

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

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Received September 15, 1996; accepted March 16, 1997

## 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 details provided by Gaia’s parallactic distances.

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

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

**Results.** The analysis performed warrants 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 of 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 phase of red supergiants (RSGs), or 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,  $T_{\text{eff}}$ , below 4500 K, low gravity ( $\log(g) < 0.7 \text{ cm s}^{-2}$ ), 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 to test 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%) is associated with stellar clusters (e.g., Messineo & Brown 2019; Messineo et al. 2017; Smith & Tombleson 2015). However, a search for individually selected RSGs is more complex than in stellar clusters, being hampered by dust obscuration and poor 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, by having a degenerate core of CO and burning fuel

in two concentric shells (H in the external, and He in the inner shell). AGBs with masses below  $8 M_\odot$  trace star formation occurred from  $\approx 40$  Myr to 13 Gyr ago, and have a much larger range of metallicity. In the last decade, step heads have been obtained in our skills to distinguish the populations of RSGs and AGBs, thanks to the Gaia data which provides parallactic distances and optical stellar energy distribution (SED) of millions of stars, and availability of photometric time-series. In the coming years, spectroscopic data at a resolution larger 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)<sup>1</sup> collects and analyzes stars that have been already reported in the literature as stars of K-M type and class I. Unfortunately, a significant portion of the gathered late-type stars were 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 gran 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 discrim-

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

inate 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 get ready 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 versus temperatures in areas, Messineo & Brown (Gaia DR2 2019) and Messineo (2023, Gaia DR3) kept as highly probable RSGs those  $\approx 400^2$  out of 1725 stars analyzed, located in areas A and B<sup>3</sup>. Messineo (2023) remarks 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, Messineo et al.'s catalog did not consider new photometric cRSGs from Gaia. Anyway, 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 has been 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. 2, the XY distribution of the new sample is shown to share the same features as the bona fide RSGs from Messineo & Brown (2019).

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

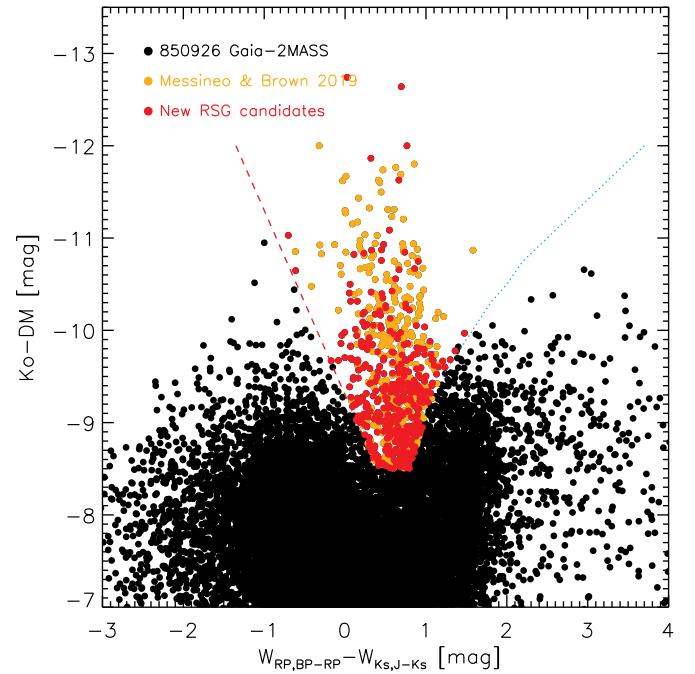
We preselected 2,167,423 data points with the extinction-free magnitude  $K_s - 1.311 \times (H - K_s - 0.2) < 8$  mag from the 2MASS catalog (470,992,970 entries) (Messineo 2024). Indeed, this range of extinction-free  $K_s$  magnitudes encloses all RSGs in areas A&B by Messineo & Brown (2019).

By using their 2MASS IDs we retrieved 1,941,750 Gaia DR3 matches (Gaia Collaboration et al. 2023), of which 1,880,040 have been assigned distances in the catalog by Bailer-Jones et al. (2021). But, only 851,612 of those have  $\frac{\varpi}{\sigma_{\varpi}(\text{est})}$  larger than 4, where  $\varpi$  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 separation lines between C-rich and RSGs, and between O-rich

<sup>2</sup> The extinction calculation determines the exact number of stars in these regions.

<sup>3</sup> As in Messineo & Brown (2019), Area A is here 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.**  $M_K$  vs.  $W_{RP,BP-RP} - W_{Ks,J-Ks} < 4$  colors of 2MASS stars brighter than  $K_s - 1.311 \times (H - K_s - 0.2) < 8$  mag and with a good Gaia parallax. Selected cRSGs (in red and orange) lie in the cone enclosed by the two curves. The dotter-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.

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 six early-type stars. The stars with B-A-F-G types, C-rich, and S-types were dropped from the sample, which remains composed of 342 O-rich stars, of which 207 with known KM spectral types and 135 were 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; de Jong et al. 2012; Sharma et al. 2022).

## 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 manual<sup>4</sup>. 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; that between the CIO and 2MASS  $H$  magnitudes brighter than 4 is +0.24 with a standard deviation  $\sigma=0.44$  mag; while, 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  $\sigma$  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 MIPSGAL 24  $\mu$ 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 the WISE measurements (confusion and blend), 2MASS J18440043-0457062 the WISE W3 and W4 magnitudes (confusion), 2MASS J10572371-6046304 the WISE W4 upper limit magnitude, and 2MASS J19283960+1718220 its GLIMPSE [3.6] magnitude (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  $T_{\text{eff}}$  in RSGs is a challenging task. A direct determination of  $T_{\text{eff}}$  requires the knowledge of the stellar radii, which are only available for a limited number of stars through interferometric measurements. More commonly,

$T_{\text{eff}}$  values are estimated using color temperatures or spectroscopic 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 spectral energy distribution (SED) can result in different  $T_{\text{eff}}$  values (and consequently, extinction estimates).

These findings raise concerns about the use of TiO bands for determining  $T_{\text{eff}}$ , leading to alternative attempts at temperature determination using atomic lines (see for example, Dicenzo & Levesque 2019; Gazak et al. 2014; Tabernero et al. 2018; Taniguchi et al. 2021, 2025). Messineo et al. (2021) showed that the temperature measurements from Gazak et al. (2014) based on  $J$ -band spectra ( $R = 11,000$ -14,000) agreed with those of Levesque et al. (2005) within 150 K. Tabernero et al. (2018) proposed 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) determined RSG temperatures using YJ spectra ( $R = 28,000$ ) and 11 pairs of atomic iron lines; their temperatures are in good agreement with the  $T_{\text{eff}}$  from TiO of Levesque et al. (2005), within 100 K.

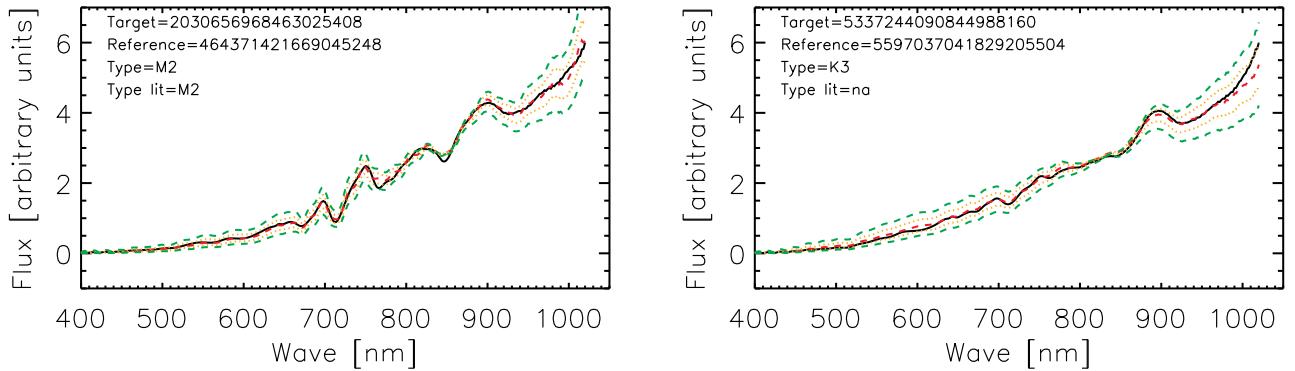
In conclusion, the use of TiO bands to determine temperatures remains valid, as it is supported by studies of atomic lines. Currently, spectroscopic temperatures can be used as a proxy for  $T_{\text{eff}}$ , with a typical accuracy of 100–150 K.

### 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-types stars was produced.

The sample contains 135 late-type stars previously unknown, 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 intrinsic  $H - K_s$  magnitudes, and, initially, we assumed a fixed M1 type with an intrinsic  $H - K_s = 0.22$  mag (Koornneef 1983) and an interstellar power law with an index of -2.1 (Messineo 2024; Messineo et al. 2005); because the associated color uncertainty is typically below 0.12 mag (the delta color between an M1 and an M5), we estimate 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-reddened 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

<sup>4</sup> <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 red-dashed 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  $\pm 0.10$  are indicated with orange-dotted and green-dashed curves, respectively. Gaia source\_ids are given in the figure labels.

color tables of Koornneef (1983). Then, spectral types were re-estimated with the new total  $A_{K_s}$  and the spectral library. On 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  $JK_s$  of 0.11 mag. In Fig. 2, two examples of BPRP spectra are shown along with the selected reference spectrum brought at the target’s extinction. A comparison with the 3D dust map of Green et al. (2019) and our total  $A_{K_s}$  values is possible for 180 stars; after transforming the map  $E(B-V)$  values to  $A_{K_s}$  (Bay19)=  $E(B-V) \times 3.1 \times 0.077$  mag, a mean difference of 0.04 mag is 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 arc-minutes; while our total  $A_{K_s}$  values are estimated with the infrared colors of the considered star. We retain 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 is estimated that the inferred spectral types are mostly 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 `trimmed_range_mag_g_fov` larger than 0.3 mag is over-plotted in red color. The variables are the dominant population for M5-M9 types. When considering only stars in areas A or B of Messineo & Brown (2019), the final sample consists of 282 stars.

### 2.2.2. Envelop extinction

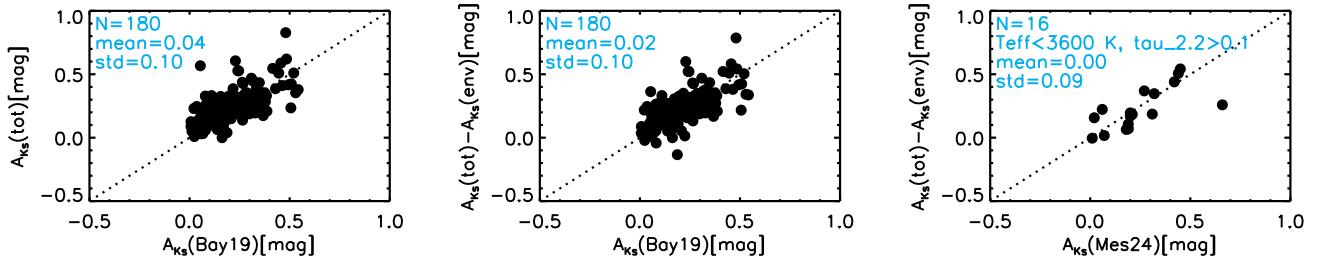
We have assumed that the interstellar extinction  $A_{K_s}(\text{int})$  can be accurately approximated by the total extinction  $A_{K_s}(\text{tot})$  computed using the intrinsic colors of naked stars. The stars are by design the reddest in the  $W_{\text{RP,BP-RP}} - W_{K_s,J-K_s}$  color, as expected 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  $0.55 \mu\text{m}$  (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 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  $\tau$  at  $2.2 \mu\text{m}$  is estimated by examining the presence and strength of the silicate feature at  $10 \mu\text{m}$  in the SED, alongside the flux excess at wavelengths longer than  $8 \mu\text{m}$ .

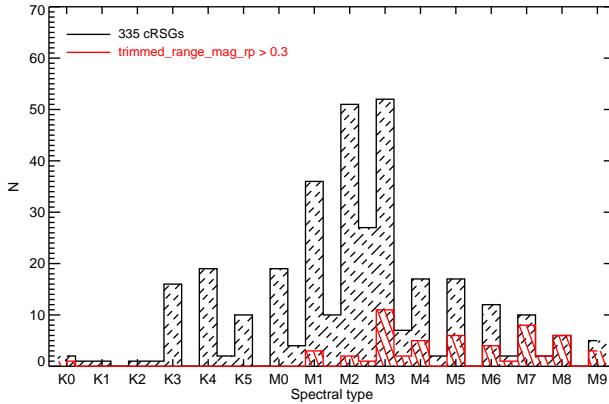
A grid of SED models was constructed using the DUSTY algorithm of Ivezić et al. (1999). The NextGen spectra of Allard et al. (2011) with  $\log_{10}(g)=0.5$ , solar metallicity  $[\text{M}/\text{H}]=0$  dex, and  $T_{\text{eff}}$  from 2600 to 4500 K in step of 100 K were utilized as input stellar models<sup>5</sup>. Cold silicates by Suh (1999) were used and the optical depth at  $2.2 \mu\text{m}$ ,  $\tau_{2.2}$ , was varied in increments of 0.02 from 0 to 1.5. A maximum size of  $1.000 \mu\text{m}$  and a minimum size of  $0.001 \mu\text{m}$  were adopted for the MNR 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 ( $F_{\lambda}$ ) 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  $T_{\text{eff}}$  of  $\pm 100$  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  $10 \mu\text{m}$  accompanied by a flux excess beyond  $8 \mu\text{m}$ <sup>6</sup>. Precisely, as seen in Fig. 5, the bulk

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

<sup>6</sup> 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 like a zigzag without displaying a clear  $10 \mu\text{m}$  feature.



**Fig. 3.** *Left panel:* Estimated  $A_{K_s}(\text{tot})$  values vs. the 3D dust map  $A_{K_s}(\text{Bay19})$  values. *Center panel:*  $A_{K_s}(\text{tot}) - A_{K_s}(\text{env})$  values vs. the 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 vs.  $A_{K_s}(\text{Mes24})$  values are plotted.



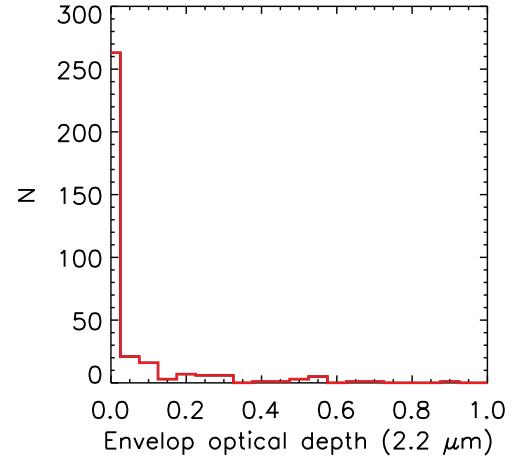
**Fig. 4.** The distribution of spectral types of the 335 analyzed late-type stars. The histogram of stars with `trimmed_range_mag_rp > 0.3` mag is shown in red.

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), and their SEDs show visible silicate features in emission, and a more accurate evaluation of interstellar extinction is needed.

The obtained  $\tau_{2.2}$  is useful for relative comparisons of different envelope types. To compare this theoretical  $\tau$  with the  $A_{K_s}(\text{int})$  and  $A_{K_s}(\text{tot})$  inferred from observations, we need to scale the model  $\tau$  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 assume 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  $\tau$ .

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

Another independent estimate of interstellar extinction,  $A_{K_s}(\text{Mes24})$ , is obtained with the technique outlined by Messineo (2024) for O-rich Mira stars. 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  $(J - K_s)_o$



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

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  $T_{\text{eff}}$  below 3600 K, budgeting of the interstellar extinction  $A_{K_s}(\text{Bay19})$  and  $A_{K_s}(\text{int}) = A_{K_s}(\text{tot}) - \tau_{2.2} \times \text{factor}$  and the factor is chosen to avoid negative  $A_{K_s}(\text{int})$ <sup>7</sup>. The obtained  $A_{K_s}(\text{int})$  values must be in agreement with the  $A_{K_s}(\text{Mes24})$  and  $A_{K_s}(\text{Bay19})$ .

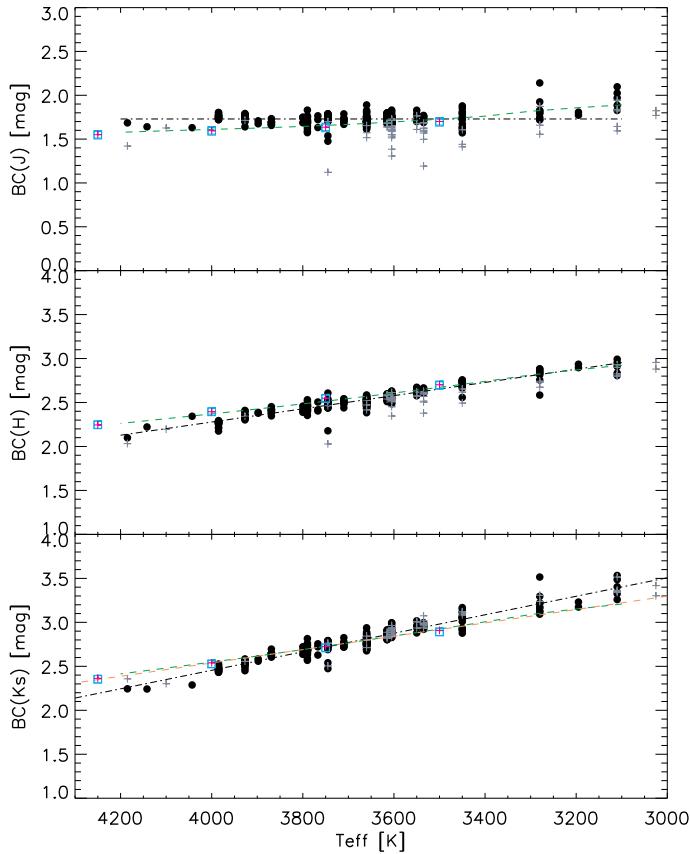
It is obtained that  $A_{K_s}(\text{int}) \approx A_{K_s}(\text{tot}) - \tau_{2.2} \times 0.3$  (see Fig. 3), and the envelope extinction  $A_{K_s}(\text{env}) \approx 0.3 \times \tau_{2.2}[0.001-1.000]$ . When the maximum gran size is  $0.25-0.35 \mu\text{m}$ , the factor becomes unity, i.e., interstellar and circumstellar extinction curves becomes similar.

When neglecting the circumstellar envelope, and assuming  $A_{K_s}(\text{tot})$  as  $A_{K_s}(\text{int})$ , the maximum overestimate of  $A_{K_s}(\text{int})$  would amount to 0.22 mag for the new sample. The correction  $A_{K_s}(\text{int}) = A_{K_s}(\text{tot}) - A_{K_s}(\text{env})$  was applied and the  $M_{\text{bol}}$  recalculated.

### 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

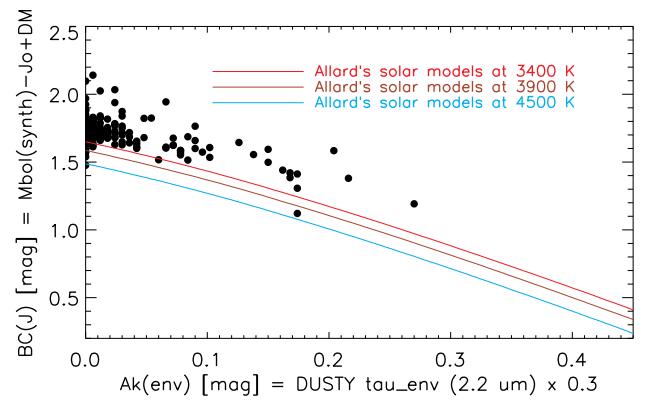
<sup>7</sup> DUSTY  $\tau_{2.2}$  decreases with decreasing maximum grain size.  $\tau_{2.2}[0.001-1.000] = 2.78 \times \tau_{2.2}[0.001-0.350]$  and  $\tau_{2.2}[0.001-1.000] = 3.40 \times \tau_{2.2}[0.001-0.250]$ .



**Fig. 6.** Top panel: For stars with  $\tau_{2.2} < 0.08$ , the bolometric corrections  $BC_J$  are plotted vs. the  $T_{\text{eff}}$  values with black-filled circles. For stars with  $\tau_{2.2} > 0.08$ , gray crosses are plotted. The BC values are calculated with the  $M_{\text{bol}}$  inferred with the atmosphere models by Allard et al. (2011) and the DUSTY code, and the absolute  $J$  magnitudes (from 2MASS). The black dotted-dashed line is the best polynomial fit of degree zero to the data points. The green dashed 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: The bolometric corrections  $BC_H$  are plotted vs. the  $T_{\text{eff}}$  values. Lines and symbols are as for the top panel. Bottom panel: The bolometric corrections  $BC_{Ks}$  are plotted vs. the  $T_{\text{eff}}$  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).

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),  $A_{K_s}$  vary of 0.03 mag in average ( $\sigma=0.01$  mag), and the bolometric magnitudes  $M_{\text{bol}}(BC_{Ks})$  change of 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 densities, and by extrapolating to the blue side with the back-body of temperature as that of 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



**Fig. 7.** The empirical  $BC_J$  values ( $M_{\text{bol}}(\text{DUSTY}) - (2\text{MASS}.J - 3.208 \times A_{K_s}(\text{int}) - DM)$ ) are plotted vs. the inferred  $A_K(\text{env})$ . For supergiants ( $\log(g)=0.5$ ) of solar metallicity and  $T_{\text{eff}}$  of 3200, 3900, and 4500 K, the theoretical  $BC_J$  calculated with the DUSTY simulation and Allard’s models are over-plotted.

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 of 0.09 with sigma=0.03 mag.

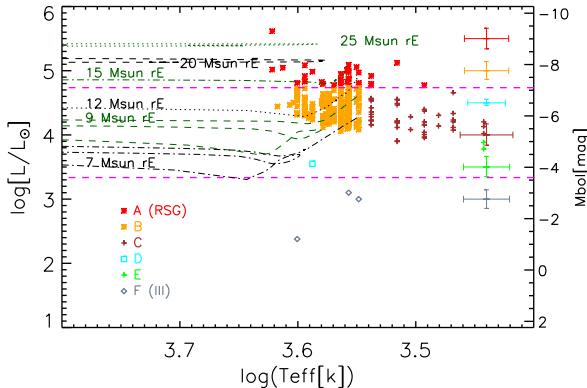
A third estimate of bolometric magnitudes ( $M_{\text{bol}}(\text{DUSTY})$ ) was obtained by integrating under the DUSTY model which best fitted the observed infrared flux densities (de-reddened). The model was scaled so that the average of the observed  $JHKs$  flux densities best matched the average 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  $M_{\text{bol}}$  uncertainty  $M_{\text{tau}_{\text{err}}} < 0.01$  mag, and the  $\tau_{2.2}$  value remains unaffected by  $T_{\text{eff}}$  variations within 100 K in the model. By shifting the best models of  $\pm 100$  K,  $M_{\text{bol}}$  variations are within 0.07 mag. When changing the assumed spectral type of one unit, after recalculating  $T_{\text{eff}}$  and  $A_{K_s}$ , the  $M_{\text{bol}}(\text{DUSTY})$  change of 0.07 with sigma=0.03 mag.

The dominant errors in  $M_{\text{bol}}$  come from the photometric uncertainties ( $\pm 0.14$  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  $\sigma$  of  $[0.09, 0.12]$  mag, see Table 1).

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

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

For the bulk of stars, the derived luminosities are consistent with those of RSGs, as shown in Fig. 8. They are mostly located in areas A & B of the luminosity versus temperature diagram.



**Fig. 8.** Luminosities versus  $T_{\text{eff}}$  of the newly selected stars. Evolutionary tracks with solar metallicity and rotation by Ekström et al. (2012) are over-plotted.

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  $T_{\text{eff}}$  values, as explained by Levesque (2018) and shown in Fig. 6. 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  $T_{\text{eff}}$  corresponding to one nearby spectral type (e.g., from M0 to M1) amount to 45–85 K (Levesque et al. 2005). Therefore, a typical uncertainty in the  $T_{\text{eff}}$  scale of 100–150 K (as noted in recent literature and described in Sect. 2.2) corresponds to two spectral types (e.g., from M1 to M3). In the  $J$ -band, for  $T_{\text{eff}}$  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 (Davies et al. 2013; Messineo 2004, 2024). To understand the impact of envelope extinction on the  $M_{bol}$  values, the empirical bolometric correction in band  $J, H$ , 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,  $J$ ,  $H$ , and  $K_s$  are the 2MASS magnitudes. These empirical BCs are plotted versus the  $T_{\text{eff}}$  values in Fig. 6. For  $T_{\text{eff}}$  larger than 3300 K and  $\tau_{2.2} < 0.08$ , the empirical  $BC_J$  values appear almost constant, with a mean value of 1.72 mag ( $\sigma = 0.05$  mag), and median value 1.72 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

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

$T_{\text{eff}}$ [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

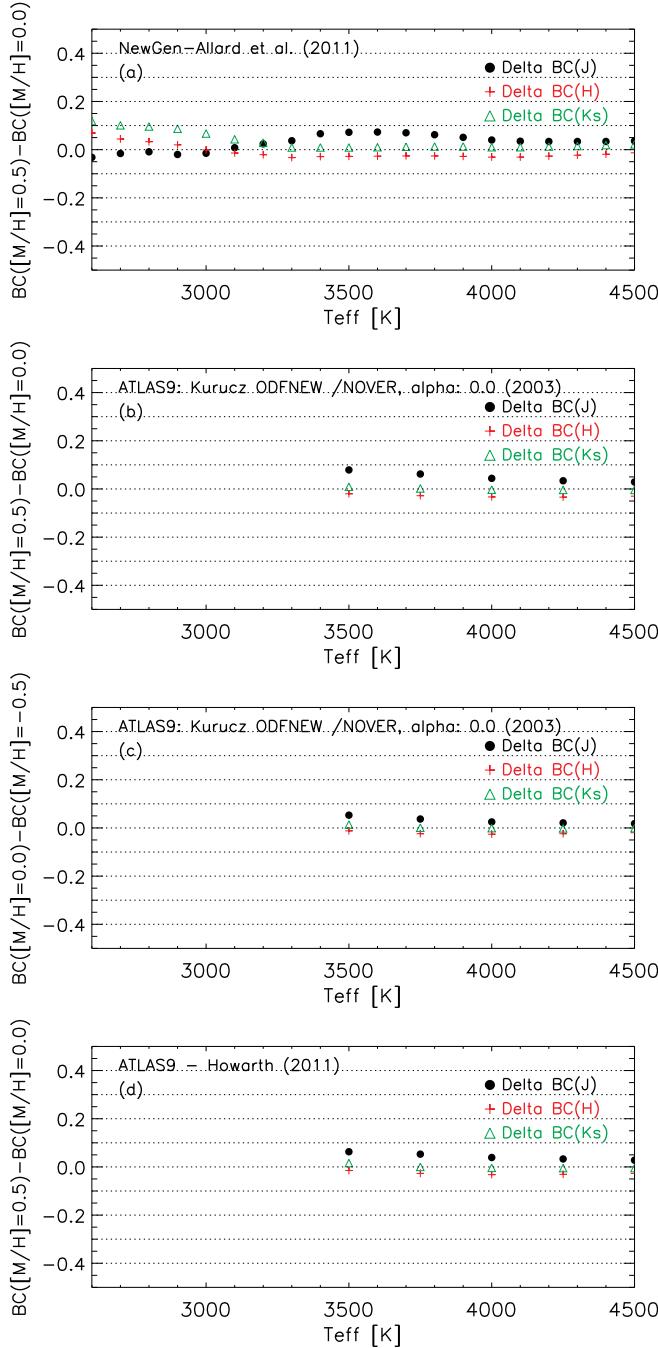
models. At 3400 K, the  $BC_{K_s}$  is 0.07 mag larger than the theoretical value, while at 4100 K, it is 0.12 mag smaller than the theoretical value. The stars with visible infrared excess are marked and deviate from the relation for naked stars. Since for naked stars the  $BC_J$  values have little dependence on temperatures, the  $BC_J$  values appear clearly to decrease with increasing  $A_{K_s}(\text{env})$  in Fig. 7. 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  $[M/H]=+0.5$  and those from models at  $[M/H]=+0.0$  are displayed. For the NextGen models (panel a),  $\Delta BC_J = 0.05$  mag with  $\sigma = 0.02$  mag when considering  $T_{\text{eff}}$  from 3200 to 4500 K;  $\Delta BC_H = -0.03$  mag with  $\sigma = 0.01$ ;  $\Delta BC_{K_s} = 0.014$  mag with  $\sigma = 0.01$ . By contrast, for the ATLAS9 models (panel b and d), the variations appear negligible:  $\Delta BC_J = 0.050$  mag with  $\sigma = 0.021$  mag when considering  $T_{\text{eff}}$  from 3200 to 4500 K;  $\Delta BC_H = -0.029$  mag with  $\sigma = 0.006$  mag;  $\Delta BC_{K_s} = -0.000$  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 much as  $\approx 0.1$  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 on their color and luminosities. Due to their young age (5–40 Myr), RSGs are found to be associated with giant molecular complexes (for example, Messineo et al. 2021, 2014a); however, at their ages, probably most of the stellar clusters have already been dissolved. They must, therefore, be detected individually, and the Gaia parallax allows us to do so.



**Fig. 9.** Panel (a): Differences between the BCs in the  $J$ ,  $H$ , 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  $T_{\text{eff}}$  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 the BCs inferred from the ATLAS9 models with  $\log_{10}(g)=0.5$ ,  $[M/H]=0.5$  dex, and  $T_{\text{eff}}=3500, 3750, 4000, 4250, 4500$  K, and the BCs inferred from the same set of models, but, with  $[M/H]=0.0$  dex. Panel (c): Differences between the BCs inferred from the 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.

Most of the efforts of the past two decades were focused on identifying clusters rich in RSGs. Till 2006, the only clusters known with 4 and 5 RSGs were Westerlund 1 and NGC 7419 (e.g., Caron et al. 2003; Clark et al. 2005). 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  $25^\circ$  and  $35^\circ$  at a heliocentric distance of about 6 kpc, located at the near end side of the Galactic bar (Chun et al. 2024; Clark et al. 2009b; Davies et al. 2007; Figer et al. 2006; Messineo et al. 2014b). The strict selection on parallax quality used in the present work has excluded any member of these three distant clusters rich in RSGs located at the near-end side of the Galactic Bar.

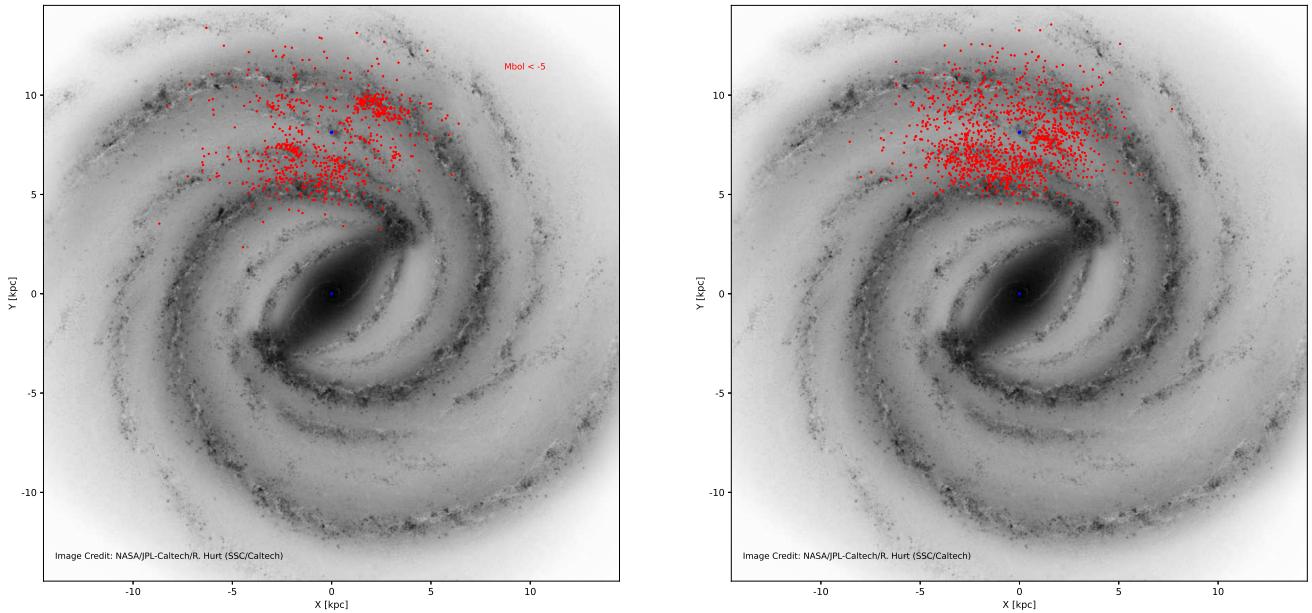
18% of the newly selected cRSG are found to be cluster members. Each stellar position was searched in VIZIER and the appearing catalogs of cluster members were annotated. Then, the memberships were re-retrieved automatically by combining the matches found in the following catalogs: Cantat-Gaudin & Anders (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), 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, but 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%.

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

### 3. XY distribution and longitude-velocity diagram

AGB stars, being old, are good tracers of the Galactic potential, and, for example, their kinematics have been studied to characterize the central Galactic Bar (e.g., Habing et al. 2006; Xia et al. 2024). To the contrary, RSGs are young and their distribution and kinematics give a picture of the Galactic locations where massive star formation occurred between 5 and 30–40 Myr ago; there is about one RSG every burst of 10,000 stars (e.g., Clark et al. 2009a). That is, RSGs are young enough to still mark sites of violent cloud collisions and gas compression, and they populate the spiral arms. Galaxies are far from precise mathematical logarithmic spirals. Spiral arms are transitional phenomena, forms, and reforms. A closer look at the pictures of gran de-



**Fig. 10.** Right panel: XY view of stars located in areas A and B of the  $M_{bol}$  versus  $T_{eff}$  diagram of Messineo & Brown (2019) and the newly selected Gaia-2MASS cRSGs, 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: Here the red data points show the complementary dataset (2122 stars with equal brightness ( $M_K < -8.5$  mag), but excluded from the cRSGs).

sign spirals shows a richness of arms and connecting ridges. In the Milky Way, there is still discussion about the actual number of spiral arms from two to four (Hou & Han 2014), or perhaps two that bifurcates.

In Fig. 10, the best sample of cRSGs, individually selected from Gaia, is overlaid on an artistic representation of the Galactic Plane based on Spitzer data by Dr. Hurt<sup>8</sup>; while, in Fig. 11, the sample of highly-probable RSGs is plotted in the XY plane, in the longitude and latitude diagram, and in the velocity versus longitude diagram. We consider a sample of **762** bright late-type stars which 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)<sup>9</sup>, **20** 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 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 system (LSR) 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.

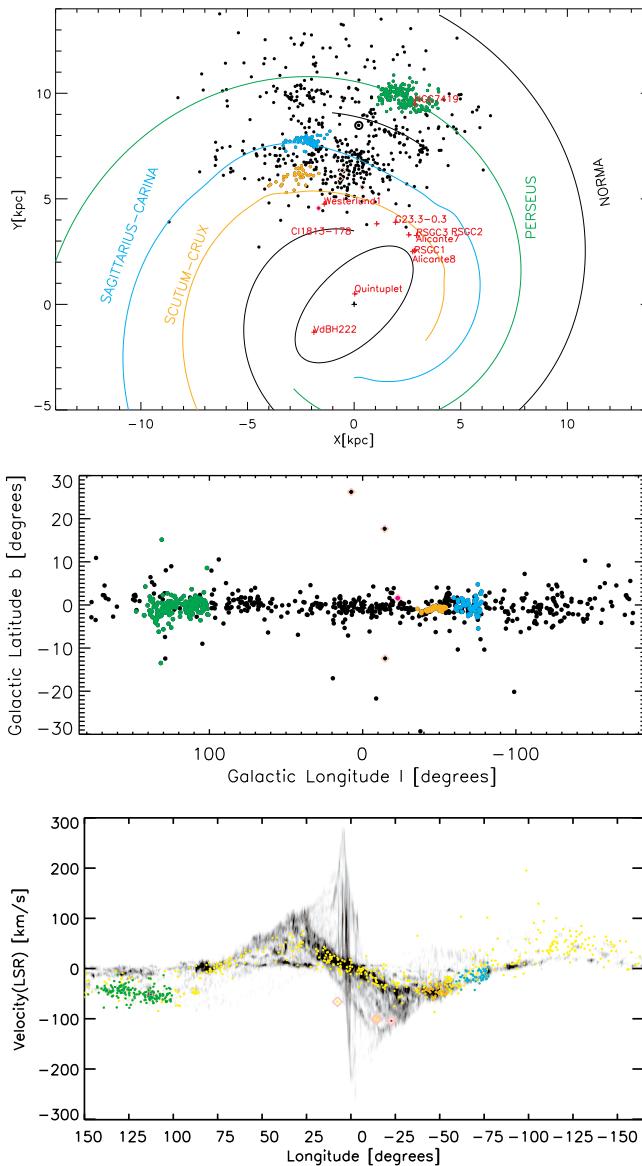
The new selection adds stars at greater distances from us, deeper into the inner Galaxy to touch the Scutum-Centaurus arm. The distribution of cRSGs appears far from being homoge-

neous, indeed, there are several over-densities of cRSGs along the spiral arms, and filaments of cRSGs decorate the inter-arm regions. I) The large over-density on the Perseus spiral arm is colored in green ( $100^\circ < l < 150^\circ$ ,  $1 < Y < 4$  kpc). II) Another concentration of stars, colored cyan, appears on the Sagittarius arm between ( $-55^\circ > l > -80^\circ$ ,  $7.3 \lesssim Y < 8.0$  kpc); in the longitude-velocity diagram, this concentration appears to be stretched along the terminal velocity curve, and to end at the tangent point<sup>10</sup> (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). III) A narrow feature, colored orange, is visible on the longitudes versus latitudes plot, showing decreasing latitudes with increasing longitudes (between  $-35^\circ > l > -55^\circ$ ,  $-2^\circ < b < 0^\circ$ ). 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). IV) A filament of cRSGs appears aligned with the local arm, another filament extends from  $-5 < X < 0$  kpc at  $Y \approx 9$  kpc. Despite the small numbers, this appearance finds 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

<sup>8</sup> the-milky-way-galaxy

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

<sup>10</sup> “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).



**Fig. 11.** *Upper panel:* XY view of cRSGs from areas A and B of Messineo & Brown (2019), along with the 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 vs. latitudes of cRSGs. The green, cyan, and orange data points are as specified in the upper panel. *Lower panel:* The  $v_{\text{LSR}}$  velocities vs. the 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.

directions where also over-densities of GMCs lie (Hou & Han 2014).

#### 4. Summary

- An exercise to select bright late-type stars, cRSGs, from GAIA and 2MASS catalogs is 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 cool bright stars, the extinction and temperatures are still highly uncertain. The photometric diagnostics presented in Messineo (2023) are here adopted 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 6 of the 335 stars have Gaia DR3 RVS data, however, they belong to areas E and C. There aren't 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, most have ages below 300 Myr. By extrapolating these percentages to the entire sample, there should be 58% of true RSGs.
- In the XY plane, the cRSGs appear to follow the spiral arms and to also 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 cdsweb.u-strasbg.fr. (and also at [mariamessineo.github.io/rsg\\_Ak](http://mariamessineo.github.io/rsg_Ak)).

**Acknowledgements.** This work has made use of data from the European Space Agency (ESA) mission *Gaia* (<http://www.cosmos.esa.int/gaia>), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, <http://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 publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center / California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This work is based on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. This research made use of data products from the Midcourse Space Experiment, the processing of which was funded by the Ballistic Missile Defense Organization with additional support from the NASA office of Space Science. This publication makes use of data products from WISE, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory / California Institute of Technology, funded by the National Aeronautics and Space Administration. This research has made use of the VizieR catalogue access tool, CDS, Strasbourg, France, and SIMBAD database. This research utilized the NASA's Astrophysics Data System Bibliographic Services.

We thank the Python, Astropy, NumPy, Pandas, Pivo, SciPy, Matplotlib communities for providing their packages. We thank Dr. Hurt for his illustrations of the Milky Way. This work uses the RSG catalog by Messineo M. & Brown A. (2019) which was supported by the National Natural Science Foundation of China (NSFC-11773025, 11421303), and USTC grant KY2030000054. MM thanks Prof. Anthony Brown for helping her to realize the 2019 catalog, and Dr. Schuyler D. Van Dyk for appreciating her infrared catalog; this fact motivated this additional search for cRSGs. Another acknowledgment goes to Prof. Frank Bertoldi for discussion on interstellar extinction.

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