

Sys-Rem

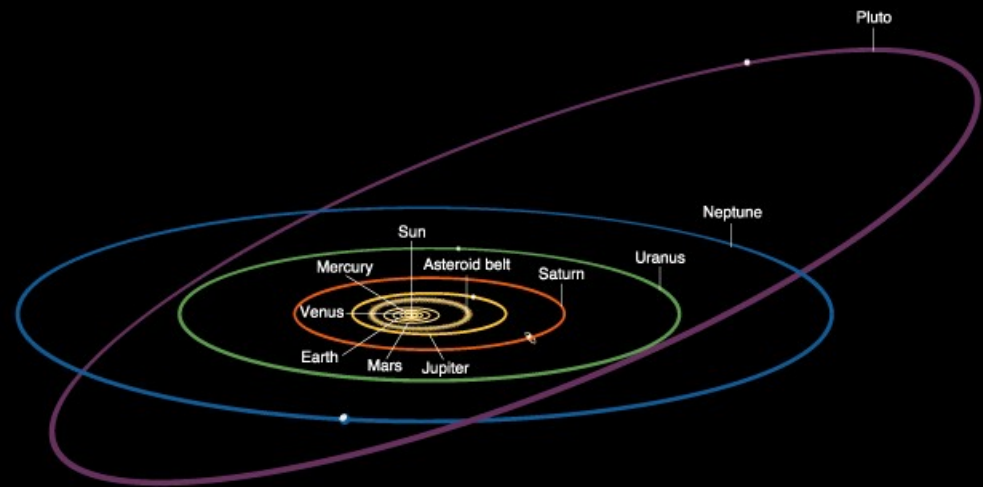
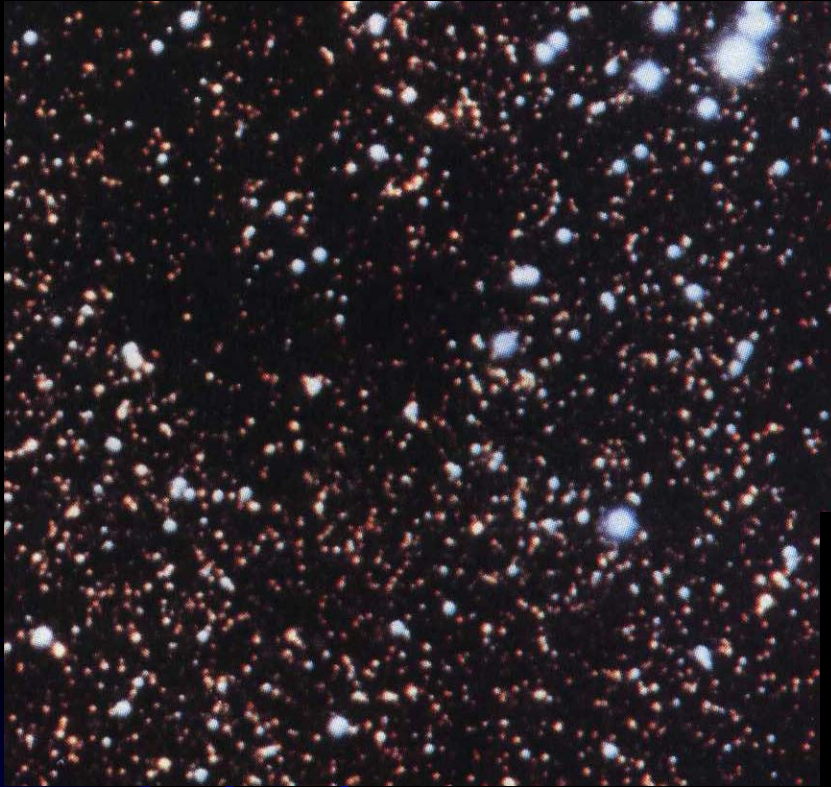
Systematics Removal
in large sets of light-curves

Omer Tamuz
Tel Aviv University

(Tamuz, Mazeh & Zucker 2005)

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

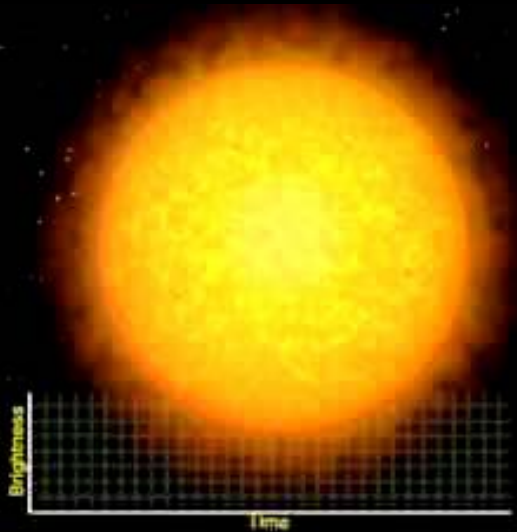
Extra-solar systems?



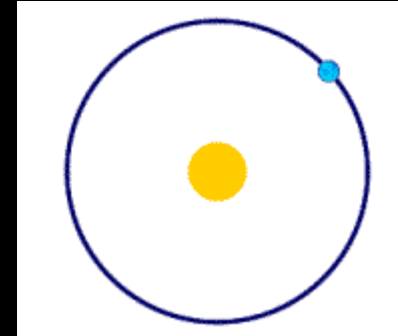
The solar system is not unique



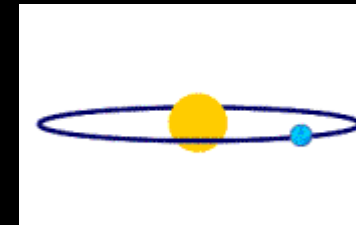
Transits



Face on

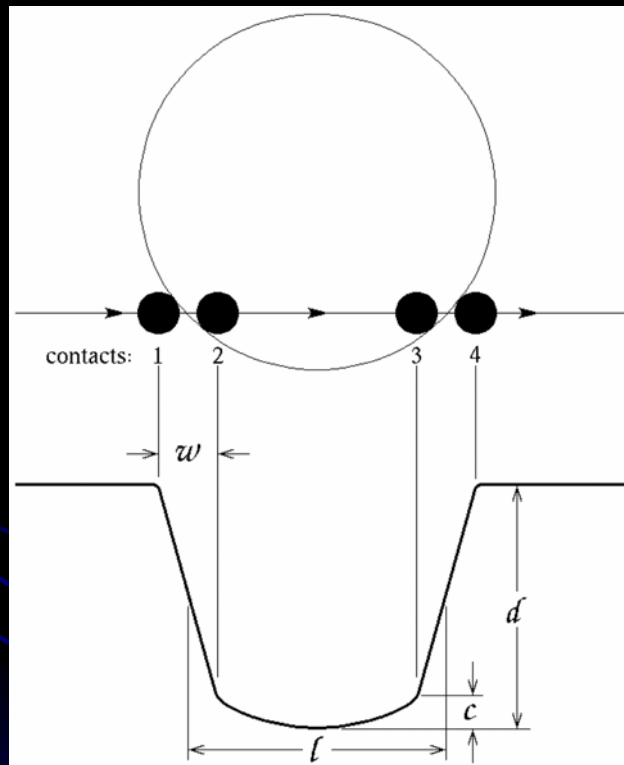


Edge on



Transits

What can we learn
from the transit
shape?



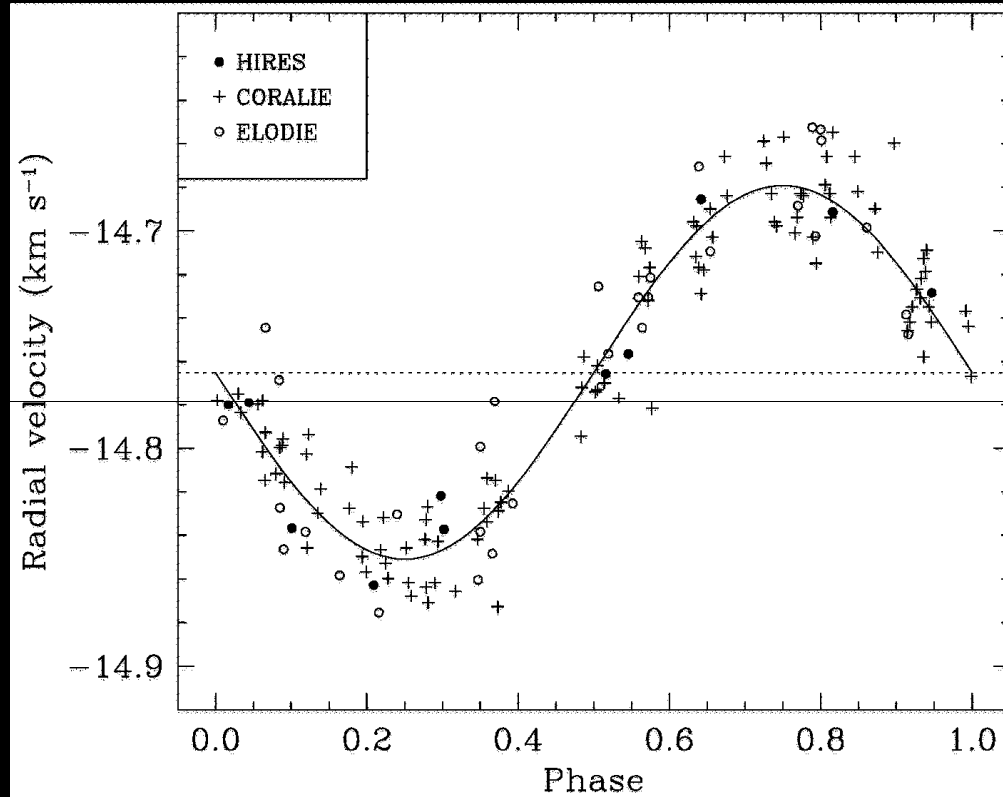
- Planet mass
- Planet radius
- Stellar radius
- Moons
- Planetary atmosphere

HD 209458

Mazeh *et al.*, 2000

Shay Zucker (Tel Aviv)

Discovered through the
Doppler shift variation of its
parent star.

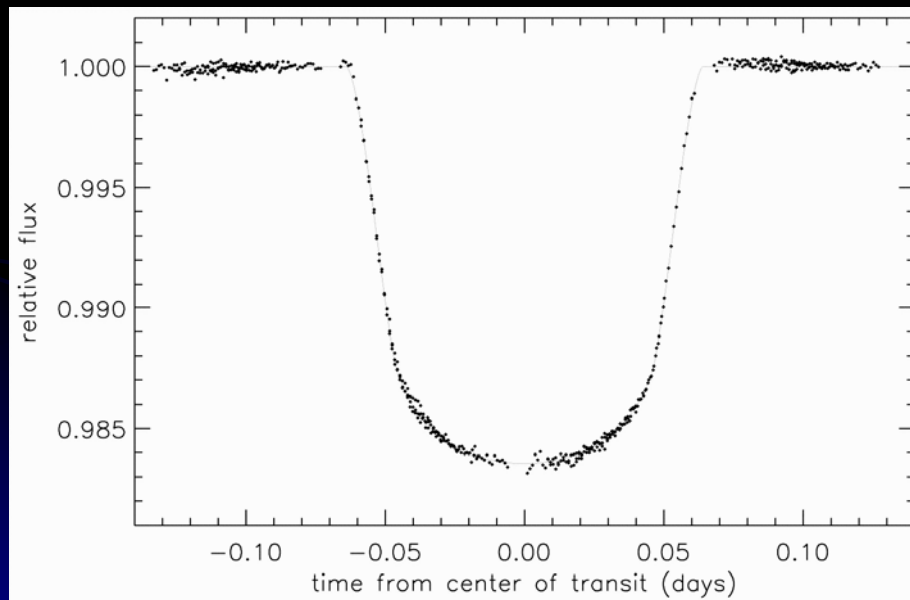


Charbonneau, Brown, Latham & Mayor 2000

Henry, Marcy, Butler & Vogt 2000

HD209458

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



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

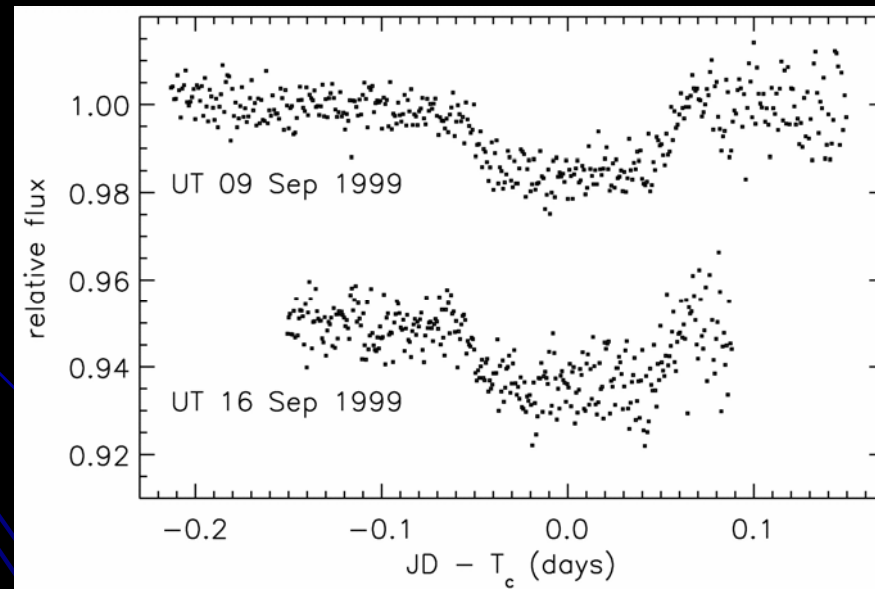
$$i = 86.7 \pm 0.1$$

$$\bar{\rho} = 0.35 \text{ g cm}^{-3}$$

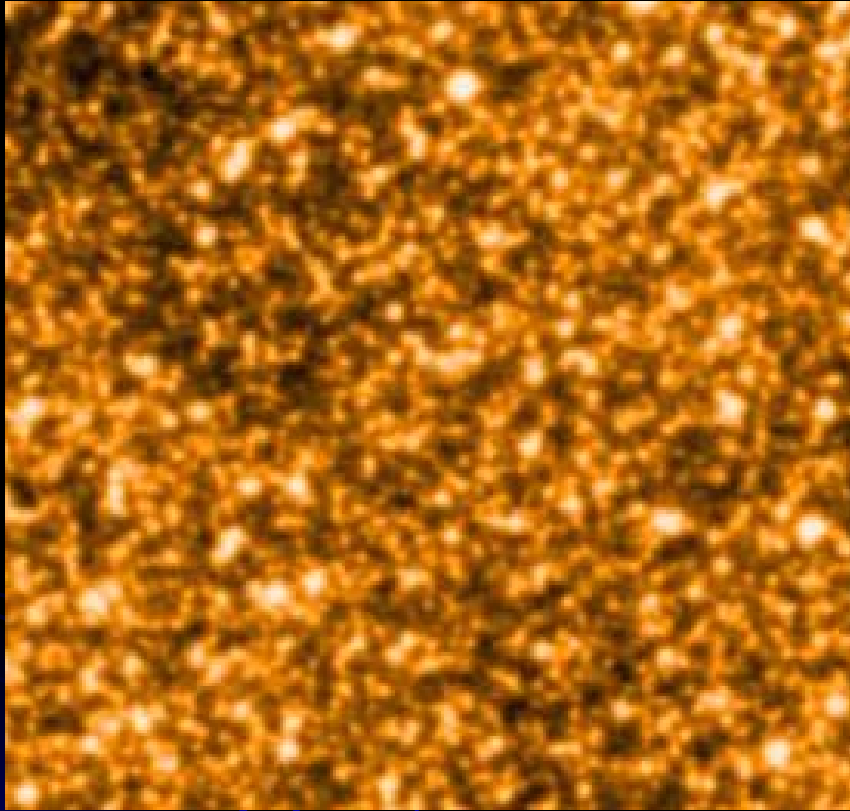
HD 209458

The discovery was made with ground based observations

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.



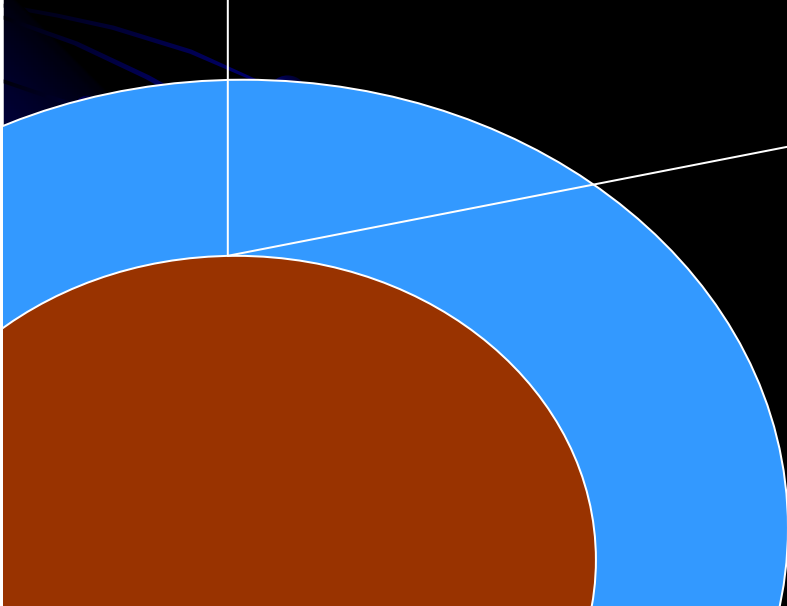
What causes the large errors in ground based photometry?

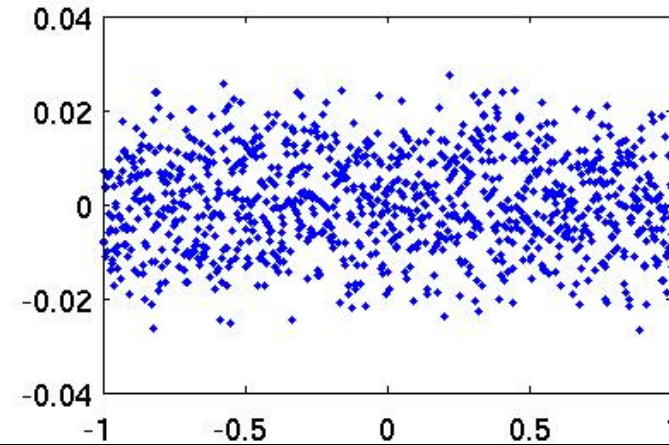
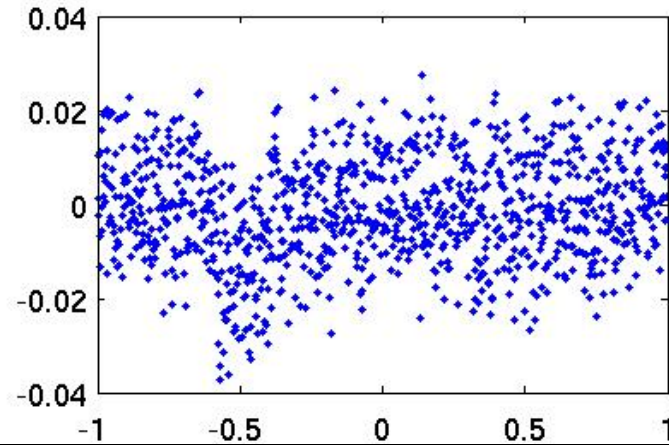
THE ATMOSPHERE

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



Let's try to correct these systematic effects...

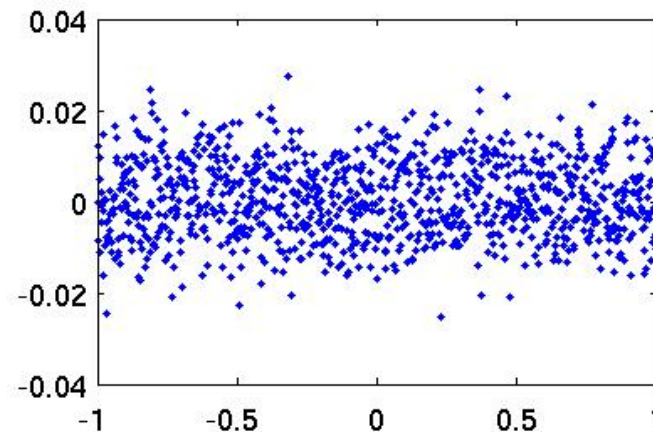
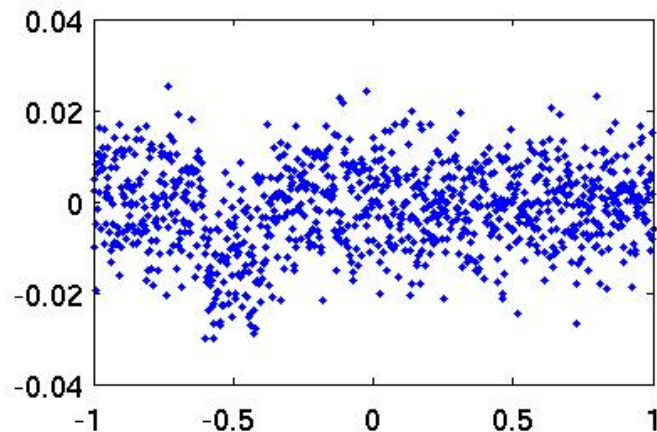




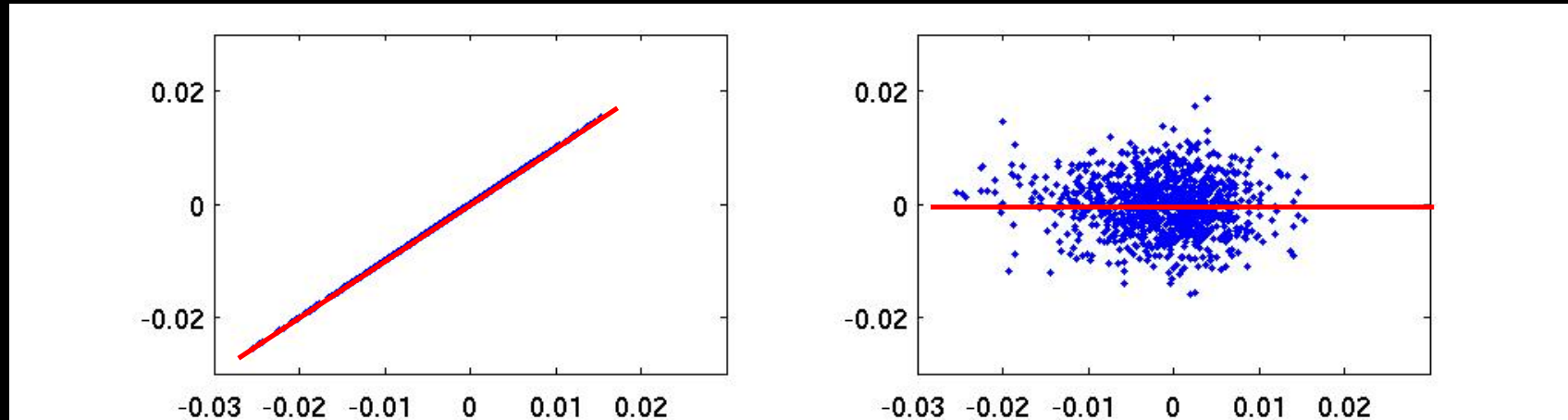
Minimizing the RMS:

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

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



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

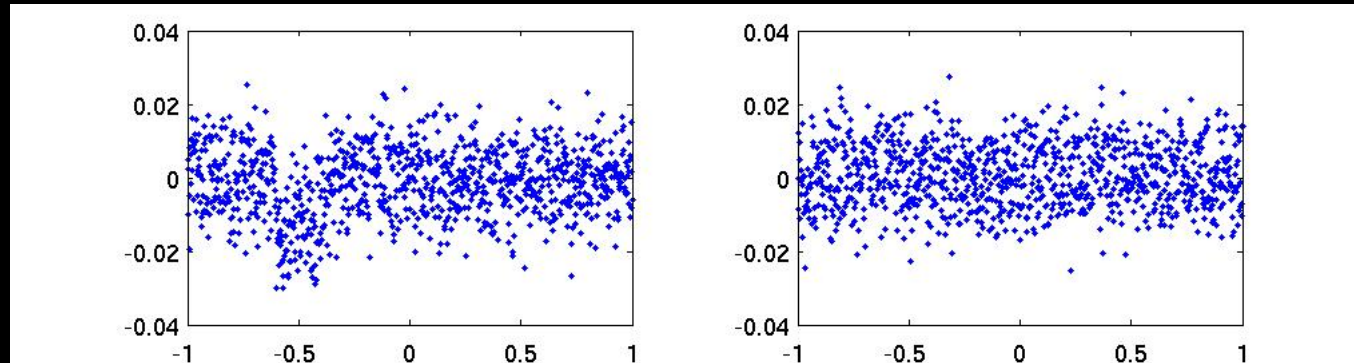


Not a very good idea...

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

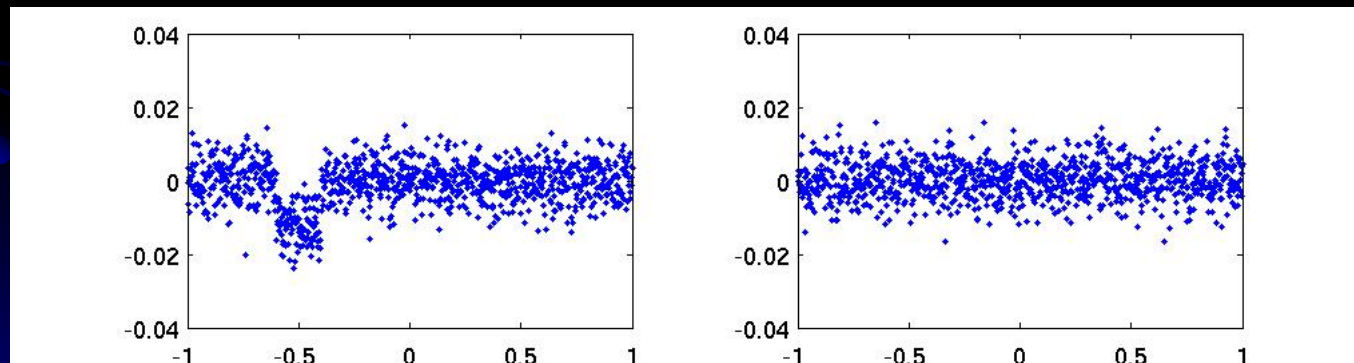
$$S = S_1 + S_2 = \sum_{i,j} \frac{(r_{ij} - c_i a_j)^2}{\sigma_{ij}^2}$$

Previous chart



New chart

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



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

What are we doing here?

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

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

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

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

The case of equal uncertainties

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


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

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


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


How do we do it?

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




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

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?

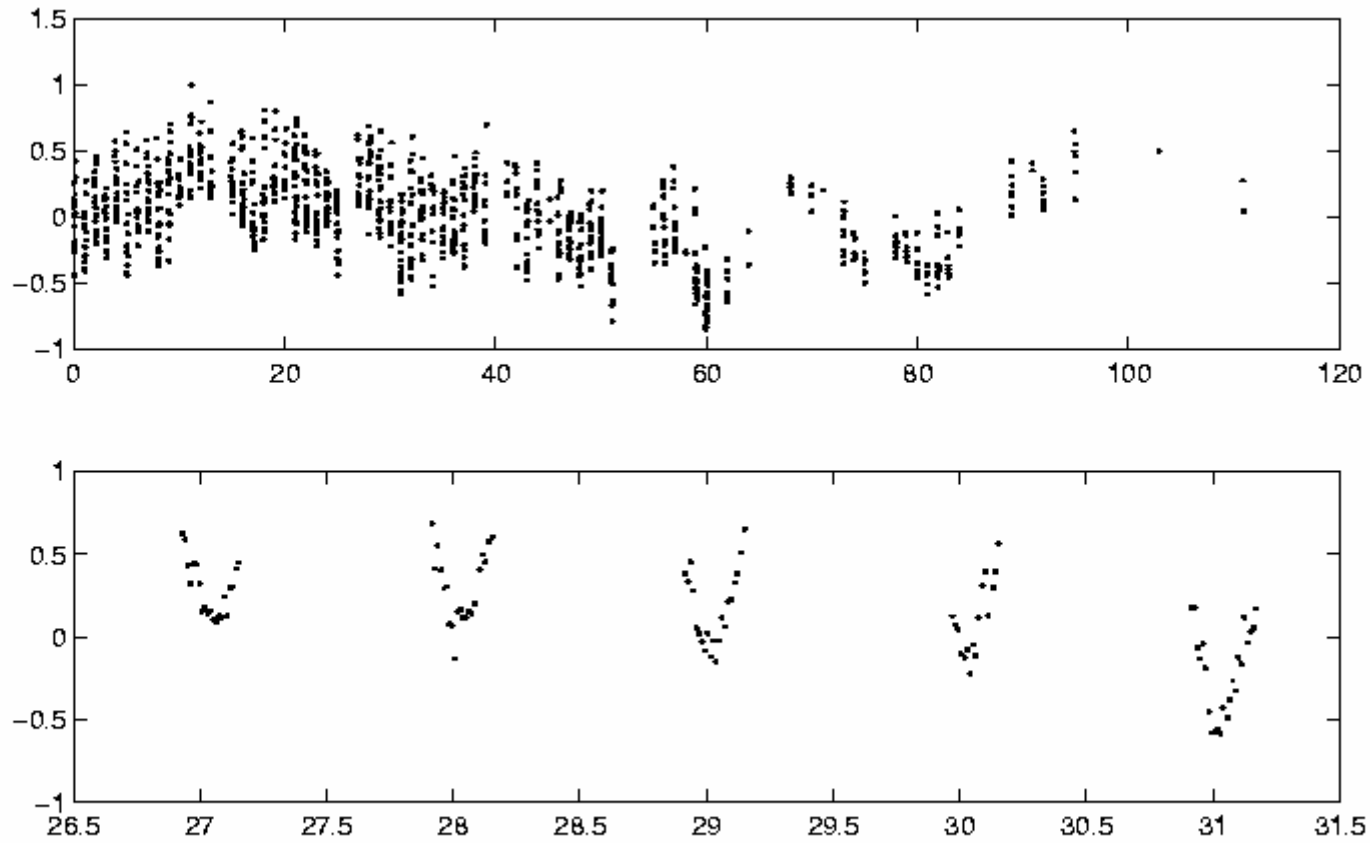


Figure 3. Third component showing similar behaviour to the first.

What effects do we actually find?

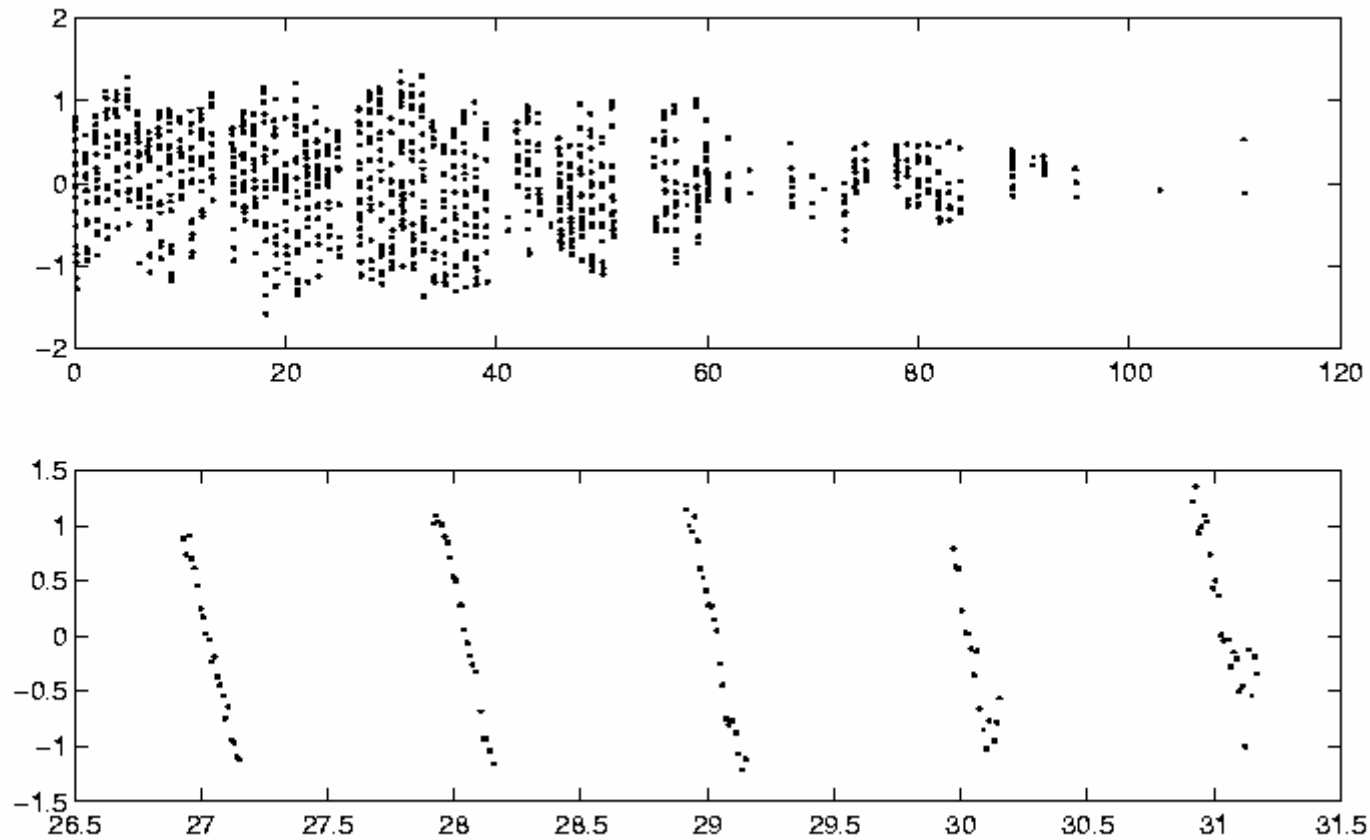
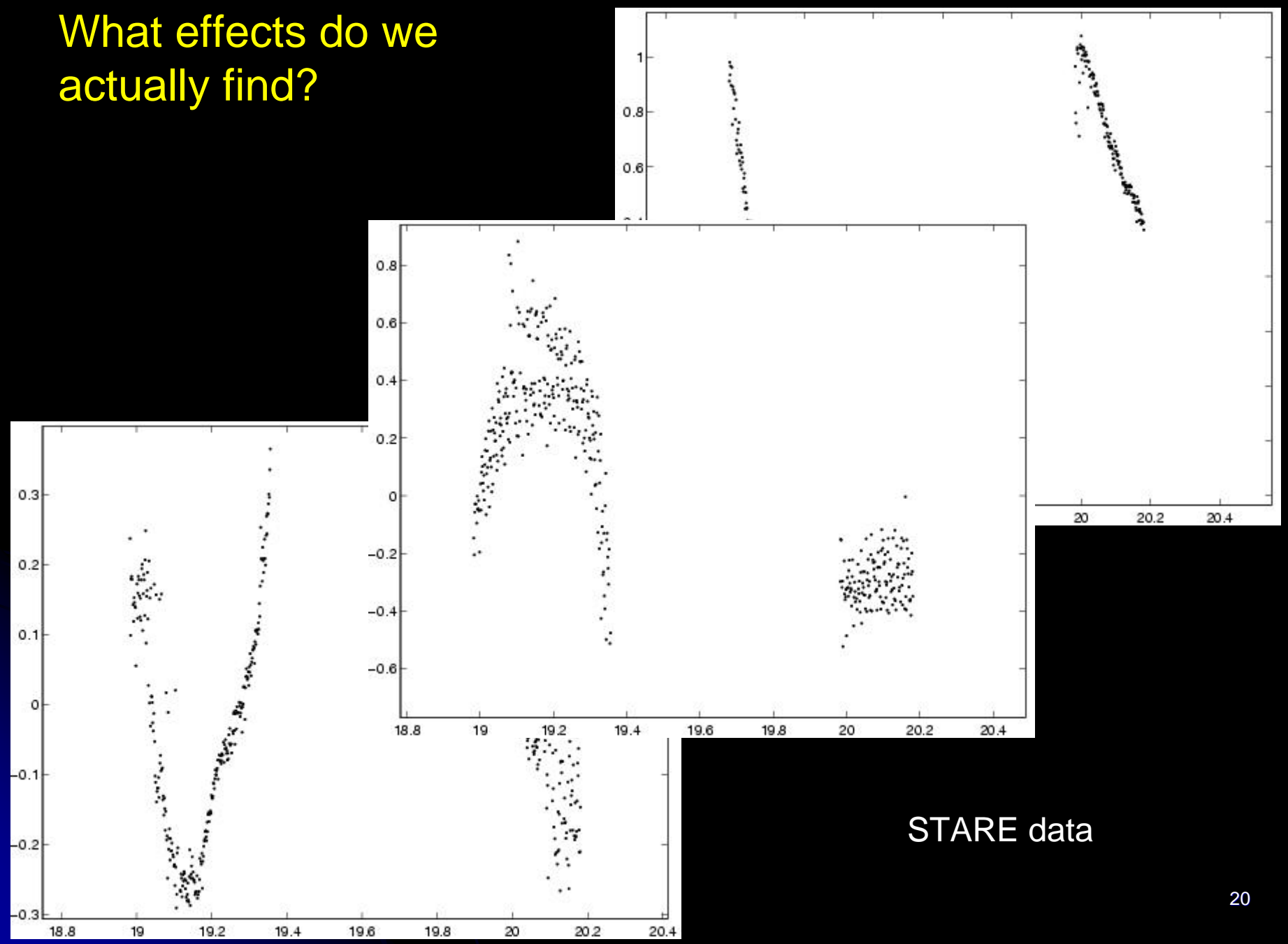


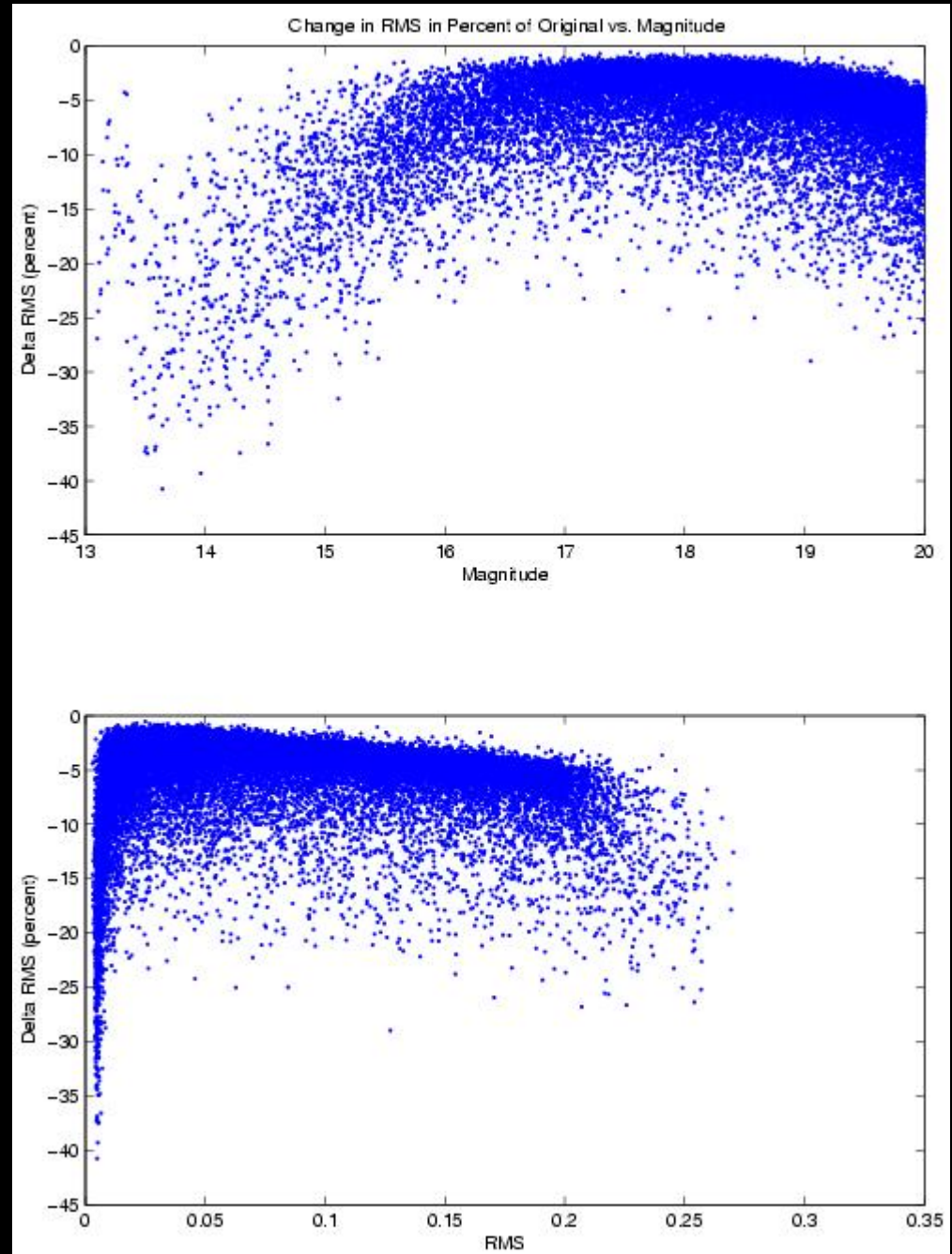
Figure 2. Second component showing linear monotonous change every observation night.

What effects do we actually find?



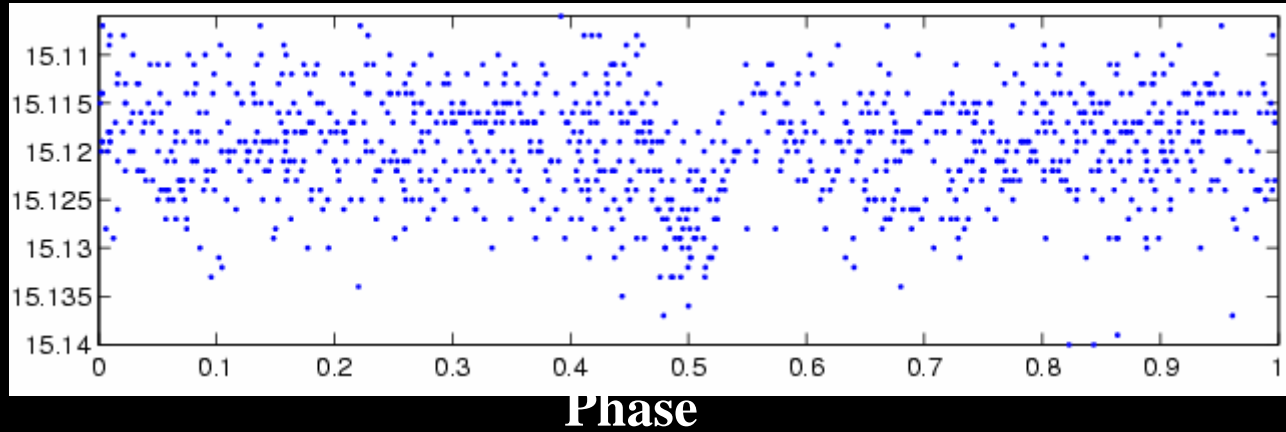
STARE data

How much noise do we actually remove?

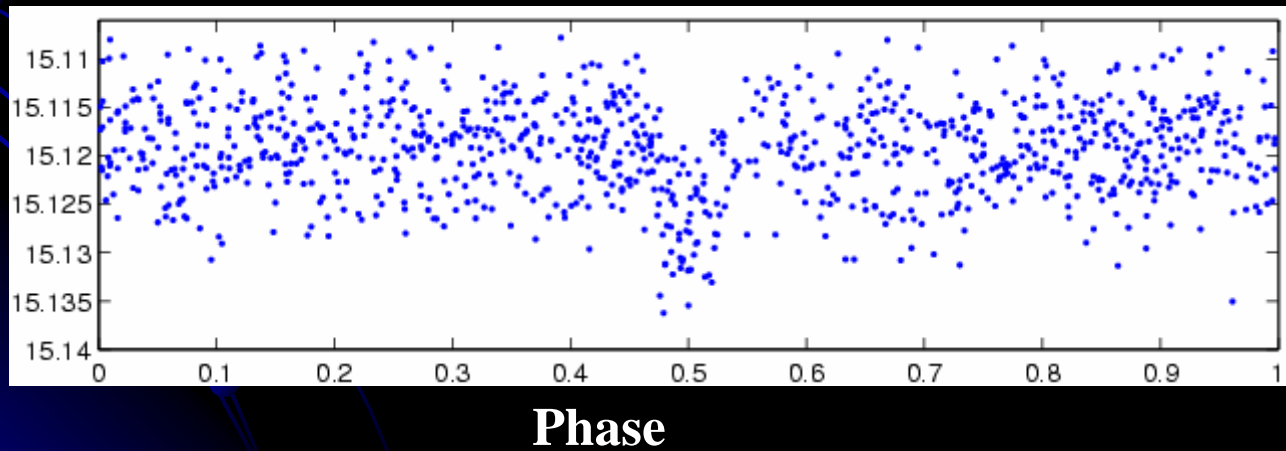


OGLE data

OGLE-TR-132, Before...



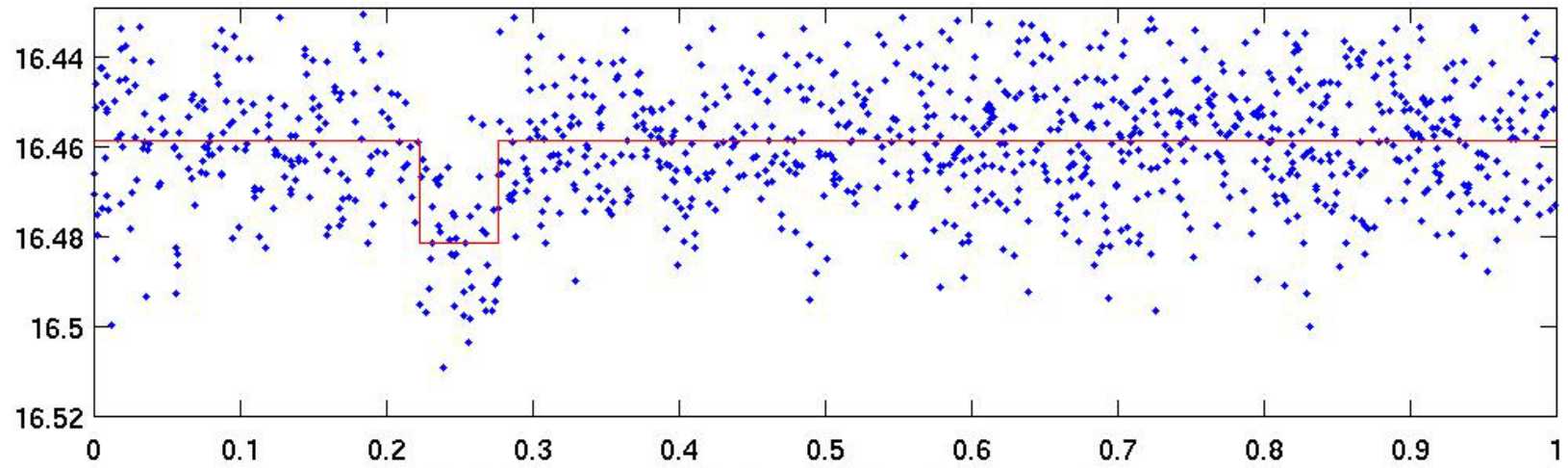
... and after



OGLE data

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

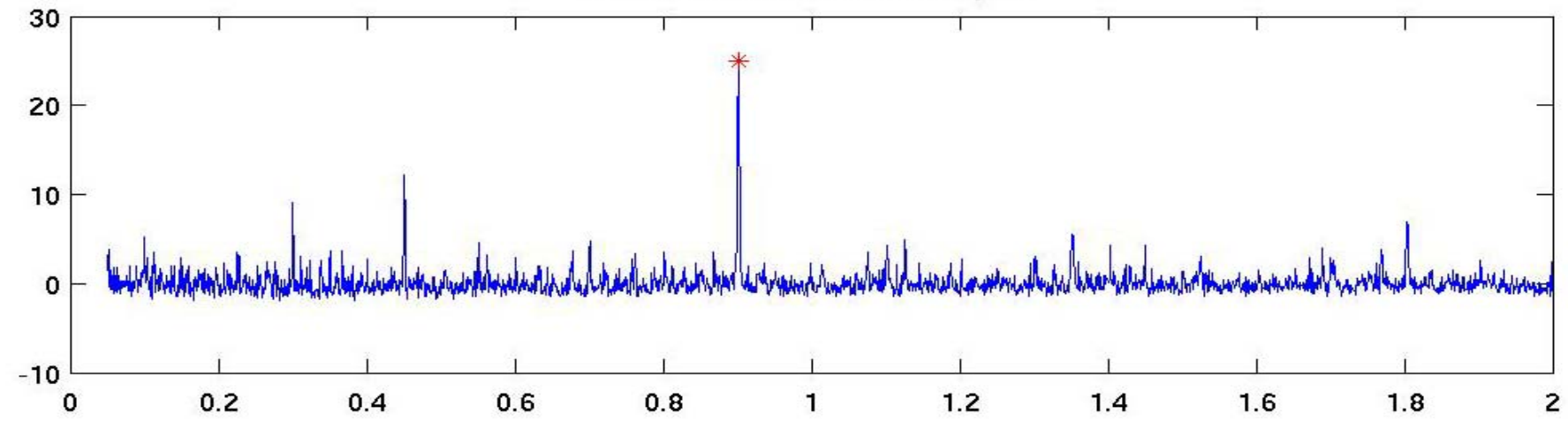
Significance: 24.91085
Corrected Lightcurve

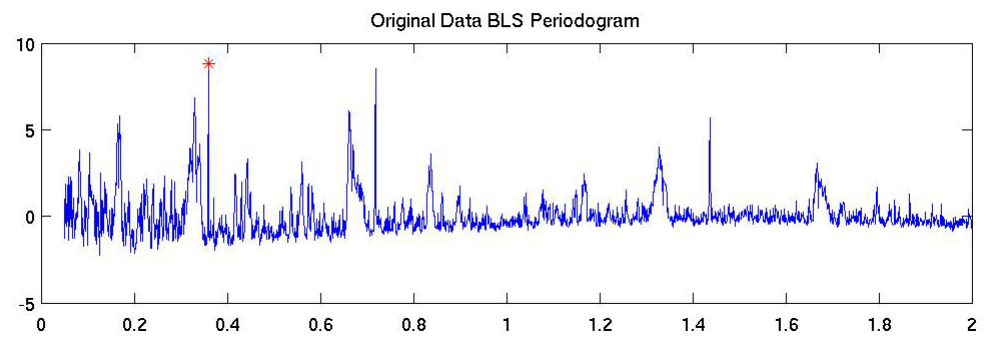
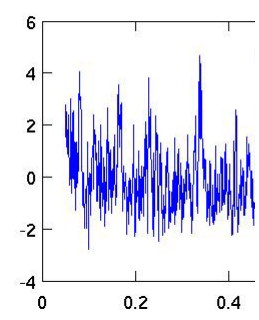
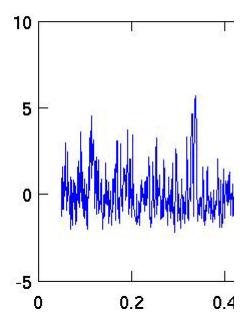
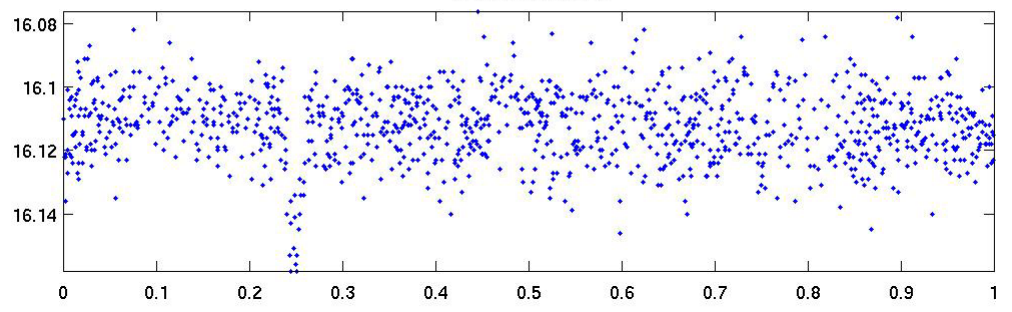
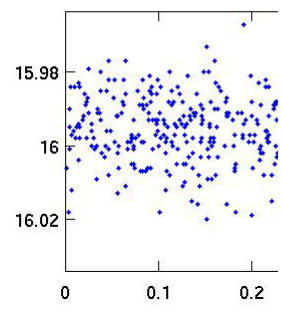
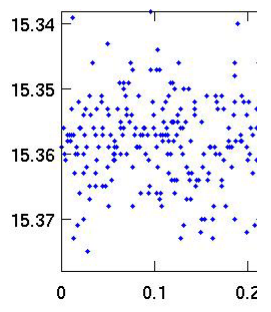
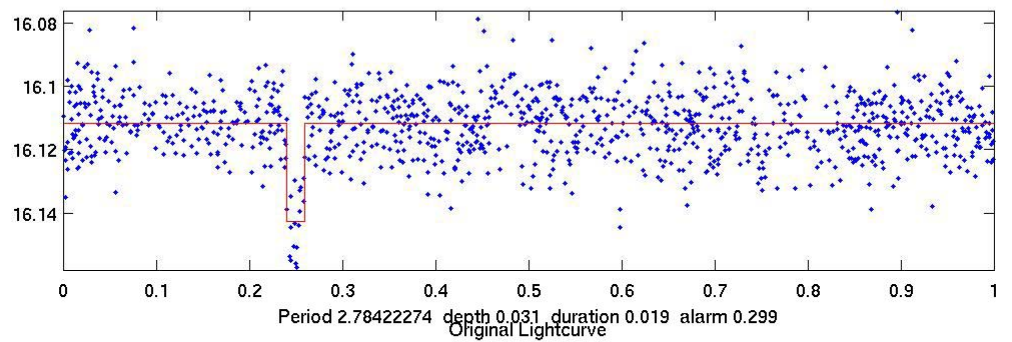
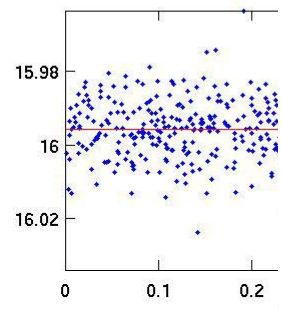
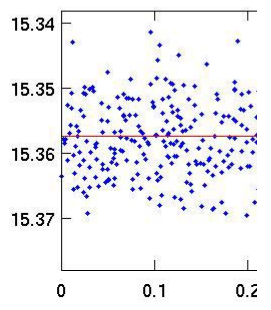
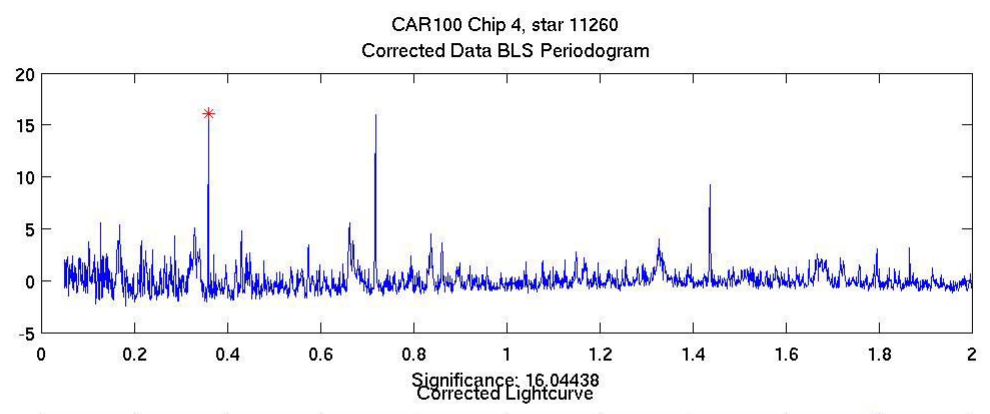
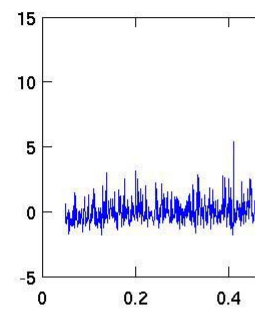
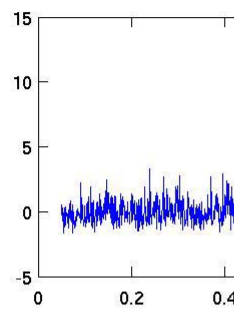


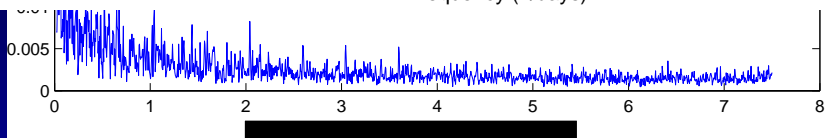
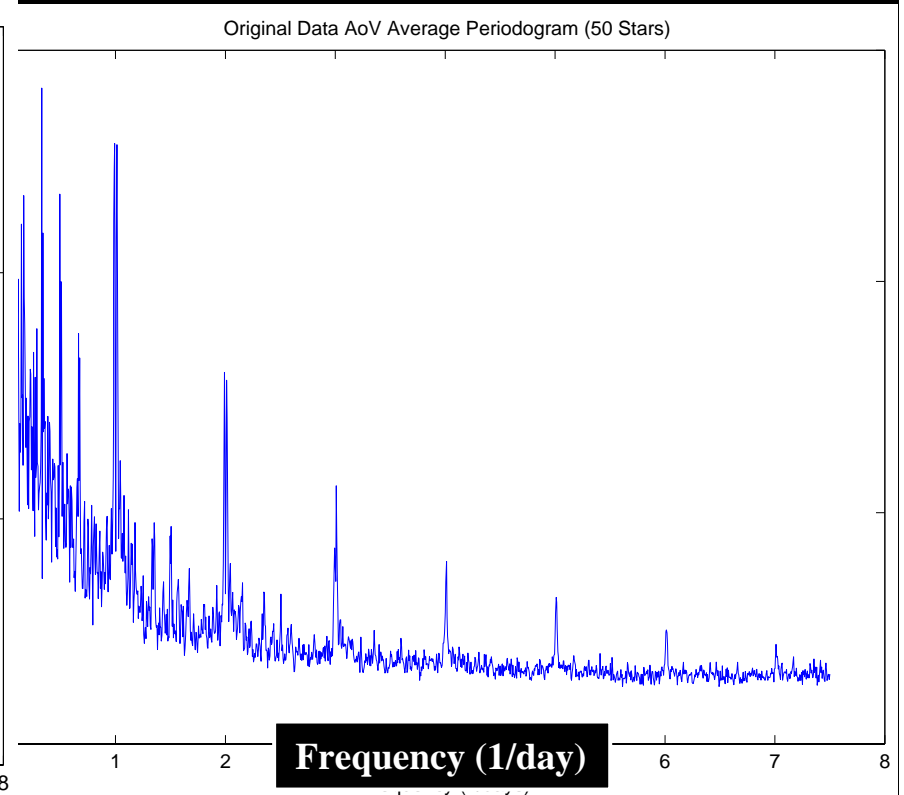
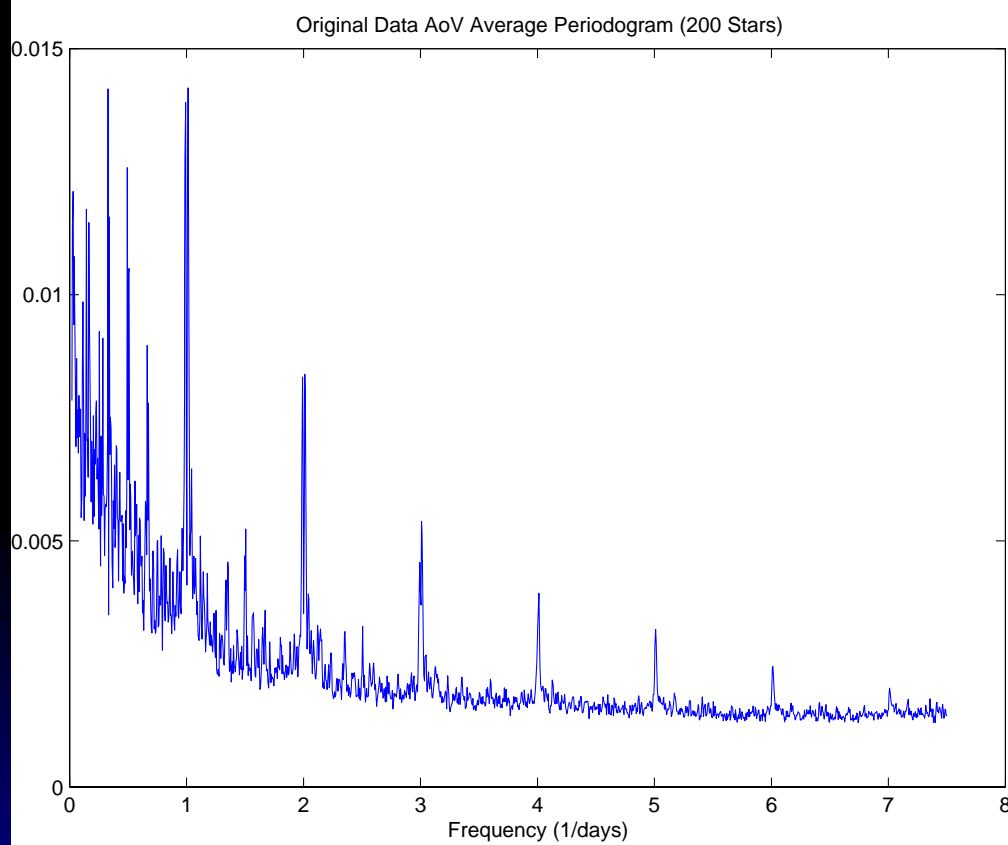
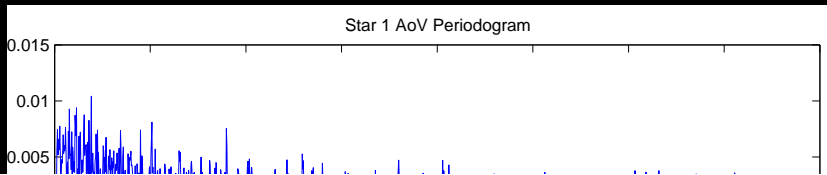
Period 1.10905730 depth 0.023 duration 0.053 alarm 0.033

Period 1.10905730 depth 0.023 duration 0.053 alarm 0.033

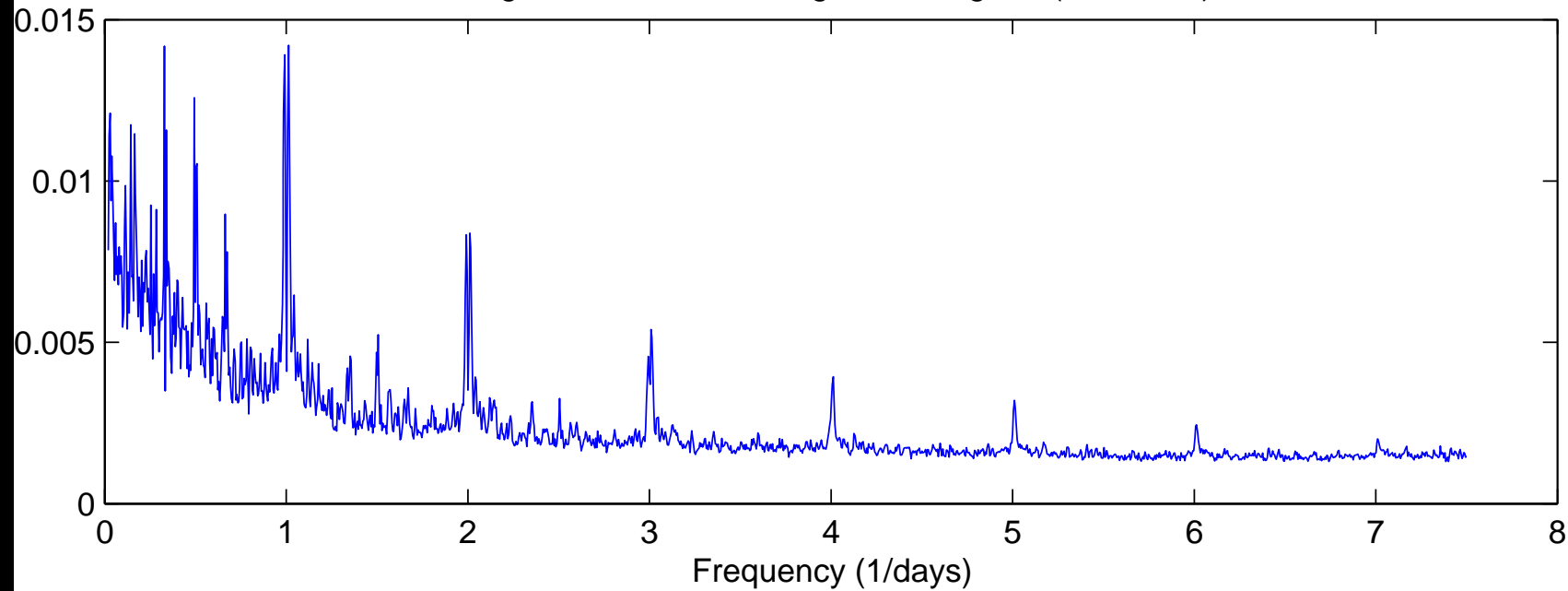
CAR100 Chip 6, star 1674
Corrected Data BLS Periodogram



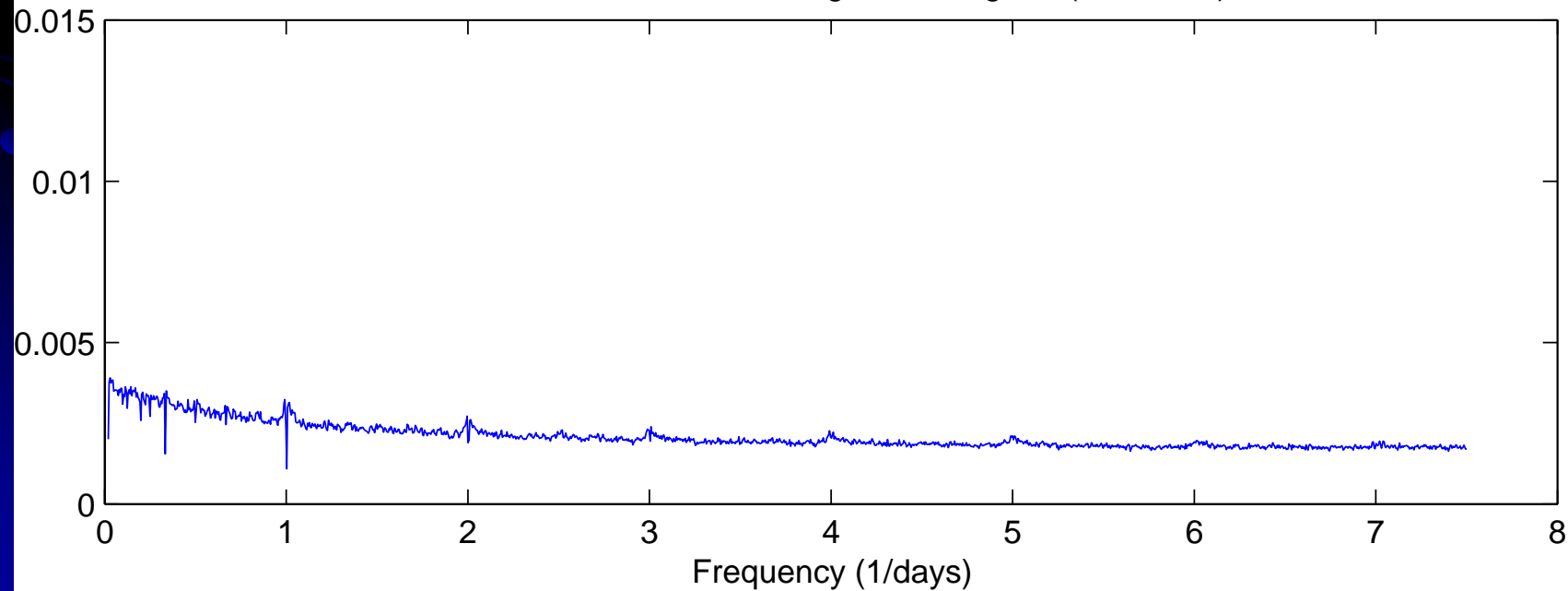




Original Data AoV Average Periodogram (200 Stars)



Corrected Data AoV Average Periodogram (200 Stars)



What do we do next?

