

Candidate red supergiants from Gaia DR3 BPRP spectra: From the Perseus to the Scutum-Crux spiral arms

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ABSTRACT

Context. Our position within the Galactic plane and the dust obscuration make it challenging to retrieve a true picture of the Milky Way’s morphology. While the Milky Way has been recognized as a barred spiral galaxy since the 1960s, there is still uncertainty about the exact number of spiral arms it contains. Currently, our understanding of the Galaxy is evolving thanks to the unprecedented detail provided by Gaia’s parallactic distances.

Aims. To shed light on the spatial distribution of red supergiants (RSGs) on the Disk and their uniformity of parameters across it, a census of Galactic RSGs detected by Gaia is needed.

Methods. Candidate RSGs were extracted from the combined Gaia DR3 and 2MASS catalogs using color criteria and parallactic distances. The sample includes 335 stars that were not included in catalogs of previously known RSGs detected by Gaia DR3. Interstellar and circumstellar extinction values were estimated from the infrared bands. Spectral types were collected from Simbad or VIZIER databases and, for 135 candidates, were inferred from the Gaia DR3 BPRP spectra. Stellar luminosities were inferred using photometric measurements and the Gaia DR3 distances.

Results. The analysis yielded a genuine sample of O-rich late-type stars, and the calculated luminosities confirm that the sample is mostly made of stars brighter than $M_{bol} = -5$ mag. This new sample represents a 40% increase in the number of highly probable RSGs compared to previous studies. When looking at the X and Y distribution on the Galactic plane, beside the populous Perseus associations of RSGs and the Sagittarius group of RSGs, a novel population of highly probable RSGs populating the more distant Scutum-Centaurus arm appears.

Conclusions.

Key words. stars: late-type – stars: supergiants – Galaxy: stellar content – circumstellar matter – infrared: stars

1. Introduction

Stars more massive than $\approx 8 M_\odot$ and below $\approx 40 M_\odot$ go through the red-supergiant (RSG) phase; this ranges from 8 to $25 M_\odot$ when rotation is included in the models (e.g., Limongi 2017; Meynet & Maeder 2000). RSGs are cool stars with effective temperatures (T_{eff}) below 4500 K and low gravity ($\log(g) < 0.7 \text{ cm s}^{-2}$), and they are metal-rich ($-0.5 < [Fe/H] < 0.5 \text{ dex}$) and luminous ($\log(\frac{L}{L_\odot}) \gtrsim 4$). Their young ages, from 4.5 to 30 Myr, ensure that they are part of the young disk of spiral galaxies, as recently observed in M31 and M32 (Massey et al. 2021a). A census of RSGs is fundamental for testing models of stellar evolution and core collapses. RSGs are He-burning stars whose fate is governed by mass-loss and rotation. They are usually found in large molecular complexes, which populate the spiral arms of the Milky Way; only a small fraction of them (about 10%) are associated with stellar clusters (e.g., Messineo et al. 2017; Messineo & Brown 2019; Smith & Tombleson 2015). However, a search for individually selected RSGs is more complex than in stellar clusters, because of dust obscuration and little knowledge of distances, and RSGs are often mistaken for asymptotic giant branch stars (AGBs) because they have similar colors and magnitudes. AGBs have different internal structures and nuclear reactions, as they have a degenerate core of CO and burning fuel in

two concentric shells (H in the external shell and He in the inner shell). AGBs with masses below $8 M_\odot$ trace star formation that occurred from $\approx 40 \text{ Myr}$ to 13 Gyr ago, and they have a much larger metallicity range. In the last decade, significant progress has been made in distinguishing the populations of RSGs and AGBs; this is thanks to Gaia data, which provide the parallactic distances and optical stellar energy distribution (SED) of millions of stars, and the availability of photometric time series. In the coming years, spectroscopic data at a resolution higher than 10,000 will become available from the GALAH, Gaia DR4 RVS, and 4MOST surveys, providing metallicity for millions of stars (e.g., Introduction of Messineo et al. 2021).

The catalog of Messineo & Brown (2019)¹ collected and analyzed stars previously reported in the literature as stars of K-M type and class I. Unfortunately, a significant portion of the gathered late-type stars turned out to be faint giants, and the parallactic distances revealed that most of the classes collected from past literature are not reliable. There should be many thousands of RSGs in the Milky Way’s grand spiral. There are 6400 RSGs in the spiral galaxies M31 and 2850 in M33 (Massey et al. 2021b, and references therein). We are still unable to count and differ-

¹ The catalog was revised to include Gaia eDR3 parallaxes (Messineo & Brown 2021; Messineo 2023).

entiate between the population of bright RSGs and the millions of fainter giants, making the census of obscured Galactic RSGs still unfeasible. According to Gehrz (1989) estimates, the Milky Way should have at least 5200 RSGs.

In order to prepare for the upcoming spectroscopic era, lists of bona fide late-type stars with high luminosities are required. Following the division of the theoretical diagram of luminosity values versus temperatures in areas, Messineo & Brown (Gaia DR2 2019) and Messineo (2023, Gaia DR3) kept those $\approx 400^2$ out of 1725 stars analyzed, located in areas A and B³, as highly probable RSGs. Messineo (2023) remarked that before relying on the temperatures listed in the Gaia database for these brilliant cool stars, one should wait for the Gaia RVS spectra release. Healy et al. (2024) report 638 candidate RSGs (cRSGs) in the Gaia DR3 catalog, exceeding the number of bona fide stars of Messineo & Brown (2019). Indeed, by design, the catalog of Messineo et al. did not consider new photometric cRSGs from Gaia. This number is still too low to account for the Galactic population.

Two main issues in the luminosity calculation exist. Since mass loss has a significant impact on the brightest and coolest stars, the first problem is the precise computation of extinction at the bright end side. Second, because $8-9 M_{\odot}$ stars might be in both evolutionary phases, there is a natural confusion at the faint side between RSGs and super-AGBs. A novel technique for estimating interstellar extinction for luminous late M-type stars is described by Messineo (2024). Interestingly, the technique uses near- and mid-infrared colors to predict interstellar extinction without taking into account the stellar environment.

Here, we examine the determination of the extinction and luminosity of about 300 additional cRSGs (Sect. 2). The envelope optical depth is empirically calibrated, and its effect on the bolometric corrections is measured. In Sect. 3, the XY distribution of the new sample is shown to share the same features as the bona fide RSGs from Messineo & Brown (2019). A summary of the main findings is given in Sect. 4.

2. New cRSGs from Gaia-DR3 and 2MASS catalogs

We preselected 2,167,423 data points with the extinction-free magnitude $K_s - 1.311 \times (H - K_s - 0.2) < 8$ mag from the 2MASS catalog (470,992,970 entries) (Messineo 2024). Indeed, this range of extinction-free K_s magnitudes encloses all RSGs in areas A&B by Messineo & Brown (2019).

By using their 2MASS IDs we retrieved 1,941,750 Gaia DR3 matches (Gaia Collaboration et al. 2023), of which 1,880,040 were assigned distances in the catalog by Bailer-Jones et al. (2021). However, only 851,612 of those have $\frac{\varpi}{\sigma_{\varpi}(\text{est})}$ larger than 4, where ϖ is the parallax and $\sigma_{\varpi}(\text{est})$ is the external parallactic error (Maíz Apellániz et al. 2021). 850,926 data points have 2MASS J , H , and K_s data (all three bands).

Following the diagnostics described in Messineo (2023), the diagram of the absolute K_s values, M_K , versus the extinction-free color $W_{RP,BP-RP} - W_{Ks,J-Ks}$, calculated as in Abia et al. (2022), was analyzed. RSGs appear to be preferentially located in a narrow range of colors between 0 and 1 mag, while the O-rich AGB stars are bluer than that, and C-rich stars are redder than that. In this diagram, two curves are drawn to roughly indicate two

² The extinction calculation determines the exact number of stars in these regions.

³ As in Messineo & Brown (2019), Area A is defined as $M_{bol} < -7.1$ mag, which is the AGB limit. Area B is coded as $-7.1 < M_{bol} < -5.0$ mag and $L/L_{\odot} > 51.3 - 13.33 \times \log(T_{\text{eff}})$, with $\log(T_{\text{eff}}[\text{K}]) > 3.548$.

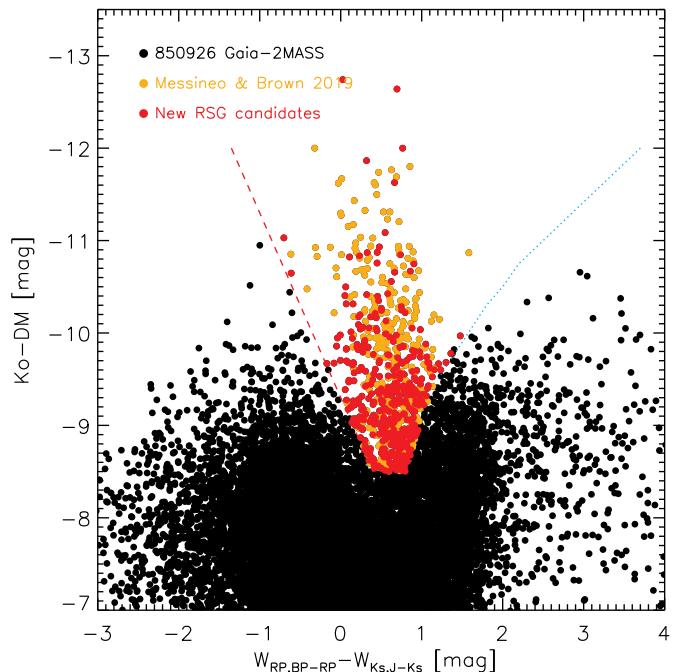


Fig. 1. M_K versus $W_{RP,BP-RP} - W_{Ks,J-Ks} < 4$ colors of 2MASS stars brighter than $K_s - 1.311 \times (H - K_s - 0.2) < 8$ mag and with good Gaia parallax. Selected cRSGs (in red and orange) lie in the cone enclosed by the two curves. The dotted cyan curve indicates a rough separation between O-rich AGB stars and C-rich AGB stars (to the right). The long-dashed red curve separates RSGs from O-rich AGBs and S-type stars. Stars included in the catalog of Messineo & Brown (2019) are colored in orange.

separation lines between C-rich and RSGs, and between O-rich and RSGs. 730 cRSGs with $M_K < -8.5$ mag are located in the cone enclosed by these two curves, as illustrated in Fig. 1. As 315 cRSGs are already included in the list of Messineo & Brown (2019), 415 stars remain. We searched for available spectral types of the 415 cRSGs in the catalog by Skiff (2014) and in SIMBAD and retrieved it for 279 stars – 185 stars are M-type stars, 22 K-type stars, 20 C-rich stars, 32 S-type stars, 14 F-G-types, and seven early-type stars. The B-A-F-G type, C-rich, and S-type stars were dropped from the sample, which remains composed of 342 O-rich stars, of which 207 with known KM spectral types and 135 previously unclassified. As shown in the following sections, additional spectral types were estimated with Gaia BPRP spectra bringing the number of available spectral types to 335, and 282 those in areas A and B.

Recently, Healy et al. (2024) published a catalog of chosen RSGs from the Gaia DR3 database, which comprised 638 entries. We count 788 stars when we concatenate the stars from areas A and B of Messineo & Brown (2019), Messineo (2023), and from the current work. The Messineo's and Healy et al.'s compilations share 490 entries. Only 12 cRSGs from the selection presented in this work are included in Healy's catalog. This motivated us to publish this additional list of cRSGs which may be useful to plan forthcoming and ongoing spectroscopic surveys (e.g., GALAH, 4MOST; Sharma et al. 2022; de Jong et al. 2012).

2.1. Available photometry

The stars were selected from Gaia and 2MASS catalogs. The Two Micron All Sky Survey (2MASS) survey is described in Skrutskie et al. (2006), and in Cutri et al. (2003), and in the online manual⁴. The stars are extremely bright at infrared wavelength, and all measurements come from the 2MASS short-exposure frames (51ms). The J -band measurements range from 1.89 to 8.68 mag, with a peak around 5 mag, while the H -band magnitudes range from 0.96 to 14.77 mag and peak at 3.5 mag, and the K_s magnitudes range from 0.66 to 7.70 mag with a peak at 3.0 mag. Stars that were saturated in the short integration frames had their profile reconstructed using the unsaturated pixels. While magnitudes of unsaturated point sources (fl_red=1) have a typical uncertainty of 0.01-0.02 mag, magnitudes of saturated sources (fl_red=3) are accurate within 0.2 mag. For 5% of the stars measurements from the Catalog of Infrared Observations (CIO) 5th edition by Gezari et al. (1996) are available; K measurements are available for all stars in the subsample: H mag for 44% and J mag for 22 %. The average difference between the CIO and 2MASS J magnitudes brighter than 4 are +0.15 with a standard deviation $\sigma=0.12$ mag. Between the CIO and 2MASS H magnitudes brighter than 4, it is +0.24, with a standard deviation $\sigma=0.44$ mag; the average difference between the CIO and the 2MASS K_s magnitudes brighter than 4 is +0.00 mag, with a standard deviation of $\sigma=0.62$ mag; however, after excluding J03232718+6545417 and J08104310–1519469, the average difference becomes 0.07 mag with a σ of 0.17 mag.

Positional matches (within 5'') in the Midcourse Space Experiment catalog (MSX, Egan et al. 2003) were found for 89% of the newly selected stars; 94% were found in the Wide-field Infrared Survey Explorer (WISE) survey (Wright et al. 2010), 25% were found in the Galactic Legacy Infrared Midplane Survey Extraordinaire (GLIMPSE) survey (Churchwell et al. 2009), and 26% were found in the MIPS GAL 24 μ m survey (Gutermuth & Heyer 2015) using a search radius of 4''.

JHK_s measurements were all retained including 2MASS upper limits; however, a flag is given to indicate sources with the good 2MASS photometry. The SED of each star was visually inspected and a few measurements which appeared unrelated to the SED were removed. 2MASS J20434317+4741398, J17594120-2857418, and J14090677-5943243 had their H -band upper-limit magnitudes removed, 2MASS J18095816-2728222 had the WISE measurements removed (confusion and blend), 2MASS J18440043-0457062 had the WISE W3 and W4 magnitudes removed (confusion), 2MASS J10572371-6046304 had the WISE W4 upper limit magnitude removed, and 2MASS J19283960+1718220 had its GLIMPSE [3.6] magnitude removed (artifact on image).

2.2. Spectral types, temperatures, and extinction of cRSGs

In this work, a selection of cRSGs is presented. Although estimates of stellar parameters are provided, they are primarily used to ensure a good selection of stars. More accurate determinations of stellar parameters will require high-resolution spectroscopic follow-up observations and updated photometry.

The determination of T_{eff} in RSGs is a challenging task. A direct determination of T_{eff} requires the knowledge of the stellar radii, which are only available for a limited number of stars through interferometric measurements. More commonly, T_{eff} values are estimated using color temperatures or spectro-

scopic temperatures (e.g., Levesque et al. 2005). Historically, the TiO bands visible in the optical spectra of RSGs have been used to determine their spectral types. By using models of stellar atmospheres (such as the MARCS models) and a fitting technique, Levesque et al. (2005) established a TiO-based temperature scale. However, as discussed in Davies et al. (2013), these models are far from perfectly reproducing observed spectra, and there is a degeneracy between extinction and temperature determination. Furthermore, both Davies et al. (2013) and Levesque (2018) demonstrated that the 1D MARCS models fail to accurately reproduce infrared fluxes, and using either the optical or infrared portion of the SED can result in different T_{eff} values (and, consequently, extinction estimates).

These findings raise concerns about the use of TiO bands for determining T_{eff} , leading to alternative attempts at temperature determination using atomic lines (see, e.g., Gazak et al. 2014; Tabernero et al. 2018; Dicenzo & Levesque 2019; Taniguchi et al. 2021, 2025). Messineo et al. (2021) show that the temperature measurements from Gazak et al. (2014) based on J -band spectra ($R = 11,000$ -14,000) agree with those of Levesque et al. (2005) to within 150 K. Tabernero et al. (2018) propose a new temperature scale based on spectral features in the CaT range ($R = 7,000$), confirming a correlation between TiO band depths and stellar temperatures. Taniguchi et al. (2025) determine RSG temperatures using YJ spectra ($R = 28,000$) and 11 pairs of atomic iron lines; their temperatures are in good agreement with the T_{eff} from TiO of Levesque et al. (2005) to within 100 K.

In conclusion, the use of TiO bands to determine temperatures remains valid, as it is supported by studies of atomic lines. Currently, spectroscopic temperatures can be used as a proxy for T_{eff} , with a typical accuracy level of 100–150 K.

2.2.1. Spectral types

We analyzed the BPRP spectra to estimate KM types of the newly selected 342 O-rich stars. 327 BPRP spectra were available, but four were excluded because of poor quality, and four stars had spectra typical of G-types. Among the 15 stars without BPRP spectra, three do not have types in SIMBAD. In conclusion, a clean sample of 335 bright K- and M-type stars was produced.

The sample contains 135 previously unknown late-type stars, which we classified solely using the Gaia DR3 BPRP spectra. Because of a degeneracy between temperatures and reddening, an independent initial guess of interstellar extinction was required. Late-type stars span a small range of naked $H - K_s$ colors, and, initially, we assumed a fixed M1-type star with a naked $H - K_s = 0.22$ mag (Koornneef 1983) and an interstellar power law with an index of -2.1 (Messineo et al. 2005; Messineo 2024); because the associated color uncertainty is typically below 0.12 mag (the delta color between an M1 and an M5), we estimated an A_{K_s} uncertainty within 0.16 mag. The optical extinction curve by Cardelli et al. (1989), extrapolated to the near-infrared with a power law of index -2.1, was used to de-redden the BPRP spectra. Spectral types were inferred by matching the de-reddened BPRP spectra of the target stars with those of reference stars, as described in Messineo (2023). A few types were visually inferred if the solution diverged. The process was reiterated; with the obtained spectral types, temperatures were estimated using the temperature scale of Levesque et al. (2005), and the total A_{K_s} extinction values were recalculated with the color tables of Koornneef (1983). Then, spectral types were re-estimated with the new total A_{K_s} and the spectral library. On

⁴ <https://irsa.ipac.caltech.edu/data/2MASS>

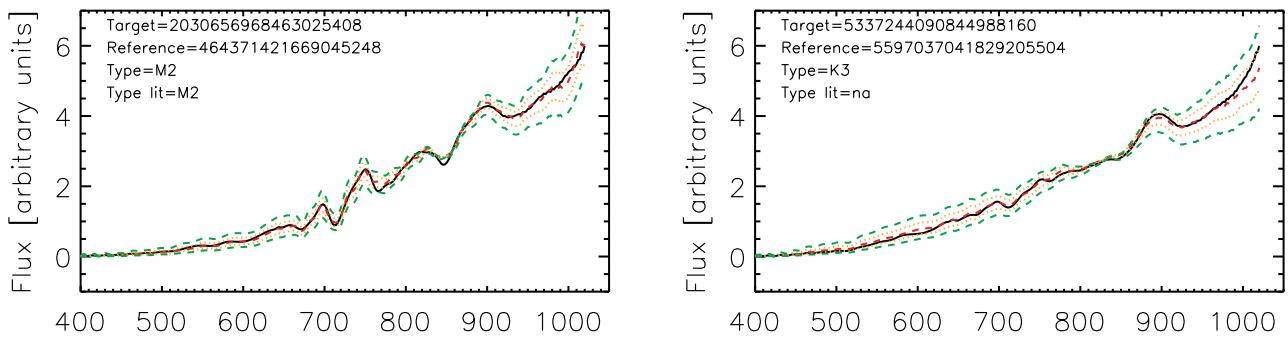


Fig. 2. Two examples of BPRP spectra. The target spectrum is shown with a black curve, and the reference spectrum with the dashed red curve. The reference spectrum was brought to the target’s extinction, which is estimated in the infrared. Extinction variations of $\Delta A_{K_s} = \pm 0.05$ mag and ± 0.10 are indicated with orange dotted and green dashed curves, respectively. Gaia source_ids are given in the figure labels.

the second iteration, as spectral types had been estimated, the total A_{K_s} values were estimated from the $J-K_s$ color excesses. The larger separation in wavelengths of the two filters ensures a more sensitive meter. Furthermore, the stars are very bright, and, generally, the fainter J magnitudes are of better quality than the H and K_s . The total A_{K_s} estimates from HK_s have an average error of 0.34 mag, while the total A_{K_s} estimates from JK_s have an average error of 0.11 mag. In Fig. 2, two examples of BPRP spectra are shown along with the selected reference spectrum at the target’s extinction. A comparison with the 3D dust map of Green et al. (2019) and our total A_{K_s} values was possible for 180 stars; after transforming the map $E(B-V)$ values to $A_{K_s}(\text{Bay19}) = E(B-V) \times 3.1 \times 0.077$ mag, a mean difference of 0.04 mag was measured with a sigma of 0.10 mag, as shown in Fig. 3. However, 3D Galactic extinction maps are made with a spatial resolution of several arcminutes; while our total A_{K_s} values were estimated with the infrared colors of the considered star. We retained our calculation of extinction. As explained in the following section, for most of the stars, the interstellar extinction $A_{K_s}(\text{int})$ can be approximated with the total stellar extinction $A_{K_s}(\text{tot})$ because the envelope optical depth is negligible.

Using the subsample of stars with spectral types in the literature, it was estimated that the accuracy of the inferred spectral types mostly fit within two spectral types. In Fig. 4, the distribution of spectral types appears to peak at M2-M3 types, as expected for RSGs (see Fig. 5 in Messineo & Brown 2019). The newly selected sample of 335 K - and M -type stars still includes variable stars. The histogram of stars with a `trimmed_range_mag_g_fov` larger than 0.3 mag is over-plotted in red. The variables are the dominant population for M5-M9 types. When only considering stars in areas A or B of Messineo & Brown (2019), the final sample consists of 282 stars.

2.2.2. Envelop extinction

We assumed that the interstellar extinction $A_{K_s}(\text{int})$ can be accurately approximated by the total extinction $A_{K_s}(\text{tot})$ computed using the intrinsic colors of naked stars. The stars are by design the reddest in the $W_{RP,BP}-W_{K_s,J-K_s}$ color, as expected for early-M types, and their mass-loss rate is anticipated to be mild. The envelope optical depth of RSGs typically falls between 0.0 and 0.7 at 0.55 μm (Humphreys et al. 2020).

The optical depth of circumstellar envelopes can be measured by fitting infrared flux densities with DUSTY models. The mid-infrared features observed in the de-reddened stellar SED

are intrinsically linked to the stellar envelope. Effective extinction ratios at mid-infrared wavelengths typically range from 0.3 to 0.5 times the value of A_{K_s} (Messineo 2024). These small variations in effective extinction ratios imply that, during the de-reddening process for interstellar extinction, the characteristics of these features remain consistent; an emission feature will consistently appear in emission, indicating an optically thin envelope. In summary, the envelope τ at 2.2 μm is estimated by examining the presence and strength of the silicate feature at 10 μm in the SED, alongside the flux excess at wavelengths longer than 8 μm .

A grid of SED models was constructed using the DUSTY algorithm of Ivezic et al. (1999). The NextGen spectra of Allard et al. (2011) with $\log_{10}(g)=0.5$, solar metallicity $[M/H]=0$ dex, and T_{eff} from 2600 to 4500 K in steps of 100 K were utilized as input stellar models⁵. Cold silicates by Suh (1999) were used, and the optical depth at 2.2 μm , $\tau_{2.2}$, was varied in increments of 0.02 from 0 to 1.5. A maximum size of 1.000 μm and a minimum size of 0.001 μm were adopted for the Mathis–Rumpl–Nordsieck (MRN) size distribution. The most basic spherical envelope assumption was made with the density decreased as R^{-2} and a dust condensation radius at 1000 K. The temperature scale of Levesque et al. (2005) was used to translate the stellar spectral types (see the section above) to temperatures. After selecting the set of models that were closest to the stellar temperature, the $\tau_{2.2}$ was deduced by minimizing the discrepancies between the infrared observed fluxes (F_{λ}) and the model flux densities at the corresponding isophotal wavelengths. The theoretical SEDs obtained from synthetic spectra and the DUSTY radiative code were compared with the observed SEDs. When varying the stellar T_{eff} of ± 100 K, the solution converged to the same $\tau_{2.2}$. While the majority of the observed SEDs are consistent with models of naked stars, some exhibit an emission feature around 10 μm accompanied by a flux excess beyond 8 μm ⁶. Precisely, as seen in Fig. 5, the bulk of stars have negligible circumstellar extinction with $\tau_{2.2} < 0.02$; for 7% of the sample, $\tau_{2.2}$ is larger than 0.25 (from 0.25 to 0.90), their SEDs show visible silicate features in emission, and a more accurate evaluation of interstellar extinction is needed.

⁵ The spectra are distributed by the Virtual Observatory SED analyzer (Bayo et al. 2008). The bt-nextgen_agss2009 (gas only) were retrieved.

⁶ This simple approach (SED modeling) could not be used for AGBs by Messineo (2024) and Messineo et al. (2018) because the AGB Miras are strongly variable; by using non-simultaneously taken single-epoch measurements, their SEDs appeared as a zigzag without displaying a clear 10 μm feature.

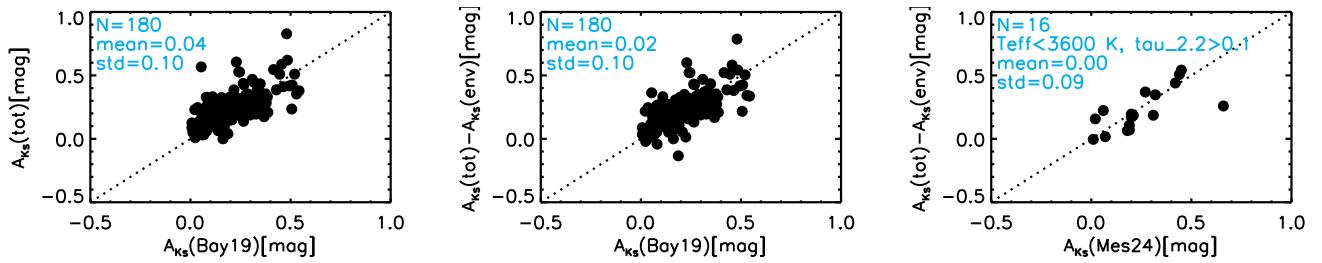


Fig. 3. *Left panel:* Estimated $A_{K_s}(\text{tot})$ values versus 3D dust map $A_{K_s}(\text{Bay19})$ values. *Center panel:* $A_{K_s}(\text{tot})-A_{K_s}(\text{env})$ values versus 3D dust map $A_{K_s}(\text{Bay19})$ values. *Right panel:* For 16 stars with $T_{\text{eff}} < 3600 \text{ K}$ and $\tau_{2.2} > 0.1$, the $A_{K_s}(\text{tot})-A_{K_s}(\text{env})$ values versus $A_{K_s}(\text{Mes24})$ values are plotted.

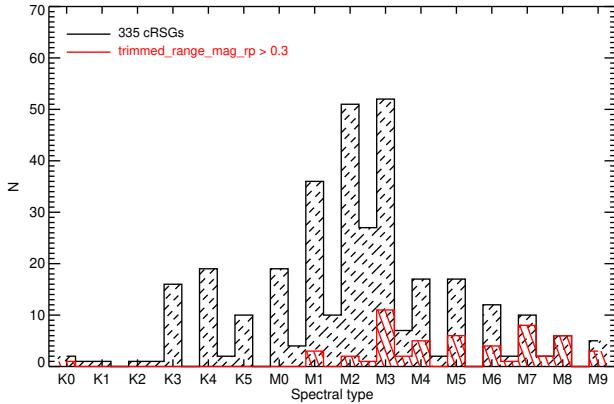


Fig. 4. Distribution of spectral types of 335 late-type stars analyzed. The histogram of stars with $\text{trimmed_range_mag_g_fov} < 0.5 \text{ mag}$ is shown in red.

The obtained $\tau_{2.2}$ is useful for relative comparisons of different envelope types. To compare this theoretical τ with the $A_{K_s}(\text{int})$ and $A_{K_s}(\text{tot})$ inferred from observations, we needed to scale the model τ to match the observed $A_{K_s}(\text{tot})-A_{K_s}(\text{int})$. $A_{K_s}(\text{tot})$ is an equivalent total extinction because it is the total extinction obtained using the interstellar extinction law. The scaling parameters will depend on various factors, including the adopted grain composition (material and sizes), envelope geometry, and dust temperature. In this study, we assumed that the silicate models proposed by Suh (1999) are appropriate for the envelopes of cool cRSGs and will primarily explore the effect of the maximum grain size on the resulting τ .

An estimate of interstellar extinction, $A_{K_s}(\text{Bay19})$, was obtained from maps (Green et al. 2019).

Another independent estimate of interstellar extinction, $A_{K_s}(\text{Mes24})$, was obtained with the technique outlined by Messineo (2024) for O-rich Miras. For mass-losing Miras, a fiducial sequence of intrinsic color-color points is adopted (e.g. in the plane $(J-K_s)_o$ vs. $(K_s-[24])_o$), and used, along with the extinction-free color definition, to infer the interstellar extinction. For example, $Q_{24}^{JK_s}=J-K_s-\text{const}\times K_s-[24]=(J-K_s)_o-\text{const}\times(K_s-[24])_o$. By measuring $Q_{24}^{JK_s}$, $(J-K_s)_o$ and $(K_s-[24])_o$ can be estimated; from the de-reddened $(J-K_s)_o$ and $(K_s-[24])_o$, the interstellar $A_{K_s}(\text{Mes24})$ is estimated, as explained in Messineo (2024).

For 16 stars with DUSTY $\tau_{2.2} > 0.1$ and T_{eff} below 3600 K, budgeting of the interstellar extinction $A_{K_s}(\text{Bay19})$ and $A_{K_s}(\text{Mes24})$, and the total extinction $A_{K_s}(\text{tot})$ was made. The $A_{K_s}(\text{int})=A_{K_s}(\text{tot})-\tau_{2.2} \times \text{factor}$, and the *factor* was chosen

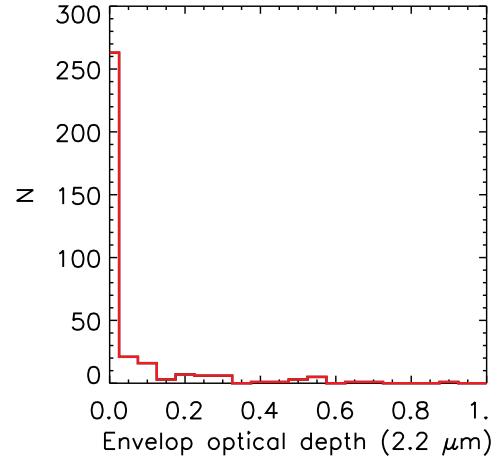


Fig. 5. Distribution of envelope optical depth at $2.2 \mu\text{m}$ of the newly selected late-type stars.

to avoid negative $A_{K_s}(\text{int})^7$. The $A_{K_s}(\text{int})$ values must be in agreement with the $A_{K_s}(\text{Mes24})$ and $A_{K_s}(\text{Bay19})$; we obtained that $A_{K_s}(\text{int}) \approx A_{K_s}(\text{tot}) - \tau_{2.2} \times 0.3$ (see Fig. 3), and the envelope extinction $A_{K_s}(\text{env}) \approx 0.3 \times \tau_{2.2} [0.001-1.000]$. When the maximum grain size is $0.25-0.35 \mu\text{m}$, the *factor* becomes unity; i.e., interstellar and circumstellar extinction curves become similar.

When neglecting the circumstellar envelope and assuming $A_{K_s}(\text{tot})$ as $A_K(\text{int})$, the maximum overestimate of $A_K(\text{int})$ would amount to 0.27 mag for the new sample. The correction $A_K(\text{int})=A_{K_s}(\text{tot})-A_{K_s}(\text{env})$ was applied and the M_{bol} recalculated.

360

370

2.3. Luminosities and bolometric corrections

One set of luminosities was obtained using the de-reddened 2MASS K_s , the Gaia distances of Bailer-Jones et al. (2021), the temperature scale, and the BC_K of Levesque et al. (2005). The infrared extinction curve was approximated with a power law of index -2.1 (Messineo 2024). When changing the assumed spectral type of one unit (from M3 to M2 or M4), A_{K_s} varies by 0.03 mag on average ($\sigma=0.01$ mag), and the bolometric magnitudes $M_{bol}(BC_{K_s})$ change by 0.09 with $\sigma=0.03$ mag.

A second set of luminosities was derived with a trapezoidal integration under the SED made with the available infrared flux

380

⁷ DUSTY $\tau_{2.2}$ decreases with decreasing maximum grain size. $\tau_{2.2}[0.001-1.000]=2.78 \times \tau_{2.2}[0.001-0.350]$ and $\tau_{2.2}[0.001-1.000]=3.40 \times \tau_{2.2}[0.001-0.250]$.

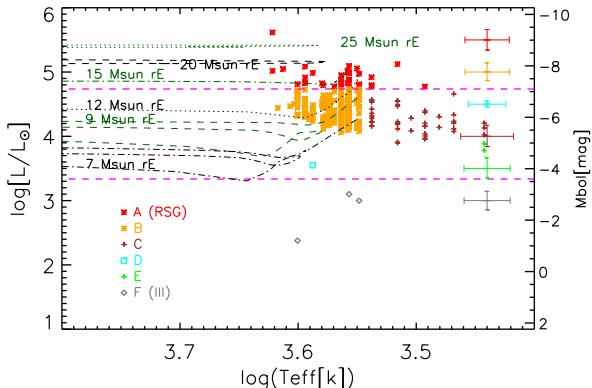


Fig. 6. Luminosities versus T_{eff} of newly selected stars. Evolutionary tracks with solar metallicity and rotation by Ekström et al. (2012) are over-plotted.

densities and by extrapolating to the blue side with the black-body of the same temperature as the star, and to long wavelengths with a linear extrapolation to zero flux at $500 \mu\text{m}$, as in Messineo & Brown (2019). The trapezoidal integration depends on the temperature through the blue extrapolation and extinction calculation. When changing the assumed spectral type of one unit (from M3 to M2 or M4), after recalculating A_{K_s} , the trapezoidal magnitudes change to 0.09 with $\sigma=0.03$ mag.

390 A third estimate of bolometric magnitudes (M_{bol} (DUSTY)) was obtained by integrating under the DUSTY model that best fit the observed infrared flux densities (de-reddened). The model was scaled so that the average of the observed JHK_s flux densities best matched the average of the model flux densities at the isophotal wavelengths of the three 2MASS filters. The integrations were obtained in the plane $F_v dv$, the adopted zero-point constant was assumed to be -18.997 , and the solar $M_{\text{bol}} = +4.74$ mag (Mamajek et al. 2015). The bin used for the $\tau_{2.2}$ grid corresponds to an M_{bol} uncertainty $M_{\text{tau}_{\text{err}}} < 0.01$ mag, and the $\tau_{2.2}$ value remains unaffected by T_{eff} variations within 100 K in the model. By shifting the best models of ± 100 K, M_{bol} variations are within 0.07 mag. When changing the assumed spectral type of one unit, after recalculating T_{eff} and A_{K_s} , the M_{bol} (DUSTY) changes by 0.07 with $\sigma=0.03$ mag.

400 The dominant errors in M_{bol} come from the photometric uncertainties (± 0.14 mag, when simultaneously decreasing or increasing the magnitudes by their errors) and the distance moduli (median errors are $[+0.24, -0.27]$ mag, average errors are $[+0.24, -0.27]$ with σ of $[0.09, 0.12]$ mag, see Table 1).

410 To calculate the global statistical errors on the three M_{bol} values, a Monte Carlo simulation was carried out (with 2,001 runs). For each star, a table of 2,001 Gaussian random errors was extracted for each available magnitude (using a different seed for each); each Gaussian had a $3 \times \sigma$ equal to the quoted magnitude error. For each adopted spectral type, a Gaussian error with σ equal to two spectral types was randomly added. For each random extraction, magnitudes, spectral types, T_{eff} , A_{K_s} , M_{bol} (BC), M_{bol} (trap), and M_{bol} (DUSTY) values were recalculated. The average magnitudes and σ values are given in Table 1.

420 The average difference between the M_{bol} values from the BC_{K_s} of Levesque et al. (2005) and those from the DUSTY models is -0.03 mag, with $\sigma = 0.09$ mag. The average difference between the trapezoidal M_{bol} values and those from the DUSTY model is -0.23 mag, with $\sigma = 0.08$ mag.

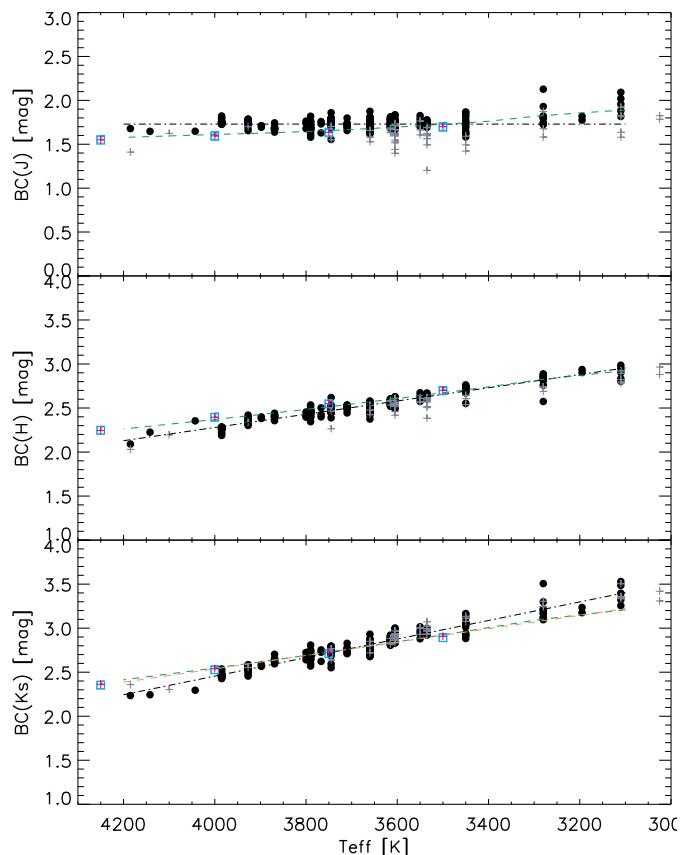


Fig. 7. Top panel: For stars with $\tau_{2.2} < 0.08$, bolometric corrections BC_J are plotted versus T_{eff} values with black-filled circles. For stars with $\tau_{2.2} > 0.08$, gray crosses are plotted. The BC values were calculated with the M_{bol} inferred with the atmosphere models by Allard et al. (2011) and the DUSTY code and the absolute J magnitudes (from 2MASS). The dotted-dashed black line is the best polynomial fit of degree zero to the data points. The dashed green line is the theoretical BC_J inferred with Allard's model ([M/H]=0, $\log(g)=0.5$). The cyan squares mark the BC_J values estimated with an ATLAS9 grid of models and for Bessel filters by Howarth (2011) ([M/H]=0.0 and $\log(g)=0.5$ dex); while our re-calculations for the 2MASS filters are marked with red crosses. Middle panel: Bolometric corrections BC_H versus T_{eff} values. Lines and symbols are as for the top panel. Bottom panel: Bolometric corrections BC_{K_s} are plotted versus the T_{eff} values. Lines and symbols are as for the top panel. The dashed-orange line is the K -band relation for naked RSGs found with MARCS models and the K -filter profile of Bessell & Brett (1988) by Levesque et al. (2005).

For the bulk of stars, the derived luminosities are consistent with those of RSGs, as shown in Fig. 6. They are mostly located in areas A and B of the luminosity-versus-temperature diagram.

The theoretical BC_J , BC_H , and BC_{K_s} values estimated with the NextGen models ([M/H]=0, $\log(g)=0.5$) of Allard et al. (2011) are listed in Table 2. The stellar temperature uncertainty affects the luminosity and the bolometric correction values. For the BC values of naked stars, uncertainties on the BC values depend on the slope of the relation between the BC values and the stellar T_{eff} values, as explained by Levesque (2018) and shown in Fig. 7. The predicted slope in the K_s filter by Allard's models is almost identical to that predicted with MARCS models by Levesque et al. (2005). The J band is particularly useful, because the gradient of the BC with increasing stellar temperature is negligible (for $T_{\text{eff}} > 3400$ K). Differences in T_{eff} corresponding to one nearby spectral type (e.g., from M0 to M1) amount to 45–

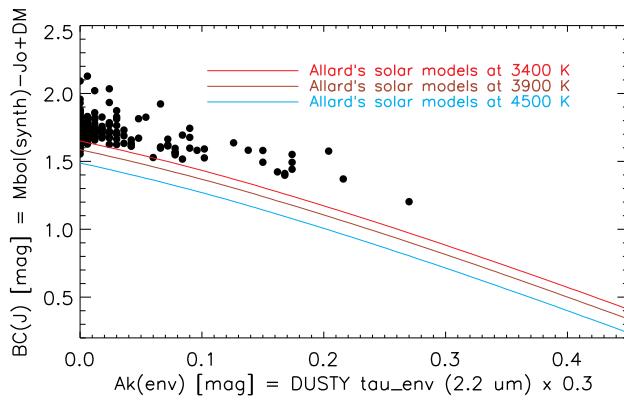


Fig. 8. Empirical BC_J values ($M_{bol}(\text{DUSTY}) - (2\text{MASS.J} - 3.208 \times A_{K_s}(\text{int}) - DM)$) are plotted versus inferred $A_K(\text{env})$. For supergiants ($\log(g)=0.5$) of solar metallicity and T_{eff} of 3200, 3900, and 4500 K, the theoretical BC_J calculated with the DUSTY simulation and Allard's models are over-plotted.

85 K (Levesque et al. 2005). Therefore, a typical uncertainty in the T_{eff} scale of 100–150 K (as noted in recent literature and described in Sect. 2.2) corresponds to two spectral subtypes (e.g., from M1 to M3). In the J band, for T_{eff} from 3400 to 4500 K, an uncertainty of 100 K implies an uncertainty in BC_J of 0.015–0.035 mag, while in the K_s band, it implies an uncertainty in BC_{K_s} from 0.063 to 0.082 mag. However, the selection of the band must also take into account the effect of circumstellar extinction, which decreases with increasing wavelengths.

The presence of thick circumstellar envelopes changes the BC values, which can significantly deviate from those for naked stars (Messineo 2004; Davies et al. 2013; Messineo 2024). To understand the impact of envelope extinction on the M_{bol} values, the empirical bolometric correction in bands J , H , and K_s , BC_J , BC_H , and BC_{K_s} values, were calculated as follows:

$$BC_J = M_{bol}(\text{DUSTY}) - (J - 3.208 \times A_{K_s}(\text{int}) - DM) \text{ [mag]},$$

$$BC_H = M_{bol}(\text{DUSTY}) - (H - 1.766 \times A_{K_s}(\text{int}) - DM) \text{ [mag]},$$

$$BC_{K_s} = M_{bol}(\text{DUSTY}) - (K_s - A_{K_s}(\text{int}) - DM) \text{ [mag]},$$

where DM is the distance modulus, and J , H , and K_s are the 2MASS magnitudes. These empirical BCs are plotted versus the T_{eff} values in Fig. 7. For T_{eff} larger than 3300 K and $\tau_{2.2} < 0.08$, the empirical BC_J values appear almost constant, with a mean value of 1.73 mag ($\sigma = 0.05$ mag) and a median value of 1.73 mag. In contrast, the theoretical BC_J has an average of 1.62 mag with a $\sigma = 0.08$ mag.

The empirical BC_{K_s} increases with decreasing temperature, but its slope is steeper than that derived from the theoretical models. At 3400 K, the BC_{K_s} is 0.07 mag larger than the theoretical value, while at 4100 K, it is 0.12 mag smaller than the theoretical value. The stars with visible infrared excess are marked and deviate from the relation for naked stars. Since for naked stars the BC_J values have little dependence on temperatures, the BC_J values clearly decrease with increasing $A_{K_s}(\text{env})$ in Fig. 8. When estimating the M_{bol} with the BC_J , one can underestimate the M_{bol} up to 0.6 mag.

The above description is based on M_{bol} values from synthetic spectra with solar metallicity. The theoretical dependence of the BC_J , BC_H , and BC_{K_s} on the metallicity is also explored. In Fig. 9, the differences between BCs from models at $[M/H]=+0.0$ and those from models at $[M/H]=+0.0$ are displayed. For the

Table 2. BCs for naked stars were derived with the NextGen models ($[M/H]=0$, $\log(g)=0.5$) of Allard et al. (2011).

T_{eff} [K]	BC_J [mag]	BC_H [mag]	BC_{K_s} [mag]
2600	2.140	2.980	3.221
2700	2.077	3.002	3.247
2800	2.013	2.998	3.254
2900	1.975	2.982	3.248
3000	1.932	2.960	3.234
3100	1.890	2.924	3.208
3200	1.857	2.870	3.152
3300	1.818	2.813	3.089
3400	1.762	2.740	3.006
3500	1.727	2.673	2.924
3600	1.696	2.608	2.845
3700	1.668	2.545	2.766
3800	1.645	2.484	2.690
3900	1.626	2.426	2.617
4000	1.611	2.370	2.548
4100	1.595	2.316	2.480
4200	1.578	2.262	2.414
4300	1.558	2.209	2.349
4400	1.537	2.156	2.284
4500	1.513	2.103	2.221

NextGen models (panel a), $\Delta BC_J = 0.05$ mag with $\sigma = 0.02$ mag when considering T_{eff} from 3200 to 4500 K; $\Delta BC_H = -0.03$ mag with $\sigma = 0.01$; and $\Delta BC_{K_s} = 0.014$ mag with $\sigma = 0.01$. For the ATLAS9 models (panel b and d) the variations are: $\Delta BC_J = 0.050$ mag with $\sigma = 0.021$ mag when considering T_{eff} from 3200 to 4500 K; $\Delta BC_H = -0.029$ mag with $\sigma = 0.006$ mag; and $\Delta BC_{K_s} = -0.000$ mag with $\sigma = 0.006$ mag. For the ATLAS9 models, similar differences are calculated when comparing models at $[M/H]=+0.0$ dex and models at $[M/H]=-0.5$ dex (which are not available in Allard's NextGen grid).

In summary, uncertainties in BCs due to metallicity can be as high as 0.1 mag. Additionally, uncertainties in BC_{K_s} resulting from uncertain temperatures are of a similar magnitude (e.g., 0.12+0.08 mag for $T_{\text{eff}}=4100$ K).

2.4. Isolation versus clustering

In the present work, we individually selected cRSGs on the basis of their color and luminosities. Due to their young age (5–40 Myr), RSGs are found to be associated with giant molecular complexes (e.g., Messineo et al. 2014a, 2021); however, at their ages, most of the stellar clusters have probably already been dissolved. They must therefore be detected individually, and the Gaia parallax allows us to do this.

Most of the efforts of the past two decades were focused on identifying clusters rich in RSGs. Until 2006, the only clusters known with four and five RSGs were Westerlund 1 and NGC 7419 (e.g., Clark et al. 2005; Caron et al. 2003). From 2006 to 2012, marvelous and rare stellar clusters rich in RSGs (RSGC1, RSGC2, RSGC3, Alicante7, Alicante8) were detected in the Milky Way between longitudes 25° and 35° at a heliocentric distance of about 6 kpc, located at the near end side of the Galactic bar (Figer et al. 2006; Davies et al. 2007; Clark et al. 2009b; Messineo et al. 2014b; Chun et al. 2024). The strict selection of parallax quality used in the present work excluded any member of these three distant clusters rich in RSGs located at the near-end side of the Galactic bar.

18 Eighteen percent of the newly selected cRSGs are found
 to be cluster members. Each stellar position was searched
 in VIZIER, and the appearing catalogs of cluster members
 were annotated. Then, the memberships were re-retrieved
 automatically by combining the matches found in the following
 510 catalogs: Cantat-Gaudin & Anders (2020), Castro-Ginard et al.
 (2022), Tarricq et al. (2022), Cantat-Gaudin et al. (2018),
 van Groeningen et al. (2023), Hunt & Reffert (2024), Kos
 (2024), Chi et al. (2023), Qin et al. (2023), He et al. (2023b),
 He et al. (2023a), He et al. (2022a), He et al. (2022b),
 Hao et al. (2022), Orellana et al. (2021), Dias et al. (2018),
 520 and Sampedro et al. (2017). If matches were found in multiple
 catalogs, only the first was retained (following the above listing)
 and only if the probability of membership was higher than 60%.
 All used catalogs, except for Sampedro et al. (2017), are based
 on Gaia data. The cluster membership is annotated in Table 1.

Theoretically, the precise age of a simple stellar population
 hosting RSGs depends on the inclusion and strength of stellar rotation. For non-rotating models, RSGs are found to populate clusters with ages from 4.5 to 40 Myr (e.g., Messineo et al. 2011). Observationally, small variations in age may arise from the selected sample of members and average parallax. Cluster parameters were taken from the compilation by Perren et al. (2023), as well as from the VIZIER database. For each cluster, the two most recent determinations of age and distance were collected. For 58% of cRSGs associated with a cluster, the cluster ages are consistent with the hosting of an RSG; i.e., they are younger than 41 Myr. For 40%, the associated clusters are older than 41 Myr; all but three cRSGs are younger than 300 Myr. The selection seems to yield $\approx 60\%$ of authentic RSGs. When excluding members from the work of Sampedro et al. (2017), which is not based on Gaia parallaxes, this percentage rises to 66%.

540 A full investigation of the stellar clusters is beyond the scope of this paper. The names of the clusters and their ages are listed in the target list (Table 1).

540 type stars that are located in areas A and B of the luminosity-versus- T_{eff} diagram and with radial velocity. 466 stars are from the literature collection by Messineo & Brown (2019)⁹, 20 are from Messineo (2023), and 276 are from the present work. For 96% of the sample, radial velocities were available in the main Gaia DR3 catalog (Katz et al. 2023). The remaining 4% of the measurements were found in the compilation of radial velocities by Tsantaki et al. (2022); this included a few measurements from APOGEE and Gaia DR2 velocities (not included in the Gaia DR3 release). The Gaia barycentric radial velocities were transformed in the local standard of rest (LSR) system using the solar motion by Reid et al. (model A5, 2019). In the XY plane of Fig. 11, the model of spiral arms made with distance measures of pulsars (Cordes & Lazio 2002) is superimposed.

550 The new selection adds stars at greater distances from us and deeper into the inner Galaxy to touch the Scutum-Centaurus arm. The distribution of cRSGs appears far from being homogeneous; indeed, there are several over-densities of cRSGs along the spiral arms, and filaments of cRSGs decorate the inter-arm regions. In Fig. 11, the large over-density on the Perseus spiral arm is colored in green ($100^\circ < l < 150^\circ$, $1 < Y < 4$ kpc). Another concentration of stars, colored cyan, appears on the Sagittarius arm at $-55^\circ > l > -80^\circ$ and $7.3 \lesssim Y < 8.0$ kpc; in the longitude-velocity diagram, this concentration appears to be stretched along the terminal velocity curve, and to end at the tangent point¹⁰ (as indicated in Table 2 of Hou & Han 2014) of the Sagittarius arm at $l \approx -78^\circ$, consistently with the arm modeling of Hou & Han (2014). A narrow feature, colored orange, is visible on the longitudes-versus-latitudes plot, showing decreasing latitudes with increasing longitudes (between $-35^\circ > l > -55^\circ$ and $-2^\circ < b < 0^\circ$). In the XY plane, this feature appears as a group of stars closer to the inner Scutum-Centaurus arm ($Y < 6.7$ kpc). In the longitude-velocity diagram, these stars lie along the terminal velocity curve and culminate at the tangent point of the Scutum-Centaurus arm at $l \approx -50^\circ$ (e.g., Englmaier & Gerhard 1999; Hou & Han 2014). A filament of cRSGs appears aligned with the Local Arm, another filament extends from $-5 < X < 0$ kpc at $Y \approx 9$ kpc.

560 Despite the small numbers, this appearance shows a remarkable resemblance with the distribution of giant molecular clouds (GMC) shown in the work of Hou & Han (2014). The cRSGs are not evenly distributed along the spiral arms, and they also populate the inter-arm regions. The two over-densities centered on the Perseus arm at $l \approx 130^\circ$, and on the Sagittarius arm at $l \approx -70^\circ$ appear symmetrically disposed around the Sun along directions where over-densities of GMCs also lie (Hou & Han 2014).

4. Summary

An exercise to select bright late-type stars, cRSGs, from GAIA and 2MASS catalogs was carried out. While Messineo & Brown (2019) made a catalog of stars previously classified as class I cool stars, Messineo (2023) looked at the Gaia DR3 parameters to locate about 20 additional cRSGs and to find out that, for

⁹ For homogeneity, the luminosities and areas of stars in Messineo & Brown (2019) and Messineo (2023) were re-estimated with the same extinction law adopted here; i.e., using an infrared extinction law with index = -2.1. They had previously been calculated with an index = -1.9.

¹⁰ “One can identify some of the dense emission ridges in the CO longitude-velocity diagram with Galactic spiral arms; where these meet the terminal velocity curve, they can be recognized as bumps where $\delta v_t / \delta l = 0$. . . The inferred spiral arm tangents coincide with features along the terminal curve” (Englmaier & Gerhard 1999).

⁸ the-milky-way-galaxy

cool bright stars, the extinction and temperatures are still highly uncertain. The photometric diagnostics presented in Messineo (2023) were adopted here to select 335 additional cRSGs, with 282 located in areas A & B (39 in area A and 243 in area B). Only 12 of these stars are included in the catalog of Healy et al. (2024). Only six of the 335 stars have Gaia DR3 RVS data; however, they belong to areas E and C. There are no Gaia DR3 RVS data for stars in areas A and B, which is our conservative definition of cRSGs.

A small percentage (18%) of stars are found to be members of stellar clusters. While 58% of the clusters are reported to be younger than 41 Myr old, most have ages below 300 Myr. By extrapolating these percentages to the entire sample, 58% should be true RSGs.

In the XY plane, the cRSGs appear to follow the spiral arms and to populate inter-arm regions. The known Perseus over-density of RSGs is clearly visible. The velocity-longitude diagram suggests that two other over-densities of the XY plane are related to tangent points. A number of cRSGs appear to be aligned with the Local Arm.

5. Data availability

Table 1, which lists the 335 new selected late-type stars, is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/> (check also at mariamessineo.github.io/rsg_Ak).

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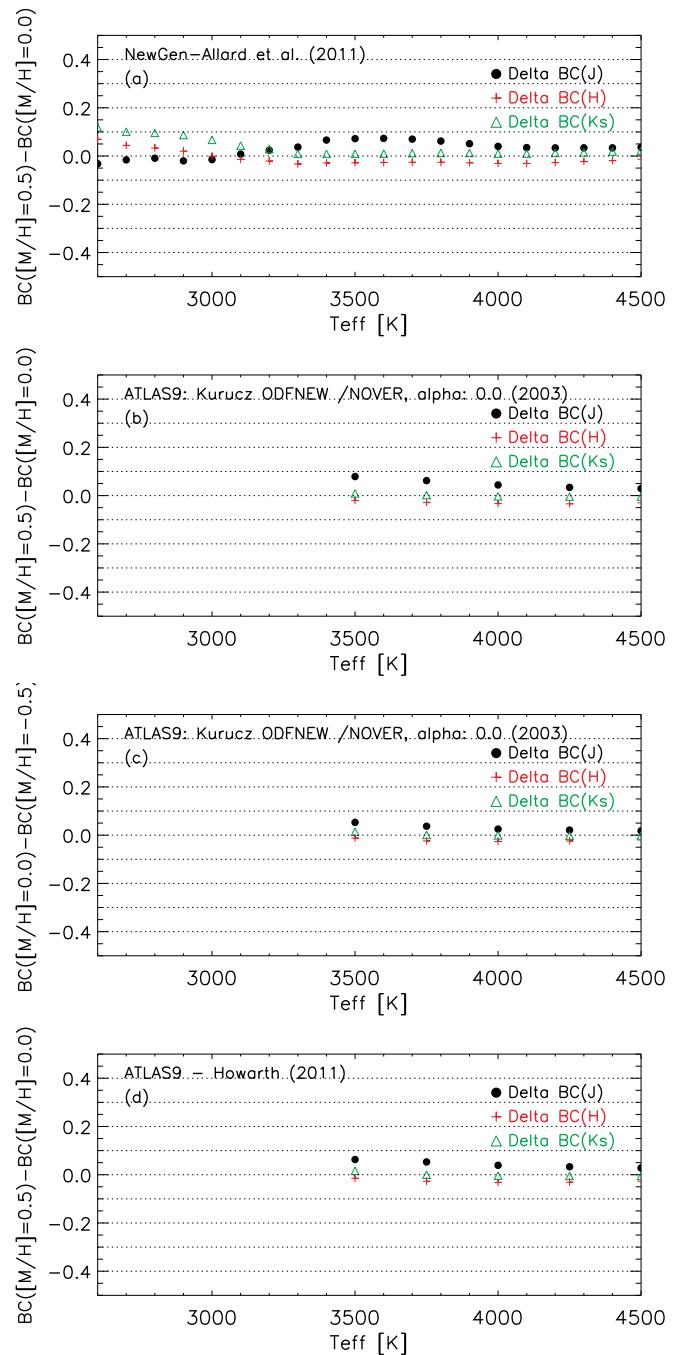


Fig. 9. Panel (a): Differences between BCs in J , H , and K_s bands inferred from the NextGen models of Allard et al. (2011) with $\log_{10}(g)=0.5$, $[M/H]=0.5$ dex, and T_{eff} ranging from 2600 to 4500 K in steps of 100 K; and the BCs inferred from the same set of models, but with $[M/H]=0.0$ dex. Panel (b): Differences between BCs inferred from ATLAS9 models with $\log_{10}(g)=0.5$, $[M/H]=0.5$ dex, and $T_{\text{eff}}=3500$, 3750, 4000, 4250, and 4500 K; and the BCs inferred from the same set of models, but with $[M/H]=0.0$ dex. Panel (c): Differences between BCs inferred from ATLAS9 models with $\log_{10}(g)=0.5$, $[M/H]=0.0$ dex, and $T_{\text{eff}}=3500$, 3750, 4000, 4250, 4500 K; and the BCs inferred from the same set of models, but with $[M/H]=-0.5$ dex. Panel (d): Similar to Panel (b); this time, the ATLAS9 models are those distributed by Howarth (2011). Dotted horizontal lines are drawn every 0.1 mag for easier visualization.

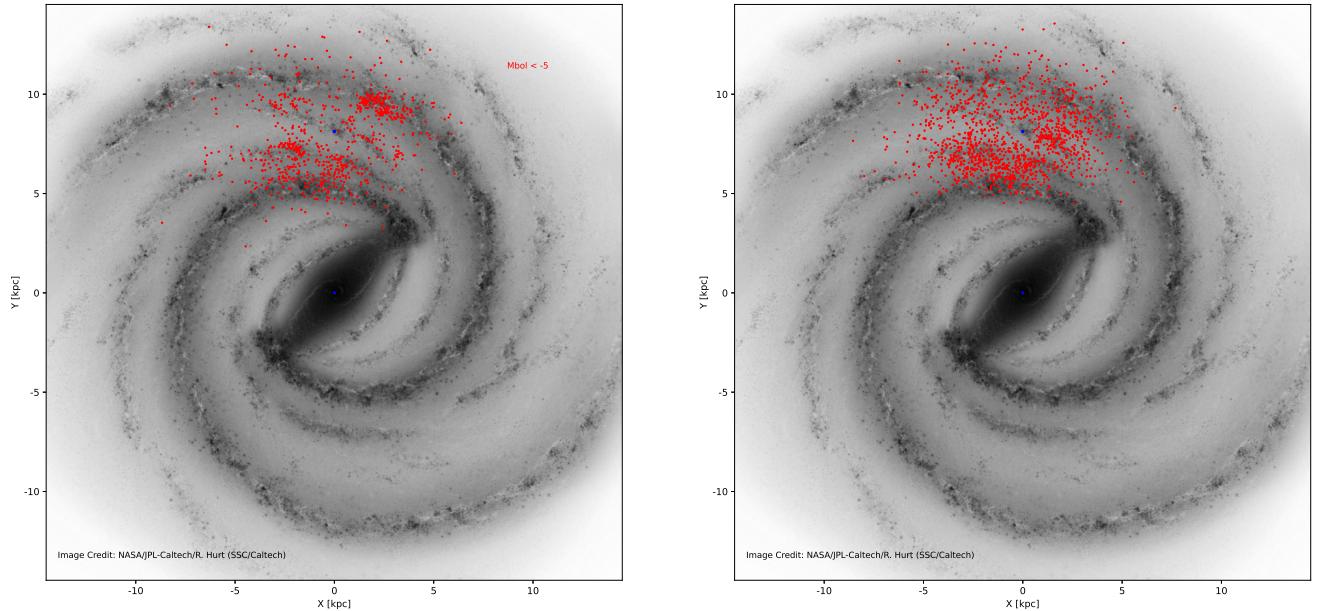


Fig. 10. *Right panel:* XY view of stars located in areas A and B of M_{bol} versus T_{eff} diagram of Messineo & Brown (2019) and newly selected Gaia-2MASS cRSGs, which are also located in areas A and B (red dots). The background grayscale image is the artistic XY view of the Galactic plane illustrated by Dr. Hurt. *Left panel:* Red data points show the complementary dataset (2122 stars with equal brightness ($M_K < -8.5$ mag), which were excluded from the cRSGs).

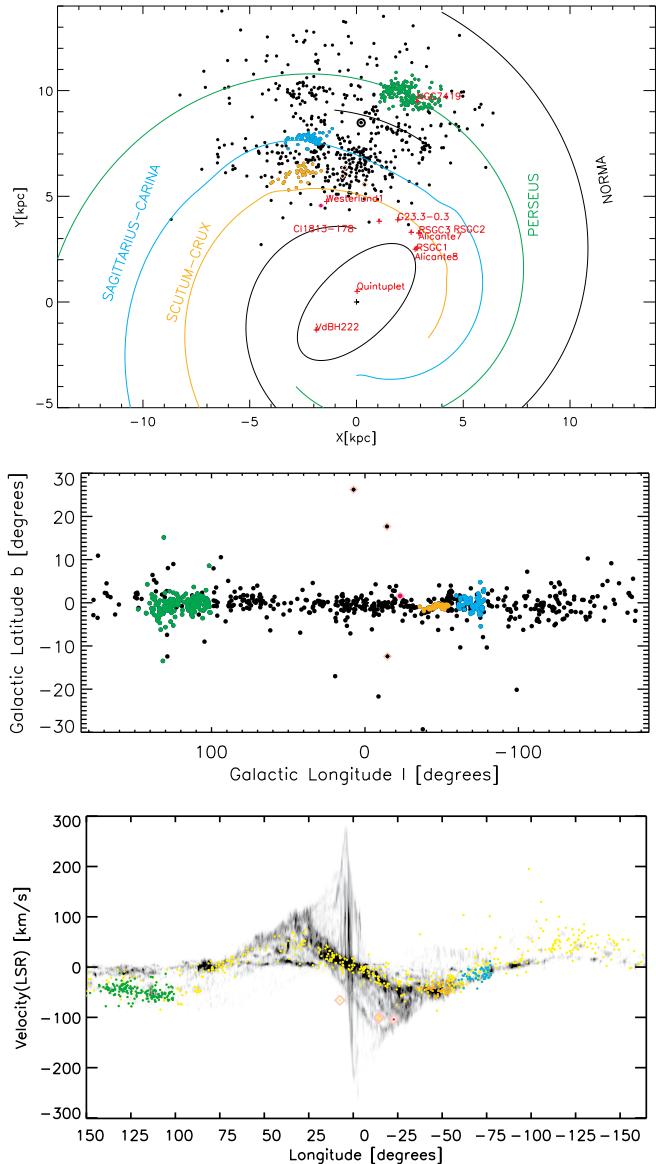


Fig. 11. *Upper panel:* XY view of cRSGs from areas A and B of Messineo & Brown (2019), along with new Gaia-2MASS cRSGs. A distance of 8.5 kpc is adopted, as in the work of Ocker & Cordes (2024). Green filled circles indicate stars located on the large over-density of RSGs of the Perseus arm. Cyan filled circles mark stars corresponding to an apparent concentration of RSGs at the tangent point of the Sagittarius-Carina arm at $l \approx -78^\circ$ (Hou & Han 2014). Orange-filled circles indicate stars located at the tangent point of the Scutum-Centaurus arm (at $l \approx -50^\circ$, Hou & Han 2014). Known massive clusters ($> 10^4 M_\odot$) rich in RSGs are marked in red. The spiral arms of Cordes & Lazio (2002), taken from the native NE2001p Python code of Ocker & Cordes (2024), are also shown. *Middle panel:* Longitudes versus latitudes of cRSGs. The green, cyan, and orange data points are as specified in the upper panel. *Lower panel:* v_{LSR} velocities versus longitudes of cRSGs (shown in yellow). The green, cyan, and orange data points are as specified in the upper panel. The background grayscale image is the CO map by Dame et al. (2001). Four points with peculiar velocities are indicated with pink diamonds; three of them are at high latitudes.