Investigating trends and transformations of Centaur surfaces

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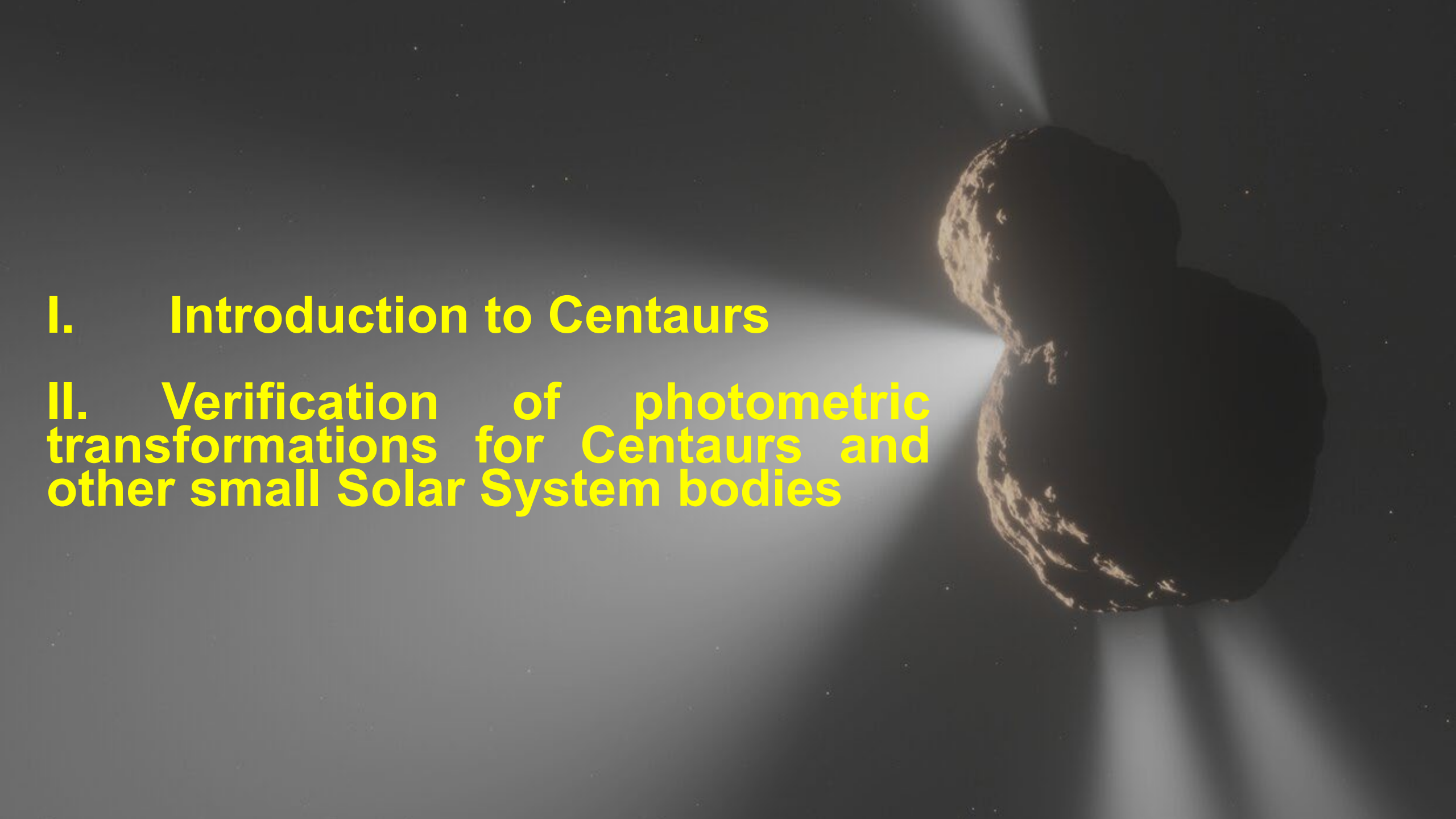
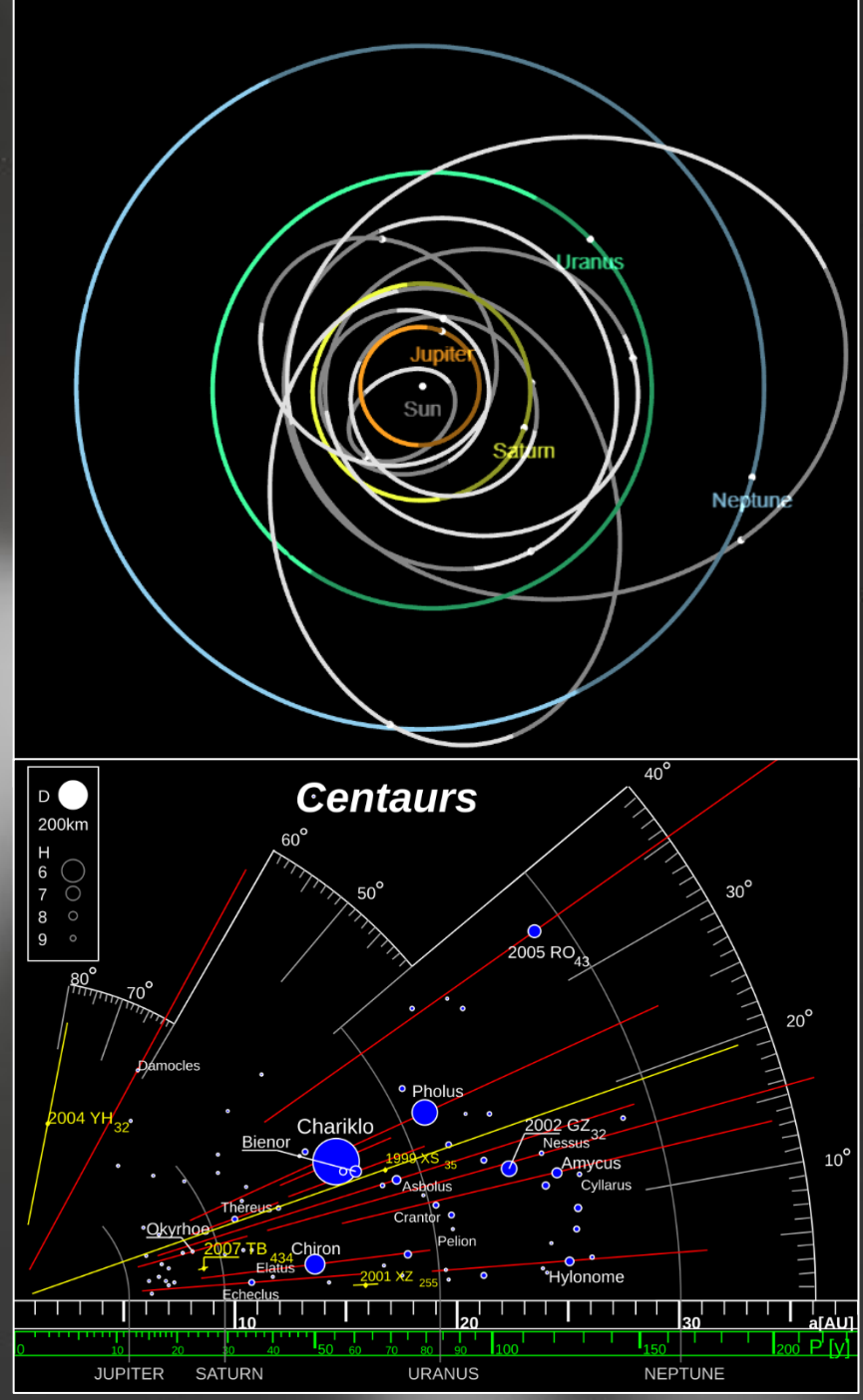


I. Introduction to Centaurs

II. Verification of photometric transformations for Centaurs and other small Solar System bodies

What are Centaurs?

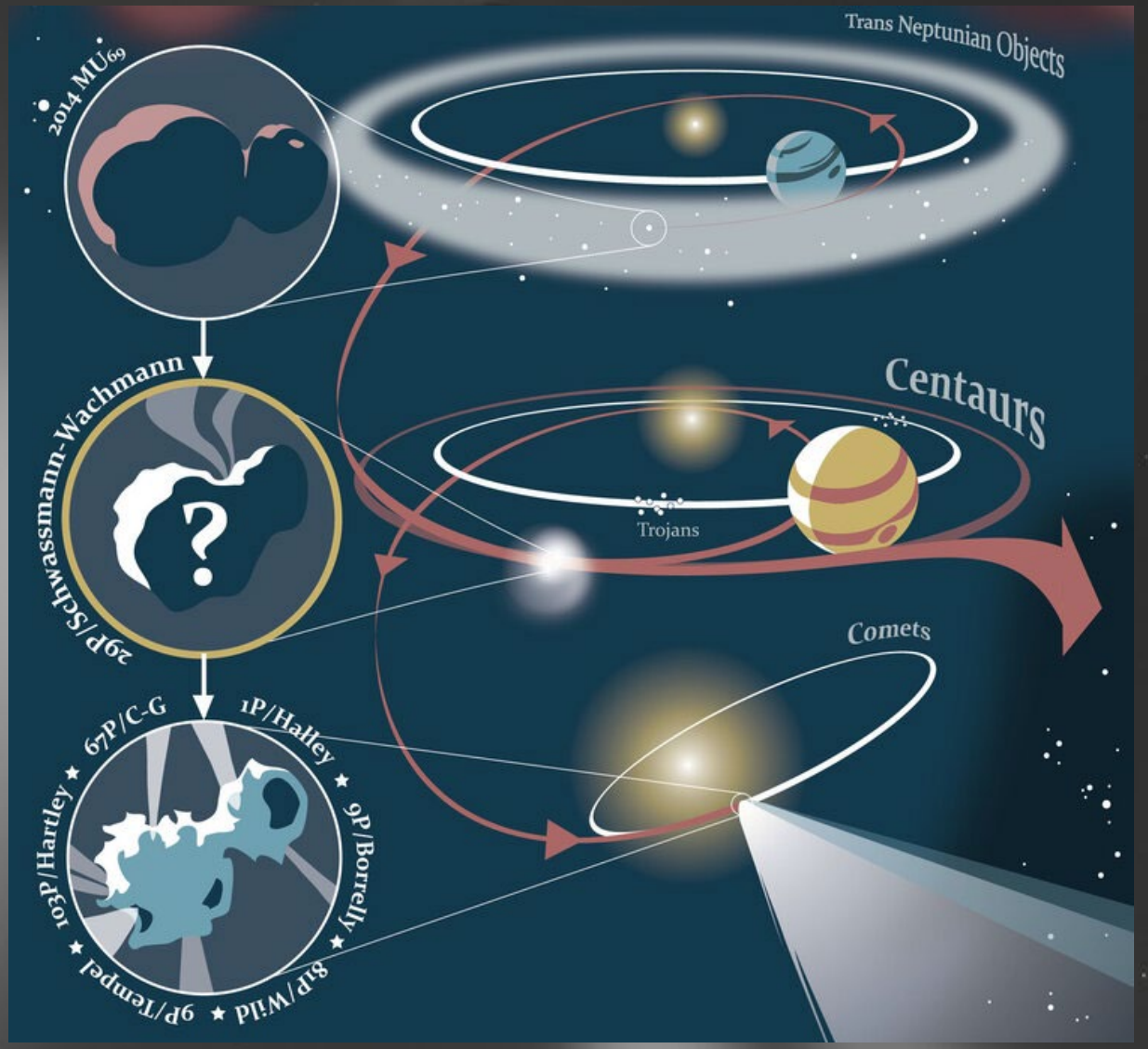
- population of small bodies of the Solar System with *q* and *a* between Jupiter and Neptune;
- non-resonant unstable orbits perturbed by giant planets (mean lifetime ~10 Myr);
- icy objects composed of frozen volatiles covered by a red layer of irradiated organic macromolecules (“tholins”);
- number of known Centaurs: ~260 – 900 (depending on the definition)



Centaur orbits (source: JPL SSD; Wikipedia)

Centaurs and other minor bodies

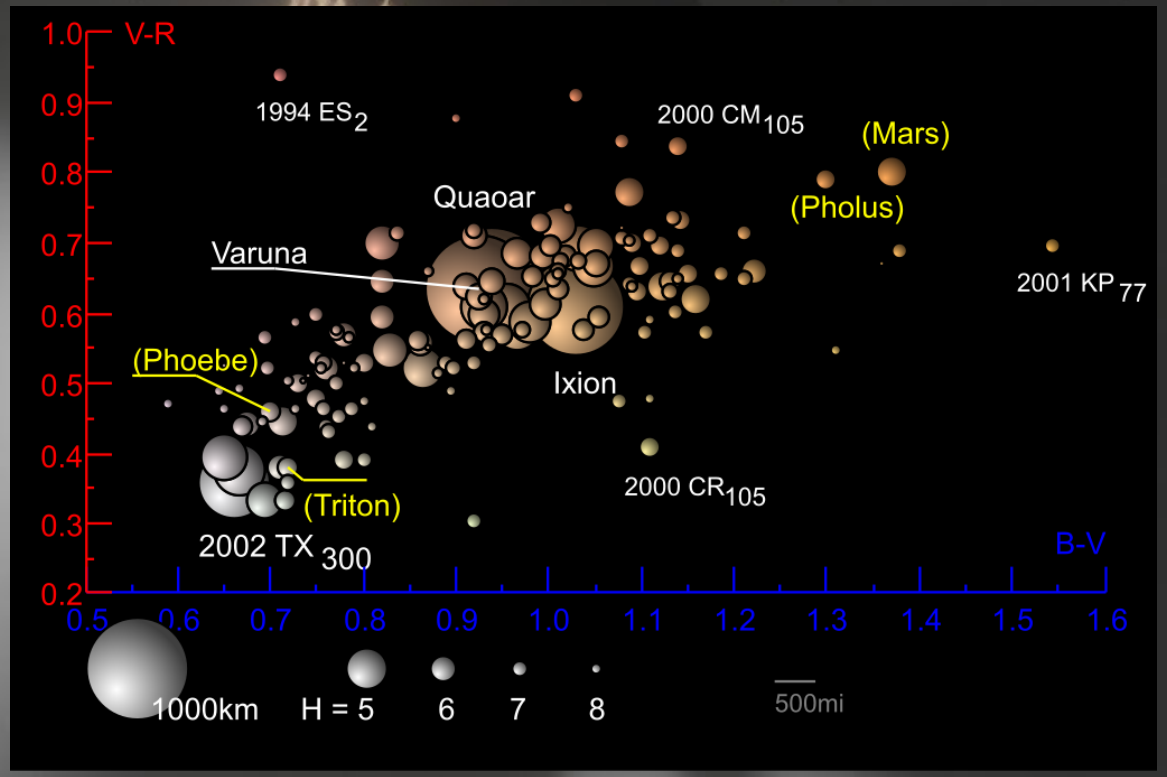
- transition group between TNOs and JFCs;
- originate in trans-Neptunian region (containing unprocessed primordial material);
- majority is ejected from the Solar System or collide with giant planets;
- ~30% of them become Jupiter-family comets;
- provide an opportunity to study the evolution of matter preserved since the origin of our planetary system;
- can help to constrain models of the Solar System formation, to understand physical and dynamical evolution of small Solar System bodies and their mutual relations



Dynamical evolution of minor planets (credit: Tyler Nordgren)

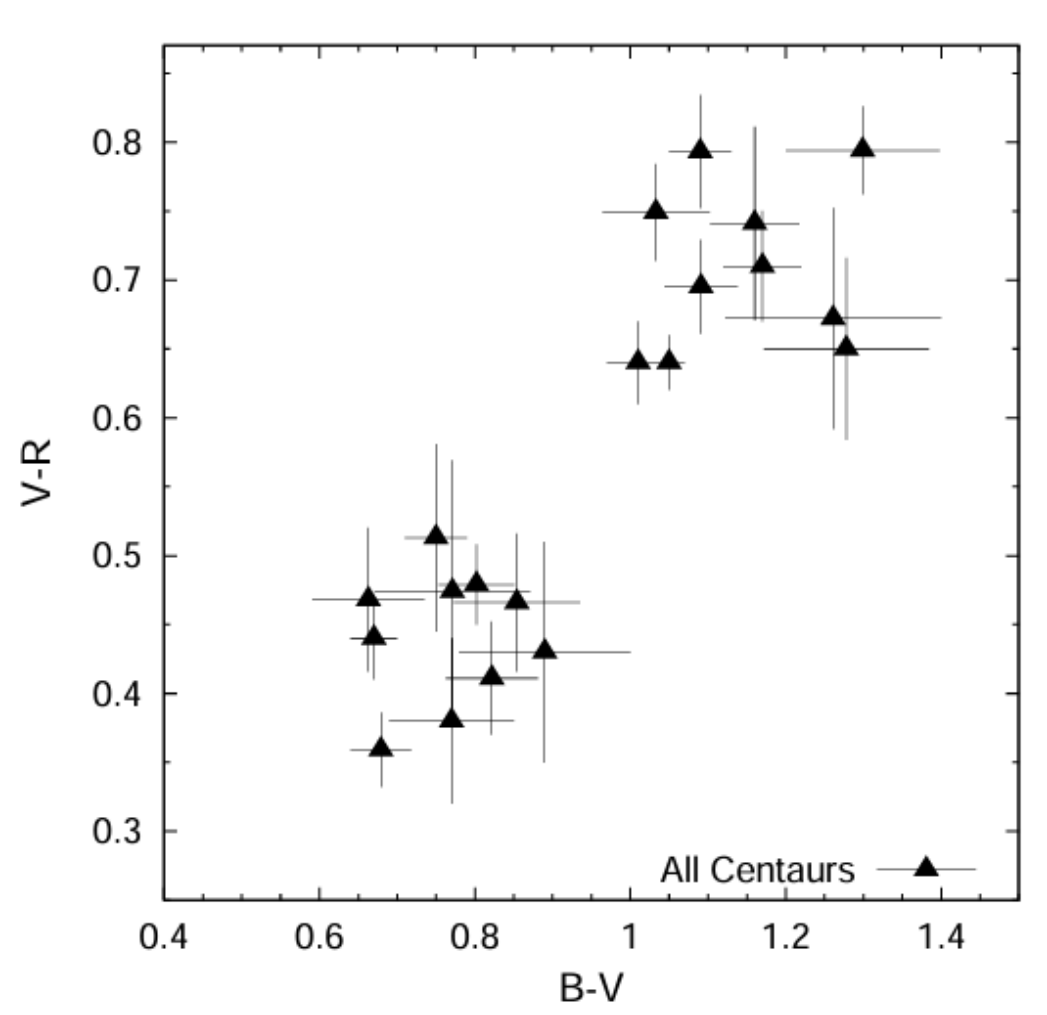
Color photometry of minor planets

- no planned space missions to Centaurs → remote observations;
- objects are dim → spectroscopic studies are limited, broadband color photometry is a solution;
- reflected light: contains information about chemical composition (minerals), physical and structural properties of the reflecting surface material;
- color indices: measure the object in different filters, then substract the magnitudes;
- color-color diagram: allows to group small bodies into different taxonomic classes with similar surface properties

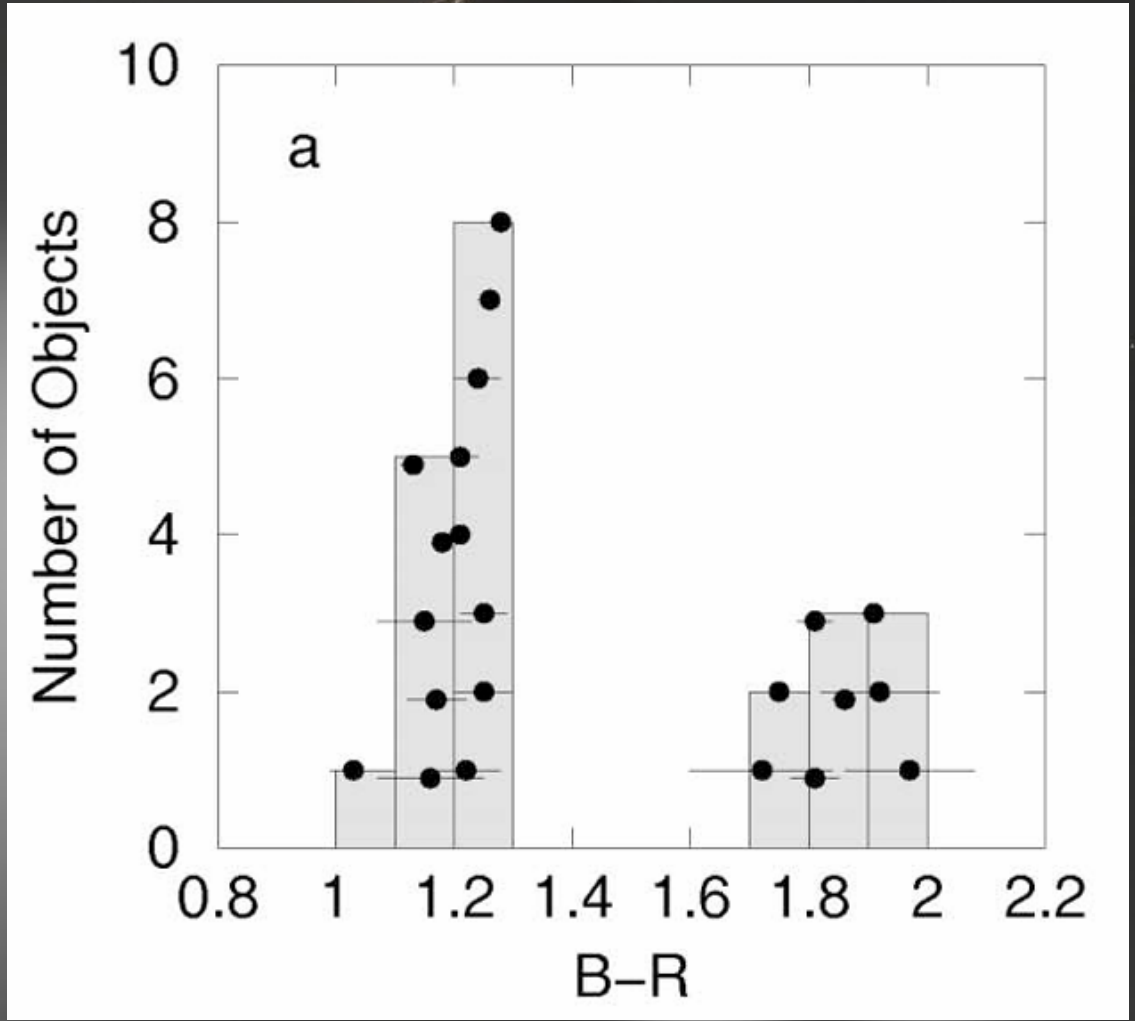


Color-color diagram of Trans-Neptunian objects showing continuous distribution of their surface color
(source: https://en.wikipedia.org/wiki/Trans-Neptunian_object)

Reality = bimodality



Sample of Centaurs on which color bimodality was first noticed (source: Peixinho et al. 2003)

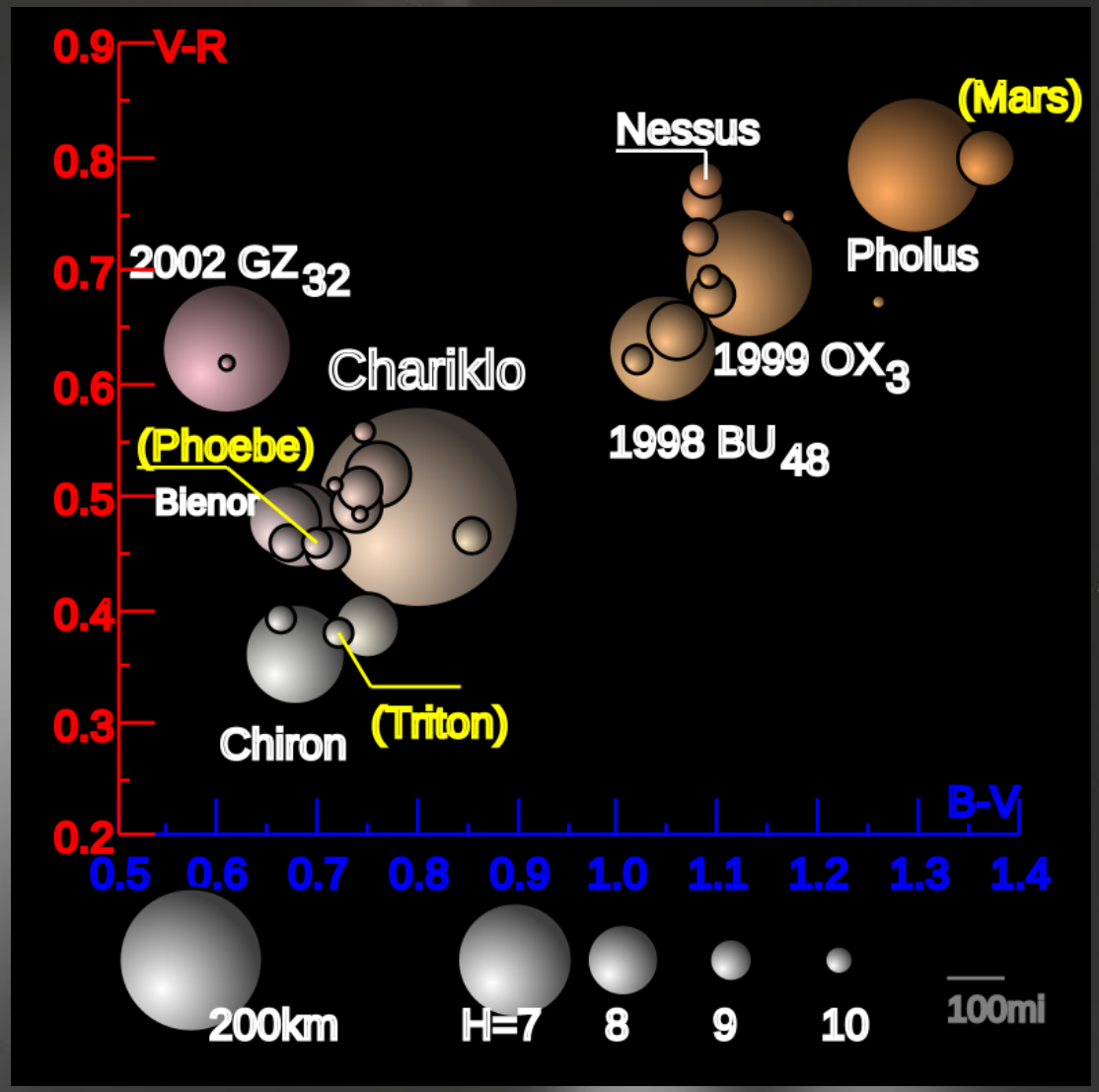


Histogram showing two color groups of Centaurs (source: Tegler et al. 2003)

Bimodality of Centaur colors

Several hypotheses have been proposed:

- origin in different parts of the TN region;
- space weathering (high-energy particle bombardment, non-disruptive collisions);
- cometary activity - “blanketing effect” (~10% of known Centaurs showcase cometary activity)

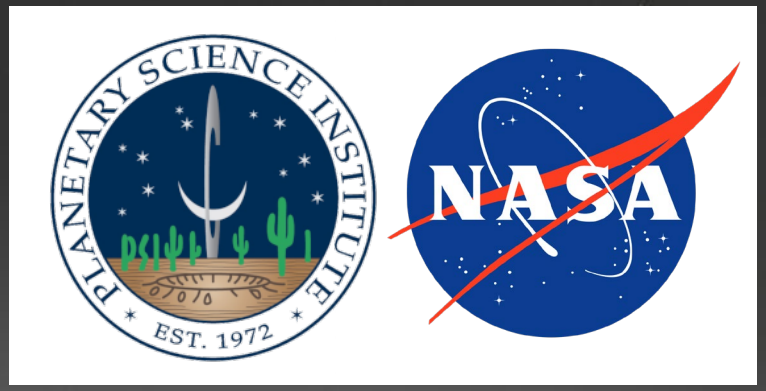


Color distribution of Centaurs. Centaurs are the only population of small bodies showing such kind of color bimodality (source: https://en.wikipedia.org/wiki/Centaur_(small_Solar_System_body))

BlanCATing effect

C(om)AT(ary) activity

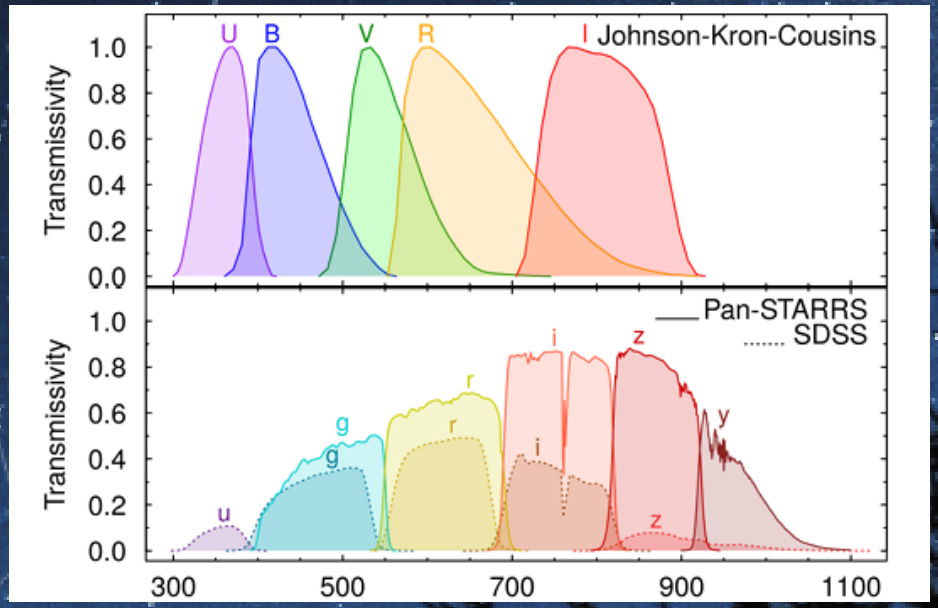
Project



- previous conclusions have been made on small numbers of studied objects;
- possible correlations between colors and cometary activity, sizes, orbital distribution are yet to be investigated in depth;
- NASA Solar System Observations Program "*Investigating Centaur surface colors: connecting surface transformation to thermal and dynamical history*" (Principal Investigator Dr. Eva Lilly, Planetary Science Institute);
- observational campaign aimed at collecting photometric color data of 50–60 Centaurs, increasing the number of Centaurs with known surface colors by a factor of two;
- goal is to cover the variety of sizes and perihelion distances to search for trends and correlations to (dis)prove mentioned hypotheses

Photometric systems

- investigation of trends → need to look on older archive data;
- observations are performed in different *standard photometric systems* = a set of defined passbands with a corresponding set of filters and a group of standard stars;
- the most popular are Johnson-Kron-Cousins $UBVR_CI_C$ and Sloan (SDSS) *ugriz* standard systems;
- old Centaur data in $UBVR_CI_C$, new data in *ugriz;*
- passbands do not match → need to transform magnitudes between them



Passbands of different photometric systems (source: Pancino et al. 2022)

Transformations between photometric systems

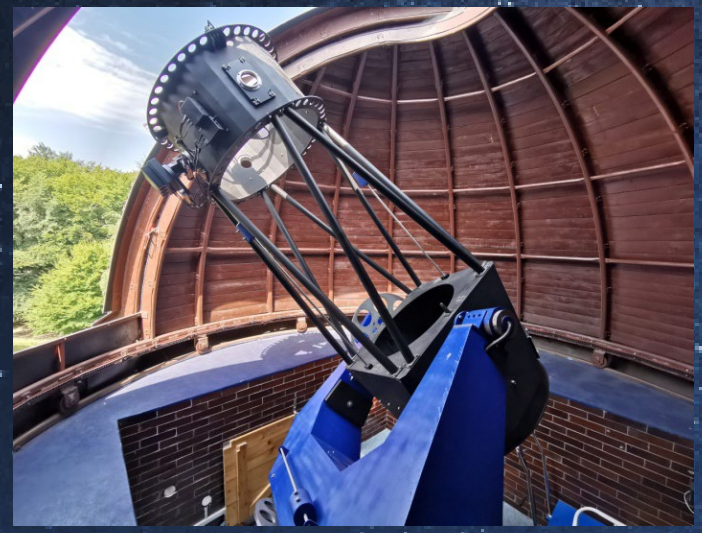
- transformation relations are found empirically by fitting the observed data and comparing magnitudes in two studied photometric systems;
- transformation coefficients are calculated using least-squares minimization method;
- many different relations can be found in literature, most of them derived for stellar and galactic communities;
- no explicit relations for small bodies (including Centaurs)

$B-g = C_0+C_1\times(g-r)$	$B-g = D_0+D_1\times(g-r)+D_2\times(g-r)^2$
$V-g = C_0+C_1\times(g-r)$	$V-g = D_0+D_1\times(g-r)+D_2\times(g-r)^2$
$V-r = C_0+C_1\times(g-r)$	$V-r = D_0+D_1\times(g-r)+D_2\times(g-r)^2$
$R-r = C_0+C_1\times(g-r)$	$R-r = D_0+D_1\times(g-r)+D_2\times(g-r)^2$
$I-i = C_0+C_1\times(g-r)$	$I-i = D_0+D_1\times(g-r)+D_2\times(g-r)^2$
$R-r = C_0+C_1\times(r-i)$	$R-r = D_0+D_1\times(r-i)+D_2\times(r-i)^2$
$I-i = C_0+C_1\times(r-i)$	$I-i = D_0+D_1\times(r-i)+D_2\times(r-i)^2$

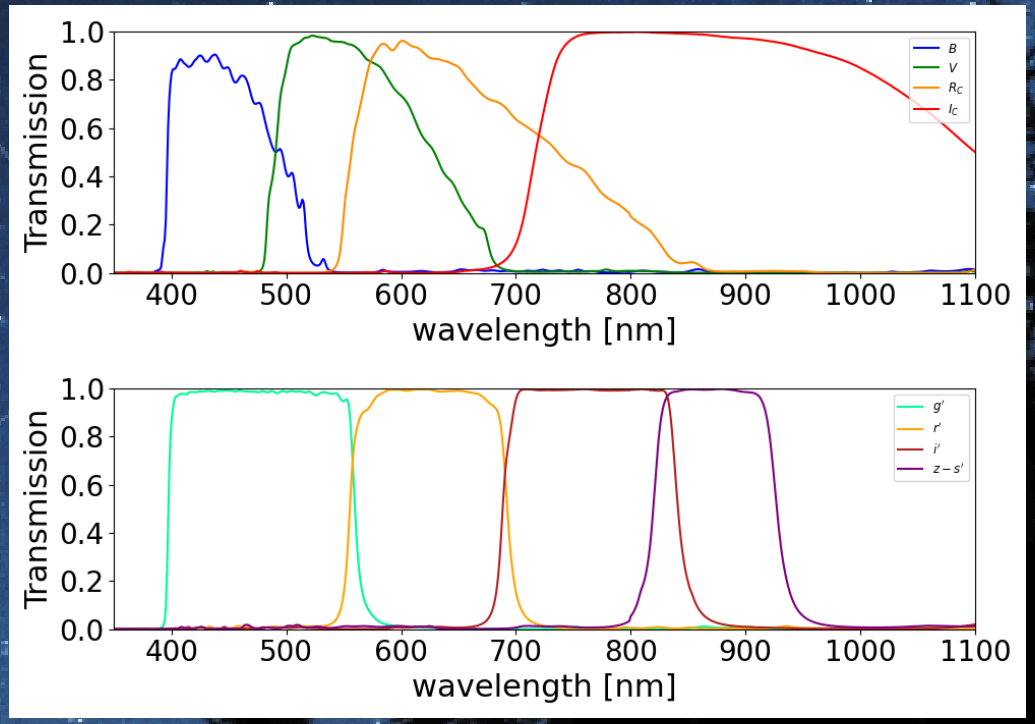
Example of linear and quadratic transformations between Pan-STARRS1 gri and BVR_CI_C systems (source: Kostov and Bonev 2018)

Observing strategy

- **objective**: to check the validity of existing transformations applied on small bodies;
- **idea**: to observe the same objects in both $UBVR_CI_C$ and *ugriz*, perform transformations and check consistency of the results;
- **implementation**: using AGO70 telescope at the the Astronomical and Geophysical observatory in Modra, Slovakia (has both BVR_CI_C and *g'r'i'z'* filters);
- **target selection**: well-known MBA of different spectral types, visual magnitude 10-14^m, non-binary, homogeneous surface and shape, h > 40°, SNR > 30-50

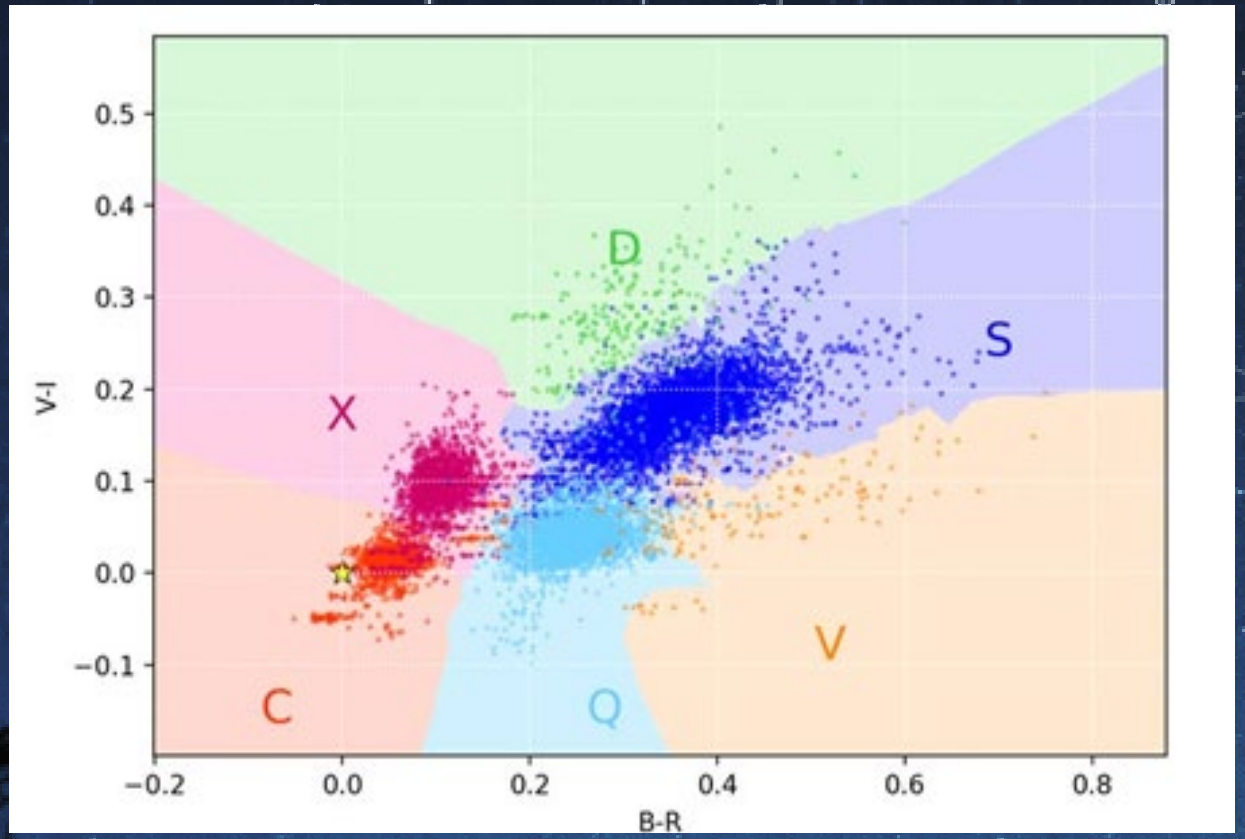


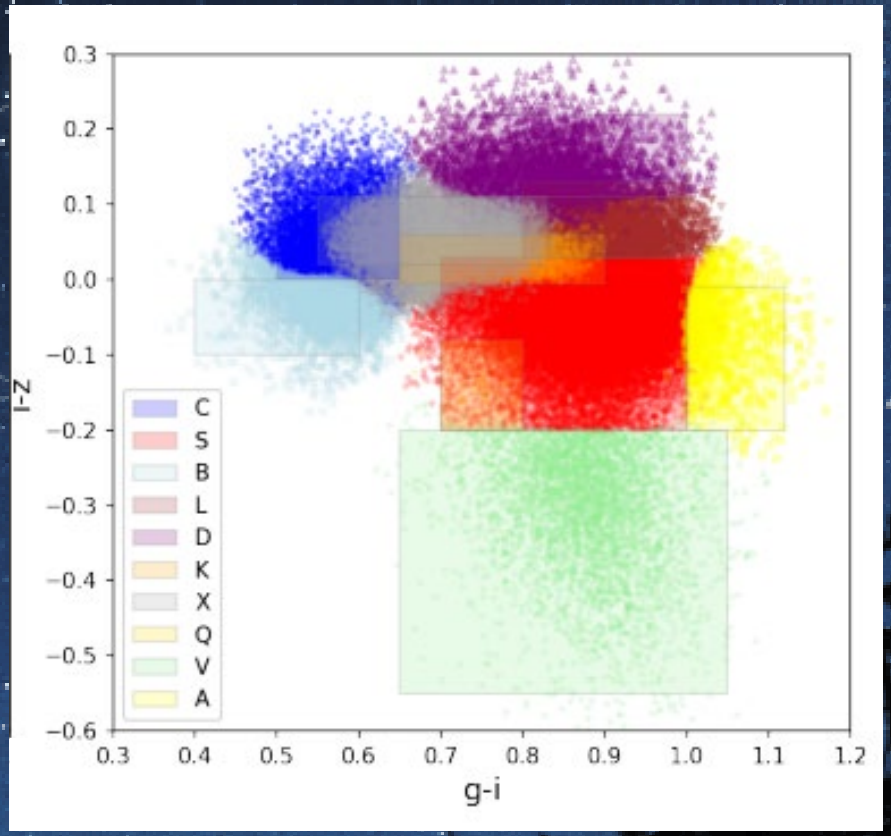
The AGO70 telescope in Modra, Slovakia (credit: Stanislav Griguš)



Spectral transition of BVR_CI_C and g'r'i'z-s' filters installed on AGO70 (source: Baader planetarium)

Calibration between photometric systems





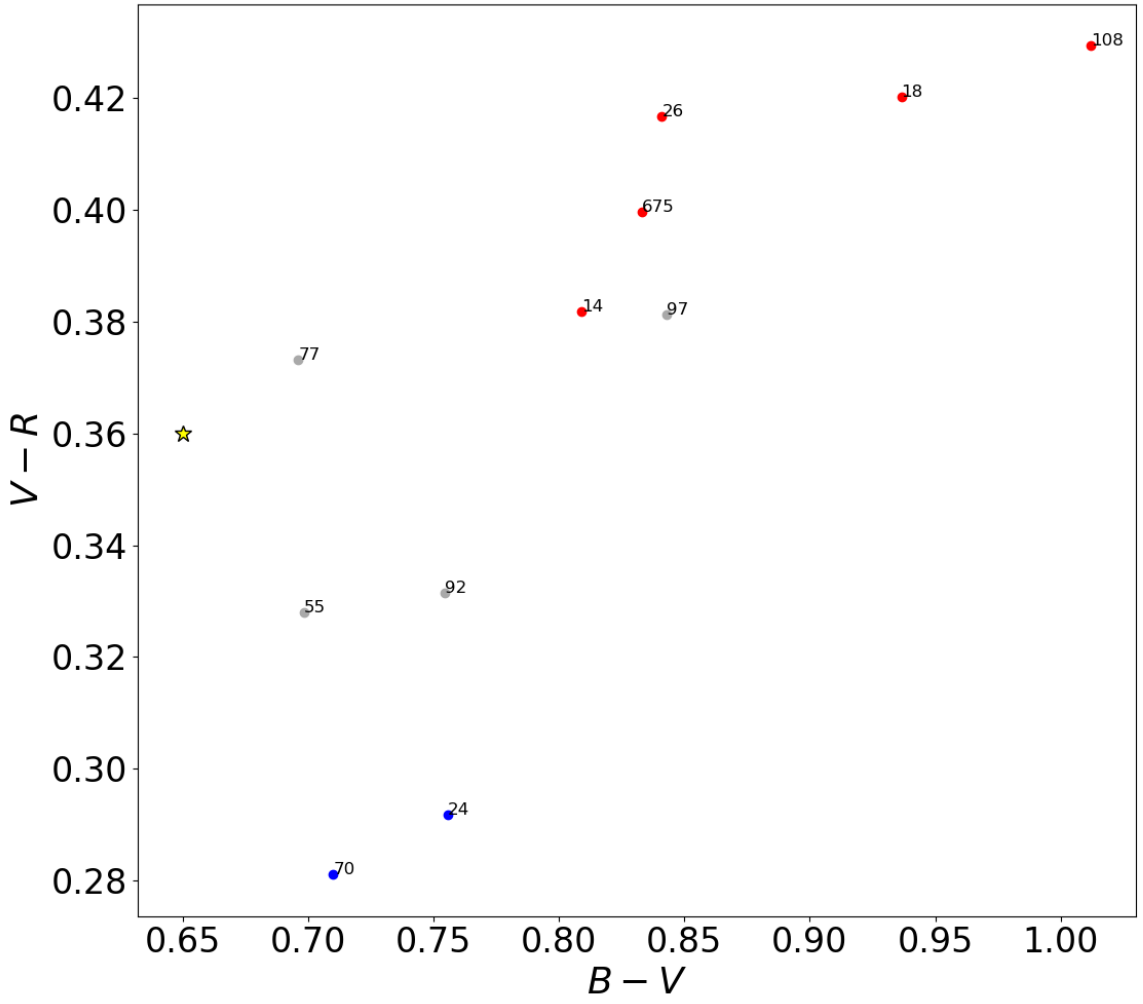
Examples of color-color diagrams we want to reproduce in both photometric systems (sources: Mommert et al. 2020; Sergeyev and Carry 2021)

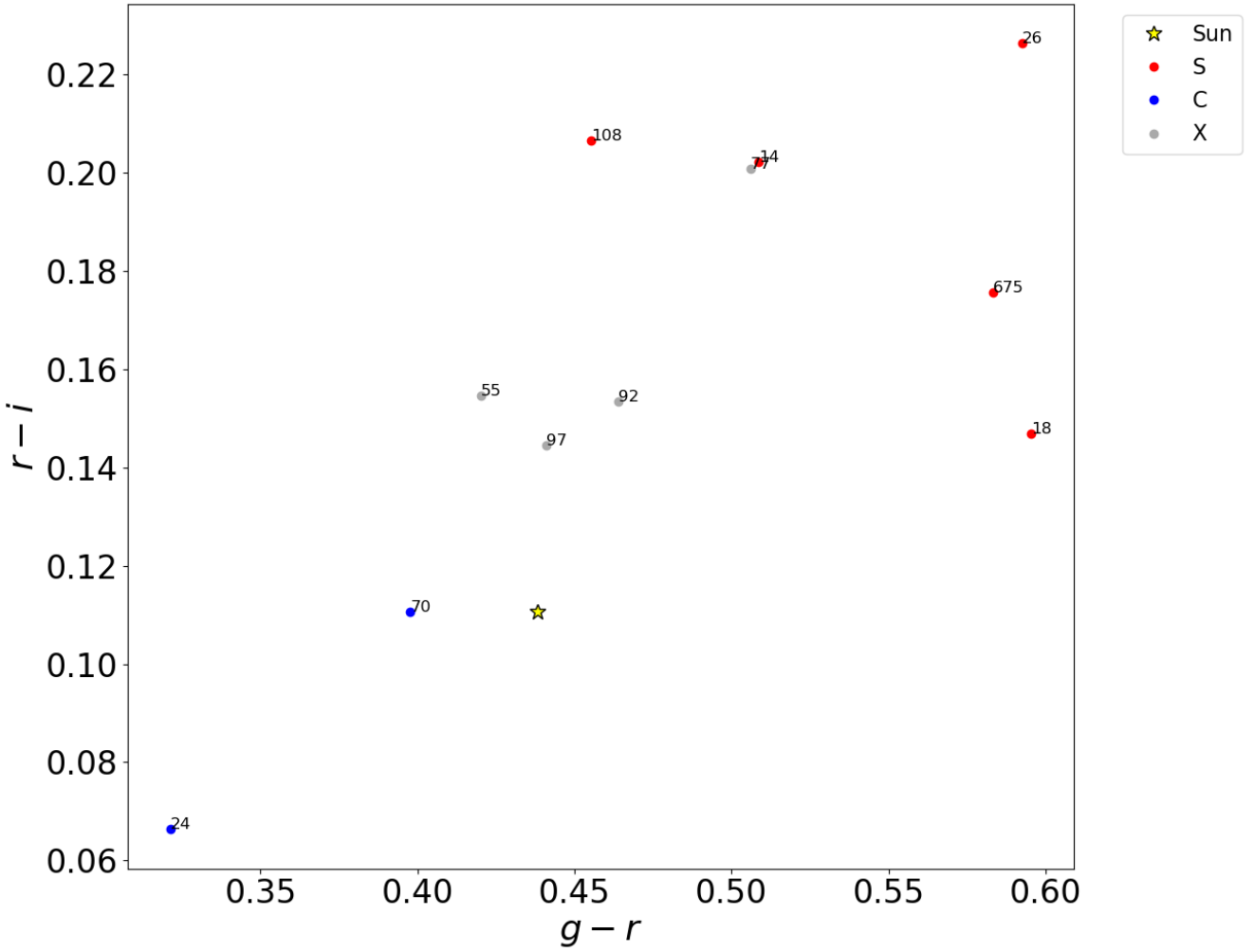
Observed targets

IAU number	Name	Spectral class (Bus-DeMeo)	Date of observations (BVRI)	Date of observations (g'r'i'z')	Visual magnitude
14	Irene	S	3.2.2025	5.2.2025	10.2
18	Melpomene	S	5.2.2025	19.2.2025	11.0
24	Themis	C	4.2.2025	5.2.2025	11.4
26	Proserpina	S	4.2.2025	5.2.2025	12.3
55	Pandora	Xk	3.2.2025	5.2.2025	12.0
70	Panopaea	Cgh	4.2.2025	5.2.2025	12.7
77	Frigga	Xe	4.2.2025	5.2.2025	12.3
92	Undina	Xk	4.2.2025	5.2.2025	12.3
97	Klotho	Xc	5.2.2025	19.2.2025	12.0
108	Hecuba	Sw	5.2.2025	19.2.2025	12.9
675	Ludmilla	Sw	4.2.2025	5.2.2025	11.7

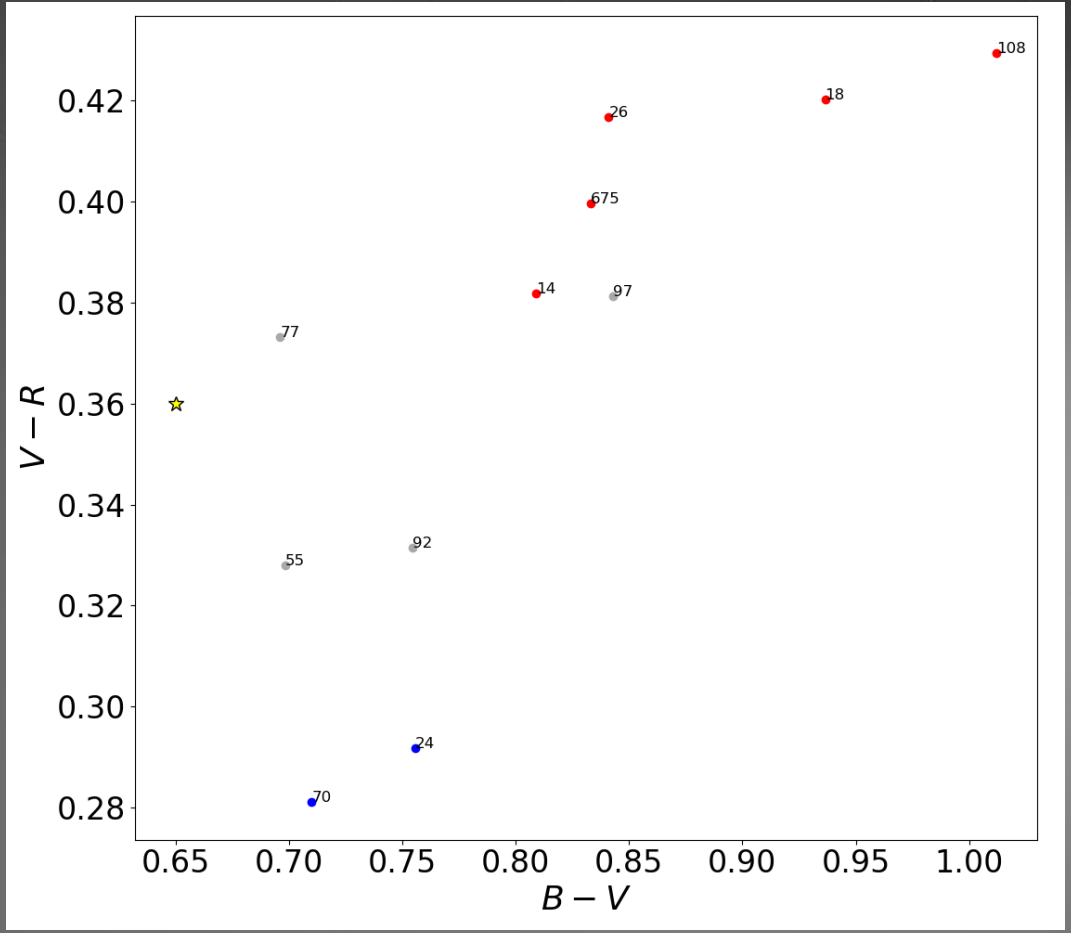
- 3 subsequent nights plus 3 additional nights of observations in both photometric systems;
- 39 targets observed (including 1 Centaur) plus standard Landolt stars for BVR_CI_C photometry;
- images processed using standard procedures (dark, flat) and transformed to standard magnitude system;
- chose 11 representative MBA targets of S,C,X spectral classes for demonstration

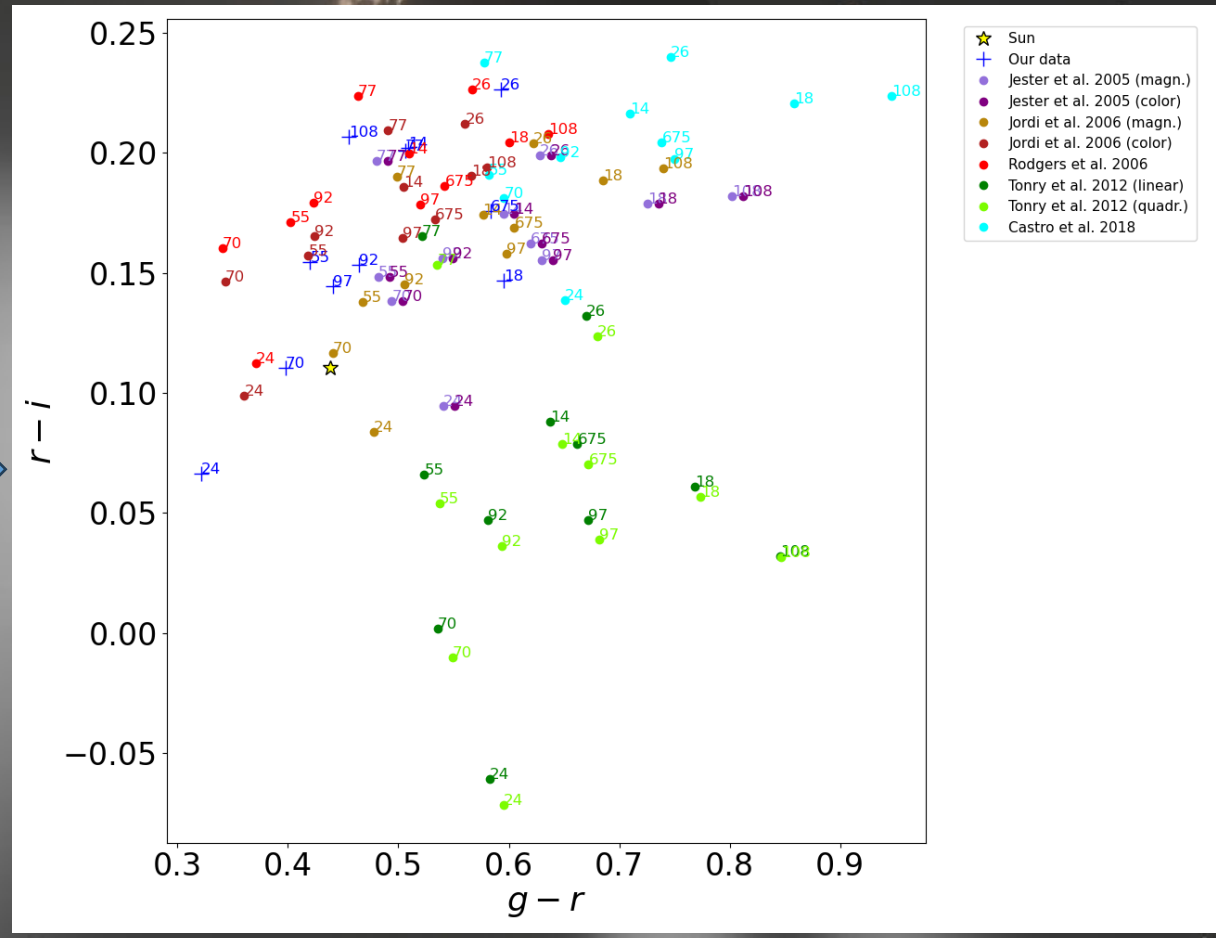
Observed targets



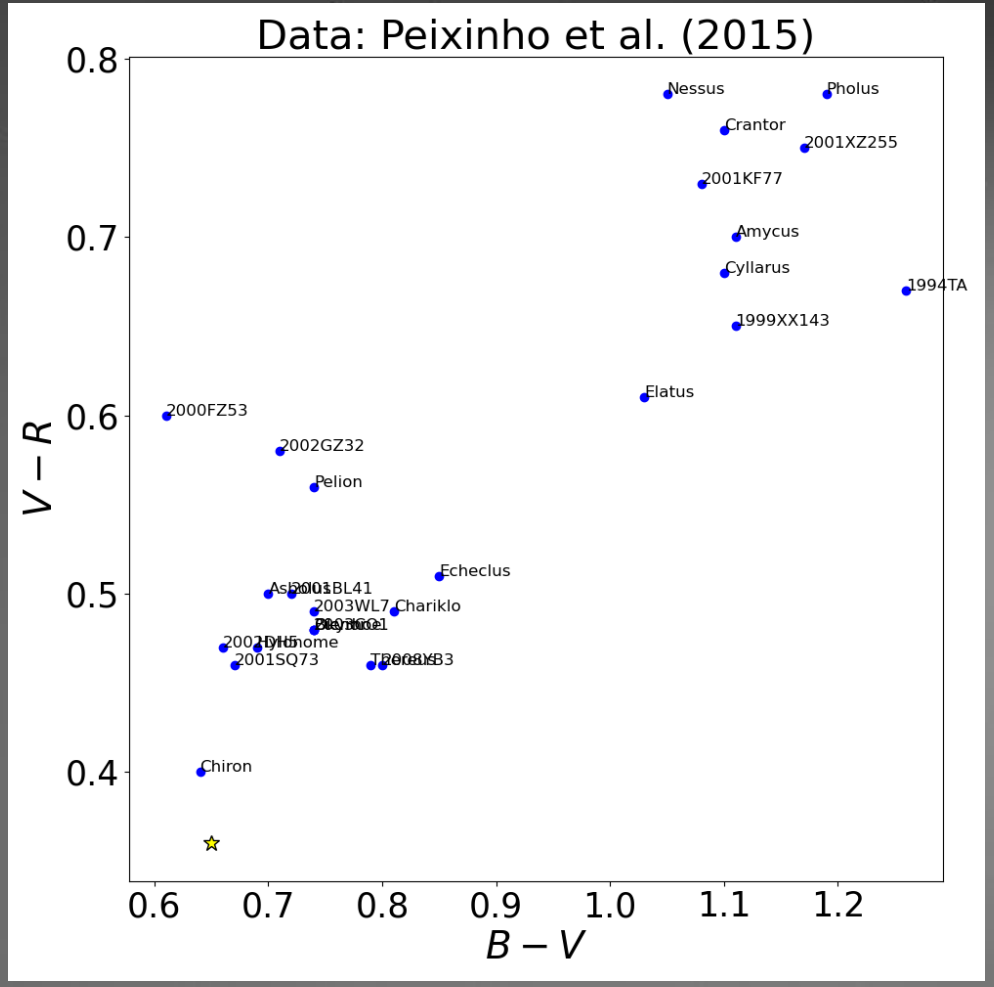


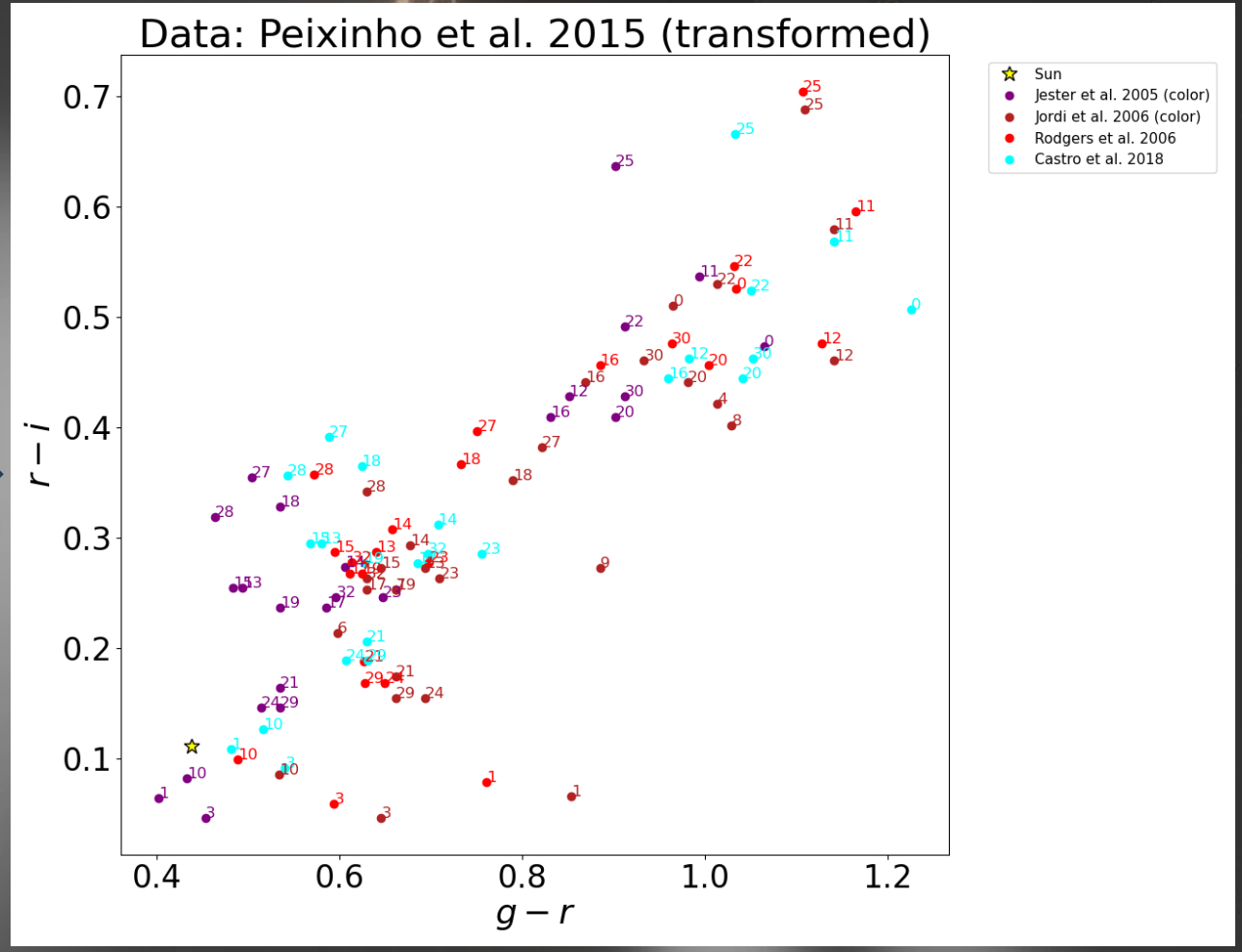
Data transforming





Application: Centaur data





Future work

- asses quantitatively which transformations are the most suitable for small Solar System bodies;
- use the best transformation relations on archive data on Centaurs;
- compare archive data with new data collected as part of our project;
- draw conclusions about surface changes of Centaurs in relation to other parameters


Thank you for attention!