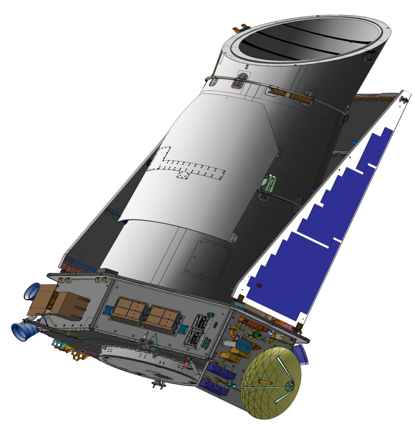
Measuring Stellar Oscillations

Capturing the Sound of Stars

Stellar oscillations, like those observed in the Sun, manifest themselves by periodic variations in the surface temperature, radius and overall brightness of the star.

In a star like the Sun, the amplitude of these variations is very small. In temperature, the variations are a tiny fraction of a degree and for light intensity (brightness), the variations are a few parts per million. Such tiny changes are exceedingly difficult to measure from the Earth, mainly because of disturbances from the Earth's atmosphere.

You can read and see more about the disturbances from the Earth's atmosphere here.



However, when observing with a satellite such as Kepler, we are no longer observing through the atmosphere, which makes extremely precise measurements possible. Measurements that are precise enough to observe solar-like oscillations in stars other than the Sun.

For other types of pulsating stars, such as those described in the previous chapter, the amplitudes are generally higher and can be measured from Earth. However, many of these stars oscillate with a few dominant frequencies (earlier referred to as "tones") with high oscillation amplitudes, and then in a much larger number of frequencies having lower amplitude. The nature of the mathematical technique used to analyse pulsating stars (this technique will be described below) is that the more data that are available, the smaller amplitudes can be detected.

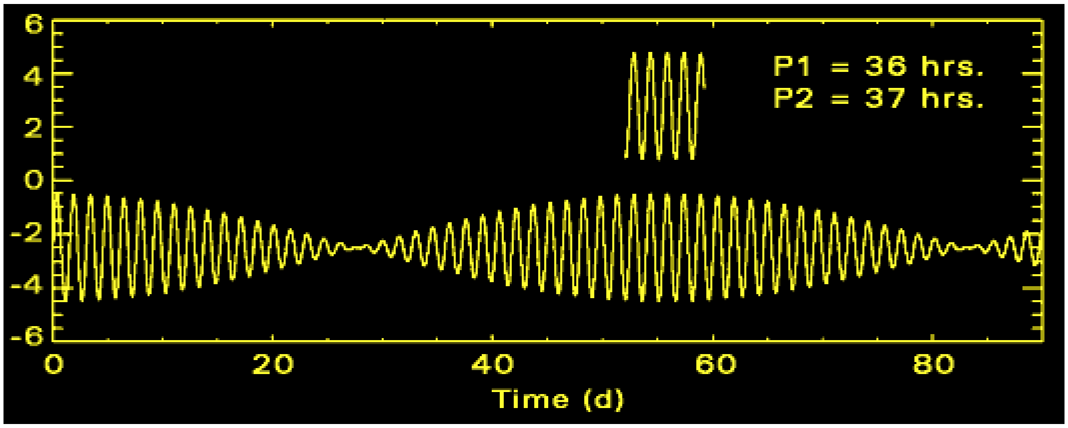
Since performing long-duration, continuous observations from the Earth is very demanding, extensive datasets only exist for a very small number of stars. One of these stars is the Delta Scuti star FG Vir, where astronomers have collected almost 2000 hours of time-series data so far. This huge effort has involved many astronomers using dozens of telescopes all across the globe, over a time span of more than a decade. The more data that is collected on this star, the more low-amplitude oscillation frequencies are being detected.

This means, that even for the "classical" variables (such as Delta Scuti, Beta Cep, SPB stars etc.), which can be observed from ground, Kepler will provide fantastic datasets, simply because of the high-precision space measurements, and because of the continuity of observations over several years. The Kepler observations will allow detection of many more oscillation frequencies compared to what can be obtained from ground. And, with more frequencies, stricter bonds on the theoretical stellar models are obtained.

Analysis of Time-Series Data

Kepler collects time-series data, which simply means that the brightness of the individual stars is measured every minute for several years (there are some modifications to this - follow the link to the Kepler homepage at the end of these pages for more details). This long duration of the observations is the first of the major strengths of Kepler, as is illustrated by the two next examples.

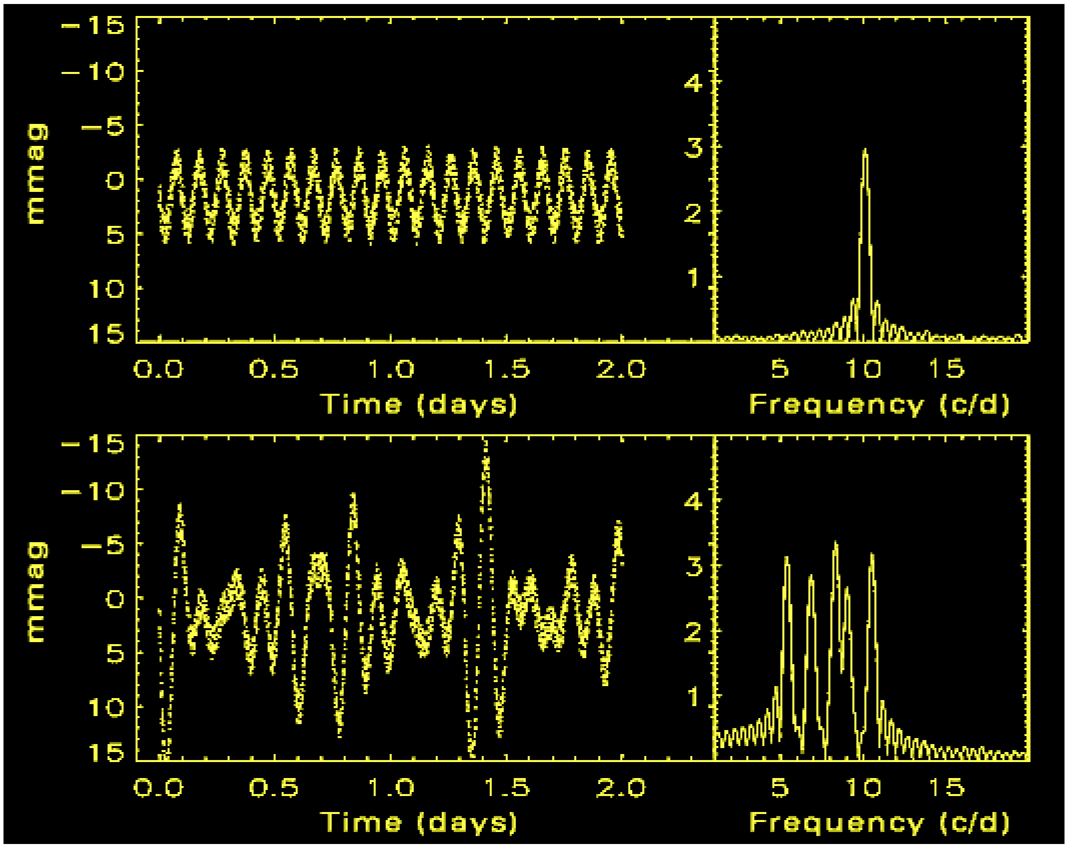
The figure below shows the light curve of a star with two oscillation frequencies (of periods 36 and 37 hours, respectively) with high amplitudes. The combined effect of the two frequencies is to cause the brightness of the star to vary sometimes with high amplitudes, sometimes with low. This effect of a slow change between constructive and destructive interference is called "beating" between the two frequencies, and is easily seen in the figure.



As the small segment above the light curve shows, we have no chance of determining both oscillation frequencies if we only observe the star for a few days - it will actually look as if the star only has a single oscillation frequency. Only by observing the star for a very long time can we determine the true nature of the star's variability, and detect both frequencies.

To understand the next example, we first need to describe "how" oscillation frequencies are actually measured - this is illustrated in the figure below. Top left is a light curve of a pulsating star with a single period, the period of oscillation is easily found by measuring the times between two wave tops. Top right is a corresponding, so-called amplitude spectrum. On the x-axis is frequency (here in cycles per day; a frequency of 24 cycles per day is the same as a period of 1 hour - the oscillation have time to go through 24 cycles in one day), on the y-axis is amplitude.

Such a figure is also referred to as a Fourier spectrum, after the mathematician who first developed the technique.



The amplitude spectrum on the top right is obtained by testing how well frequencies in some interval - here from 1 to 19 cycles per day - matches the observed light curve shown on the left. This is done by mathematical fits (using the computer, naturally) of sine-waves to the light curve, starting with a sine of, for instance, 1.00 c/d, then 1.01 and so on, up to 19 c/d.

For frequencies far from the oscillation frequency (10 c/d), this fit will be poor, resulting in low amplitude in the amplitude spectrum. But at the frequency actually present in the light curve, the fit will be very good - a sine wave with a frequency of 10 c/d matches the light curve well - resulting in a peak at that frequency in the amplitude spectrum.

This technique becomes very powerful if more than one oscillation frequency is present in the light curve, as shown in the bottom plots of the figure. Now we have a star oscillating in five frequencies, resulting in a very complicated light curve. But, using the amplitude spectrum we can tell that the 5 frequencies are 5, 7, 8.5, 9 and 11 c/d, something we would never have been able to do from the light curve alone. This is also the technique used for extracting the millions of oscillation frequencies in the Sun, mentioned in the previous chapter.

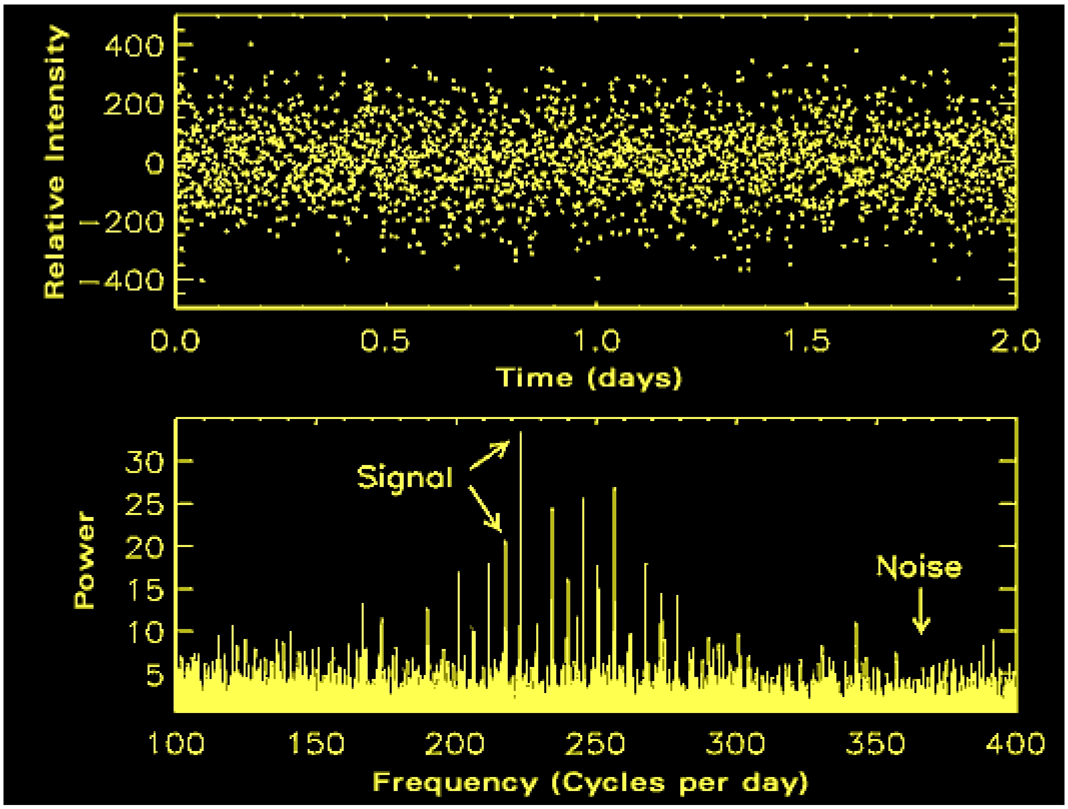
Noise and Disturbances

So, the amplitude spectrum allows us actually to find the oscillation frequencies, even in very complicated-looking light curves. But it has another interesting feature too. Measurements of starlight, even from space, are subjected to noise: there is an unavoidable, natural and fundamental noise called photon-noise, or counting statistics - a true measure of some object of nature such as a star will always have some degree of uncertainty to it.

Then there is instrument noise, noise from scattered Sun/Earth/moon-light into the telescope, noise from the data reduction procedures, and so on. In short, even the best observations will have some noise. And if this noise is too high, much higher than the amplitudes of oscillation for some star, then these oscillations cannot be measured.

Or, at least, they cannot be "seen" in the light curve. This is shown in the figure below. The upper panel shows how observations of a distant, solar-like star will look. This plot just shows two days worth of data, out of a much longer time series. It looks just like noise. But the amplitude spectrum in the lower panel (30 days of data were used in the calculation and the result is shown as power, which is just the amplitude squared), clearly reveals the presence of oscillation frequencies. These were hidden in the noise in the time series but can be extracted using the Fourier spectrum, because here the noise level drops as more data are becoming available (there is simply more data to fit to).

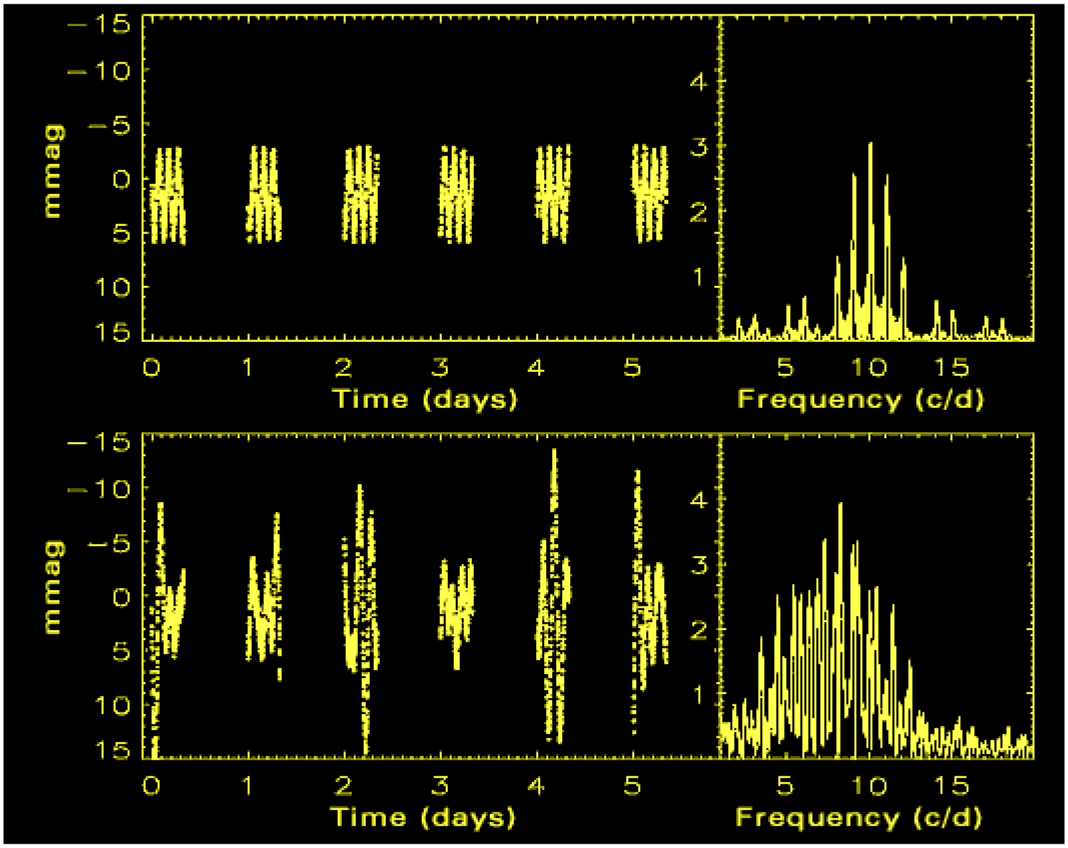
So, even low-amplitude frequencies embedded in noise in the time series can be detected using the Fourier technique. The long duration of the Kepler observations is very important indeed.



The need for continuous observations

There is another important aspect of Kepler that makes it superior to observations from ground: the observations are continuous, not affected by the day/night rhythm or bad weather.

Imagine we are using a telescope here on Earth to observe the star from above, oscillating with just a single period. During daytime we can of course not observe. This introduces gaps in the time series as is illustrated in this figure:



Here, the Fourier technique runs into trouble.

We don't know the light curve of the star in the daytime (because we don't measure it) and this lack of data introduces false peaks in the amplitude spectrum - these are called aliases and occur simply due to the absence of information in the daytime, as is described here.

They make it very difficult to determine which peaks are due to true oscillation frequencies in the star, and which are caused by the gaps.

The SONG Project

So the continuous observations of Kepler is a very strong advantage compared to ground-based observations.
This is in fact also the main argument for building **SONG**, a network of ground-based, automatic telescopes, which will do time series observations of stars much brighter than the ones which will be observed with Kepler.
SONG will use the technique of spectroscopy, which is less disturbed by the atmosphere, but which is limited to bright stars.

Although the science goals of Kepler and SONG are similar, the two projects are not in competition, but are complementing each other.
We also note that although planets will be detected with SONG, these will only be planets in close orbit around its parent star, an earth-like planet in an earth-like orbit cannot be detected from ground with any present-day technique. It is simply impossible because of the level of precision required to obtain the detection. But such a planet can be detected by intensity measurements from space - it can be detected by Kepler.