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Hidden knowledge in the Milky Way

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in 1970

Contents

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Abstract

Here is proposed the creation of a catalog of known Galactic red supergiants (RSGs) based on Gaia DR3 data. The catalog of RSGs by Messineo & Brown (2019) will be revised and used as the training set for extracting new RSGs. Furthermore, several $1^\circ \times 1^\circ$ *fields across the Galactic plane (*15°*,* 25°*,* 35°*) will be chosen and Gaia DR3 parameters (parallaxes, spectral energy distribution, spectral-types temperatures, metallicity) of all 2MASS infrared bright stars with colors of late-type stars (AGBs and RSGs) will be analyzed, for extracting clean samples of RSGs and for estimating relative stellar counts and surface densities. Eventually, but not less important, new infrared constrains will be derived useful for extracting obscured candidate RSGs.*

1 State of the art and preliminary work: Bright late-type stars in the inner Galaxy

DENIS and 2MASS catalogs were released at the end of the 90's. That was very exciting, we had the first near-infrared image surveys of the entire Galactic plane. Near-infrared data were combined with mid-infrared data from ISOGAL, MSX, and GLIMPSE and the selection of individual Galactic stars based on their energy stellar distribution had started. Amazing work has been carried out since then, to discover that the Galactic disk is full of marvelous bubbles, and that there is an old Bar at the center of the Galaxy. We were searching for tracers, stellar tracers of the Galaxy, to decompose it into basic components. Asymptotic giant branch (AGB) stars and planetary nebulae were the first stellar tracers of the central bar, the stars of the central peanut box.

Nowadays, we have arrived at the epoch of archeoastronomy with millions of parallaxes, radial velocities, and spectra, becoming publicly available and ready to be used, as well as time-series data. The entire book of Astronomy needs to be re-checked, everything has to be recomputed. But still, something is missing, and I am especially referring to the topic that I have mostly followed, i.e., to our knowledge of evolved late-type stars and evolved massive stars in the most obscured and central regions of the Milky Way.

Massive stars allow for a morphological and kinematic mapping of the youngest components of the Milky Way, such as spiral arms and the central 200 pc disk, and it is commonly believed that the galactic Bar is devoid of it. Massive stars are a measure of the youth and thickness of the disk, and they can be used to map variations of chemical abundances in the disk. Among them, RSGs are cool stars with temperatures from 4500 K to 3000 K and ages from 8 to 30 Myr. In the inner Galaxy, uncertain distances and dust obscuration hamper the detection of RSGs, which remain hidden in a sea of AGB stars. AGBs have properties similar to those of RSGs, but lower initial masses and are much older (from 50 Myr to 12 Gyr). In order to study the evolution and morphology of the Milky Way, *it is crucial to distinguish RSGs from AGB stars*, as their spatial distributions are predicted to be different in a barred gravitational potential. Only a few thousand RSGs populate the Galaxy (less than 1,000 RSGs are known and more than 5,000 are expected). But, to enlarge this number a careful analysis of their dissimilarities is required. There is a large amount of Galactic data and recent results to be reconsidered to improve our tools.

Most of the forthcoming spectroscopic surveys (GALAH, 4MOST, LAMOST), and time series (e.g. LSST) will be performed with CCD at optical wavelength, covering only to 0.7-0.9 μm. The new data should allow for a precise classification of individual stars and to build a 3D image of the portion of the Galaxy observed. All the detailed knowledge acquired from the close 2-3 kpc, must, then, be applied to the inner Galaxy, where most of the mass is. This presented study aims to collect new knowledge and to build an infrared transfer function.

1.1 Evolved late-type stars

In this writing, the term "late-type stars" is used to indicate bright evolved stars cooler than 4600 K. They divide in RSGs and AGBs.

RSGs are massive stars ($9 <$ masses < 40 $M_{\odot}$), i.e., stars without a degenerated state in their core, and are typically observed when burning He.

AGB stars are stars of low and intermediate mass (< 9 $M_{\odot}$) which are characterized by two layers of burning matter, He in the inner shell and Hydrogen in the outer shell, while the central core of CO is in an electron-degenerate state.

AGB stars come with different chemistry. Those with masses from 1 to 5 $M_{\odot}$ evolve from an

O-rich envelope ([C/O] < 1) to a C-rich envelope ([C/O] < 1), due to the dredge-up materials that enrich the surface. S-stars are stars in an hybrid state, transiting toward a C-rich chemistry.

Late-type stars are often named with terms indicating their variability type (e.g., Mira, semiregular, irregular, long period variables, and large amplitude variables) or their envelope types (e.g., OH/IR stars).

1.2 How are inner Galactic late-type stars photometrically identified?

A combination of near- and mid-infrared bands allows us to identify mass-loosing late-type stars. The availability of multi-wavelength photometry and improved spatial resolutions (from 18.3 of MSX to a few arcs of GLIMPSE) allows doing that quite straightforwardly nowadays. Interstellar extinction reddens the stellar energy distribution. Mass-loss increases with redder stellar colours, from naked giants to enshrouded OH/IR stars which may have circumstellar extinction even higher than $A_{\rm V}$=40 mag. A good decomposition of the total interstellar extinction must be performed in the two basic components (interstellar and circumstellar). In Messineo et al. (2002) and Messineo et al. (2005), 2MASS, DENIS, MSX, and ISOGAL catalogs were used to successfully extract a sample of obscured SiO masing late-type stars and estimate their intrinsic colours.

Nowadays, the availability of multi-wavelength data allows for a better determination of the Galactic interstellar extinction laws, as well as for good templates of the stellar energy distribution. One can define colors free of interstellar extinction which directly indicate a certain type of intrinsic stellar energy distribution (knowing the class of objects), and even distinguish certain classes of objects. For example, Messineo et al. (2012) analyzed near- and mid-infrared colors of evolved stars in the Galactic plane by using 2MASS and GLIMPSE data. We use the $Q1$ and $Q2$ parameters, which are colors free of interstellar extinction. These parameters represent deviations of infrared color-color data points from the vector of interstellar extinction. It is possible to establish some criteria of selection for a particular inner Galactic class of objects; for example, Wolf Rayet (WR) stars and RSGs. 40% of the known RSGs appears bluer than Asymptotic Giant Branch stars (AGB) and may be identified by their narrower range of $Q1$ and $Q2$. The predictions were successfully tested by Messineo et al. (2016) and Messineo et al. (2017). The color criteria were used to spectroscopically search in the GLIMPSE I North area of the inner Galaxy with 2mass and GLIMPSE data. About 50% of the sample appeared to be consistent with RSGs. Distances, however, remain the biggest issue. For obscured stars, usually distances are inferred using the interstellar extinction as a meter of distances. Kinematic distances are not allowed in the central regions, being the Galaxy characterized by non-circular motion. However, these old photometric selections based on single epoch data appear now inadequate, because biased by a color cut and because based on single epoch measurements. Late-type stars vary often. With the huge amount of new data and library recently developed, and machine learning method, it is time to cross-correlate all available information.

1.3 An infrared catalog of known RSGs, mostly optically visible

In order to build a large scale view and history of the Milky Way, I spend a few years making a compilation of know Galactic RSGs from the literature. The catalog comprises about 1400 known candidate RSGs, which appeared in the literature at least once as class I stars (Messineo & Brown 2019); most of the entries were already included in the spectroscopic list by Skiff (2014). The infrared photometric catalog was crossmatched with Gaia data EDR3 (Messineo & Brown 2021), and good distances and luminosity were inferred for 966 stars. There is a tail of 110 stars (11%) brighter than the AGB luminosity limit (Mbol=-7.1 mag); at least 49% of the stars are brighter than Mbol=-5.0 mag and earlier than M4, which means they are more massive than 7 $M_{\odot}$, making them likely RSGs. Unfortunately, 28% of the sample appears to have luminosity below the tip of the red giants. By reordering it, a clean sample of RSGs is obtained. This nearby training set is a golden key for unlocking the inner Galaxy.

1.3.1 The luminosity-temperature relation

In Messineo & Brown (2019), the average magnitudes of RSGs per spectral type are derived, and a revision with EDR3 Gaia data is made by Messineo & Brown (2021). Interestingly, the stellar bolometric magnitudes appear to linearly correlate with the stellar temperatures, as shown in 1. This is a remarkable relation because it may allow astronomers to use RSGs as indicators of distances.

1.3.2 The period-luminosity relation of RSGs

A well-studied sample of variable RSGs is listed in the work of Chatys et al. (2019) and Kiss et al. (2006), with data covering 61 years of observations. The authors analyzed data from the AAVSO archive to determine the stellar periods. RSGs may have a short period (100-1000 d) as well as a long period (> 2000 d), as already seen in bright Mira AGBs. The periods of Galactic RSGs pulsating in their fundamental mode are distributed around the relations derived by Soraisam et al. (2018). The RSG period-luminosity of stars pulsating in the fundamental mode exists and appears to be independent of metallicity. In the Milky Way, it is particularly difficult to determine it because of the small amplitudes, extinction, and uncertain distances.

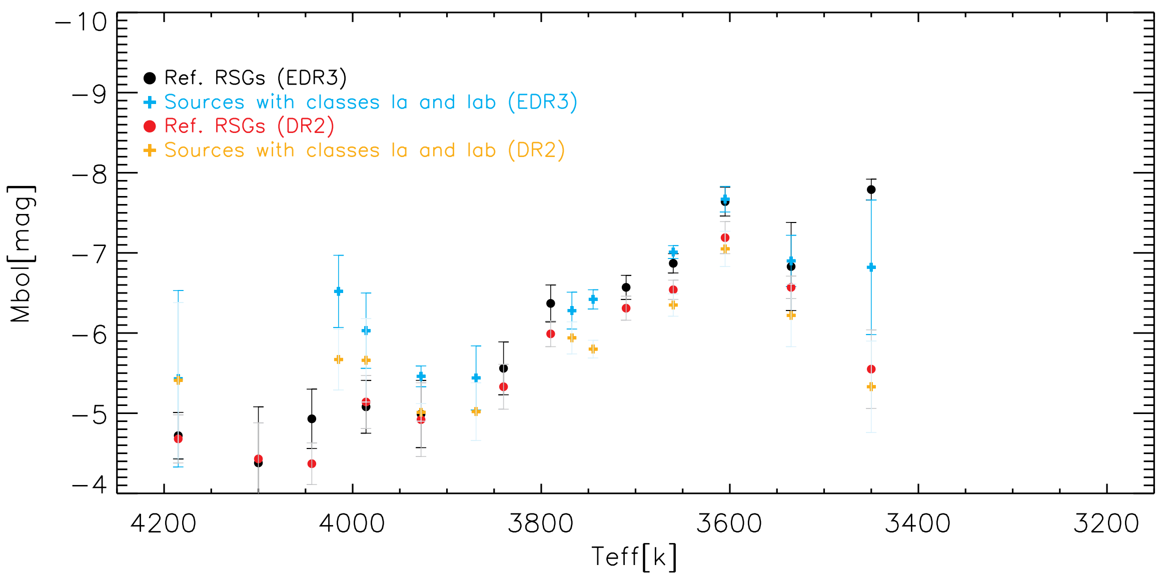

Figure 1: *This Figure is taken from Messineo & Brown (2021) ans is an updated version of the figure number 7 appearing in Messineo & Brown (2019). The average M_{bol} values per spectral type are plotted versus the $T_{\rm eff}$ values. The average M_{bol} values estimated with distances from Bailer-Jones et al. (2021) are used. Black filled circles indicate the M_{bol} values with EDR3 data for the sample of reference RSGs (the M_{bol} with DR2 values are shown in red). Cyan crosses show the average M_{bol} values obtained with EDR3 data for class Ia and Iab stars (for comparison, the previously M_{bol} with DR2 values are shown in light orange).*

Furthermore, RSGs have multiple periods, and often the algorithm used to analyze the periodicity may only yield the highest power frequency, which does not necessarily correspond to the fundamental mode.

The fundamental mode pulsators in Chatys et al. (2019) appear to fall onto the period-luminosity relation found in M31 by Soraisam et al. (2018), but the temporal baseline is 60 years. Baselines of a few years, such as those delivered by Gaia, will allows to determine only the short periods, and may have a period uncertainty of more than 100 d as Fig 2 suggests.

While the periods of RSGs range from 100 to 1000, similarly to Mira AGB stars, the amplitudes of Galactic RSGs are smaller (< 0.8 in G-band) than those of Mira AGBs (up to 8 mag). Therefore, *amplitudes are a very useful tool to separate RSGs from AGBs*; furthermore, amplitudes can be easily estimated. About 10% of the stars in Messineo's catalog are flagged as long-period variables (Holl et al. 2018). Those variables coincide with later spectral types from K5 to M7 (Messineo & Brown 2020); their average variation in G-band is 0.51 mag with a dispersion around the mean of 0.38 mag, as shown in Fig. 2.

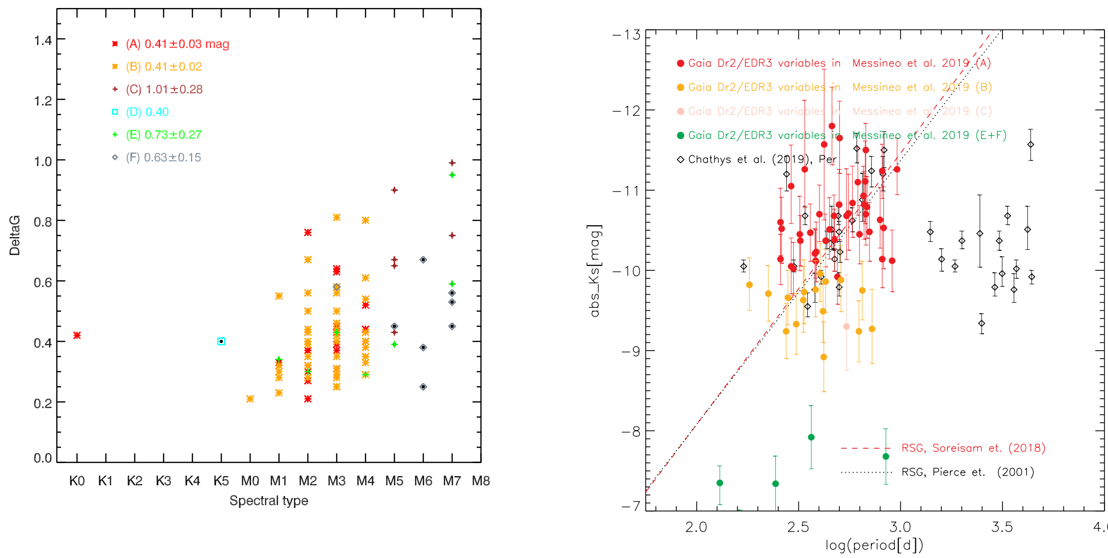

Figure 2: Right panel: *As in Messineo & Brown (2020), differences beween the maximum and minimum magnitudes measured in G-band versus spectral types. The legends list the average ΔG measured in the areas of the HR-diagram defined by Messineo & Brown (2019) (from A to F).* **Left panel:** *M_K values vs. periods of Galactic RSGs. Periods are from Chatys et al. (2019) and are marked with black diamonds. Gaia variable late-type from the catalog of Messineo & Brown (2019) are marked with filled circles in red. The distances are from Gaia EDR3 (Messineo & Brown 2021).*

1.4 Spectroscopic identification of RSGs

A large amount of optical spectroscopic surveys (Galah, LAMOST, 4MOST) at high and medium resolution is soon becoming available. This will constitute **a great test-bed for late-type stars**, to extract the useful differentiating properties for the inner Galaxy where most of the Galactic mass is located.

The GALAH survey is made with the HERMES detector on the Anglo-Australian Telescope and will release more than 1 million spectra of Galactic southern stars at R=28,000 in the 4700 to 7600 nm (e.g. Sharma et al. 2020). The 4MOST detector, installed on the ESO/Vista telescope, will survey the sky to acquire more than 20 million spectra at R$\approx$ 5000 (from 390 to 1000 nm) and R$\approx$20,000 (from 395 to 456.5 nm & from 587 to 673 nm) of southern stars, starting on 2024 (e.g., de Jong et al. 2012). Gaia, LAMOST, and 4MOST are particularly useful because, by covering till 1 μm, they provide a bridge between the study of the nearby regions and the central Galaxy.

Since late-type stars are cold, they are naturally brighter at infrared light, where extinction is about 10 times lower than at optical wavelengths. Infrared detectors allow us to penetrate the inner Galactic regions. However, the spectra of RSGs and AGBs may appear very similar, and large spectral coverage and high-resolution are required to distinguish them. Usually, the strength of CO band-heads at 2.29 μm and the shape of the continuum, which changes due to water vapor absorption, are used to detect RSGs. However, in about 7% of RSGs water vapor is also seen. Furthermore, single epoch K-band observations alone do not allow to distinguish RSGs from all subtypes of AGB stars. While Mira AGB variables are easily identified by their strong water absorption, S-type stars may look very similar to RSGs. Little is also known about the spectral appearance of super AGB stars (s-AGB) stars. AGBs are far more numerous than RSGs. An in-depth spectroscopic study of these bright luminous late-type stars is essential for the proper construction of the Galactic luminosity functions of AGBs and RSGs, expecially for the central regions, where parallaxes are not available.
Recently, Messineo et al. (2021) analyzed low-resolution spectra (R=2000) of late-type stars covering from 0.7 to 2.4 μm, and identified five lines correlating in strengths with the stellar luminosity (from 1.16 μm to 1.29 μm due to Fe, Ti, Mn, and Ca). This is very promising as these atomic lines help us to distinguish RSGs from AGBs in the inner Galaxy.

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2 Research plan, including proposed research methods

2.1 Anticipated total duration of the project

Three years.

2.2 The Ultimate Objective

The work aims to optimize our knowledge on classification of Galactic late-type stars. With a comparative method, the optical properties and infrared of RSGs and AGBs stars will be revised. The new findings at optical wavelengths should be translated at infrared wavelengths to define a new strategy to distinguish RSGs from AGBs and to build a catalog of candidate RSGs in the inner Galaxy. Such a catalog may serve as the efficient input for follow-up spectroscopic surveys. Such a catalog, alone, may provide a direct evidence for a different distribution on the Galactic plane of the two categories of stars. *It is a key project for the still hidden formation history of the Milky Way. Where are the central Disk high-velocity RSGs? is there a population of RSGs populating the Galactic bar?* The distribution of RSGs may be a step function of age, and the low-end mass, 8-9 $M_{\odot}$, could be populating the Bar. Stars of different ages are distributed differently on the Galactic plane. It may be misleading to talk about the initial mass function of RSGs, without being able to clearly distinguish RSGs from AGBs.

2.3 Work program including proposed research methods

The money here request should serve to finance three years of work.

- The first step (during the first and the second year) is to review the properties of nearby RSGs. The catalog of 1400 known bright luminous late-type stars of Messineo & Brown (2019) will be updated with distances and parameters (Temperatures, gravity, metallicity, periods, amplitudes) released from the DR3 Gaia data. As in Messineo & Brown (2019), this will be a fast compilation soon available to everybody for more detailed analysis.
  The parameters of the 470 million stars with Gaia DR3 BP/RP spectra can be exploited to extract new RSGs.

- The second step (during the second and the third year) is to define reference stars in fields a moderate interstellar extinction which are easily accessible at both optical and infrared wavelengths. Reference stars (AGBs and RSGs) with known parameters will be the training set. Distances, extinction, luminosity, bolometric corrections, and mass-loss will be estimated. Improved infrared diagnostics to identify new RSGs will be established. Surface density per stellar type will be estimated.

- New candidate RSGs (without parallaxes) will be also extracted and made available to everyone for high-resolution infrared spectroscopy. Infrared spectroscopy is still quite expansive, and a detection rate of 80% is preferable for targeted surveys for good use of telescope time. A multi-slit spectrograph still requires a pre-selection of targets. Blind surveys are interesting, but they may only carried out in small selected areas of the sky.

2.3.1 First step: Revised catalog of RSGs based on DR3

A new version of the Gaia data release, DR3, will be released on the upcoming June, 13th, 2022[1]. Besides the updated parallax values, the new release will provide new products. Astrometry parameters and source classification for 1.59 billion sources will be released, radial velocities from 33 million, as well as astrophysical parameters (spectral types, Teff, logg, [M/H],

[1] https://www.cosmos.esa.int/web/gaia/dr3

extinction) for 470 million objects based on the low-resolution BP/RP spectra. An updated catalog of variables will be also released, from 86,000 LPV in DR2 to 1,700,000 in DR3. The first catalog of binary parameters with 813,687 objects will be released. Light curves for 1,720,588 late-type stars.

From a compilation of 1400 stars listed in the literature as a possible RSGs, Messineo & Brown (2019) found 889 sources with good Gaia DR2 parallaxes, while Messineo & Brown (2021) retrieved 966 good Gaia EDR3 parallaxes. The upcoming DR3 release (1.5 billion sources) may have parallaxes for most of the 1400 candidates in Messineo's catalog. Furthermore, the Gaia DR3 by delivering temperatures, spectral types, and gravity of 470 million stars with low-resolution BP/RP spectra will provide the first Gaia selected catalog of RSGs. Stars with $[M/H] < 0.5$ dex and logg < 1 cm s^{-2}, cool and with G-band amplitudes < 0.5 mag should be regarded as RSGs. This test sample may already allow us to prepare for the first Gaia initial mass function of Galactic RSGs.

The sample of reference stars Galactic RSGs studied in Messineo & Brown (2019) allowed us to obtain, for the first, estimates of the average absolute magnitudes of RSGs per bin of 1 spectral type and has revealed the existence of a clear relation between stellar temperatures and stellar luminosities, making them suitable direct indicators of distances for extragalactic studies. The DR3 release will allow to refine the average magnitudes per spectral type and the luminosity-temperature relation.

A revised catalog with a summary of properties of known RSGs (e.g. average magnitudes per spectral type, luminosity-temperature, luminosity-period, and luminosity-gravity relations) will be delivered within the first year of the fellowship with a publication.

2.3.2 Second step: The two extreme ends and contaminants

Have we learned to go down in luminosity and with confidence separate AGBs from 8$M_\odot$ RSGs? and where are they? being old, they could be distributed differently than massive RSGs; for example, they could be populating the long Bar as AGB stars do. Are the low-mass end RSGs tracing the near-end side of the Bar? This important issue requires careful analysis, based on secure stellar classes and spectral types.

The second year of the fellowship should be spent comparing the properties of bright late-type stars, i.e., super AGB stars (s-AGB), S-stars, Mira-AGBs, and RSGs in a few designed fields of the Galaxy. Gaia spectral types and Gaia BP/RP spectra will allow a precise study of the stellar energy distribution. A large amount of broad-band photometry is already available from optical to infrared (e.g. SDSS, PANSTARRS, 2MASS, WISE). High-resolution spectra from LAMOST, 4MOST, and APOGEE could supplement the Gaia low-resolution spectra and provide spectral diagnostic in the red part of the spectrum. Existing catalogs of late-type stars will be used to define/check the set of reference stars, for example the LAMOST S-stars catalog by Chen et al. (2022), the compilation of Galactic AGBs by Suh (2021). Luminosities will be estimated, and periods, amplitudes, and spectroscopic parameters will be used to estimate the luminosity class. Relative counts of bright late-type stars (brighter than the tip of the red giant branch) may be estimated in each studied field.

Fields $1^\circ \times 1^\circ$ in size will be selected along the Galactic plane (e.g., 45°, 35°, 25°, and 15°) at moderate extinction ($A_{\rm K}$=0.8-1.2 mag), where the surface density of each type can be estimated. In each field, clean samples of RSGs, O-rich AGB, C-rich AGB, and S-stars, will be extracted and properties and relative density analysed. All properties will be analyzed in a comparative manner (counts, luminosity ranges, intrinsic colours, amplitudes, periods).

2.3.3 New catalogs of obscured candidate RSGs

From the detailed analysis in the selected fields, with the resulting tables in hands and count ratios, it may be possible to obtain improved and more realistic infrared diagnostics/cuts for RSG selection in the obscured inner Galaxy ($-10^\circ <$ long $< +10^\circ$), where parallaxes are missing; for example, by building guesses on distances and intrinsic stellar energy distribution, and using any existing information on amplitudes. In summary, candidate RSGs can be extracted and the fraction of contaminants will have an empirical-made function.

2.3.4 Strange objects: Thorne-Żytkow Objects

The period-luminosity diagram is a good diagnostic tool to locate Thorne-Żytkow Objects (e.g. DeMarchi et al. 2021; O'Grady et al. 2020). Those rare objects are the merger product of a binary system with a neutron star. Their appearance resemble RSGs, but there are peculiar chemical signatures in their spectra. There is only one such object in the Magellanic Clouds (Levesque et al. 2014), and it has a large amplitude (> 4 mag), which distinguishes it from other RSGs. Bright objects lying in the RSGs sequence with large amplitudes must be considered for high-resolution spectroscopy. In recent years, these strange objects have earned more attention due to the new possibility to measure gravitational waves. It is possible that the LSST survey and Gaia survey may unveil more of them, as about 100-200 such objects are expected to populate the Milky Way (e.g. DeMarchi et al. 2021).

3 Handling of research data

Tables and catalogues will be described in referred publications, and therefore stored in the Journal archive. Furthermore, the astronomical data products will also be made available via repositories on github (github gives a warranty of 20 years on free repositories) and/or on the astronomical Vizier database $http : //vizier.u - strasbg.fr/$.

4 Relevance of sex, gender and/or diversity

Astronomers do not discriminate in gender, and race. Despite the great technical skills, we do not let the new era hybridize us, keeping high our human spirit.

At the age of 51 years, Maria returned back to Europe. Currently, She is applying for several astronomical positions, as well as for financial supports for her research. COVID is making the re-entering process quite slow, and now the Ukrainian war is (at least temporarily) splitting the unified world of scientists.

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6 Relevance of project to research career objectives

Despite being a simple program, devoted to create an updated catalog of RSGs with collection and comparison of existing data, the program will contribute to a fundamental understanding of the history of our Galaxy evolution. The main aim is to improve the photometric identification of RSGs and AGBs, using new available information, for example on variability and extinction.

It is believed that the Bar is old and dissolving only populated by giants and AGB stars. Stellar migrations may account for a small population of bright RSGs populating the Galactic Bar. Also one need to recall that what today we call RSG population is only the bright tail of such a population (12-25 $M_{\odot}$), as we are still unable to locate RSGs of 8-9 $M_{\odot}$ which are supposedly much more numerous.

7 Curriculum Vitae

Maria Messineo

Maria Messineo has extensively worked on Galactic stellar populations, with major focus on Galactic structure and evolution. She started her science activity in 1996, when she builded a database of existing photometric data for 61 Globular Clusters to determine new metallicity indicators. During the PhD she analyzed a sample of color-selected AGB stars, and carried a search for SiO masers. The maser kinematics revealed for the first time a clear stellar component belonging to the central 200-pc nuclear disk of the Milky Way. From 2004 Maria is actively studying massive stars in the Galactic plane, mainly at infrared wavelenghts. In particular, she has experimented several methods of photometric source selection, and reported a successful survey of inner Galactic RSGs. She is currently learning about time series to implements more complex, but efficient selections. Due to COVID and war, she has self-sponsored herself for this last semenster.

Education
PhD in Astronomy 2004, Leiden Observatory, Netherlands
Master in Astronomy 1997, University of Bologna, Italy

Appointments
11/2021 - present : USTC affiliated, and Freelancer in Brandenburg
10/2015 - 11/2021 : Researcher at USTC
10/2010 - 10/2015 : Researcher at the Max Planck Institut fuer Radioastronomy
10/2009 - 09/2010 : ESA fellow
07/2007 - 07/2009 : Postdoctoral researcher at the Rochester Institute of Technology
09/2004 - 07/2007 : ESO fellow
12/1999 - 06/2004 : PhD at the University of Leiden
04/1999 - 11/1999 : Research Assistant at the Astronomical Observatory of Bologna
06/1998 - 11/1998 : Summer Research Assistant at the Space Telescope Science Institute