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Hunting for massive late-type stars in the inner Disk of the Milky Way.

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Abstract

The census of Galactic red supergiants (RSGs) is highly incomplete, mainly because of our position in the Disk and, consequently, of high dust obscuration. More than hundred new RSGs have been recently discovered in massive clusters (e.g. RSGC1, RSGC2, and RSGC3) located between 25° and 30° of Galactic longitude, where the near-side of the Bar ends and meets the spiral arms. Starburst clusters containing RSGs are easily detectable, but rare. It is likely that there is a sea of sparse RSGs in the inner Galaxy. Indeed, we have been analyzing a sample of about hundred distant-obscured luminous late-type stars in isolation. Stars were selected as candidate RSGs from the GLIMPSEI North catalog by using the color criteria of Messineo *et al.* (2012). The infrared spectra unveil an extraordinary large rate of detections ($>$ 61%) (Messineo *et al.*, 2016). Our new recent results suggest the presence of an extended structure, perhaps a stellar ring surrounding the central Bar.

1 Introduction

Red supergiants (RSGs) are among the brightest stars at infrared wavelengths. With currently available facilities, they are detectable in external galaxies to distances of a few Mpc (Lardo *et al.*, 2015). By losing mass at high-rates they enrich the interstellar medium; eventually, they explode as supernovae and create marvelous compact objects.

Stars with initial masses between 8 to 40 $M_\odot$ go through the RSG evolutionary phase. Their path on the theoretical plane (effective temperature, $T_{\rm eff}$, versus luminosity) is not well established yet; for example, the number of loops from red to blue they pass through and their final stellar fates are uncertain, because strongly influenced by metallicity, mass-loss, and rotation, all of which are difficult to model.

RSGs have ages from 5 to 30 Myr. In particular, a simple stellar population with ages of 10-30 Myr is dominated at infrared by RSG light (Figer *et al.*, 2006). About a thousand RSGs are currently known in the Milky Way, while more than 5000 are expected (Messineo *et al.*, 2016, 2012; Gehrz, 1989). Similar in colors to asymptotic giant branch stars (AGBs), RSGs are difficult to distinguish from giants without distance information, unless they are in clusters. Thanks to infrared large scale mappings of the Galactic plane, such as 2MASS, MSX, and GLIMPSE[1], two massive starburst clusters rich in RSGs (RSGC1 and RSGC2) were detected by Figer *et al.* (2006) and Davies *et al.* (2007). They appear as large overdensities of solely RSGs, i.e. a large number of infrared bright stars within a small volume (e.g., 1-3 pc^3, Pfalzner, 2009), because in K-band blue supergiants drawn from the same simple stellar populations are about 4 magnitudes fainter than RSGs. After about 10 years of searches, we have found about hundred RSGs in inner Galactic RSGC clusters (e.g., RSGC1, RSGC1, RSGC3, RSGC3, and RSGC5, Figer *et al.*, 2006; Davies *et al.*, 2007; Clark *et al.*, 2009; Negueruela *et al.*, 2010, 2011). Large complexes of RSGs have been found in the surroundings of these massive RSGCs (Negueruela *et al.*, 2010, 2011). These RSGCs with longitudes between 25° and 30° are located where the near-side of the Bar ends and meets the spiral arms. It appears clear that RSGs are a key ingredient to understand Galactic structure, and that we have only seen the peak of the iceberg.

Intrigued by these findings, we have embarked on a the search for Galactic RSGs. In Sect. 2 we summarize some of our results on RSGs in clusters. Enriched by new considerations on infrared colors of late-type stars (Sect. 3), we realized that with some estimate of distances it was possible to search for RSGs in isolation, as described in Sect. 4.

2 A search for RSGs in stellar clusters

In the last decade, more than 3000 candidate stellar clusters have been identified in the Galactic plane (e.g. Mercer *et al.*, 2005). A combination of observations at near- and mid-infrared wavelengths allows to select candidate massive clusters (e.g., Messineo *et al.*, 2009). Typically, it is assumed that

[1]2MASS stands for Two Micron All Sky Survey (Cutri *et al.*, 2003), MSX for Midcourse Space Experiment (MSX) (Egan *et al.*, 2003; Price *et al.*, 2001), GLIMPSE for Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (Churchwell *et al.*, 2009)

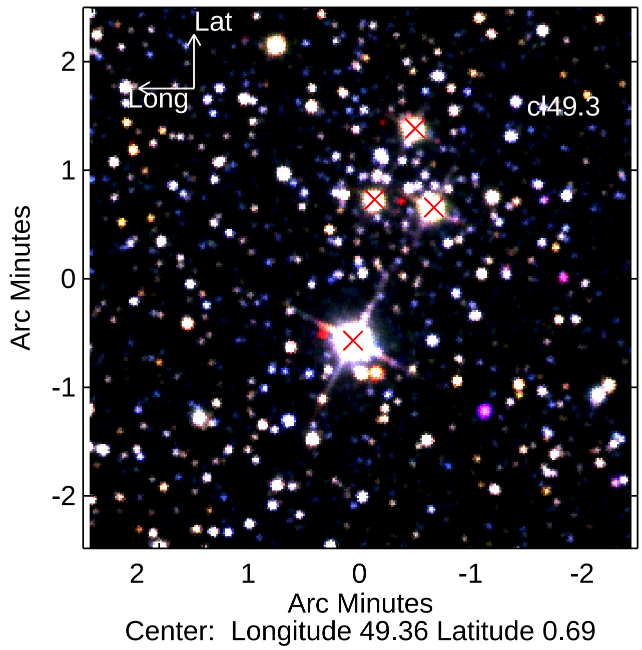

Figure 1: 2MASS JHK composite image of the RSGC cluster cl49.3 (Messineo *et al.*, 2014). At infrared wavelengths, the light of this cluster is dominated by four RSG stars, marked with crosses.

bright massive stars are found in the center of young massive stellar clusters ($> 10^3$ $M_\odot$). By locating small over-densities of stars, dominated by bright and obscured late-type stars (see, for example, Fig. 1), two other clusters of RSGs, one in the Sagittarius-Carina spiral arm at a distance of 7 kpc, and another in the Scutum-Crux arm at a distance of 4 kpc were confirmed by Messineo *et al.* (2014). The RSGs were spectroscopically confirmed in HK band by their low content of water absorption, and strong CO band-heads at 2.29 μm. Difficulties arise when trying to determine distances, since RSGs are not standard candles. However, deep color-magnitudes of the Galactic plane are available from the UKIDSS and VVV surveys[2] down to K=18-19 mag. These datasets allow us to detect a large number of red clump stars distributed along the line of sight of the examined RSGs. In the case of the cluster cl49, a well defined clump sequence appears in the $J-K$ versus K diagram; this sequence allows to derive distances as a function of interstellar extinction (A_K). Eventually, the RSG distance is the interpolated value at the A_K value of the RSG. The accuracy of the measurement depends on the slope and width of the clump sequence, but it can be as good as ~ 0.15 mag (Messineo *et al.*, 2014).

3 2MASS-GLIMPSE colors

A combination of observations at near- and mid-infrared wavelengths is a powerful tool to identify massive mass-losing stars. Messineo *et al.* (2012) compared 2MASS-GLIMPSE colors of a large variety of known Galactic stars – Wolf-Rayet stars, luminous blue variables, AGBs, and RSGs. The authors use two extinction free colors $Q1$ and $Q2$ to analyze the distribution of various type of stars. In the $Q1$ versus $Q2$ plane there are regions preferentially populated by a specific type of stars. Indeed, 46% of the analyzed RSGs have $0.1 < Q1 < 0.5$ mag and $0.5 < Q2 < 1.5$ mag (see Fig. 2).

4 A sparse sea of RSGs

We used the results of Messineo *et al.* (2012) to select candidate obscured distant late-type stars, i.e. stars with 2MASS-GLIMPSE colors typical of RSGs (right panel of Fig. 2), selected to be brighter than $M_{\rm bol} = 6.1$ mag for an initial hypothetic distance of 4 kpc. The spectroscopic infrared search was carried out with the 4m NTT telescope located on La Silla. With 94 observed targets and a detection rate of at least 61%, we have increased the number of RSGs in the searched area by 25% (Messineo *et al.*, 2016, and references therein).

Detections of Galactic RSGs are of primary importance to understand star formation that occurred 4.5-30 Myrs ago and Galactic morphology. The XY distribution of the new detected RSGs is shown in Fig. 3. The targets are located in the inner Galaxy between 10° to 60° of longitude; their Galactocentric distances range from 3 to 7 kpc. The spatial extent of the new detected RSGs strengthens the presence of a possible stellar ring surrounding the central Bar, suggested by observations of young star forming regions by Sanna *et al.* (2014). The heights, Z, of the new RSGs, obtained with the IDL routine of Gagné *et al.* (2014), are shown in Fig. 4. By fitting the function $f = 1 - exp(-|Z|/H)$, as in (Olivier *et al.*, 2001), we estimate an height scale, H, of about 57 pc.

For comparison, in Fig. 3 we also illustrate the locations of massive young open clusters ($\sim 10^4$ $M_\odot$). Positions and masses of Quintuplet, Arches, Galactic center cluster, and Cl1806-20 are taken from Figer (2008, and references therein), Cyg OB2, RSGC1, RSGC2, RSGC3, NGC3603, Trumpler14, Westerlund1, Westerlund2, W49A from Messineo *et al.* (2009, and references therein), Cl1813-178 from Messineo *et al.* (2011), Alicante 8 from Negueruela *et al.* (2010), Alicante 7 from Negueruela *et al.* (2011), DBS2003-179 from Borissova *et al.* (2012), Danks1 from Davies *et al.* (2012a), Mc81 from Davies *et al.* (2012b), Perseus OB1 from Pierce *et al.* (2000) NGC7419 from Marco & Negueruela (2013), and VdBH 222 from Marco *et al.* (2014). We note that young stellar clusters with mass estimated larger than 10^4 $M_\odot$ and older than 4.5 Myr – i.e. clusters that host RSG members – are preferentially located in the Perseus arm (Perseus OB1, NGC7419), in the innermost part of the the Scutum-Crux arm (the five RSGCs, Cl1813-178, and most likely Westerlund1). VdBH222 is located at the far-end side of the Bar (Marco *et al.*, 2014). Quintuplet is a few tens of parsec away from the Galactic center and contains one RSG.

Only two of the 94 stars targeted by Messineo *et al.* (2016) are in the direction of a known cluster or candidate cluster (Messineo et al., 2016b). It is likely that there is a sea of RSGs sparse in the inner Galaxy in apparent isolation.

It is likely that the upper part of the mass function will result shallower than previously estimated. For the less obscured part of the Disk ($V < 20$ mag), Gaia parallaxes will allow classification of stars based on precise luminosities and spectroscopy, and, consequently, it will allow a precise revision of the field mass function.

[2]UKIDSS stands for UKIRT Infrared Deep Sky Survey (Lucas *et al.*, 2008), VVV for the VISTA Variables in the Via Lactea survey (Soto *et al.*, 2013)

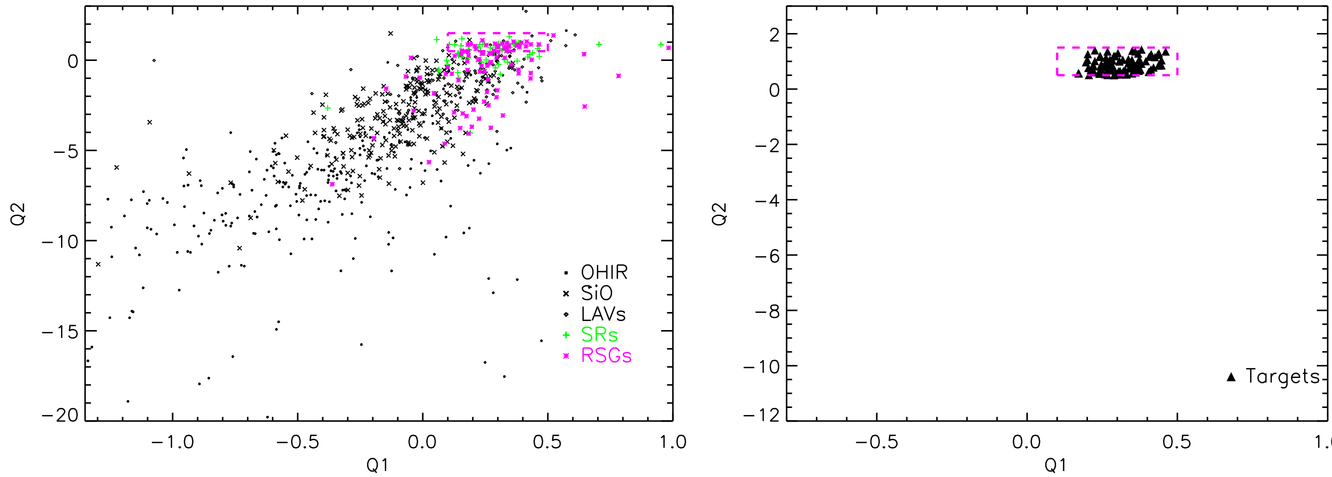

Figure 2: *Left panel:* $Q1$ versus $Q2$ values of known Galactic late-type stars. Dots marks a sample of AGB OH/IR stars (Sevenster, 2002), crosses a sample of Mira-like stars with SiO masers (Messineo *et al.*, 2002, 2004), diamonds mark an additional sample of Mira stars in the vicinity of the Galactic center (Glass *et al.*, 2001), green pluses indicate AGB semi-regular variables in the Baade windows (Alard *et al.*, 2001), and magenta asterisks indicate a sample of RSGs (Messineo *et al.*, 2012, and reference therein). The dashed box encloses 46% of the considered RSGs. *Right panel:* 2MASS-GLIMPSE targets selected for the RSG search by Messineo *et al.* (2016).

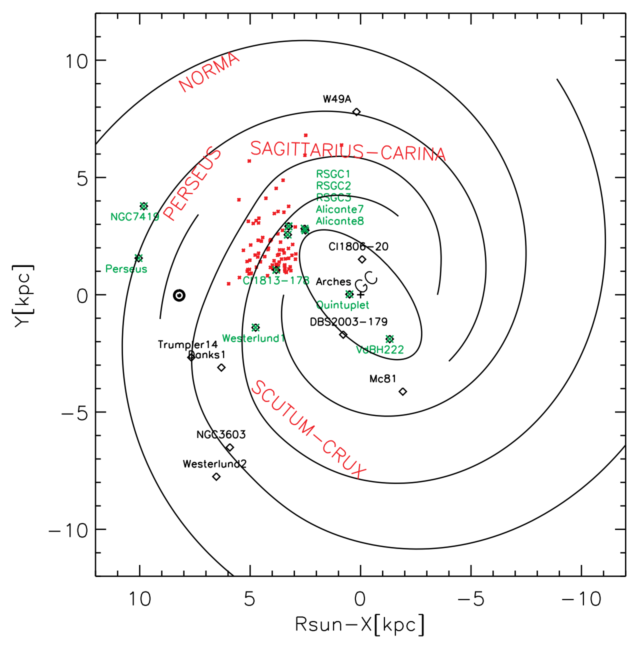

Figure 3: XY view. RSGs from the work of Messineo *et al.* (2016) are marked with red asterisks. For comparison, known massive stellar clusters ($> 10^4$ $M_\odot$) are indicated with diamonds (and those older than 4 Myr with green crosses, see text). Spiral arms are from Cordes & Lazio 2002.

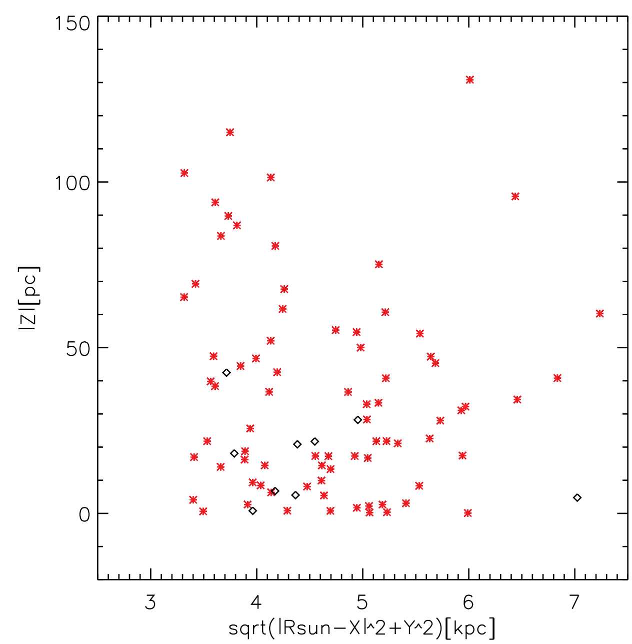

Figure 4: The heights (Z) of the new sample of RSGs as a function of Galactocentric distances. For comparison, values of known massive stellar clusters (10^4 $M_\odot$) are displayed with black diamonds.

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