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:

- 60% Exam on lecture course
- 40% Homeworks

Text Books

- *Fourier Analysis of Time Series: An Introduction* (2nd edition - 2000) – P. Bloomfield: ISBN: 978-0-471-88948-9
- *"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

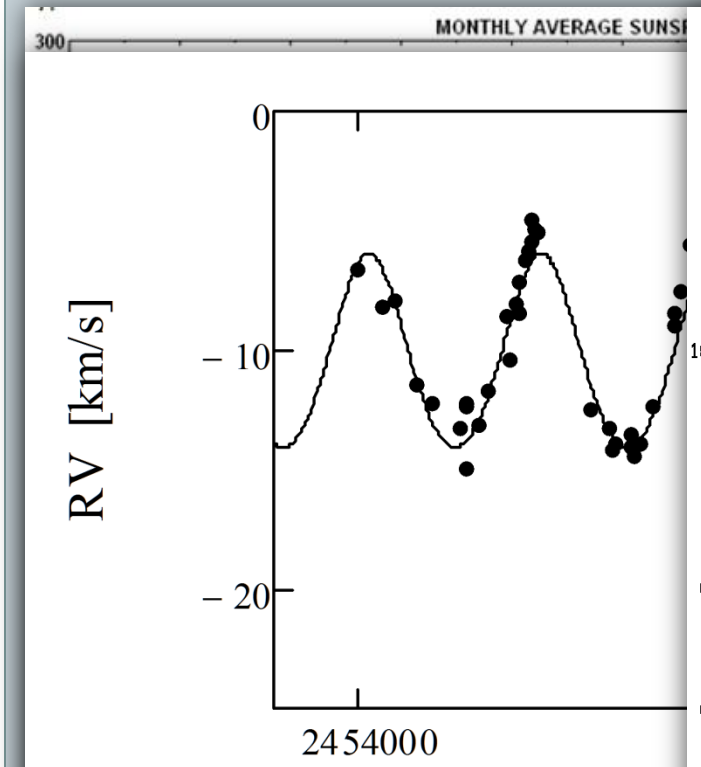
- Time series is a collection of data points, arranged in a natural order (time) ⟶ 1-d sequence;
- Sometimes, more than one parameter is observed at each time point ⟶ multi-d sequence.

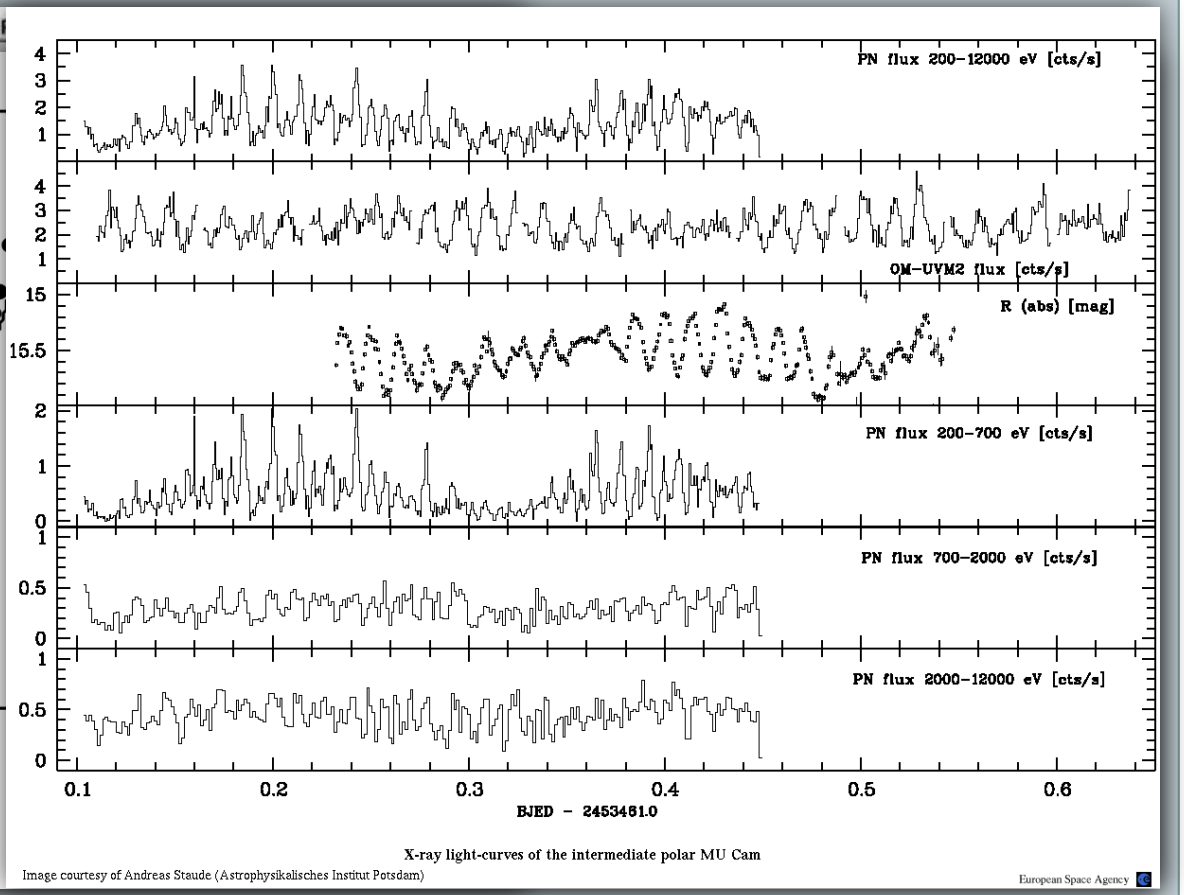
Time Series in Astronomy

- 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

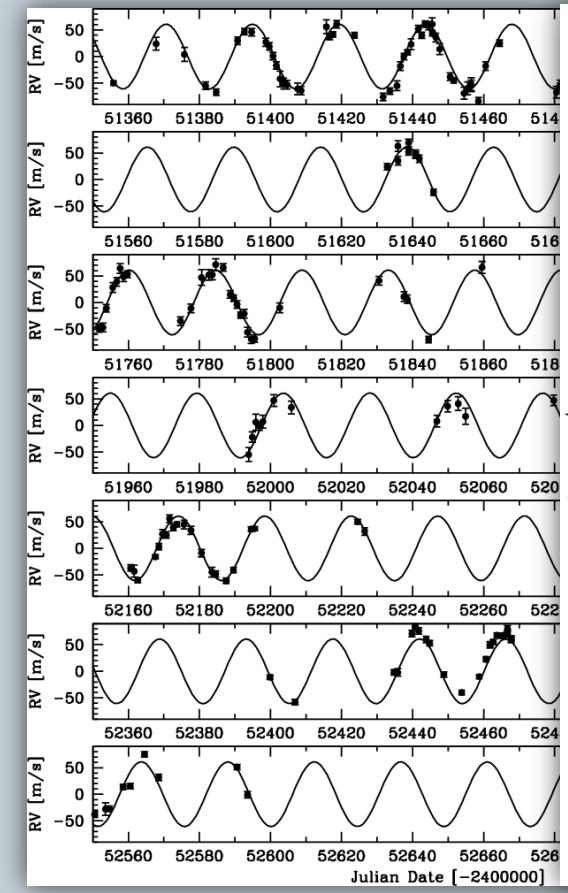
- Astronomical time series are somewhat different if to compare with standard time series often used in other branches of science and businesses.
- The random, often sparse and gapped nature of astronomical observational sequences makes most of techniques of the standard time series analysis unusable.

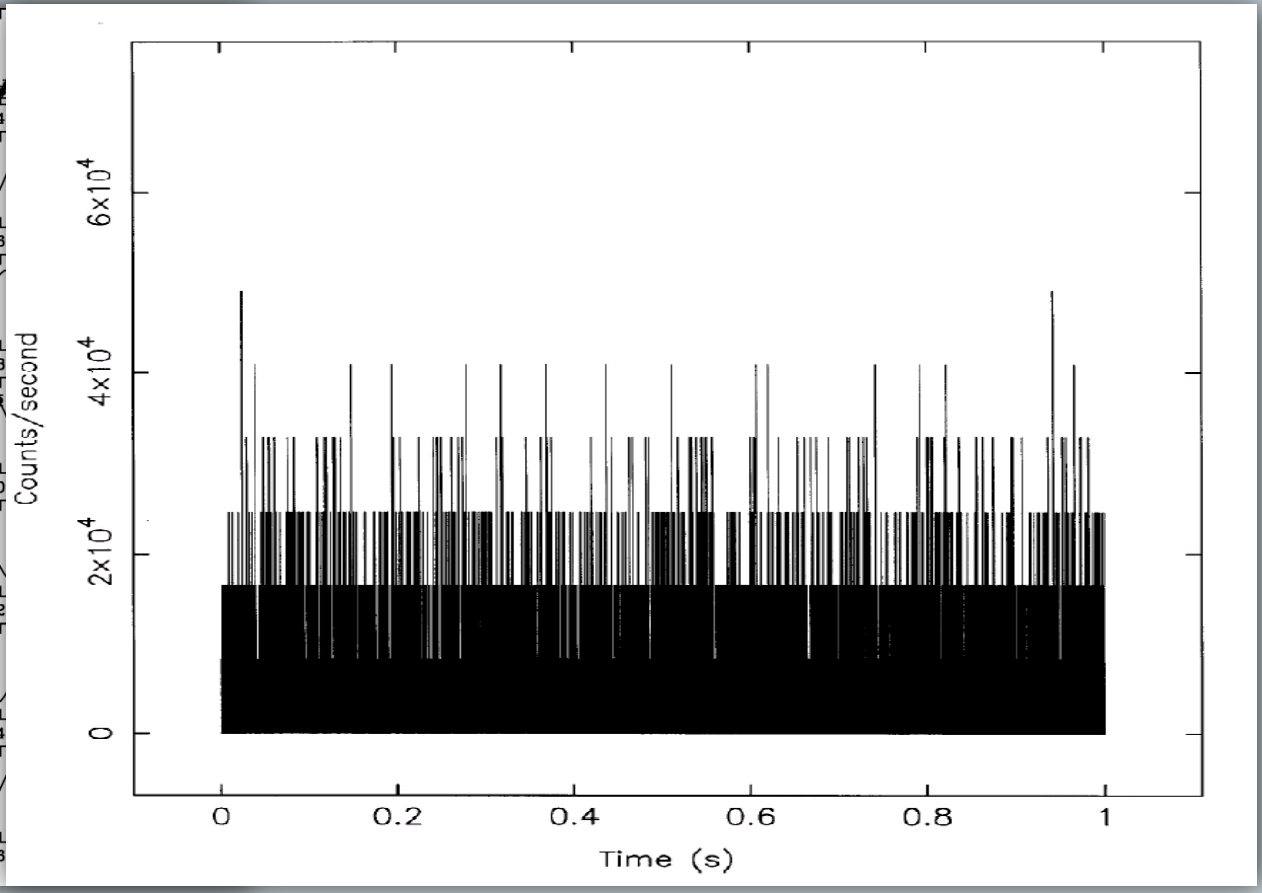
Time Series

- 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.

Some Questions That We'd Like to Answer:

- 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:

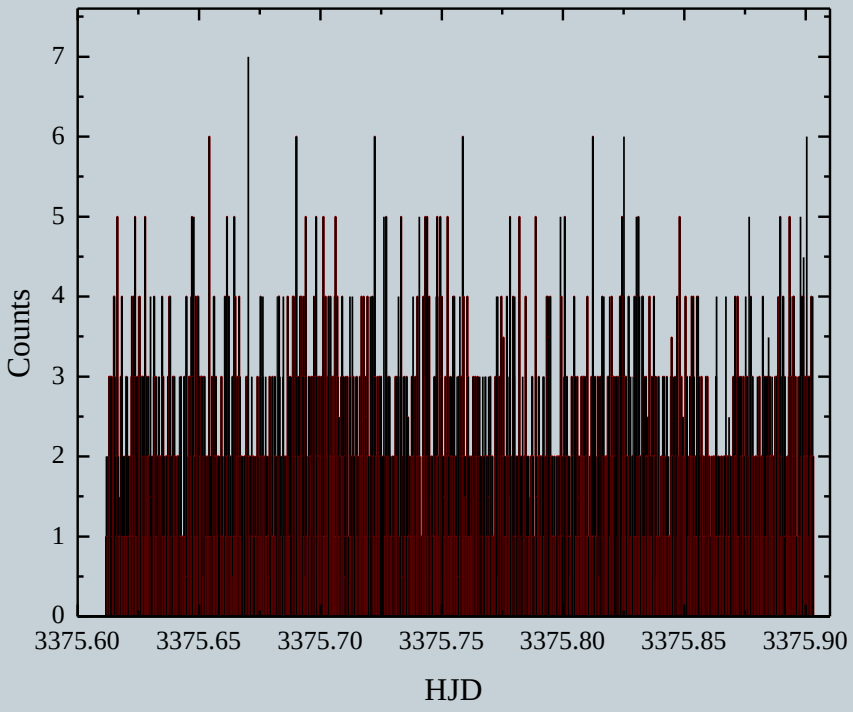
- Evenly or unevenly sampled data
- Signal and noise level
- Light-Curve
- Length of Time Series

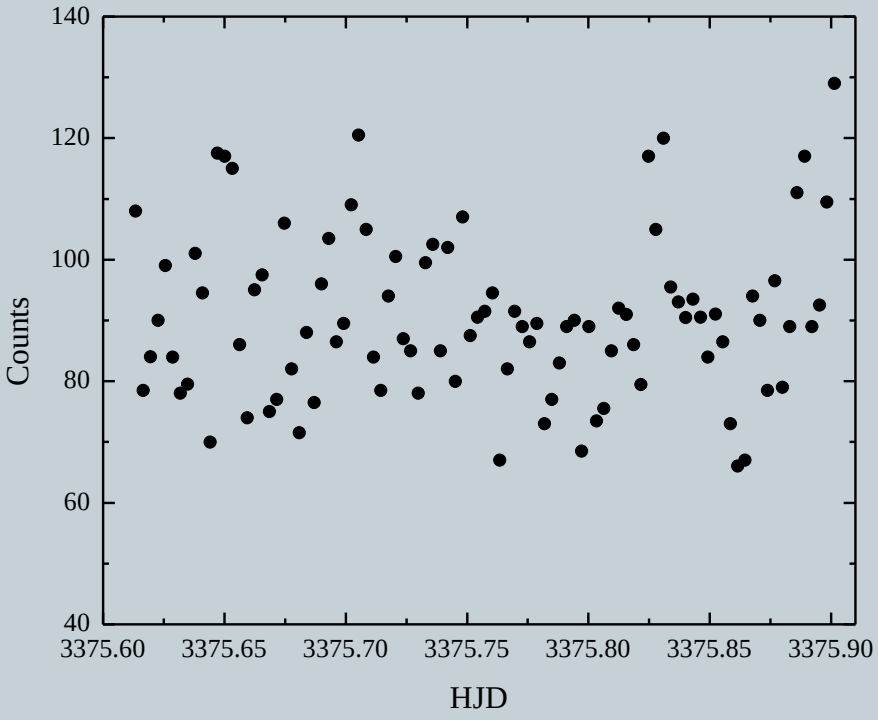
Too many different methods. Even astronomers sometimes have difficulties to compare the techniques they routinely apply. Problems of terminology and differing conventions hamper the flow of information between the various branches.

Timing Starts with a Lightcurve

Sometimes we have to apply time binning, but:

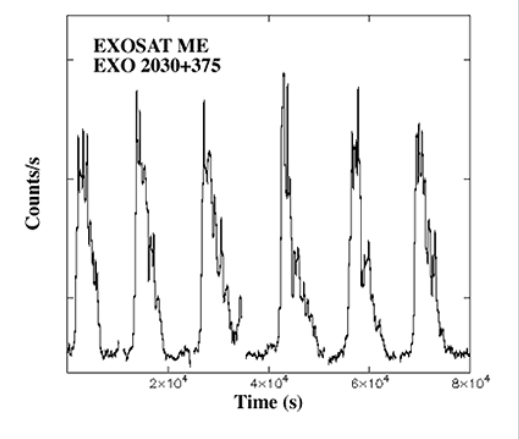
- Always choose integer multiple of “natural” time unit for binning
- Don’t bin any more than you have to - save it for subsequent analysis



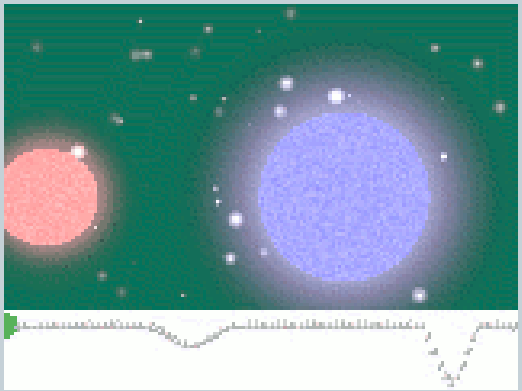


Light Curve

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



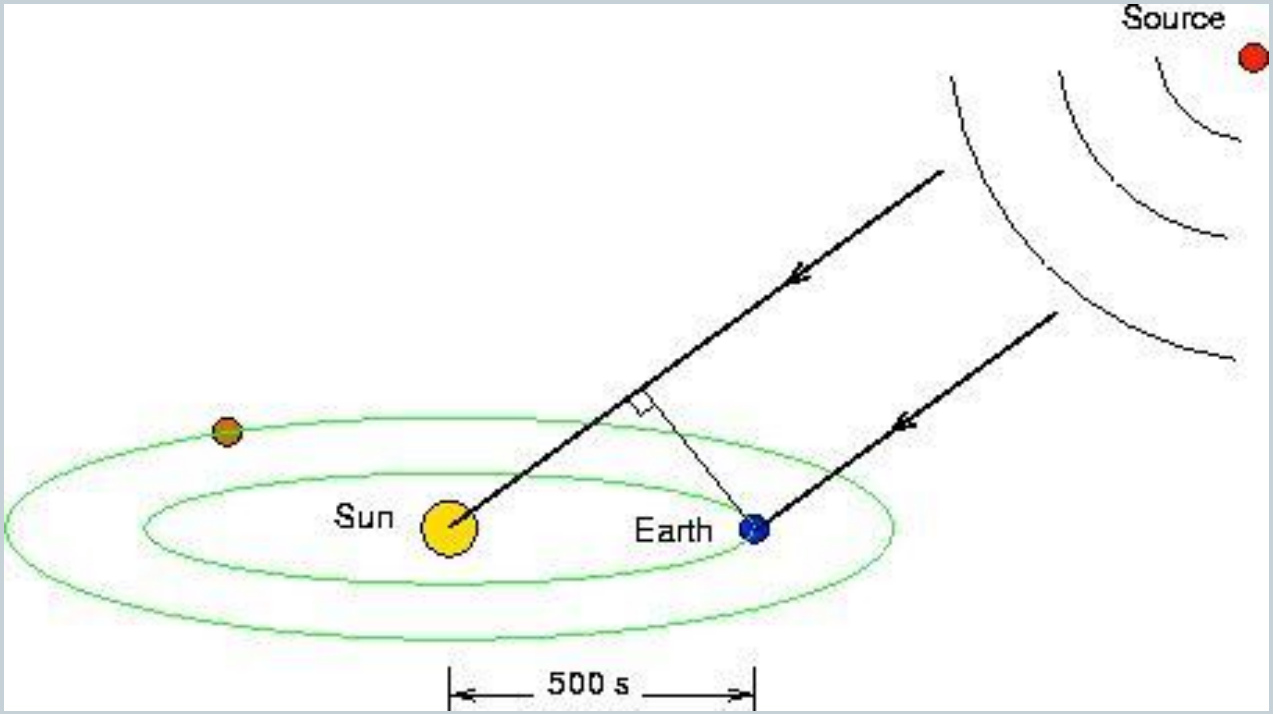
- No periodicity, only noise. But ”One person’s noise is another one’s data”!



Time

Precision Absolute & Relative Timing: Dates or Seconds

Do not forget about the heliocentric or barycentric correction!



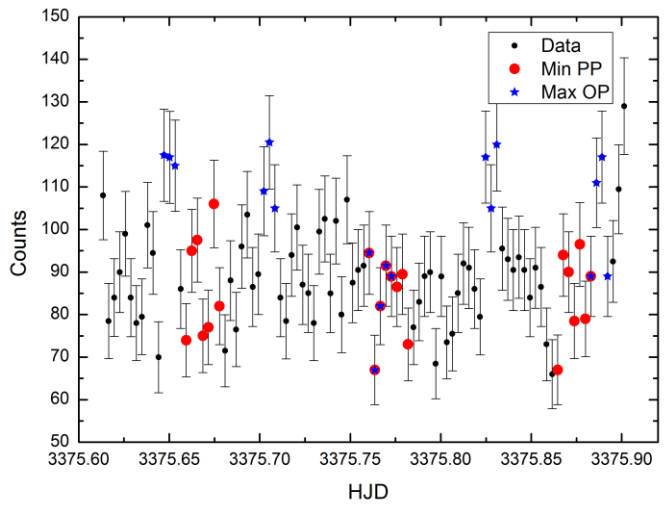
Ephemeris and Phases

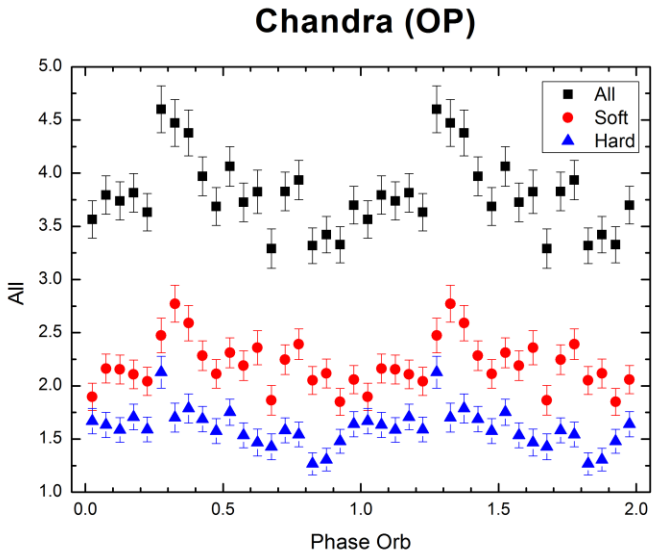
For a periodic process, we may want to obtain accurate **ephemeris**: $Min\ or\ Max = T_o + Period \cdot E$

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

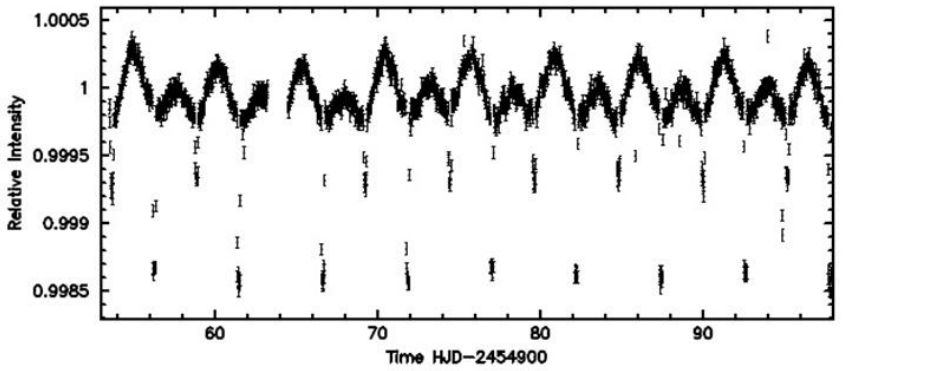
$$\varphi = \frac{t - T_0}{Period} - int\left[\frac{t - T_0}{Period}\right]$$

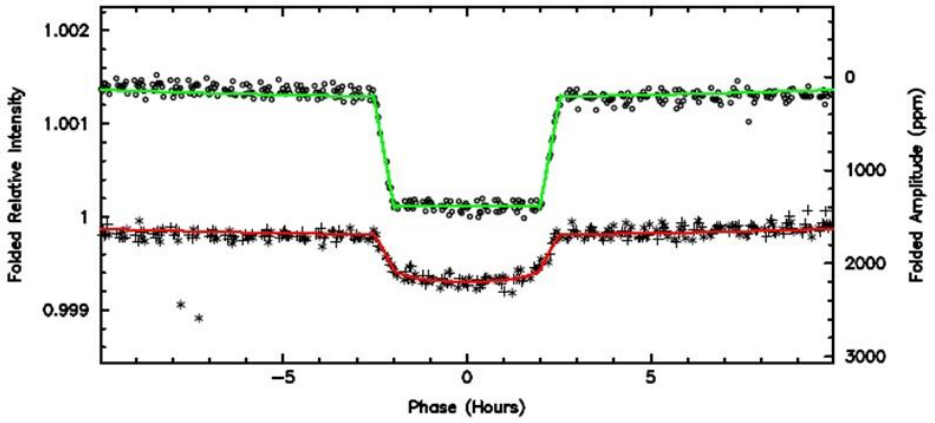
Folded Lightcurve



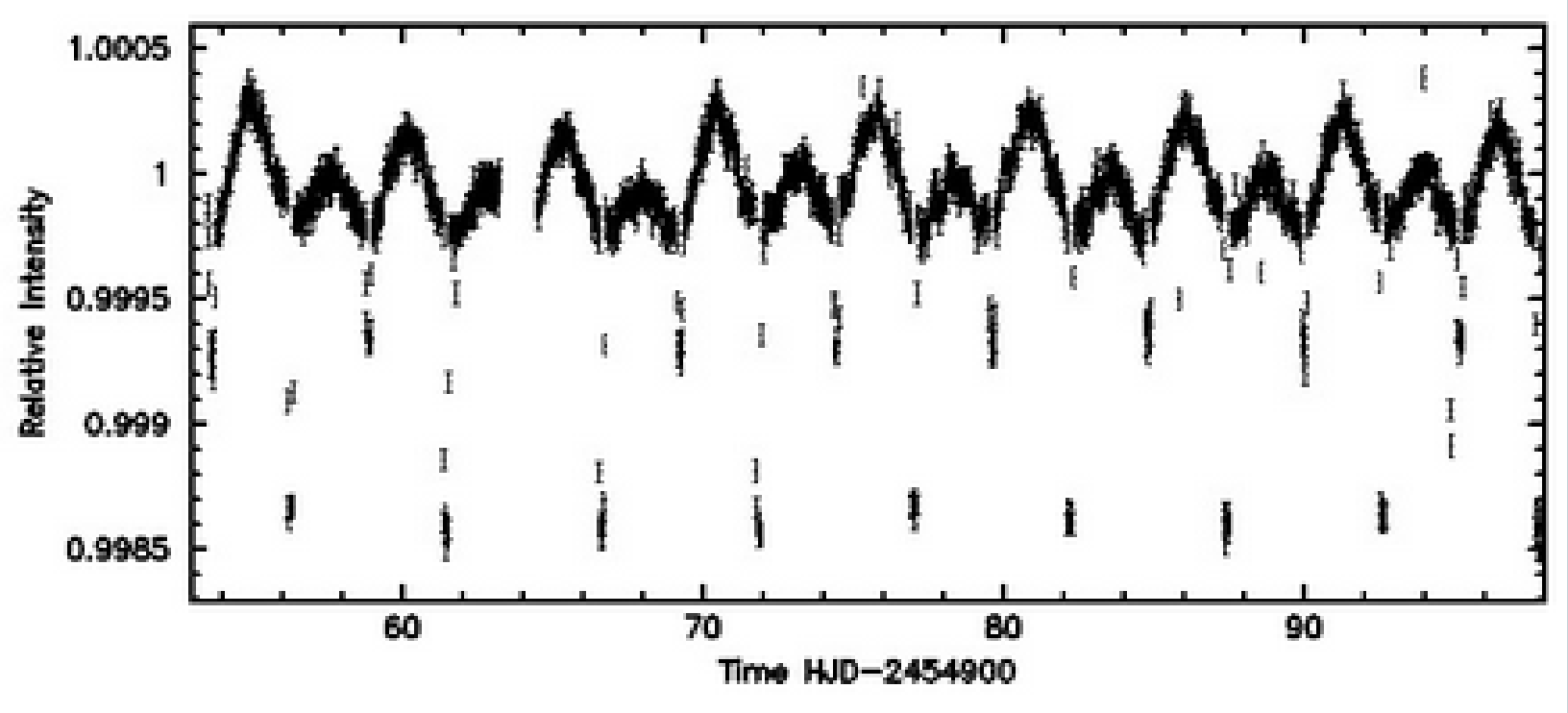


Folded Lightcurve





Simplest methods of Time Series Analysis



Curve-Fitting Approach

- The simplest periodic data are those consisting of a single cosine (sine) wave:

$$x(t) = a\cos(\omega t - \varphi) = A\cos\omega t + B\sin\omega t$$