Time Domain Observations with Small telescope

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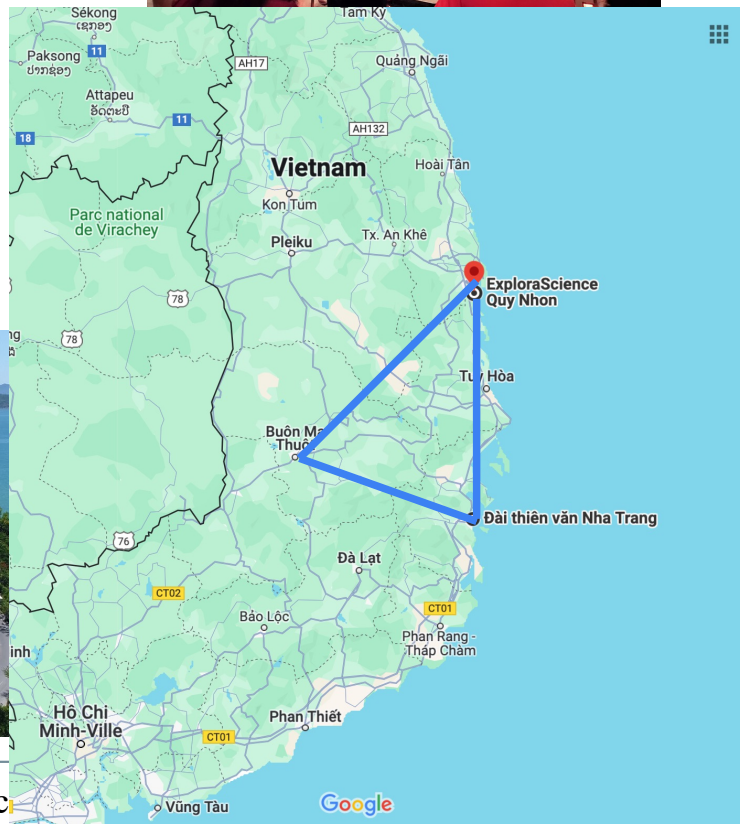
(AUP)

Why?

We are having a network of 3 working telescopes around Quy Nhon.

- Quy Nhon Observatory
- Nha Trang Observatory
- Tay Nguyen Observatory (in construction)

I want to take advantages of these facilities to do some sciences with them and to develop instruments.



Disclaimer

Time-domain optical astronomy DONE by a single-dish radio astronomer

Credits: Michael Richmond (Physics Department, Rochester Institute of Technology)
Daisaku Nogami & Mikio Kurita (Kyoto University)
GROWTH Summer School
ZTF Summer School

Radio astronomer

Minute to degree beamsize
Can observe the whole day and night
Moderately bad weather might be OK
Light pollution is ok
Radio signal interference is not acceptation

Optical astronomer

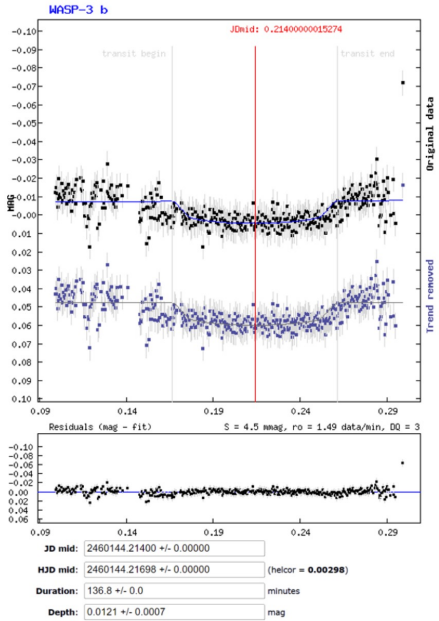
Seeing
Can't observe during the daytime
Perfect weather
Light pollution is a problem
You can still you your mobile phone in the observing room

Time-domain Observations

We observe the targets **over a period of time** and expect that the signals of the targets **vary**.
This is interesting because we can see physics in action.

We want to obtain a **lightcurve**, or a series of measurement of brightness over time.

Variability of astronomical objects is known on time scales from ms to 10^10 yr



Cadence of the observation ~ Temporal resolution

- A few minutes for exoplanet transit, occultation
- Minutes/hours/days for variable stars
- Hours/Days for supernova

Time-domain Observations

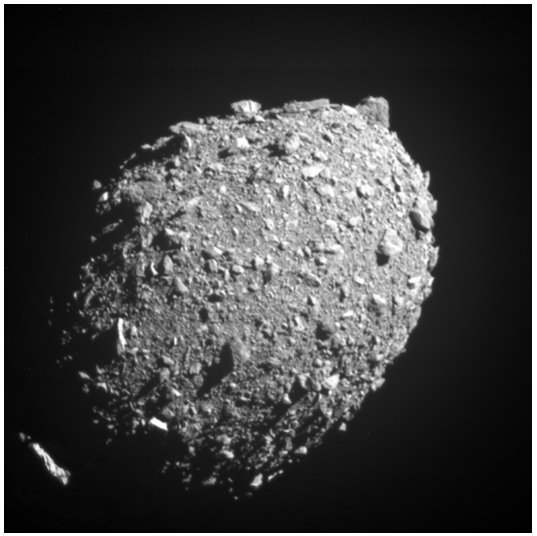
Rich phenomenology
TDA Touches essentially every field of astronomy

- **Our solar system:** Asteroids (NEO), KB Objects
- **Variable stars**: stellar evolution, better understanding of physical phenomena
- **Extrasolar planets** (microlensing, transits,etc…)
- **High energy phenomena** (SN, GRB)
- **Cosmology** (AGN, Blazars, etc)

Interesting Physics causes of intrinsic variability:

- Evolution: structural changes etc., long time scales
- Internal processes, e.g., turbulence inside stars
- Accretion/collapse: protostars, CVs, GRBs, QSOs
- Thermonuclear explosions (SNe)
- Magnetic field reconnections, e.g., stellar flares
- Line of sight changes (rotation, jet instabilities, star spots…)
- Black hole, gravitational waves

Time-domain Observations: Asteroid



Dimorphos imaged by DART mission

IAU 2006 resolution: Any solar system object that is “not a planet, a dwarf planet, nor a natural satellite”.
SSSB includes: asteroids, comets, large meteoroids, most objects in the outer solar system
Anything larger than dust (~1m) and smaller than 1000 km except for natural satellites.

Asteroids are rocky bodies
With irregular shapes
Around their axes, they rotate
Therefore their light curves bright and fade

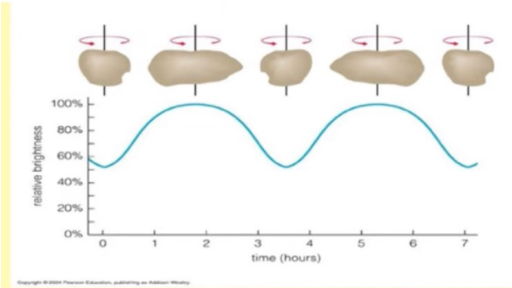


Image copyright Pearson/Addison Wesley

And we are interested in the shape and periods of the light curves

Asteroid Dinkinesh

Time-domain Observations: Asteroid

Discover new ones need to go to mag 20 or fainter
But ONLY ~15% (1M) have measurements to measure positions
improve orbits
AND ONLY 1% have light curves with known periods
A lot can be done by our telescopes

Collaborative Asteroid Lightcurve Link (CALL)
https://science.nasa.gov/solar-system/asteroids/

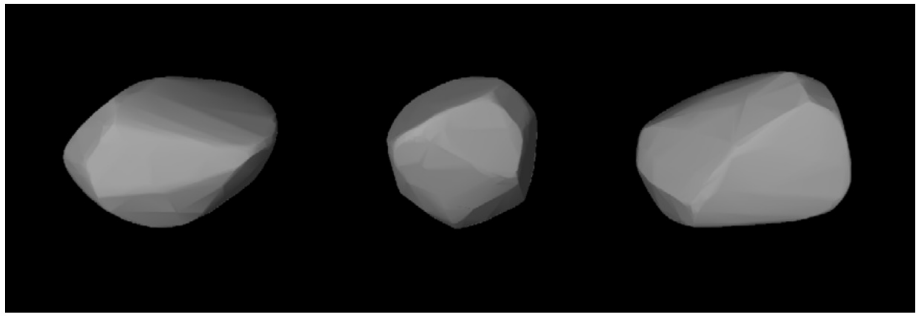


Fig. 32. Shape model of (174) Phaedra.

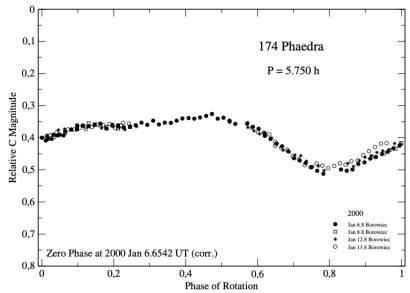


Fig. 8. Composite lightcurve of (174) Phaedra in 2000.

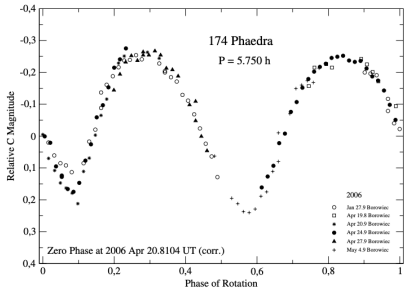


Fig. 11. Composite lightcurve of (174) Phaedra in 2006.

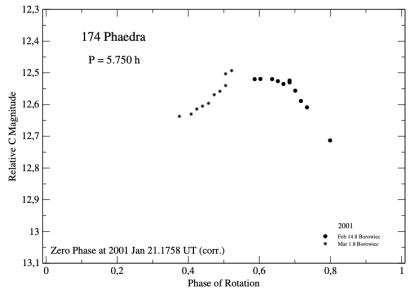


Fig. 9. Composite lightcurve of (174) Phaedra in 2001.

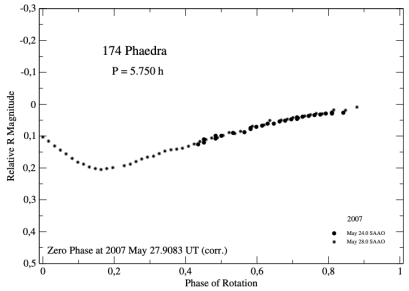


Fig. 12. Composite lightcurve of (174) Phaedra in 2007.

Marciniak et al., 2007, 2011

Time-domain Observations: Asteroid

How many asteroids have good rotation periods?

- 96% of the first 1000 numbered objects
- 79% of the next 1000
- 62% of the next 1000
- 17% of the next 7000
- 4% of the next 10,000

Step 1: choose an asteroid which needs additional measurements of position from CALL or MPC
Step 2: acquire images of an asteroid with cadence of 1-hr
Step 3: measure the position of the asteroid in each image (ImageJ or Python)

https://minorplanetcenter.net/iau/mpc.html
https://mpbulletin.org/issues/MPB_51-3.pdf
Current shape model: Asteroid Inversion Model: https://astro.troja.mff.cuni.cz/projects/damit/
Observation: Asteroid Astrometry with Astro ImageJ https://britastro.org/wp-content/uploads/2018/11/Tutorial_AIJ_Photometry_v2.06.pdf
New project: Polarized lightcurve of asteroid
New project: Shape Modelling using GAN
New project: Parallax distance of asteroid

Time-domain Observations: Astrometry & Photometry of Asteroid

Astrometry:
For each observation, we can determine astrometric parameters from the mid-time of the observed lightcurve: The distances (in AU) from the asteroid to the Sun and the Earth, the solar phase angle, the J2000.0 ecliptic longitude (λ), and latitude (β). (*Marciniak et al., 2007, 2011, 2023*)

Photometry:
From the phase diagram, we can determine the number of peak, peak locations and period

Shape modelling:
Sbpy python implementation of the inversion problem to derive shape parameters (*Kaasalainen & Torppa2001; and Kaasalainen et al. 2001, 2003, Mommert, et al., 2019*)

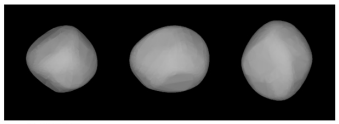


Fig. 16. Shape model of 276 Adelheid.

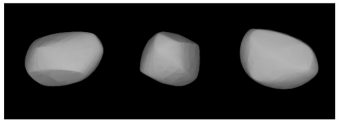


Fig. 17. Shape model of 556 Phyllis.

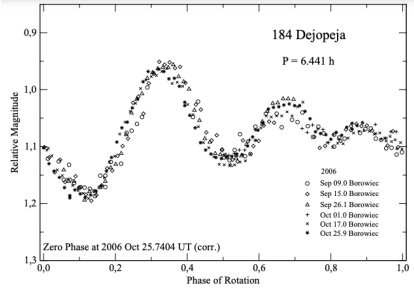


Fig. 4. Lightcurve of 184 Dejopeja in 2006.

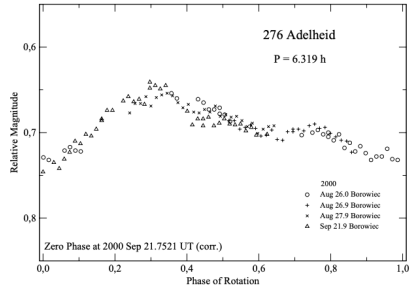


Fig. 5. Lightcurve of 276 Adelheid in 2000.

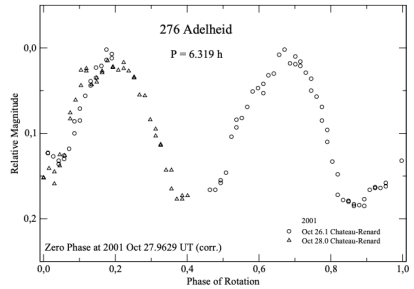
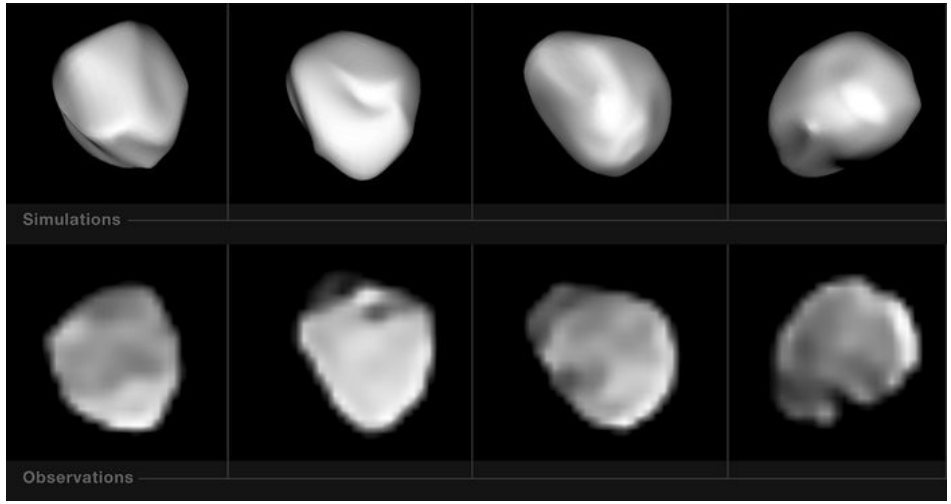


Fig. 6. Lightcurve of 276 Adelheid in 2001.

Example of 6 Hebe asteroid observed by QNO

QNO observation (Le Quang Thuy)



Shape simulation & VLT observation
https://www.eso.org/public/images/potw1725a/

Time-domain Observations: Variable stars

GCVS contains over 45,000 variable stars
Most have poorly known properties
Multicolor light curves can help to measure

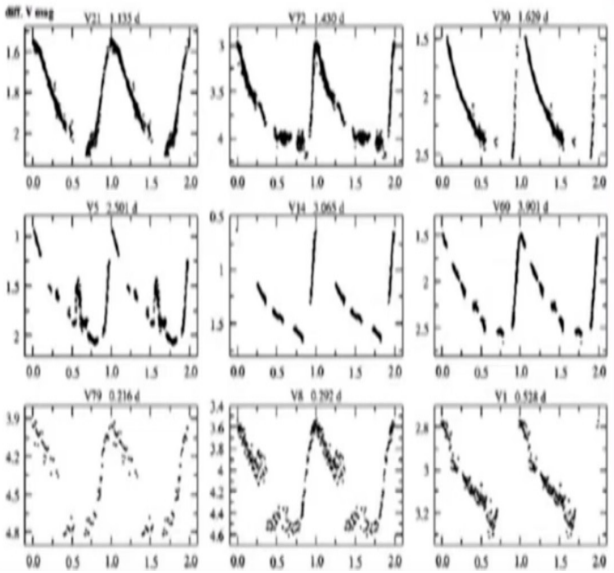
- stellar radii
- stellar temperatures
- stellar masses

AAVSO http://www.aavso.org/
Center for Backyard Astrophysics
http://cbastro.org

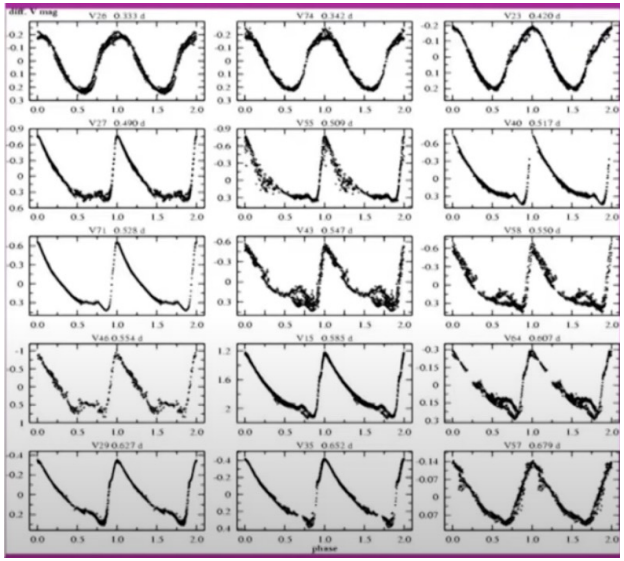
Variable types	Frequency of measurements
Long-period variable (Cephed, Mira, Carbon stars ,etc)	1 week
RR Lyrae	Many per night on any night
Eclipsing binaries	Many per night on selected night
Cataclysmic variable	Many per night (only during outburst)

Time-domain Observations: Variable stars

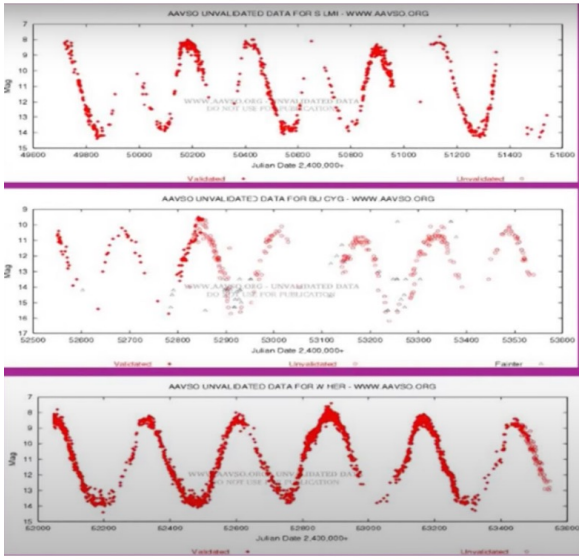
Cepheds



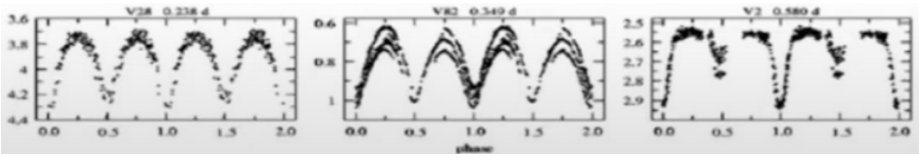
RR Lyraes



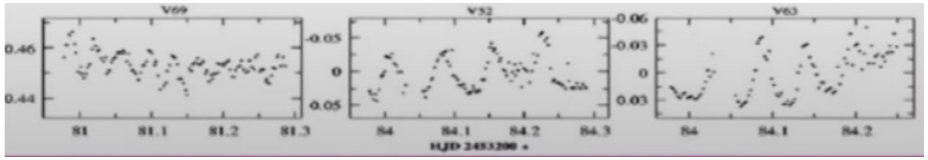
Mira



Eclipsing binaries



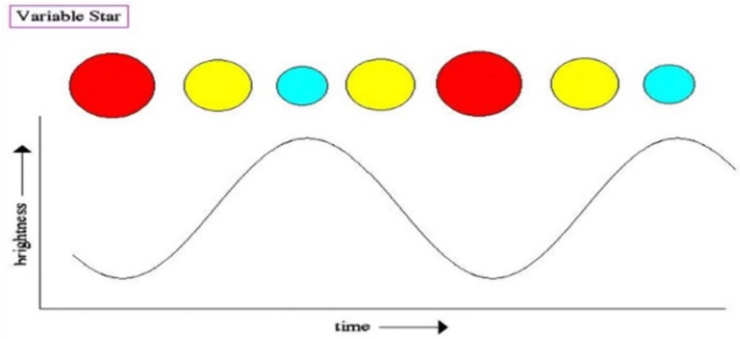
Delta Scutis



Szekely et al., 2007

Time-domain Observations: Variable stars

Periodic luminosity change by pulsating variables are caused by the same physics: An unstable equilibrium between outward pressure and inward gravity. So, their radii and surface temperature changes simultaneously.



Cepheids and RR Lyraes are standard candles and often used to measure distances to galaxies.

Famous Luminosity-Period relation

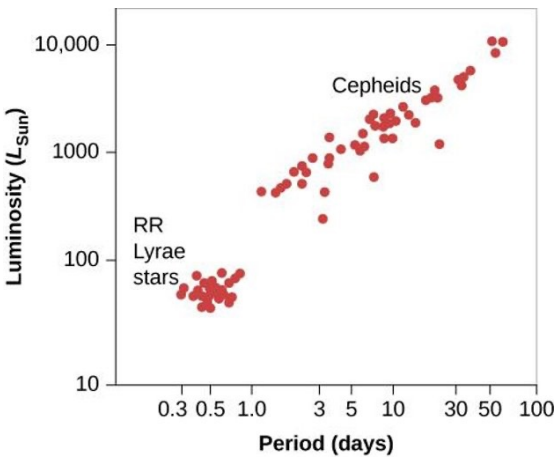
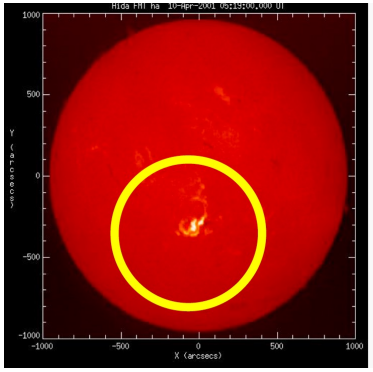


Figure from abyss.uoregon.edu/js

Time-domain Observations: Starspots

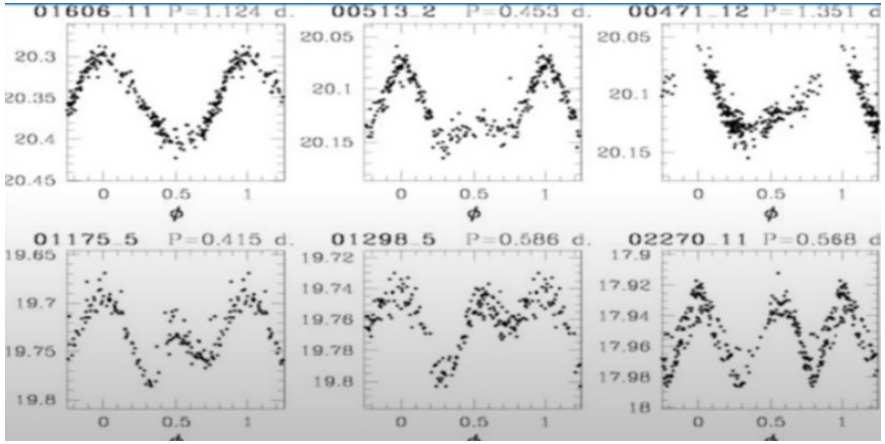


Like our Sun, stars may have rotational variability due to starspots.

This variability can change a lot as starspots come and go, it can be difficult to find a specific rotation period of the stars.

Younger stars have faster rotation, so it is easier to determine their period.

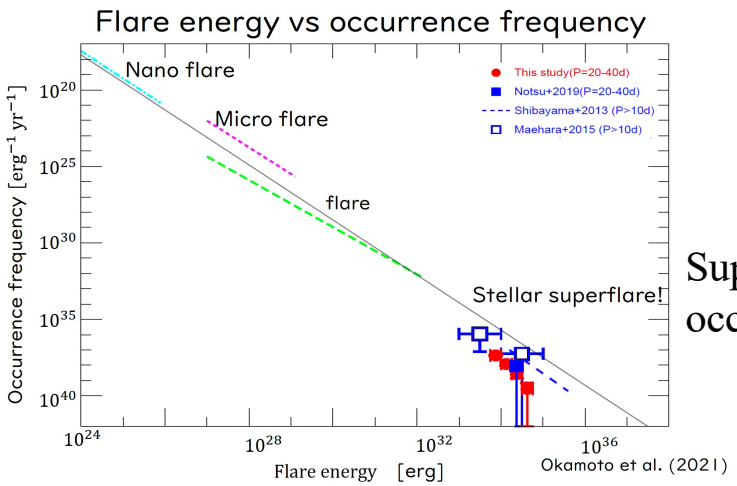
Lightcurves and periods of starspots in NGC2061



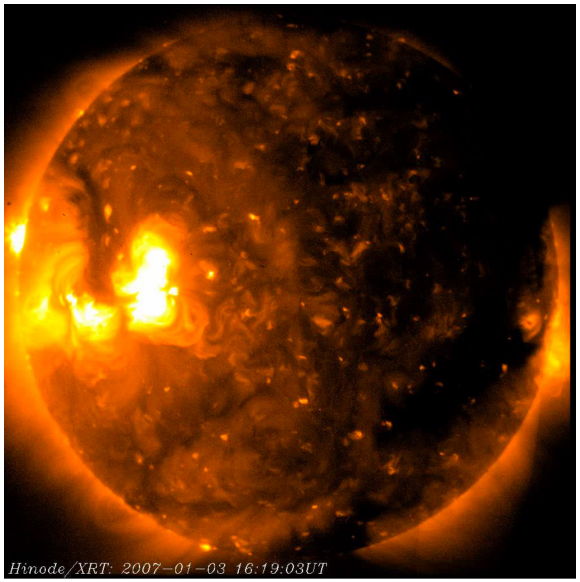
De marchi et al., 2007

Time-domain Observations: Sun and Stars flares

Like our Sun, stars have flares on the surface
The most energetic explosions
Mostly around starspots due to the release of magnetic energy.
Observed in all wavelengths from X-ray to radio.
Timescale: minutes to hours



Superflare above 10^34 erg occurs once every 6000 years



The Sun observed by an X-ray telescope onboard the satellite HINODE.
The place where the flare is occurring appears to shine.

PI: Professor Hiei (NAOJ, Japan)

De marchi et al., 2007

Time-domain Observations: Flares projects

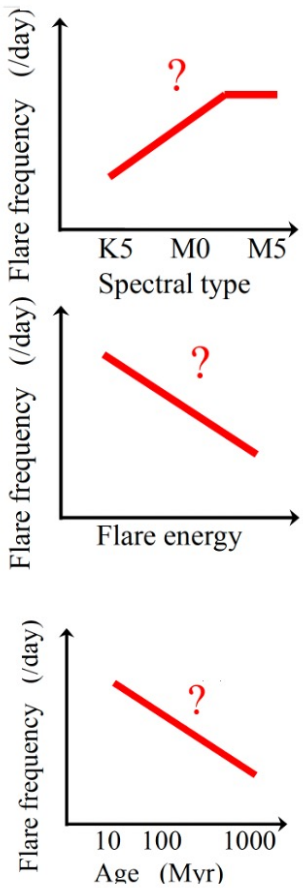
Remaining Questions can be answered by observations with QNO-type telescope

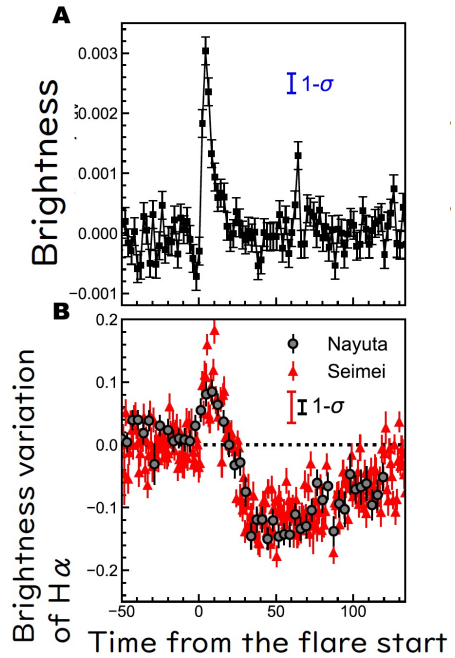
Statistical analyses

1.Flare frequency vs flare energy
2.Flare frequency vs spectral type
3.Flare frequency vs age
…
These will give new basic info on the inner stellar structure and stellar evolution.

Project

Long-time monitoring of open clusters to detect flares on many M-type stars (brighter than 20 mag).





Time-resolved spectroscopy during a flare in a solar-type star for the first time!
EK Dra (V~7.6)
Namekata et al. 2022, Nature Astro

Time-domain Observations: Flares projects

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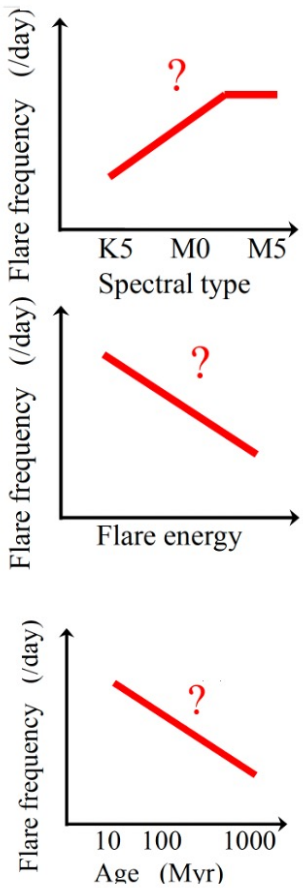

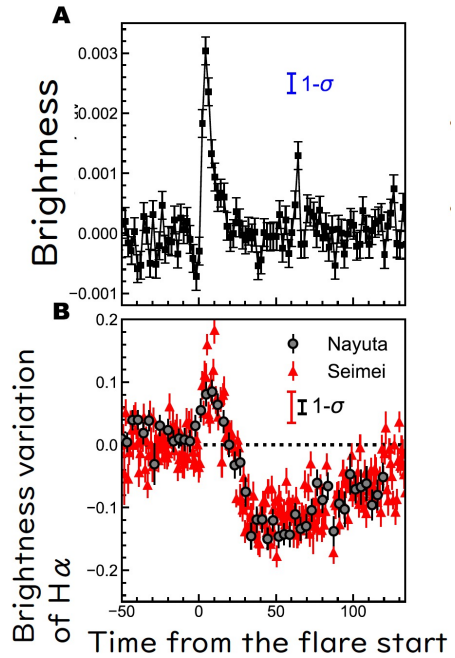

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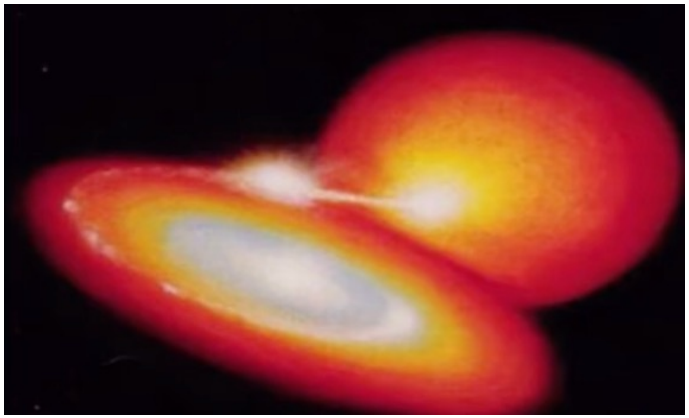
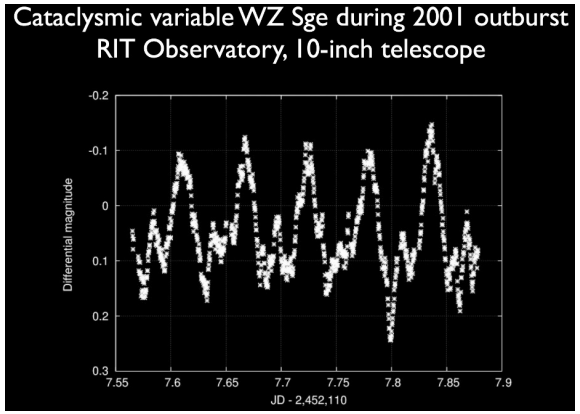
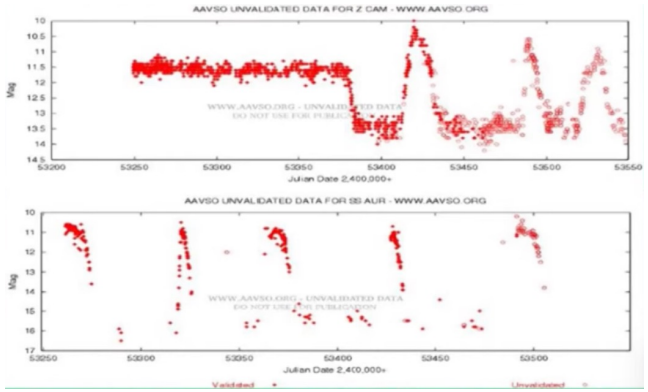
Time-domain Observations: Cataclysmic variable

Cataclysmic variable:
White dwarfs accrete material from a companion star, either main sequence or evolved stars. in their binary system,

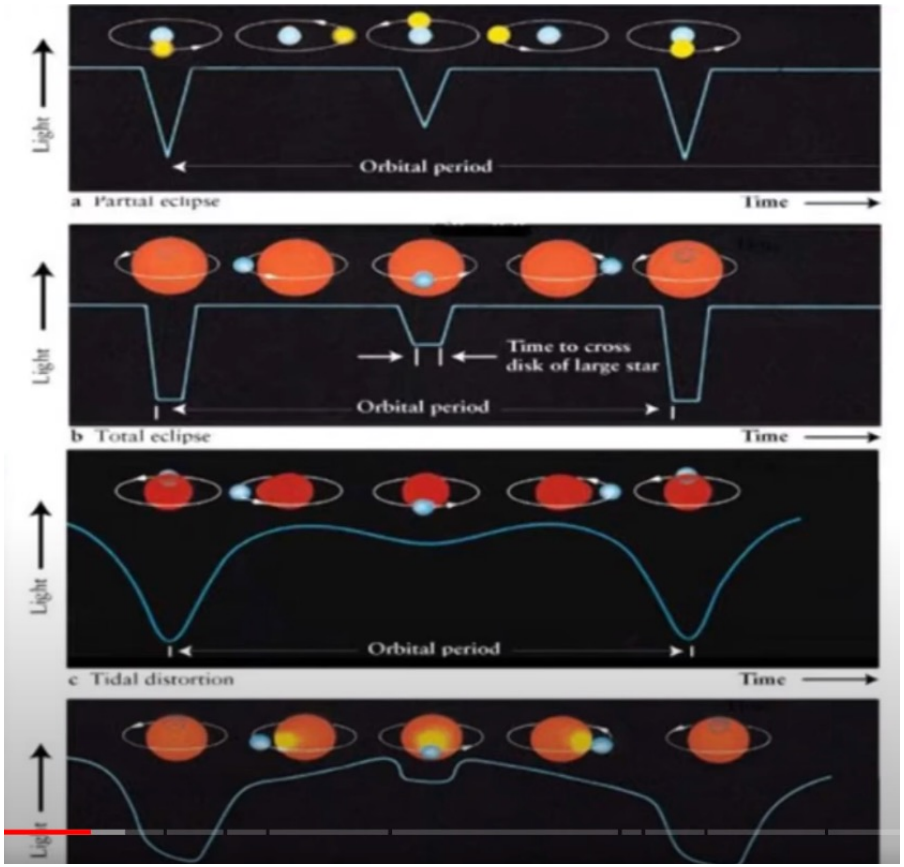
Hydrogen layer that builds up on surface of WD heats until H fusion starts on the surface, leads to a sudden, short burst of light.

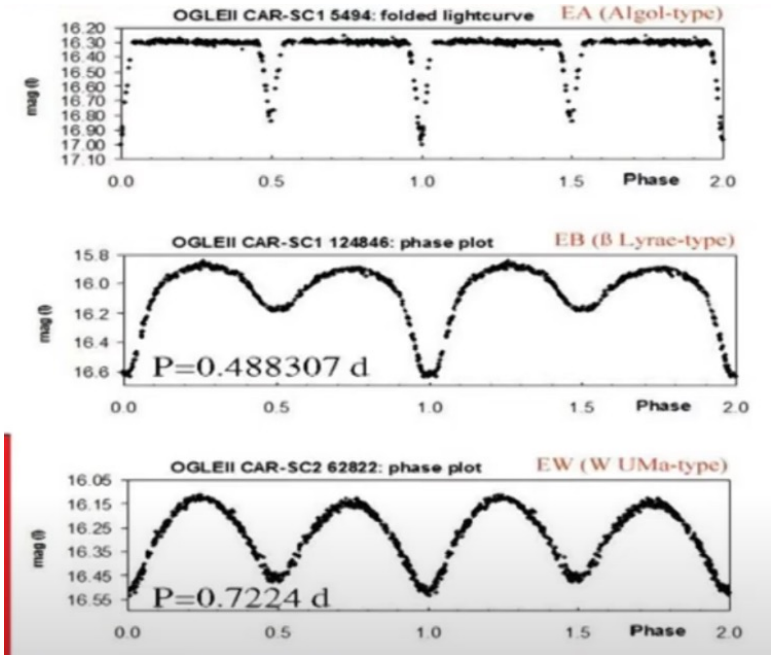






Time-domain Observations: Eclipsing binaries





Hummerich et al. 2013

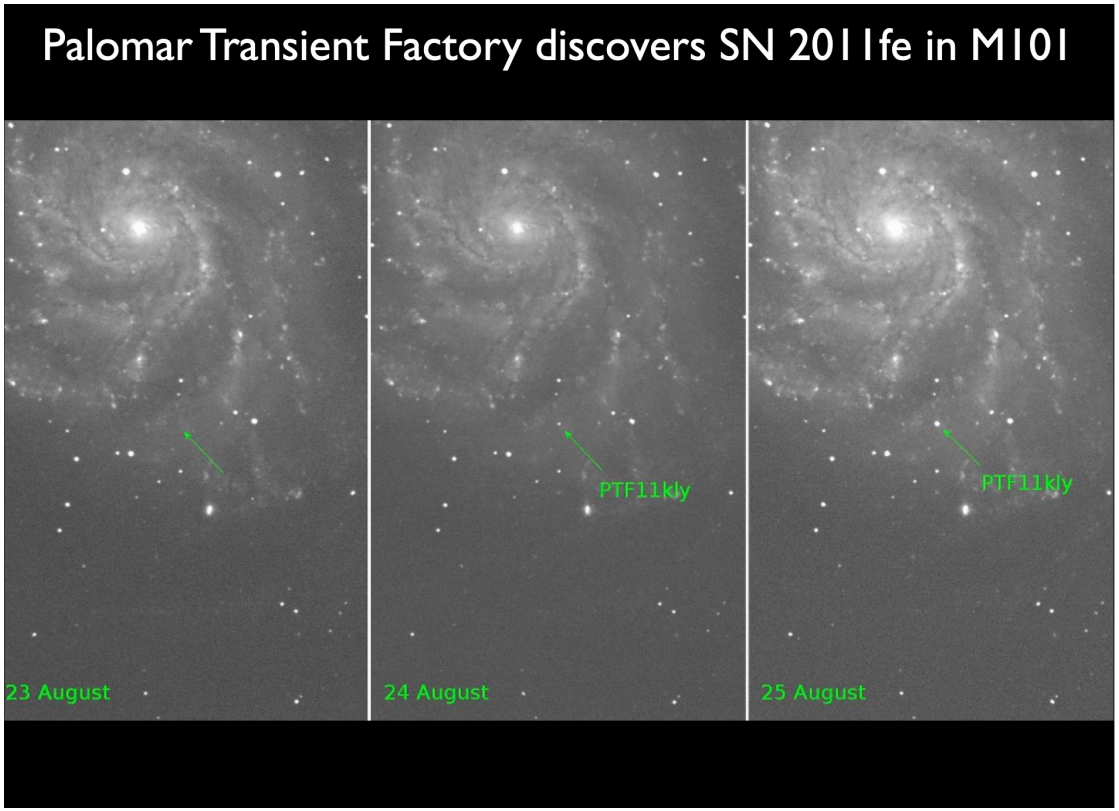
Time-domain Observations: Supernovae

Can we discover new ones?

- Hundreds found each year most are faint, embedded in host galaxy
- Requires monitoring of many galaxies

We can follow-up photometry of known events plenty are bright, mag < 13 at peak

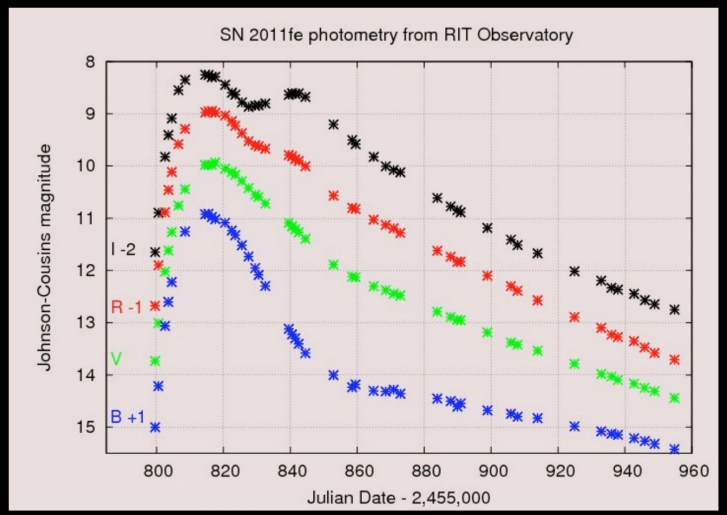
- Need photometric filters since shape of lightcurves change with filters



Time-domain Observations: Supernovae

- List of active SN
- https://www.rochesterastronomy.org/snimages/
- Central Bureau for Astronomical Telegrams (also home of IAU Circulars) http://www.cbat.eps.harvard.edu/index.html
- Astronomer's Telegram http://www.astronomerstelegram.org/
- Dave Bishop's supernova site http://www.rochesterastronomy.org/supernova.html
- Notes on novae and supernovae http://spiff.rit.edu/richmond/sne/aavso/nova_sn.html

Measurements made with a 12-inch telescope

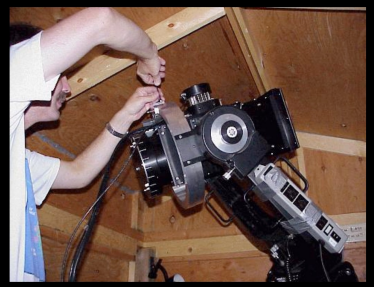


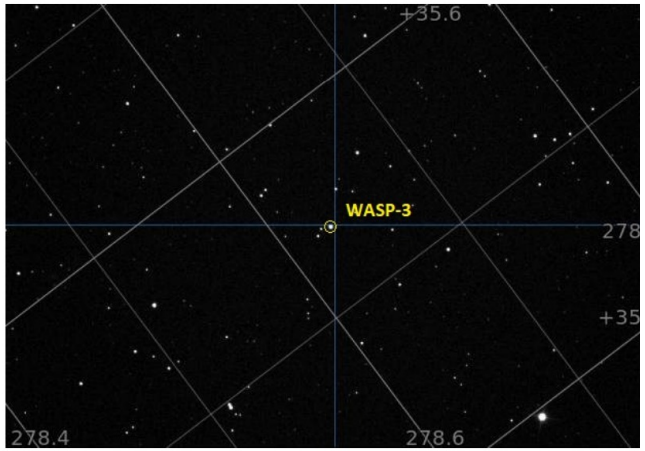
Time-domain Observations: Exoplanets

- Exoplanet transits can be detected with small telescopes
- Discover new ones requires survey of thousands of stars
- Follow-up photometry of known events need high-precision photometry
- One good night is all it takes

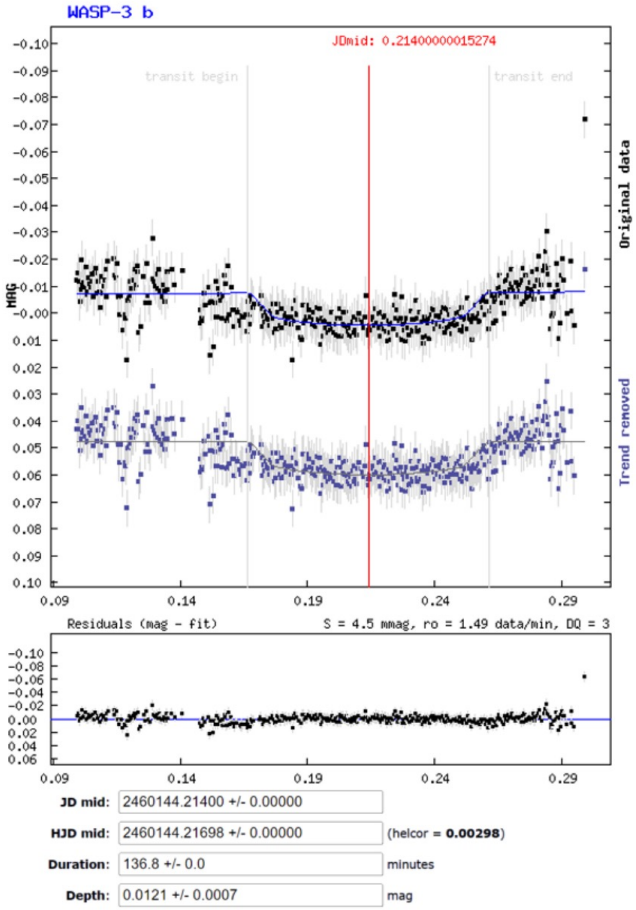
The first transit observations were made with the STARE 4-inch telescope in 1999

Charbonneau et al., ApJ 529, L45 (2000)





Tue Nguyen-Van, et al. (2023)



Time-domain Observations: Exoplanets

- TransitSearch.org
  http://www.transitsearch.org/
- Exoplanet transit database
  http://var.astro.cz/ETD
- Amateur exoplanet archive
  http://brucegary.net/AXA/x.htm
- ensemble photometry
  http://spiff.rit.edu/ensemble/

Projects:

Confirm TESS exoplanet candidate

- 7203 TESS-candidates but only 543 were confirmed
- Confirmation requires lightcurve monitoring in different filters and/or radial velocity measurement.

Discover new ones requires survey of thousands of stars

Time-domain Observations: Observational Difficulty

UNIVERSITY ASTRO LAB LEVEL 1

- astrometry of known asteroids
- photometry of variable stars
- detecting exoplanet transits
- asteroid light curves

THESIS/SENIOR PROJECT

- asteroid light curves
- detailed analysis of variable star light curves
- Followup obs of known supernovae
- exoplanet timing measurements

RESEARCH

- finding new asteroids
- finding new supernovae
- Confirming exoplanet candidate
- finding new exoplanets

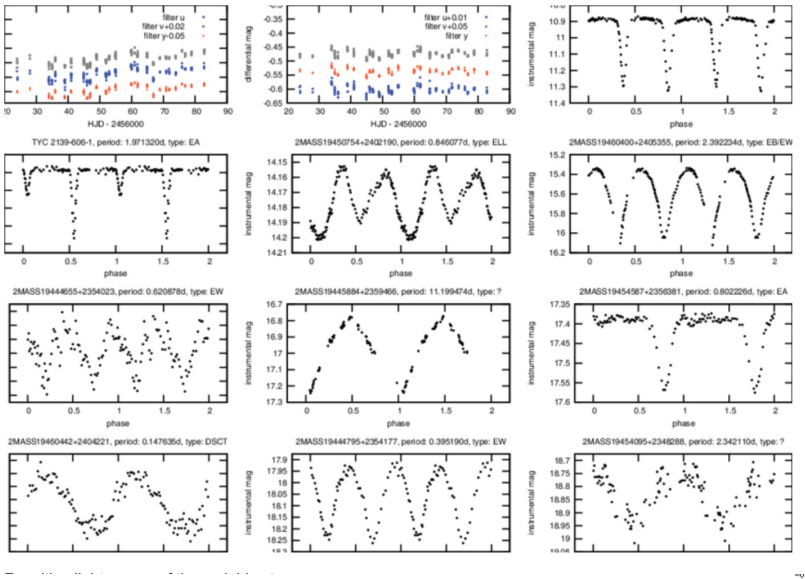
Time-domain Observations: Analysis

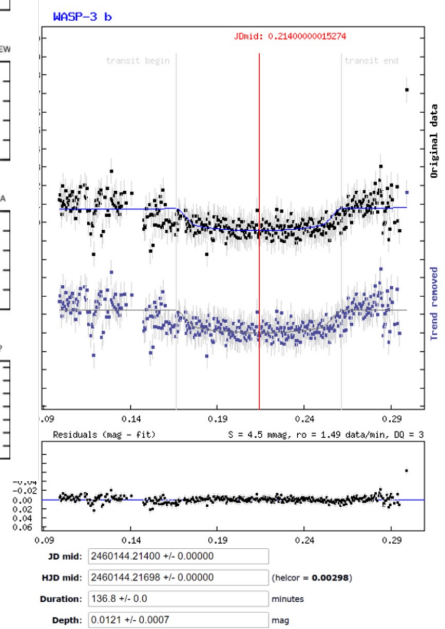
You got the lightcurve, what next?

.

We look for patterns and characteristics of the lightcurve shapes and periodicity. They are important to determine types of objects

How do LC shapes compare across different types?
How does amplitude of variability compare across different types?
How do periods compare across different types?





Sowicka et al. 2014

Time-domain Observations: Lightcurve Analysis

To construct phase diagram from a raw lightcurve containing many epochs (Phase up)
To identify and derive shape, period, amplitude
To derive period from the raw lightcurves using string-length, Fourier analysis, Lomb-Scargle Periodogram
To interpret the physics of the targets from the lightcurve

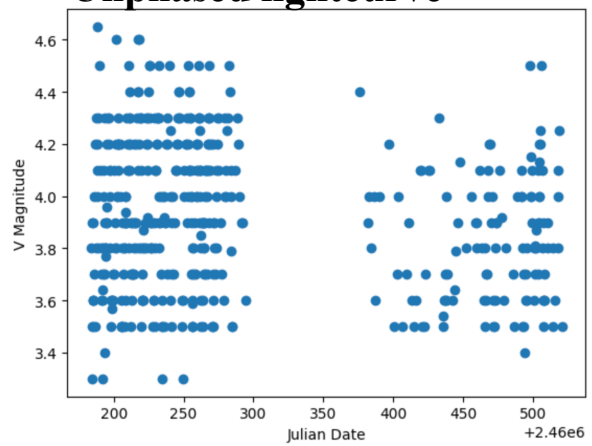
Time-domain Observations: Lightcurve Analysis

Phase up
Light curve observed over multiple epochs over long baseline can be phased up to yield a more precise phase diagram

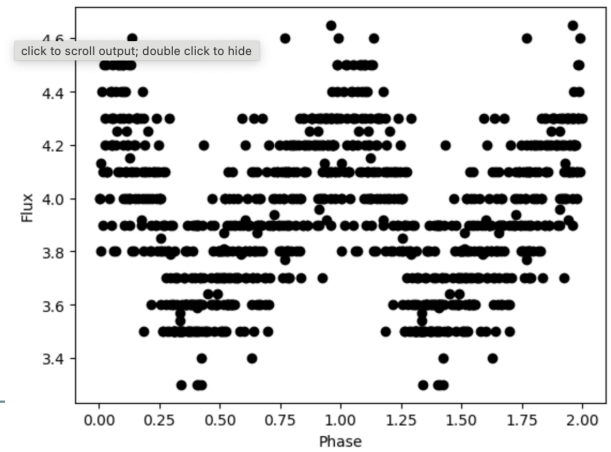
$$\Phi = \frac{(t-E)}{P} - Integer\left[\frac{(t-E)}{P}\right]$$

Φ: phase
t: time of the observation
E: starting time
P: period

Unphased lightcurve



Phased lightcurve



Time-domain Observations: Period determination

Brute force method (string-length minimization method) in time domain
Guess a trial period *P*
Create a trial phase diagram
Calculate the *string length* Θ

$$\Theta = \frac{\sum_i (m_i - m_{i+1})^2}{\sum_i (m_i - \bar{M})^2}$$

Θ: string length
m_i: magnitude at phase i
M: averaged magnitude of the phase diagram

Repeat again for many different period
The trial period with the minimum string length is close to the true period

Time-domain Observations: Fourier transform

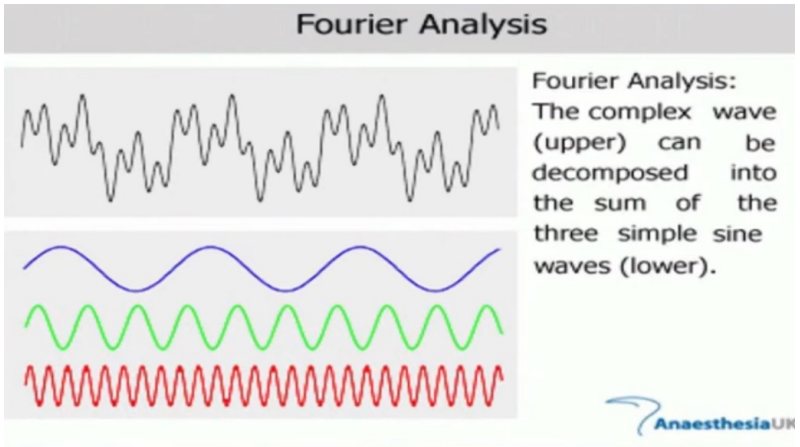
Light curves are periodic
We can Fourier transform it to frequency domain

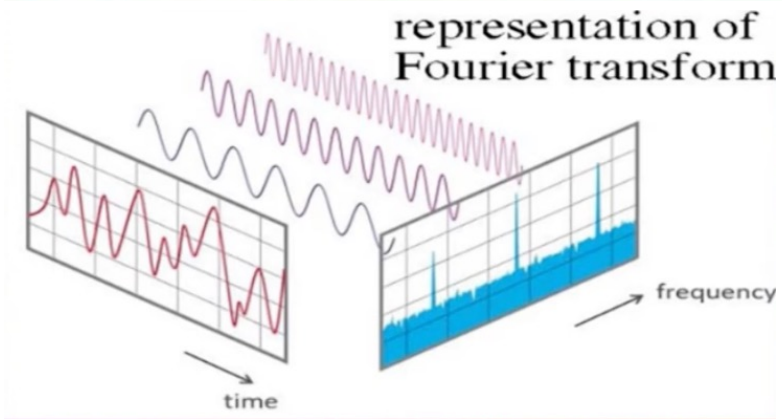
Guess a period P
We fit trial sets of sines waves to the data
A lightcurve can be created by combining multiple sine waves

$$V(t)=\bar{V}+\sum_{l=t}^{n}\left[A_l\sin\left(\left(\frac{2\pi l}{P}\right)(t-t_o)\right)+B_l\cos\left(\left(\frac{2\pi l}{P}\right)(t-t_o)\right)\right]$$

$\bar{V}$: mean magnitude of lightcurve
A_l, B_l: Fourier coefficients
P: trial period
t: time
t_o: zero-point time, which should be near middle of time span of observations
n: # of "orders" to be included in the trial set of sine waves

Repeat again for many different period
The trial period with the minimum RMS error would be the nearest solution





Time-domain Observations: Fourier transform

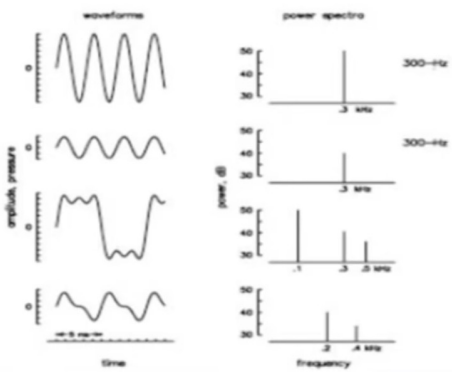
If a sine wave at a specific frequency contribute more to the signal of the lightcurve, the power on the Fourier spectrum is also larger.

A FT of the lightcurve breaks down the LC into each of its contributing sine wave frequencies.

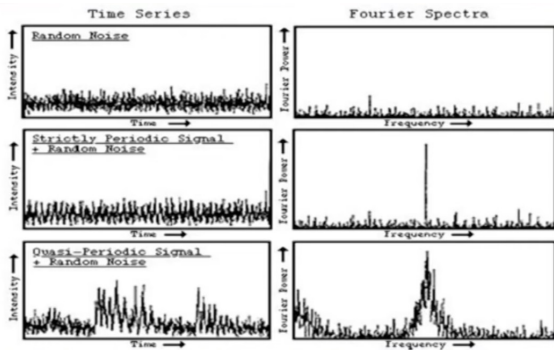
The transform computes the power spectrum of the lightcurve: how much power exists in the lightcurve at each frequency.

A classic FT requires the data points to be evenly spaced in time, not likely in astronomical observations.

Clean signals & FT



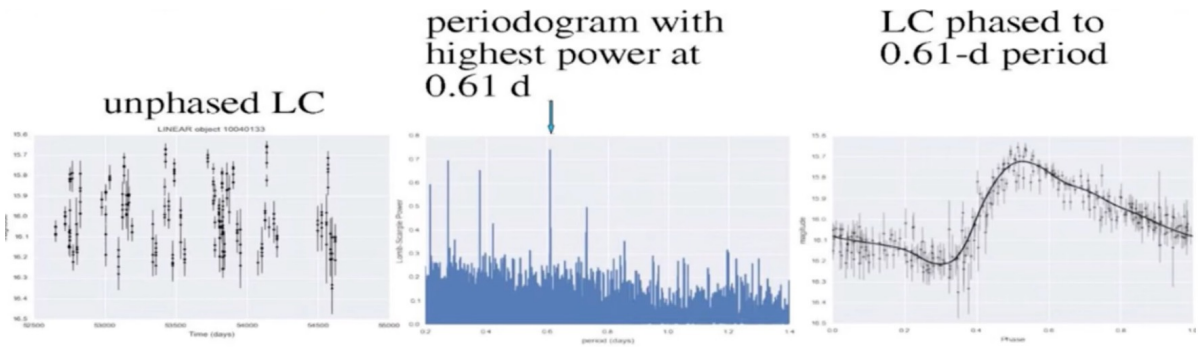
Noisy signals & FT



Time-domain Observations: Fourier transform

A type of FT was developed for unevenly-spaced data, called Lomb-Scargle periodogram.

LSP does not calculate the exact quantity of power as the FT. but it can be used to indicate the most powerful frequencies in the lightcurve.



$$P_{LS}(f)=\frac{1}{2}\left[\left(\sum_n g_n\cos(2\pi f[t_n-\tau])\right)^2/\sum_n \cos^2(2\pi f[t_n-\tau])\right]$$
$$+\frac{1}{2}\left[\left(\sum_n g_n\sin(2\pi f[t_n-\tau])\right)^2/\sum_n \sin^2(2\pi f[t_n-\tau])\right]$$

$$\tau=\frac{1}{4\pi f}\arctan\left(\frac{\sum_n \sin(4\pi f t_n)}{\sum_n \cos(4\pi f t_n)}\right)$$

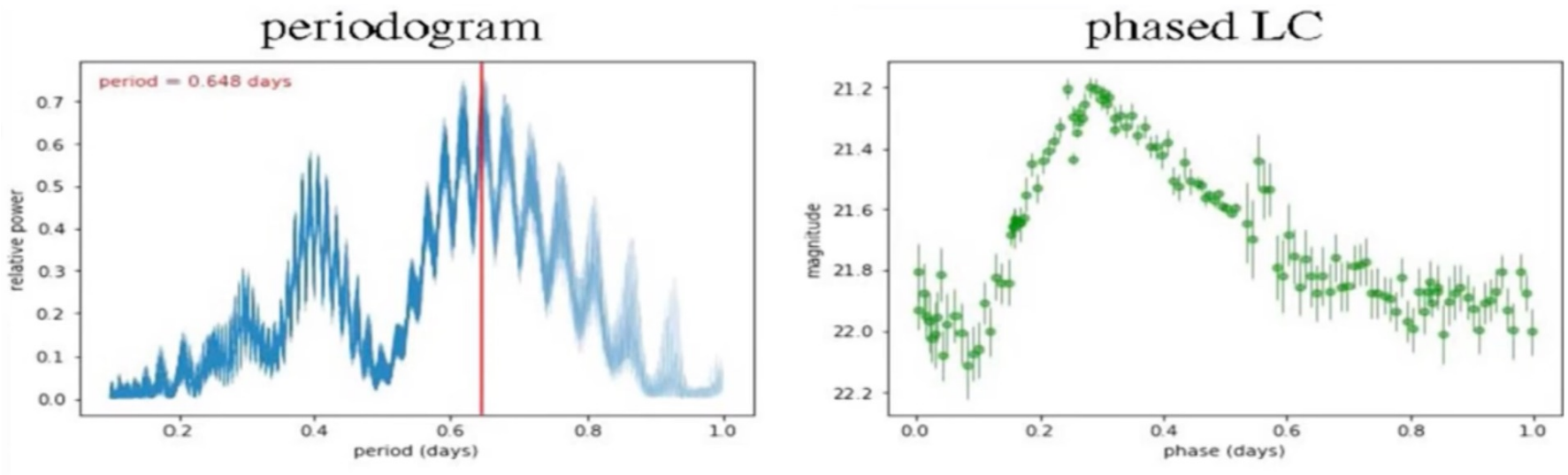
g_n: the magnitude of the individual observed data points
t_n: the time data point n was observed

τ is specified to ensure that result is invariant with time-shift.

Jakevdp.github.io/blog/2015/06/13/lomb-scargle-in-python

Time-domain Observations: pseudo-power

The pseudo-power spectrum may show power at other frequencies:
noise, harmonics and windowing of the data

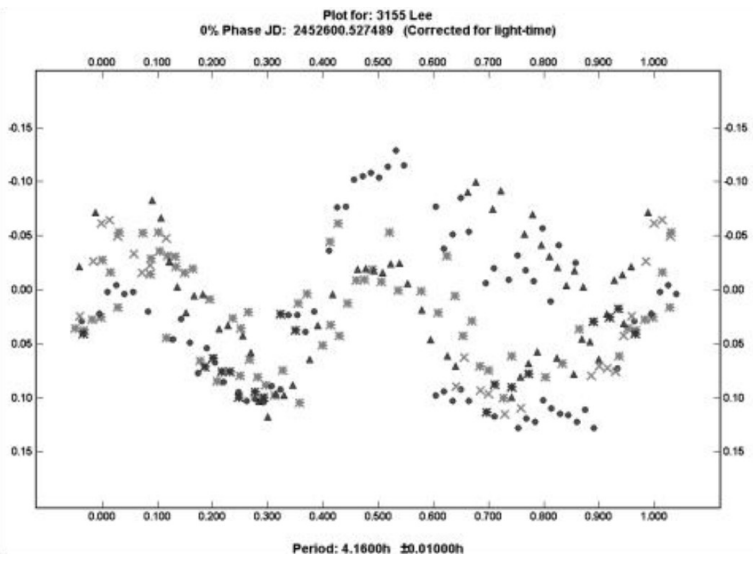


Jakevdp.github.io/blog/2015/06/13/lomb-scargle-in-python

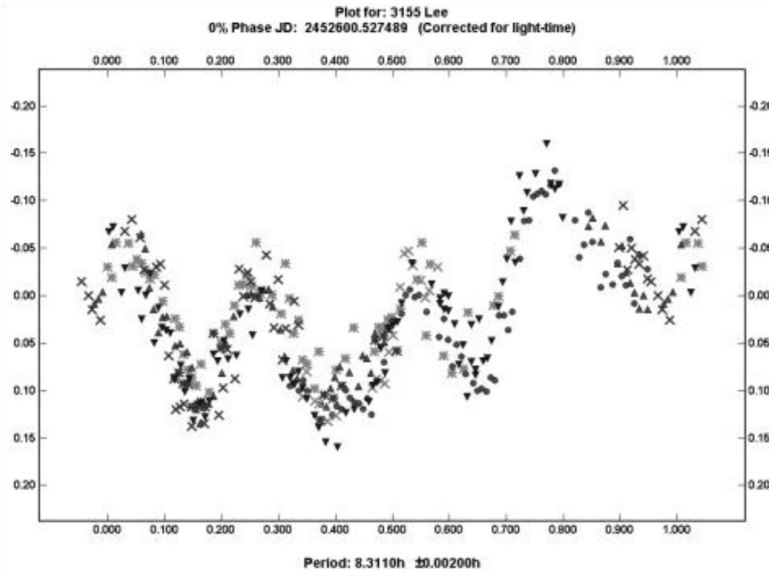
Time-domain Observations: Alias

Alias period: false period related to the true period of to the observation frequency.
Common alias period: ½ or 2x the true period, or period near 12 or 24 h.

Not correct: 4.166 h



Correct: 8.311 h



Observational Projects during 3S24

We will observe asteroids and conduct astrometric/photometric study of the asteroids and do shape modelling.
Observations might start tonight.

Thank you!