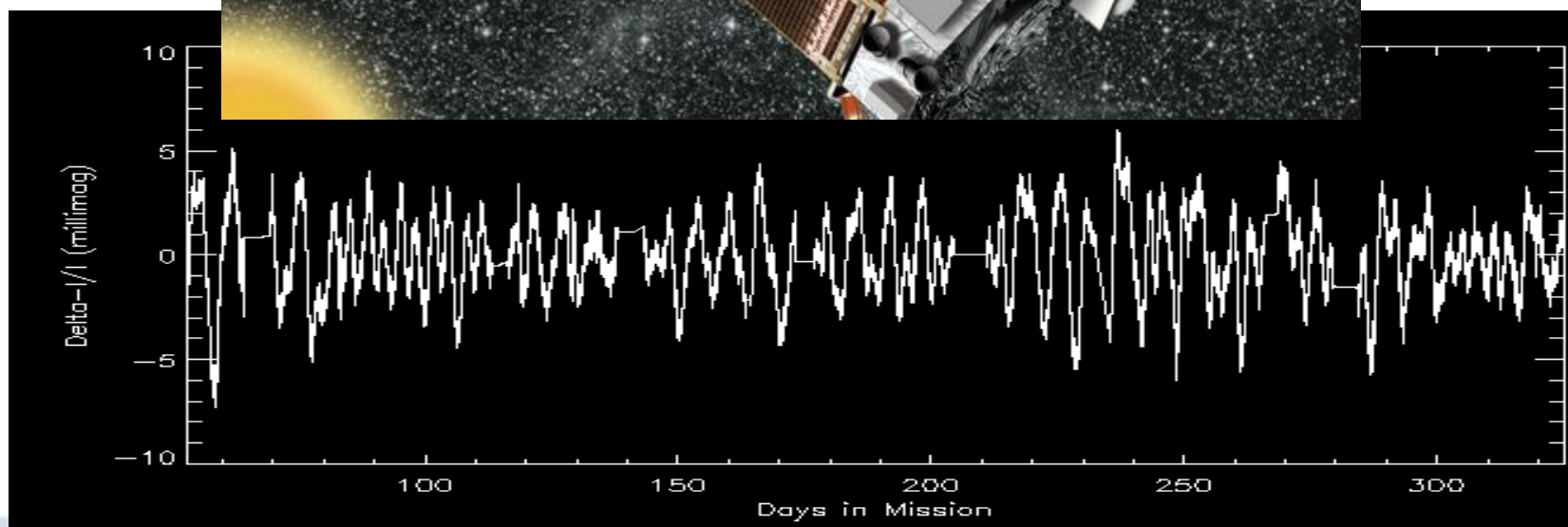
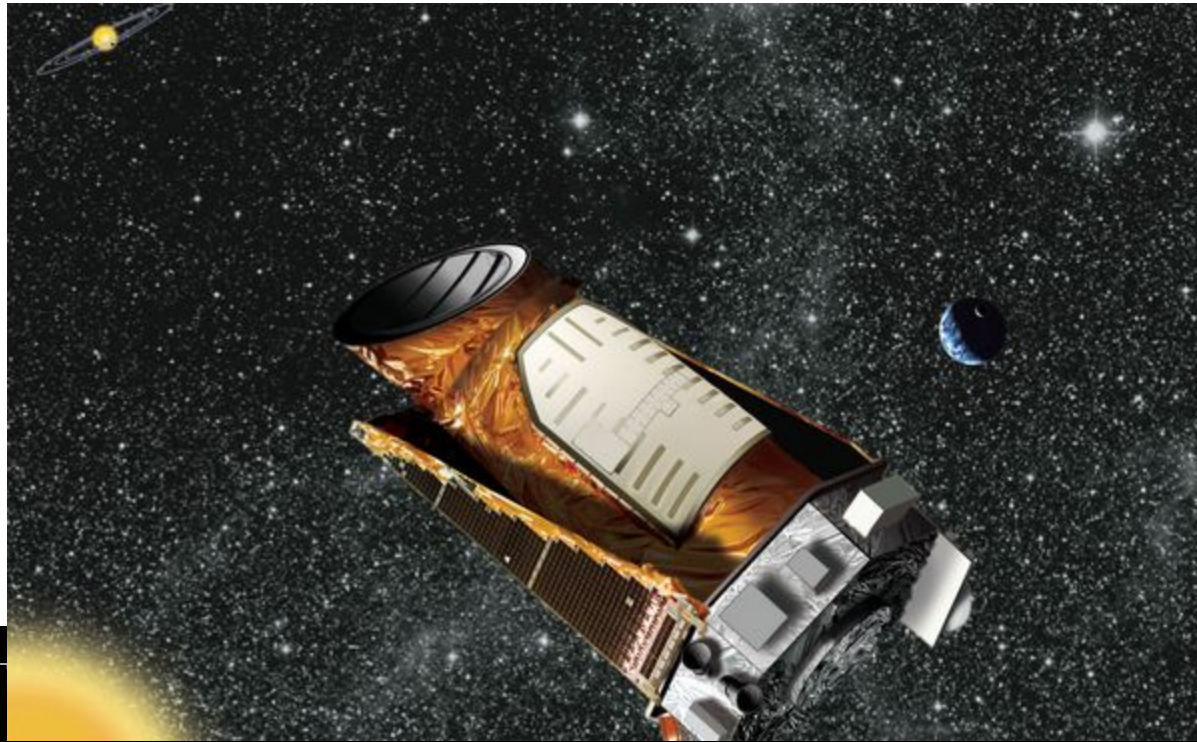


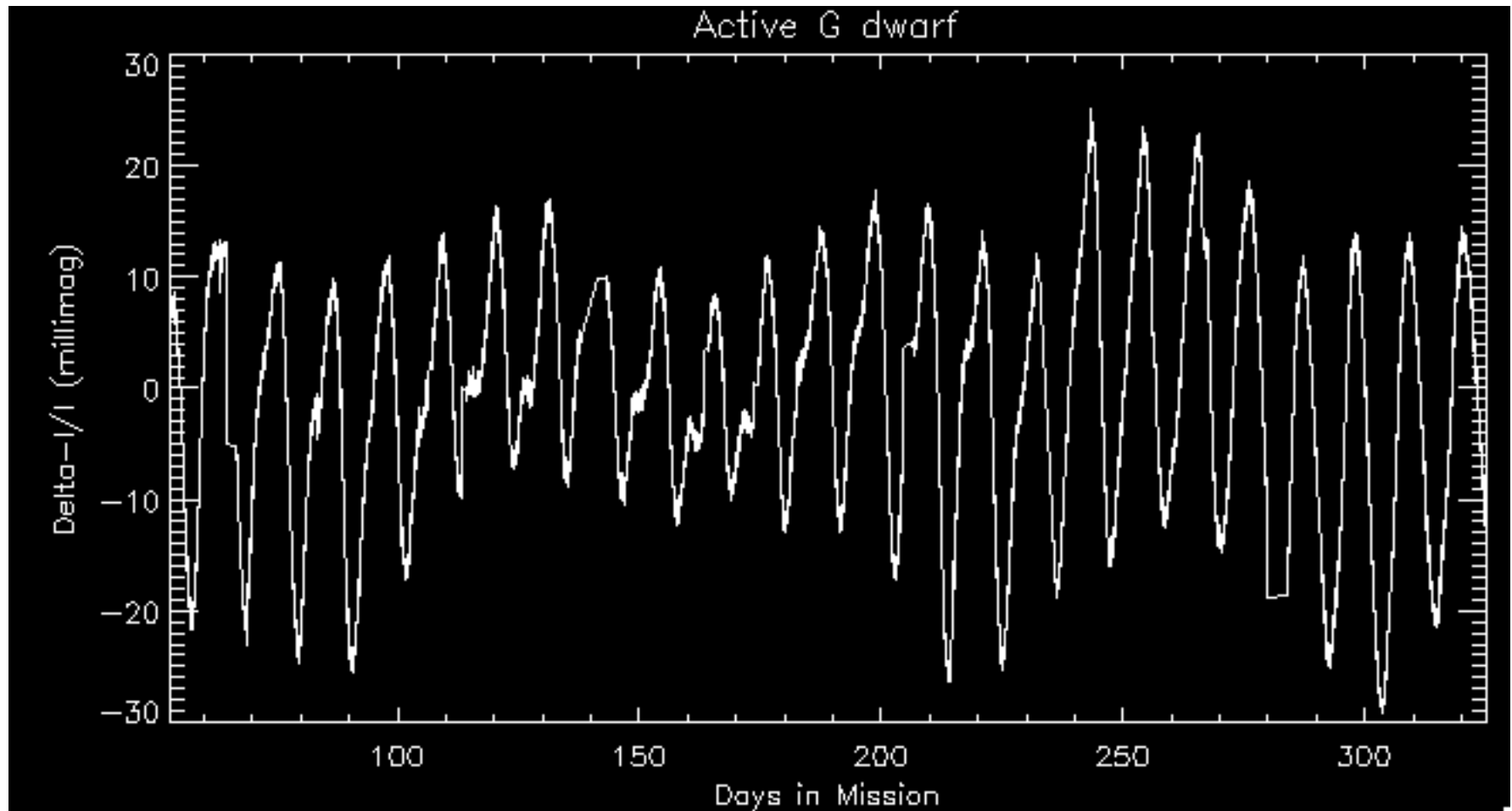
# The Promise of Kepler for Studying Stellar Differential Rotation

Gibor Basri, UC Berkeley



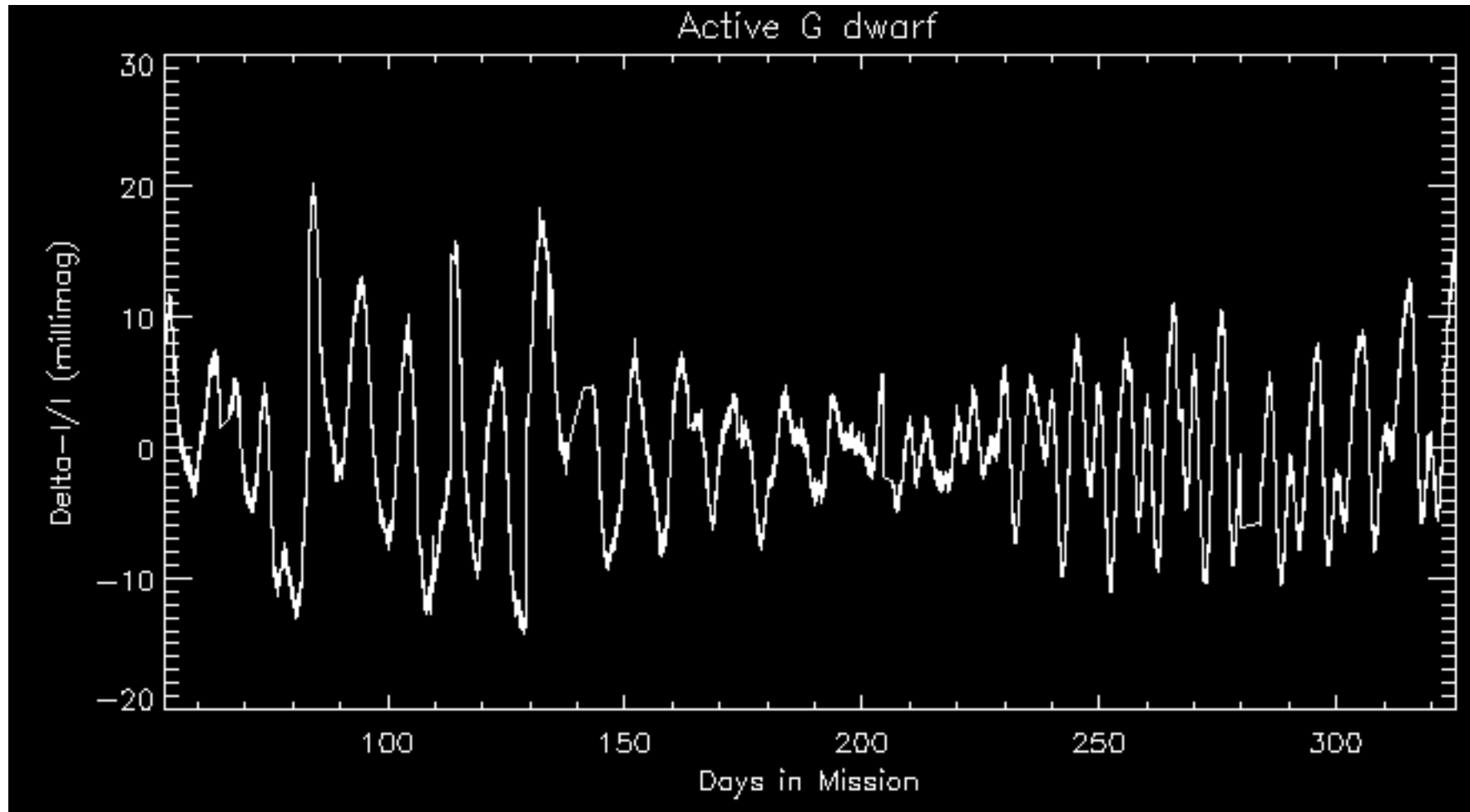
# Kepler Light Curves

The Kepler mission will collect long strings of activity for thousands of stars. Some have very obvious starspots, and rotation periods are easy.

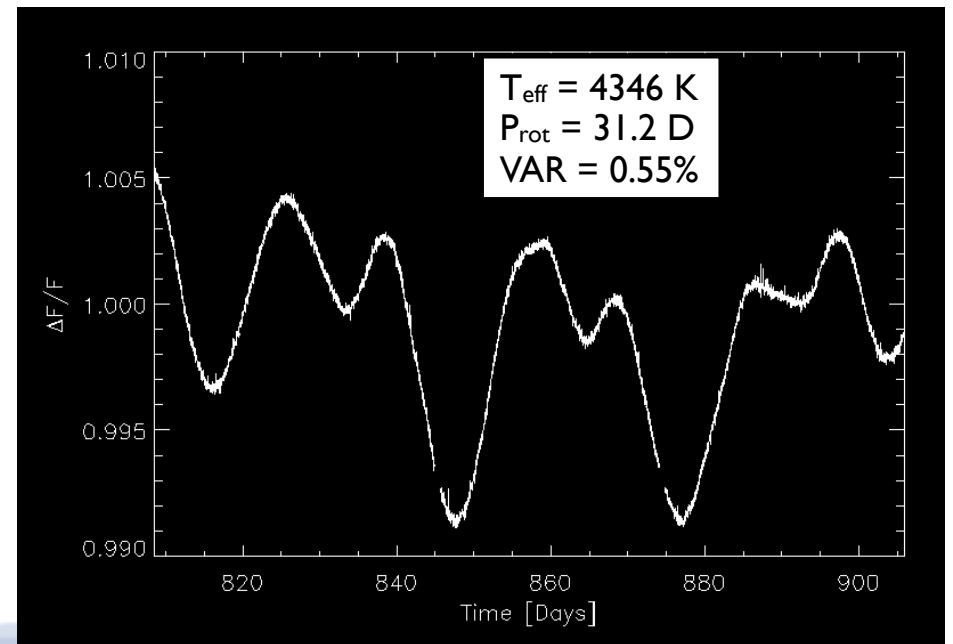
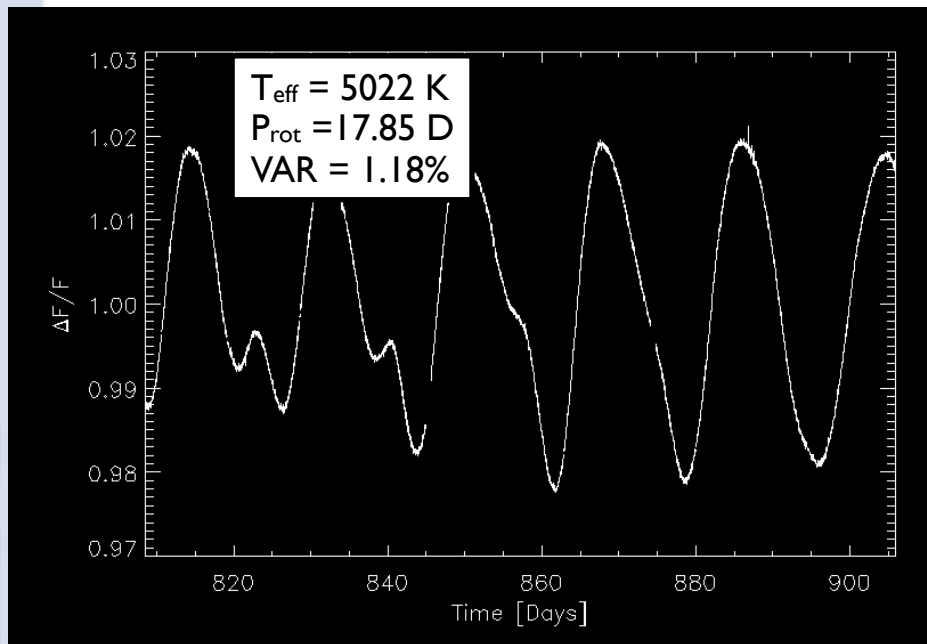
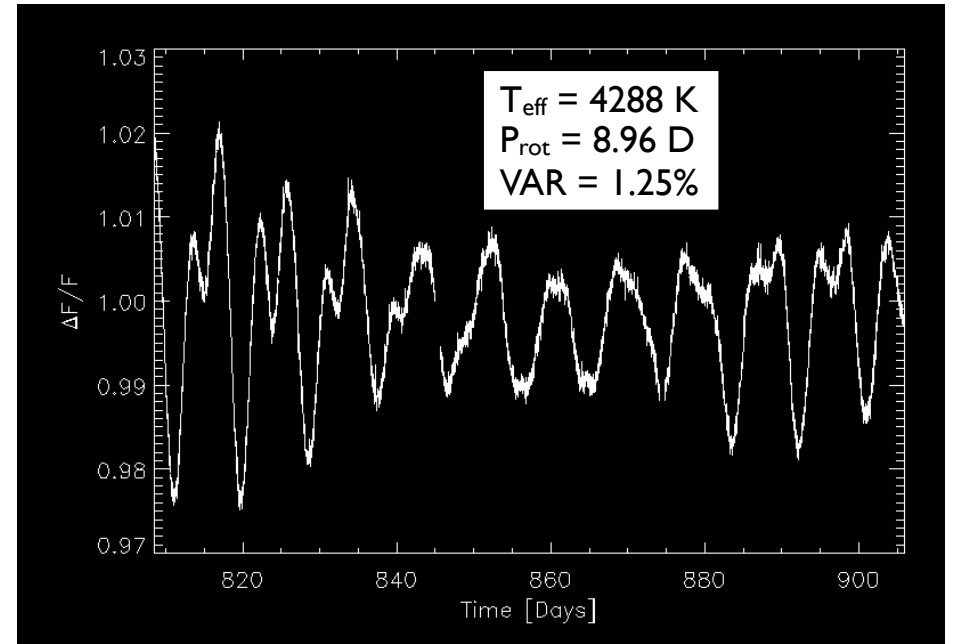
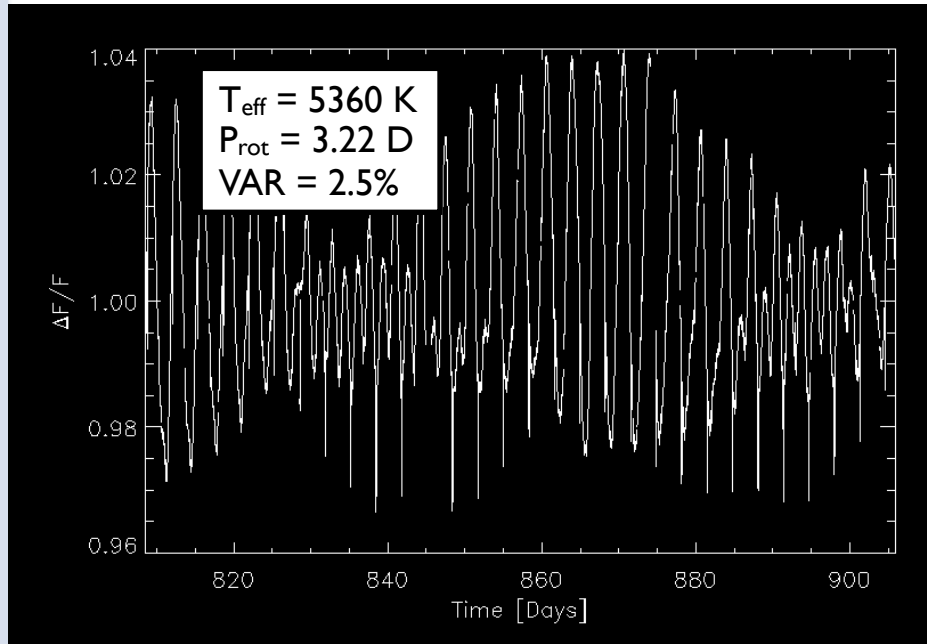


# Kepler Light Curves

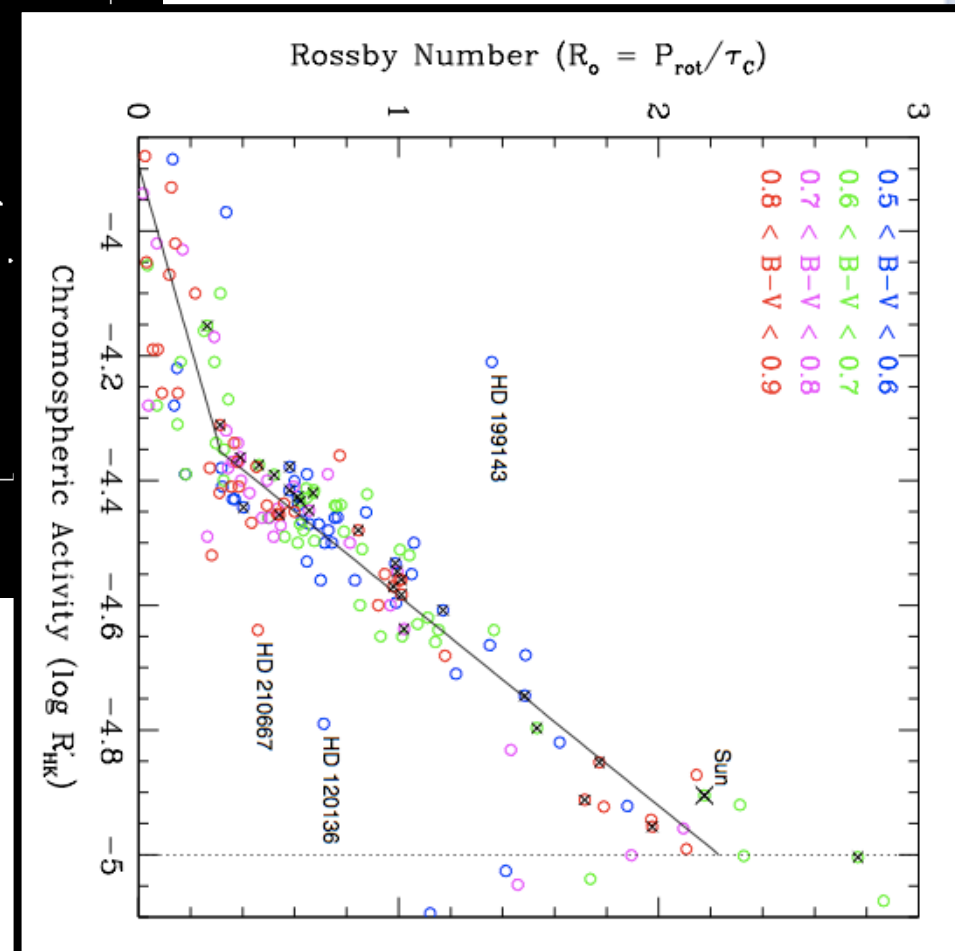
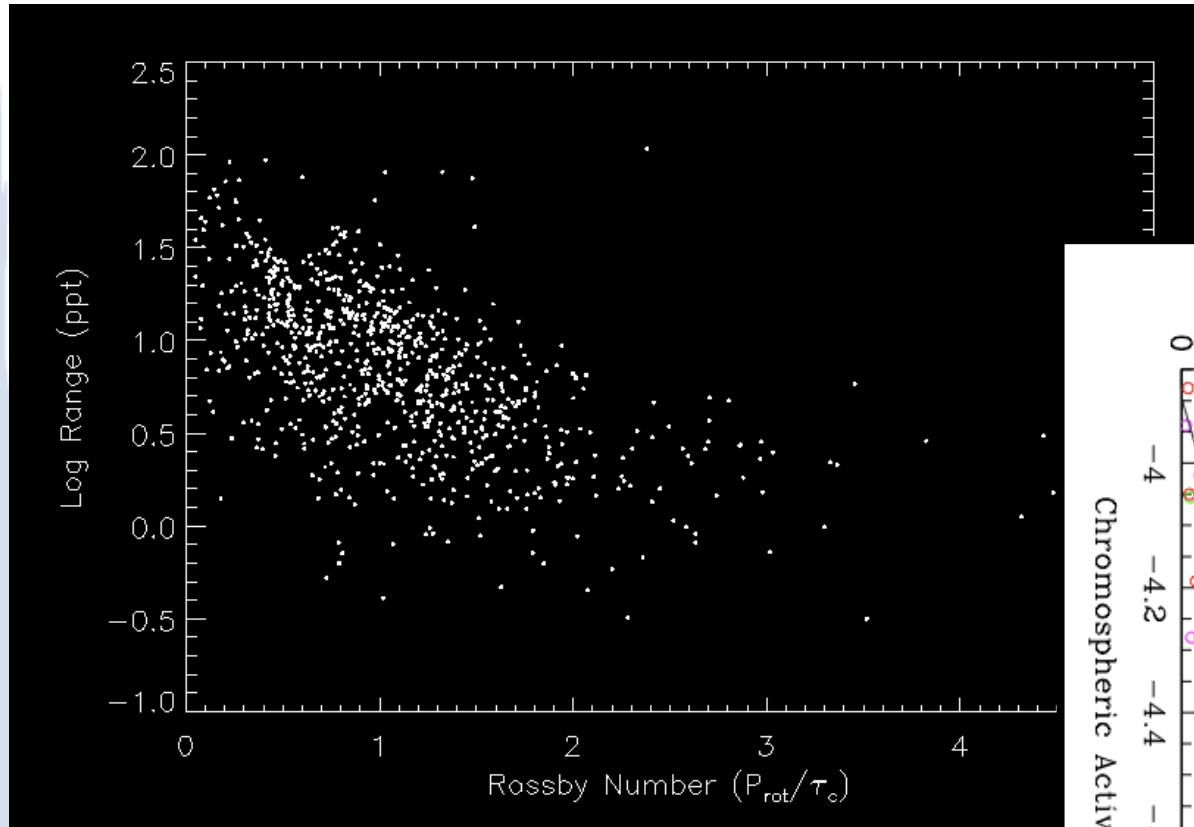
Differential rotation shows up as changes in amplitude and frequency of dips. A possible source of confusion is spot evolution. Can we separate them?



# A Variety of Periods and Morphologies

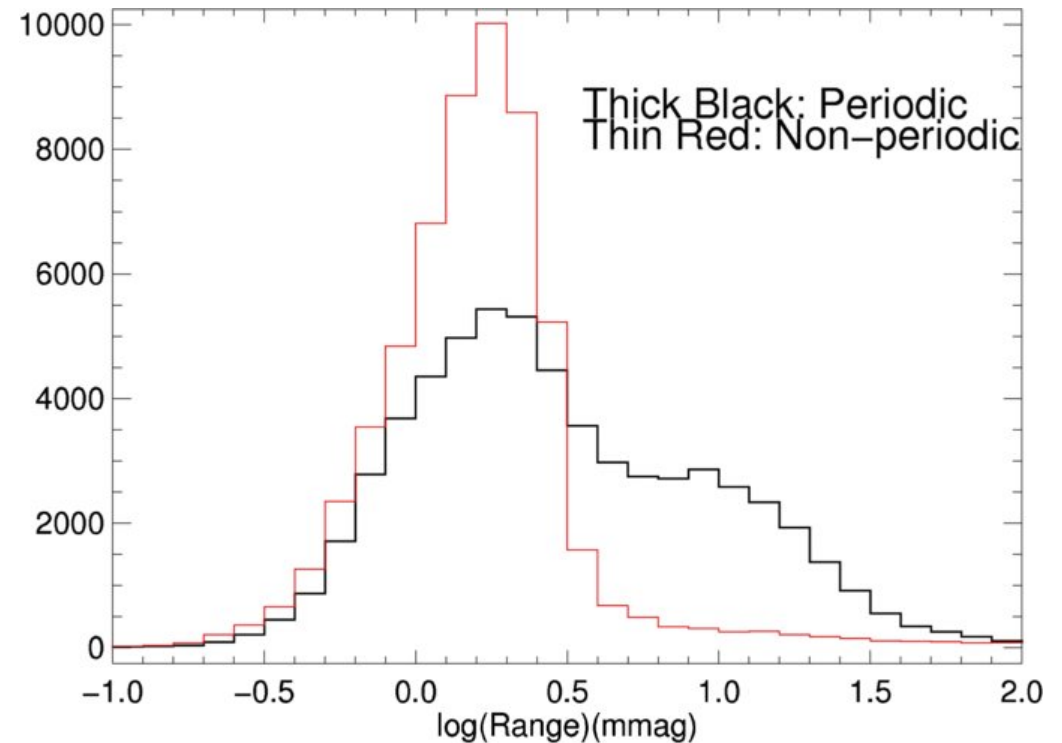
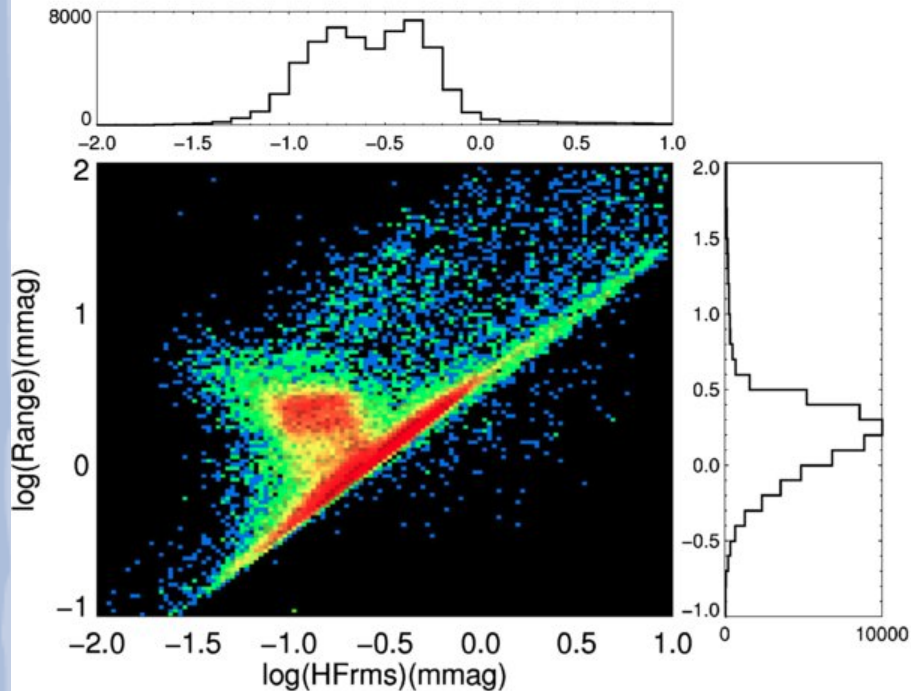
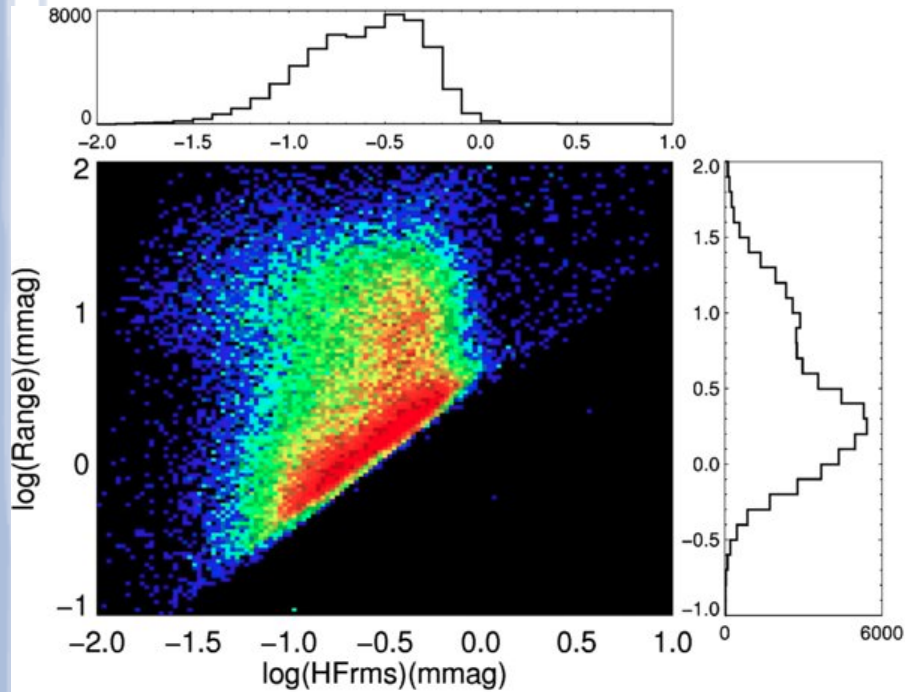


# The Rotation-Activity Relation in Photometric Variability Amplitude



# Range of Variability on Non/Periodic Stars

The period stars show greater amplitudes.  
The abscissa is high frequency noise.  
The red giants stand out in the non-periodic sample.





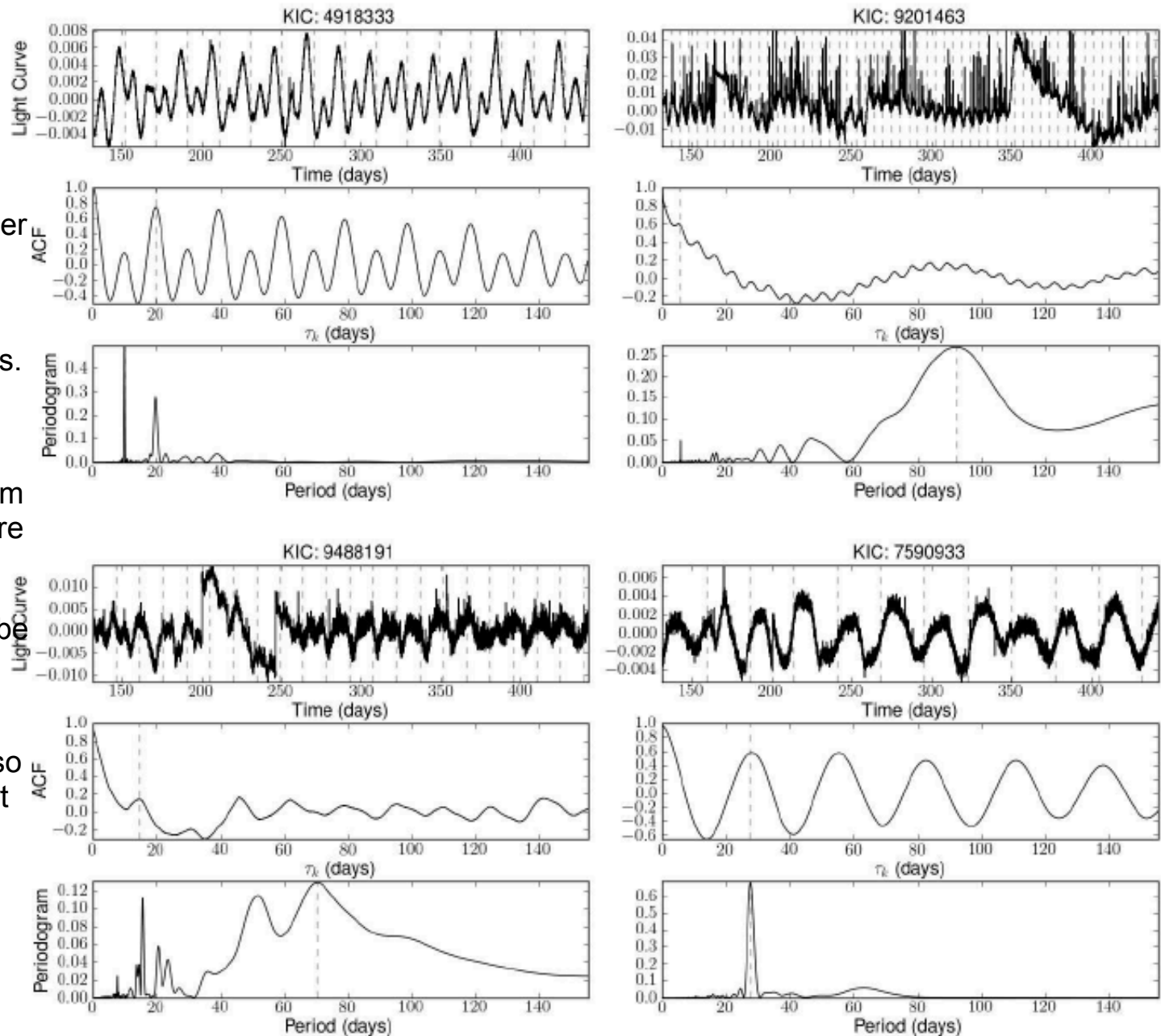
# Finding Rotation Period Can be Tricky

McQuillan, Aigrain, Mazeh have done a nice job of finding a better way to identify real periods in Kepler light curves.

Rather than just use a periodogram analysis, they also look at autocorrelations. The combination is pretty good at finding period aliases, and rejecting long periods that the periodogram likes to pick up but which are likely secular instrument effects. It is also tolerant of jumps and spikes that can be problematic.

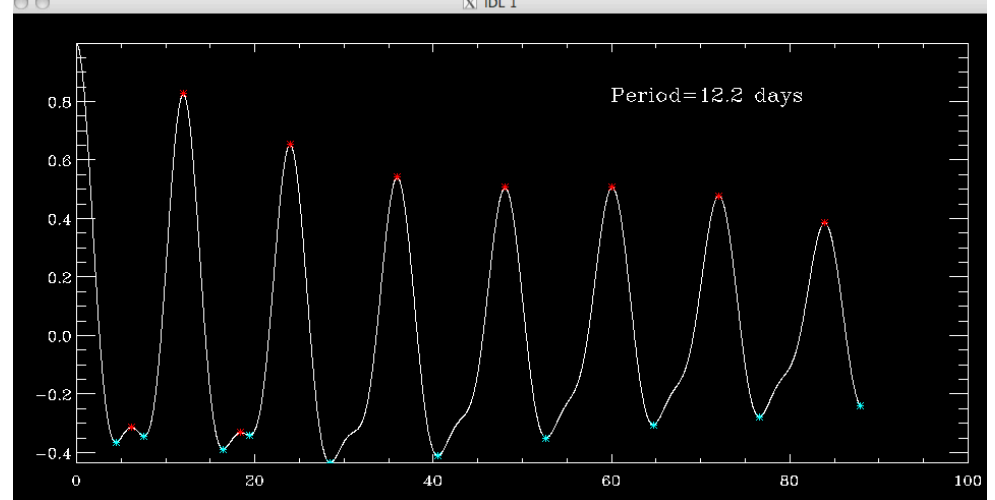
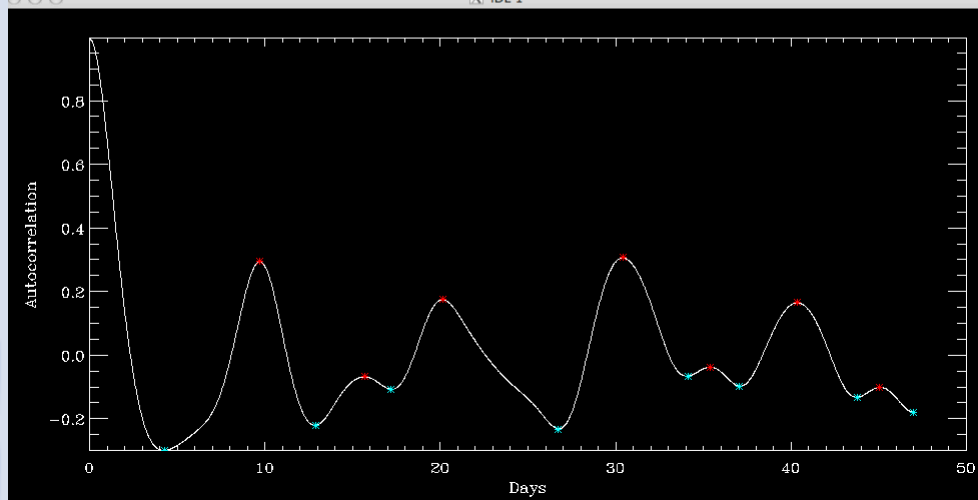
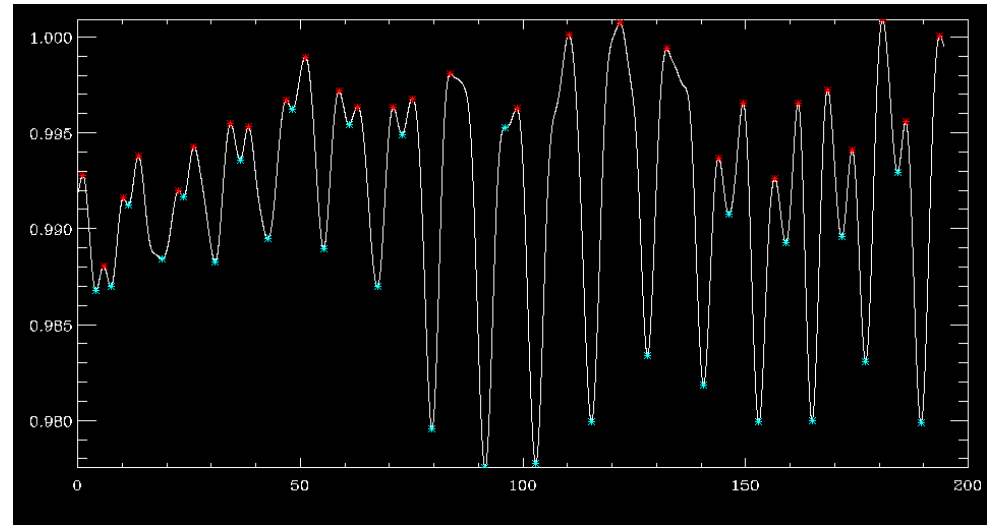
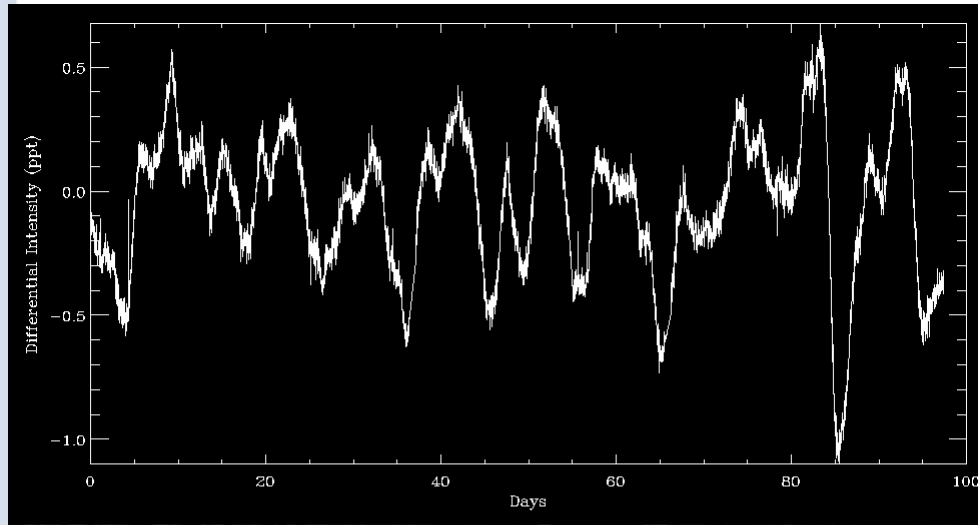
There are some tricks that need to be played with to properly smooth the data (so as not to find spurious short periods).

This can be found in a new paper on M dwarf rotations that is on arXiv.



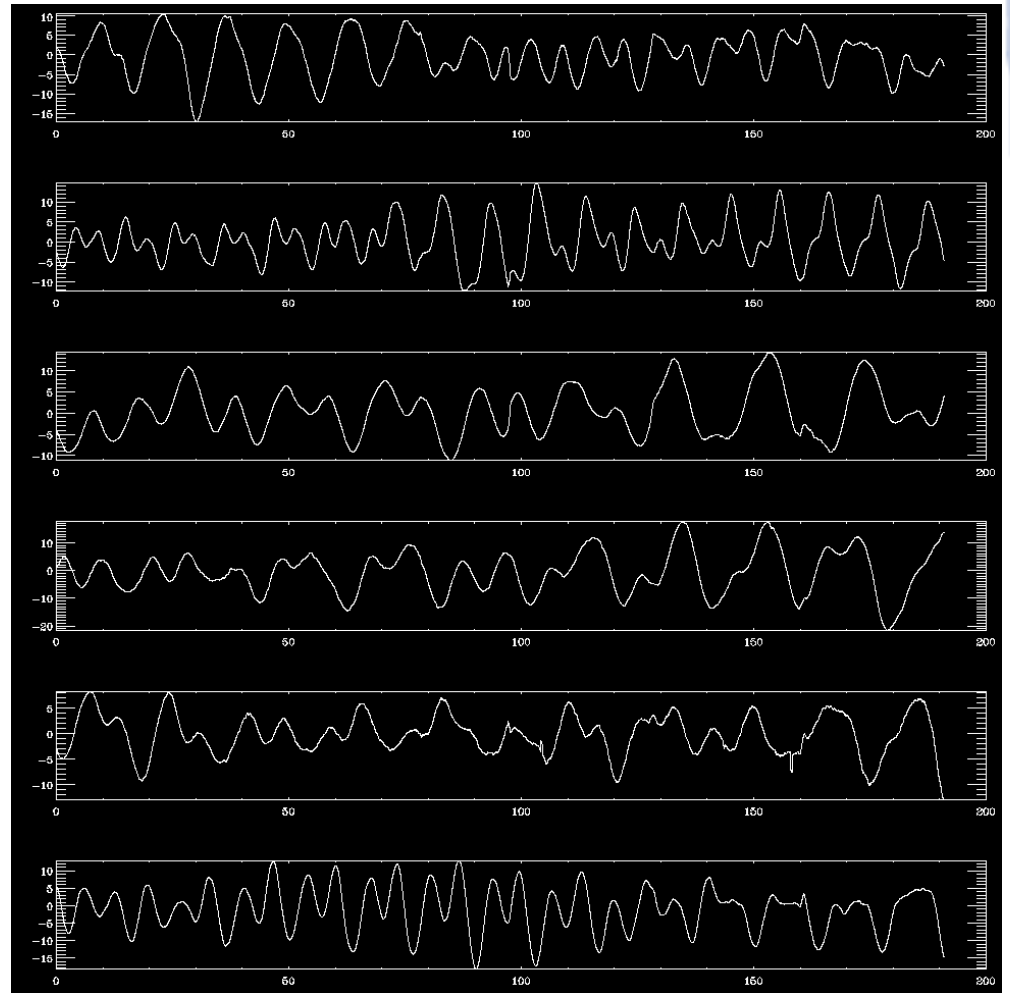
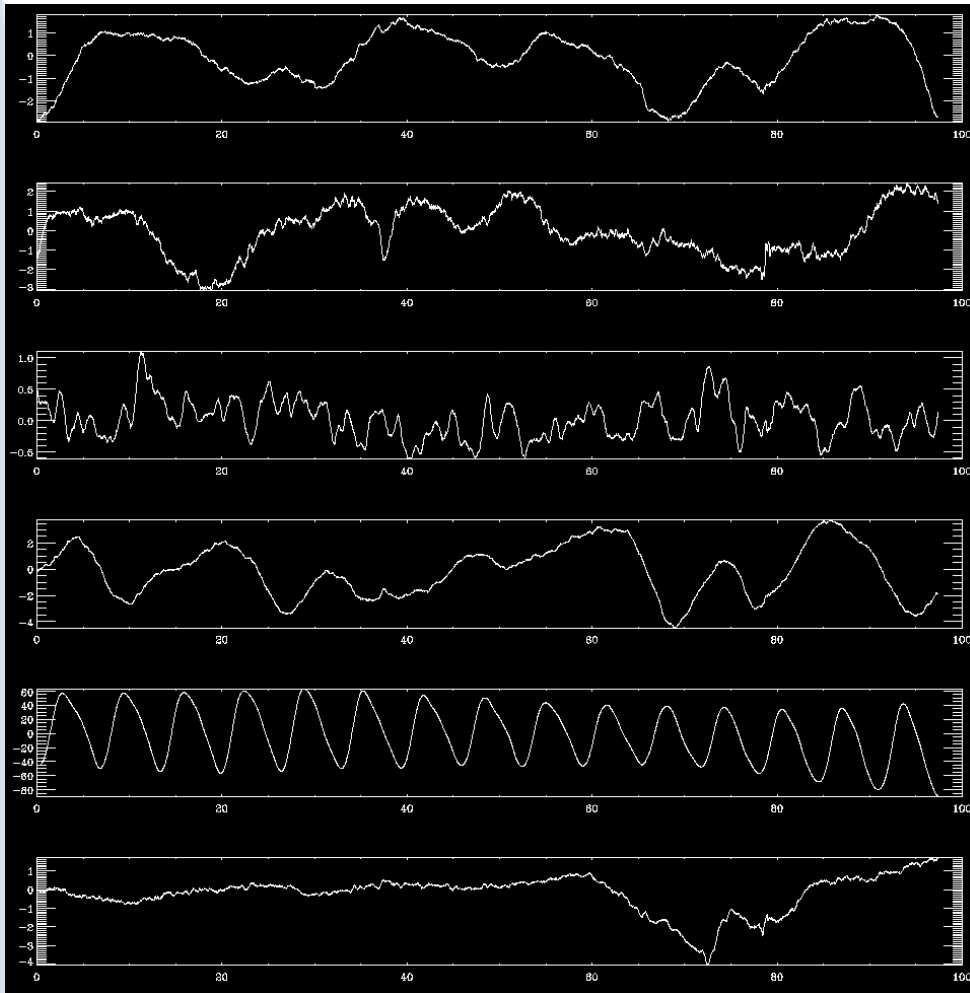
# Finding Rotation Periods

I use the period to find an ideal smoothing width. The ratios of the first few auto-correlation peaks identify the real period. I can then identify peaks and troughs.



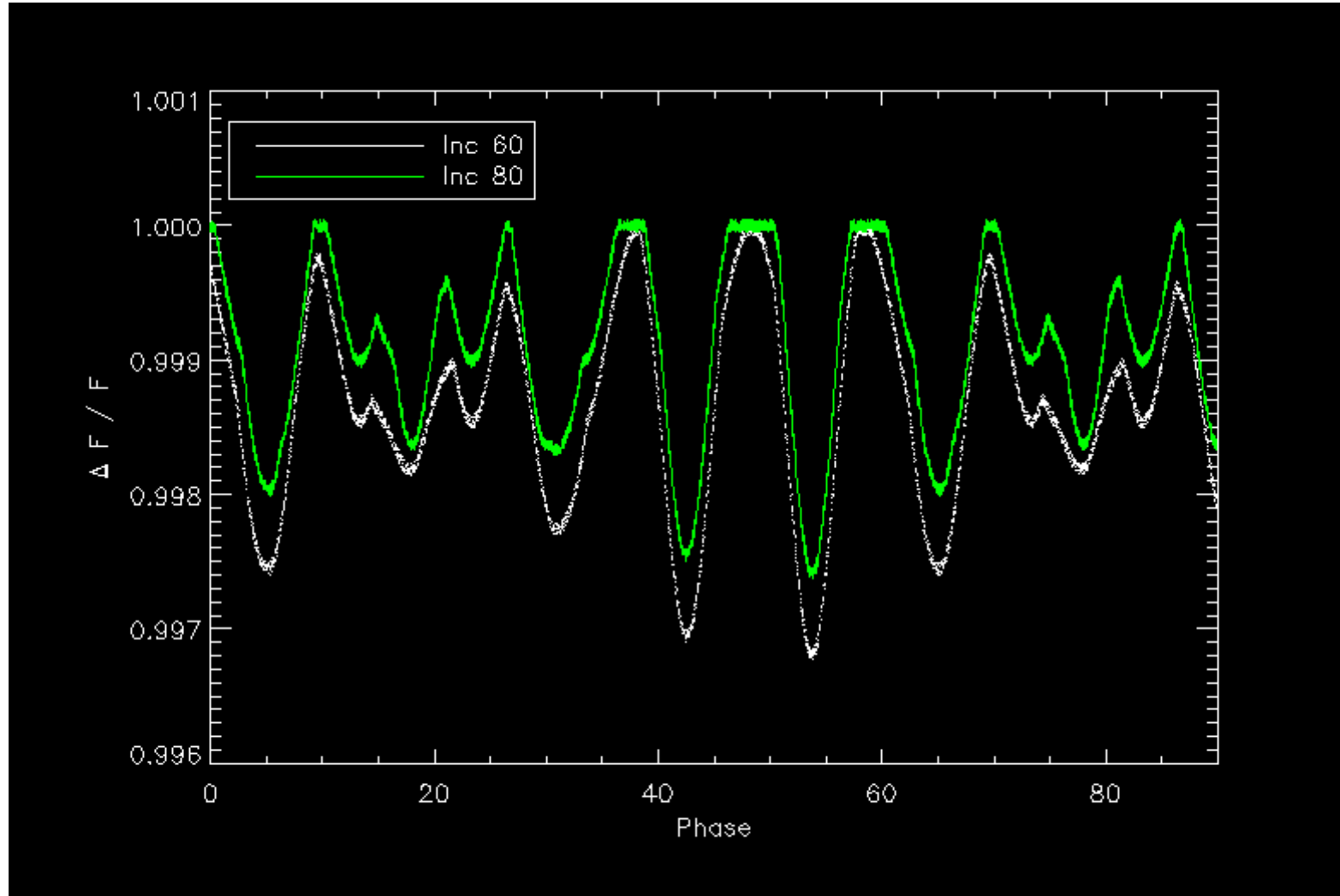


# Locating Differential Rotators



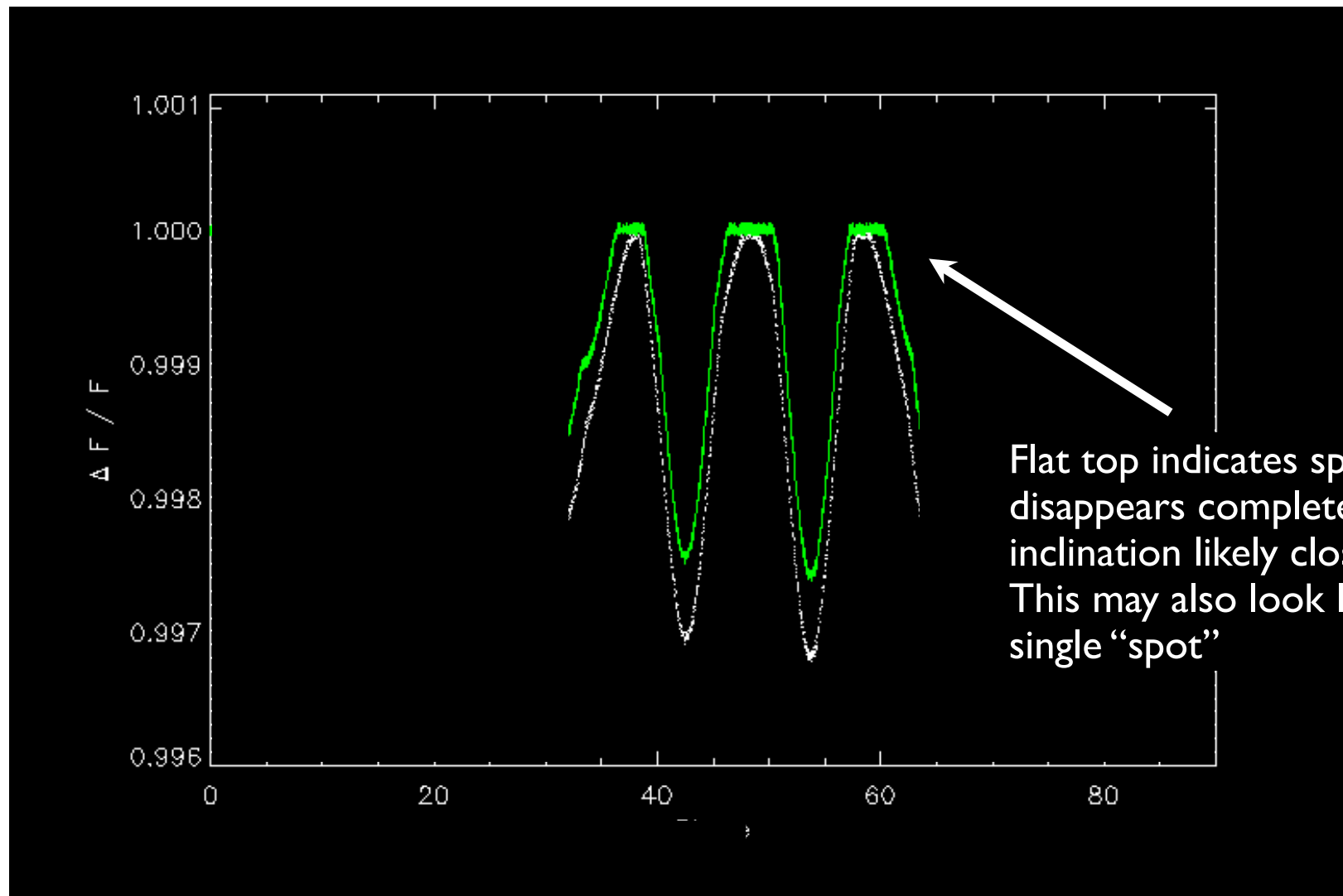
The right panel are a few random light curves, while the panel on the left uses metrics about the peak/dip amplitude variations and half/full period spacing to pull out likely differential rotators. This is still in early stages of development.

# Differential Rotation easily leads to complexity

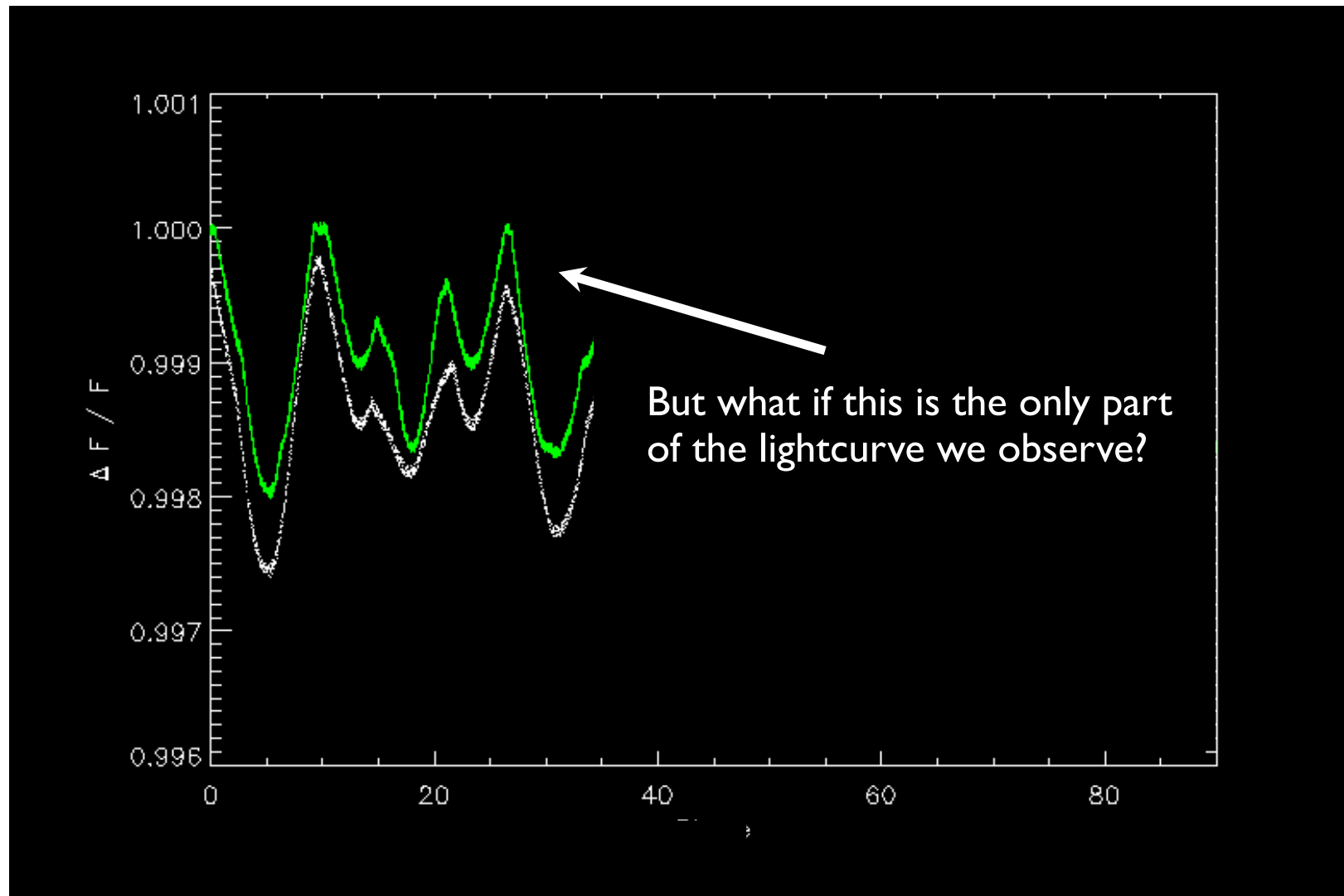


*Walkowicz, Basri & Valenti, 2013*

# Signature of high inclination (rarely seen)



# It May Depend a lot on When You are Looking...

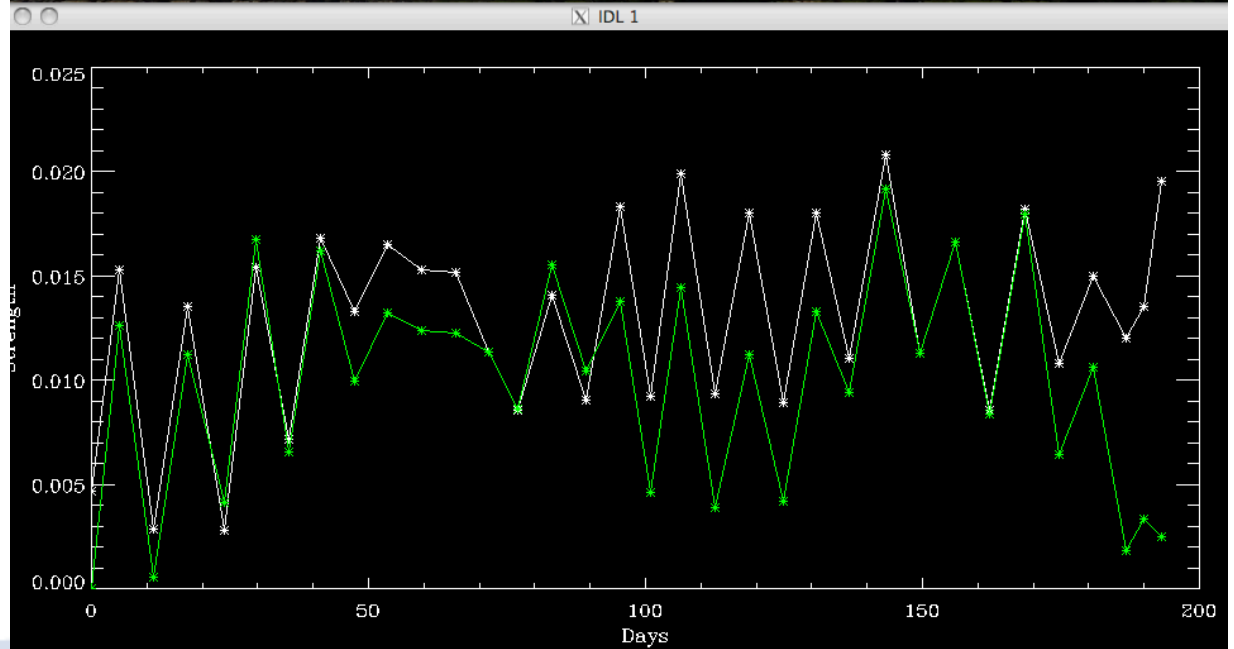
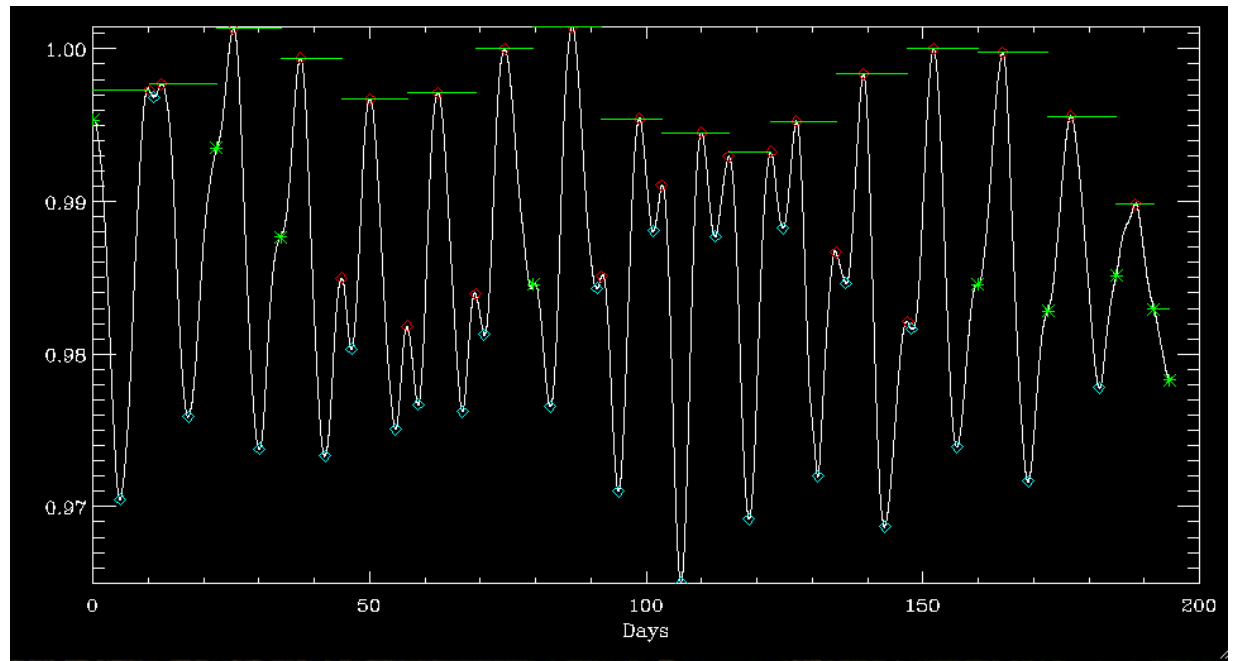


# Determining Spot Coverage

Because Kepler does not do absolute photometry, and even if it did we could not be sure what the “pristine” continuum level would be, it is not clear what the absolute covering fraction of spots is. Furthermore, we cannot trust that the continuum level is the same over a light curve (we know there are secular changes in the photometry), so it is unclear how from what level to measure each spot.

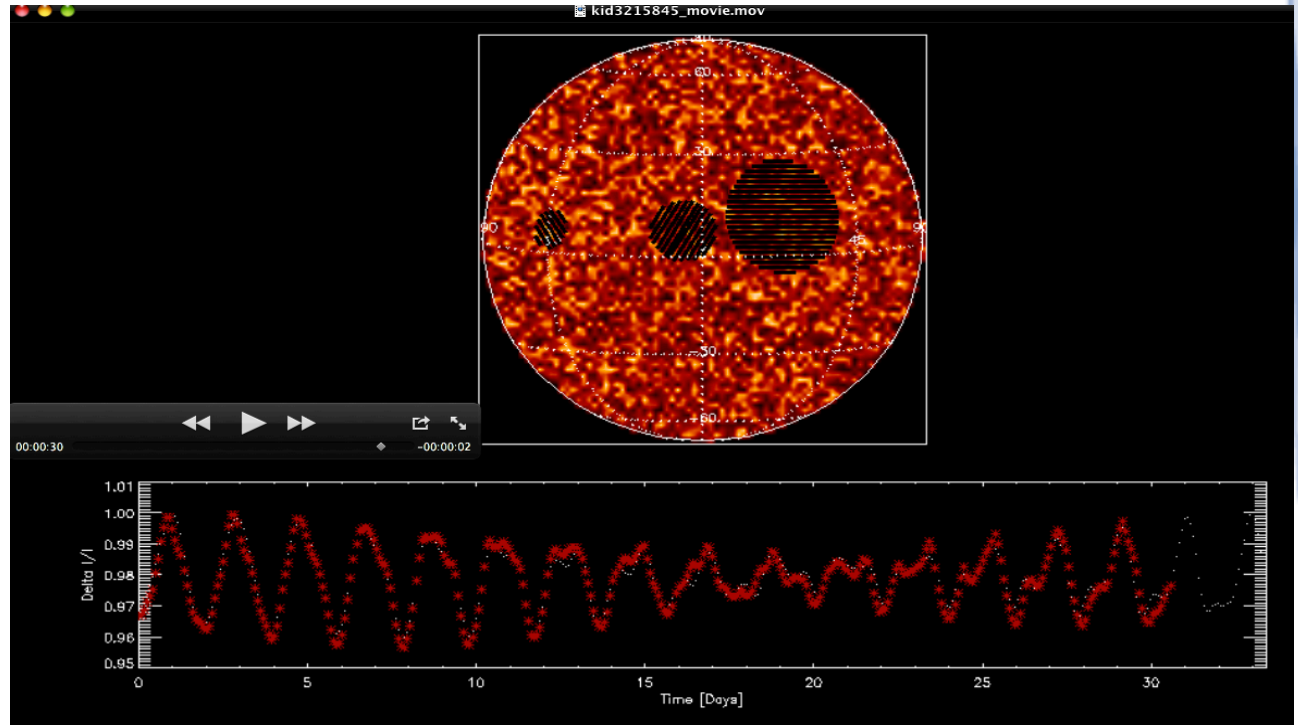
I take limiting cases: using the local peak heights to determine the “continuum” for each spot, and setting a flat continuum level at the highest level (or maybe a little less to account for noise and possible facular contributions).

A signature of differential rotation is adjacent alternating “spot strengths”, which change or disappear and reappear over time. Of particular note is a switch in the symmetry of the big and small dips. It is worth emphasizing that we are really just measuring hemispheric coverage with this type of analysis.





To actually understand why a lightcurve looks as it does, one needs to know where spots are on the visible surface. This depends on how the star is oriented, the number, size, and location of spots in stellar coordinates, the inclination, rotation period, and differential rotation law, and the time evolution of the spots. In principle, all that could be learned from an inverse solution. In practice it is hard (especially in an automated way for thousands of stars).



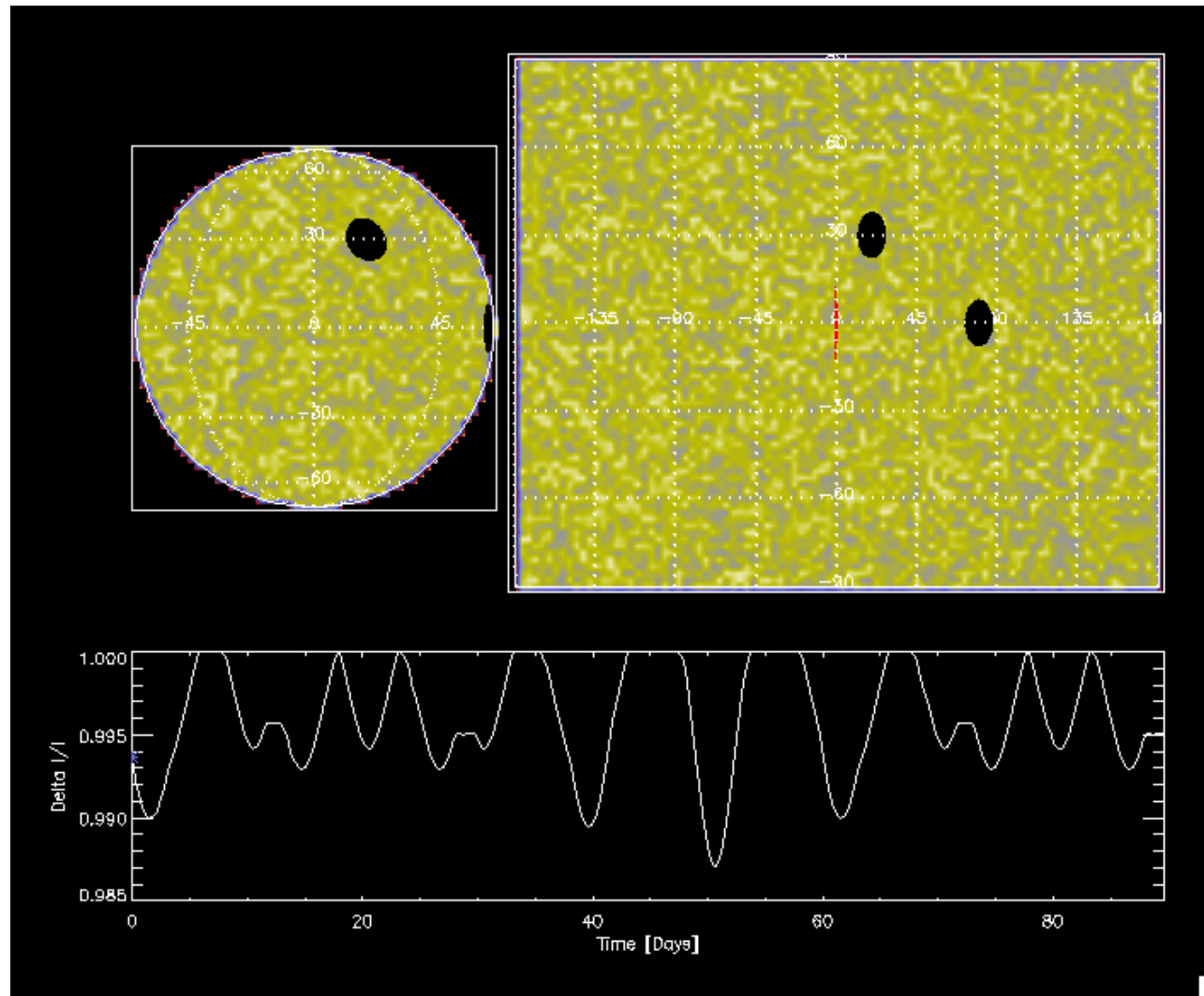
Simple, adaptable lightcurve model Uses Marquardt least squares to simultaneously fit parameters:

- » Inclination
- » longitude of each spot (assumes circular spots)
- » Spot size and number of spots
- » Spot-to-photosphere contrast ratio
- » Linear and quadratic limb darkening coefficient

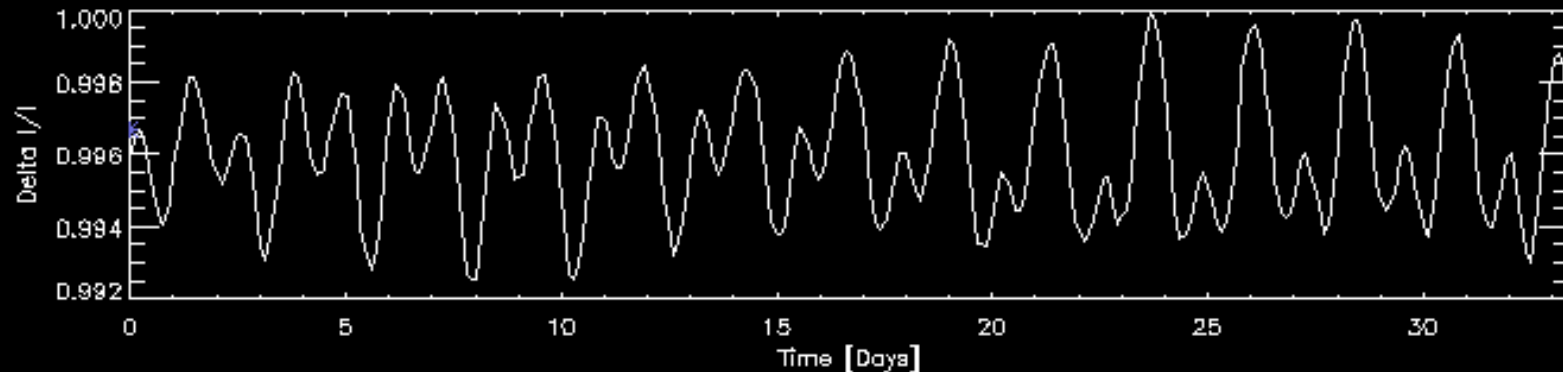
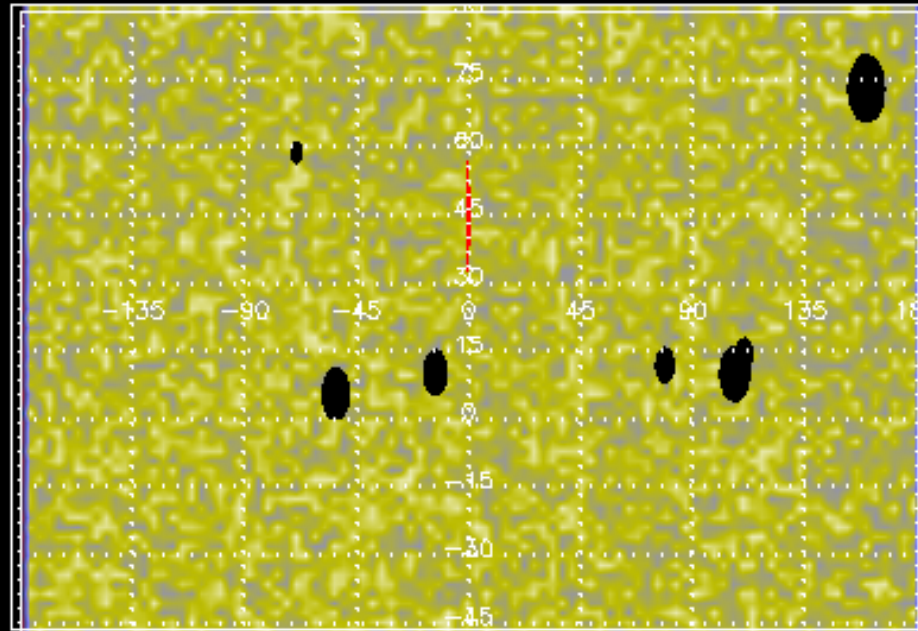
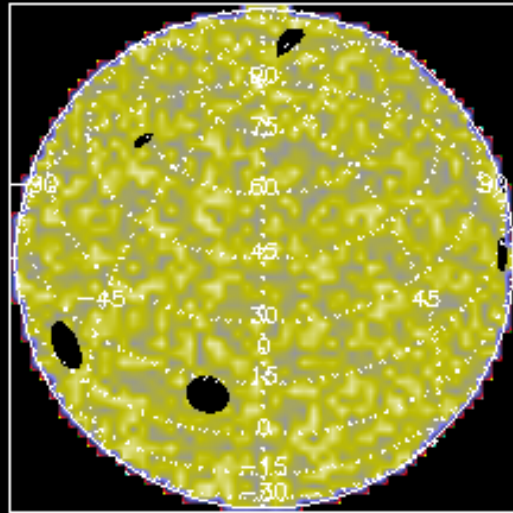


# Light Curves as Diagnostics of Differential Rotation - Model

Differential rotation means that spots can deepen dips when both apparent, or clear empty swaths leading to a brighter star. The amount and frequency with which this occurs depends on the number and location of spots, and their relative angular velocities.



# Light Curves as Diagnostics of Differential Rotation - Data



# Improvements Needed in Automated Spot Modeling

There are a number of fundamental improvements needed before we can consider publishing believable differential rotation results:

- › The spot code has to treat period aliasing more effectively
- › The code has to be clever about removing unneeded small spots
- › The code needs to reconsider its solutions as it learns more info
- › We need to understand real spot contrasts better
- › Differential rotation has to follow some sensible latitude law
- › Spot evolution has to be accounted for (this is hard)
- › We must use longer strings of data in which period, inclination, and differential rotation are consistently maintained

There are some real degeneracies between inclination and latitude, spot contrast and size, differential rotation and time evolution, and symmetry around the sub-observer band which will have to be dealt with. In principle there is information about all these, but it is a poorly posed inverse problem (Walkowicz et al. 2013).

# Initial Indications on Differential Rotation from Kepler

- There are a large number of stars that will yield information on differential rotation in the Kepler dataset
- More than half of the total sample will provide a rotation period (this will be spectral type dependent)
- Of the stars that have significant range and periodogram power, at least 20-30% will produce information on differential rotation (tens of thousands)
- Many of the stars with differential rotation show 10-20% differences in rotation periods for different spots
- We have a lot of work to do to distinguish between true differential rotation and spot evolution, but the rapidly rotating stars seem to preserve active longitudes over many rotations
- It will be difficult, however, to deduce differential rotation laws, since both the stellar inclination and the spot latitudes won't be easy to get



# Conclusions

The Kepler mission is an amazing addition to stellar science, with unprecedented precision, along with complete and lengthy coverage

Almost all stars are variables as seen by Kepler

Stellar activity is seen on a huge number of stars

We can learn much more about spot evolution, surface differential rotation, and maybe stellar cycles

The data will require more work to fully recover the astrophysical information

