Search for the Nova Super-Remnants candidates - Physical background and future progress of the campaign

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Bezovec 2025

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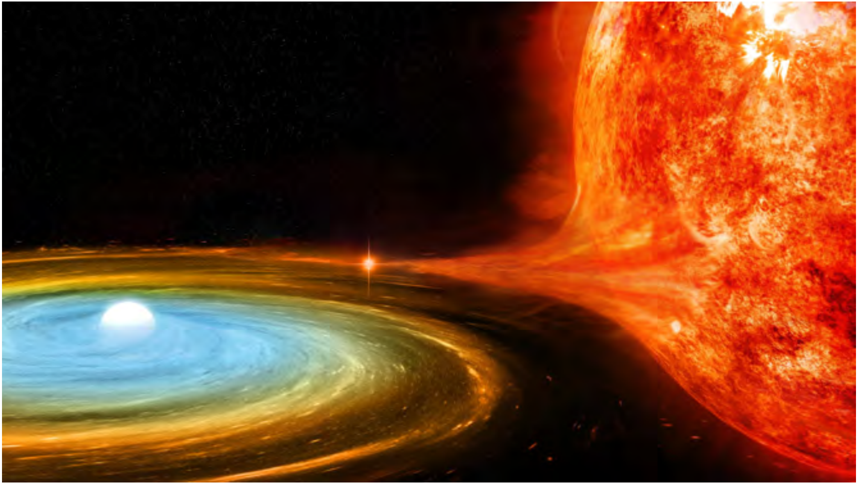
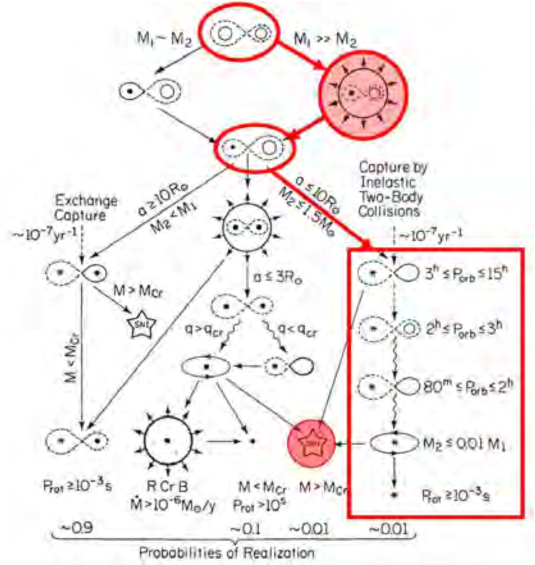


Introduction

Basic question: What are the progenitors of type Ia Supernovae?

Evolution of close binaries according Iben 1991



Cataclysmic variables as a progenitors of SN Ia

The mass of the WD must reach the Chandrasekhar limit despite the repeated nova explosions. Modelling of Hillman et. al 2016 suggest it is possible even taking into account the helium flashes.

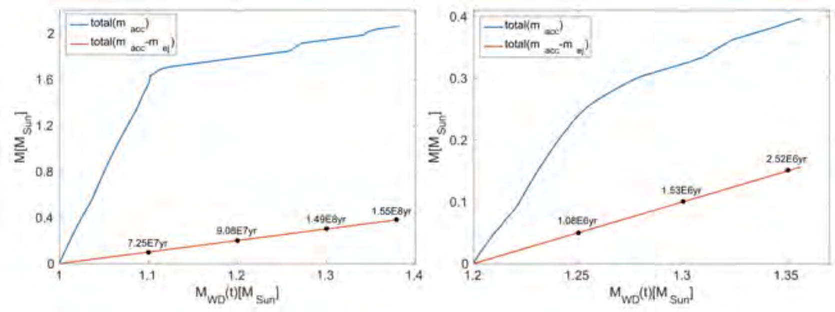


Figure: Accretion rates of $2.10^7 M_\odot yr^1$ (left) and $5.10^7 M_\odot yr^1$ (right)

RN as the best candidate to produce SN Ia

Recent studies with multi-cycle nova eruption models have shown that white dwarfs can grow in mass towards the Chandrasekhar limit (Yaron et al. 2005, Hachisu et al. 2007, Kato et al. 2015, Hillman et al. 2015, Hillman et al. 2016, Starrfield et al. 2021)

Recurrent novae has high mass WDs and high accretion rate. The result is high rate of nova explosions but also fast evolution to SN Ia explosion.

Recurrence of the nova eruptions

Probably each CVs undergo nova eruption many times

Frecuency $\propto M_{WD}$

- $M_{WD} \sim 1.4 M\odot$ - 1 year cycle (M31N 2008-12a)
- low-mass WDs - $> 1 Myr$
- $M_{WD} > 1.2 M\odot$ - recurent nova

Recurent nova: > 1 eruption in a century.

Only 11 known Galactic recurent novae. However, according Pagnotta and Schaefer, 2014 calculation - 25% of novae are RN.

Recurence time on $\dot{M}$ vs M_{WD} plot

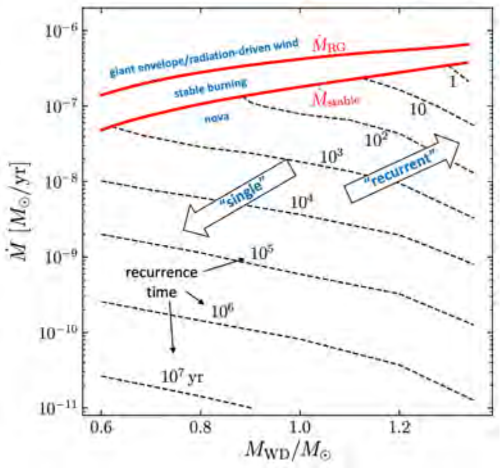


Figure: from Chomiuk et al. 2020.

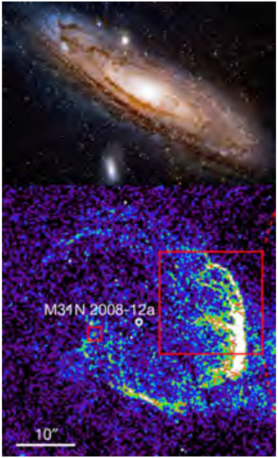
M31N 2008-12a Nova Super-Remnant

Fastest recurring nova: erupting annually

- WD accretes more mass than it ejects
- as such, WD is growing towards the Chandrasekhar limit

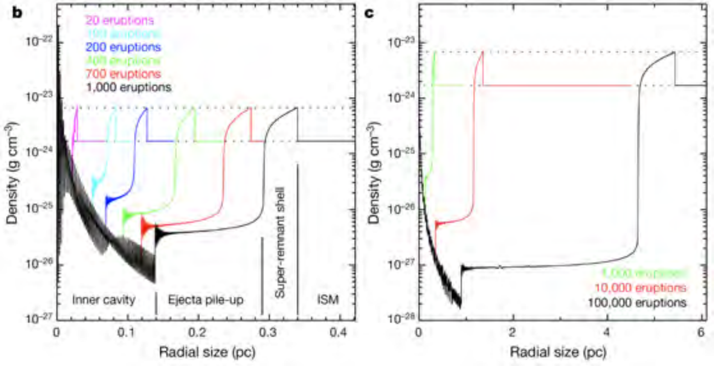
Hα observations with the Liverpool Telescope revealed a vast nebulosity coincident with the central nova

More observations unveiled a structure 134 parsecs across (Darnley et al. 2019) →The first discovered nova super-remnant

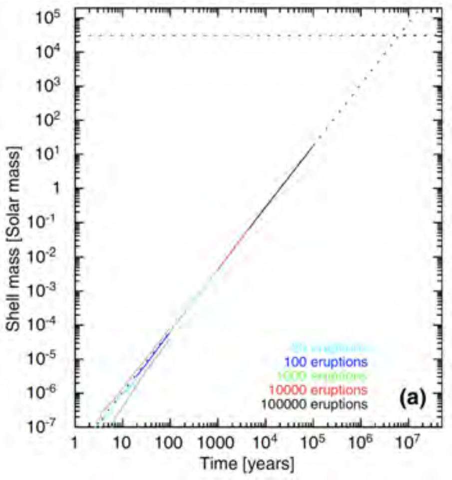


Simulation of M31N 2008-12a NSR

A series of 1D hydrodynamical simulations of nova ejecta demonstrated that repeated nova eruptions can sweep up the surrounding ISM into a shell at the edge of the growing super-remnant (Darnley et al. 2019).



The mass increase of Nova Super-remnant



NSR this size (67 pc) grown by annual nova eruptions sweeping up the surrounding ISM over 6.10^6 years

Total mass swept up is about $3.10^4 M_\odot$

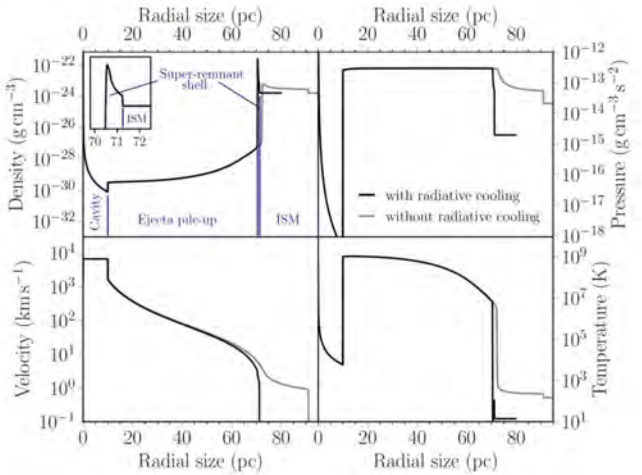
The size and mass of this super-remnant demonstrate that 12a has not just been erupting frequently for a decade as observed, but for millions of years (Darnley et al. 2019)

Simulations of other NSR

Reference simulation in Healy-Kalesh et al. 2023:

- ISM density 1 hydrogen atom per cubic cm
- WD temperature 10 million Kelvin
- initial WD mass 1 solar mass
- accretion rate 1.10^{-7} solar mass per year
- number of eruptions 1,900,750
- evolutionary time 31 million years
- resolution 200 AU/cell

Simulation of the shell formation



System parameter influences on NSR growth

Large impact on NSR growth

- ISM density
- mass accretion rate

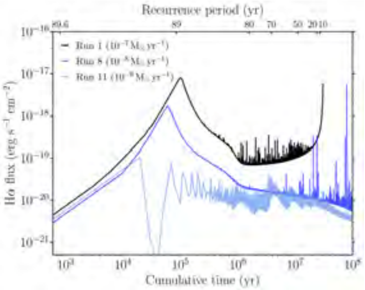
Little impact on NSR growth

- white dwarf temperature
- initial white dwarf mass

- increase in local ISM density results in a smaller NSR
- Lower accretion rate leads to more extended, but less well-defined NSRs

Modelling NSR $H\alpha$ emission

- initially the emission increases as the early NSR shell sweeps the local ISM
- the shell temperature then decreases allowing for recombination and a drop in flux
- $H\alpha$ emission then increases as highly energetic eruptions impact the inner edge of the high density NSR shell



Observations

Difference between "Supernova Remnant" and "Nova Super-Remnant"

- The absence of $[O_I]$ and $[O_{III}]$ emission in NSR
- Expansion velocity

Nova shell vs Nova super-remnant

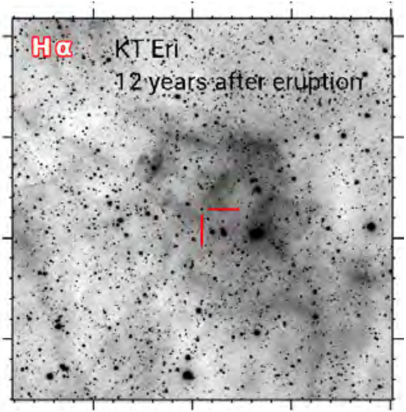


Figure: HR Del nova shell **10 x 10 arcsec** (left). HST image from Harman and O'Brien, 2003
KT Eri nova super remnant **49 x 49 arcmin** (right). Condor image from Shara et al., 2024

Nova super-remnants discovered so far

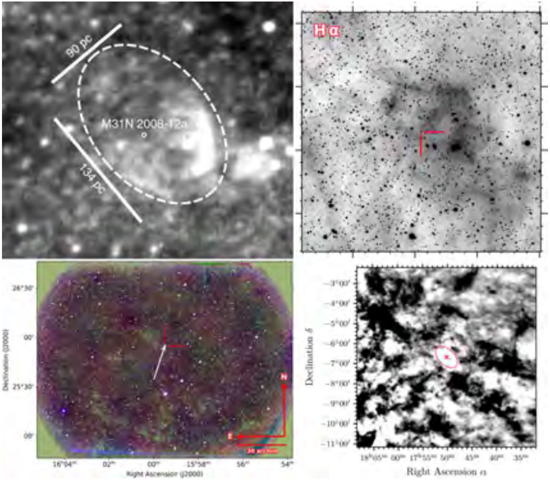


Figure: From the top left: M31N 2008-12a, KT Eri, T CrB, RS Oph cavity

Basic parameters of known NSR

	M31 12a	KT Eri	T CrB	RS Oph cavity
Distance [pc]	7.5x10^5	5110	914	1600
Angular size [']	0.6x0.4	36	120	40x12
Physical size [pc]	134x90	50	32	16x5
Surface brightness [$erg\ s^{-1} cm^{-2} arcsec^{-2}$]		4x10^{-17}	6.6x10^{-18}	
WD mass [$M\odot$]	1.38	1.23	1.37	1.35
dM/dt [$M\odot\ yr^{-1}$]	$\sim 10^{-6}$	3.5x10^{-7}	3x10^{-8}	1.2x10^{-7}
Recurrence [year]	1	$\sim$ 50	80	15
NSR age [year]	6x10^6	5x10^4	$\sim$2x10^5	
NSR mass [$M\odot$]	10^{5-6}		< 300	

Selection of NSR candidates

Known Recurent Novae

All of them has low declination except T CrB which NSR was already discovered and its angular size is large.

Only 11 known Galactic recurent novae. But remember!

According Pagnotta and Schaefer, 2014 calculation - 25% of novae are RN.

Dec positive	observable	southern
T CrB	CI Aql	V394 CrA
	RS Oph	IM Nor
	V3890 Sgr	V745 Sco
	V2487 Oph	T Pyx
	U Sco	
	KT Eri	

Pagnotta and Schaefer, 2014 search among Classical Novae

Criteria

- outburst amplitude smaller than 14.5 - 4.5 x log(t3)
- orbital period $>$0.6 days
- infrared colors of J - H $>$ 0.7 mag and H - K $>$ 0.1 mag
- FWHM of $H\alpha > 2000 kms^{-1}$
- high excitation lines, such as Fe_X or He_{II} near peak
- eruption light curves with a plateau
- white dwarf mass greater than $1.2 M\odot$

Pagnotta and Schaefer, 2014 search among Classical Novae

Results - best candidates

Target	Declination	Galactic latitude	year of outburst
V0838 Her	+12 14 02	+6.619	1991
V1721 Aql	+07 06 44	-0.083	2008
KT Eri	-10 10 43	-32.020	2009
V477 Sct	-12 16 15	-2.789	2005
V4643 Sgr	-26 14 15	-00.201	2001
V2672 Oph	-26 44 13	+2.529	2009
V4739 Sgr	-30 00 41	-7.966	2001
V4160 Sgr	-32 12 28	-6.969	1991
DE Cir	-61 57 16	-3.816	2003
CP Cru	-61 45 09	+0.735	1997

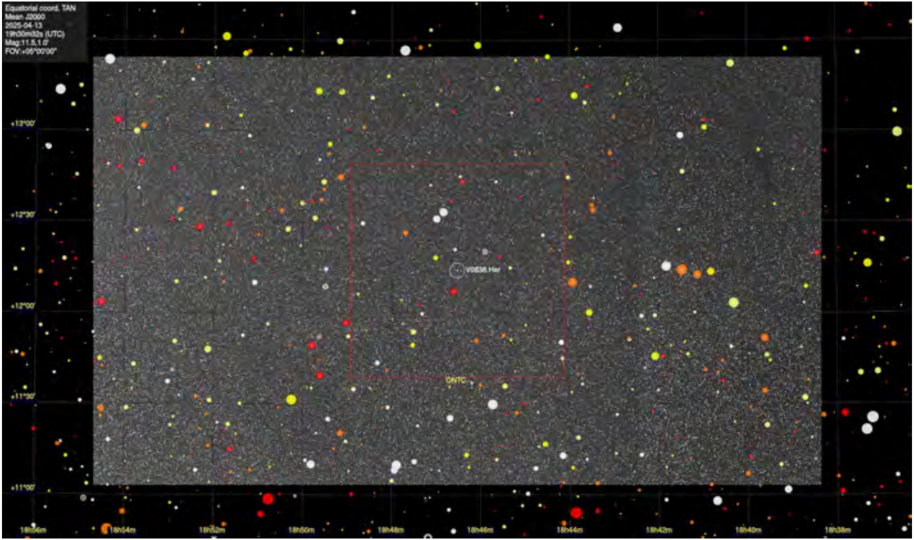
Pagnotta and Schaefer, 2014 search among Classical Novae

Added RNe candidates among CNe erupted after 2014

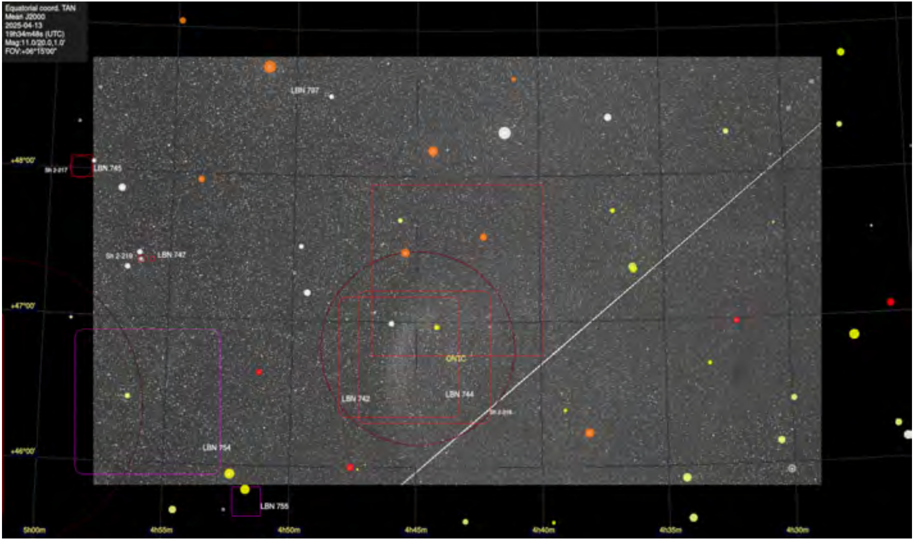
Target	Dec	b	dist	P_{orb}	FWHM	WD_{mass}
V0838 Her	+12	+6	3128	0.29764	5000	1.38
V0392 Per	+47	+1	3402	3.21997	5000	1.35
V1674 Her	+16	+6	3216	0.15302	6000	1.36
V2860 Ori	+12	-3	5969	0.42258	4000	1.35

Expected **50 pc** size of the NSR corresponds to **50 arcmin** angular size at the distance of **3400 pc**.

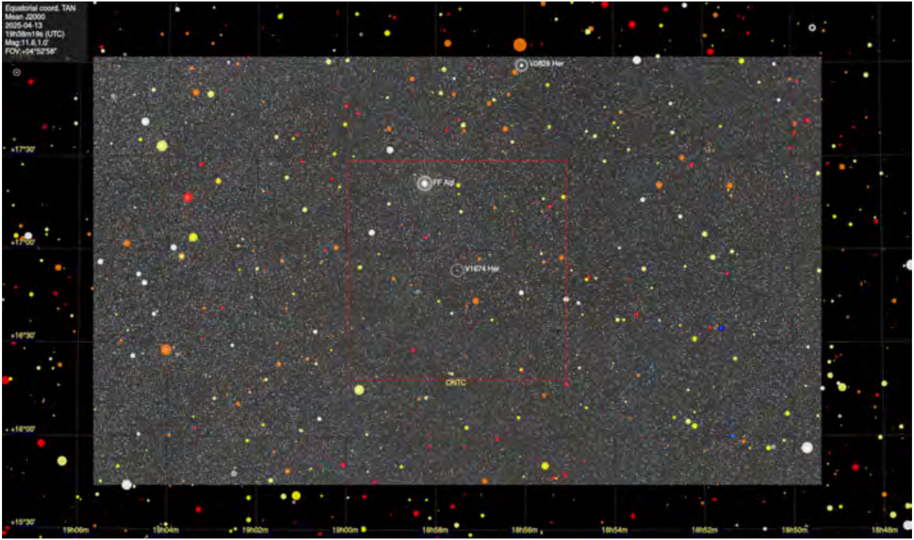
70 x 70 arcmin frame on the DSS image of V838 Her FoV



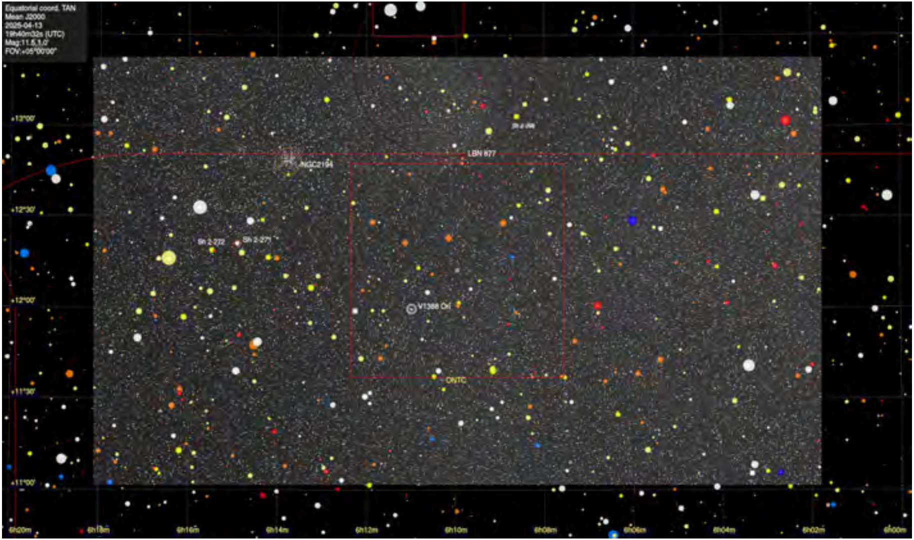
70 x 70 arcmin frame on the DSS image of V392 Per FoV



70 x 70 arcmin frame on the DSS image of V1674 Her FoV



70 x 70 arcmin frame on the DSS image of V2860 Ori FoV



Search for NSR candidates among Nova like cataclysmic variables

Gilmozzi & Selvelli, 2023, Accretion rates of 42 nova-like stars with IUE and Gaia data

- NLs have the same accretion rate as novae
- But all the sample is close to us $< 1.3 kpc$
- The best candidate is V363 Aur
- BZ Cam has nebulosity of 2 arcmin size. But is not NSR nor nova shell. Its emisson is produced by shocks. Wind interacting with ISM.

Additional search for NSR candidates among more distant NLs

$M_v \sim 3.5 mag$ at 3 kpc is $m_v \sim 16 mag$

The search was limited to objects with NL type in VSX, $Dec > 10^\circ$, galactic latiduted $|b| > 10^\circ$ and Distance 2 - 5 kpc

Target	Dec	b	dist	P_{orb}	M_v	$log\,\dot{M}$	J-H	H-K
V363 Aur	+36	+2	816	0.32124	3.5	8.0	0.34	0.16
V825 Her	+41	+34	1048	0.206	4.1	8.6	0.28	0.07
ZTF18 abaebjo	+68	+22	2878	0.206			0.57	0.28
SDSS J195939.71 +655440.9	+65	+18	3774	0.3263				

Condor Array Telescope

Six apochromatic refracting telescopes of objective diameter 180 mm, f/7

Lanzetta et al., 2023.

- Dark Sky New Mexico Observatory
- CMOS cameras ZWO ASI6200MM
- Scale 0.86 arcsec/px
- FOV 2.29 x 1.53 deg
- Filters broad band - Sloan g', r', i'
- Filters narrow band - *HeII* 468.6 nm, [*OIII*] 500.7 nm, *HeI* 587.5 nm, $H\alpha$ 656.3 nm, [*NII*] 658.4 nm, [*SII*] 671.6 nm.

Our campaign

Instruments collecting data

KK 30cm - newtonian 300/1200 mm on EQ8 mount

- AO on Kolonica Saddle, operated by Karel Kolomazník
- CMOS camera MII C3-61000
- Scale 0.65 arcsec/px
- FOV 103 x 68.8 arcmin
- Filters broad band - L, R, G, B
- Filters narrow band - [*OIII*] 500.7 nm, $H\alpha$ 656.3 nm, [*SII*] 671.6 nm.

ONTC - newtonian 406/1800 mm on GM3000 mount

- AO on Kolonica Saddle, Pavol A. Dubovský and Robert Adam
- CMOS camera MII C4-16000
- Scale 1.03 arcsec/px
- FOV 70.4 x 70.4 arcmin
- Filters broad band - B, V, R, I
- Filters narrow band - [*OIII*] 500.7 nm, $H\alpha$ 656.3 nm, [*SII*] 671.6 nm.

Instruments collecting data

100ED APO refracting 100/412.5 on EQ6 mount

- AO on Kolonica Saddle, Robert Barsa
- CMOS Camera QHY268M
- Scale 1.88 arcsec/px
- FOV 196 x 129 arcmin
- Filters broad band - Astronomik: Luminance L3, Deep Sky RGB
- Filters narrow band - Ha 6nm MaxFR, SII 6nm MaxFR, OIII 6nm MaxFR

Newton 350/1400

- Stupava, Drahomír Volný
- Atik APX60 Mono
- Scale 0.56 arcsec/px
- FOV 88 x 59 arcmin
- Filters narrow band - [*OIII*] 3.5nm, $H\alpha$ 3.5nm, [*SII*] 3.5nm.

Instruments collecting data

100ED APO refracting 100/550 on EQ6-R Pro mount

- Devínska nová ves, Matúš Trembáč
- ZWO ASI294MM 4.64 μm
- Scale 1.75 arcsec/px
- FOV 119 x 81 arcmin
- Filters narrow band - Antilia [$OIII$] 4.5nm, $H\alpha$ 4.5nm, [SII] 4.5nm

Refracting Sv503 102 ED f/7 + reducer 0,8x $\rightarrow$f/5.6 on HEQ5 mount

- Boldog, Martin Mančuška
- CMOS; 3008x3008; 1x1 (SV605MC)
- Scale 1.36 arcsec/px
- FOV 67.8 x 67.8 arcmin
- Filters narrow band - [$OIII$] 5nm, $H\alpha$ 5nm, [SII] 5nm.

Instruments collecting data

Newton 250/1000

- Miloš Gnida
- ZWO ASI1600MM 3.8 μm
- Scale 0.79 arcsec/px
- FOV 61 x 46 arcmin
- Filters narrow band - Baader [*OIII*] 6.5nm, $H\alpha$ 6.5nm, [*SII*] 6.5nm

Refracting 130/910

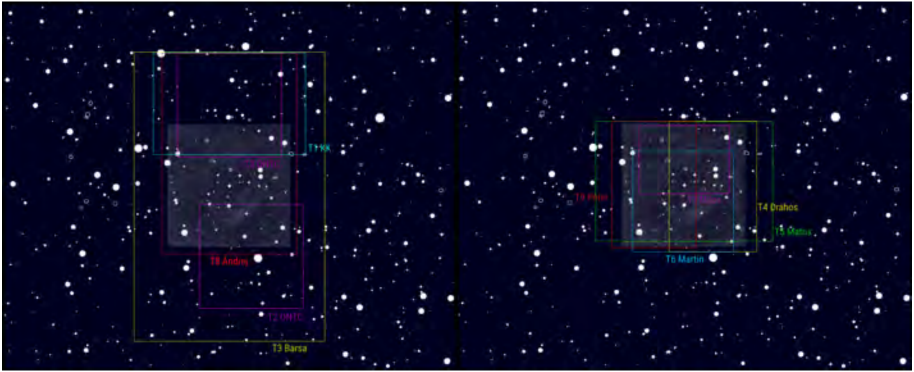
- Adam Kováč
- ZWO ASI6200MM 3.76 μm
- Scale 0.86 arcsec/px
- FOV 136 x 91 arcmin
- Filters narrow band - Antilia [*OIII*] 4.55nm, $H\alpha$ 4.5nm, [*SII*] 3nm.

Instruments collecting data

Newton 250/950

- Peter Jurista
- ZWO ASI 2600MM 3.8 μm
- Scale 0.82 arcsec/px
- FOV 85 x 57 arcmin
- Filters narrow band - Astronomik [*OIII*] 6.0nm, $H\alpha$ 6.0nm, [*SII*] 6.0nm

Distribution of FoV in the pilot campaign on Z Cam



Results of the pilot campaign on the Z Cam nova shell

- This work was supported by the project APVV-20-0148 From interacting binaries to exoplanets.
- This work was supported by the project Through Poloniny to the Stars financed by Europian Union NextGenerationEU.

More about our campaign: astrofoto.astrokolonica.sk

Thank you for your attention