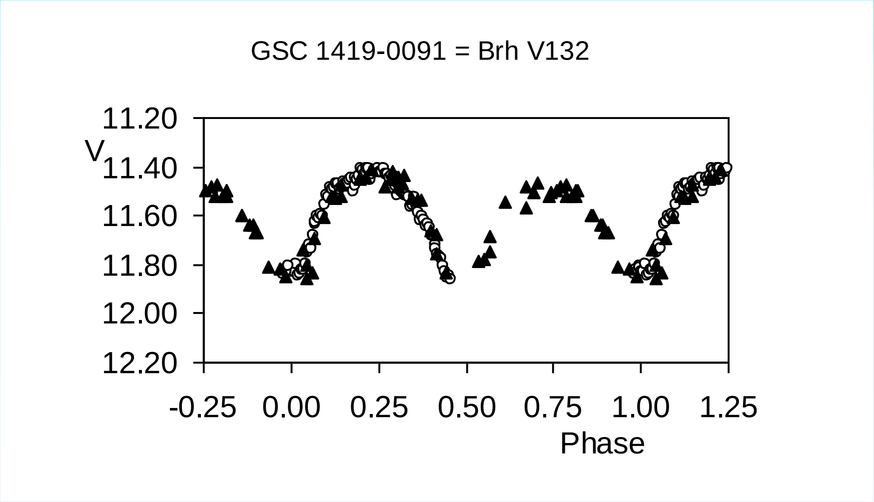
Discovery and time series analysis of chemically peculiar (CP2 and CP4) stars

Klaus Bernhard

My observing site on a balcony in Linz, Austria



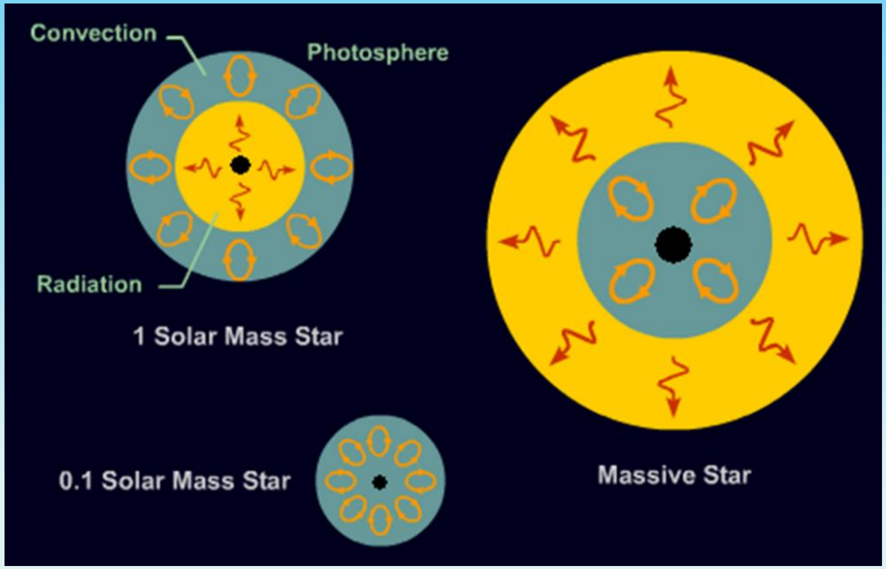
combination of own observations and data mining in publicly available surveys (ASAS)

Introduction

What are chemically peculiar stars?

- slowly rotating hot main-sequence stars (spectral classes early B to early F) with peculiar surface compositions (10-15% of upper main-sequence stars)

- peculiar composition is due to processes that took place after the star formed, in particular the competition between radiative levitation and gravitational settling in surface layers (Michaud 1970; Richer et al. 2000)

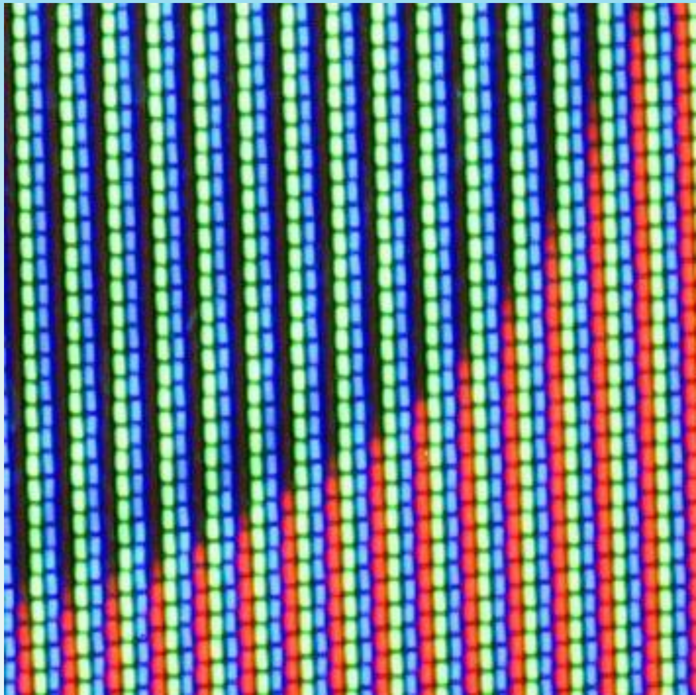


- most chemical elements tend to sink under the force of gravity; those with numerous absorption lines near the local flux maximum are driven outwards by radiative pressure

Introduction

ID	Common name	Main characteristics
CP1	metallic-line (Am) stars	underabundances of Ca and Sc, overabundances of iron-peak and heavier elements
CP2	magnetic Ap stars	enhanced Si, Cr, Sr, Eu, or rare earth elements
CP3	HgMn stars	enhanced Hg, Mn, and other heavy elements
CP4	He-weak stars	weak He lines

CP2 and CP4 stars: organized magnetic fields with non-uniform distribution of chemical elements; surface spots of enhanced or depleted element abundance; elements involved: silicon, strontium, chromium, europium, and many other elements.



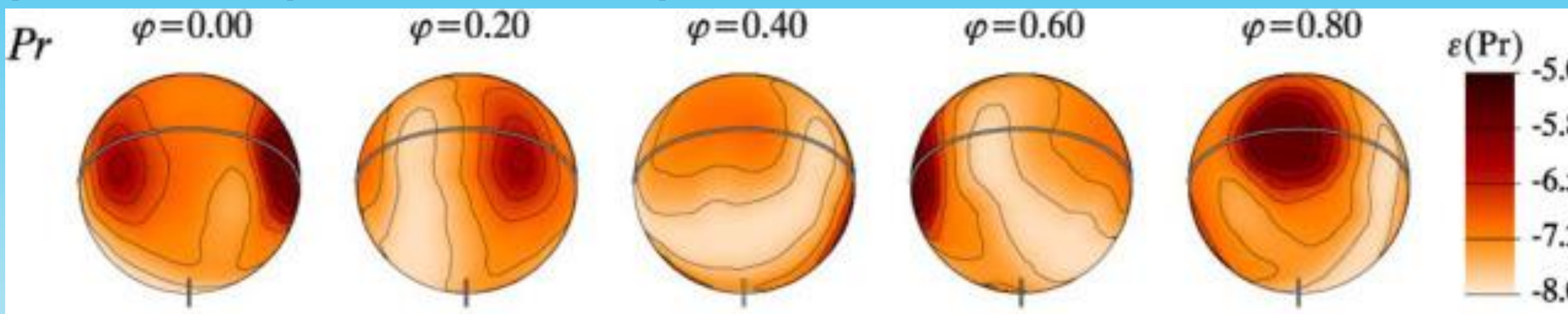
Most suitable for variable star astronomy!
Photometrically variable CP2/4 stars are traditionally referred to as **α2 Canum Venaticorum (ACV)** Variables, after their bright prototype.

Elements like europium: not very rare on earth; used for example in computer screens…

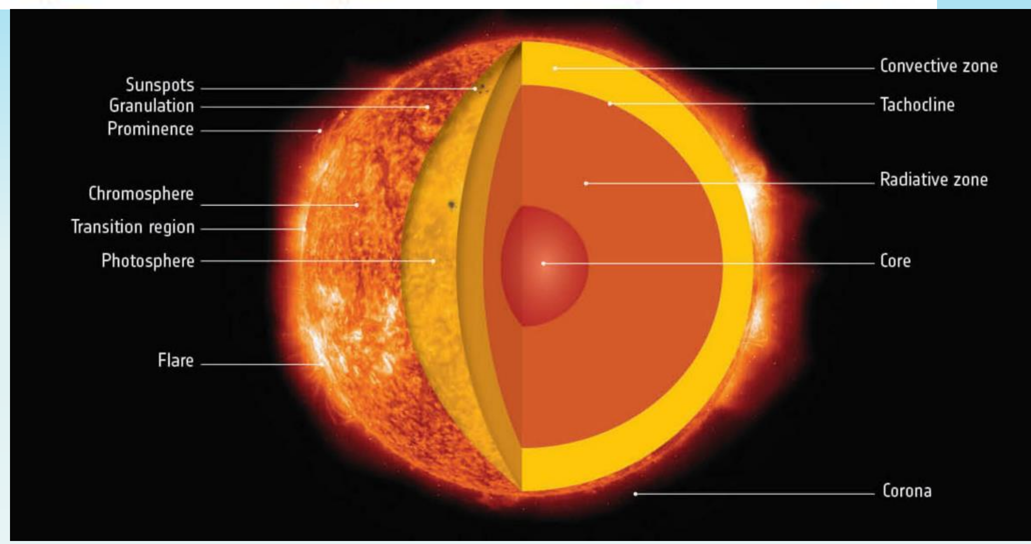
What do ACV light curves look like?

• non-uniform distribution of chemical elements: brighter and fainter spots/areas; brightness varies in different spectral bands

• "Oblique rotator model" (Stibbs 1950):
photometric period = rotation period

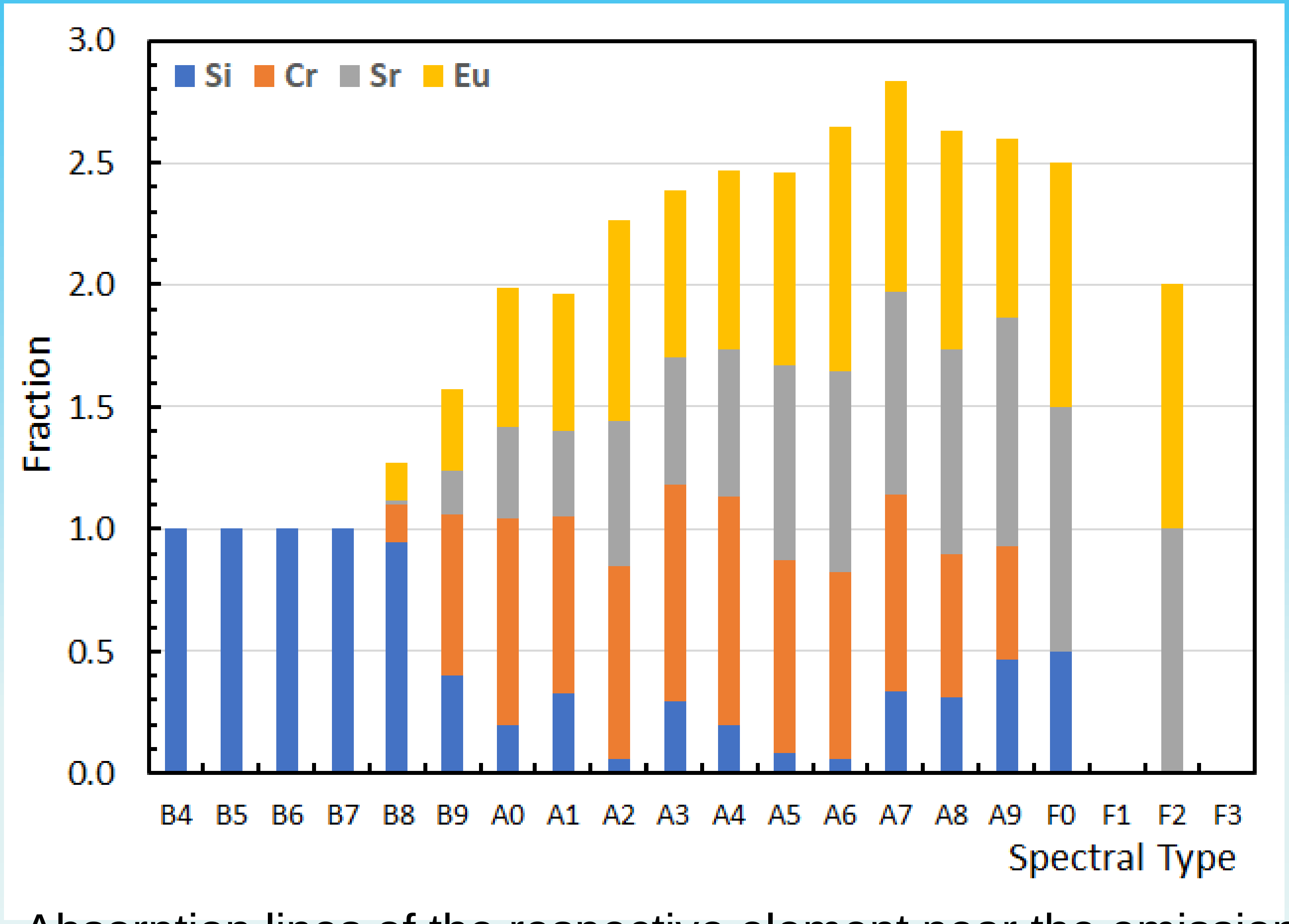


- Surface looks quite different from that of our sun; Figure: ESA



Surface temperatures and overabundant elements

From: A plethora of new, magnetic chemically peculiar stars from LAMOST DR4
(S. Hümmerich, E. Paunzen, K. Bernhard, 2020)



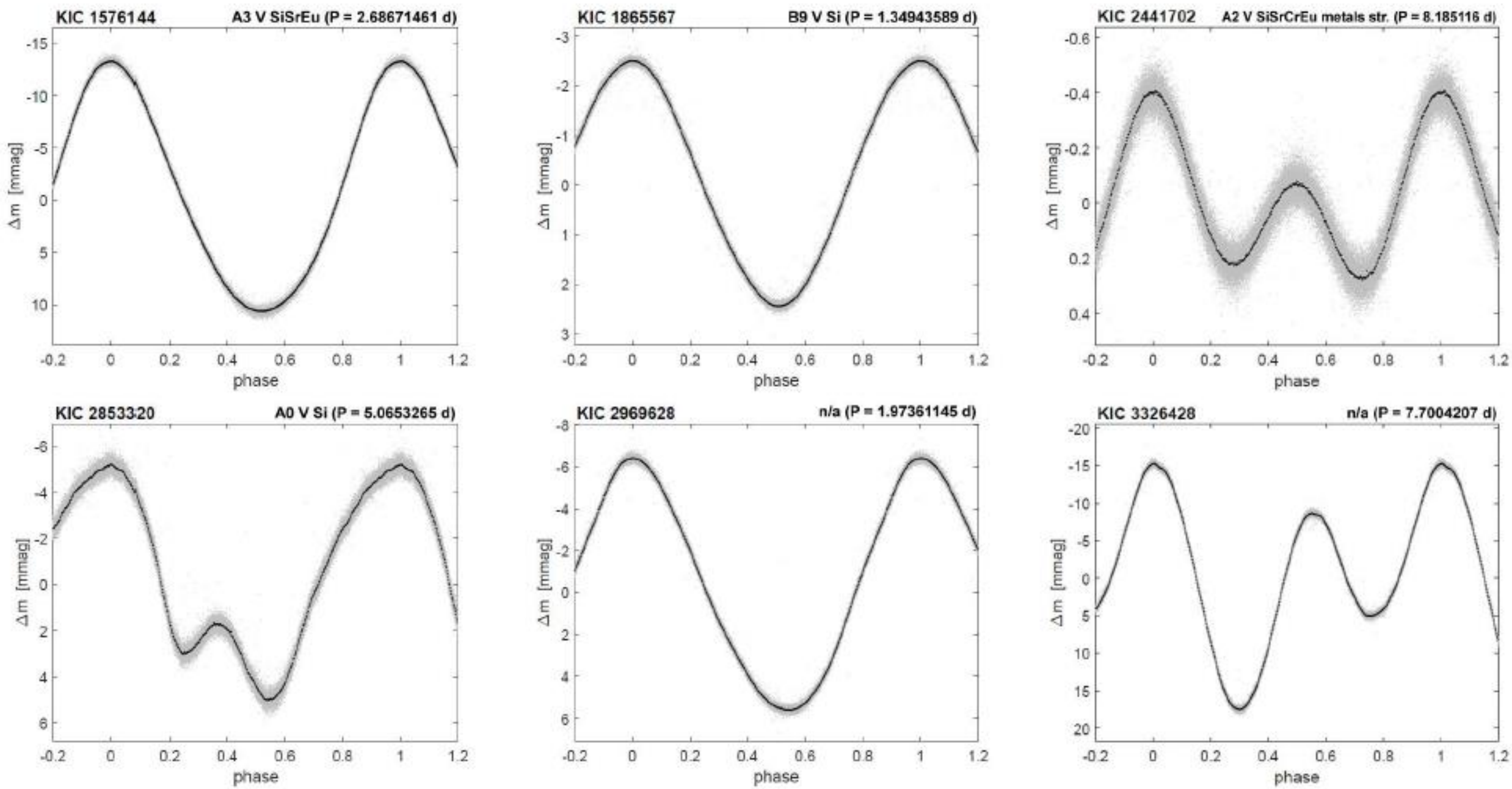
Absorption lines of the respective element near the emission maximum of the star

What do ACV light curves look like?

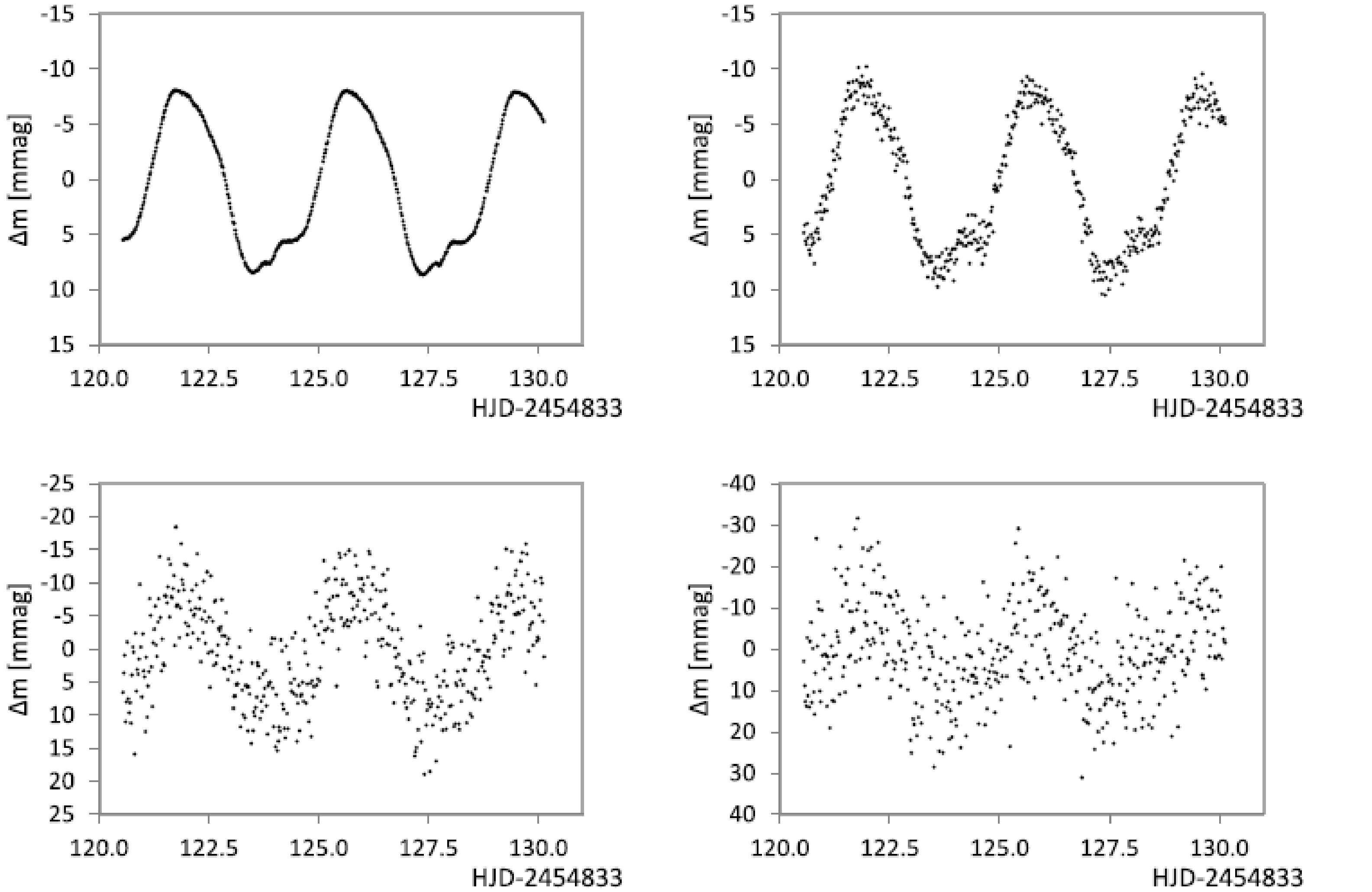
Astronomy & Astrophysics manuscript no. kepler1_rev1
August 20, 2018

The *Kepler* view of magnetic chemically peculiar stars

S. Hümmerich[1,2], Z. Mikulášek[3], E. Paunzen[3], K. Bernhard[1,2], J. Janík[3], I.A. Yakunin[4], T. Pribulla[5], M. Vaňko[5], and L. Matěchová[3]



Addition of Gaussian scatter ('artificial error') of 1, 5 and 10 mmag



<u>Characteristics of ACV light curves:</u>

- single wave, double wave or complex; peak-to-peak amplitude in most cases <0.2 mag

- usually one single frequency, in rare cases additionally pulsations

- chemical star spots much more stable than Sun-like spots

- periods usually between 1 and 10 d, longer or shorter periods possible: 0.5 d - 5 yr (and more!)

- multiband photometry exhibits interesting features: varying light curve shapes in different passbands, even antiphase variation is possible

- <u>confirmation with spectroscopic methods is required; the groups of CP2 and CP4 stars are by definition classified via their spectroscopic characteristics</u> (mostly enhanced lines of certain elements in the blue-violet spectral region; see for example Gray & Corbally, 2009)

<u>Where to get data?</u>

- own observations or data from various sky surveys;

a few examples:

ASAS-SN:
20 telescopes in different places
Nikon telephoto f400/2.8 lenses, diameter 14 cm
ProLine PL230 CCD cameras
https://asas-sn.osu.edu/

Kepler:
Satellite mission for exoplanets
0.95 m Schmidt telescope
21 modules with two 2200x2048 CCDs
https://archive.stsci.edu/kepler/

The All Sky Automated Survey (ASAS, Poland)

- "low-cost project" for photometric monitoring of the southern sky and parts of the northern sky ($\delta < +28°$)

- data of the third phase (ASAS-3; 2000 – 2009) publicly available

- good photometry for 10^7 stars in the range 7 < V < 14 mag

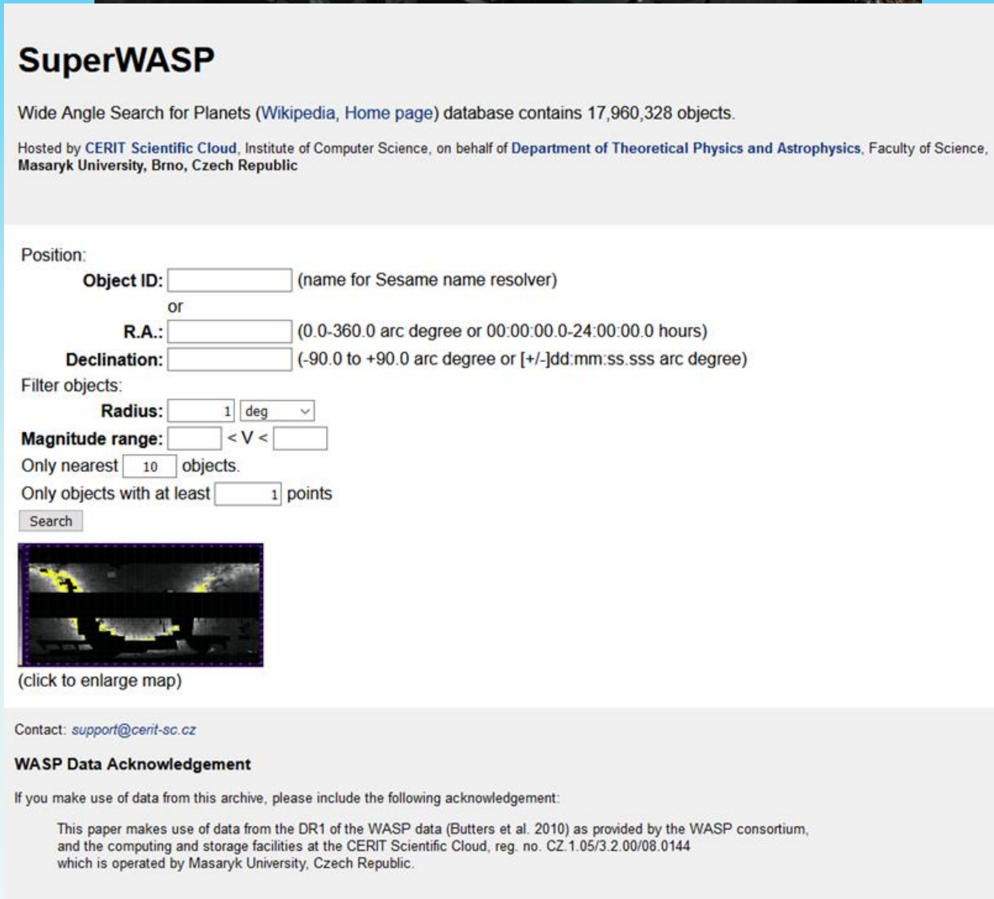
- suitable also for the search for microvariables (variability amplitude: 4-5 mmag; especially in the range 8 < V < 10 mag, for example Pigulski 2014)

- even known exoplanets have been confirmed in ASAS data (Hümmerich & Bernhard, 2015)

ASAS telescopes, Las Campanas, Chile; source: ASAS homepage

SuperWASP (Instituto de Astrofísica de Canarias (IAC) and six universities from the United Kingdom)

- Observatorio del Roque de los Muchachos (La Palma)
- South African Astronomical Observatory (SAAO)
- stations equipped with eight f/1.8 200mm Canon lenses and 2048 x 2048 Andor CCDs, field of view 7.8°x7.8°
- ca. 18 million suitable light curves in the range of 8 – 14 mag



SuperWASP

Wide Angle Search for Planets (Wikipedia, Home page) database contains 17,960,328 objects.

Hosted by CERIT Scientific Cloud, Institute of Computer Science, on behalf of Department of Theoretical Physics and Astrophysics, Faculty of Science, Masaryk University, Brno, Czech Republic

Position:
Object ID: (name for Sesame name resolver)
or
R.A.: (0.0-360.0 arc degree or 00:00:00.0-24:00:00.0 hours)
Declination: (-90.0 to +90.0 arc degree or [+/-]dd:mm:ss.sss arc degree)
Filter objects:
Radius: 1 deg
Magnitude range: < V <
Only nearest 10 objects.
Only objects with at least 1 points
Search

(click to enlarge map)

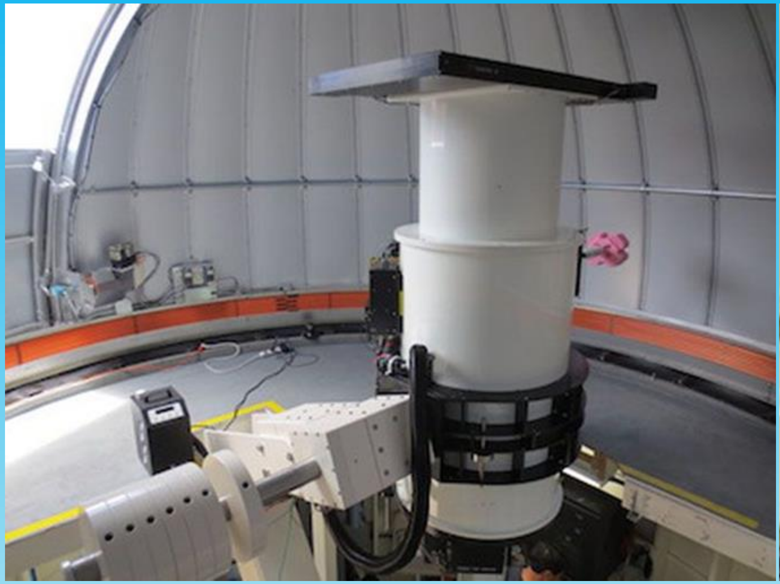
Contact: *support@cerit-sc.cz*

WASP Data Acknowledgement

If you make use of data from this archive, please include the following acknowledgement:

This paper makes use of data from the DR1 of the WASP data (Butters et al. 2010) as provided by the WASP consortium, and the computing and storage facilities at the CERIT Scientific Cloud, reg. no. CZ.1.05/3.2.00/08.0144 which is operated by Masaryk University, Czech Republic.

Some deep surveys



ATLAS (**A**steroid **T**errestrial-impact **L**ast **A**lert **S**ystem)

- 50 cm diameter f/2 Wright-Schmidt telescope with 110 megapixel camera
- field of view: 7.4°x7.4°; complete sky visible from Hawaii two times per night; objects brighter than 20 mag

http://mastweb.stsci.edu/mcasjobs/

ZTF (The **Z**wicky **T**ransient **F**acility new time-domain survey)

- first light at Palomar Observatory in 2017.
- 47 square degree, 600 megapixel cryogenic CCD mosaic science camera; objects brighter than 20.5 mag

Could also identify faint ACVs in the galactic halo

Most surveys provide an automatic analysis and classification of variable stars. Why does it still make sense to search for ACVs in these data bases? example: ATLAS

A First Catalog of Variable Stars Measured by the Asteroid Terrestrial-impact Last Alert System (ATLAS)

A. N. Heinze[1], J. L. Tonry[1], L. Denneau[1], H. Flewelling[1], B. Stalder[2], A. Rest[3,4] K. W. Smith[5], S. J. Smartt[5], and H. Weiland[1]

Results

- analysis of 142 million light curves with at least 100 data points from the first 2 years of observation
- 4.7 million variable star candidates with light curves
- among them 427.000 clearly variable stars, identified and classified with "machine learning"
- among them 214.000 specific variables (eclipsers etc.)
- **141.000 new discoveries**

The mysterious 'upside-down CBH' variables - close eclipsing binaries?

A First Catalog of Variable Stars Measured by the Asteroid Terrestrial-impact Last Alert System (ATLAS)

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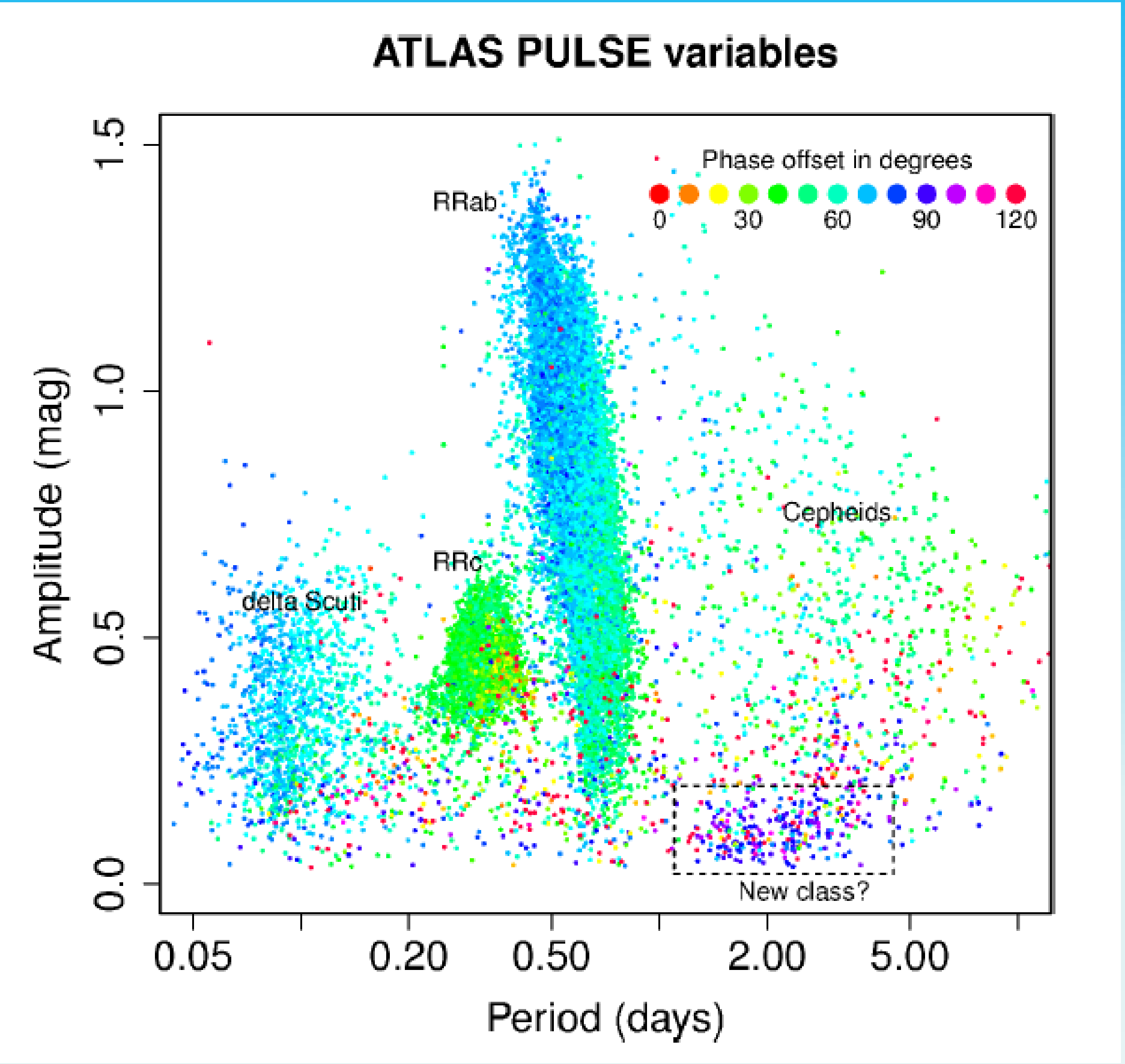
7. Interesting and Mysterious Subtypes

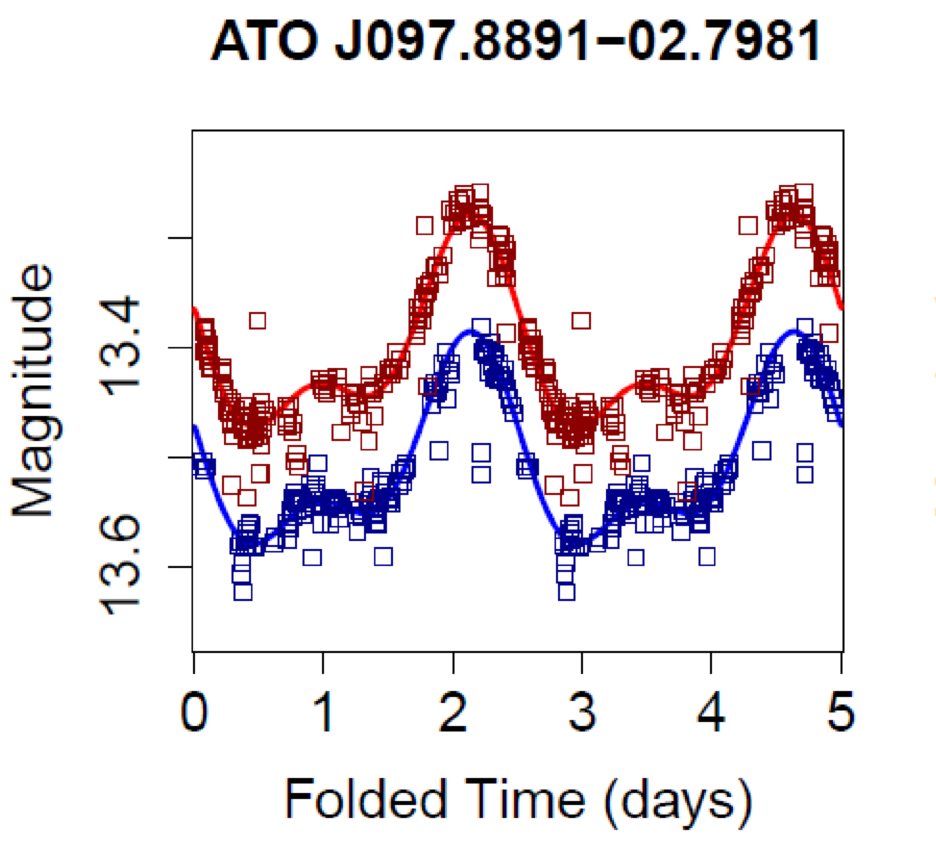
7.1. 'Upside-down CBH' Variables

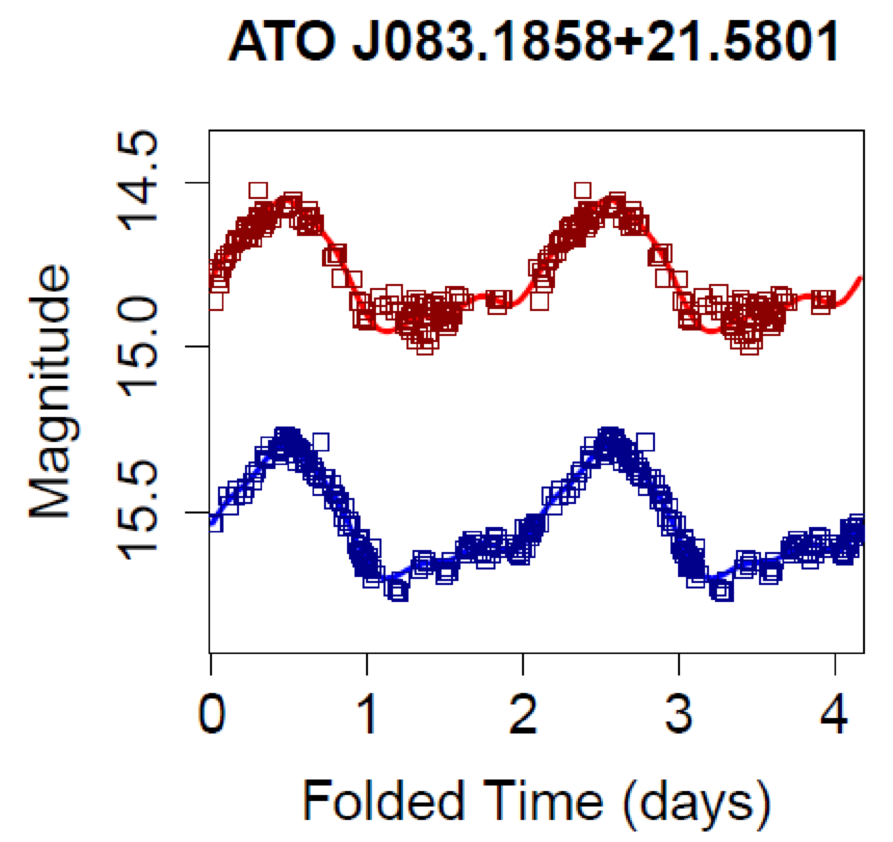
These objects correspond to the possible new class of variables labeled in Figure 23. We first noticed them long before constructing the figure, when we were screening lightcurves manually in order to construct the training set for machine learning. A distinctive lightcurve shape, not matching any known type of variable, was seen repeatedly in the course of our screening. When

Location of proposed new type of variables in the period vs. amplitude diagram



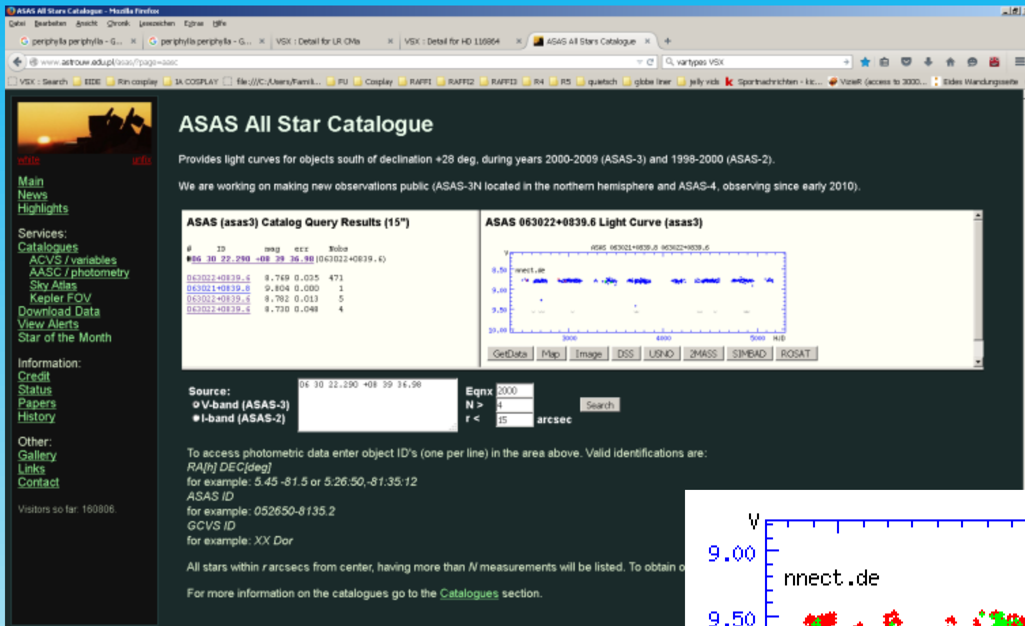
These "unknown variables" look exactly like (and in all likelihood are!) ACV variables.



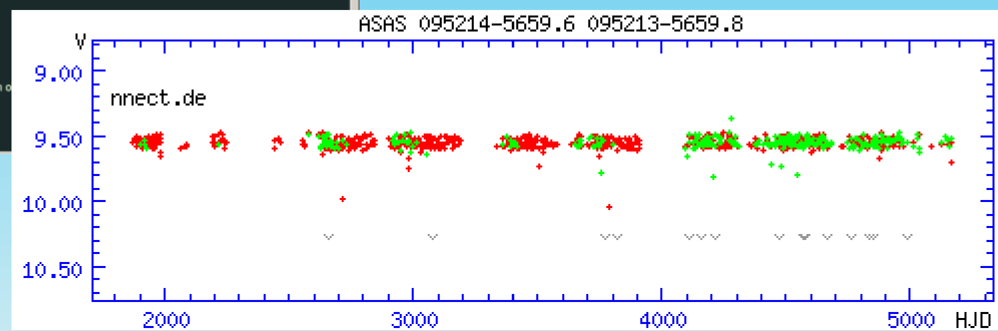


➔ Many surveys ignore the rather rare class of ACV variables. They frequently end up mixed with other groups (like RS CVn stars) or are listed as MISC-type or 'unsolved' variables.

How to download time series data:



Example of an ACV project: download of light curves of spectroscopically confirmed ACVs (Renson & Manfroid 2009; 5000 objects)

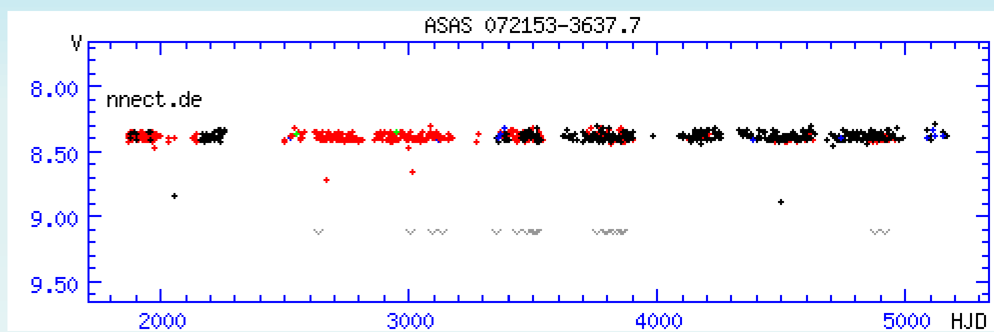


- removal of obvious outliers

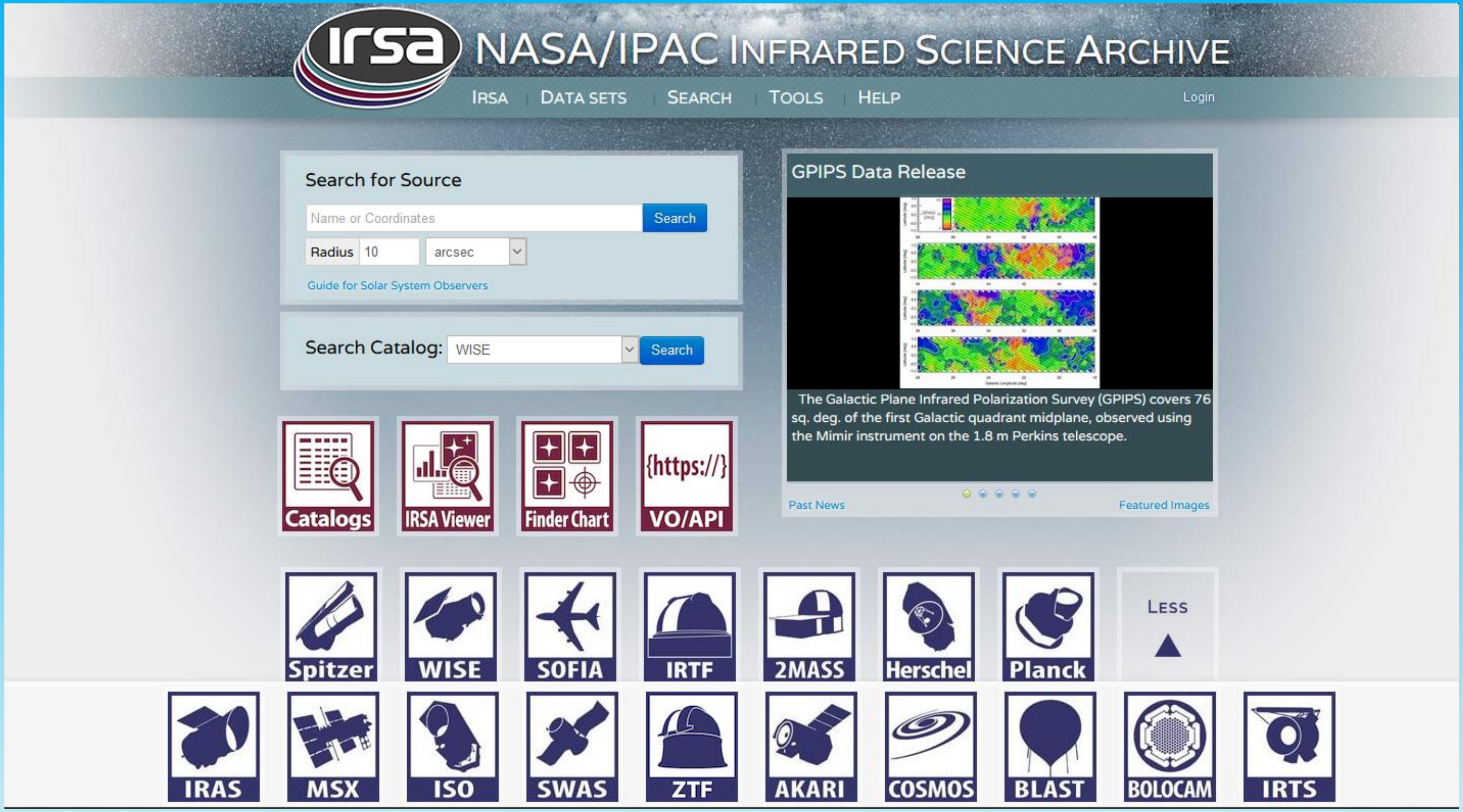
- removal of data points with quality flag of 'D' (='worst data, probably useless')

- removal of instrumental trends, zero point issues between data sets

- **workflow may be applied to many surveys**



ZTF data query in the NASA/IPAC Infrared Science Archive:



Obtain the available g-band lightcurves within 5 arcsec of a source position:

https://irsa.ipac.caltech.edu/cgi-bin/ZTF/nph_light_curves?POS=CIRCLE 298.0025 29.87147 0.0014&BANDNAME=g

In this way the light curves of your seminar were downloaded

OR use the private homepage of Dr. Chen:

http://variables.cn:88/lcz.php?SourceID=109576

Survey data sets are tricky, take care of HJD/MJD issues!

Astronomy

TONIGHT'S SKY
Waukesha, WI
October 27, 2020

SUN & MOON | MERCURY & VENUS | MARS, JUPITER & SATURN

Sun
RISE 7:22 AM
SET 5:51 PM

Moon
4:40 PM
3:15 AM

PHASE Waxing gibbous
DISK 84%

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Two stars will merge in 2022 and explode into red fury

Get ready for a big nova event.

By John Wenz | Published: Friday, January 6, 2017

STScI

Survey data sets are tricky!


scienceAlert
Trending
(NASA, ESA and H.E. Bond (STScI))

SPACE

4 Years From Now a New Star Was Predicted to Appear in Our Sky. But There Was a Typo

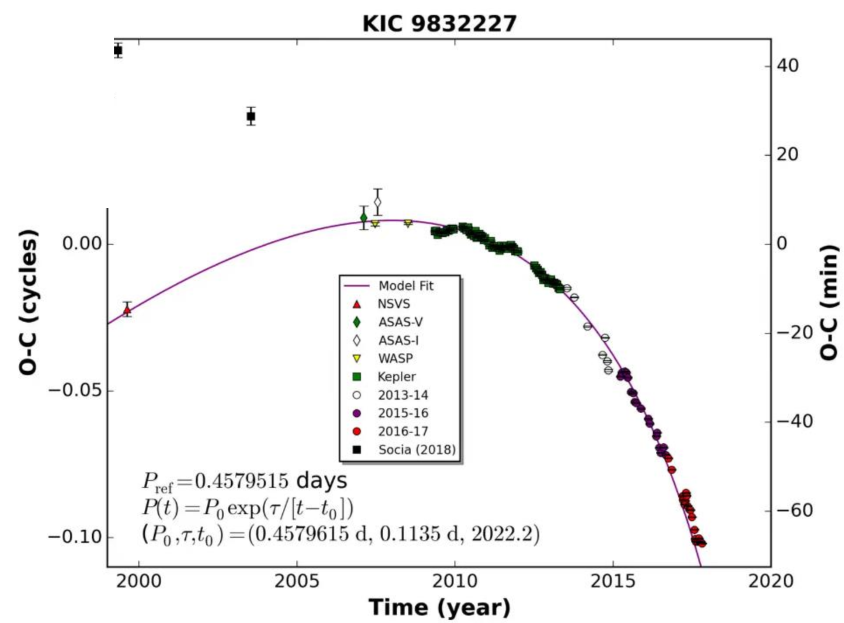
MICHELLE STARR 10 SEPTEMBER 2018

Well, this sure is one parade that's getting rained out of existence. A spectacular astronomical event that had been predicted for 2022 now isn't going to happen after all.

MJD Modified Julian Date:

MJD=HJD-2400000.5

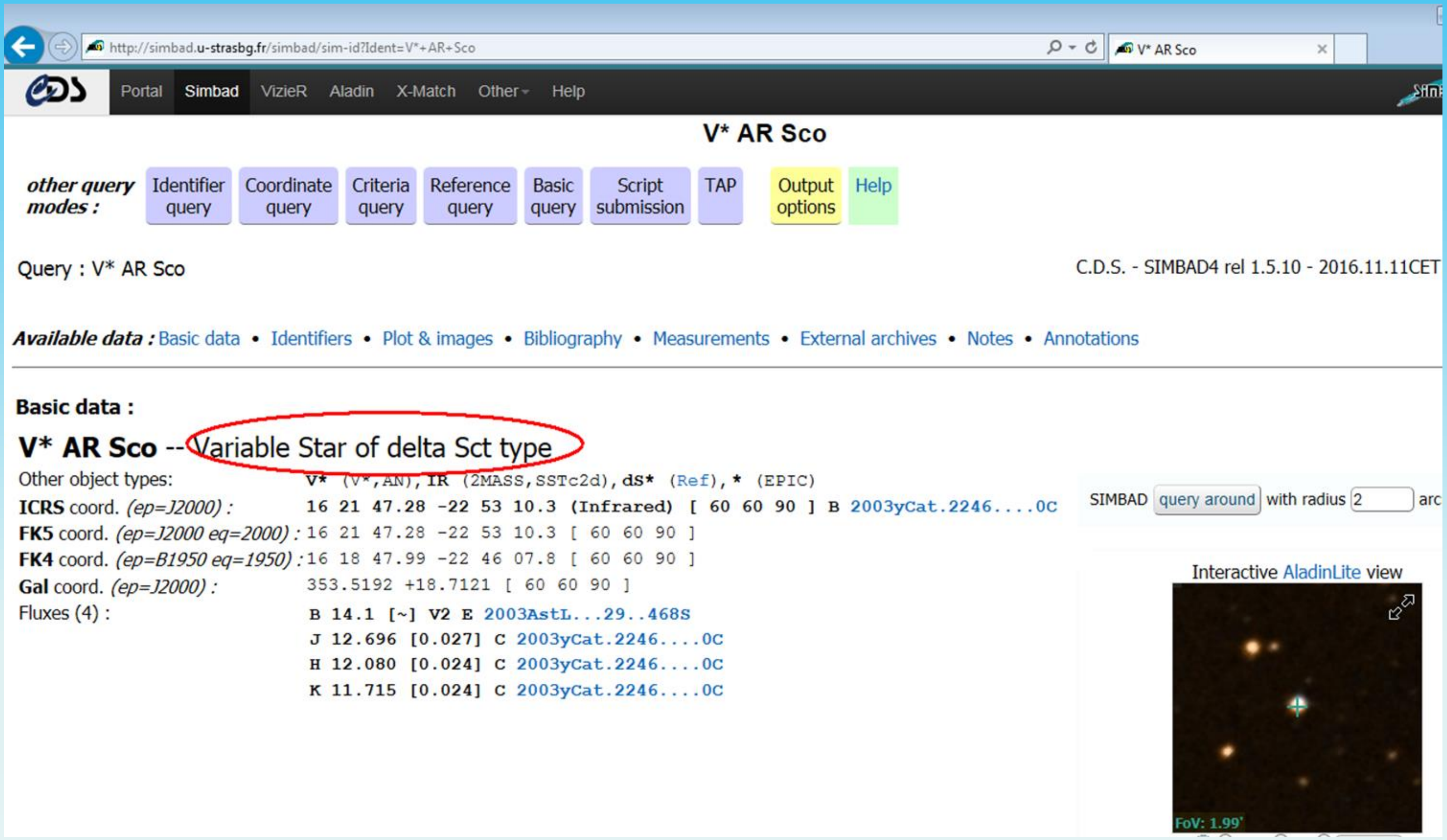
not: MJD=HJD-2400000



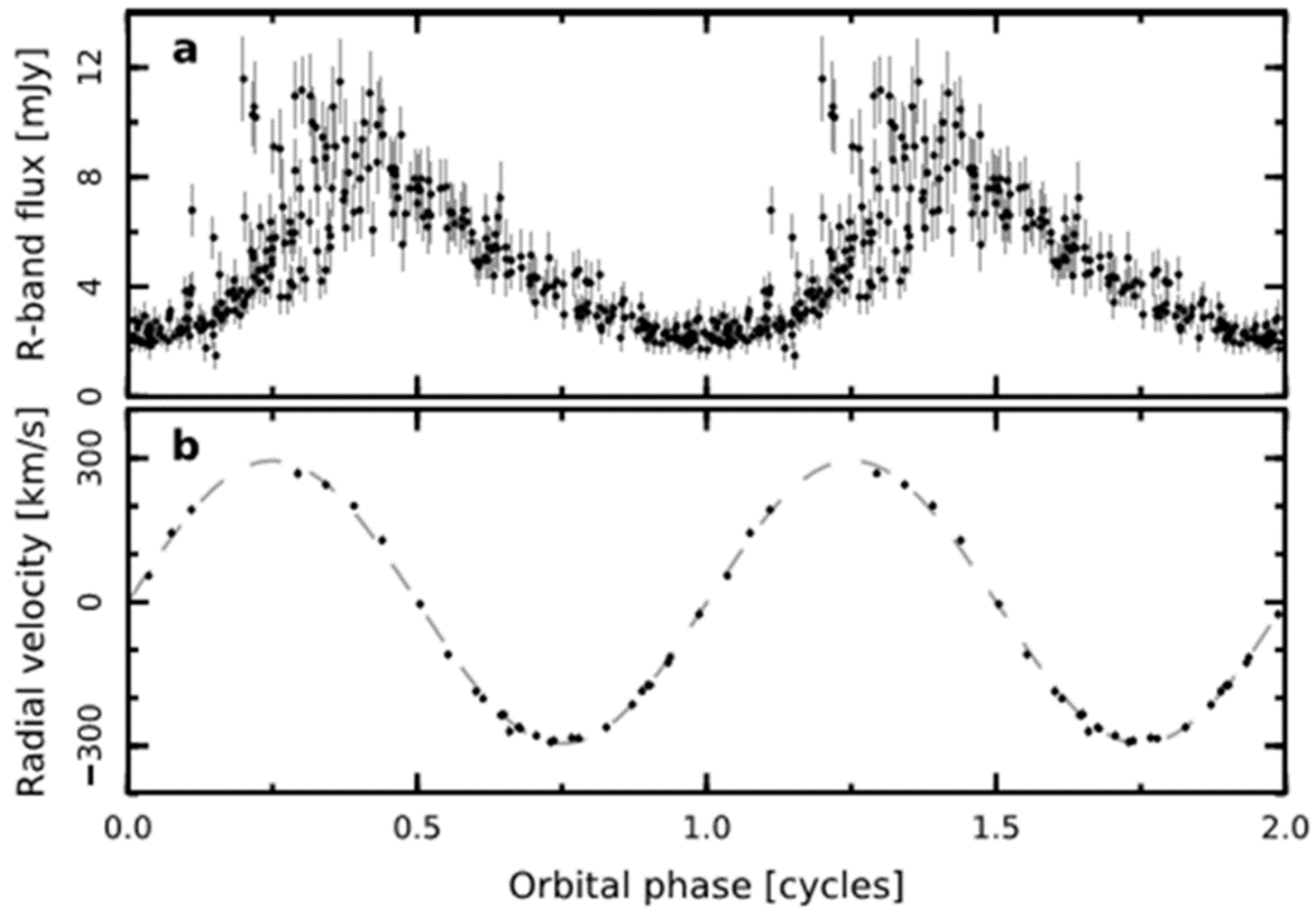
The modified Julian Date (MJD) was introduced by the Smithsonian Astrophysical Observatory in 1957, when storage space was still very expensive.

On the other hand: don't give up, if you come across weird data.

On the contrary: you might possibly be on the brink of an interesting discovery! Although these are rare, they do happen.



As in the case of AR Sco:



A striking example of the productivity of collaborations between amateur and professional astronomers.

STARGAZER'S CORNER:ADVENTURES UNDER THE NIGHT SKY

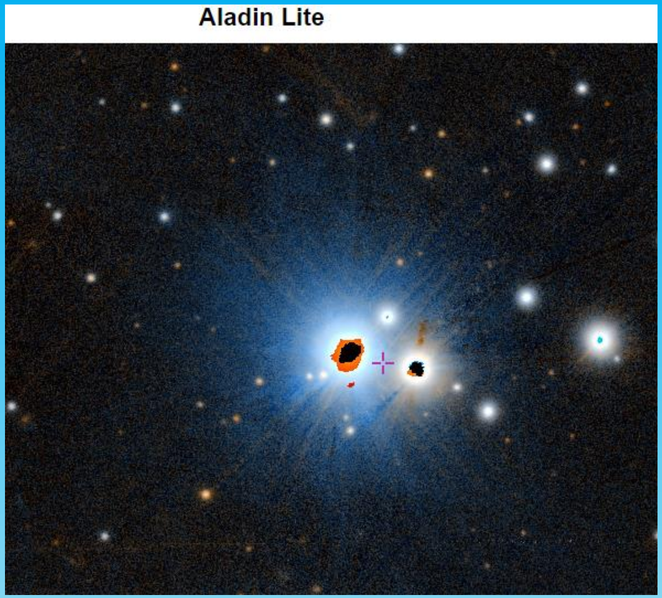
AMATEURS HELP DISCOVER PULSING WHITE DWARF

BY: FRANZ-JOSEF HAMBSCH | AUGUST 15, 2016 | 2

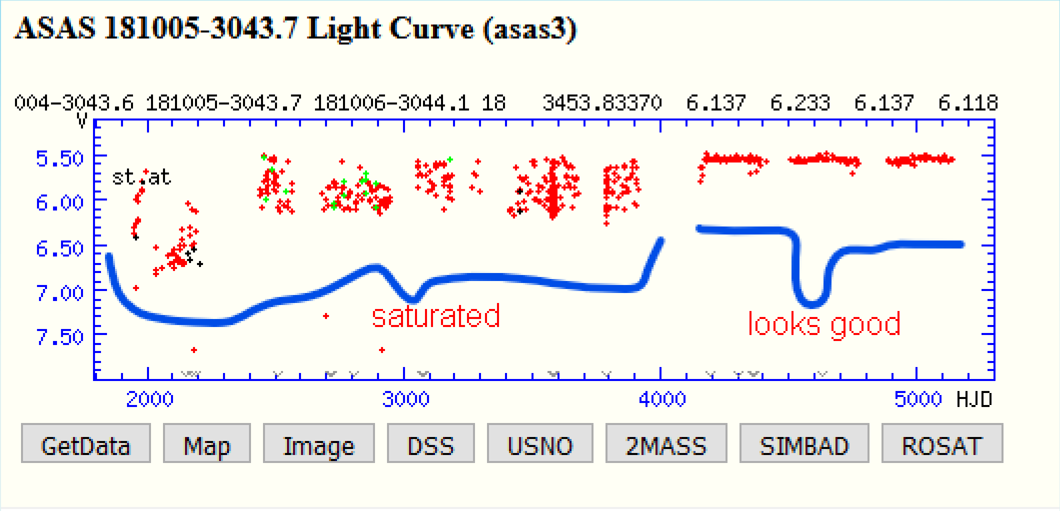
An artist's impression shows the exotic binary system, AR Scorpii.
M. Garlick / University of Warwick / ESO

Other troubles with survey data sets

- **blending**



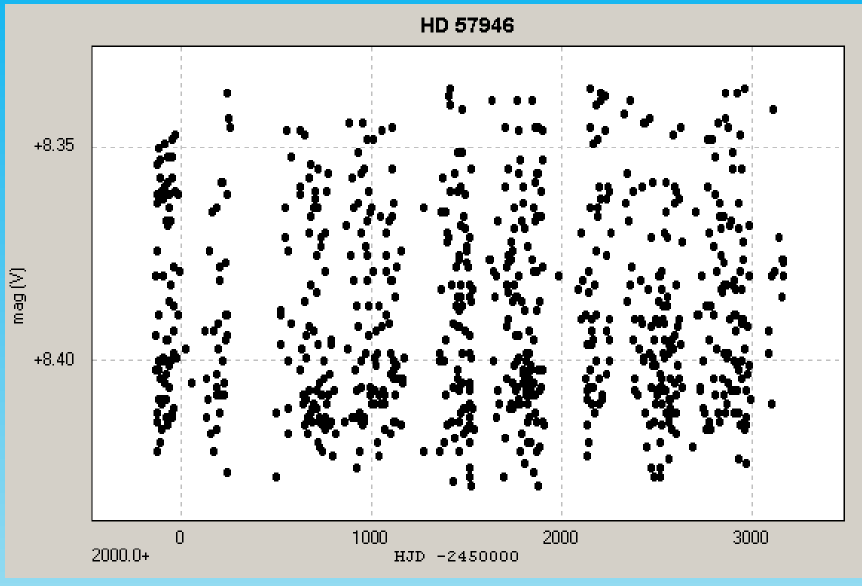
- **saturation**



What are time series analysis?

- A time-series is a **series of observations** (or measurements, data) taken at different times. We thus obtain a set of data pairs (t, x), where t is the time and x is the observation (data value).
- We assume that t is error free, and that x is a **combination of the true signal plus some error**.
- Time-series analysis is the application of mathematics to find **periodic signals** in data. In doing so, we ultimately want to learn something about the physics involved in the phenomenon.
- 1. **Fourier methods**: these methods attempt to represent a set of observations with a series of trigonometric functions (sines and cosines, with different periods, amplitudes and phases). Examples: Lomb-Scargle, Bloomfield, Discrete Fourier Transform (DFT; Deeming) ...
- 2. **Statistical methods**: instead of fitting the observational data with trigonometric functions, statistical methods compare points in the observational data to other points at fixed time intervals or "lags" to see how different they are from one another. These methods are very suitable for the analysis of observational data that include **non-sinusoidal periodic components**. Examples: ANOVA (observations fit with periodic orthogonal polynomials), PDM, Lafler-Kinman ...

Time series analysis of an improved data set



Many programs available: Period04, (University of Vienna, Austria), Peranso (Vanmunster & Paunzen), vartools (University of Princeton, USA)

Sinusfit with fourier analysis

Period04 (Lenz & Breger 2005)

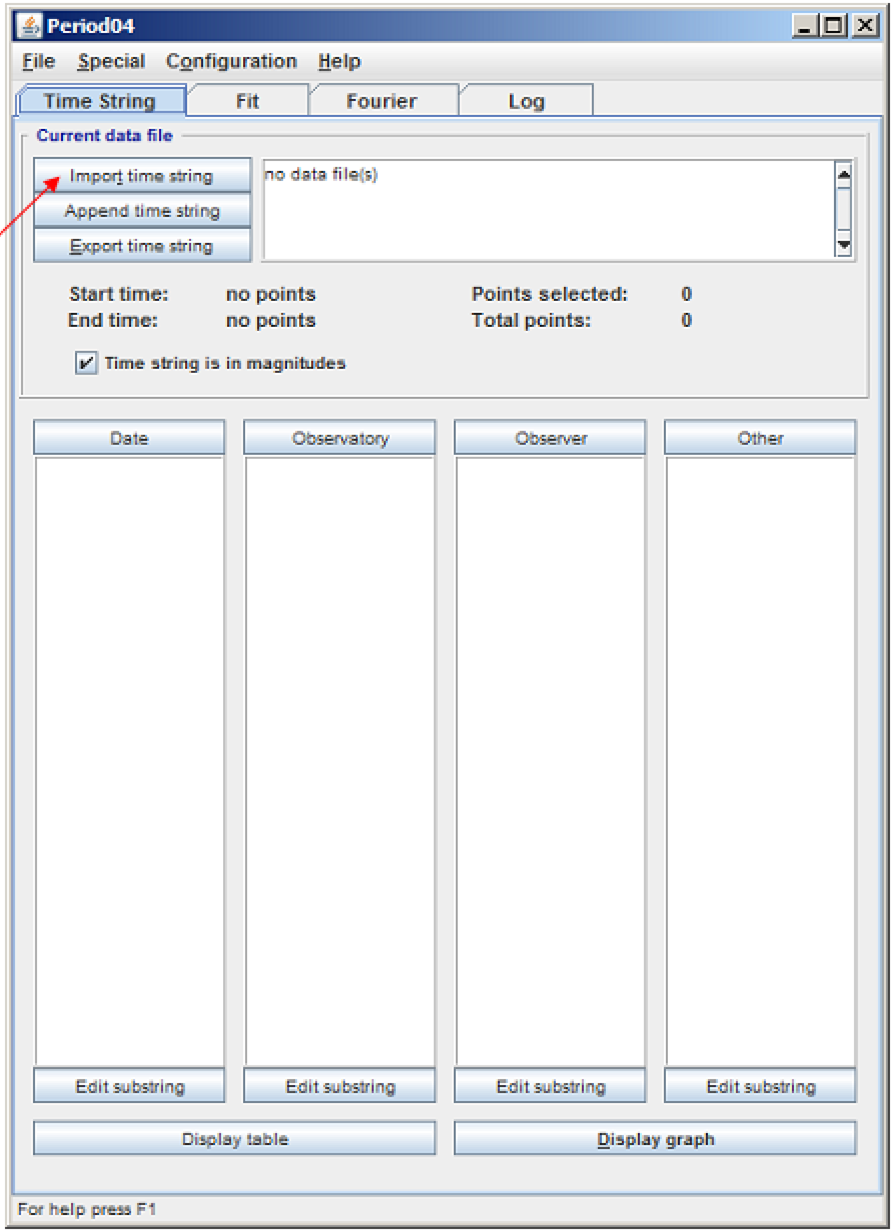
Fitting formula: $Z + \Sigma\, A_i \sin(2\pi\, (\Omega_i\, t + \Phi_i))$

Calculations based on: (●) Original data ( ) Adjusted data

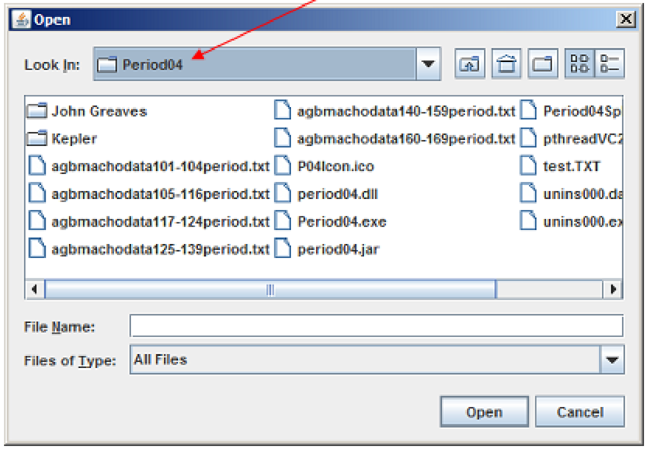
Period04: example workflow

(1)
data import

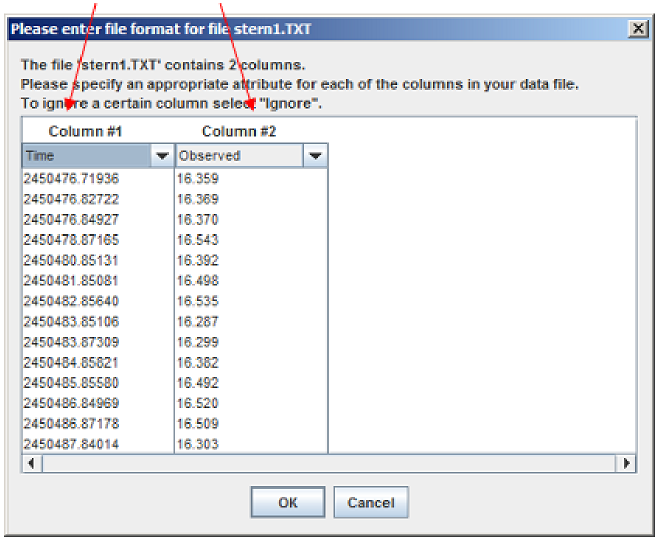
import textfile with time series data



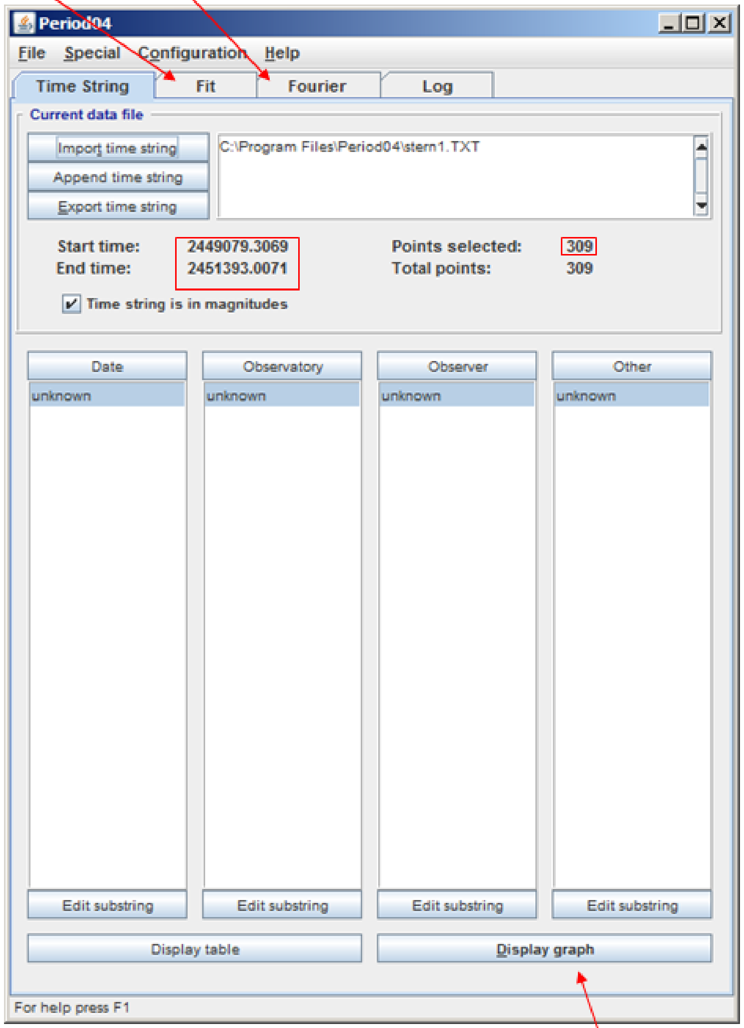
(2) Choose the directory containing the corresponding textfile(s) and confirm with "Open".



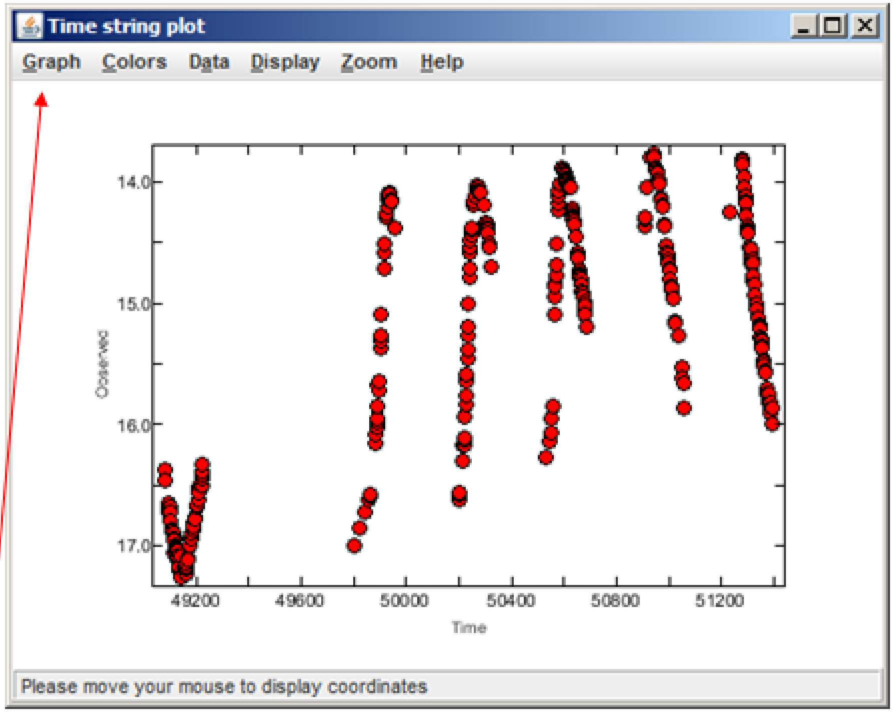
(3) The first column ("Column #1") should contain the date of observation in Julian Days (JD) format. The second column ("Column #2") lists the observed magnitudes. These colums need to be defined as "Time" and "Observed".



After the import of the time string, you will be faced with the window shown below, which lets you track the start and end times of the time series data. In the following workflow, use will be made of the tabs "Fit" and "Fourier".



"Display graph" lets you view the light curve (see following page).

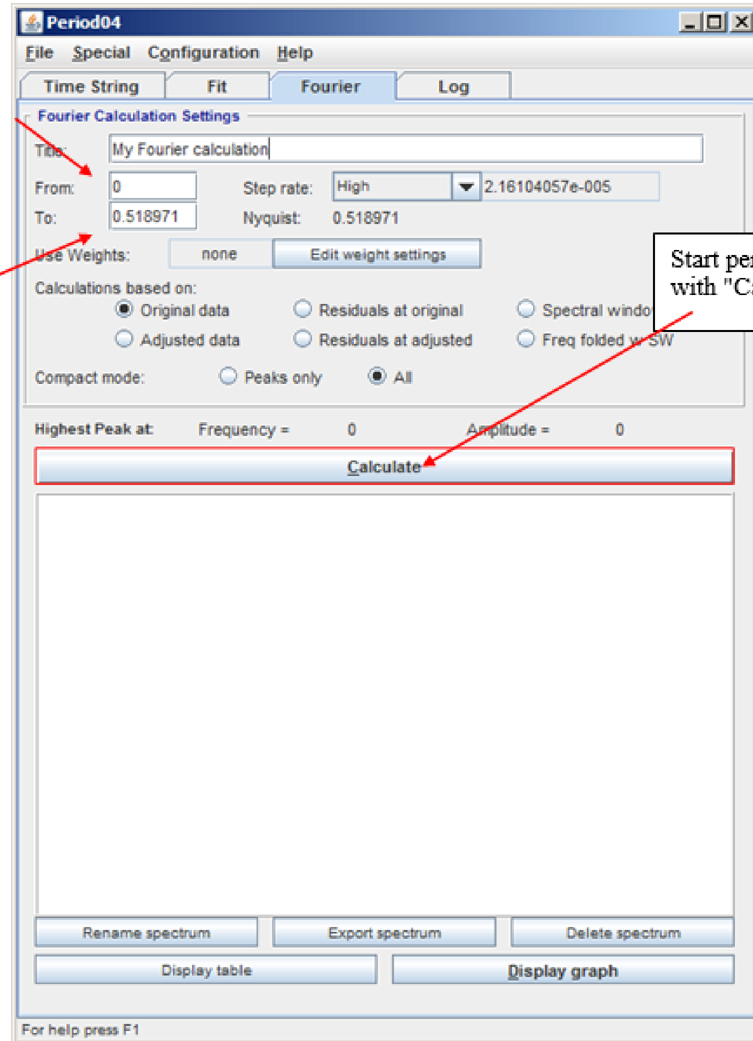


(Light curve view via "Display graph".)

The current light curve view can be exported via "Graph" ➔ "Export Graphs As" ➔ "jpg" (…).

(4) period search

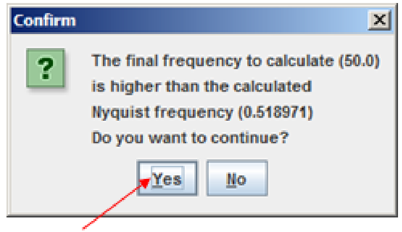
For the period search, we change to the tab "Fourier". The frequency range may need to be adjusted in the input fields "From" and "To". **It is important to note that Period04 uses and returns frequency values (*f*, which is given in "cycles per day"; period $P = 1/f$).**

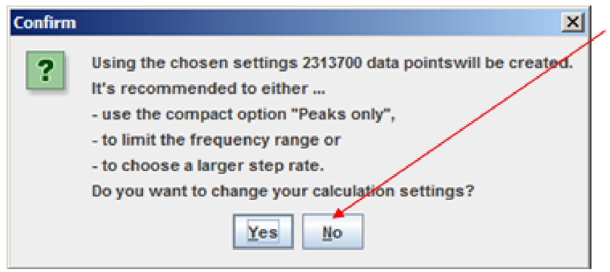


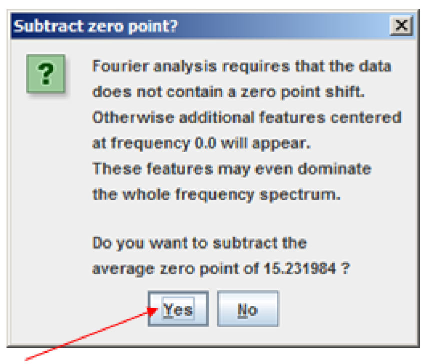
Start period search with "Calculate".

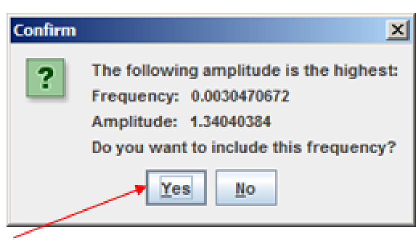
Nyquist frequency <0.5 fs

Before the period search starts, you will need to click through some (or all) of the below listed windows. As a first rough guideline, if you are not sure what to do, use the options indicated by the red arrows. (Of course, depending on the situation, these setting may need to be adjusted!)





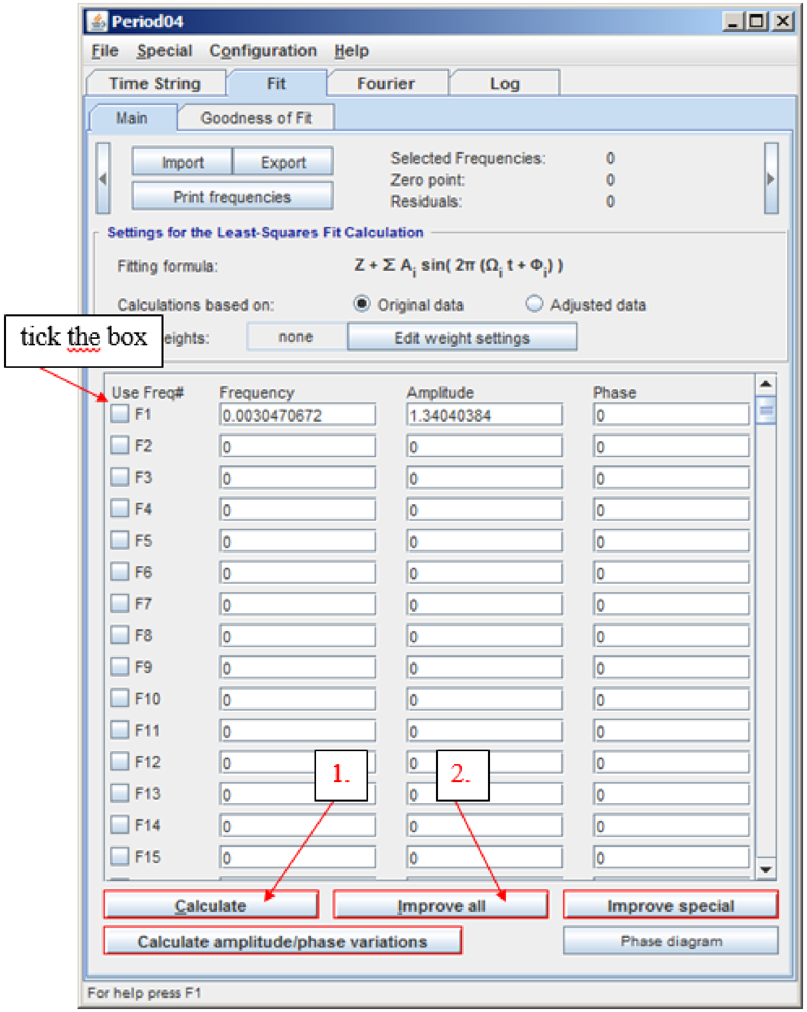




Period04 now lists the derived frequency (F) and the corresponding amplitude (A). Using the button "Display graph", we can now visualize the Fourier spectrum.

(5) improving a derived frequency via least-squares fit

Under the tab "Fit", we can improve the derived frequency / frequencies via a least-squares fit. To do so, we need to tick the boxes next to the corresponding frequencies (next to "F1" in the example shown below). Then confirm with "Calculate" and "Improve all".

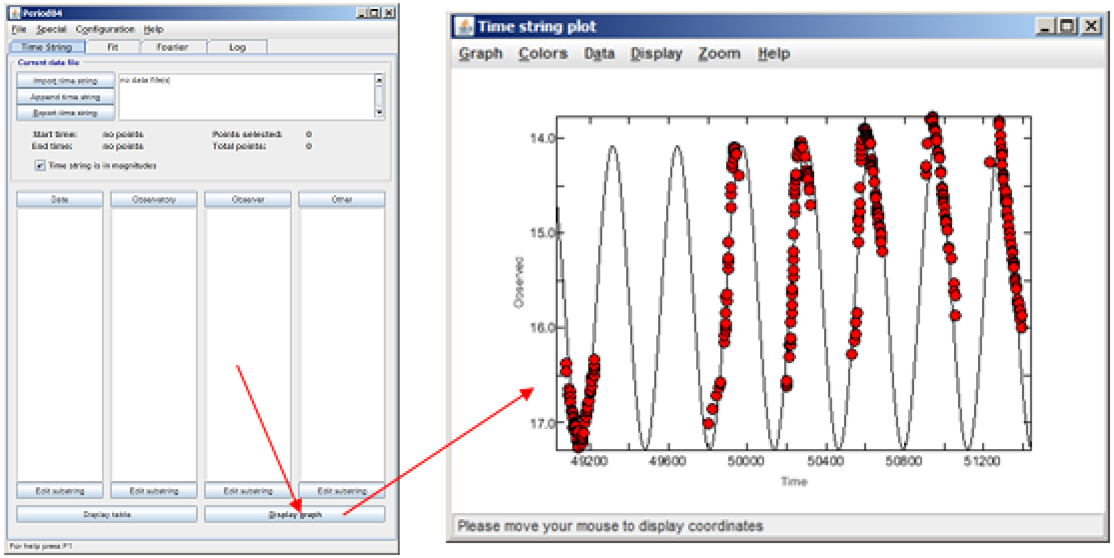


➔ In the illustrated example, we derive a frequency of $f = 0.00305$ cycles per day (c/d), which corresponds to a period of $P = 327.9$ days (1/0.00305=327.86885).

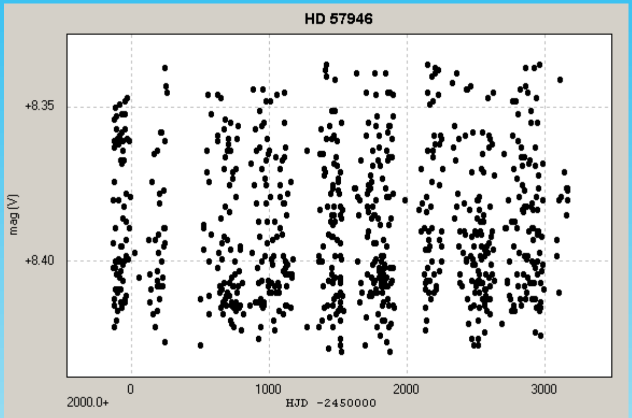
(6) light curve fit

To visualize the light curve fit, we change back to the tab **"Time String"** and select "Display graph". Period04 now shows the original light curve plus the sine-wave fit. This is useful to do a quick visual "sanity check" on the derived frequency.

In the illustrated example, the derived frequency fits the observations well, as illustrated below.

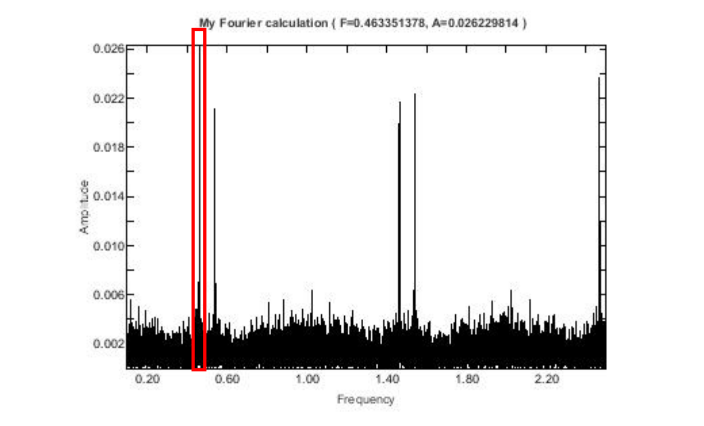


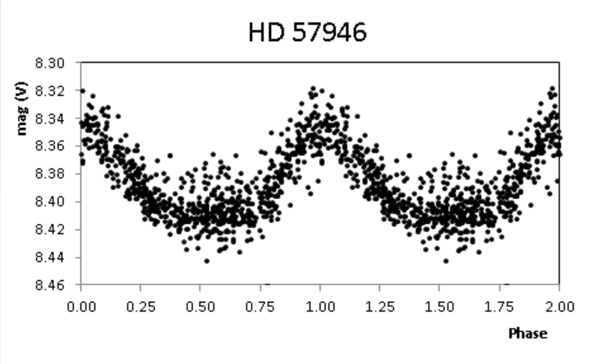
Result of period analysis with Period04 (Lenz & Breger 2005)



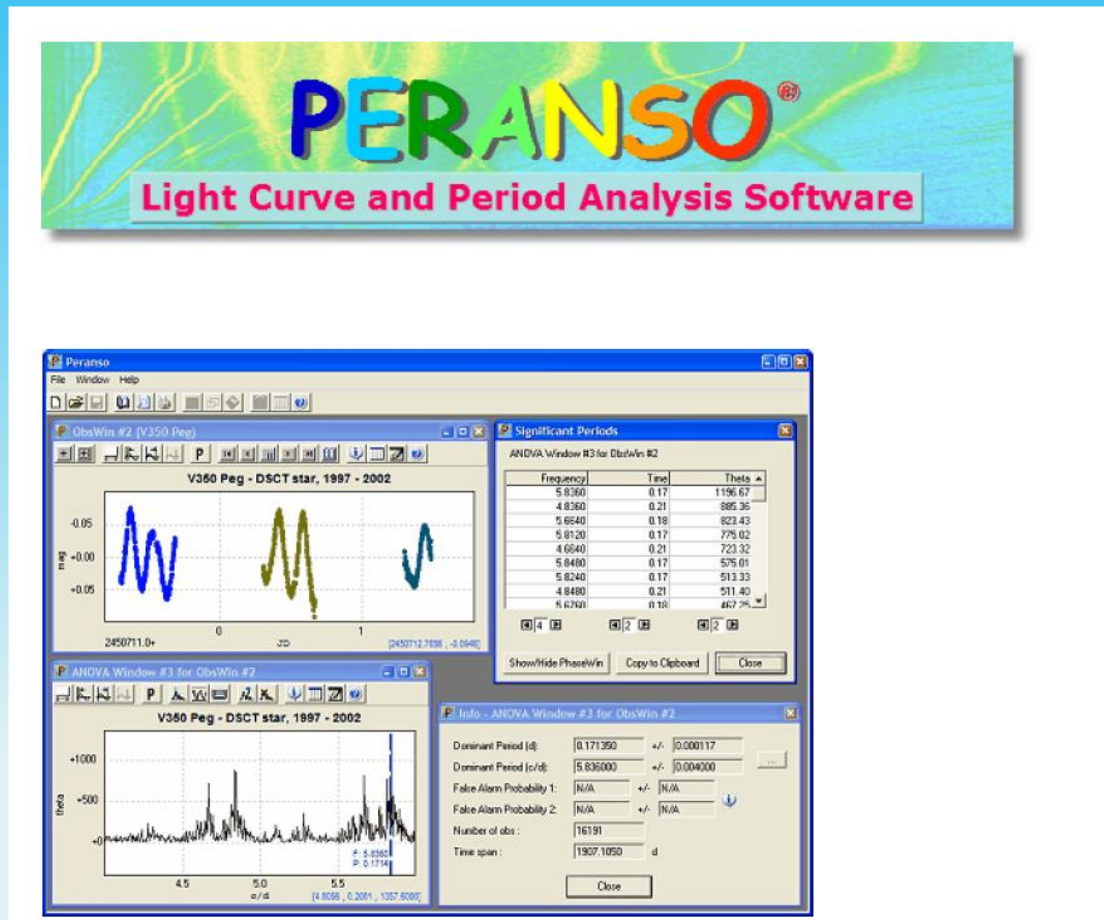
Attention needs to be paid to the presence of strong "daily alias" peaks in the Fourier diagrams.

- aliases: dependant on sample frequency
- daily aliases: 1-f; f+1, (1-f)+1 etc.
- sometimes alias frequencies can even dominate over the true frequencies





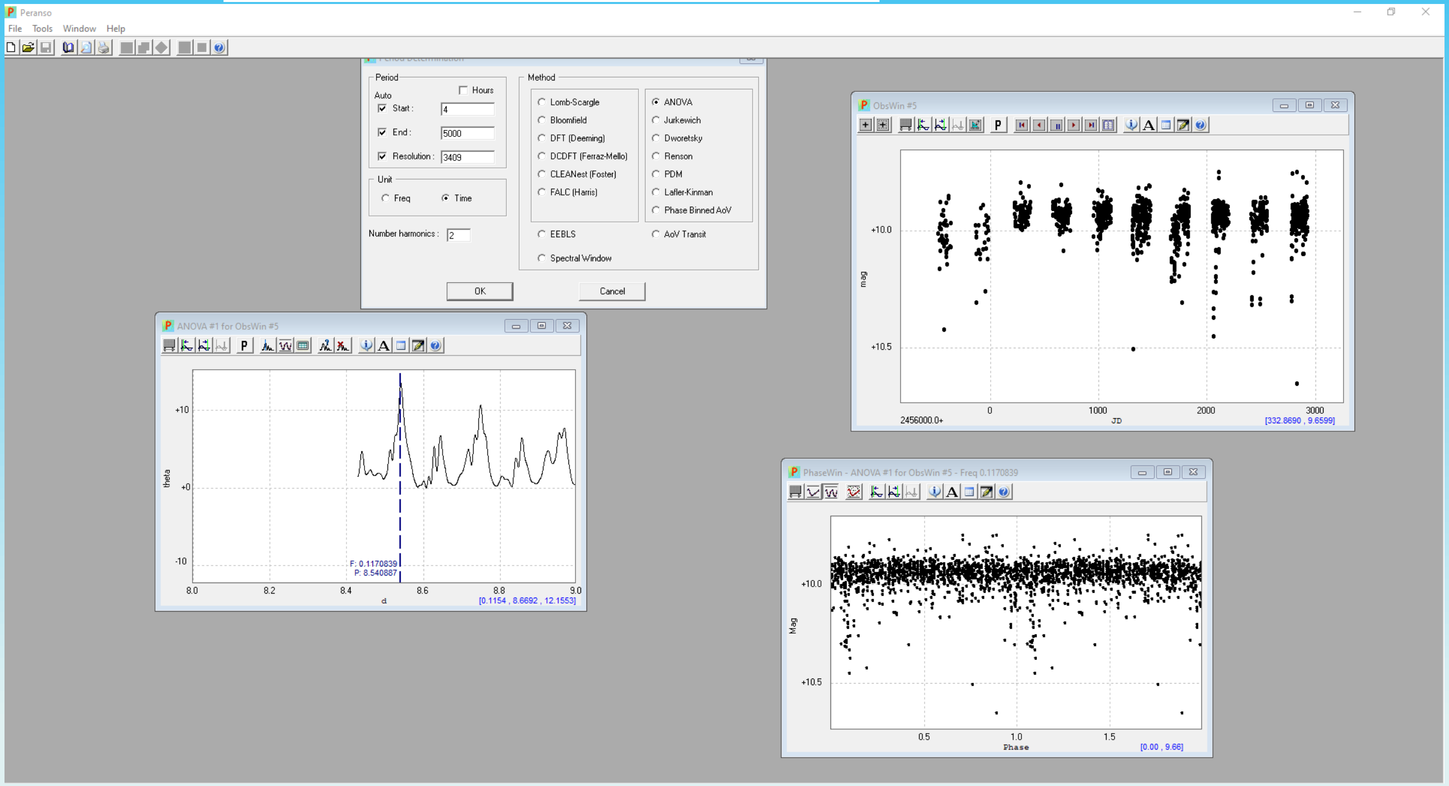
Peranso (Vanmunster & Paunzen)



Peranso

- The Observations Window (ObsWin)
- The Period Window (PerWin)
- The Phase Window (PhaseWin)

Use Mouse to Zoom in/out and to activate/deactivate observations.



Peranso supports two categories of period analysis methods for **variable stars and asteroids** :

1. Fourier methods : these methods attempt to represent a set of observations with a series of trigonometric functions (sines and cosines, with different periods, amplitudes and phases). They are one of the oldest forms of time-series analysis and are also quite flexible. Fourier methods supported by *Peranso* are : Lomb-Scargle, Bloomfield, Discrete Fourier Transform (Deeming) DFT , Date Compensated Discrete Fourier Transform (Ferraz-Mello) DCDFT, CLEANest and FALC (Harris).

2. Statistical methods : instead of fitting the observation data with trigonometric functions, statistical methods compare points in the observation data to other points at fixed time intervals or "lags" to see how different they are from one another. These methods are very suitable for the analysis of observation data that include non-sinusoidal periodic components.

   Within this category, *Peranso* implements :

   a. *String methods* : these methods fold the observation data on a series of trial periods, and at each trial period the sum of the lengths of line segments joining successive points (the string-length) is calculated. Minima in a plot of string-length versus trial frequency indicate possible periods. *Peranso* implements two string methods : Dworetsky, Renson and Lafler-Kinman.

   b. *Phase Dispersion Minimization* (PDM) : is a classical method of distinguishing between possible periods, by finding the period that produces the least observational scatter ("best phasing of data") around the mean light curve.

   c. *Jurkewich method*

   d. *ANOVA method*

Peranso furthermore implements one specific method for **exoplanet transits** :

- *Edge Enhanced Box-fitting Least Squares* (EEBLS) : this method analyses stellar photometric time series in search for periodic transits by exoplanets, looking for signals characterized by a periodic alternation between two discrete levels, with much less time spent at the lower level.

Peranso

Which method for which data set?

• *Delta Cepheids* and *RR Lyrae* variables can generally be well analyzed with the Lafler-Kinman method.

• If you expect a variable to be *multi-periodic*, use CLEANest.

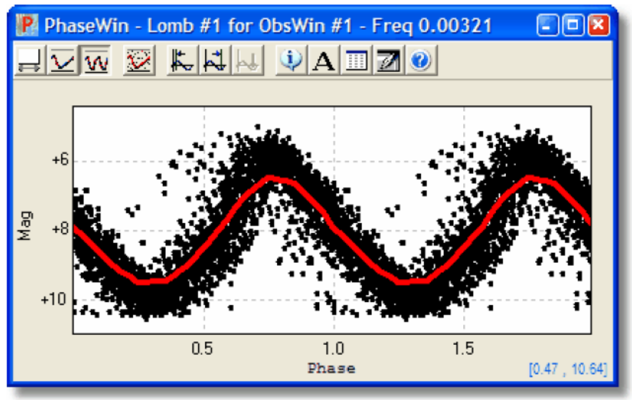
• If the light curve is highly *non-sinusoidal*, use ANOVA.

• PDM is also well suited for analyzing highly *non-sinusoidal* light curves consisting of only a few observations procured over a limited period of time.

- Consult the manual for special purposes!

Peranso (Vanmunster&Paunzen)

finally you hopefully get something like this:



Copy Image to Clipboard

Creates a bitmap copy of the current *Peranso* window and places it on the Microsoft Windows clipboard. The toolbar of the active window is never copied.

Copy Data to Clipboard

Copies the X axis (phase) and Y axis (mostly magnitude) values of the current Phase Window to the Microsoft Windows Clipboard.

Export Data to File...

Saves the X axis (phase) and Y axis (mostly magnitude) values of the current Phase Window to a text file. The user will be prompted to enter the location and name of the file, using a standard Microsoft Windows File Save dialog box.

<u>ZTF Survey:</u>
<u>Basis of the new ACVs of your seminar</u>

The **Z**wicky **T**ransient **F**acility (ZTF) new time-domain survey

- first light at Palomar Observatory in 2017
- 47-square-degree, 600 megapixel cryogenic CCD mosaic science camera
- objects brighter than 20.5 mag
- **3 band photometry in *g*, *r* and (partly) *i***

CrossMark

The Zwicky Transient Facility: System Overview, Performance, and First Results

Eric C. Bellm[1], Shrinivas R. Kulkarni[2], Matthew J. Graham[2], Richard Dekany[3], Roger M. Smith[3], Reed Riddle[3], Frank J. Masci[4], George Helou[4], Thomas A. Prince[2], Scott M. Adams[2], C. Barbarino[5], Tom Barlow[2], James Bauer[6], Ron Beck[4], Justin Belicki[3], Rahul Biswas[7], Nadejda Blagorodnova[2], Dennis Bodewits[6], Bryce Bolin[1,8,36], Valery Brinnel[9], Tim Brooke[4], Brian Bue[10], Mattia Bulla[7], Rick Burruss[3], S. Bradley Cenko[11,12], Chan-Kao Chang (章展誥)[13], Andrew Connolly[1], Michael Coughlin[14], John Cromer[3], Virginia Cunningham[6], Kishalay De[2], Alex Delacroix[3], Vandana Desai[4], Dmitry A. Duev[2], Gwendolyn Eadie[1,15,16,37], Tony L. Farnham[6], Michael Feeney[3], Ulrich Feindt[7], David Flynn[4], Anna Franckowiak[17], S. Frederick[6], C. Fremling[2], Avishay Gal-Yam[18], Suvi Gezari[6,12], Matteo Giomi[9], Daniel A. Goldstein[2,38], V. Zach Golkhou[1,16,37], Ariel Goobar[7], Steven Groom[4], Eugean Hacopians[4], David Hale[3], John Henning[3], Anna Y. Q. Ho[2], David Hover[3], Justin Howell[4], Tiara Hung[6], Daniela Huppenkothen[1], David Imel[4], Wing-Huen Ip (葉永烜)[13,19], Željko Ivezić[1], Edward Jackson[4], Lynne Jones[1], Mario Juric[1], Mansi M. Kasliwal[2], S. Kaspi[20], Stephen Kaye[3], Michael S. P. Kelley[6], Marek Kowalski[9,17], Emily Kramer[10], Thomas Kupfer[2,21,22], Walter Landry[4], Russ R. Laher[4], Chien-De Lee[13], Hsing Wen Lin (林省文)[13,23], Zhong-Yi Lin (林忠義)[13], Ragnhild Lunnan[5], Matteo Giomi[9], Ashish Mahabal[2,24], Peter Mao[3], Adam A. Miller[25,26], Serge Monkewitz[4], Patrick Murphy[27], Chow-Choong Ngeow[13], Jakob Nordin[9], Peter Nugent[28,29], Eran Ofek[30], Maria T. Patterson[1], Bryan Penprase[31], Michael Porter[3], Ludwig Rauch[17], Umaa Rebbapragada[10], Dan Reiley[3], Mickael Rigault[32], Hector Rodriguez[3], Jan van Roestel[33], Ben Rusholme[4], Jakob van Santen[17], S. Schulze[18], David L. Shupe[4], Leo P. Singer[11,12], Maayane T. Soumagnac[18], Robert Stein[17], Jason Surace[4], Jesper Sollerman[5], Paula Szkody[15], F. Taddia[5], Scott Terek[4], Angela Van Sistine[34], Sjoert van Velzen[6], W. Thomas Vestrand[35], Richard Walters[3], Charlotte Ward[6], Quan-Zhi Ye (葉泉志)[2,4], Po-Chieh Yu (俞伯傑)[13], Lin Yan[2], and Jeffry Zolkower[3]

Filter transmission and mosaic CCDs

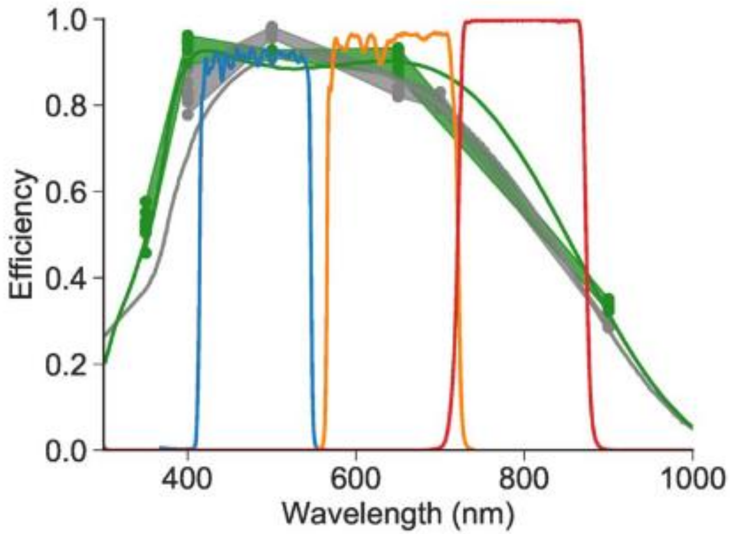


Figure 2. On-axis filter transmission for the ZTF *g*, *r*, and *i*-band filters (blue, orange, and red lines). Gray and green points are measurements of the quantum efficiencies of the CCDs with single- and double-layer anti-reflective coatings, respectively. Shaded regions show the range of these measurements, while gray and green lines show a model of the quantum efficiency for each configuration. (A color version of this figure is available in the online journal.)

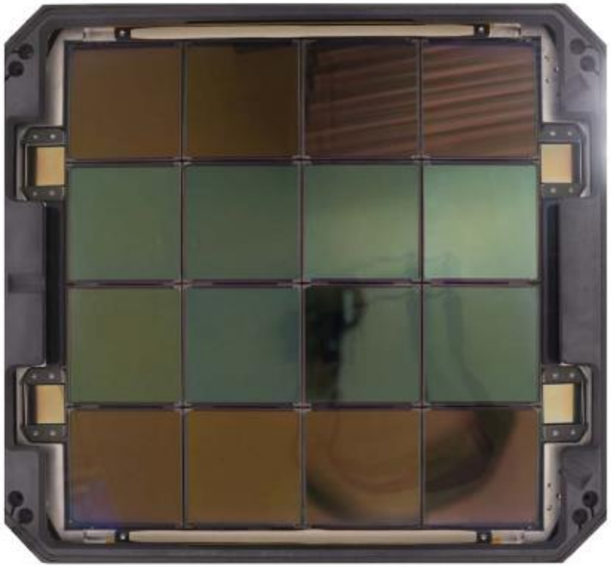


Figure 1. Image of the ZTF focal plane. The top and bottom rows of $6k \times 6k$ science CCDs have a single-layer anti-reflective coating, while the middle rows have a dual-layer coating. Four $2k \times 2k$ CCDs are located on the perimeter of the mosaic; one serves as a guider while the remaining three control tip, tilt, and focus. North is up and east is left.
(A color version of this figure is available in the online journal.)

The ZTF Catalog of Periodic Variable Stars by Chen et al. (2020)

The Zwicky Transient Facility Catalog of Periodic Variable Stars

Xiaodian Chen,[1] Shu Wang,[1] Licai Deng,[1] Richard de Grijs,[2,3,4] Ming Yang,[5] and Hao Tian[6]

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(Received 2019 November 29; Revised 2020 May 18; Accepted 2020 Jun 11)

Submitted to ApJS

ABSTRACT

The number of known periodic variables has grown rapidly in recent years. Thanks to its large field of view and faint limiting magnitude, the Zwicky Transient Facility (ZTF) offers a unique opportunity to detect variable stars in the northern sky. Here, we exploit ZTF Data Release 2 (DR2) to search for and classify variables down to $r \sim 20.6$ mag. We classify 781,602 periodic variables into 11 main types using an improved classification method. Comparison with previously published catalogs shows that 621,702 objects (79.5%) are newly discovered or newly classified, including ~700 Cepheids, ~5000 RR Lyrae stars, ~15,000 δ Scuti variables, ~350,000 eclipsing binaries, ~100,000 long-period variables, and about 150,000 rotational variables. The typical misclassification rate and period accuracy are on the order of 2% and 99%, respectively. 74% of our variables are located at Galactic latitudes, $|b| < 10°$. This large sample of Cepheids, RR Lyrae, δ Scuti stars, and contact (EW-type) eclipsing binaries is helpful to investigate the Galaxy's disk structure and evolution with an improved completeness, areal coverage, and age resolution. Specifically, the northern warp and the disk's edge at distances of 15–20 kpc are significantly better covered than previously. Among rotational variables, RS Canum Venaticorum and BY Draconis-type variables can be separated easily. Our knowledge of stellar chromospheric activity would benefit greatly from a statistical analysis of these types of variables.

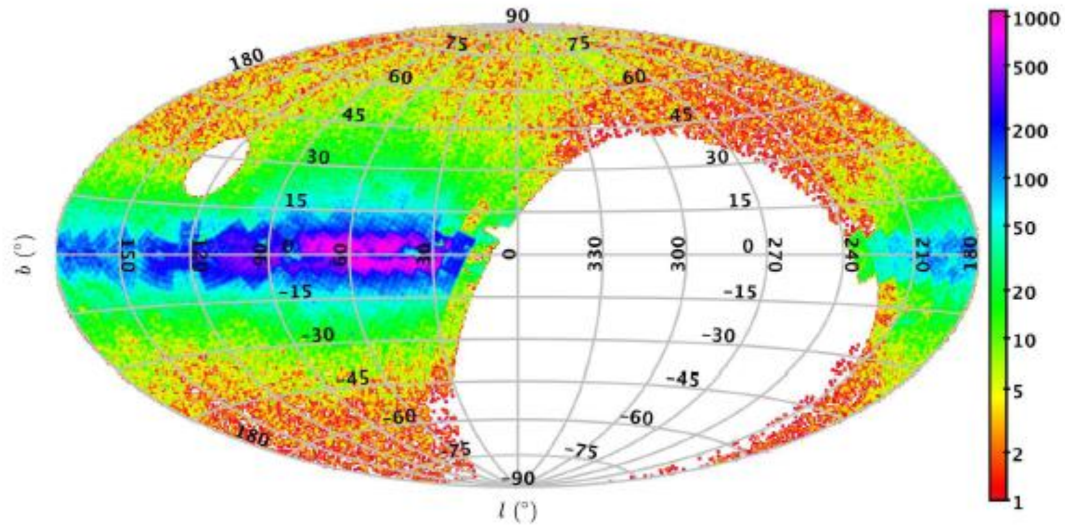


Figure 6. Distribution map (in Galactic coordinates) of the 781,602 periodic variables classified in ZTF DR2.

ZTF time series analysis

Fourth order Fourier function

$$f = a_0 + \sum_{i=1}^{4} a_i \cos(2\pi i t/P + \phi_i),$$

a_i and ϕ_i **amplitudes and phases for each order**

R^2 **represents how well LCs are fit by the Fourier function**

Selection criteria for variability types in Chen et al. (2020)

Table 1. Criteria adopted to classify different types of variables

Type	Selection criteria
LAD	$R^2 > 0.4$, Amp. < 0.2, FAP < 0.001, $M_{W_{gr}} - M_{W_{gr}}(\mathrm{PL}) < 3\sigma_{\mathrm{DM}}$, $P < 0.2$ days
HAD	$R^2 > 0.4$, Amp. > 0.2, FAP < 0.001, $M_{W_{gr}} - M_{W_{gr}}(\mathrm{PL}) < 3\sigma_{\mathrm{DM}}$
RRc	$R^2 > 0.6$, Amp. > 0.08, FAP < 0.001, $M_{W_{gr}} - M_{W_{gr}}(\mathrm{PL}) < 3\sigma_{\mathrm{DM}}$, $\phi_{21} < 1.9$
RRab	$R^2 > 0.6$, Amp. > 0.08, FAP < 0.001, $M_{W_{gr}} - M_{W_{gr}}(\mathrm{PL}) < 3\sigma_{\mathrm{DM}}$
Cepheid	$R^2 > 0.6$, Amp. > 0.08, FAP < 0.001, $M_{W_{gr}} - M_{W_{gr}}(\mathrm{PL}) < 3\sigma_{\mathrm{DM}}$, $P < 40$ days
Eclipsing binary	$R^2 > 0.4$, Amp. > 0.08, FAP < 0.001
Mira	$R^2 > 0.4$, Amp. $>= 2$, FAP < 0.001 , $P > 80$ days
SR	$R^2 > 0.4$, Amp. < 2, FAP < 0.001, $P > 20$ days
BY Dra	$R^2 > 0.4$, FAP < 0.001, $2.8 < M_{W_{gr}} < 4.6$, $0.25 < P < 20$ days
RS CVn	$R^2 > 0.4$, FAP < 0.001, $M_{W_{gr}} = M_{W_{gr}}$(Eclipsing binary), $P < 20$ days
EW	$a_4 <= a_2(a_2 + 0.125)$
	$a_2(a_2 + 0.125) < a_4 < a_2(a_2 + 0.375)$, $a_4/a_2 <= 0.43$
EA	$a_4 >= a_2(a_2 + 0.375)$
	$a_2(a_2 + 0.125) < a_4 < a_2(a_2 + 0.375)$, $a_4/a_2 > 0.43$

There is no type "ACV"!

Results

Type	Total	New (fraction)
Cep-I	1262	565 (44.8%)
Cep-II	358	154 (43.0%)
RRab	32,518	3034 (9.3%)
RRc	13,875	2178 (15.7%)
δ Scuti	16,709	15,396 (92.1%)
EW	36,9707	306,375 (82.9%)
EA	49,943	40,201 (80.5%)
Mira	11,879	4,997 (42.1%)
SR	119,261	97,737 (82.0%)
RS CVn	81,393	70,957 (87.2%)
BY Dra	84,697	80,108 (94.6%)
Total number	781,602	621,702 (79.5%)

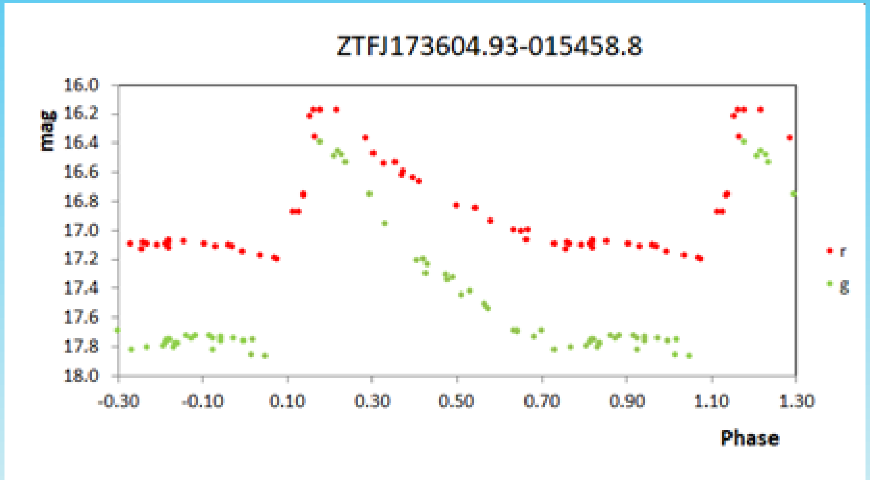
ACV variables may be included in the category 'RS CVn variables' (objects with starspots).

http://variables.cn:88/ztf/ or doi.org/10.5281/zenodo.3886372.

A few examples of interesting light curves

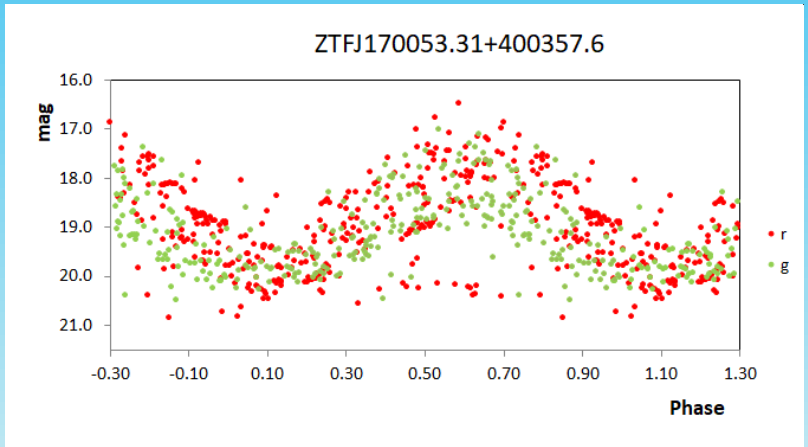
P = 0.4362979 d

g band amplitude larger than *r* band amplitude: pulsator!



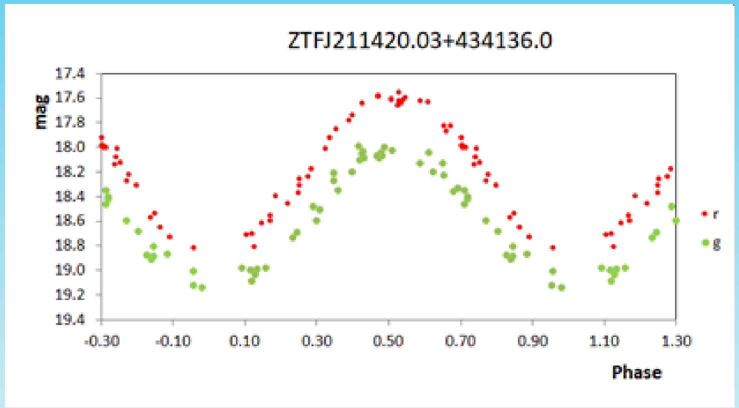
Folded light curve with large scatter

P = 0.080869 d

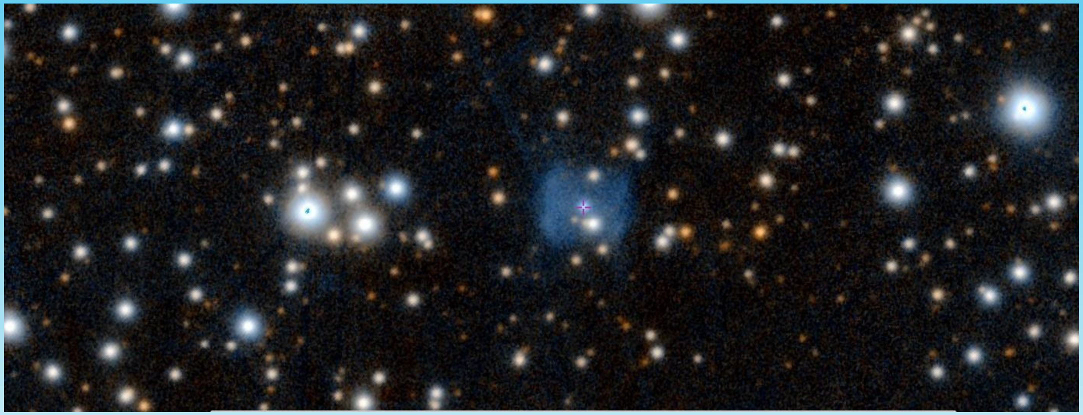


rotational variable with large amplitude?

P = 0.364225 d



It is the central star of the planetary nebula Ou 5:



We come back to the ~81.000 RS CVn stars and want to search ACVs within this group:

Assuming that 30 seconds are needed for the visual inspection of a light curve, an inspection of all stars within this group would take
81.000*30/60/60 = 675 hours!
Possible but impractical...

Therefore we need further constraints:
Gaia temperature >6000 K (ACVs are hot!)
variability amplitude <0.3 mag (typical for ACVs)
...
~1400 objects
time for visual inspection:
1400*30/60/60 ~ 12 hours: this is fine!

Homepage of Xiaodian Chen: Visualization of the light curves

Xiaodian's Homepage

THIS IS THE WEBSITE OF MY CAREER IN ASTRONOMY

Home   About me   WISE catalog   ZTF catalog

ZTF Catalog of Periodic Variable Stars contains 781,602 periodic variables found based on ZTF Data Release 2. The source catalogs are available in the Article or Here (variables (64M), Suspected variables (57M)). The photometric catalog can be accessed from

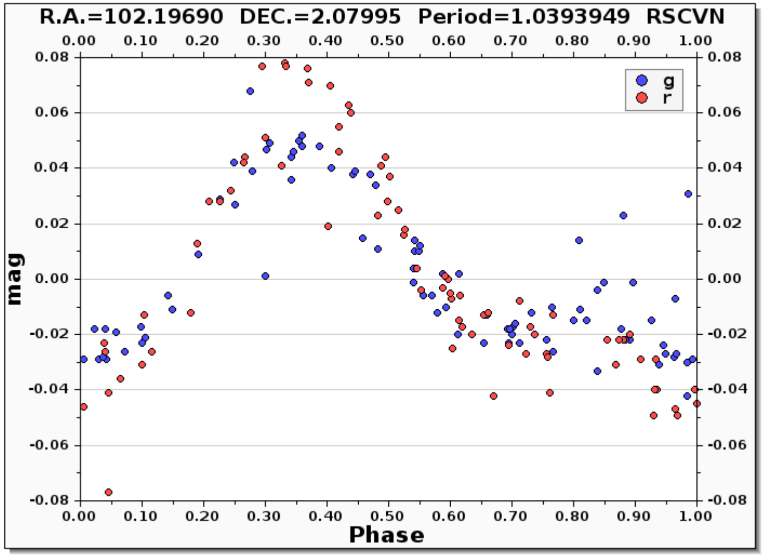
DOI 10.5281/zenodo.3886372

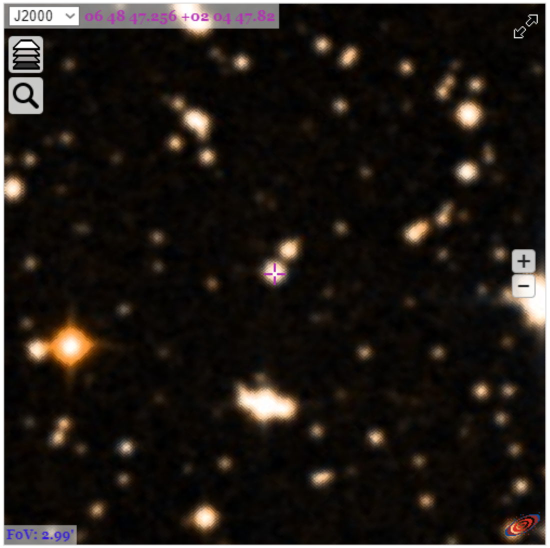
We recommend to use "SourceID" to search LCs.

ID2:	SourceID:	RAdeg:	DEdeg:
ID2	SourceID	From	From
		To	To
Per:	**gmag:**	**rmag:**	**Ampg:**
Per	gmag	rmag	Ampg

Period: 1.0393949 ID: ZTFJ064847.25+020447.8 SourceID: 167603

R.A.: 102.19690 DEC.: 2.07995 Type: RSCVN g: 14.544 r: 14.502 Num_g: 86 Num_r: 75 Amp_g: 0.071 Amp_r: 0.110 R_{21}: 0.434 φ_{21}: 3.697





DSS color DSS blue 2MASS AllWISE GLIMPSE 360

Not fold LC | fold LC | To VizieR | Download csv

Try new period

Period: Try new Period SourceID: 167603

Submit this period

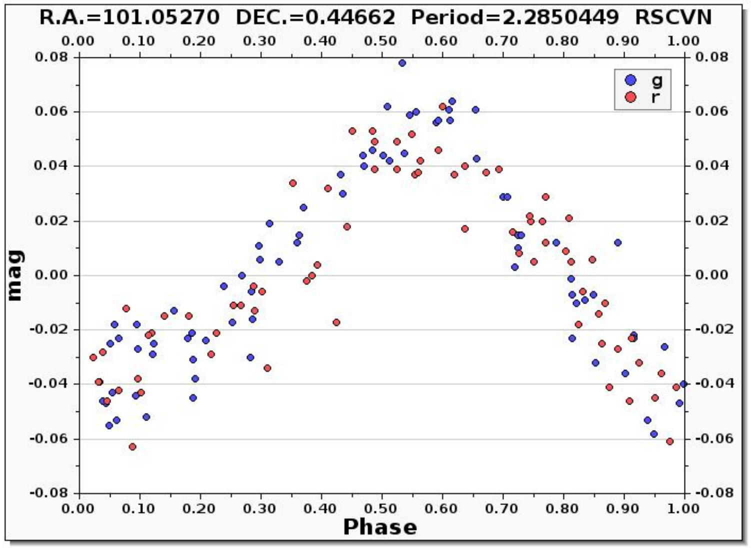
Every second counts…

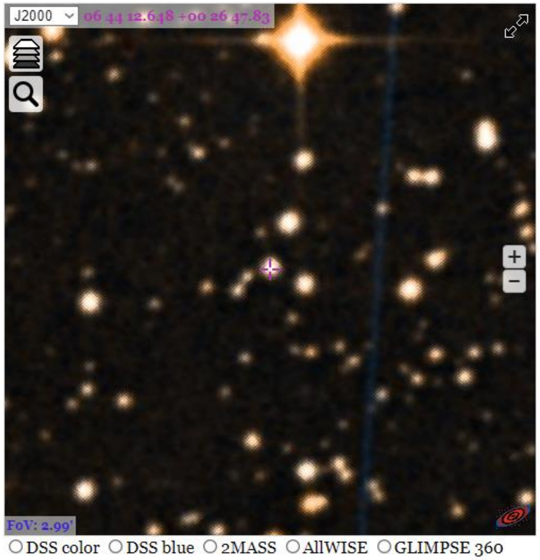
T eff (Gaia DR2)	ZTF ID	ZTF Link	ID in Chen	our classification	Test	Type Chen e
		http://variables.cn:88/lcz.php?Period=&SourceID=232692		HAGDOR Sebastian		
6668.15	ZTFJ205525.83+472338.1	http://variables.cn:88/lcz.php?SourceID=647388	647388	ACV + YSO in nebula?		RSCVN
8977.67	ZTFJ193501.38+282225.7	http://variables.cn:88/lcz.php?SourceID=466609	466609	ACV amp r>amp g		RSCVN
8609.5	ZTFJ064847.25+020447.8	http://variables.cn:88/lcz.php?SourceID=167603	167603	ACV amp r>amp g		RSCVN
8424	ZTFJ232236.78+512549.1	http://variables.cn:88/lcz.php?SourceID=766253	766253	ACV amp r>amp g		RSCVN
7923.5	ZTFJ060420.41+265942.2	http://variables.cn:88/lcz.php?SourceID=142876	142876	ACV amp r>amp g		RSCVN
7794.5	ZTFJ225454.64+542804.4	http://variables.cn:88/lcz.php?SourceID=752623	752623	ACV amp r>amp g		RSCVN
7786.5	ZTFJ022326.83+543425.3	http://variables.cn:88/lcz.php?SourceID=49348	49348	ACV amp r>amp g		RSCVN
7738	ZTFJ225444.50+572009.4	http://variables.cn:88/lcz.php?SourceID=752530	752530	ACV amp r>amp g		RSCVN
7184	ZTFJ050755.19+495727.2	http://variables.cn:88/lcz.php?SourceID= 109643	109643	ACV amp r>amp g		RSCVN
7144.56	ZTFJ001616.48+622426.9	http://variables.cn:88/lcz.php?SourceID=6851	6851	ACV amp r>amp g		RSCVN
7117.5	ZTFJ003646.27+602633.8	http://variables.cn:88/lcz.php?SourceID=13878	13878	ACV amp r>amp g		RSCVN
7090.75	ZTFJ005928.14+603315.8	http://variables.cn:88/lcz.php?SourceID=21480	21480	ACV amp r>amp g		RSCVN
6620	ZTFJ235154.72+621521.9	http://variables.cn:88/lcz.php?SourceID=777806	777806	ACV amp r>amp g		RSCVN
6351.33	ZTFJ221304.21+533624.2	http://variables.cn:88/lcz.php?SourceID=724125	724125	ACV amp r>amp g		RSCVN
6323	ZTFJ014643.20+562950.9	http://variables.cn:88/lcz.php?SourceID=36511	36511	ACV amp r>amp g		RSCVN
6016	ZTFJ053725.01+382012.3	http://variables.cn:88/lcz.php?SourceID=126942	126942	ACV amp r>amp g		RSCVN
6471.75	ZTFJ195955.94+371754.2	http://variables.cn:88/lcz.php?SourceID=556995	556995	ACV amp r>amp g (g almost zero)		RSCVN
9001	ZTFJ071633.43-020221.4	http://variables.cn:88/lcz.php?SourceID=178837	178837	ACV antiphase	-1	RSCVN
8113.25	ZTFJ193403.66+632537.7	http://variables.cn:88/lcz.php?SourceID=462790	462790	ACV antiphase	-1	RSCVN
8062.89	ZTFJ183551.46+334749.7	http://variables.cn:88/lcz.php?SourceID=283584	283584	ACV antiphase	0	RSCVN
7994	ZTFJ194356.38+470830.9	http://variables.cn:88/lcz.php?SourceID=502294	502294	ACV antiphase	-1	RSCVN
7932	ZTFJ203922.63+262122.2	http://variables.cn:88/lcz.php?SourceID=628110	628110	ACV antiphase	0	RSCVN
7894.5	ZTFJ213829.74+332758.7	http://variables.cn:88/lcz.php?SourceID=692335	692335	ACV antiphase	-1	RSCVN
7850.33	ZTFJ203527.35+244945.9	http://variables.cn:88/lcz.php?SourceID=623156	623156	ACV antiphase	1	RSCVN
7805	ZTFJ190408.37+445439.3	http://variables.cn:88/lcz.php?SourceID=354952	354952	ACV antiphase: Sebastian ACV	-1	RSCVN
7557.21	ZTFJ012145.50+443625.8	http://variables.cn:88/lcz.php?SourceID=28191	28191	ACV antiphase	2	RSCVN
7470	ZTFJ222357.65+474904.5	http://variables.cn:88/lcz.php?SourceID=732962	732962	ACV antiphase	-1	RSCVN
7455	ZTFJ190831.71+511959.8	http://variables.cn:88/lcz.php?SourceID=371025	371025	ACV antiphase	0	RSCVN
7430	ZTFJ182441.88+485404.5	http://variables.cn:88/lcz.php?SourceID=267243	267243	ACV antiphase	-1	RSCVN
7391.5	ZTFJ072604.40-062330.9	http://variables.cn:88/lcz.php?SourceID=181600	181600	ACV antiphase	-1	RSCVN
7314.99	ZTFJ054550.47+533903.3	http://variables.cn:88/lcz.php?SourceID=131711	131711	ACV antiphase	-0	RSCVN
7271	ZTFJ212905.49+142755.5	http://variables.cn:88/lcz.php?SourceID=682595	682595	ACV antiphase	-1	RSCVN
7267.94	ZTFJ205319.55+313746.4	http://variables.cn:88/lcz.php?SourceID=644926	644926	ACV antiphase	-1	RSCVN

Examples of objects that were sorted out: unspecific light curve

Period: 2.2850449 ID: ZTFJ064412.64+002647.8 SourceID: 165303

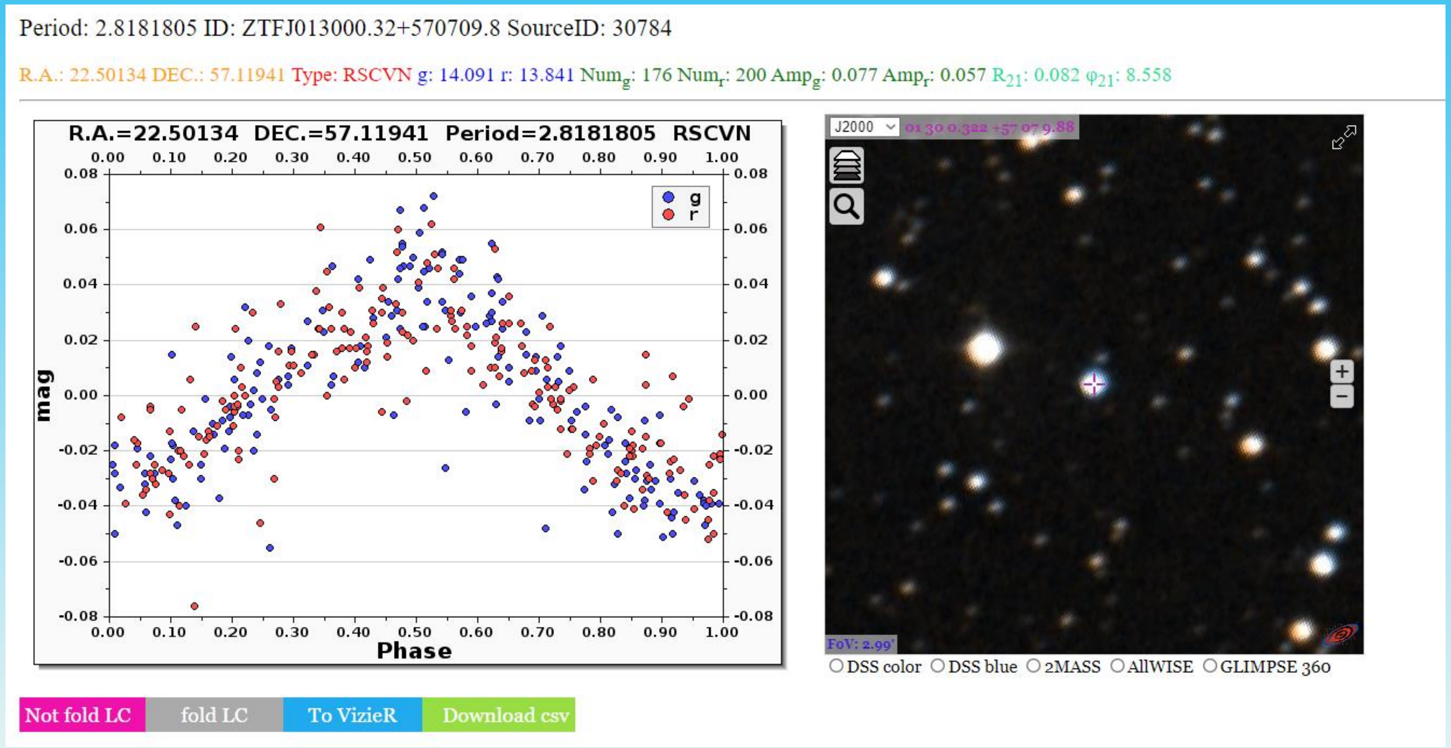
R.A.: 101.05270 DEC.: 0.44662 Type: RSCVN g: 15.233 r: 14.988 Num_g: 77 Num_r: 71 Amp_g: 0.107 Amp_r: 0.092 R_{21}: 0.142 φ_{21}: 9.016





Not fold LC | fold LC | To VizieR | Download csv

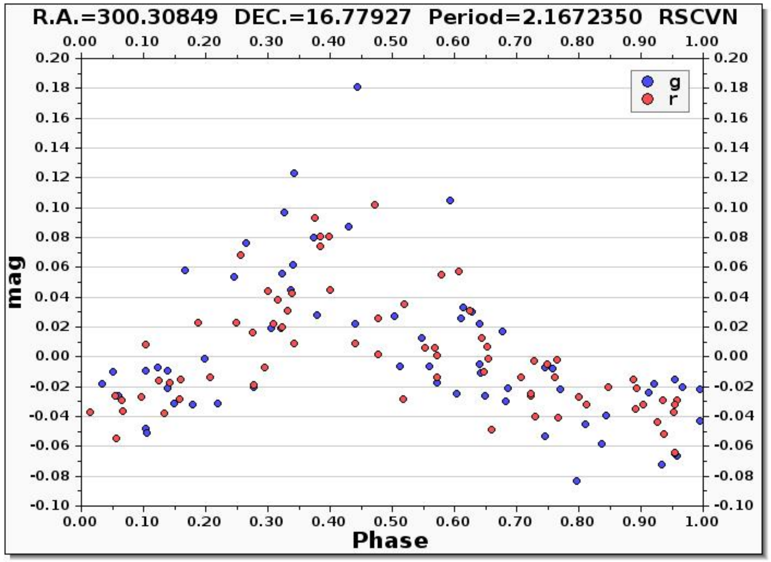
Examples of objects that were sorted out: unspecific light curve-similar object

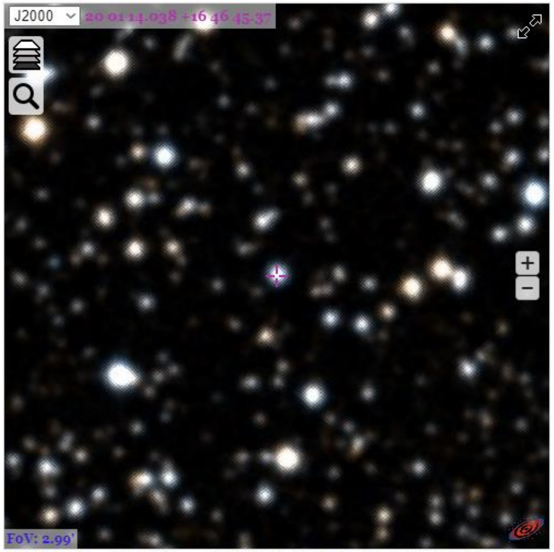


Examples of objects that were sorted out: likely Gamma Doradus pulsating variable

Period: 2.1672350 ID: ZTFJ200114.03+164645.3 SourceID: 560676

R.A.: 300.30849 DEC.: 16.77927 Type: RSCVN g: 15.332 r: 15.042 Num_g: 63 Num_r: 72 Amp_g: 0.113 Amp_r: 0.105 R_{21}: 0.245 φ_{21}: 3.945

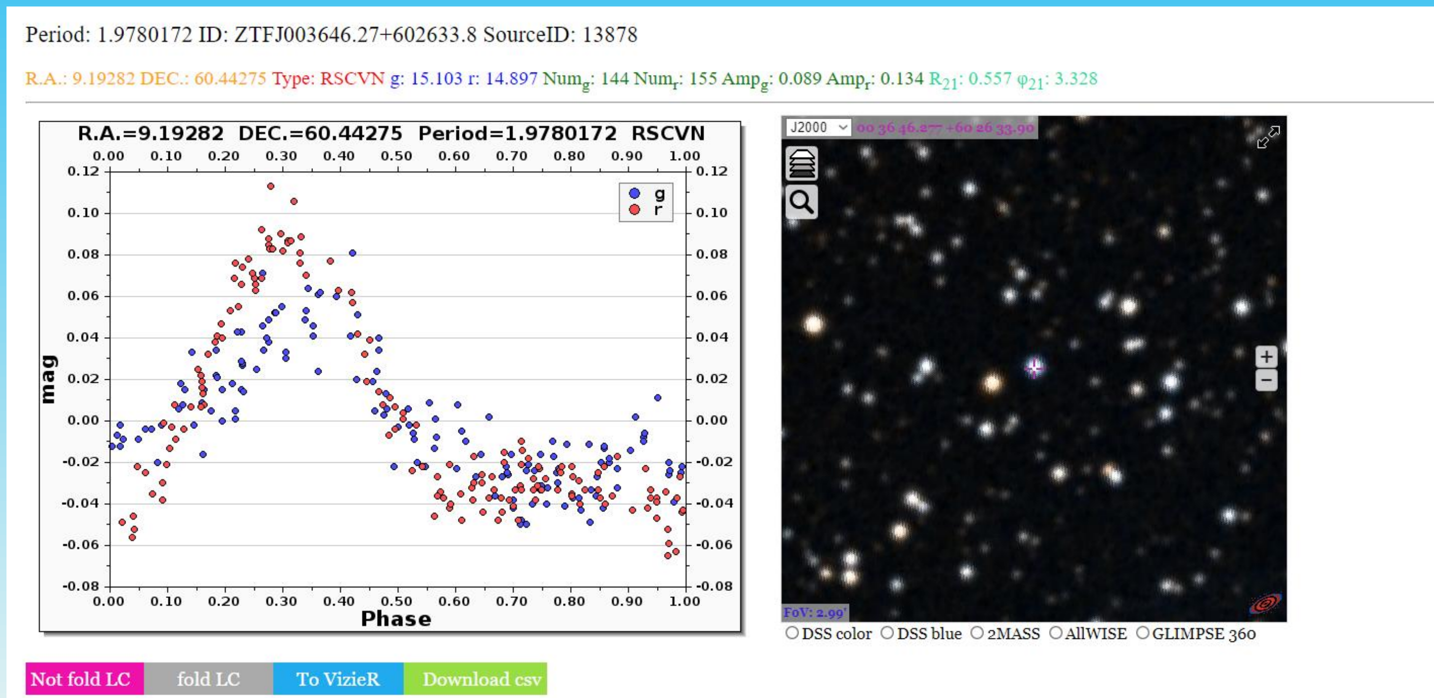




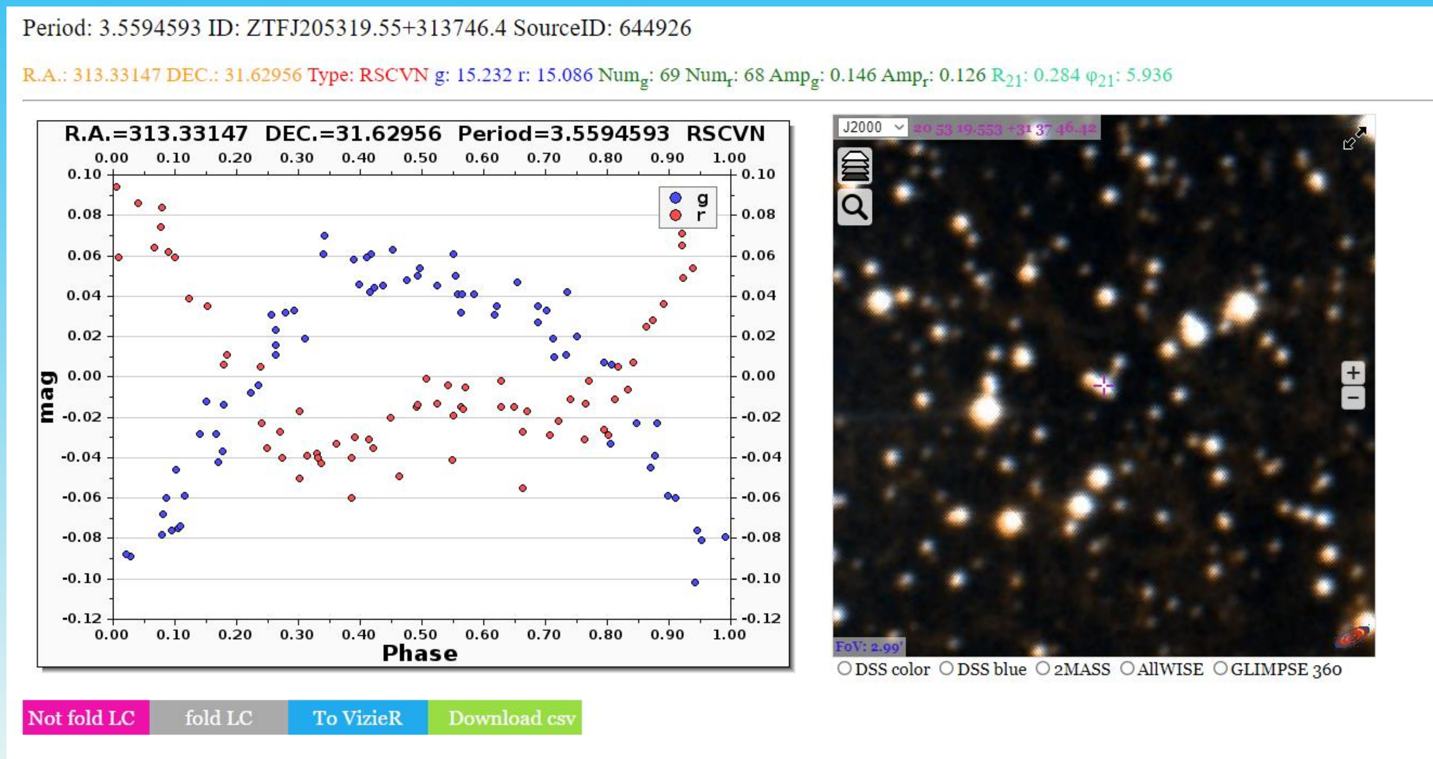
○ DSS color ○ DSS blue ○ 2MASS ○ AllWISE ○ GLIMPSE 360

Not fold LC | fold LC | To VizieR | Download csv

Only 2 types of objects were kept, which are almost certainly ACVs:
***r* band amplitude > *g* band amplitude**

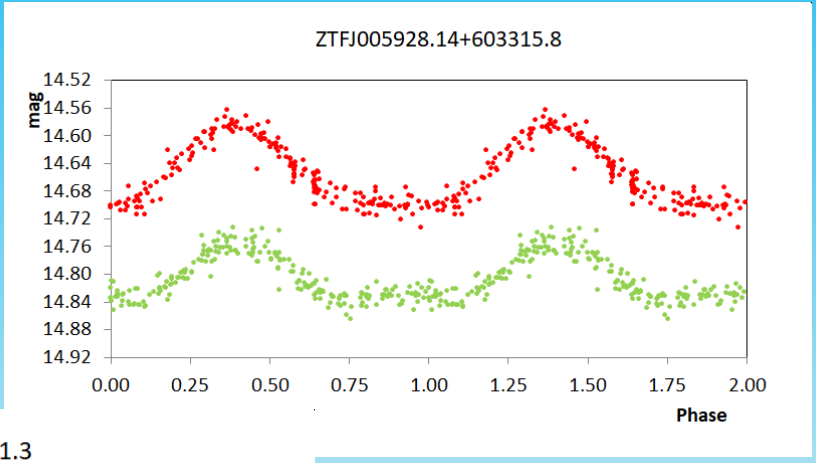


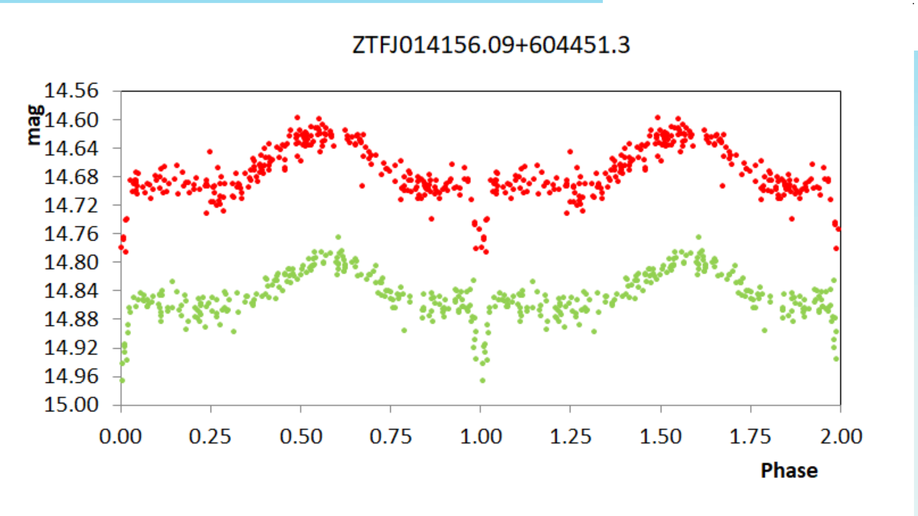
<u>Only 2 types of objects were kept, which are almost certainly ACVs: antiphase variations are present</u>



Result: 87 objects, light curves made with MS EXCEL

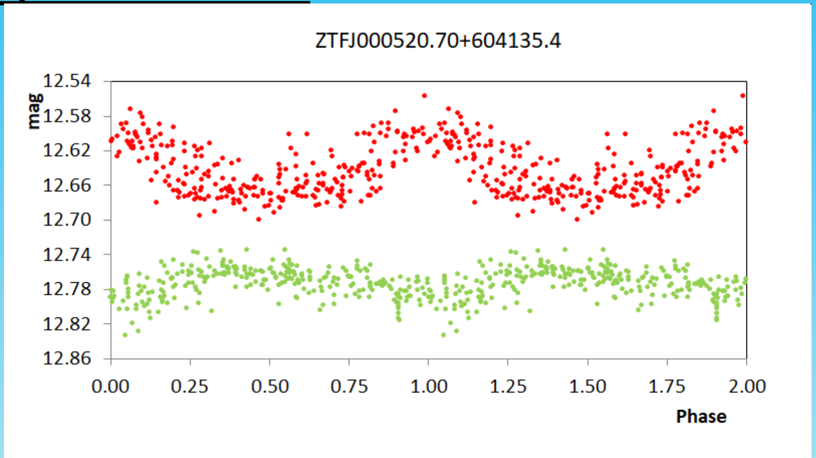
examples with amplitude r > g

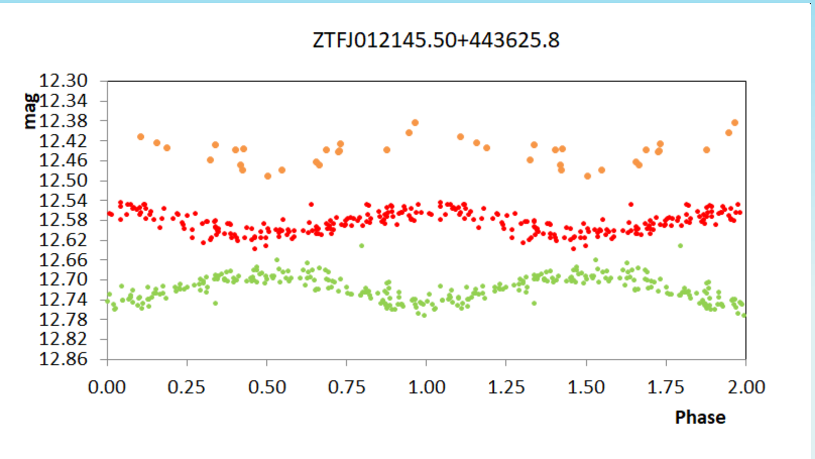




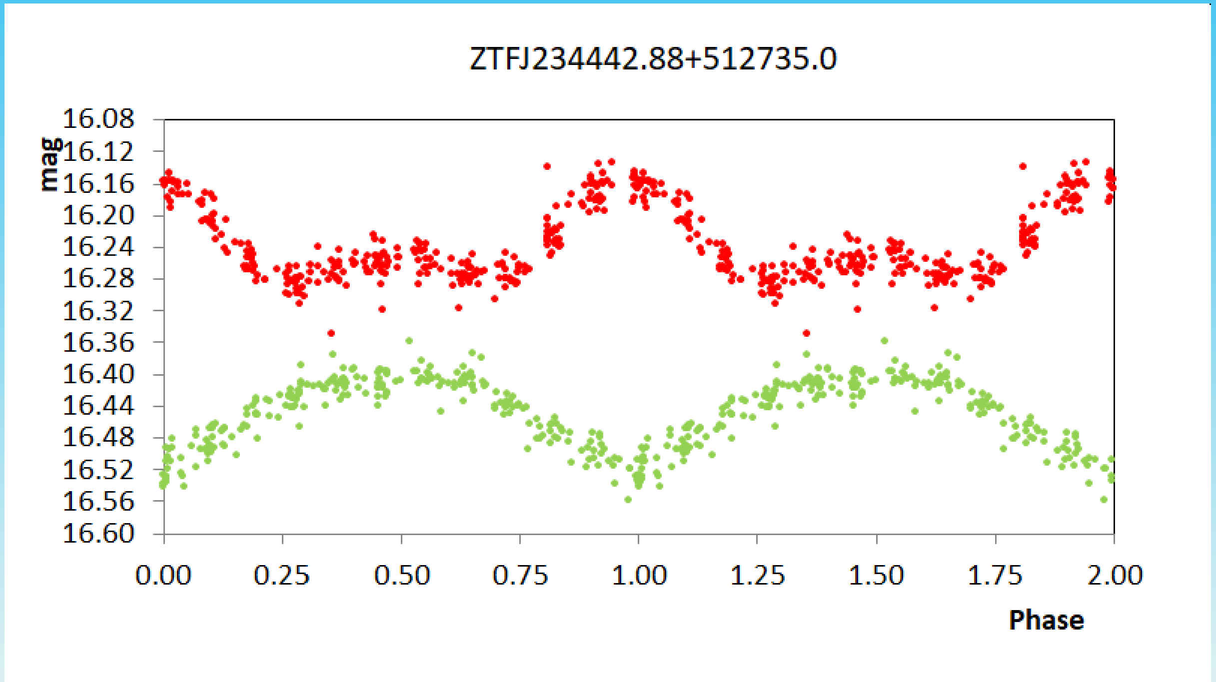
Result: 87 objects, light curves made with MS EXCEL

Examples with antiphase variation





Depending on the investigated passbands, ACV stars may show considerably different light curve shapes:



<u>Have fun with the new ACV objects!</u>

<u>Thank you very much and all the best for your seminar.</u>

Thanks also to my colleague Stefan Hümmerich for his help in preparing this talk!