Time-series analysis in Astronomy

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Course Plan

- Introduction
- Time Series Analysis
  - Methods for evenly sampled data
  - Methods for unevenly sampled data
- Timing methods in Optical and X-ray Astronomy
- Timing features in Optical and X-ray Astronomy

Caveats

- This course wishes to be practical and not theoretical and relevant to the analysis of optical and X-ray data
  - There are plenty of good theoretical books and papers
- Entirely based on my own experience
  - Alternative methods must exist but will not be reviewed here

Assessment

Your grade will be based on:

- 50% Exam on lecture course
- 25% Homeworks
- 25% Project

Text Books

- *Fourier Analysis of Time Series: An Introduction* (2nd edition - 2000) – P. Bloomfield: ISBN: 978-0-471-88948-9
- *"Asteroseismology"* (2010) – C. Aerts, J. Christensen-Dalsgaard, D. W. Kurtz: ISBN: 978-1-4020-5178-4
- *"Fourier techniques in X-ray timing"* (1988) – M. van der Klis (available on site)
- *"Astronomical Time Series Analysis: Lecture Notes"* – Jaan Pelt (available on site)

Introduction

TIME SERIES, LIGHT CURVES
TIME, FREQUENCY, PHASE, EPHEMERIS

Time Series

- Time series is a collection of data points, arranged in a natural order (time) → 1-d sequence;

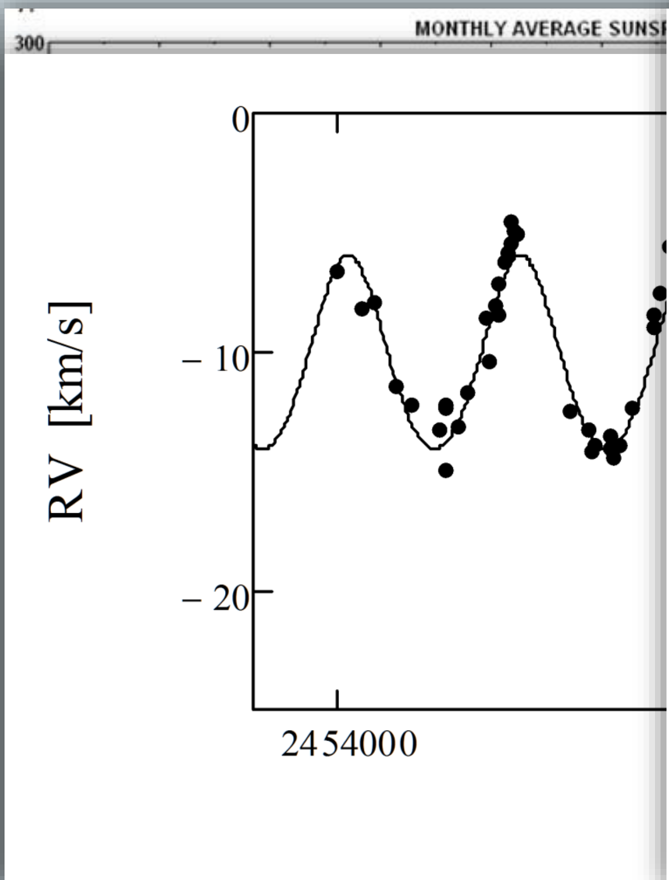
- Sometimes, more than one parameter is observed at each time point → multi-d sequence.

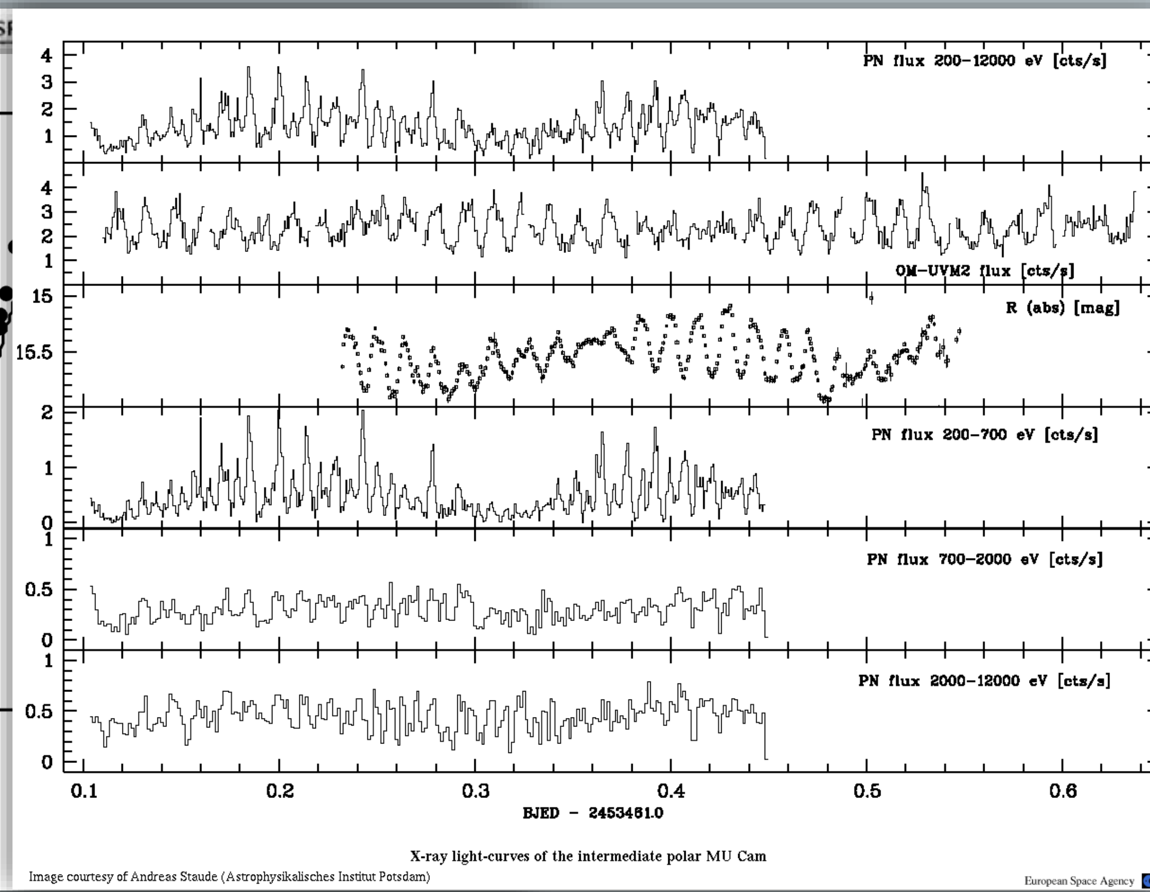
Time Series in Astronomy

- **Periodic phenomena:** binary orbits (stars, extrasolar planets); stellar rotation (radio pulsars); pulsation (helioseismology, Cepheids)
- **Stochastic phenomena:** accretion (Cataclysmic Variables, X-ray binaries, Seyfert galaxies, quasars); scintillation (interplanetary & interstellar media); jet variations (blazars)
- **Explosive phenomena:** thermonuclear (novae, X-ray bursts), magnetic reconnection (solar/stellar flares), star death (supernovae, gamma-ray bursts)

Time Series

- Many obvious examples:





Time Series

- Astronomical time series are somewhat different if to compare with standard time series often used in other branches of science and businesses.

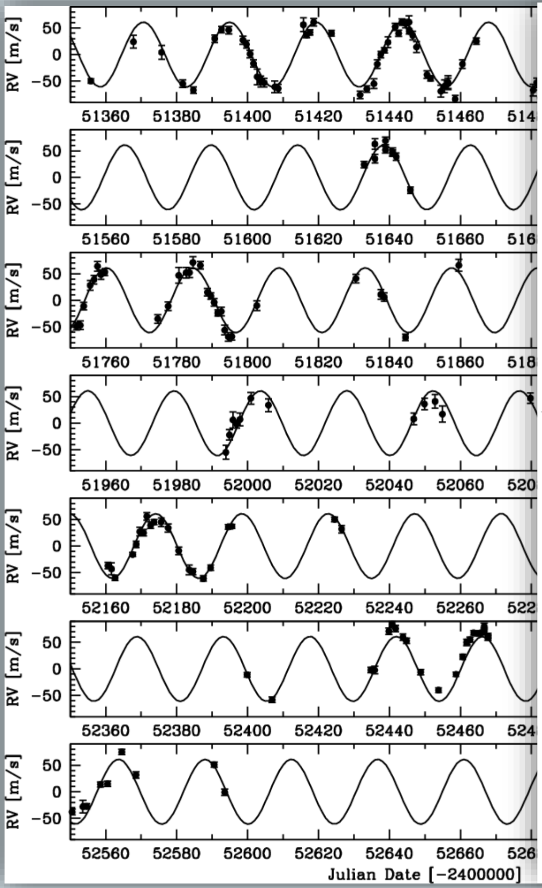
- The random, often sparse and gapped nature of astronomical observational sequences makes most of techniques of the standard time series analysis unusable.

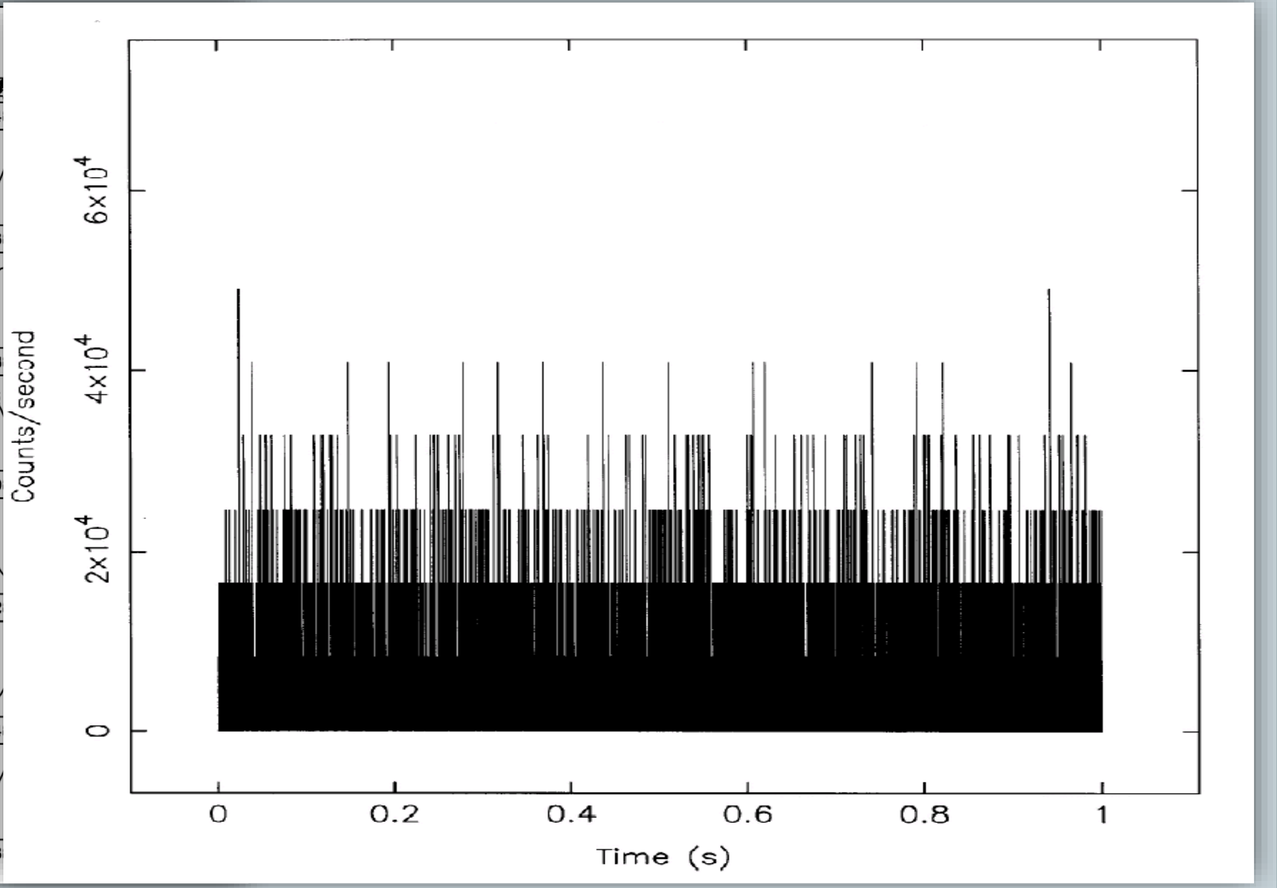
Time Series

- In statistics, signal processing, and businesses applications, a time series analysis deals with records with **equal** intervals between them.
- Difficulties in astronomical time series:
  - **Gapped** data streams:
    - Diurnal & monthly cycles; satellite orbital cycles; telescope allocations
  - Heteroscedastic measurement errors:
    - Signal-to-noise ratio differs from point to point
  - Poisson processes:
    - Individual photon/particle events in high-energy astronomy

Time Series

- More examples:





Timing Analysis

Time series analysis comprises methods for analyzing time series data in order to extract meaningful statistics and other characteristics of the data.

<u>Some Questions That We'd Like to Answer:</u>

- Does My Source Vary?
- On What Time Scales Does it Vary?
- Are the Variations Periodic or Aperiodic?
- How Do Different Energy Bands Relate to One Another?

Timing Analysis

Method used for time-series analysis depends on the time-series itself:

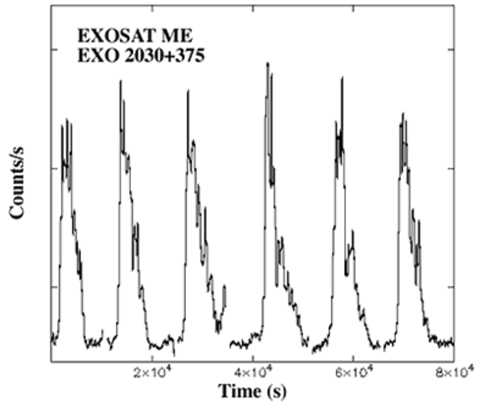
- Evenly or unevenly sampled data
- Signal and noise level
- Light-Curve
- Length of Time Series

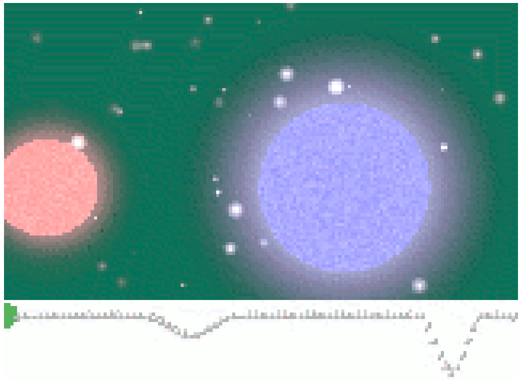
Too many different methods.

Even astronomers sometimes have difficulties to compare the techniques they routinely apply.

Problems of terminology and differing conventions hamper the flow of information between the various branches.

Timing Starts with a Lightcurve





- Sine-like
- Impulse-like
- Eclipses
- Complex, multiperiodicity

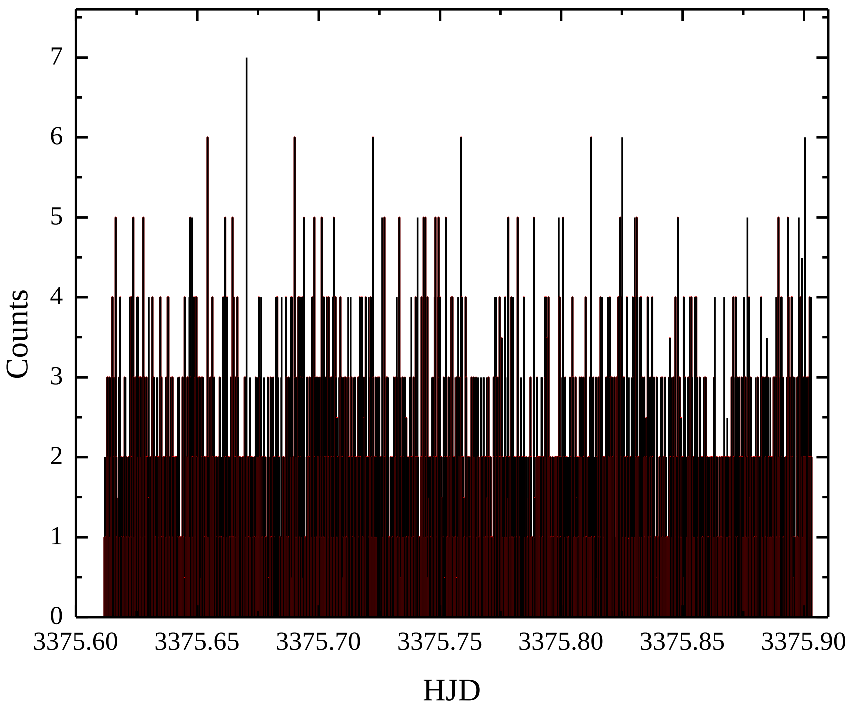
- No periodicity, only noise.

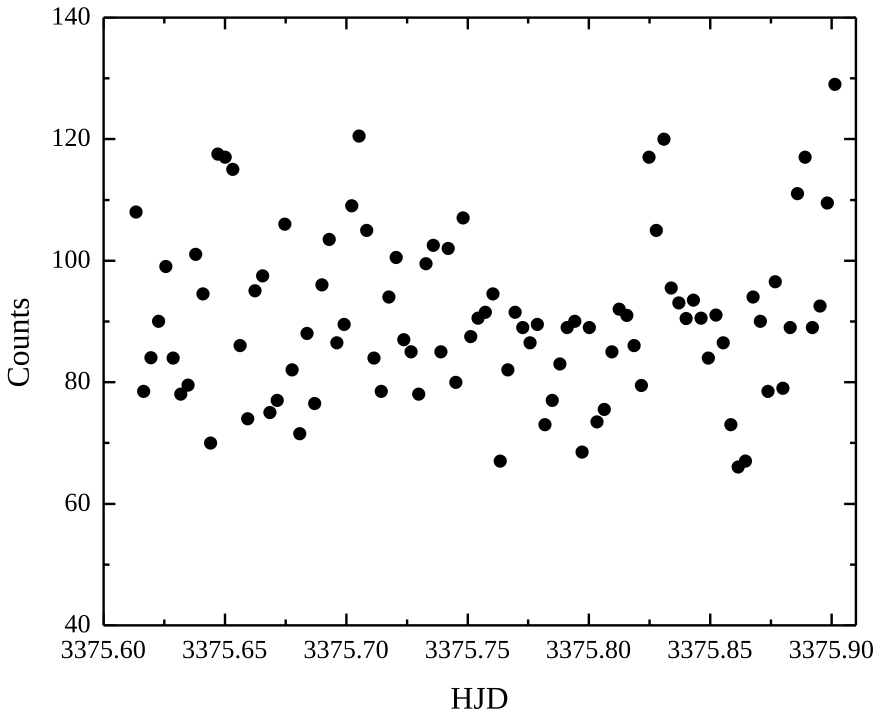
But "One person's noise is another one's data"!

Lightcurve

Sometimes we have to apply time binning, but:

- Always choose integer multiple of “natural” time unit for binning
- Don’t bin any more than you have to - save it for subsequent analysis





Time

There are a number of ways to express the absolute time.

One familiar way is calendar time, e.g.,

2025 January 7 at 14:45 EET

The Calendar Date **The Clock Time**

The Timezone (EET: Eastern European Time, GMT+2 hours)

Quite a clumsy system, difficult to use in astronomy

How many days have passed since your birthday?

Time

- UTC is Coordinated Universal Time, measured using atomic clocks, and is the basis of all civil timekeeping on Earth. All civil atomic clocks and computer time services provide time in UTC.
- UTC is *almost* (**but not the same!**) as Greenwich Mean Time (GMT) which starts at midnight in Greenwich, England.
- The **Julian Day** number (**JD**) is the count of the number days that have elapsed since Greenwich Mean Noon on January 1, -4712 (4713 BC) in the Julian Proleptic Calendar.
- Julian Days start at **noon**, unlike UTC Gregorian Calendar days which start at midnight.
- There are a lot of JD-calculators available online, e.g., https://www.aavso.org/jd-calculator

Time

Julian Dates:

2025 January 7 at 14:45 EET = **JD** 2460683.03125

An alternative to JD is the **Modified Julian Date (MJD)**, an abbreviated, 5-digit version of the Julian Date defined as:

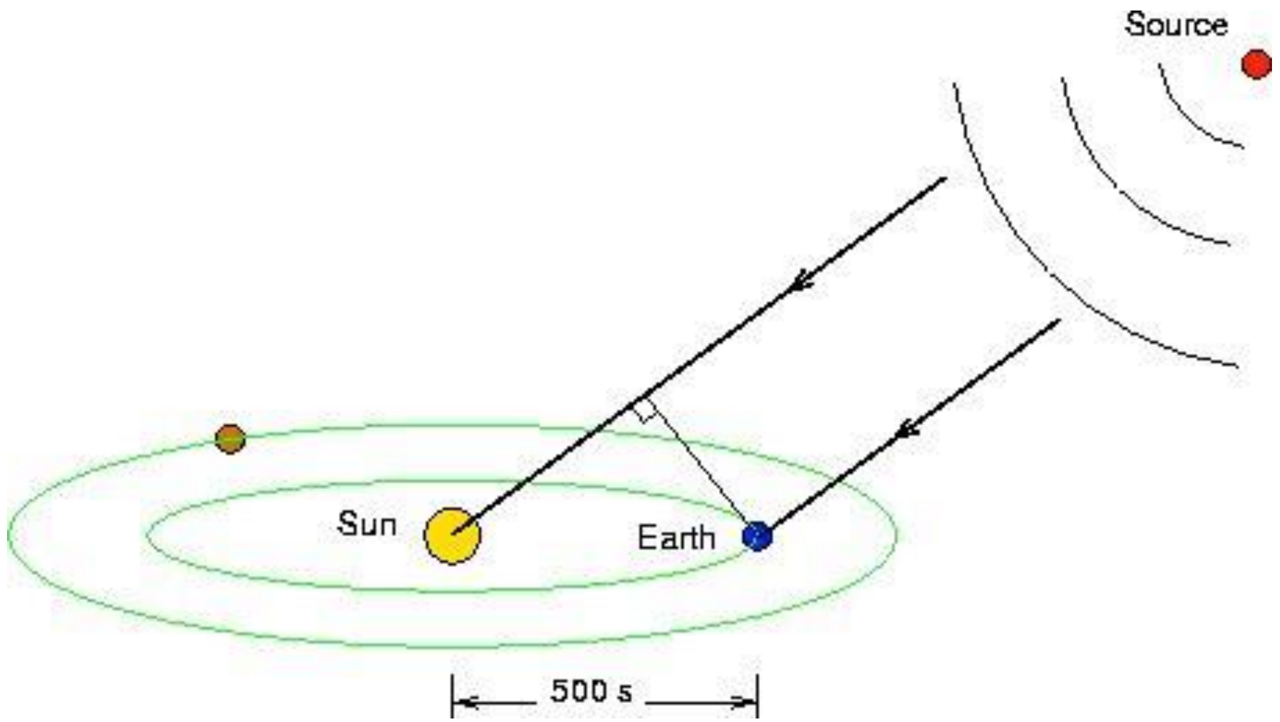
MJD = JD - 2400000.5

2025 January 7 at 14:45 EET = **MJD** 60682.**5**3125

So, how many days have passed since your birthday?

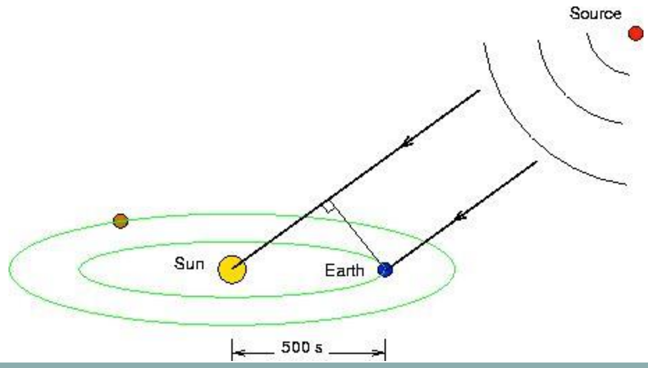
Heliocentric / Barycentric correction

Do not forget about the **heliocentric** or **barycentric** correction!
(to both **Times** and **Radial Velocities**)



Time (HJD and BJD)

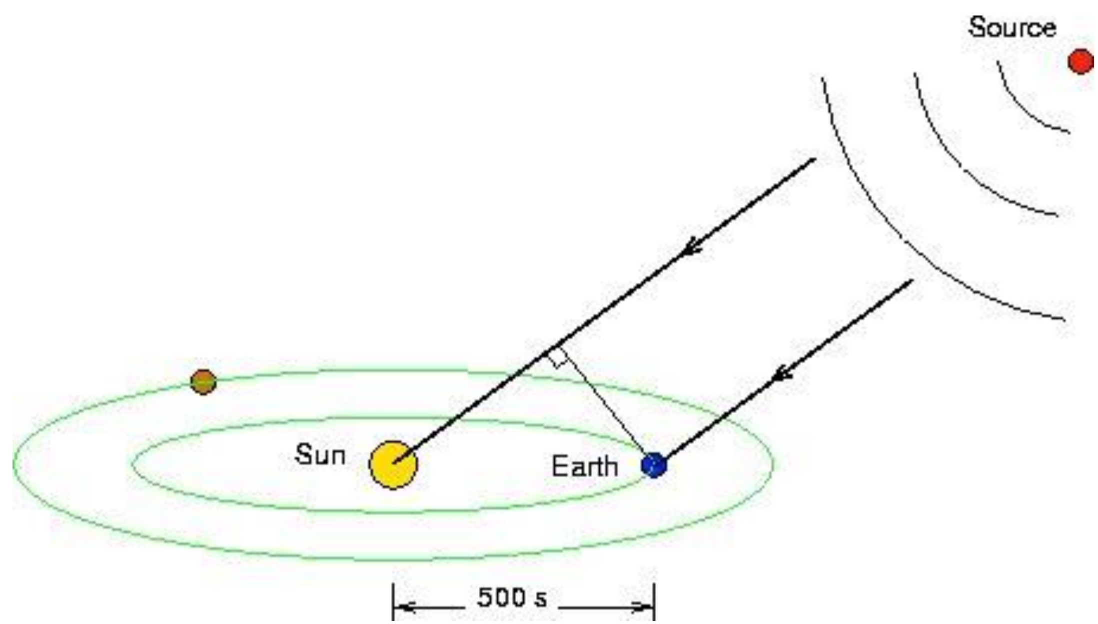
- The **Heliocentric Julian Date (HJD)** is the Julian Date adjusted to the center of the Sun.
  - It depends on the JD of the observation and the celestial coordinates of the object.
  - This is important for long-term secular studies where timing data will extend over either a large fraction of a year or many years.
  - The correction can amount to as much as about 16 minutes for observations taken 6 months apart.
- A more accurate way to express this is relative to the dynamical center-of-mass ("**barycenter**") of the Solar System, since the Sun also moves relative to the barycenter.



Heliocentric / Barycentric correction

- HJD calculator (does not work now): ~~http://www.physics.sfasu.edu/astro/javascript/hjd.html~~

- Barycentric Velocity Correction: http://astroutils.astronomy.ohio-state.edu/exofast/barycorr.html



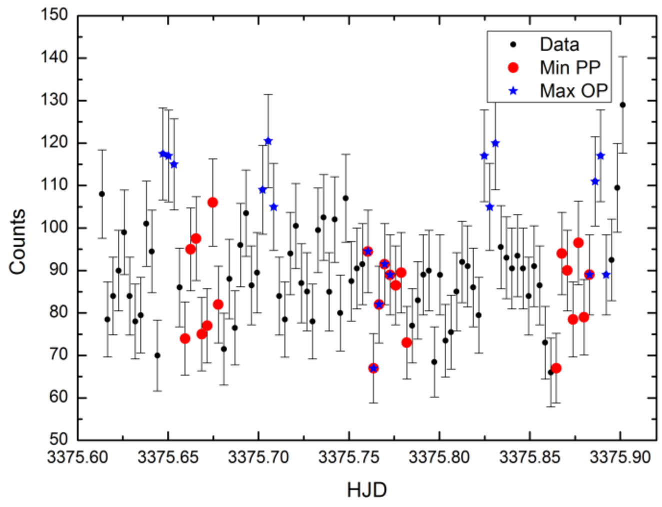
Ephemeris and Phases

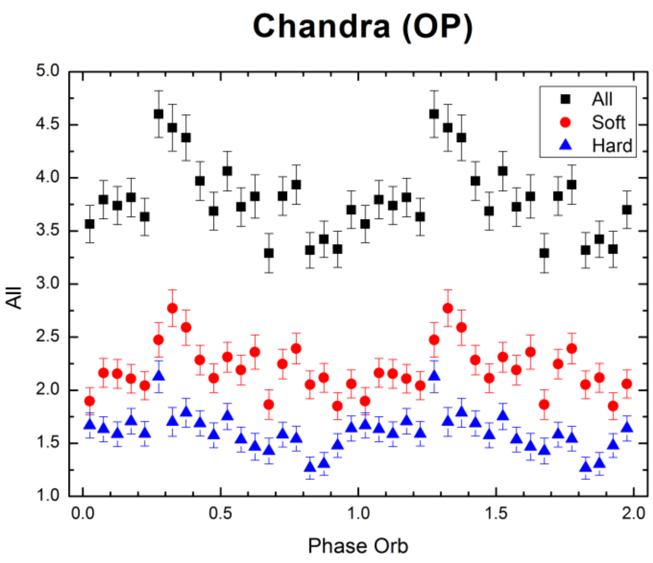
For a periodic process, we may want to obtain accurate **ephemeris**: $Min\ or\ Max = T_o + Period \cdot E$

For a periodic process, time can be expressed as ***phase***, for which one unit of time is **the period**:

$$\varphi = \frac{t - T_0}{Period} - int\left[\frac{t - T_0}{Period}\right]$$

Folded Lightcurve (phase diagram)





Folded Lightcurve