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A long-term monitoring campaign of Galactic Red Supergiants and the quest for SN premonitory signs

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Abstract

The studies of pre-supernova outbursts have received lot of attention because of their high diagnostic power for the nature of the supernova progenitor and the implications on the structure of the circumstellar medium (CSM) in the immediate surrounding of the exploding SNe. **So far, the study of the outbursts have been mostly confined to archive data of extragalactic SNe**, resulting in a handful of cases in which SN precursors have been securely identified. These 'a-posteriori' surveys have been proved very useful to characterize the diversity of the SNe 'zoo', but **they suffer a bias against the very rich L ≤ $10^5 L_\odot$ population of low-mass Red Supergiants (RSGs) and they lack homogeneous pre-SN data.**

To overcome this limitation, **we assembled a literature-based catalog of a coeval and co-distant sample of 239 galactic RSGs** in the Scutum-Crux region, which gives us the possibility to change the observational paradigm of pre-SN outburst studies.

We launched a long-term monitoring campaign aimed to characterize the multi-color light curves of this large sample of RSGs, to detect late-stage outbursts and to compare them with very recent models of the final phases of low-mass RSGs before SN explosion, thus **possibly predicting core collapse of specific objects before it occurs**. We present this on-going project and some preliminary results.

1. Introduction to Pre-SN outbursts

Bright pre-SN outbursts have already been studied in extragalactic SN progenitors (e.g. Pastorello & Fraser 2019), common in > ~ 20 $M_\odot$ stars (LBV, WR, etc.). **BUT not much is known on pre-SN outburst of 7-15 $M_\odot$ RSGs (precursors of Type IIP/L SNe).**

<u>**Early interacting SNe:**</u>

1. Flash ionization signatures the very first days, then transition IIn -> IIP. Consistent with massloss Mdot=10^{-3} $M_\odot$/yr for 1 yr, too much for standard RSG wind (< $10^{[-8,-5]}$). E.g. SN2013fr (Yaaron+ 2017), SN2013fs (Bullivant+ 2018), SN2020tlf (Jacobson-Galan+ 2022, Fig. 1)
2. **Need for massive ejections at most few years before explosion.**
3. **Pre-SN outbursts of low-mass RSGs are much weaker then SN2009ip-like outbursts !! <u>WE NEED NEARER RSGs !!! (See Fig. 1 & 2)</u>**

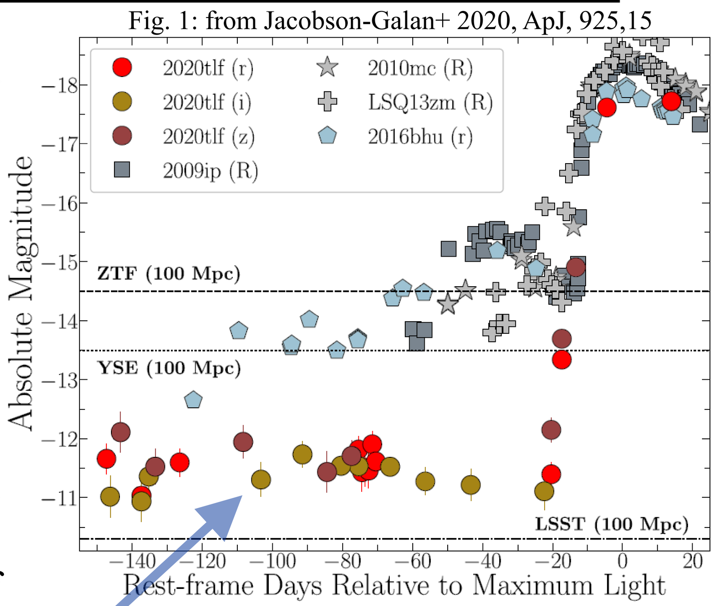


Fig. 1: from Jacobson-Galan+ 2020, ApJ, 925,15

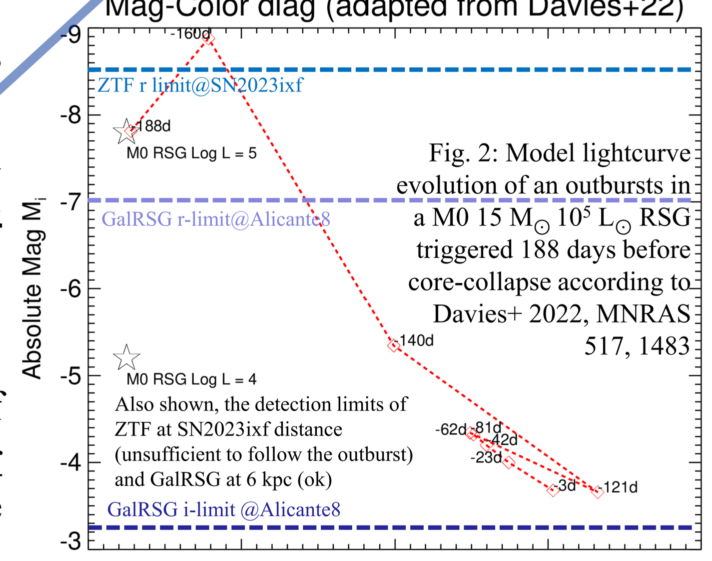


Fig. 2: Model lightcurve evolution of an outbursts in a M0 15 $M_\odot$ 10^5 $L_\odot$ RSG triggered 188 days before core-collapse according to Davies+ 2022, MNRAS 517, 1483

Also shown, the detection limits of ZTF at SN2023ixf distance (unsufficient to follow the outburst) and GalRSG at 6 kpc (ok)

<u>**Why low-mass RSGs undergo pre-SN outbursts?**</u>

- **Nuclear flashes** that ignite dynamical burning of <u>oxygen (>~1000d pre-SN), neon (~200-100d), or silicon (~10-20d)</u> could lead to the ejection of the outer layers of the stellar envelope in the final years to months before explosion (e.g Dessart et al. 2010; Woosley & Heger 2015).
- Alternatively, <u>**late-stage burning phases**</u> **can induce gravity waves** that propagate outwards and inject energy into the stellar envelope, leading to eruptions of ~1 $M_\odot$ worth of material in the final months before explosion (e.g. Fuller 2017; Wu & Fuller 2021).
- **See <u>Fig. 2 and 3</u> for expected optical/NIR emission**

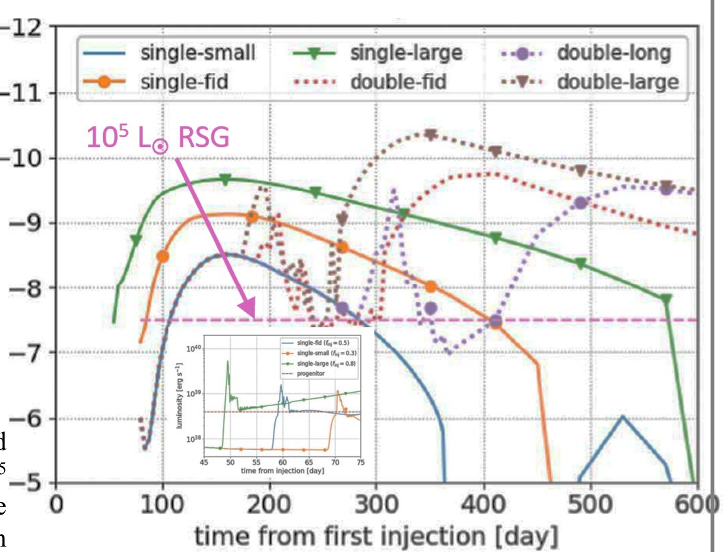


Fig. 3: Model of a long-term Pre-SN outburst R-band lightcurve (single and double injection) in a 15 $M_\odot$ 10^5 $L_\odot$ RSG according to Tsuna+ 2023, ApJ 945, 104. The dashed line is the quiescent emission

<u>!! Pre-SN outbursts in low-mass RSGs may give us the time remaining to the SN !!</u>
<u>But they are faint, we need to go «galactic»</u>

2. The sample of Galactic Red Supergiants

Our sample is made of 2 parts. **Part I includes the 105 RSGs** in the 6 Scutum-Crux arm massive clusters at approx. the same distance (~ 6 kpc) and age (~ 15 Myr). (Davies 2007, Davies+2008, Clark+2009, Neguerela+2011, Neguerela+2010, Gonzalez+2012)

<u>**Scutum-Crux massive clusters**</u>

They are all at ~ 6 kpc, approx. coeval (~ 15 Myr) and within few deg in the sky

Total 105 RSG

Nome	Coord J2000	# RSG	Dist. Kpc (mag)	Mass 10^4 $M_\odot$	Age Myr	Exctinction A(x) in mag							
						V	g	r	i	z	J	H	K
Chi Persei	022200 +570800	6	2.3 (11.8)	0.5-1	12.5	1.8		1.9	1.0	0.7			
NGC 7419	225420 +604854	5	3 (12.6)	0.5-1	14	5.4	5.7	4.0	3.0	2.2			
RSGC1	183757 -065248 (Sct)	13	5.8-6.6 (14.0)	2-4	7-12	23.2	24.7	17.3	12.8	9.6	5.4	3.4	2.3
Stephenson2 (RSGC2)	183920 -060141 (Sct)	26	5.8 (13.8)	2-4	16-20	12.9 11.9 13.4	14.2	10.0	7.4	5.6	3.1	2.0	1.3
RSGC3	184524 −032313 (Sct)	15	6.0 (13.9)	2-4	16-20	15.1	16.2	11.3	8.4	6.3	3.5	2.3	1.5
Alicante 8	183400 −071400	13+10	6.6 (14.1)	1-2	16-20		20.5	14.3	10.6	8.0	4.5	2.8	1.9
Alicante 7	184429 -033002	13+3	6.0 (13.9)	10	16-20	15.1	16.2	11.3	8.4	6.3	3.5	2.3	1.5
Alicante 10	184530 −034000	8+4	5 (13.5)	1-4	16-20	15.1	16.2	11.3	8.4	6.3	3.5	2.3	1.5

Part II of our sample includes the 134 RSGs found in 2012/2016 around the Scutum-Crux arm massive clusters, in the same sector of the Galactic Plane.

Part II: field RSGs

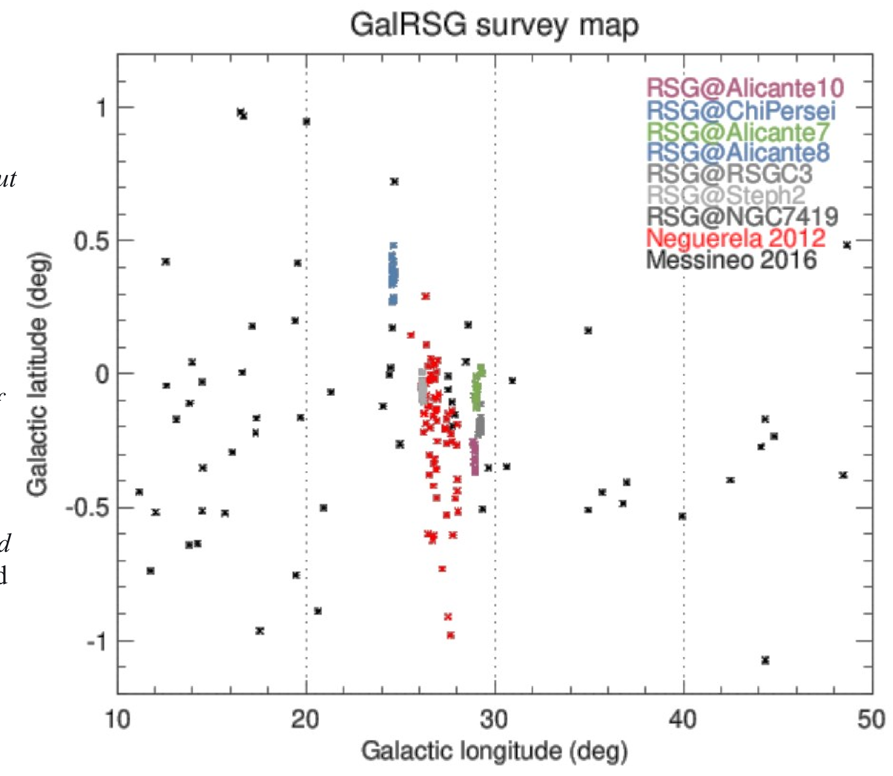
Neguerela+12, +72 RSGs

... Stephenson 2 is not an isolated cluster, but part of a huge structure likely containing hundreds of red supergiants, with radial velocities compatible with the terminal velocity at this Galactic longitude (and a distance ~6 kpc). In addition, we found evidence of several populations of massive stars at different distances along this line of sight.

Messineo+16, +62 RSGs

Discovery of an extraordinary number of red supergiants in the inner Galaxy (we selected the "High probability" list)

Part II: 134 RSGs



<u>Part I+II includes a total of 239 RSGs</u> for which we have luminosities and mass-loss rates from literature. It is the most homogenous sample of galactic RSG ever compiled.

3. The monitoring campaign

The campaign started in 2022 with a pathfinder, and will cover 2023, 2024 and 2025.

<u>**Advantages:**</u>

1. **Higher sensitivity allows us to target mid/low-L RSGs (i.e. the majority) and their precursors.** $10^5 L_\odot$ means M_R ~ -7.5. Absorption may not be a problem
2. **Multi-band optical/NIR homogeneous coverage**, whereas current extragalactic precursors data come from very different instruments/setup or no colors. Eg. ZTF gri-filter survey (started in 2018) only has r-filter data (no color) after 2020
3. **Short and regular cadence**. Need to be few days at most (optimal 1-2 days), whereas current archive extragalactic data are often too sparse
4. **No need of large telescopes**. Small slew overheads.

<u>**Observations:**</u>

- **INAF-REM@LaSilla for RSGs in clusters (Part I)**: 3-yr long term program (2023-2025), 2-day cadence, simultaneous griz-JHK images
- **INAF-VST@Paranal for Field RSGs (Part II):** 2023 and 2024 semesters granted, Sloan iz filters, 5-10 days cadence in 2023, 5 days in 2024
- **C14@INAF-OAPa**: pathfinder campaign in 2022, filler for the high-L RSGs only

<u>**A few preliminary results:**</u>

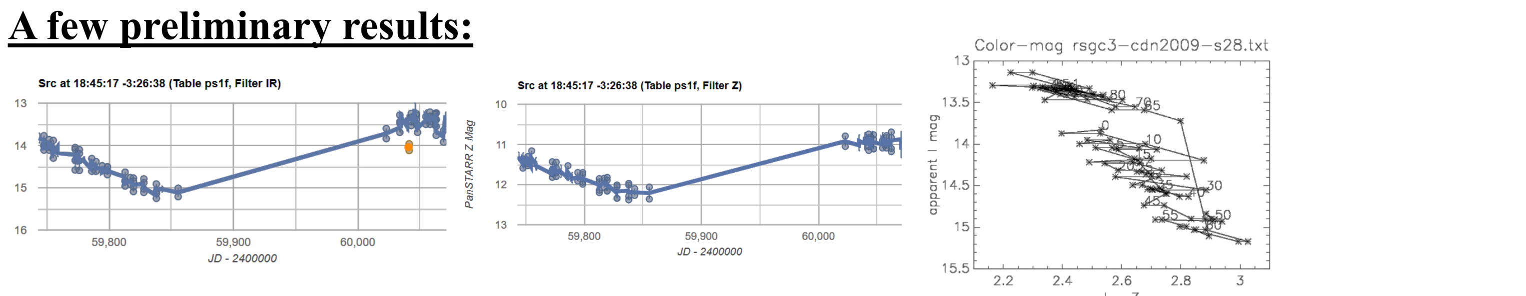


Fig. 5: 2022 and 2023 i- and z-band lightcurve of S28 source in RSGC3 cluster and color-magnitude plot. This seems a typical case of RSG opacity-driven pulsations. 2024 and 2025 observations will be added to characterize the long-term variability.

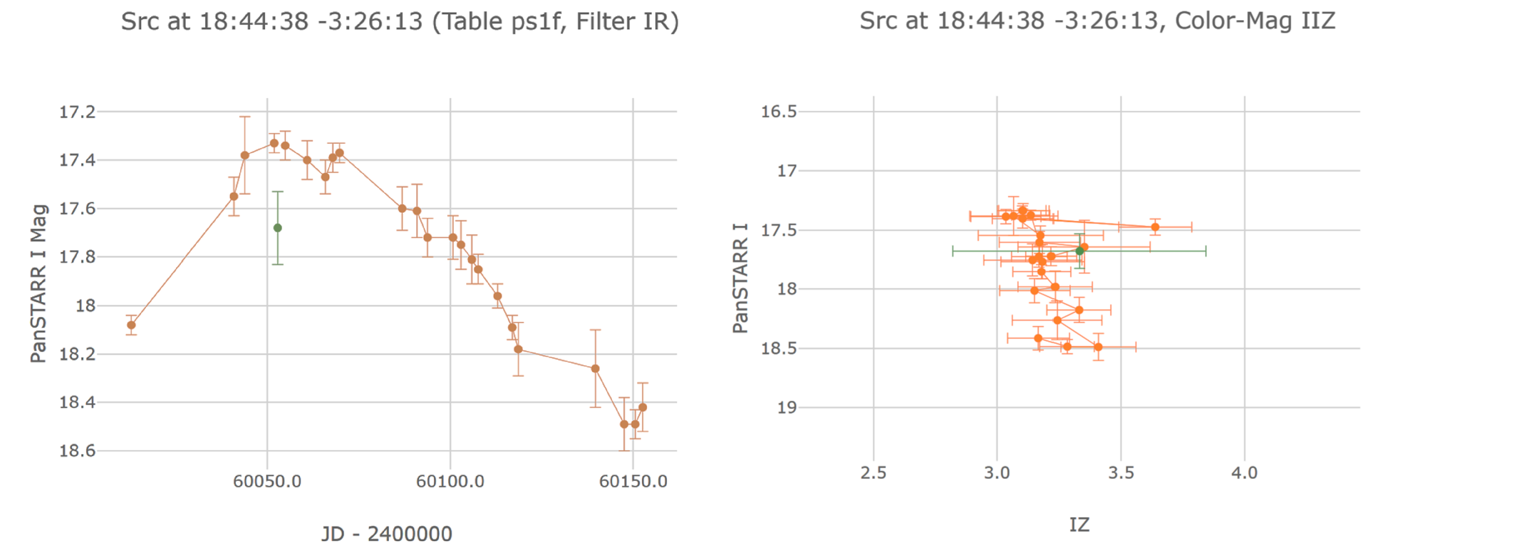


Fig. 6: 2023 z-band VST lightcurve of a RSG around Alicante7 cluster and color-magnitude plot. The shape and timescale of this lightcurve is compatible with outburst model (e.g Fig. 2), but the full project baseline is needed to exclude pulsations. Characterization of RSG long-term variability is necessary to detect any Pre-SN outburst on top of it.

4. Conclusions

1. The approx. **coeval and co-distant large sample of RSGs** in the Scutum-Crux/central bar region provide a unique opportunity to study faint pre-SN activity of "low-mass" RSGs
2. A **short-cadence dedicated monitoring optical/NIR campaign** on these RSGs, combined with state-of-the-art models, opens the possibility to derive their evolutionary stages with high unprecedented precision
3. **Current surveys are not deep/short enough** for "low-mass" RSGs and/or lack iz and NIR colors. Vera Rubin baseline survey cadence is too long: 795 visits/10yr, split between ugrizy filters -> 30 days per filter, 3 times longer in high-dust galactic plane region
4. **GalRSG multi-band/short-cadence lightcurve database will have a lasting legacy value and represents a framework for future studies of massive star populations, even in the era of current and future all-sky surveys**