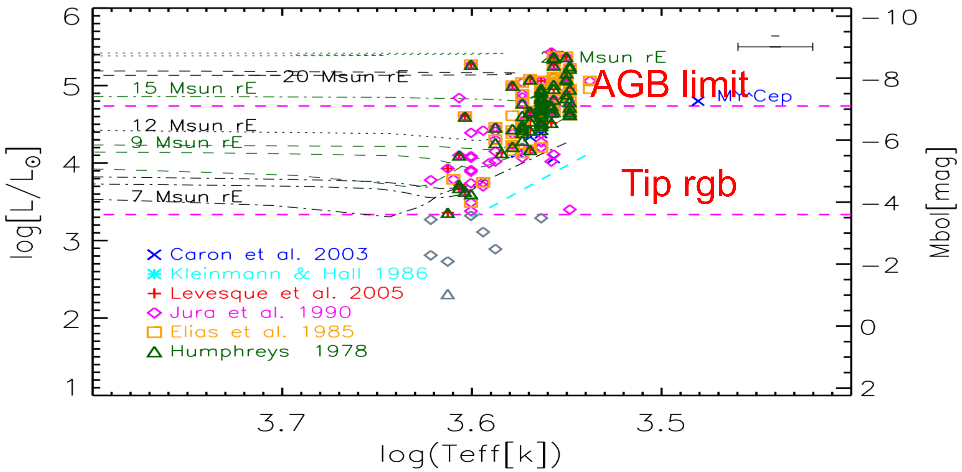
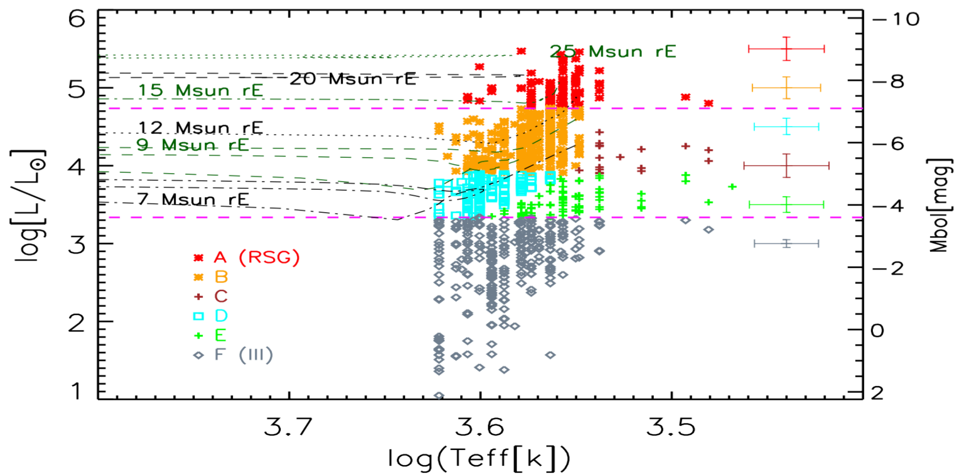
BPRP spectra of bright late-type stars in the Galactic Disk

Maria Messineo

Bright cold late-type stars:
Red Supergiants and AGB stars

Messineo M., Brown, A. G. A. 2019, AJ, 158,20 +doi10.5281/zenodo.4964818



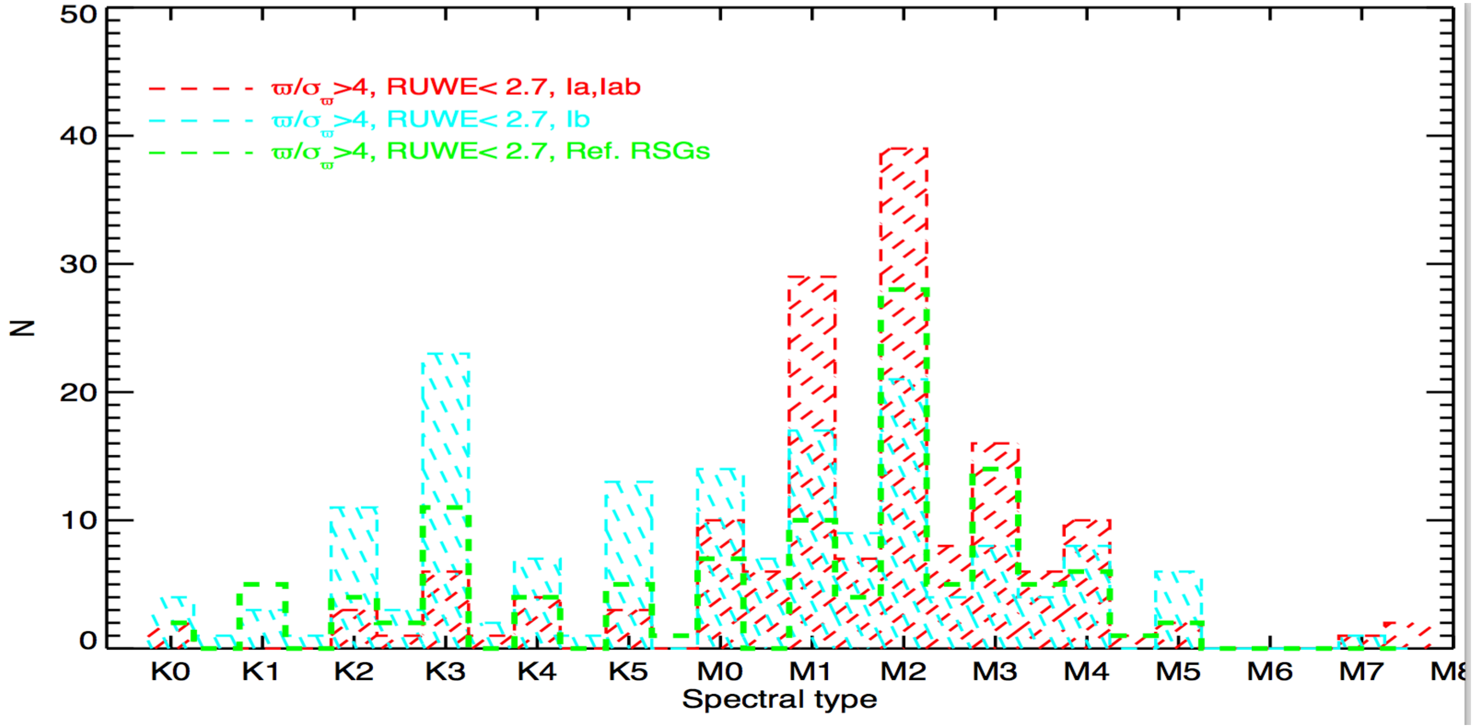


RSGs from
Jura 1990; Elias et al. 1985; Humpreys et al 1978;
Levesque et al. 2005; Caron et al. 2003; Kleinmann & Hall 1986

Stellar tracks are from Ekstroem et al. (2012)

Messineo & Brown (2019)
1406 K-M I stars collected from literature
1396 Gaia matches found
966 plx omega/sigmaomega >4
G-band from 9-20 mag
Area A & B (red & orange) mostly RSGs

Distribution of Spectral types: RSGs



Classes Ia and Iab peak at M2.

Class Ib peaks at K3.

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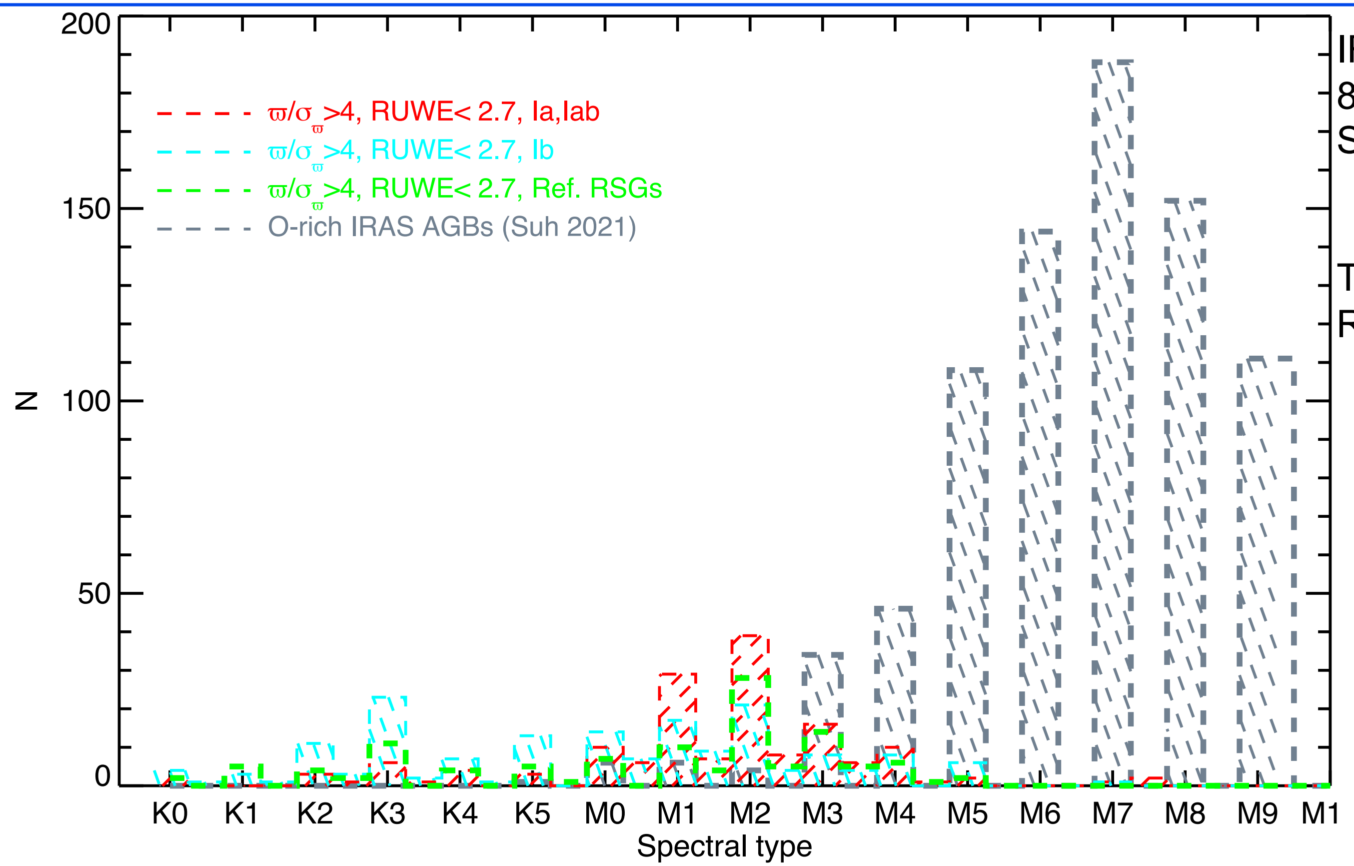
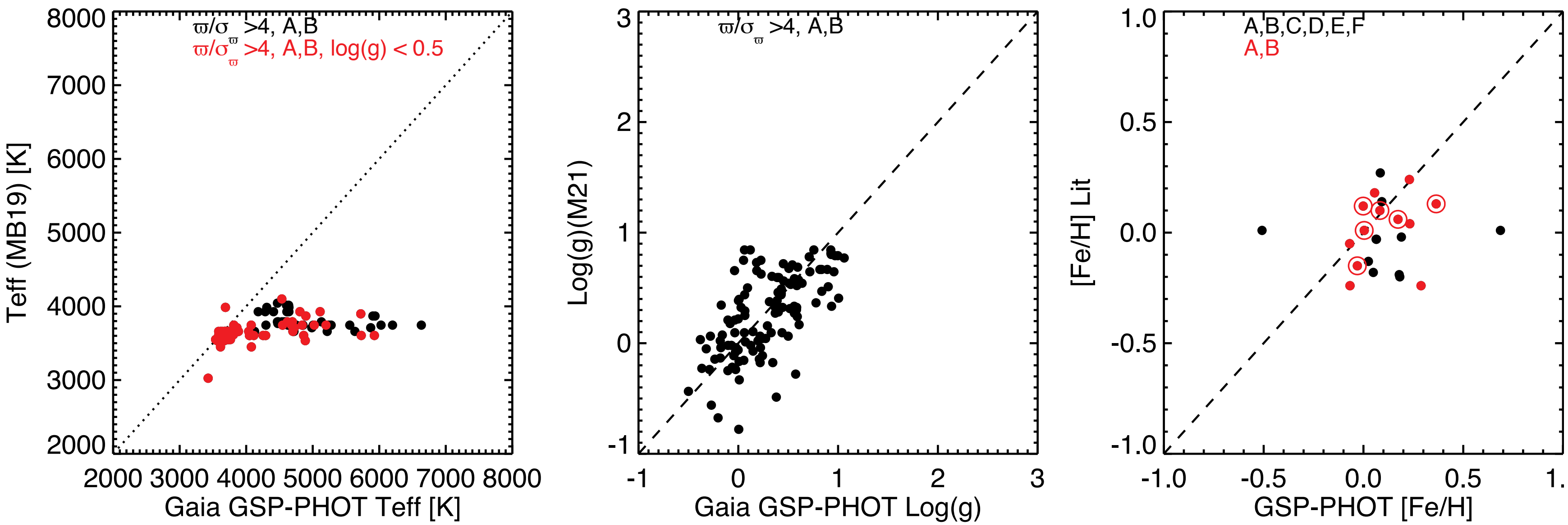
Distribution of Spectral types: RSGs & TP-AGBs



IRAS-AGBs 5000
800 Sp. Types
Suh (2021 ApJS,256,43)

TP-AGB > M4
RSGs mostly M0-M4

Gaia-DR3 APIS parameters of RSGs:
FAILURE for K I stars temperatures



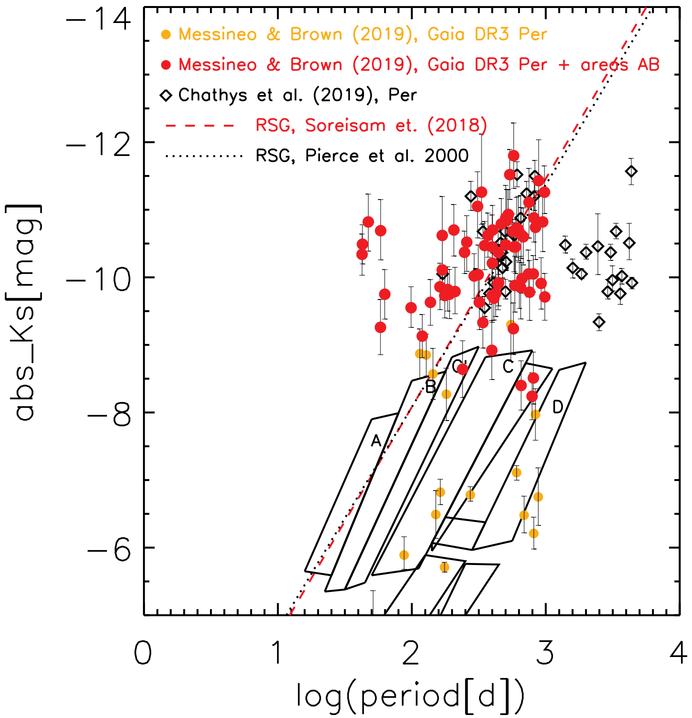
Stars are from the catalog of Messineo M., Brown, A. G. A. 2019

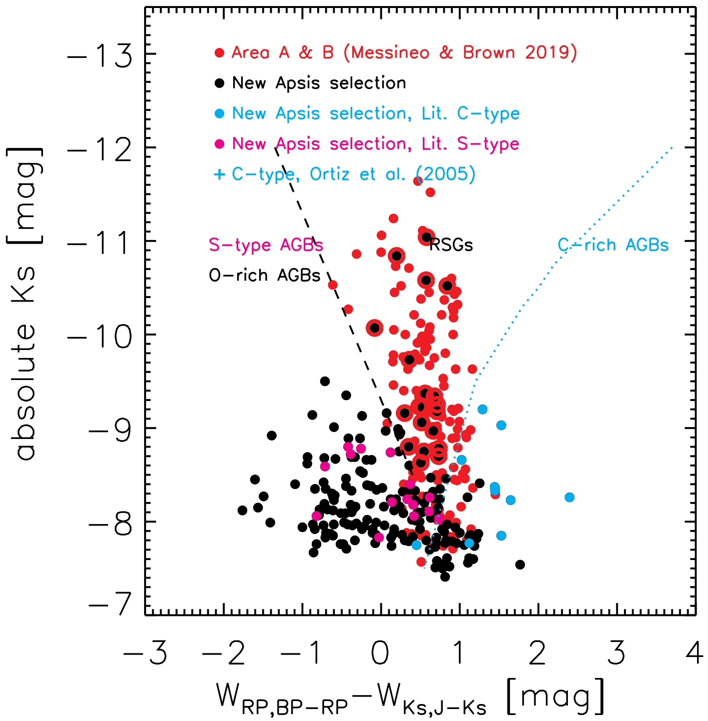
Gaia-DR3 photometric selection of AGBs and RSGs

RSG
Ampl(K) < 0.25 mag
Wood et al. (1983)

Ampl(I)=2.2Ampl(J)
Messineo (2022)

87/1060
have periods
Ampl(G) < 0.5 mag

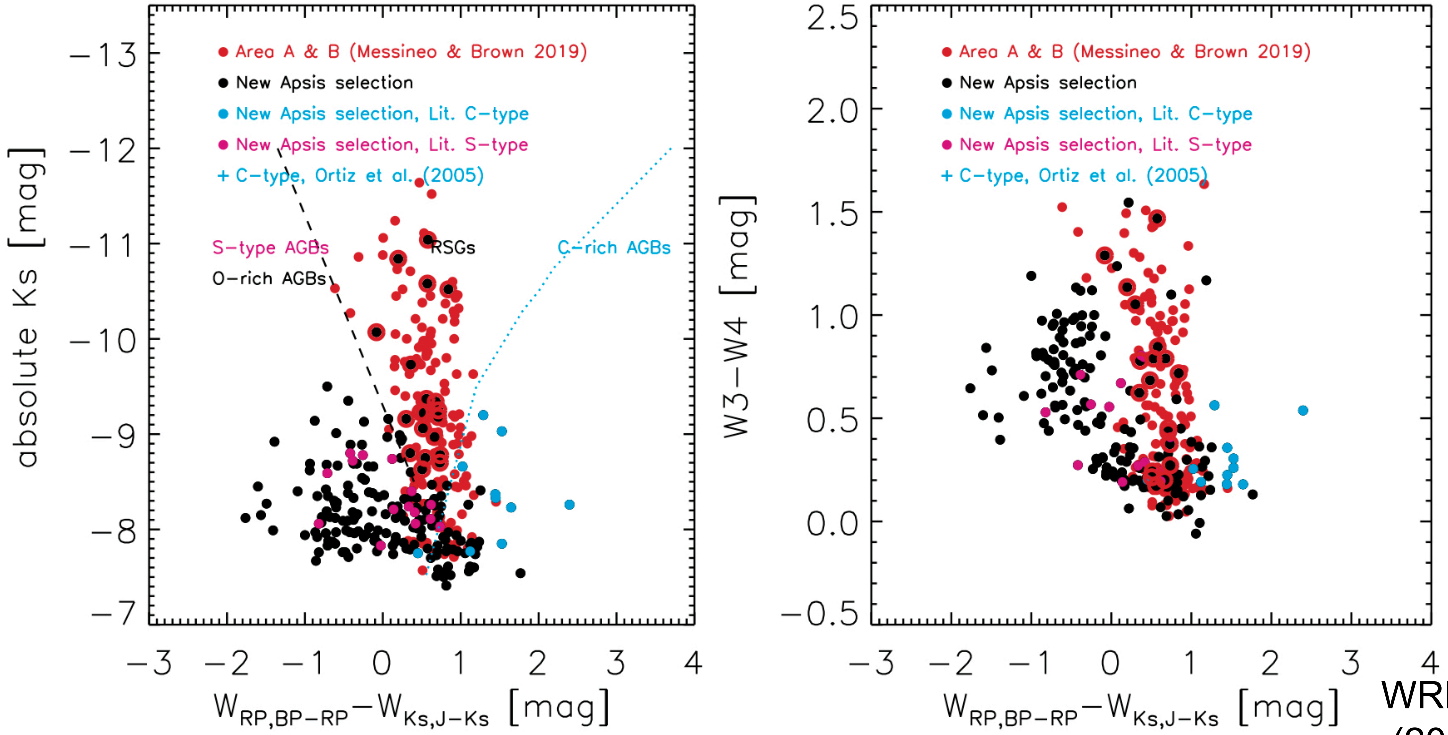




Stars are from the catalog of Messineo M., Brown, A. G. A. 2019, Fig. from Messineo (2023)
AGB sequences A, B, C', C, D are from Riebel et al. (2010)

Color as in Abia et al. (2023)

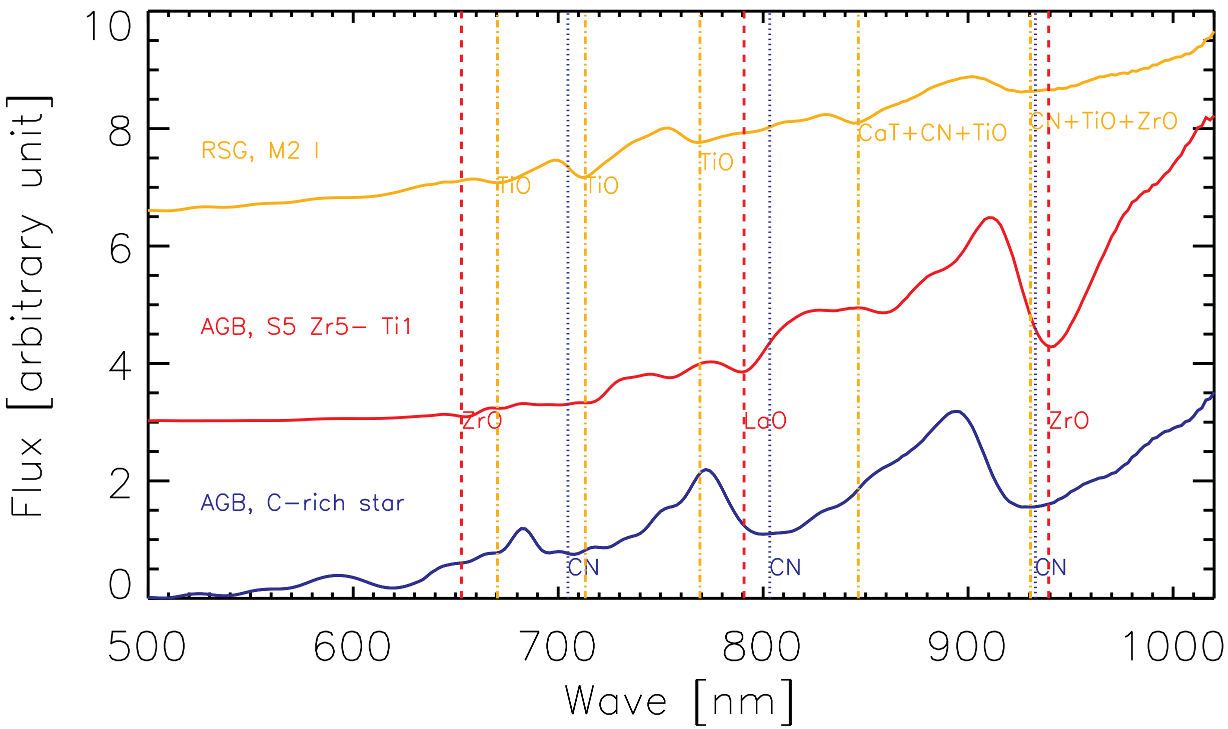
Gaia-DR3 photometric selection of AGBs and RSGs



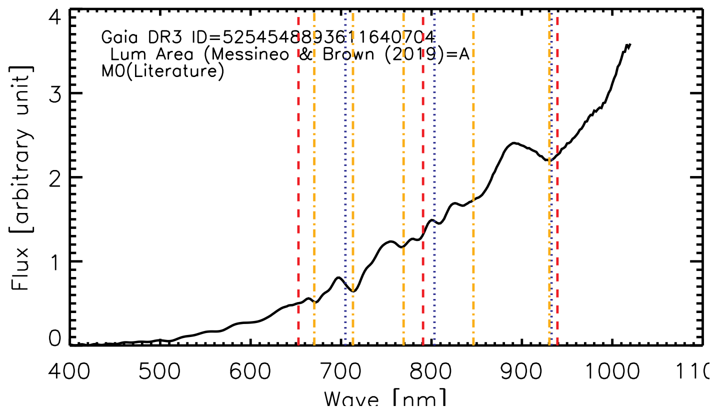
WRP-WKs as in Abia et al. (2023)

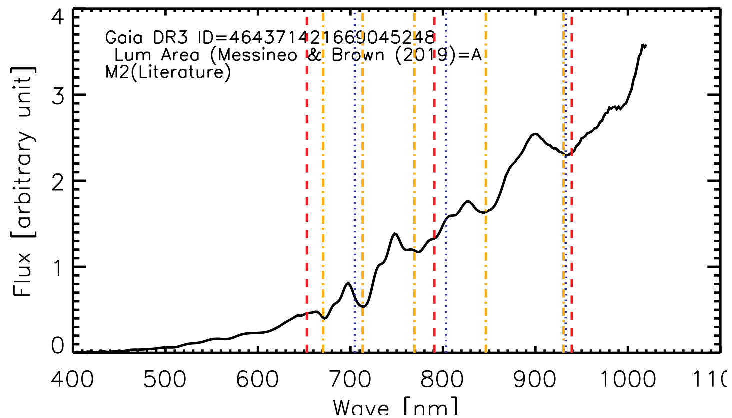
Stars are from the catalog of Messineo M., Brown, A. G. A. 2019, Fig. from Messineo (2023)

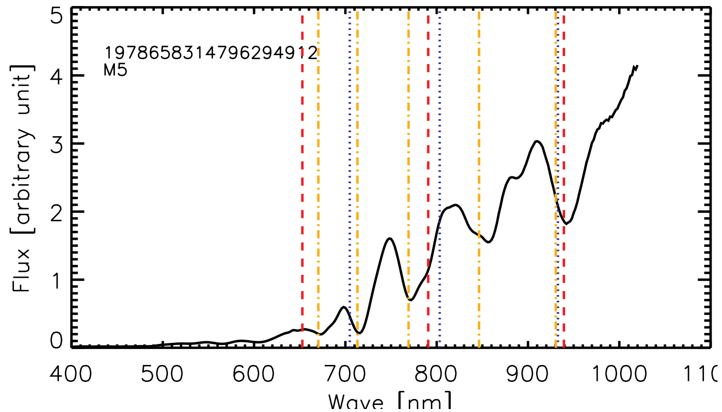
Gaia-DR3 BPRP spectra of AGBs and RSGs

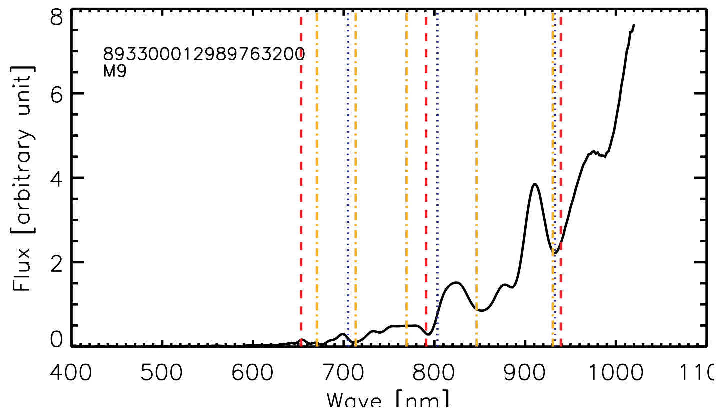


Gaia-DR3 BPRP spectra: Spectral classification









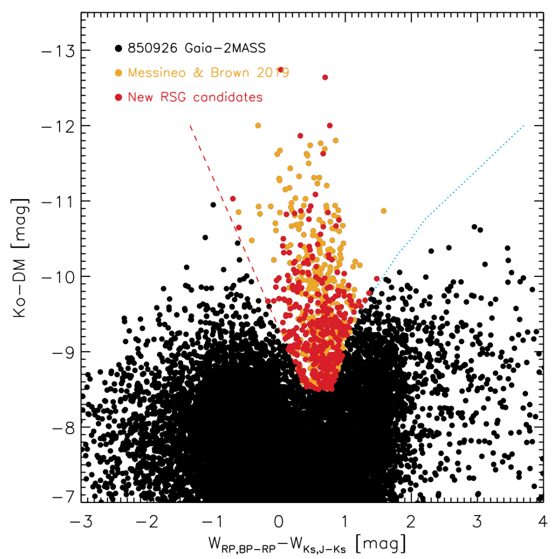
Summary and results

• 486 RSGs (A+B) are collected by Messineo & Brown (2019)
12% variable (delta G band < 0.5 mag)
133 (A+B) have BPRP spectra
Aks from 2MASS_JHK + BPRP spectra yields spectral type within 1 class for O-rich
Empirical library (fit + visual inspection)

• Apis parameters have not reliable temperatures (temperature & extinction degeneracy
and yield only 20 new RSGs.
Gaia photometry and BPRP spectra allow us to identify O-rich, C-rich, and S-type star
Flags need to be used with care

• Using the MKs vs WRP-WKs diagram 350 additional candidate RSGs are identified
The number of cRSGs (486+342) is comparable to that recently reported
by Haley et al. (2024). Recall that we expect about 3-5000 of them! Where are they?

In the herz of Gaia



BPRP SPECTRA OF BRIGHT LATE-TYPE STARS IN THE GALACTIC DISK

M. Messineo[1]

Abstract.
This is the talk I gave on "Galactic red supergiants using data from Gaia" at the conference "The BRITE side of the stars," which took place in Vienna from August 20 to 23, 2024.

Keywords: infrared: stars – stars: supergiants – stars: evolution

1 Presentation

Red supergiants (RSGs) and asymptotic giant branch stars (AGBs) are the brightest stars at infrared wavelengths, easily detectable even at a distance of a few megaparsecs. Mass-loss controls their complex evolution, and their winds enrich and shape the interstellar medium. Even though the Milky Way is the nearest laboratory of resolved stellar populations, dust obscuration and poor knowledge of distances hamper a clear separation of the RSG and AGB populations. Such separation is necessary to comprehend the morphology of the Milky Way and its history of star formation.

Messineo & Brown (2019) list around 500 genuine spectroscopic Galactic RSGs, and Suh (2021) reports about 20,000 AGB stars in the catalog.

A catalog of known RSGs (Figs. 1 and 2)
The catalog of Messineo & Brown (2019) lists stars which have been already reported in the literature at least once as stars with K-M types and class I. Unfortunately, as Fig. 1 illustrates, a significant portion of stars were discovered to be faint giants, indicating that most of the reported classes are not secure, and must be revised with Gaia parallactic distances. The catalog contains 1521 stars; 1060 stars were found to have good distances after cross-referencing the infrared photometric catalog with Gaia data EDR3 (Messineo & Brown 2019; Messineo 2023). 49% of the stars are brighter than $M_{\rm bol}$=−5.0 mag and earlier than M4, indicating that they are more massive than 7 $M_\odot$ and are hence likely RSGs. In the $M_{\rm bol}$ versus $T_{\rm eff}$ diagram of Fig. 1, these stars occupy areas A & B, as defined in Messineo & Brown (2019). A tail of 120 stars exceeds the AGB luminosity limit ($M_{\rm bol}$=−7.1 mag).

That RSGs are generally not later than M5 is clear from the histograms provided in Fig. 2. On the other hand, termal pulsing AGBs are of later types.

Gaia DR3 APIS parameters (Figs. 3)
Messineo (2023) has compared the stellar parameters of RSGs provided by the Gaia GSP-phot pipeline for the low-resolution spectra (BPRP spectra) (Fouesneau et al. 2022) with parameters collected from the literature. As shown in Fig. 3, the GSP-phot pipeline temperatures are overestimated for bright cool stars; this is most likely due to the degeneracy between temperature and extinction. This means that many RSGs are lost by the APIS, because they get classified as G or even F stars. When using the current APIS parameters (from DR3), and selecting ranges of $T_{\rm eff}$ log(g), and metallicity which are typical of RSGs, only 203 stars are retrieved, and after analising their BPRP spectra, distances, luminosities, and variability, only 20 new RSGs are confirmed.

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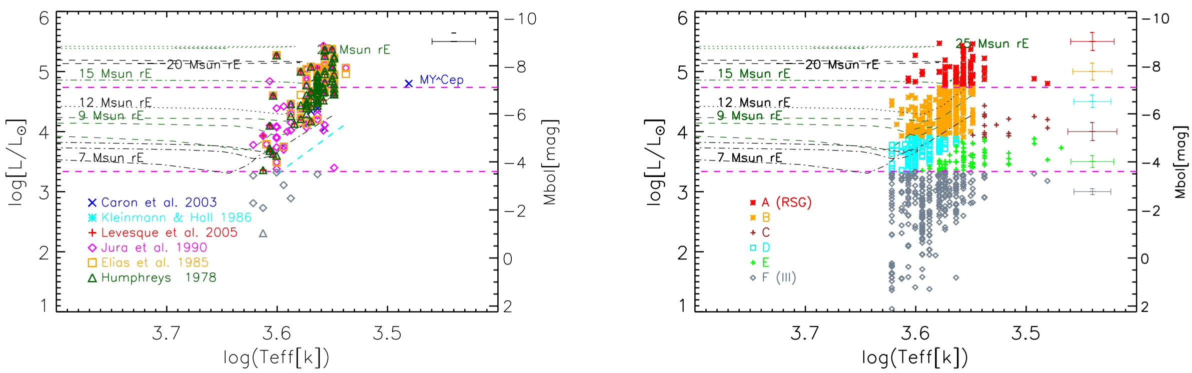

Fig. 1. Left panel: $M_{\rm bol}$ versus $T_{\rm eff}$ of RSGs. The sample of reference RSGs by Messineo & Brown (2019) is displayed here, as it appears in their Fig. 3 (upper left panel). These reference stars are known RSGs reported in various academic works such as Jura & Kleinmann (1990), Elias et al. (1985), Humphreys (1978), Levesque et al. (2005), Caron et al. (2003), and Kleinmann & Hall (1986). The stellar tracks are from Ekström et al. (2012). **Right panel:** $M_{\rm bol}$ versus $T_{\rm eff}$ values of stars with good distances from the catalog of Messineo & Brown (2019). As in Fig. 4 of Messineo & Brown (2019), the stars are color-coded according to where they are on the diagram. Highly likely RSGs with $M_{\rm bol}< -7.1$ mag (Area=A) are indicated by red asterisks. Sources with $M_{\rm bol}< -5.0$ mag and types <M4 (Area=B) are indicated by orange asterisks. Most of the RSGs are found in Areas A and B. Stars that are less bright than the red giant branch tip, $M_{\rm bol}$=-3.6 mag, are undoubtedly giants, despite being mistakenly reported as class I in previous literature. The stellar tracks are from Ekström et al. (2012).

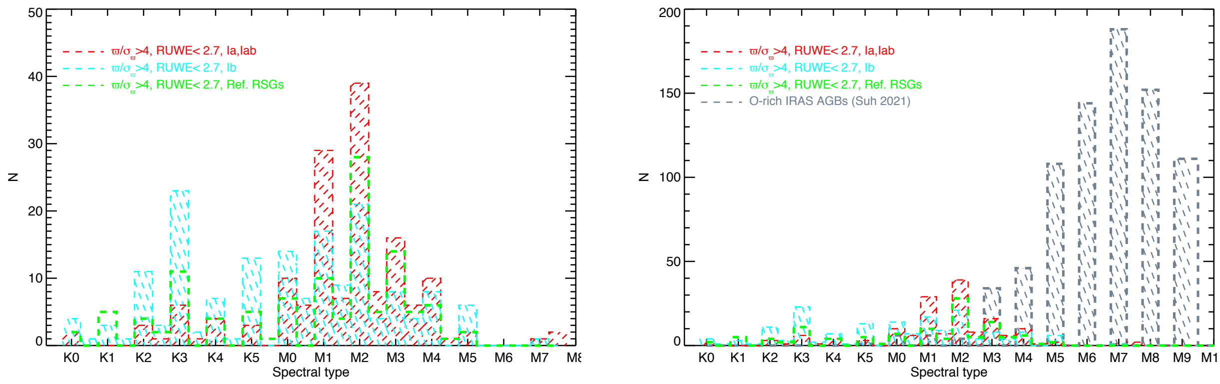

Fig. 2. Left panel: In Messineo & Brown (2019), this figure corresponds to the right panel of Fig. 5. The histogram of the spectral types of the reference RSGs is shown in green. Other stars spectroscopically observed and reported as class Ia, Iab, or Ib are shown in red and cyan, respectively. **Right panel:** A histogram of AGB types (in gray) is overimposed on the RSG histograms. The RSG's histograms peak at M2; typically, Galactic thermal pulsing AGBs have types later than M4. The AGBs are taken from the catalog of Suh (2021).

Photometric RSG stars (Figs. 4 and 5)
The APIS parameters for bright late-type stars are not yet very reliable, as demonstrated in the previous slide. Precise $T_{\rm eff}$, log(g), and metallicity will become available when Gaia RVS spectra (DR4) become available; in the interim, a photometric selection is recommended.

RSGs live in a narrow range of extinction-free colour $\rm W_{RP,BP-RP}-W_{K_S,J-K_S}$ (from 0 to 1), while carbon stars are redder than that, and O-rich AGB stars and S-type stars are bluer than that (Messineo 2023), as shown in the right panel of Fig. 4. Furthermore, for variable stars, amplitudes can discriminate between Mira AGBs and RSGs (Wood et al. 1983; Messineo 2022; Lebzelter et al. 2023). Indeed, AGB Miras usually have G-band amplitudes larger than 0.5 mag, whereas RSGs vary only a few dex of magnitude. The WISE W3-W4 versus $\rm W_{RP,BP-RP}-W_{K_S,J-K_S}$ colours is also an interesting diagram for studying late-type stars (Fig. 5). As demonstrated by Messineo (2023), the $\rm W_{RP,BP-RP}-W_{K_S,J-K_S}$ colour is a temperature indicator, while the

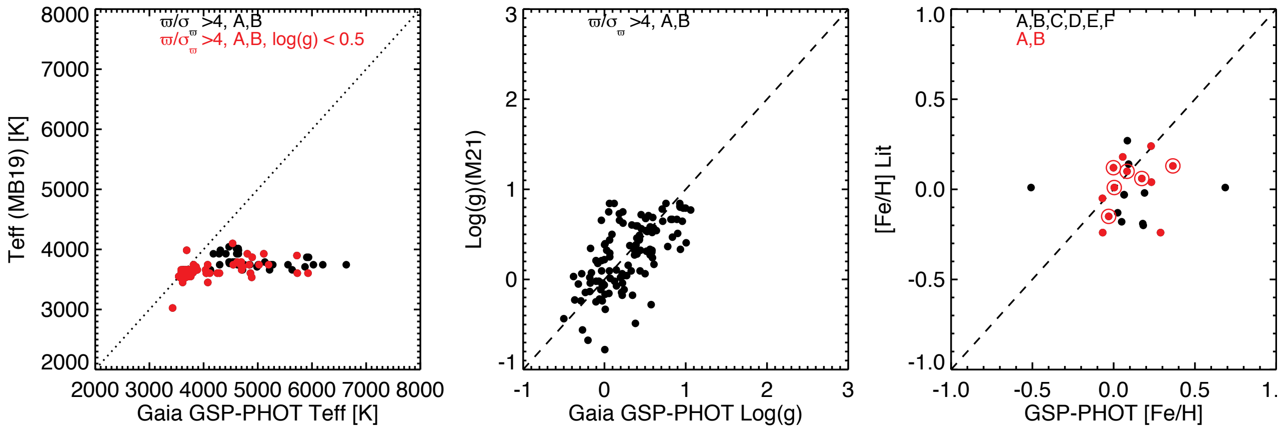

Fig. 3. Left panel: Left panel: As shown in Fig. 1 in Messineo (2023), the diagram of the $T_{\rm eff}$ values gathered from the literature versus those deduced by the Gaia pipeline using the Gaia DR3 BPRP spectra. The stars in the sample come from Messineo & Brown (2019). Only stars in areas A & B are are plotted and those with lower gravity (log(g) $<$ 0.5 dex) are coloured in red. **Middle panel:** the gravity values, log(g), given by the Gaia GSP-PHOT pipeline are compared with those estimated with luminosities and the formula by Messineo et al. (2021). **Right panel:** The metallicity values derived from the Gaia DR3 BPRP spectra are compared with those gathered from the literature, as shown in Fig. 3 in Messineo (2023).

W3-W4 colour is a sensitive indicator of mass-loss.

Features seen in the BPRP spectra (Figs. 6 and 7)
Due to their low spectral resolution (R=80-20) and large coverage (330-1050 nm) (Montegriffo et al. 2023), the BPRP spectra only allow us to identify the broad patterns that result from molecular absorption. AGB stars are classified as O-rich, S-type, and C-type based on their molecular features, which also indicate their evolutionary phase and internal mixing.

Strong TiO absorption bands can be seen in the spectra of O-rich AGB stars and RSGs, as shown in Fig. 6; strong CN absorption features can be found in the spectra of C-rich stars at 704.8 nm, 803.3 nm, and 932.8 nm; ZrO absorption bands can be found in the spectra of S-type stars at 652.9 nm and 939.3 nm, and LaO (at 790.7 nm). The LaO band appears in S4-type and is strong in S5 and later types. The three types of chemistry are all detected with the Gaia low-resolution spectrograph. The molecular features appear weaker at greater extinction.

The TiO feature strengths in O-rich stars vary with temperature. This appears in Fig. 7 where the spectra of an M0, M2, M5, and M9 star are shown. Messineo (2023) demonstrates that RSGs can be classified within 1-2 types using BPRP spectra and an empirical library.

Summary and final remarks (Figs. 8)
A statistical separation of C-rich, O-rich AGBs, and RSGs is made possible by Gaia photometry and light curves combined with infrared data from 2MASS-WISE (Abia et al. 2022; Messineo 2023). As shown in Fig. 8, about 330 candidate RSGs are photometrically selected, in addition to those included in the catalog of Messineo & Brown (2019) and to the 20 selected with APIS parameters by Messineo (2023). Messineo & Brown (2019) has 486 stars from regions A & B in its catalog. The total number of high probable RSGs is comparable to that reported in the recent study by Healy et al. (2024), which includes 578 stars.

For bright cool stars, the Apis parameters do not yet deliver temperatures that can be relied upon. An empirical library and a prior on interstellar extinction can be used to obtain good spectral types of AGBs and RSGs from the Gaia BP/RP spectra, which are rich in signatures of TiO, CN, ZrO, and LaO. I have used 2MASS_JHK data to calculate interstellar extinction, $A_{\rm K}$. K-and M-types can be reproduced with an accuracy of two subtypes. Using particular absorption patterns found in their BP/RP spectra that are attributable to ZrO and LaO, S-type stars (S4 and later) can also be recognized. In conclusion, Gaia BPRP spectra allow us to identify O-rich, C-rich, and S-type stars. Since bright cool stars constitute a small Gaia sample, it is usually advisable to look at the spectra with the eyes, and the flags (e.g. carbon flag) that the ESA team provides

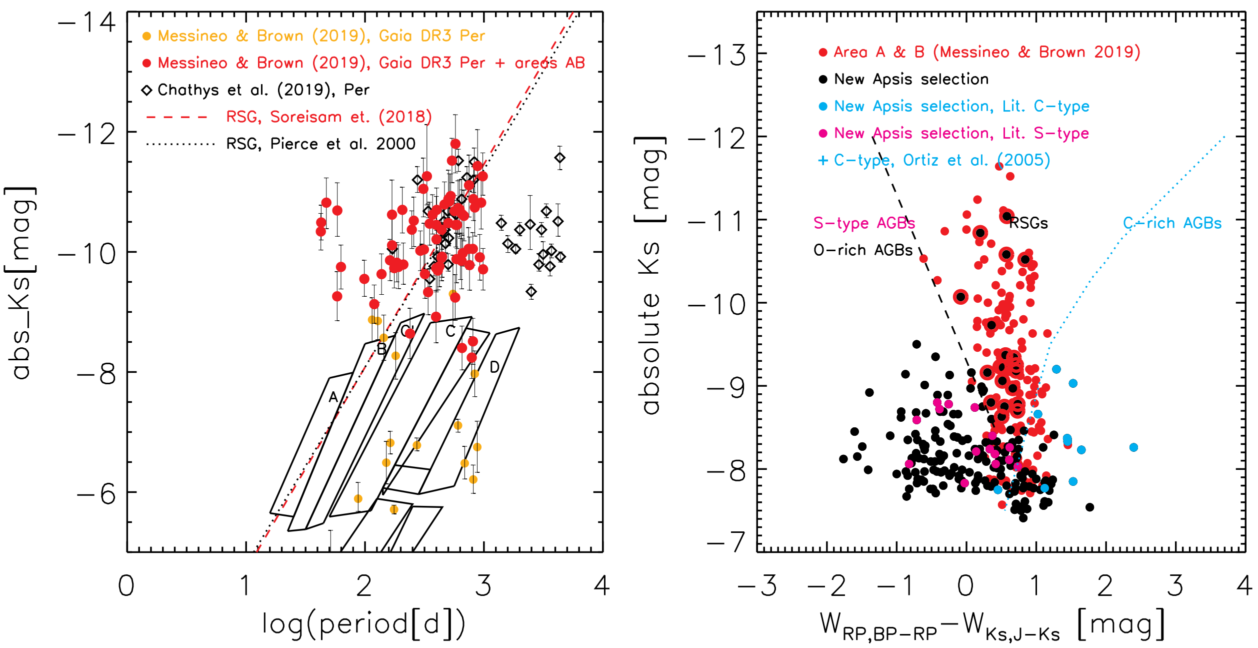

Fig. 4. Right panel: This is a remake of Fig. 7 in Messineo (2023). Absolute K_s magnitudes versus Gaia DR3 periods (log(P)) for the Gaia variables in the catalog of Messineo & Brown (2019) (orange and red filled dots). Superimposed with diamonds are the periods of Chatys et al. (2019) calculated with 50 years of data, which also reveals the LSP periods of RSGs. As indicated in the legend, the period-luminosity relations by Soraisam et al. (2018) and Pierce et al. (2000) are also displayed. **Left panel:** This figure is similar to Fig. 8 in Messineo (2023). Red filled circles represent the absolute K_s magnitudes versus the extinction-free color $W_{\rm RP,BP-RP} - W_{\rm K_S,J-K_S}$ of stars from area A & B (highly-probable RSGs) of Messineo & Brown (2019). Filled dots colored in black, magenta, and cyan represent the O-rich, S-type, and C-rich AGBs analyzed by Messineo (2023). The black dots that are red-encircled represent the 20 new RSGs that Messineo (2023) detected using APIS parameters. The long-dashed line separates the bulk of O-rich AGBs from the sequence of known RSGs, while the cyan-dotted curve separates the O-rich and C-rich stars (Abia et al. 2022).

should be verified.

About 800 RSGs have been identified using Gaia data, however there should be between 3 and 5 thousand RSGs in the Milky Way! Where are they?

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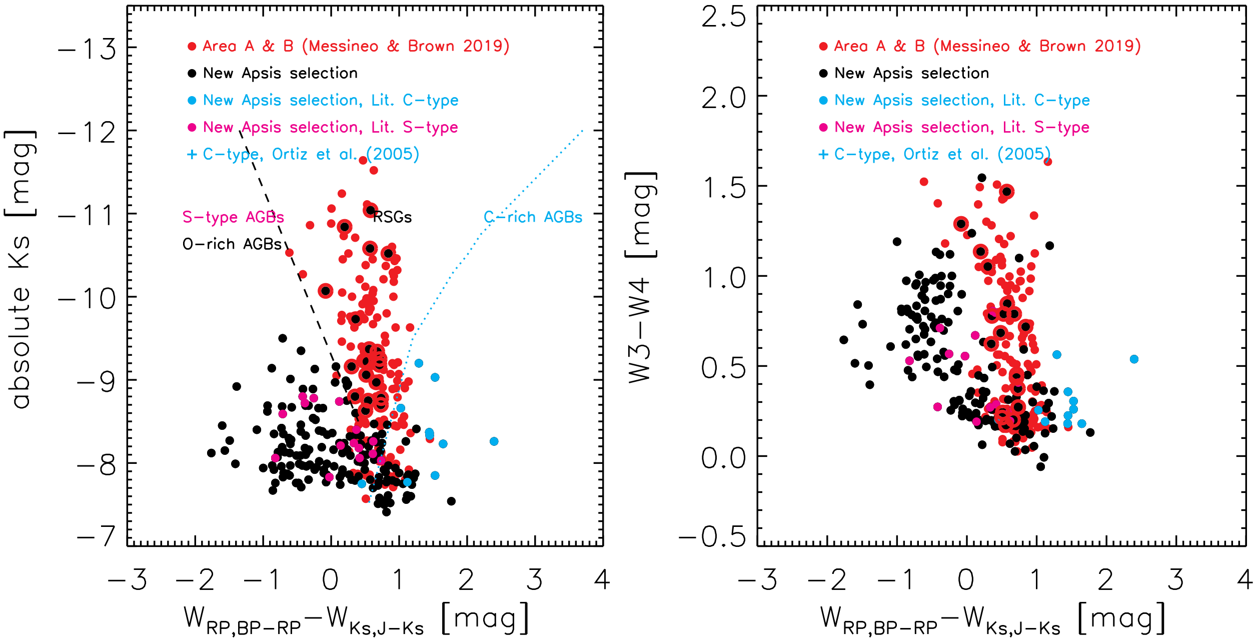

Fig. 5. Right panel: This is similar to Fig. 8 in Messineo (2023). Red filled circles represent the absolute K_s magnitudes versus the extinction-free color $\mathrm{W_{RP,BP-RP}}-\mathrm{W_{K_S,J-K_S}}$ of stars from area A & B of Messineo & Brown (2019). The O-rich, S-type, and C-rich AGBs are shown with filled dots colored in black, magenta, and cyan, respectively. The black dots that are red-encircled represent the 20 new RSGs that Messineo (2023) detected using APIS parameters. **Left panel:** The WISE W3-W4 colours versus the extinction-free colours $\mathrm{W_{RP,BP-RP}}-\mathrm{W_{K_S,J-K_S}}$. Symbols are as in the left panel.

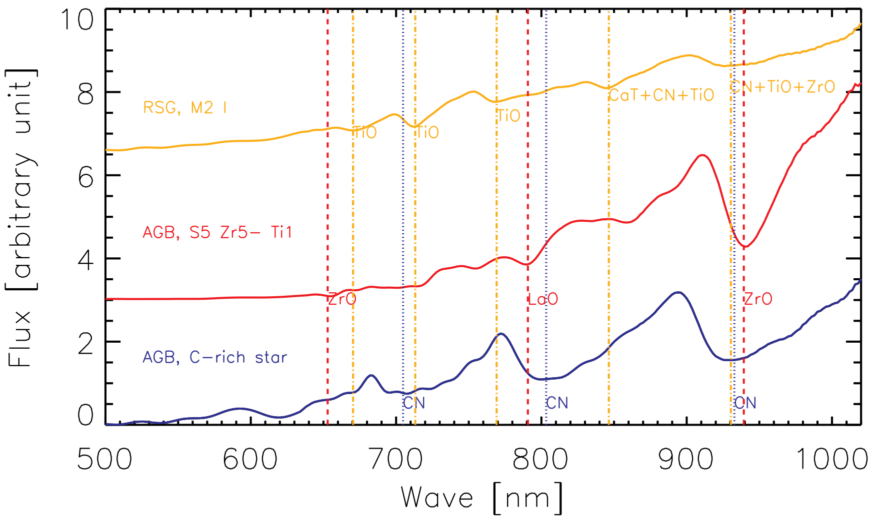

Fig. 6. Three examples of Gaia DR3 BPRP spectra are displayed. The top spectrum in orange shows an M2I star, the middle red spectrum shows an S5 AGB star, and the bottom blue spectrum is from a C-rich AGB star. The vertical lines mark typical absorption features seen in M0-M2 O-rich stars (orange dotted-dashed lines), in late S-stars (red long-dashed lines), in C-rich stars (blue dotted lines)

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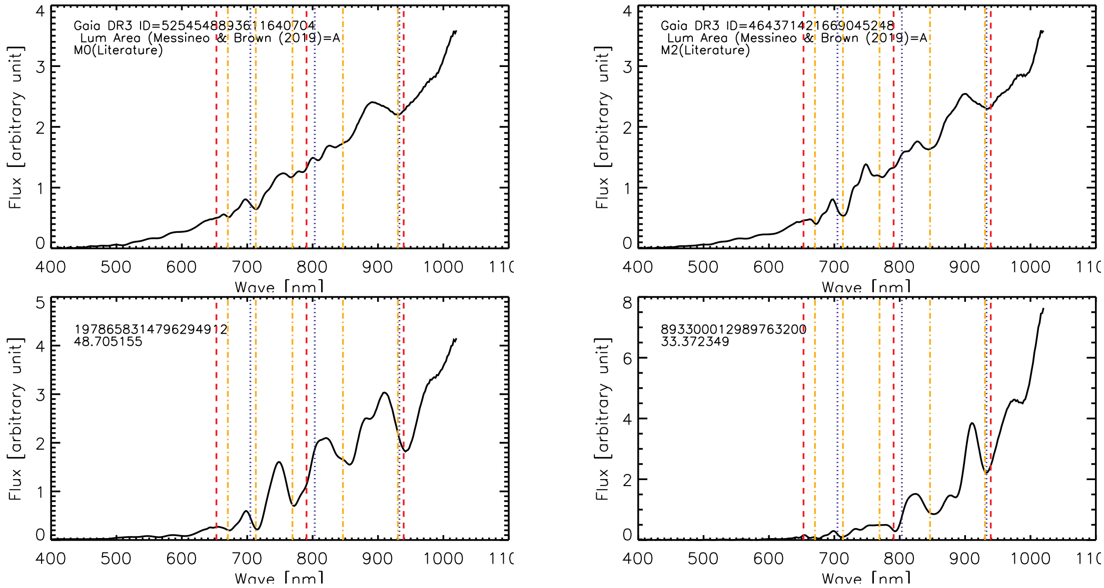

Fig. 7. Gaia DR3 BPRP spectra of M-type stars. The upper-left panel shows an M0 star, the upper-right panel an M2, the lower-left side an M5, and the lower-right panel an M9 star. Vertical lines are as described in Fig. 6.

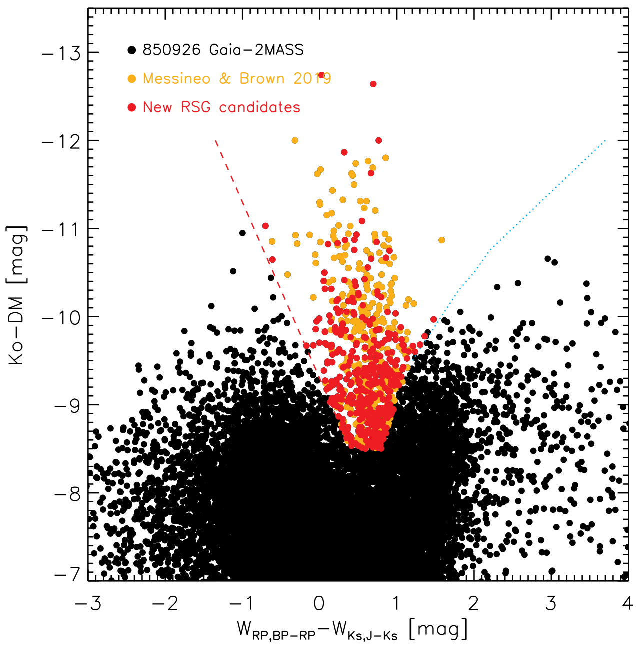

Fig. 8. "In the Herz of Gaia". Absolute K_s magnitudes are plotted versus $\mathrm{W_{RP,BP-RP}} - \mathrm{W_{K_S,J-K_S}}$ colours. In this diagram, two curves are drawn to roughly indicate two separation lines between C-rich and RSGs (cyan), and between O-rich and RSGs (red) (Abia et al. 2022; Messineo 2023). 730 candidate RSGs (2MASS-Gaia matches) are located in the cone enclosed by the two curves and have $M_{\mathrm{K}} < -8.5$ mag and $\mathrm{W_{RP,BP-RP}} - \mathrm{W_{K_S,J-K_S}} < 4$ mag. 415 new candidate RSGs remain (red points), downsized to 330 after some cleaning, as 315 candidates are already included in the list of Messineo & Brown (2019) (orange points).

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