Sys-Rem

Systematics Removal

in large sets of light-curves

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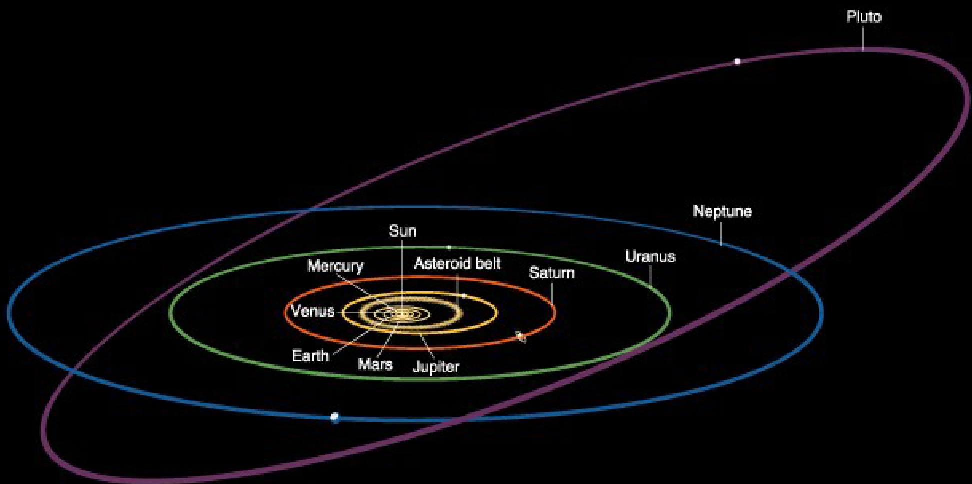
(Tamuz, Mazeh & Zucker 2005)

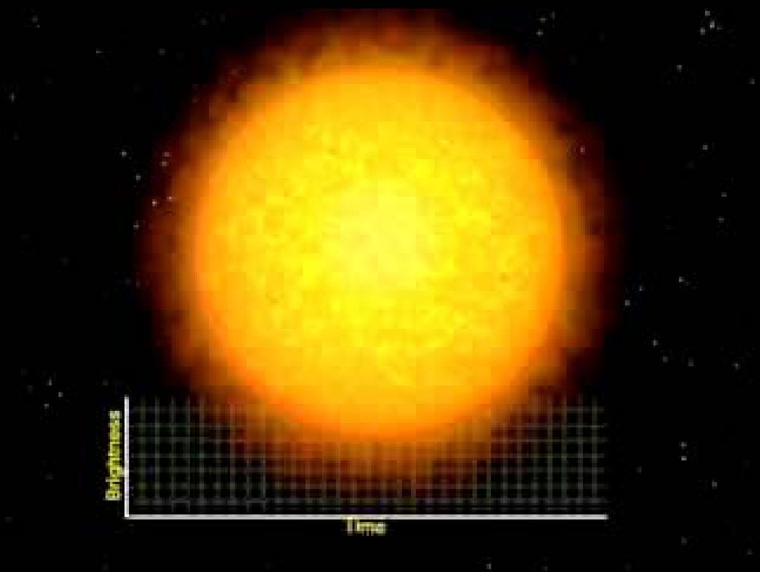
- Tsevi Mazeh (Tel Aviv)
- Shay Zucker (Weizmann)

Extra-solar systems?

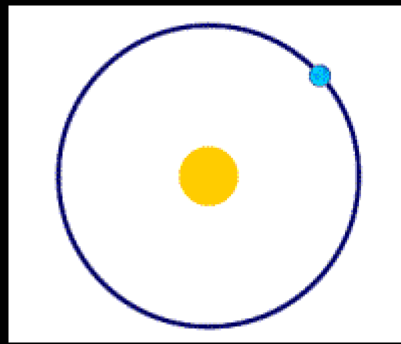


The solar system is not unique

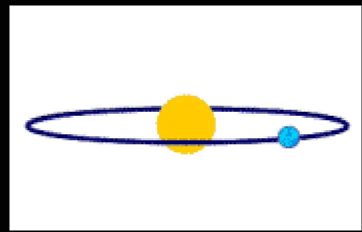
Transits



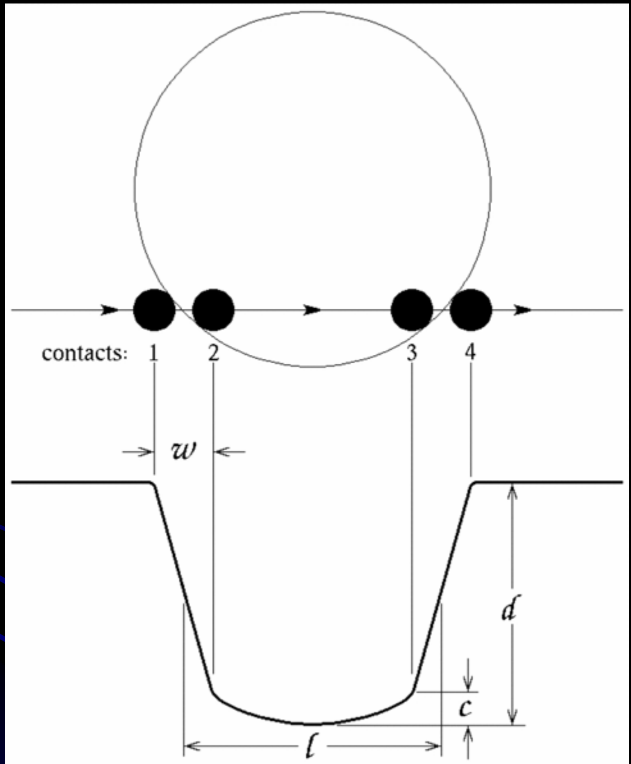
Face on



Edge on



Transits



What can we learn from the transit shape?

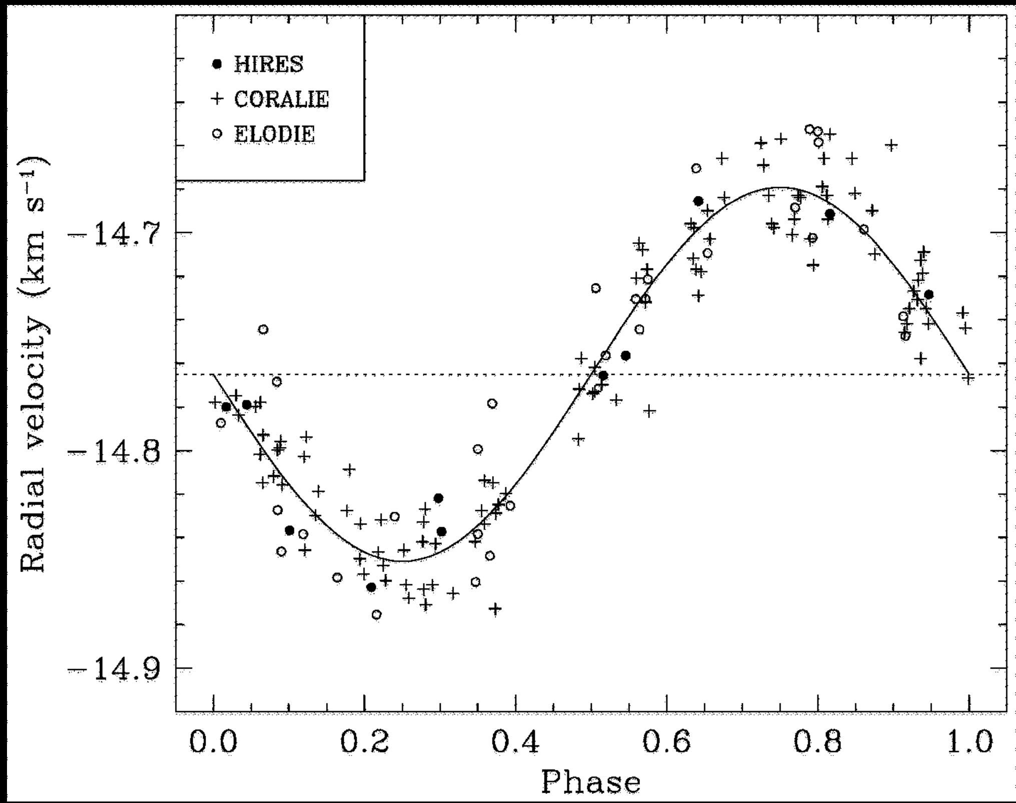
- **Planet mass**
- **Planet radius**
- **Stellar radius**
- **Moons**
- **Planetary atmosphere**

HD 209458

Mazeh *et al.*, 2000

Shay Zucker (Tel Aviv)

Discovered through the Doppler shift variation of its parent star.

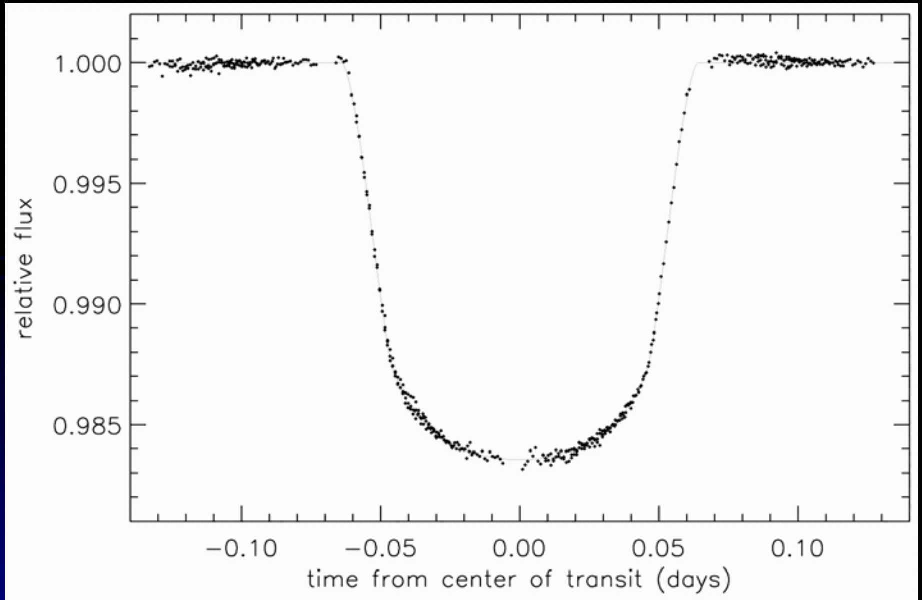


Charbonneau, Brown, Latham & Mayor 2000

Henry, Marcy, Butler & Vogt 2000

HD209458

Relative Error $\approx 10^{-4}$



$$R_{\mathtt{Planet}} = 1.35 \pm 0.06\ R_{\mathtt{Jup}}$$

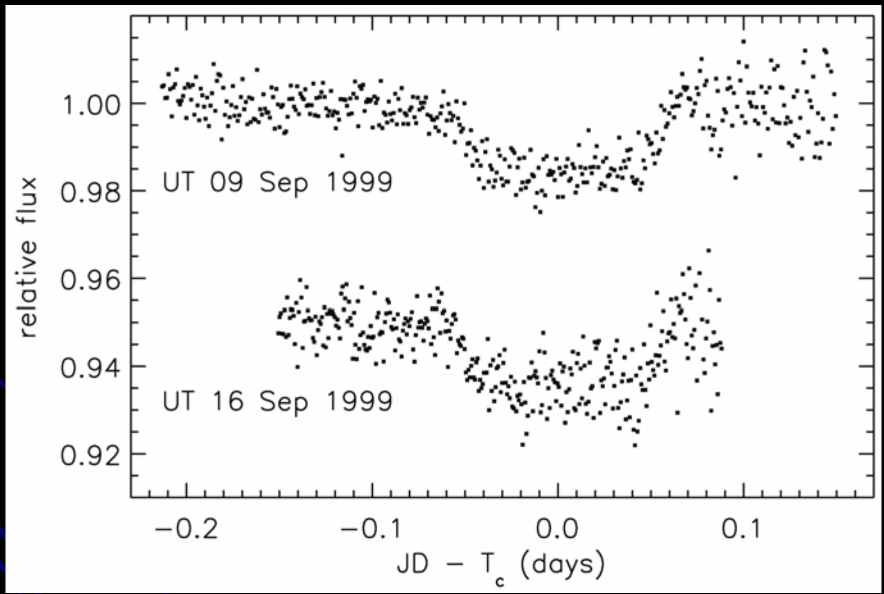
$$i = 86^{\circ}.7 \pm 0^{\circ}.1$$

$$\overline{\rho} = 0.35\ \mathrm{g\ cm^{-3}}$$

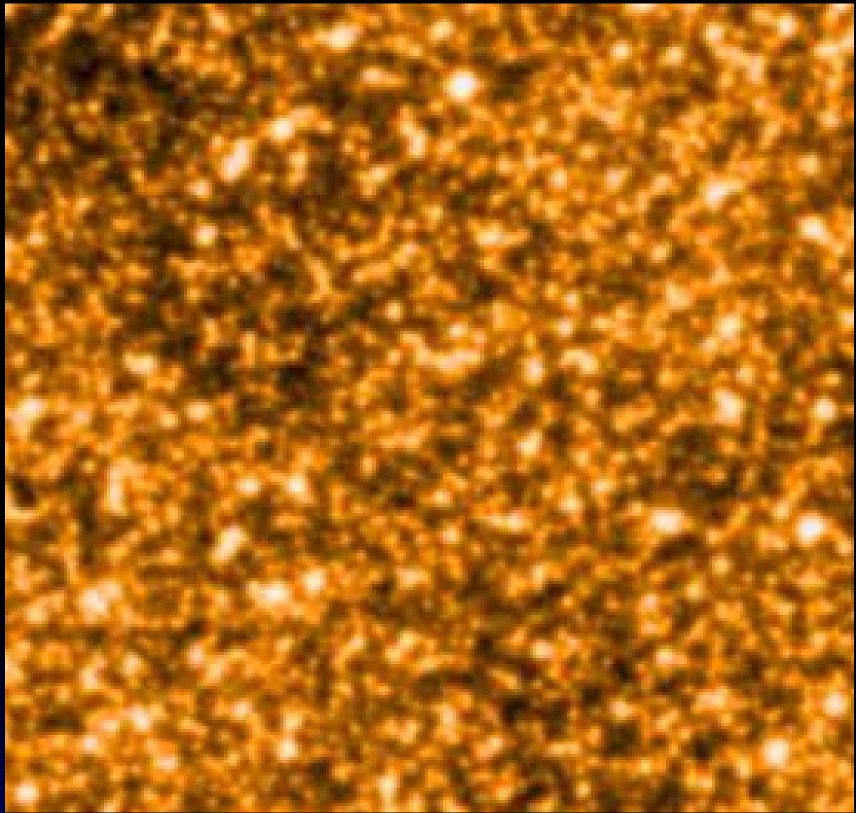
HD 209458

The discovery was made with ground based observations

$$\text{Relative Error} \approx 10^{-2}$$



Photometric Search



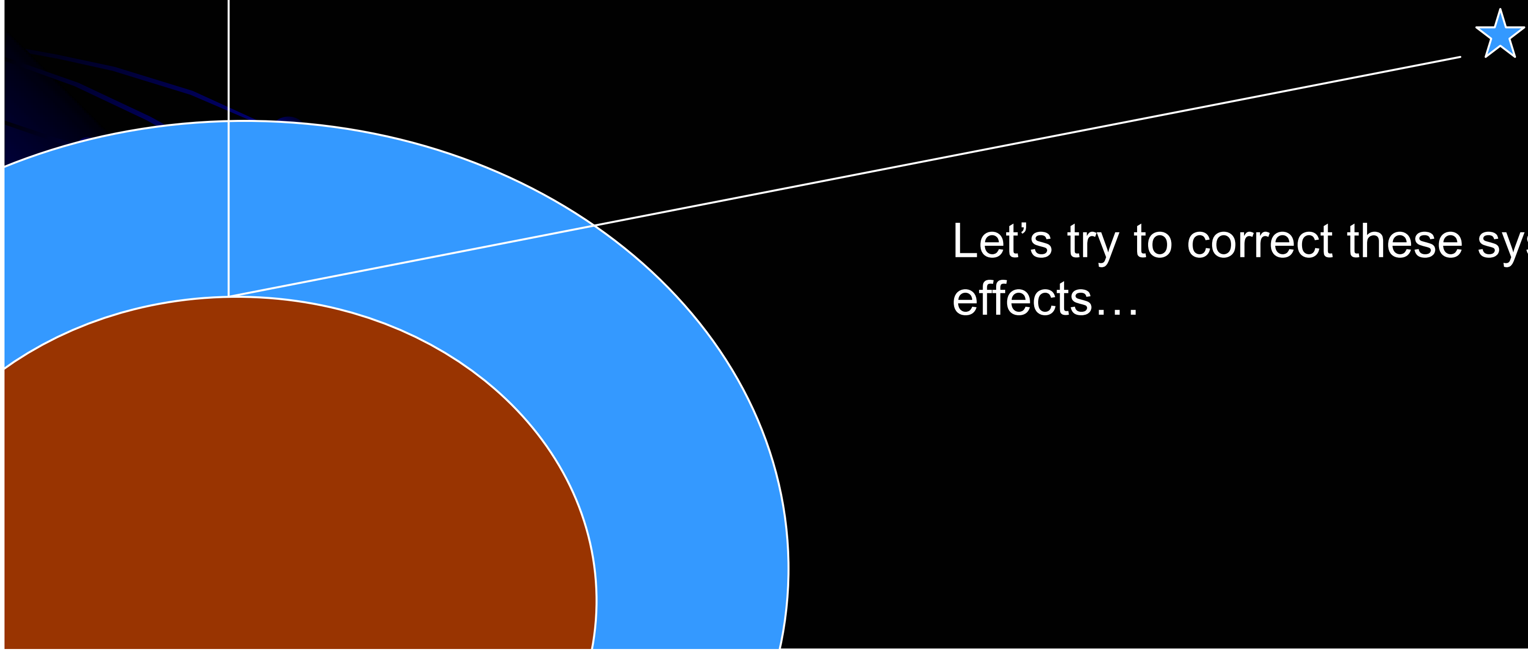
Measure the magnitude of many stars over and over again.

Try to find a star exhibiting periodic transits.

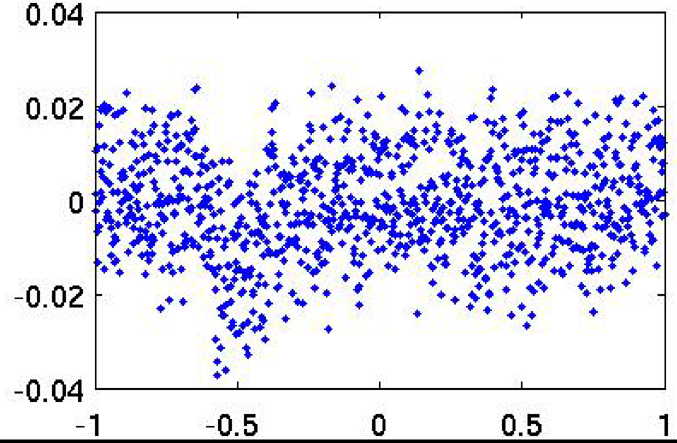
What causes the large errors in ground based photometry?

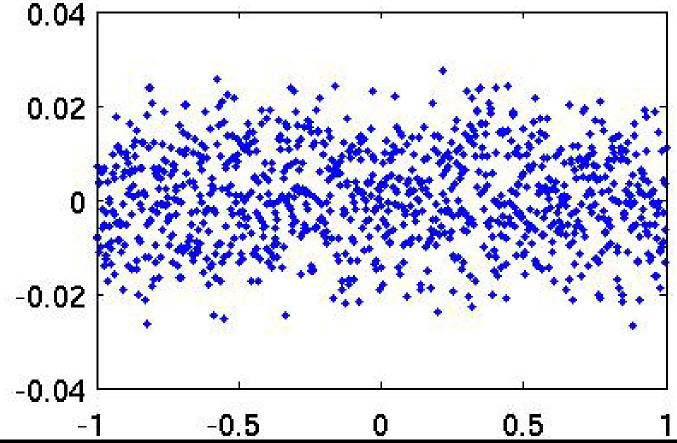
THE ATMOSPHERE

- Local atmospheric conditions
- Clouds & dust
- Variations in airmass



Let's try to correct these systematic effects…

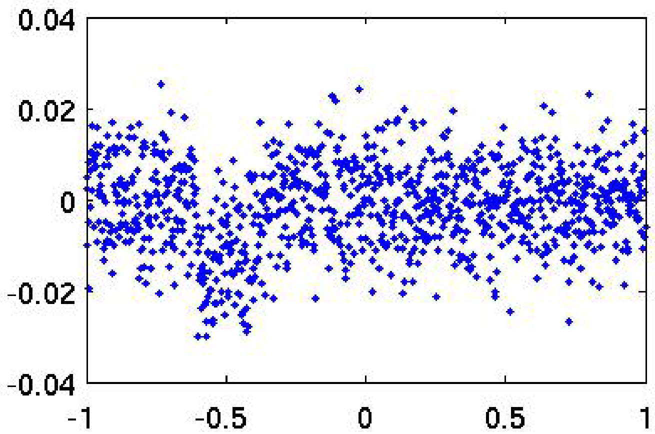


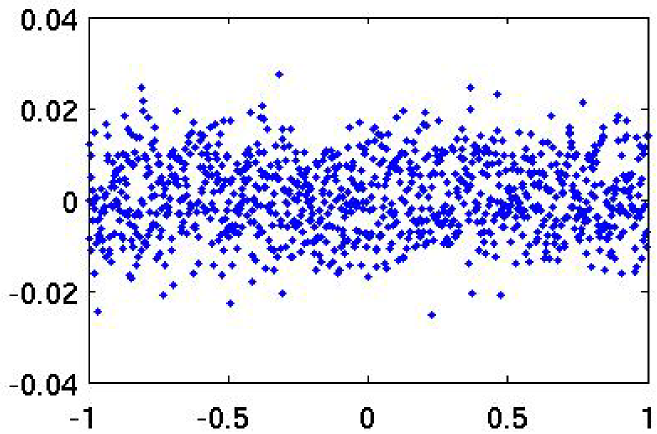


Minimizing the RMS:

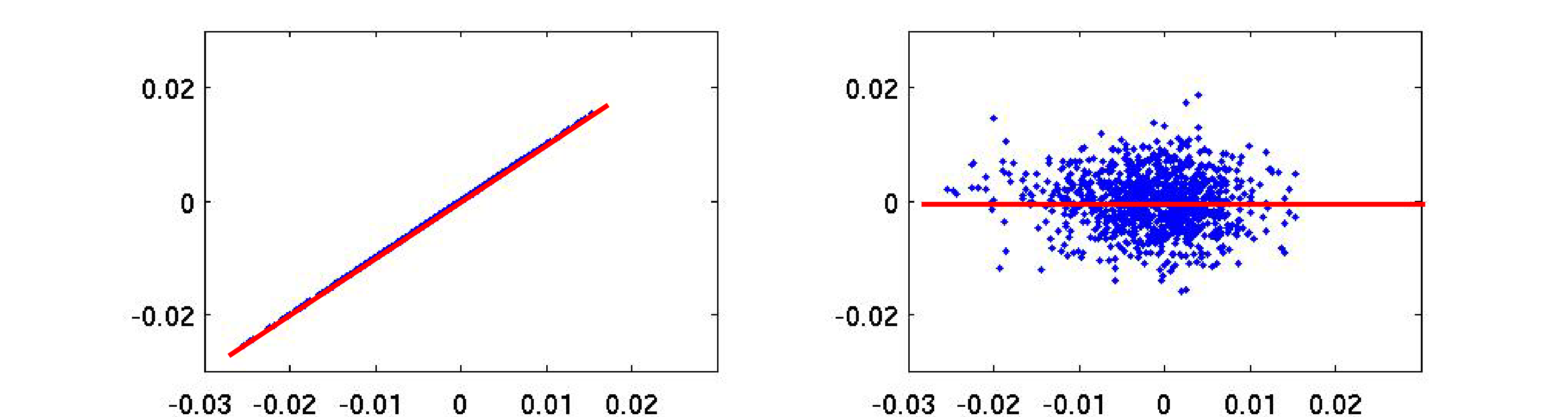
$$r'_{1i} = r_{1i} - c_1 a_i$$

$$r'_{2i} = r_{2i} - c_2 a_i$$





Idea No. 2: Let's plot vs. a better parameter

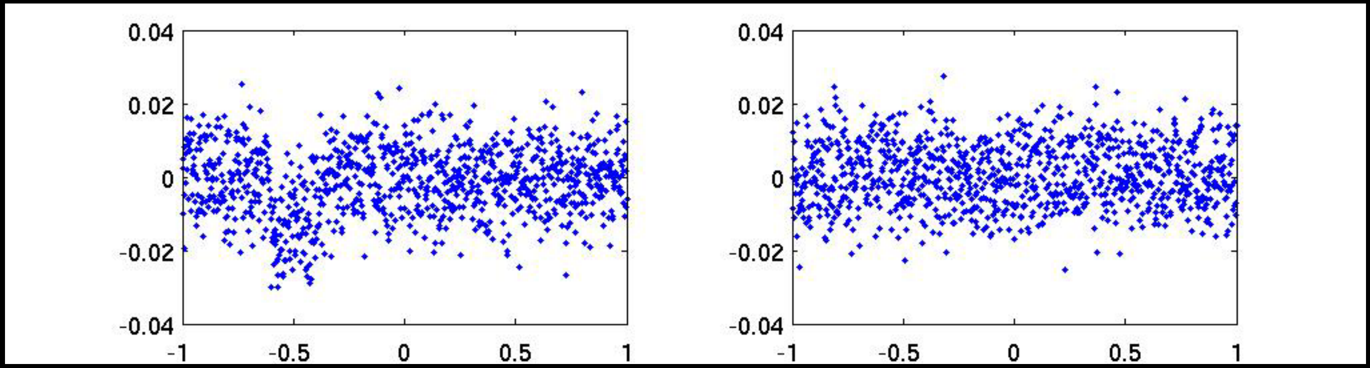


Not a very good idea…

Idea No. 2a: Let's plot vs. the optimal parameter!

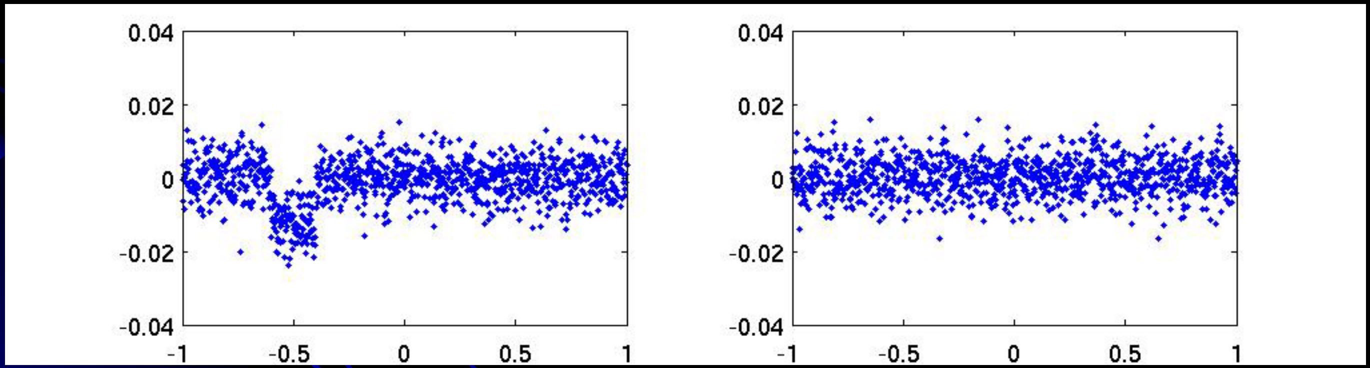
$$S = S_1 + S_2 = \sum_{i,j} \frac{\left(r_{ij} - c_i a_j\right)^2}{\sigma_{ij}^2}$$

Previous chart



Idea No. 3: Let's do that again!

New chart



$$r'_{ij} = r_{ij} - c_i^{(1)} a_j^{(1)} - c_i^{(2)} a_j^{(2)} - \ldots$$

What are we doing here?

$$r_{ij} \approx c_i a_j$$

$$\begin{pmatrix} r_{11} & r_{12} & \cdots & \cdots & \cdots \\ r_{21} & r_{22} & \cdots & \cdots & \cdots \\ r_{31} & & & & \\ r_{41} & & & & \\ \cdots & & & & \\ \cdots & & & & \\ \cdots & & & & \\ \cdots & & & & \end{pmatrix} \approx \begin{pmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ \cdots \\ \cdots \\ \cdots \\ \cdots \end{pmatrix} \times \begin{pmatrix} a_1 & a_2 & \cdots & \cdots & \cdots \end{pmatrix}$$

$$\sum_{i,j} (r_{ij} - c_i a_j)^2$$

$$\sum_{i,j} \frac{(r_{ij} - c_i a_j)^2}{\sigma_{ij}^2}$$

The case of equal uncertainties

$$\sum_{i,j} (r_{ij} - c_i a_j)^2$$

SVD Decomposition: $R = U^T D V$

$$\begin{pmatrix} r_{11} & r_{12} & \cdots & \cdots & \cdots \\ r_{21} & r_{22} & \cdots & \cdots & \cdots \\ r_{31} \\ r_{41} \\ \cdots \\ \cdots \\ \cdots \\ \cdots \end{pmatrix} \approx \begin{pmatrix} r_{11} & r_{12} & \cdots & \cdots & \cdots \\ r_{21} & r_{22} & \cdots & \cdots & \cdots \\ r_{31} \\ r_{41} \\ \cdots \\ \cdots \\ \cdots \\ \cdots \end{pmatrix} = \begin{pmatrix} c_1^{(1)} & c_1^{(2)} & \cdots & \cdots & \cdots \\ c_2^{(1)} & c_2^{(2)} & \cdots & \cdots & \cdots \\ c_3^{(1)} \\ c_4^{(1)} \\ \cdots \\ \cdots \\ \cdots \\ \cdots \end{pmatrix} \begin{pmatrix} a_1^{(1)} & a_2^{(1)} & a_3^{(1)} & \dots & \dots \\ a_1^{(2)} & a_2^{(2)} \\ \dots & \dots \\ \dots & \dots \\ \dots & \dots & & & \dots \end{pmatrix} \dots) + \dots$$

$$\begin{pmatrix} r_{11} & r_{12} & \cdots & \cdots & \cdots \\ r_{21} & r_{22} & \cdots & \cdots & \cdots \\ r_{31} \\ r_{41} \\ \cdots \\ \cdots \\ \cdots \\ \cdots \end{pmatrix} = \begin{pmatrix} c_1^{(1)} & c_1^{(2)} & \cdots & \cdots & \cdots \\ c_2^{(1)} & c_2^{(2)} & \cdots & \cdots & \cdots \\ c_3^{(1)} \\ c_4^{(1)} \\ \cdots \\ \cdots \\ \cdots \\ \cdots \end{pmatrix} \begin{pmatrix} \lambda^{(1)} & & & \\ & \lambda^{(2)} & & \mathbf{0} \\ & & \dots & \\ & \mathbf{0} & & \dots \\ & & & & \dots \end{pmatrix} \begin{pmatrix} a_1^{(1)} & a_2^{(1)} & a_3^{(1)} & \dots & \dots \\ a_1^{(2)} & a_2^{(2)} \\ \dots & \dots \\ \dots & \dots \\ \dots & \dots & & & \dots \end{pmatrix}$$

How do we do it?

$$\sum_{i,j} \frac{\left(r_{ij} - c_i a_j\right)^2}{\sigma_{ij}^2}$$

$$S_i^2 = \sum_j \frac{(r_{ij} - c_i a_j)^2}{\sigma_{ij}^2}$$

Assume a_j are known, solve for c_i

$$c_i = \frac{\sum_j r_{ij} a_j / \sigma_{ij}^2}{\sum_j a_j^2 / \sigma_{ij}^2}$$

$$S_j^2 = \sum_i \frac{(r_{ij} - c_i a_j)^2}{\sigma_{ij}^2}$$

Now c_i are known, solve for a_j

$$a_j = \frac{\sum_i r_{ij} c_i / \sigma_{ij}^2}{\sum_i c_i^2 / \sigma_{ij}^2}$$

What kind of 'systematics'?

- Colour-dependent atmospheric extinction
  - c_i – colour, a_j – airmass
- Contaminating light (moon, earth)
- Position-dependent CCD response
- **Unknown effects**

What effects do we actually find?

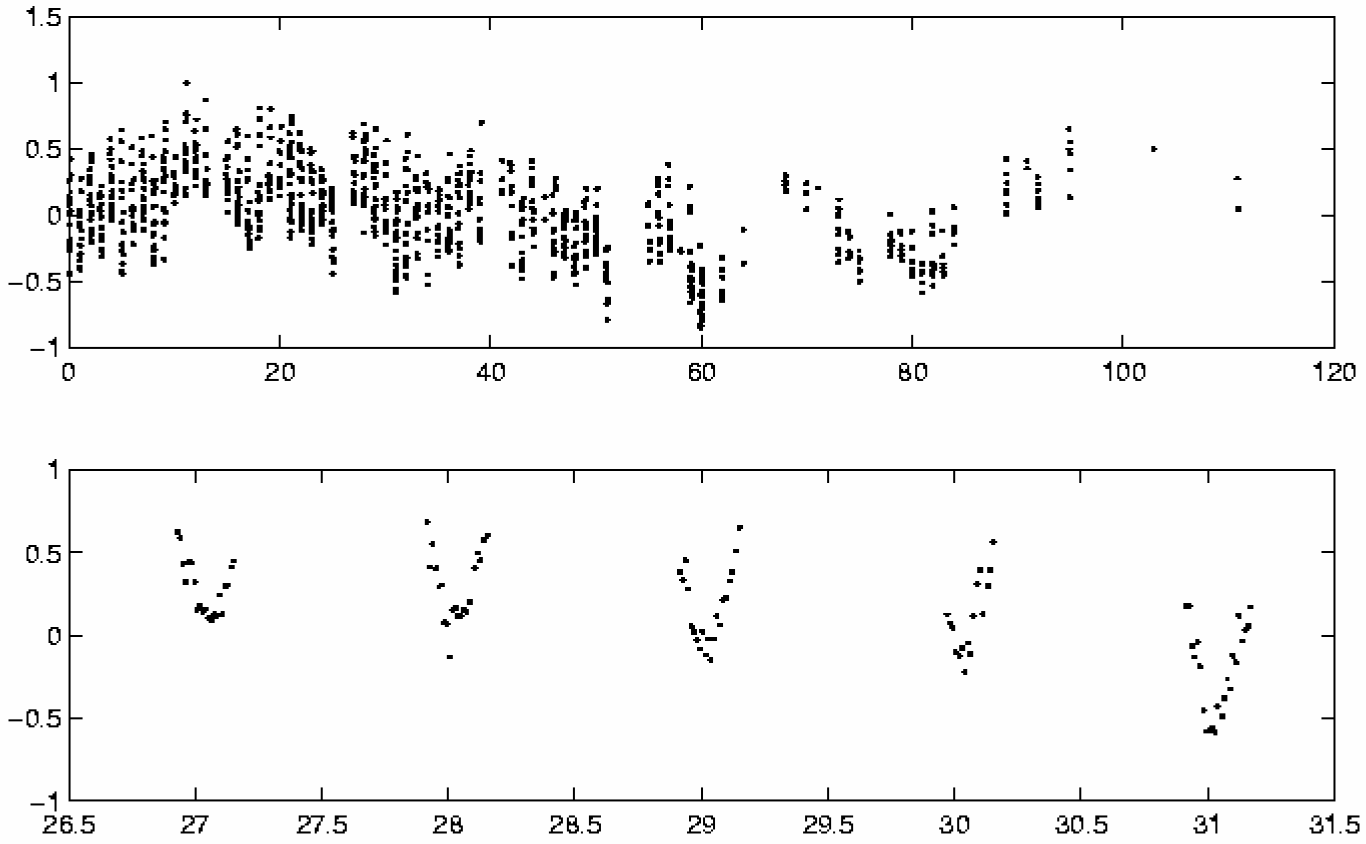


Figure 3. Third component showing similar behaviour to the first.

OGLE data

What effects do we actually find?

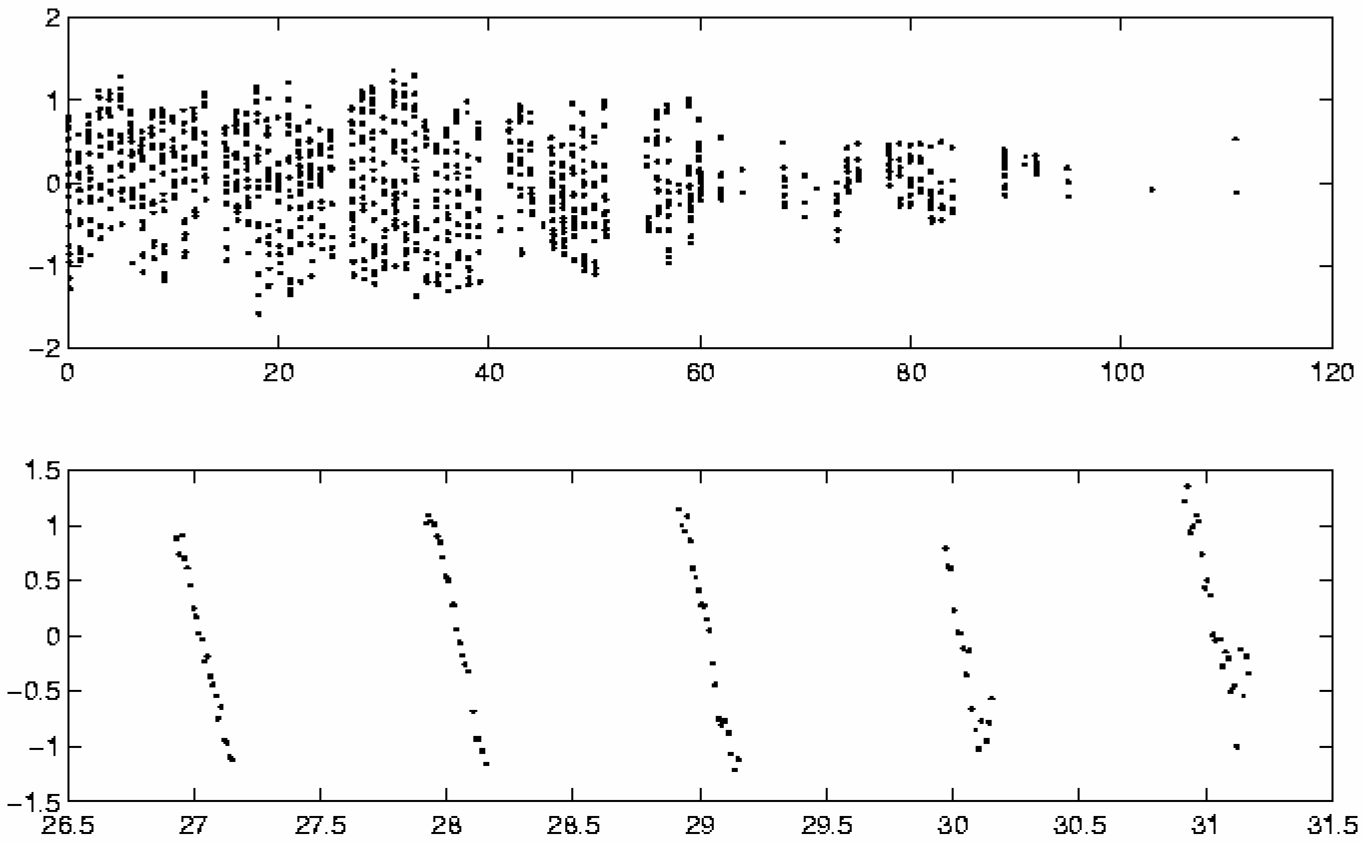
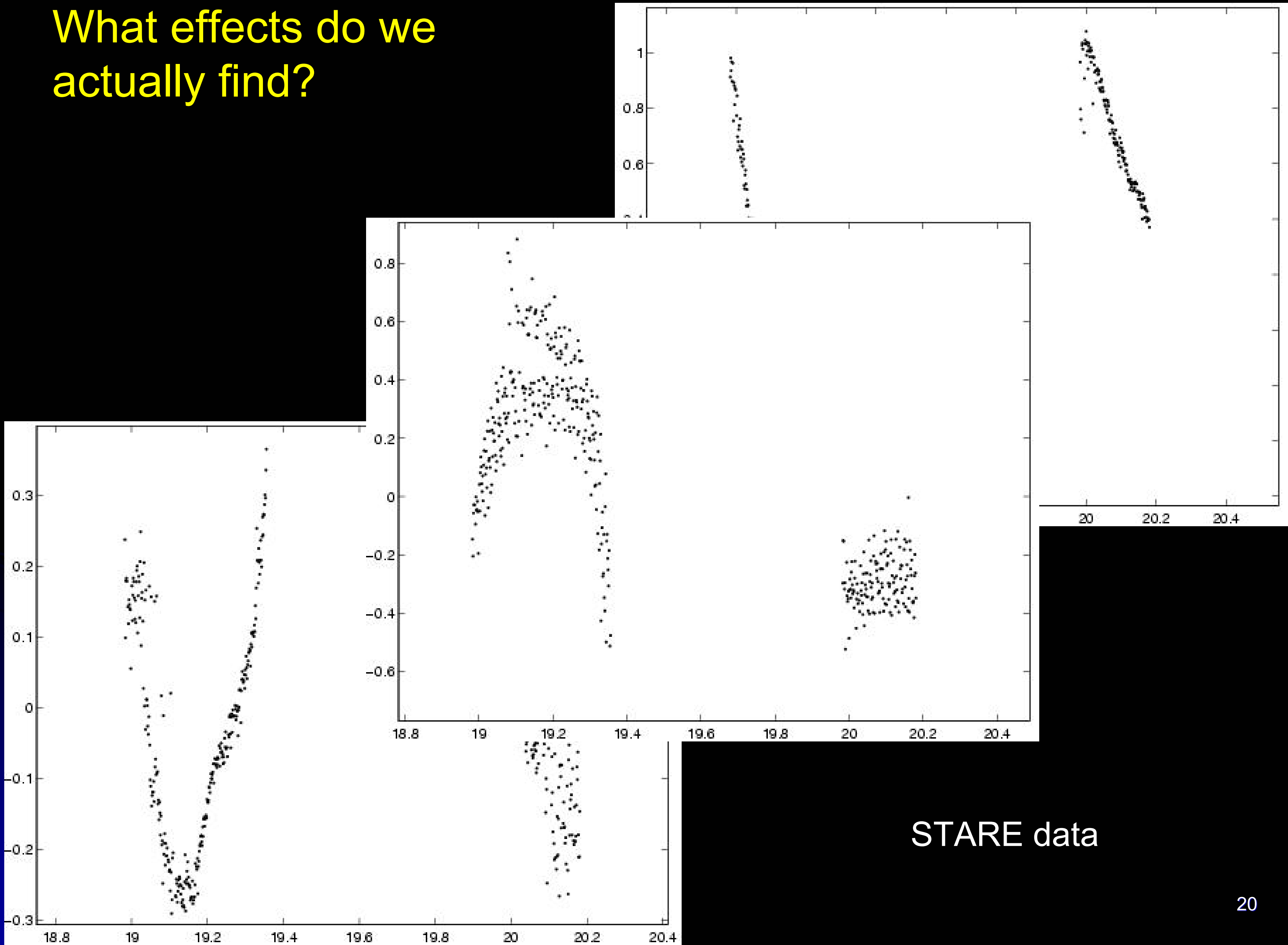


Figure 2. Second component showing linear monotonous change every observation night.

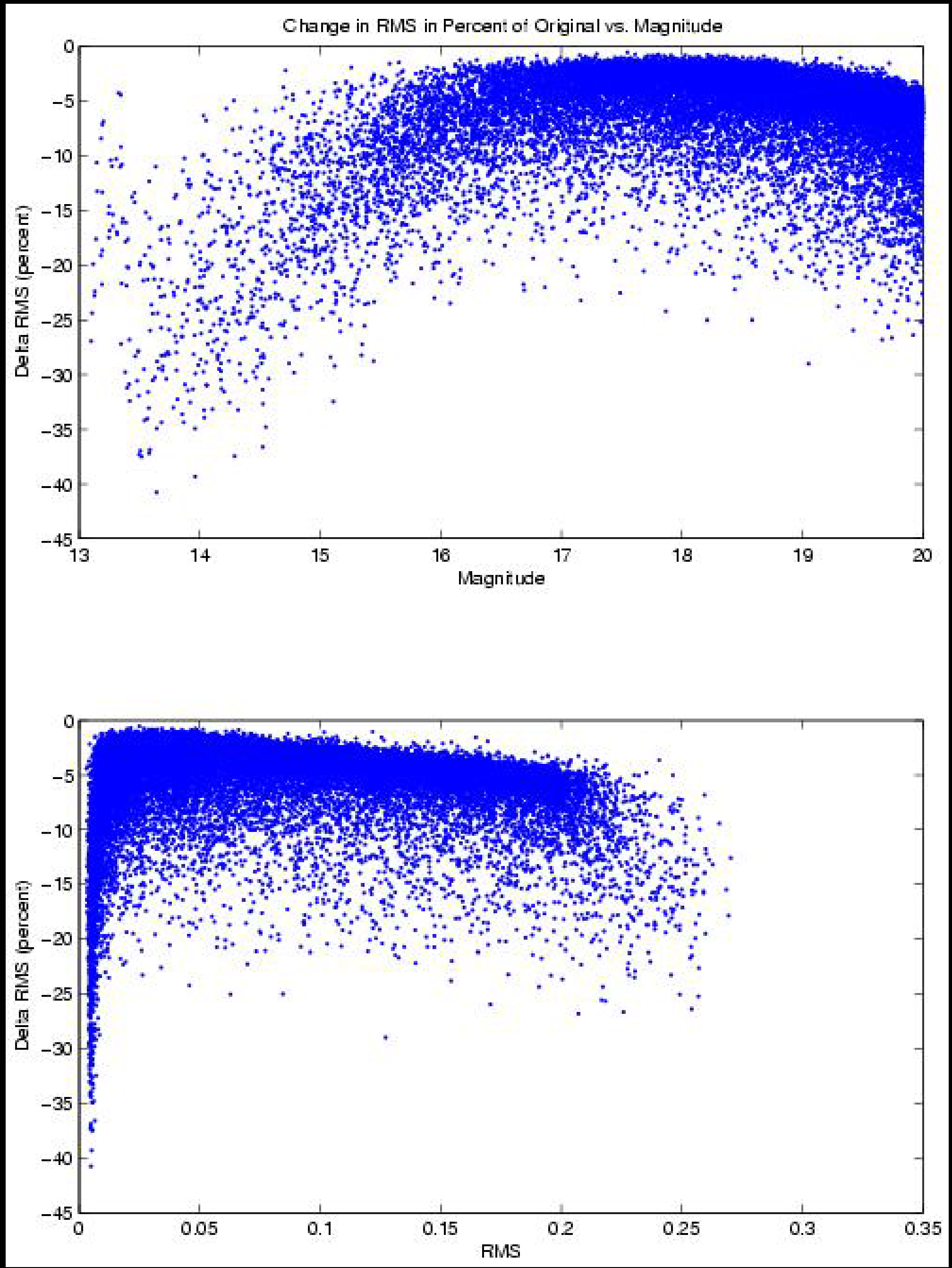
OGLE data

What effects do we actually find?



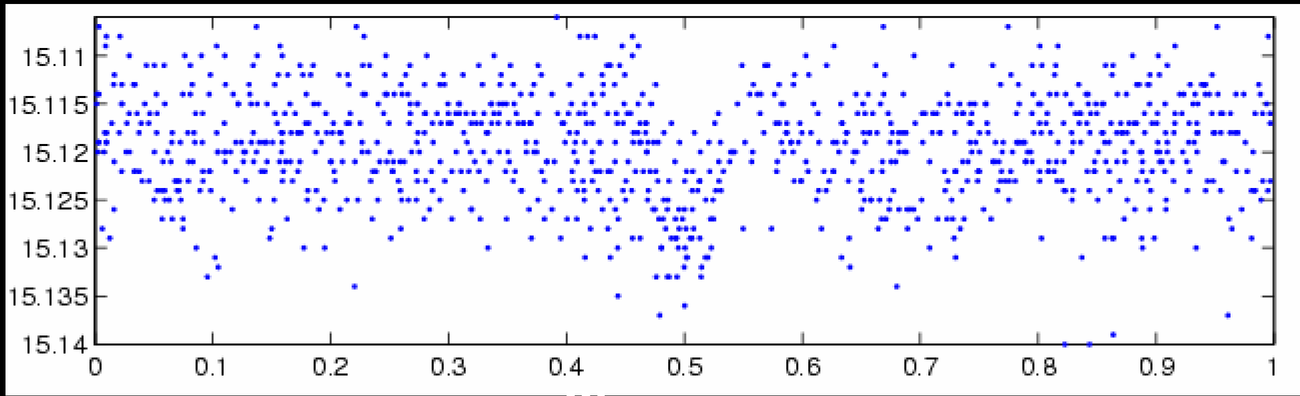
STARE data

How much noise do we actually remove?



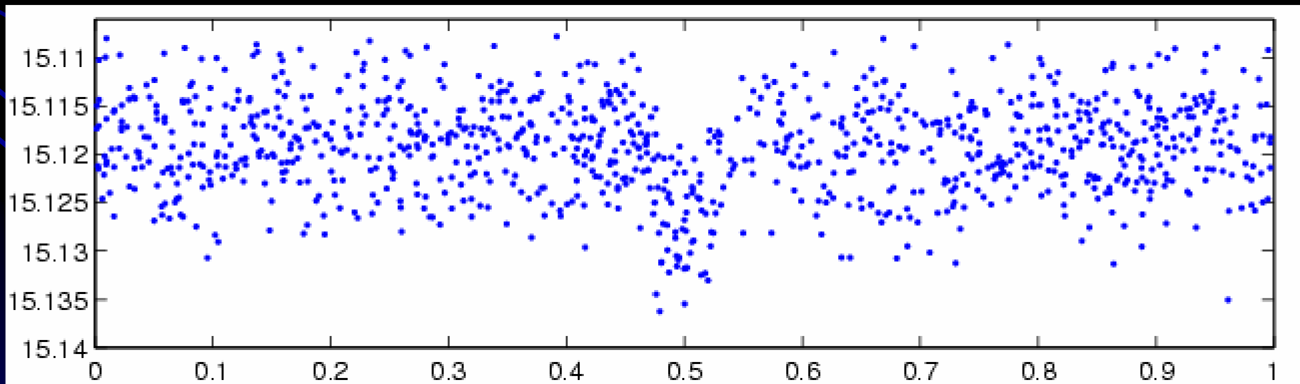
OGLE data

OGLE-TR-132, Before…



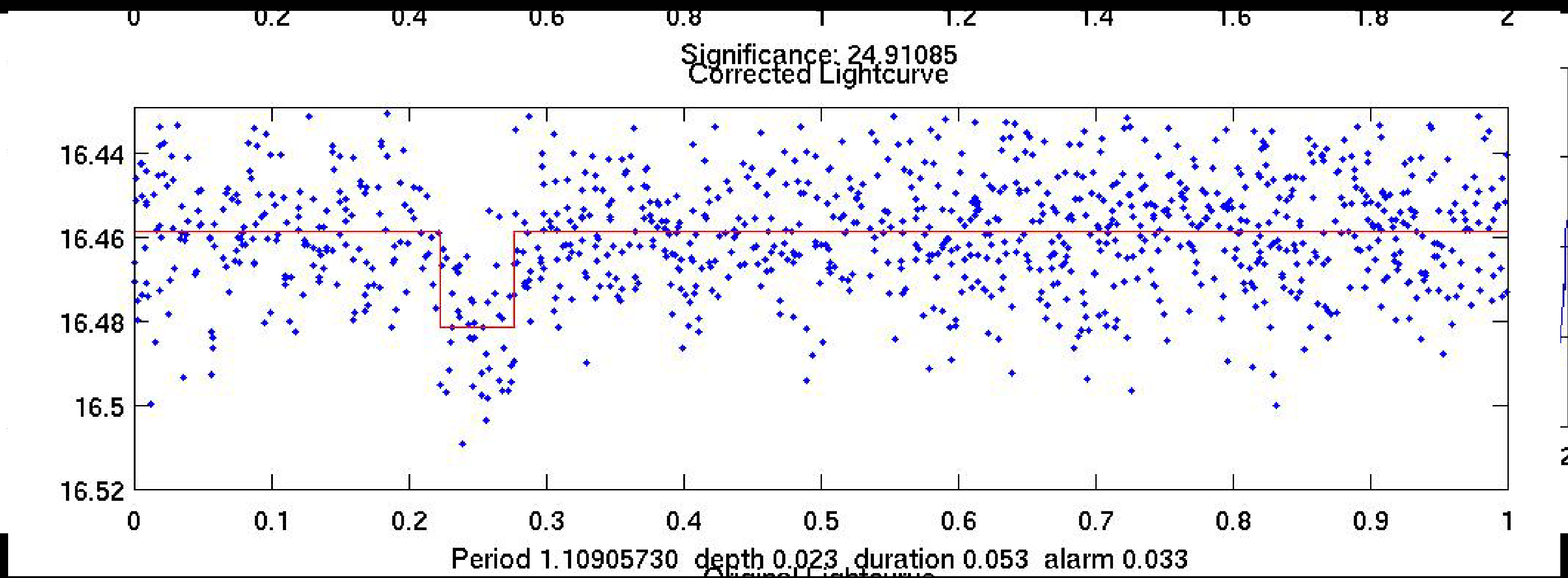
Phase

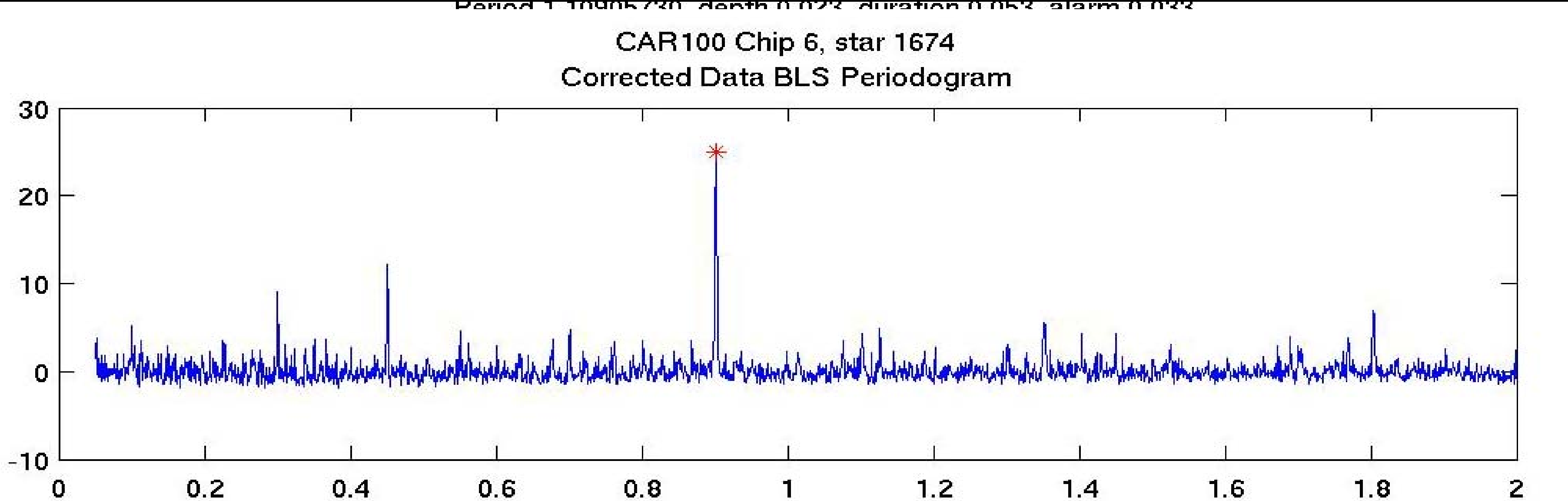
… and after

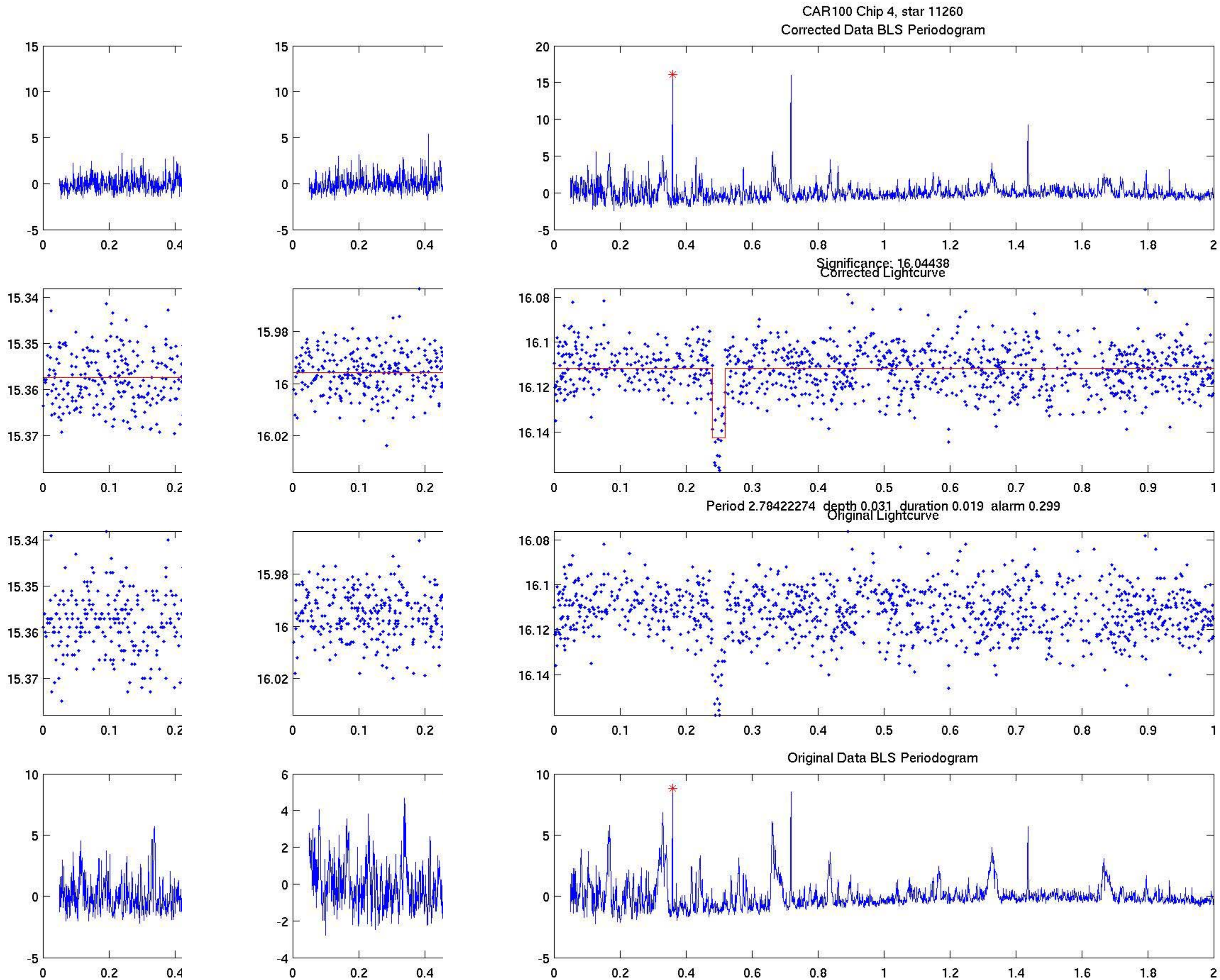


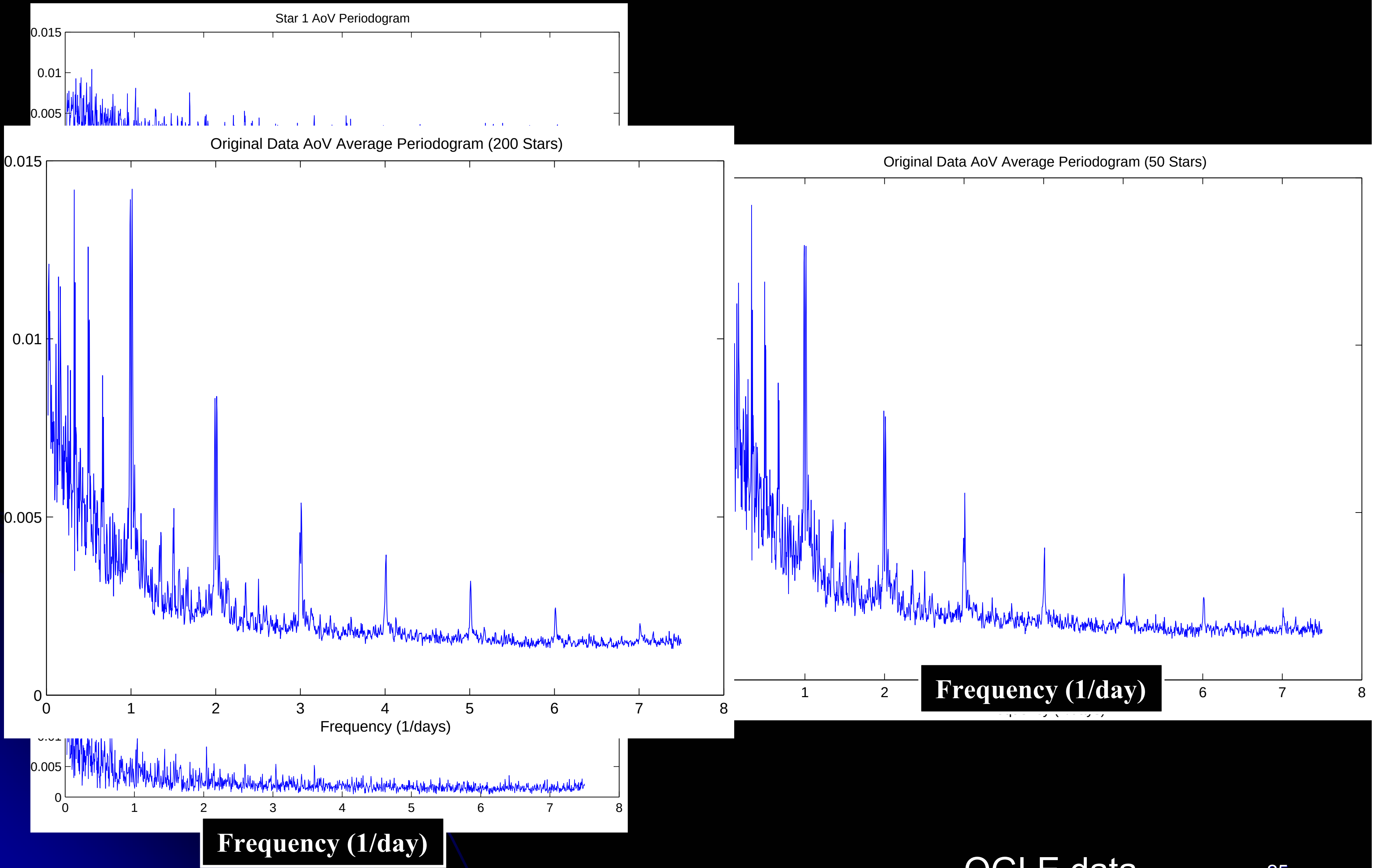
Phase

OGLE data

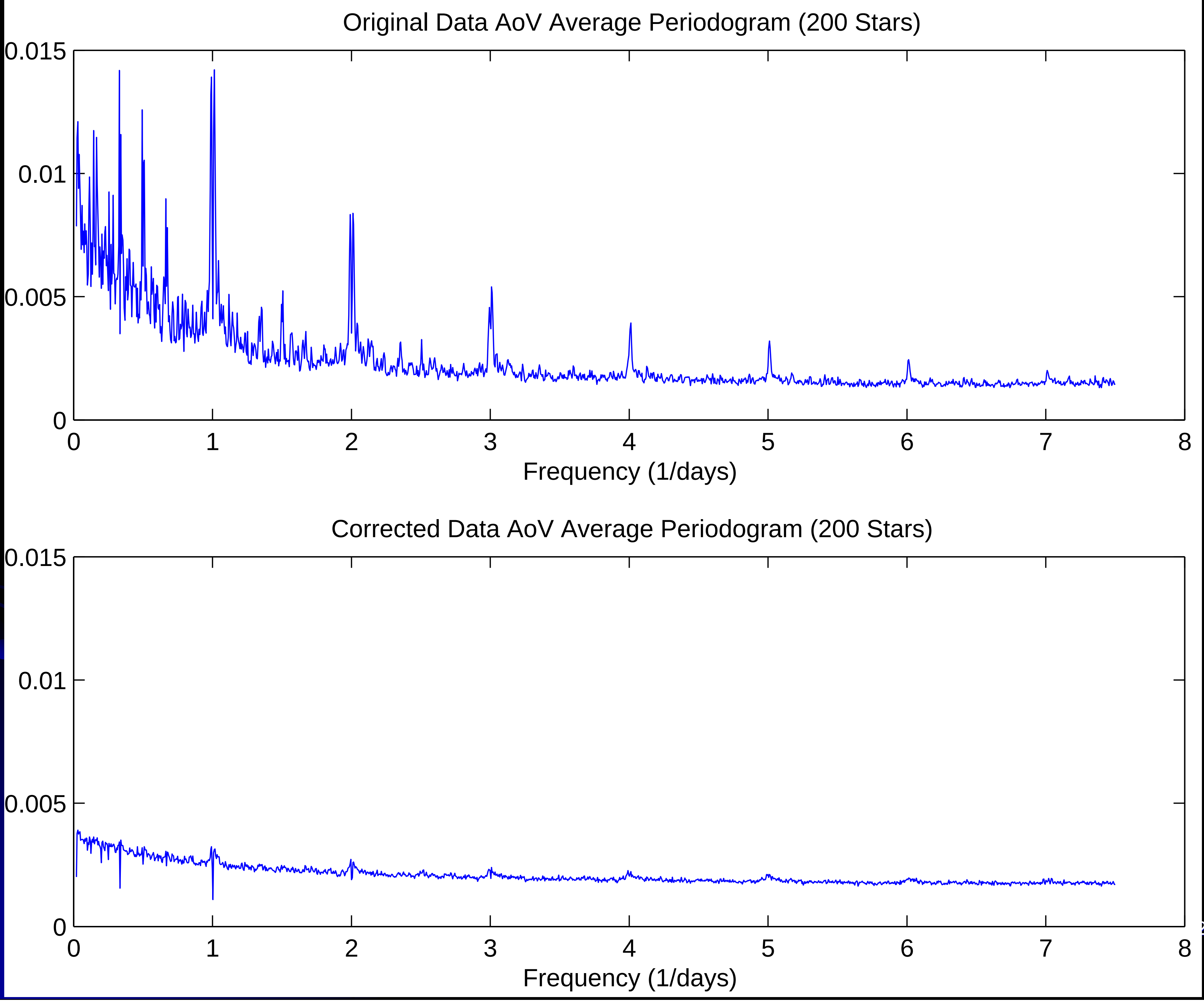

Significance: 24.91085
Corrected Lightcurve
16.44
16.46
16.48
16.5
16.52
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Period 1.10905730 depth 0.023 duration 0.053 alarm 0.033


CAR100 Chip 6, star 1674
Corrected Data BLS Periodogram
30
20
10
0
-10
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


CAR100 Chip 4, star 11260
Corrected Data BLS Periodogram
Significance: 16.04438
Corrected Lightcurve
Period 2.78422274 depth 0.031 duration 0.019 alarm 0.299
Original Lightcurve
Original Data BLS Periodogram


Star 1 AoV Periodogram
Original Data AoV Average Periodogram (200 Stars)
Frequency (1/days)
Original Data AoV Average Periodogram (50 Stars)
Frequency (1/day)
Frequency (1/day)

OGLE data


Original Data AoV Average Periodogram (200 Stars)
0.015
0.01
0.005
0
0 1 2 3 4 5 6 7 8
Frequency (1/days)
Corrected Data AoV Average Periodogram (200 Stars)
0.015
0.01
0.005
0
0 1 2 3 4 5 6 7 8
Frequency (1/days)

What do we do next?