *Gaia* EDR3; they are all in close binary systems. Yet 14 of them had a full astrometric solution in *Gaia* DR2. With twelve more months of observations, the residuals went up and the *Gaia* EDR3 solution did not meet the restrictive quality cuts (astrometric_sigma5d_max $<$ 1.2 mas or visibility_periods_used $\geq$ 9; Lindegren et al. 2021). This should no longer be a problem in the next data release with the improved astrometric solution, taking the orbital motion into account.

2.3. Astrometry

We replaced the SIMBAD output astrometry by that of *Gaia* EDR3 when available (312 stars and brown dwarfs), except for three cases in binary systems from Benedict et al. (2016; GJ 831 A, GJ 791.2 A, and CD-68 47 A), who accounted for orbital motion and determined their astrometry with a higher precision. Whereas the HIPPARCOS determinations were more precise compared to *Gaia* DR2 values for some bright stars, this was no longer the case compared to *Gaia* EDR3 values.

2.4. Photometry

In Table A.1, we also provide the *Gaia* photometry (G, G_{BP}, and G_{RP}) for 345 objects. The photometry of all of them is from *Gaia* EDR3, except for three brown dwarfs (2MASS J17502484–0016151 A, 2MASS J08354256–0819237, and Luhman 16 B) that are in *Gaia* DR2, but not in *Gaia* EDR3. In unresolved systems, we often tabulate just the primary (or system) magnitudes. We included an estimate of the G magnitude (G_ESTIMATE) for the other 86 objects using different procedures, as indicated by the G_CODE value in the catalogue and summarised by Table 2. The addition of the G_ESTIMATE column provides a quick way to identify objects that should be detectable by *Gaia*, but they should not be used for scientific purposes.

2.5. Spectral type and object category

We reviewed the output spectral types provided by default from the SIMBAD query. We did not calculate an average spectral type from all determinations, but took the most recent reliable spectral type based on spectra. In Table A.1 we indicate the method used for the spectral type determination, from photometry or spectroscopy, in the optical or near-infrared. Only 40 objects, mainly in close binary systems, have no spectral type.

We classified all the objects of the 10 pc sample in five categories (OBJ_CAT[5] in Table A.1): stars (K and earlier spectral types), low-mass stars (M and early-L types), white dwarfs, brown dwarfs (including the M9-type object BD+16 2708 Bb from its dynamical mass determined by Dupuy & Liu 2017), and exoplanets. For components in close binaries with no information on the spectral type, we assigned them to the low-mass stars category by default. However, this classification should be taken with caution since we know that some of them can actually be brown dwarfs, such as L 768–119 B, GJ 867 D, and Wolf 227 B, which have mass estimates that may place them in the substellar range (Nidever et al. 2002; Davison et al. 2014; Winters et al. 2018). The probable brown-dwarf nature of the three star candidates is indicated in the COMMENT field of Table A.1.

2.6. Line-of-sight velocities

The SIMBAD query provides line-of-sight velocities for 287 objects. Among them, 129 come from *Gaia* DR2 or its catalogue of radial velocity standard stars (Soubiran et al. 2018), and 48 precise measurements come from Lafarga et al. (2020). Radial velocities of multiple systems may be inaccurate, but we tried to use the same source for the two components of a binary system when available, or we only listed a single measurement when this was not the case.

3. Astrophysical content and statistical exploration

In this section we describe the content of the 10 pc sample in terms of astrophysical objects, as illustrated by Fig. 1. It shows the G-band absolute magnitude as a function of the $G - J$ colour for all objects with *Gaia* G and 2MASS (Two Micron All Sky Survey; Skrutskie et al. 2006) J magnitudes and spectral type determination. As a comparison, the GCNS objects with G and J magnitudes are also shown. In Table 3 we summarise the spectral and multiplicity distribution of our sample.

3.1. Multiple systems

Multiple systems are reported in large databases such as the Catalog of Components of Double and Multiple Stars (Dommanget & Nys 2002) or the Washington Double Star catalog[6] (Mason et al. 2001). Multiplicity is also indicated in the SIMBAD output (OBJ_TYPE=**). For all multiple system candidates we confirmed that the hypothesis of being part of that system was consistent with the most recent parallax determinations. We discarded five companion candidates: BD+42 2320 with β CVn, BD+02 521 with κ^{01} Cet, and 2MASS

[5] OBJ_TYPE in SIMBAD.
[6] http://www.astro.gsu.edu/wds/

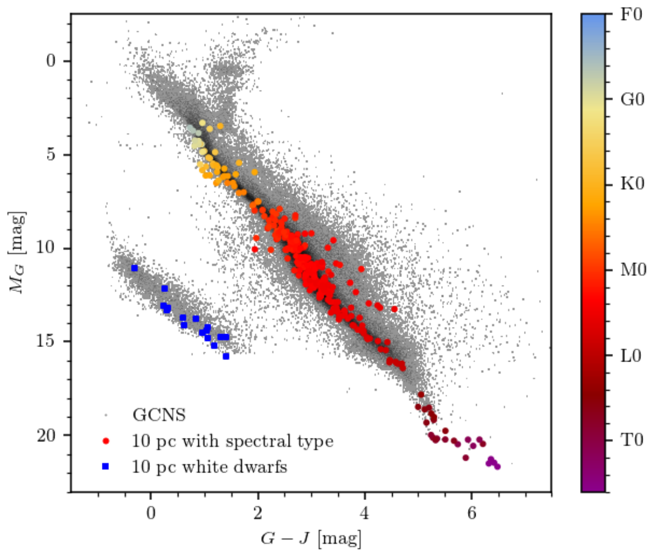

Fig. 1. Colour-absolute magnitude diagram of the 10 pc sample, over-imposed on the GCNS (grey dots). The colour bar indicates the spectral type. White dwarfs are in dark blue.

Table 3. Summary of the 10 pc sample.

Type	Number
O	0
B	0
A	4
F	8
G	18
K	38
M	249
L	21
T	45
Y	19
D	20
N/A	41
Exoplanets	77
Total	541
Single	246
Binary	69
Triple [(a)]	19
Quadruple [(a)]	3
Quintuple [(a)]	2

Notes. In the column Type, O, B, A... Y stand for stellar and sub-stellar spectral types, D for white dwarfs, and N/A for objects without a spectral type. The Sun (G2 V star) and its eight planets are not included. [(a)]The name of the triple, quadruple, and quintuple systems are given in Table 5.

J12141817+0037297 with GJ 1154, based on their *Gaia* DR2 parallax, while the companions of HD 50281 AB and BD+43 2796 were identified in the *Gaia* EDR3 with low parallaxes. In addition, three spectroscopic binary candidates (BD+19 5116 A, BD+19 5116 B, and G 13–22) that are known to be active stars were discarded. Details on these discarded components are given in the `COMMENT` column of Table A.1.

As already stated in Sect. 2.2, the future *Gaia* data releases will provide solutions for a large number and type of binary (astrometric, spectroscopic, and eclipsing) with periods from 0.2 d to more than 5 yr, in amounts of hundreds of thousands in the third *Gaia* data release (*Gaia* DR3) and millions in the fourth *Gaia* data release (*Gaia* DR4), as predicted by the *Gaia* Universe Model Snapshot (Robin et al. 2012). Within the 10 pc sphere, one can expect very good forthcoming astrometric solutions, including orbital parameters. Such new astrometry would complete the characterisation of the systems, even the closest ones; the expected limit is 0.12 arcsec, but *Gaia* astrometry will provide information on binarity even for objects it cannot resolve.

3.2. White dwarfs

Twenty objects are white dwarfs, six of which are part of multiple systems. Their spectral type distribution is nine DA, five DQ, four DZ, and two DC. They all have a precise parallax from *Gaia* EDR3 except for Procyon B, most likely due to the short current separation and brightness difference of about 10 mag with respect to Procyon A. With a more eccentric orbit than Procyon B and a similar brightness ratio with the primary, Sirius B offered, however, a more favourable situation to be detected by *Gaia*.

Our 10 pc sample may be supplemented with new faint, dark, white dwarfs in the future, in particular in unresolved multiple systems. For example, we found two candidates in our list. G 203–47 is a spectroscopic binary Reid & Gizis (1997) with one possible white dwarf component: Delfosse et al. (1999) argued that the companion's mass is too large ($M > 0.5\,M_{\odot}$) to be something other than a degenerate star. Likewise, CD–32 5613 was quoted as an unresolved double white dwarf by Toonen et al. (2017).

3.3. Brown dwarfs

According to Smart et al. (2017), *Gaia* can detect L5 dwarfs to 29 pc, T0 dwarfs to 14 pc, T6 dwarfs to 10 pc, and T9 dwarfs to 2 pc, assuming a magnitude limit G of 20.7 mag. These predictions are consistent with the 10 pc sample: The latest object with a *Gaia* parallax determination is just T6. There are, however, a few examples for which *Gaia* does not determine an astrometric solution or even a detection. This is the case for the nearest pair of brown dwarfs, Luhman 16 AB (L7.5+T0.5; Luhman 2013). Whereas both components are in *Gaia* DR2, *Gaia* EDR3 tabulates only the A component and neither of the two releases provides a solution with a parallax. The other cases where *Gaia* failed to acquire astrometry are listed in Table 4. Except for three objects close to the faint limit of *Gaia*, all are in multiple systems for which the current *Gaia* astrometric solution is applying a single star solution. For nearby objects in multiple systems, the orbital motion induces large residuals in the single star solution that the pipeline marks as errors and a full solution is not provided. Future *Gaia* data release will employ multiple star solutions so we expect full astrometric solutions for these brown dwarfs.

We completed our compilation of brown dwarfs with those presented by Kirkpatrick et al. (2019), Best et al. (2020), and, especially, Kirkpatrick et al. (2021), from where we added 38 ultra-cool objects with new or more precise parallaxes. We expect the 10 pc census to be further supplemented with cool T- and Y-type dwarfs in the near future. Of the 19 candidates with `NB_OBJ` ≥ 1001 (Sect. 2.1), 15 are T and Y dwarfs, while Kirkpatrick et al. (2021) report additional candidates with only parallax estimates that could fill in the 10 pc sample (e.g., the binary CWISE J061741.79+194512.8 AB with a parallax estimate of 133 mas).

Table 4. Brown dwarfs expected to have a full astrometric solution in future *Gaia* data releases.

Name	Parallax (mas)	Spectral type
Luhman 16 A	501.6 ± 0.1	L7.5
Luhman 16 B	501.6 ± 0.1	T0.5
ϵ Ind C	270.7 ± 0.7	T6.0
SCR J1845–6357 B	249.7 ± 0.1	T6.0
Scholz's Star B	147.1 ± 1.2	T5.0
SCR J1546–5534 B	119.1 ± 0.7	T6.0
2MASS J16471580+5632057	116.0 ± 29.0	L9 pec
WISE J223617.59+510551.9	102.8 ± 1.9	T5.5
CFBDS J213926+022023 A	101.5 ± 2.0	L8.5
CFBDS J213926+022023 B	101.5 ± 2.0	T3.5
2MASS J07584037+3247245	101.3 ± 3.3	T2.5
BD+16 2708 B	100.5 ± 0.1	M9

3.4. Exoplanets

The existing exoplanet catalogues, such as the Extrasolar Planets Encyclopædia[7], the NASA Exoplanet Archive[8], the Exoplanet Orbit Database[9], or the Open Exoplanet Catalogue[10], are not fully consistent. Discrepancies are partly due to different selection criteria, notations, and diligence in updating their data bases, and they are also due to the heterogeneity of information provided in discovery papers that different catalogues capture in different ways. As a consequence, it is almost impossible to achieve full homogeneity, and any direct comparison between catalogues can be difficult depending on the specific application. This is the case even for the sample of exoplanetary systems nearest to the Sun.

We cross-matched the Extrasolar Planets Encyclopædia and the NASA Exoplanet Archive in order to select the most reliable set of stars with exoplanets within 10 pc, and we added those that we considered to be confirmed to our catalogue. The most recent discovery added to our catalogue is the transiting rocky planet GJ 486 b (Trifonov et al. 2021). The astrometry given in Table A.1 is the one of the host star, and the discovery reference is given in the `SYSTEM_BIBCODE` field.

Non-listed candidate, unconfirmed, or controversial exoplanets are enumerated, though, in the corresponding `COMMENT` field of the host star. For them, we employ the term 'candidate' when the publication reported the companion with that terminology or when the statistical evidence was not strong for the presence of the signal. A notable example is the second long-period planet candidate orbiting Proxima Centauri c (Damasso et al. 2020). We use the term 'unconfirmed' or 'controversial' when the radial-velocity or imaging signal has not been seen by different groups analysing the same datasets, when different groups use different datasets and do not find the same signals, or when the radial-velocity signal can be explained in terms of stellar activity variations. This nomenclature is also used to point at discovery announcements in papers that have only appeared on the arXiv open-access repository of electronic preprints, but have not been accepted for publication after a reasonable amount of time. Noteworthy examples include radial-velocity signals of an unclear nature and period in the time series of the nearby K dwarf HD 219134 (Motalebi et al. 2015; Vogt et al. 2015; Gillon et al. 2017), the putative directly imaged planet around Fomalhaut (e.g., Kalas et al. 2008; Janson et al. 2020; Pearce et al. 2021, and references therein), and a number of terrestrial-mass companions tentatively detected inside and outside the temperate zones of nearby M dwarfs, such as GJ 581 (which harbours the most highly debated habitable-zone system, see, Trifonov et al. 2018, and references therein), τ Ceti (Tuomi et al. 2013a; Feng et al. 2017a), GJ 667 C (Delfosse et al. 2013; Anglada-Escudé et al. 2013; Feroz & Hobson 2014), and HD 40307 (Mayor et al. 2009a; Tuomi et al. 2013b; Díaz et al. 2016).

After applying the filters above, we came up with a total of 77 known and confirmed planets within 10 pc. In the case of a circular orbit, their true (for the few that are seen in transit) or minimum (for the radial-velocity-detected companions) astrometric signal in arcsec is $\alpha = (M_p/M_\star) \times (a_p/d)$, with M_p and $M_\star$ in the same units, d in pc, and a_p in au. The astrometric signature of the vast majority of short-period ($P < 100$ d) super-Earths and sub-Neptunes within 10 pc are not expected to be detected by *Gaia*, as their amplitude will usually fall well below the end-of-nominal-mission systematic noise floor for the along-scan astrometric measurements in the bright star regime (~50 µas for a single CCD crossing, see e.g., Lindegren et al. 2021). Indeed, the much expected catalogue of tens of thousands of exoplanets will be mostly populated by gas giants in the 1–4 au separation regime (e.g., Sozzetti & de Bruijne 2018, and references therein). However, there are over a dozen exoplanet candidates for which we expect to see the astrometric signature. Some of these exoplanets may have already been detected with the three-year time baseline of *Gaia* DR3, and most of them should be detected in *Gaia* DR4. However, their actual detectability in future *Gaia* data releases relies on the effectiveness of a successful calibration of the astrometric data in the very bright star regime ($G \lesssim 9$ mag). We list below the radial-velocity exoplanet candidates that should be detected by *Gaia*:

- GJ 15 Ac is expected to induce $\alpha > 570$ µas, but it has a period in the neighbourhood of 20 yr (Pinamonti et al. 2018). Even a 10-yr *Gaia* mission will not see more than half of the orbit. The planet's motion should be detected as a curvature effect in the stellar proper motion and described in terms of an acceleration solution.
- ϵ Eri b, with an orbital period of ~7.4 yr (Hatzes et al. 2000; Mawet et al. 2019) and an expected $\alpha \sim 1000$ µas, should be easily detectable. The host star is, however, very bright ($G = 3.46$ mag) and the major source of uncertainty is the effective calibration of the astrometric time-series.
- ϵ Ind A b has a semi-major axis of ~10 au, but the minimum mass of a massive super-Jupiter (Feng et al. 2019). It should be detected as an acceleration solution; however, simlar to ϵ Eri, the host star is very bright ($G = 4.32$ mag).
- GJ 649 b, with $a_p = 1.13$ au (Johnson et al. 2010), should induce $\alpha > 65$ µas. It might be detectable if its true inclination is small.
- GJ 3512 b has $a_p = 0.33$ au (Morales et al. 2019), but it orbits a mid-M dwarf; therefore with $\alpha > 130$ µas, it should be detectable.
- GJ 849 b with $a_p = 2.35$ au (Butler et al. 2006a) and $\alpha > 500$ µas should be easily detectable.
- GJ 849 c has a long period $P \sim 15$–20 yr (Feng et al. 2015), so it might be detectable as an acceleration solution on top of the signal induced by GJ 849 b.

[7] http://exoplanet.eu/
[8] https://exoplanetarchive.ipac.caltech.edu/
[9] http://exoplanets.org/
[10] http://openexoplanetcatalogue.com/

Table 5. Names of triple and higher order systems.

Multiplicity	Name
Triple	α Cen; EZ Aqr; ϵ Ind; GJ 1245; o^{02} Eri; 36 Oph; G 41–14; BD-17 588; HD 16160; HD 156384; HD 50281; 41 Ara; α PsA; LP 881-64; HD 115953; AT Mic; BD+66 34; G 184-19; BD+16 2708
Quadruple	GJ 570; μ Her; GJ 867
Quintuple	ξ UMa; HD 152751

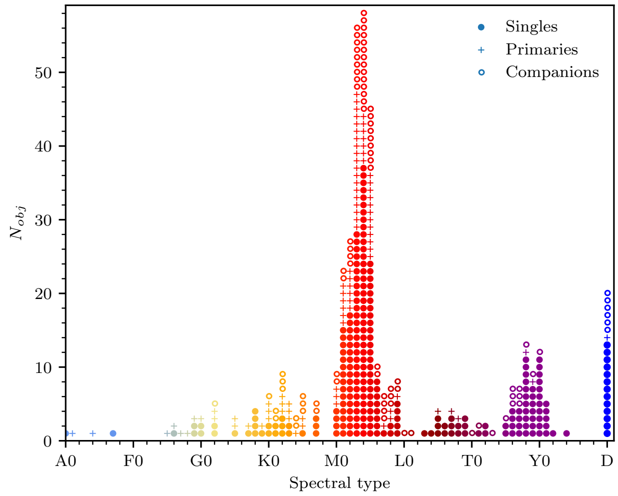

Fig. 2. Spectral type distribution of the 10 pc sample. D are white dwarfs. The different symbols indicate single stars, primaries, and companions.

- GJ 433 c with $\alpha > 100$ µas is, in principle, detectable; however, its period is >10 yr (Feng et al. 2020a), so it might be described in terms of an acceleration solution.
- HD 219134 g is possibly a sub-Saturn-mass object with an unclear but long ($P > 5$ yr) period (Motalebi et al. 2015; Vogt et al. 2015; Gillon et al. 2017), likely inducing $\alpha >$ 100 µas. It is in principle detectable, but the K-dwarf host star is very bright ($G = 5.23$ mag), so the same calibration issues as in the case of ϵ Eri and ϵ Ind A will need to be successfully addressed.
- GJ 876 b, with $\alpha \sim$ 250–350 µas (depending on the actual inclination angle, see Correia et al. 2010), was detected by the *Hubble* Space Telescope (Benedict et al. 2002) and it is expected to be clearly identified by *Gaia*.
- GJ 876 c has an expected $\alpha \sim 70$ µas, but with a period of only 30 d (Marcy et al. 2001) it will likely be very difficult for *Gaia* due to the possible degeneracy with periodic aliases of the scanning law.
- GJ 832 b as $a_p \sim$ 3.5–4.0 au (Bailey et al. 2009), and with $\alpha > 1000$ µas should be clearly detectable by *Gaia*, either as acceleration or a full orbital solution.
- GJ 9066 c has $a_p = 0.87$ au (Feng et al. 2020b), and with $\alpha > 200$ µas it is expected to be detectable by *Gaia*.
- The candidate Proxima Cen c with $a_p = 1.5$ au is expected to induce $\alpha > 170$ µas (Damasso et al. 2020). A confirmation of its existence by *Gaia* should be possible.

3.5. Statistics

In terms of statistical studies, the 10 pc sphere is two-fold. Only in this nearby volume one can expect to detect and characterise all objects, but it also probes a small volume and, thus, offers small statistics. As a result, the 10 pc sphere is complementary to statistically more significant samples with larger volumes, but that suffer from incompleteness. Keeping that in mind, below, we provide a few numbers on the multiplicity rate, spectral type distribution, and luminosity class, which give an overall picture of the immediate vicinity to our Sun.

There is no giant star within 10 pc and only four evolved stars, which are all sub-giants. These are β Hyi, µ Her Aa, δ Pav, and δ Eri. There are only about five pre-main-sequence stars within 10 pc: the triple system AT Mic A, AT Mic B, AU Mic being a bona-fide member, and YZ CMi being a candidate member of the ~24 Myr β Pictoris association (Zuckerman et al. 2001; Alonso-Floriano et al. 2015a; Mamajek & Bell 2014), and AP Col, which may belong to the ~50 Myr Argus / IC 2391 association (Riedel et al. 2011, but see Bell et al. 2015 about the existence of the Argus association).

Almost half of the stars and brown dwarfs are in multiple systems. As summarised in the bottom part of Table 3, our 10 pc sample contains 246 single, 69 double, 19 triple, three quadruple, and two quintuple systems (`NB_SYS` in Table A.1). Following the definitions of Reid & Gizis (1997), for example, and adding the Sun as a single star, these numbers translate into a multiplicity frequency (which quantifies the number of multiple systems within the sample) and a companion frequency (which quantifies the total number of companions) of 27.4 ± 2.3% and 36.5 ± 3.2%, respectively. In Table 5, we give the names of the triple, quadruple, and quintuple systems for convenience.

The spectral type distribution is shown in Fig. 2. We found 249 M stars among the 423 objects with a measured spectral type, which translates into a ratio of 58.9 ± 5.8%. This relatively small value is in contrast with other higher previous determinations of the order of 70% (e.g., Henry et al. 2006; Bochanski et al. 2010). This small value probably comes from a more complete sample of brown dwarfs compared to older studies. In the substellar regime, L-type objects amount to only half the number of T-type ones.

There are 41 objects without a spectral type measurement, all being secondary components of close binaries. They could slightly bias these proportions, so we used published individual masses, either computed from orbit fitting or estimated from adaptive optics contrast measurements, to estimate their spectral types. We found 36 possible M stars, four possible L dwarfs, and one possible white dwarf (all of them marked in the column `COMMENT` in Table A.1). The proportion of M stars now becomes 61.3 ± 5.9%, which is not significantly different from the ratio derived from measured spectral types only.

More than half of the M dwarfs (57.0 ± 7.3%) have spectral types M3.0 V to M5.0 V. This proportion remains stable when including the estimated spectral types of the unresolved secondary components (57.4 ± 6.9%). Translating these numbers into an observed mass function requires some care, but it seems to indicate that the number of stars increases up to about 0.3 $M_{\odot}$ (~M4.0 V; Cifuentes et al. 2020) and decreases for later M spectral subtypes. This maximum of the mass function, similar to other slope changes observed in very young open clusters (e.g., Peña Ramírez et al. 2012), corresponds to the fully-convective transition in the main sequence.

4. The 10 pc sample in the future

4.1. Science cases and the next upgrades

Apart from multiplicity studies, mass function analyses, and long-term exoplanet surveys, there is a number of science topics that can be covered with the 10 pc catalogue. One of them is kinematics and membership in thin and thick disc populations and stellar moving groups and associations. There are on-going efforts to relate precise Galactocentric space velocities to youth features for a sample of over 2000 nearby M dwarfs (Cortés-Contreras, priv. comm.) and to measure, for the first time, radial velocities of a number of late-type ultracool dwarfs (Cooper, priv. comm.). These works will be presented in forthcoming publications and will complement future releases of the 10 pc catalogue.

Further improvements of the 10 pc catalogue include adding the new *Gaia* DR3 astro-photometric data (expected in 2022), updating spectral types for poorly investigated companions and radial velocities of the faintest brown dwarfs, and adding more parameters useful for a variety of topics, such as atmospheric astrophysical parameters ($T_{\rm eff}$, $\log g$, [Fe/H]), chromospheric (equivalent widths of Hα and Ca II) and coronal (X-rays) activity indicators, and rotational velocity. Some novel parameters, for instance the exozodi level, will also be useful for future space missions such as the Large Interferometer for exoplanets (Quanz et al. 2021).

4.2. Obsolescence

This catalogue will inevitably need to be updated when *Gaia* and other surveys issue their next data releases. Apart from extremely cool objects similar to WISEA J085510.74–071442.5, new objects probably hide in the Milky Way plane (see the discoveries by Beamín et al. 2013; Scholz 2014; Scholz & Bell 2018; Faherty et al. 2018). Such new objects, in spite of their expected large proper motions, will likely be detected by state-of-the-art photometric surveys from the ground such as the Panoramic Survey Telescope and Rapid Response System (Kaiser et al. 2002), J-PLUS/J-PAS (Solano et al. 2019), and, specially, the Legacy Survey of Space and Time (LSST Science Collaboration et al. 2009), as well as from the space. In particular, the ESA medium-class *Euclid* space mission will cover more than 35% of the celestial sphere in the red optical and near-infrared Y, J, and H bands with an unprecedented depth and spatial resolution (Laureijs et al. 2011). The *Euclid* Legacy Science on Ultracool Dwarfs will be particularly sensitive to low Galactic-latitude, high proper-motion, very red late-type dwarfs that have not been identified yet (Martín et al. 2020). The NASA SPHEREx space mission, with its all-sky, low-spectral-resolution capabilities in the 0.75–5.0 μm range (Crill et al. 2020), will also help to discover new ultracool objects.

In addition to the yield from these photometric surveys, we expect that most of the new additions to the 10 pc sample will be very close companions to our targets. First, current and future spectroscopic surveys and adaptive optics observations will probably resolve some of the single stars into multiple components (e.g., Baroch et al. 2018; Fouqué et al. 2018; Winters et al. 2019a). Second, the component of the 10 pc catalogue that will see the largest increase in number corresponds to new exoplanets that will be discovered or confirmed in the coming years as most stars are orbited by at least one exoplanet. For instance, Dressing & Charbonneau (2015) predicted 2.5 ± 0.2 small and close-by planets per M star, so we could expect more than 600 new exoplanets to be discovered, outnumbering the number of stellar and sub-stellar objects within 10 pc. Such an optimistic estimation is in line with the recent discovery of small planets around the closest stars, such as Proxima Centauri (two planets: Anglada-Escudé et al. 2016; Damasso et al. 2020; Kervella et al. 2020), Barnard's star (one planet: Ribas et al. 2018), or Lalande 21185 (one planet: Díaz et al. 2019; Stock et al. 2020)[11]. However, even if these new planets are predicted from *Kepler*'s results, we will probably not detect more than a fraction of them in the coming years for several reasons: (i) Planets with periods close to that of stellar rotation will mostly go undetected; (ii) stellar activity will prevent others from being detected; and (iii) close in planets on highly inclined orbits with small $\sin i$ values imply small radial-velocity semi-amplitudes.

While the closest planets have, in general, been discovered with precision radial-velocity spectrographs working in the red optical and/or near-infrared (especially designed for M-dwarf surveys; e.g., CARMENES, ESPRESSO, GIANO-B+HARPS-N, HPF, IRD, MAROON-X, SPIRou, and, in the future, NIRPS and CRIRES+)[12], the NASA TESS space mission (Ricker et al. 2015) is also discovering small transiting planets at less than 10 pc, such as GJ 357 b and GJ 486 b (Luque et al. 2019; Trifonov et al. 2021; see also GJ 436 b, a Neptune-sized planet at 9.8 pc discovered by Butler et al. 2004 and Gillon et al. 2007). A few more transiting planets in the immediate vicinity might also be detected in the near future with SPECULOOS from the ground (Sebastian et al. 2021) and PLATO from space (Rauer et al. 2014). Finally, global astrometry with *Gaia*, particularly in the case of a fully extended 10 year mission, might unveil the presence of ∼10−20 new cold giant planets up to Jupiter-like orbital separations (Sozzetti & de Bruijne 2018, see Sect. 3.4).

4.3. Didactics

The 10 pc sample has tremendous outreach potential. The objects are our nearest neighbours, they cover a large range of stellar and brown dwarfs parameter space, and many of them have a significant historical story that can be shared. If we just consider the first few objects, α Cen A is almost a solar twin, α Cen C (Proxima) harbours the nearest terrestrial habitable-zone planet and has another candidate planet, Barnard's star is an old thick-disc dwarf with the largest proper motion on the sky, Luhman 16 AB is a brown dwarf binary, and WISEA J085510.74–071442.5 is the coolest brown dwarf known to date. Among the first ten objects, only one system, α Cen, is visible to the naked eye; the brightest star, Sirius, is 12th in distance; and, the object with a first measured parallax, 61 Cyg, is 28th in distance.

[11] CN Leo, the third closest stellar system to the Sun, is an active M dwarf with a large radial-velocity scatter in the visible range that prevented the discovery of small planets until now (Tal-Or et al. 2018), but near-infrared observations are less sensitive to activity and may reveal a planetary system in the future.

[12] https://carmenes.caha.es/ext/instrument/index.html; https://www.eso.org/sci/facilities/paranal/instruments/espresso.html; http://www.tng.iac.es/instruments/giano-b/; https://plone.unige.ch/HARPS-N/; https://hpf.psu.edu/; http://ird.mtk.nao.ac.jp/IRDpub/index_tmp.html; https://www.gemini.edu/instrumentation/maroon-x/; http://spirou.irap.omp.eu/Instrument/Cryogenic-spectrograph; https://www.unige.ch/sciences/astro/exoplanets/en/projects/nirps/; https://www.eso.org/sci/facilities/develop/instruments/crires_up.html

To aid in this outreach, we produced some divulgative material that we release with this contribution. The three-dimensional nature of the dataset makes creating maps more of a challenge than for more traditional terrestrial cartography. We generated maps in several different formats from the data, including a rotating animation of all the objects in the catalogue[13], a 3D fly-through JavaScript web application, a top down poster (see Fig. B.1), and two 5 pc and 10 pc maps with 'star columns' showing distance above and below the galactic plane. All the resources are available online[14].

5. Conclusions

We provide a catalogue of all objects closer than 10 pc from the Sun. It contains 540 objects divided between 373 stars, including 20 confirmed white dwarfs and one candidate white dwarf, 85 confirmed and three candidate brown dwarfs, and 77 confirmed exoplanets in 339 systems made up of 69 binaries, 19 triplets, three quadruplets, and two quintuplets.

During the catalogue compilation, we extensively checked all individual entries from what is available in the published literature. In particular, it contains the most recent astrometry from the last *Gaia* data release when available.

The catalogue will be used to assess the quality of the forthcoming *Gaia* releases to place limits on the frequency of planets and other components within multiple systems, as well as providing targets for focused planetary searches. The 10 pc sample is incredibly varied: Our first ten neighbouring systems include two confirmed and two candidate planets, a thick-disc object, a white dwarf, and four brown dwarfs. We recognise the didactic value of this sample and have provided various materials for that exploitation.

The latest addition to the 10 pc sample is the planet GJ 486 b (Trifonov et al. 2021), but the last free floating objects have been discovered using the WISE (Wide-field Infrared Survey Explorer; Wright et al. 2010) survey. The coolest and lowest-mass object WISEA J085510.74–071442.5, a >Y4-type ultra-cool dwarf, was discovered by Luhman (2014) as the result of significant data-mining, and we concur with the result of Kirkpatrick et al. (2021) that the 10 pc volume is probably still not complete for objects later than spectral type Y2. The distribution of these lowest mass objects will indicate the minimum mass cutoff for stellar formation; therefore, finding all objects in this local volume will provide an important constraint for formation mechanisms. In addition, as the latest addition attests, the discovery of planets and other components within known systems is on the increase as our detection ability improves. Hence, while we expect the number of very low mass objects, planets, and low mass components with 10 pc within systems to increase, we do not expect to add any more higher mass, isolated, earlier type objects to the 10 pc census.

Acknowledgements. The authors thank the referee for useful and prompt comments. C.R. thanks Catherine Turon for fruitful discussions on the parallax measurements across the history. C.R. thanks Will J. Cooper for his contribution to plotting. This work was supported by the "Programme National de Physique Stellaire" (PNPS) of CNRS/INSU co-funded by CEA and CNES. R.L.S. and A.S. acknowledge support from the Italian Space Agency (ASI) under contract 2018-24-HH.0. A.S. acknowledges the financial contribution from the agreement ASI-INAF n.2018-16-HH.0. J.A.C. acknowledges financial support from the Agencia Estatal de Investigación of the Ministerio de Ciencia, Innovación y Universidades and the ERDF through project PID2019-109522GB-C51/AEI/10.13039/501100011033. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (`https://www.cosmos.esa.int/gaia`), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, `https://www.cosmos.esa.int/web/gaia/dpac/consortium`). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program. This research has made use of data obtained from or tools provided by the portal `exoplanet.eu` of The Extrasolar Planets Encyclopædia. This research has made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory. This research has made use of the TOPCAT (`http://www.starlink.ac.uk/topcat/`) tool (Taylor et al. 2005).

[13] `https://www.aanda.org`
[14] `https://gruze.org/10pc/resources`

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Appendix A: References in the 10 pc catalogue

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Appendix B: Illustration

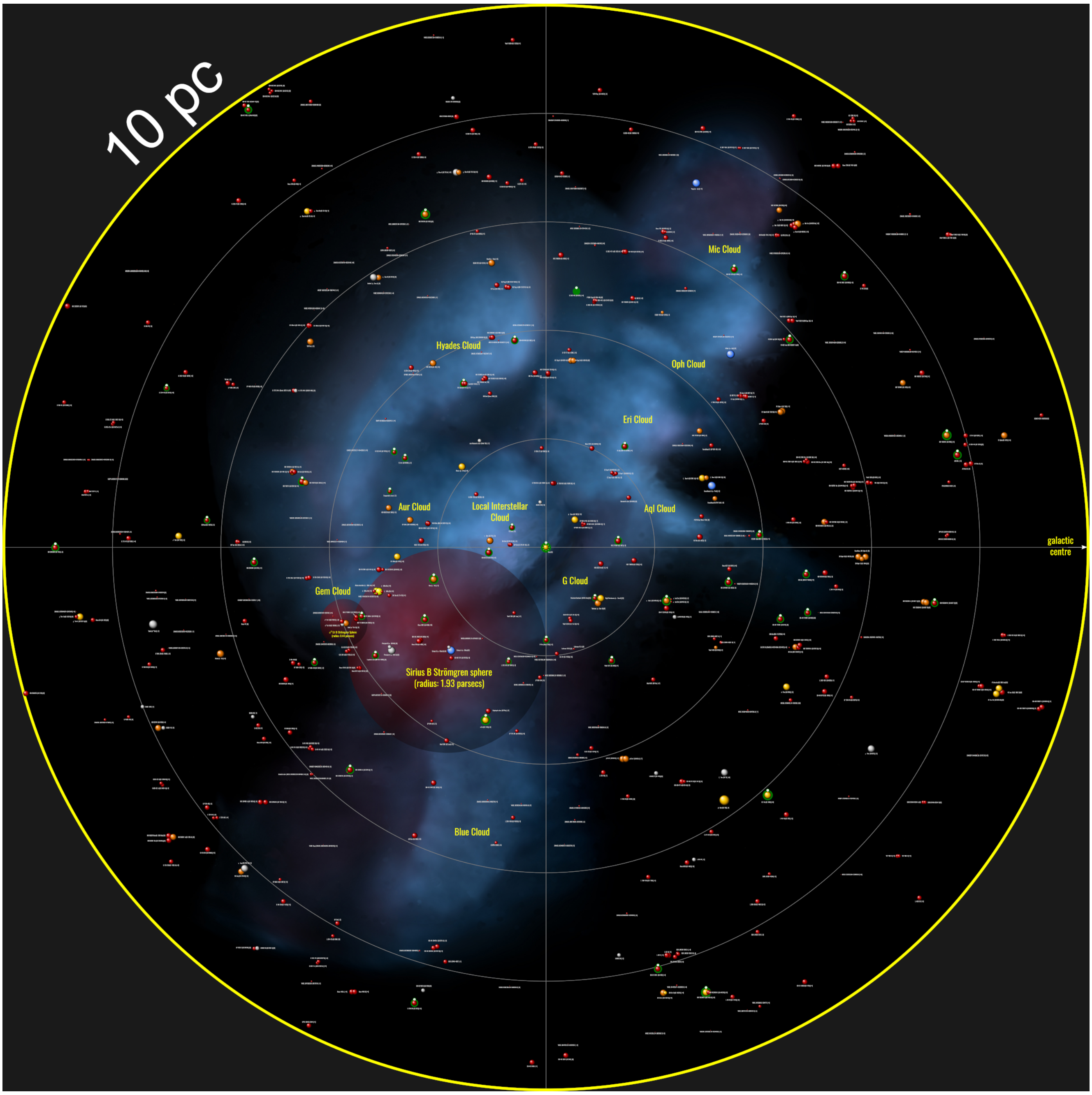

Fig. B.1. Orthographic projection from above the galactic plane. Guide circles are shown every two parsecs. Distance above or below the galactic plane, in pc, are given in square brackets after the star label. Green circles show the number of confirmed planets. A higher resolution, zoomable map is available online.