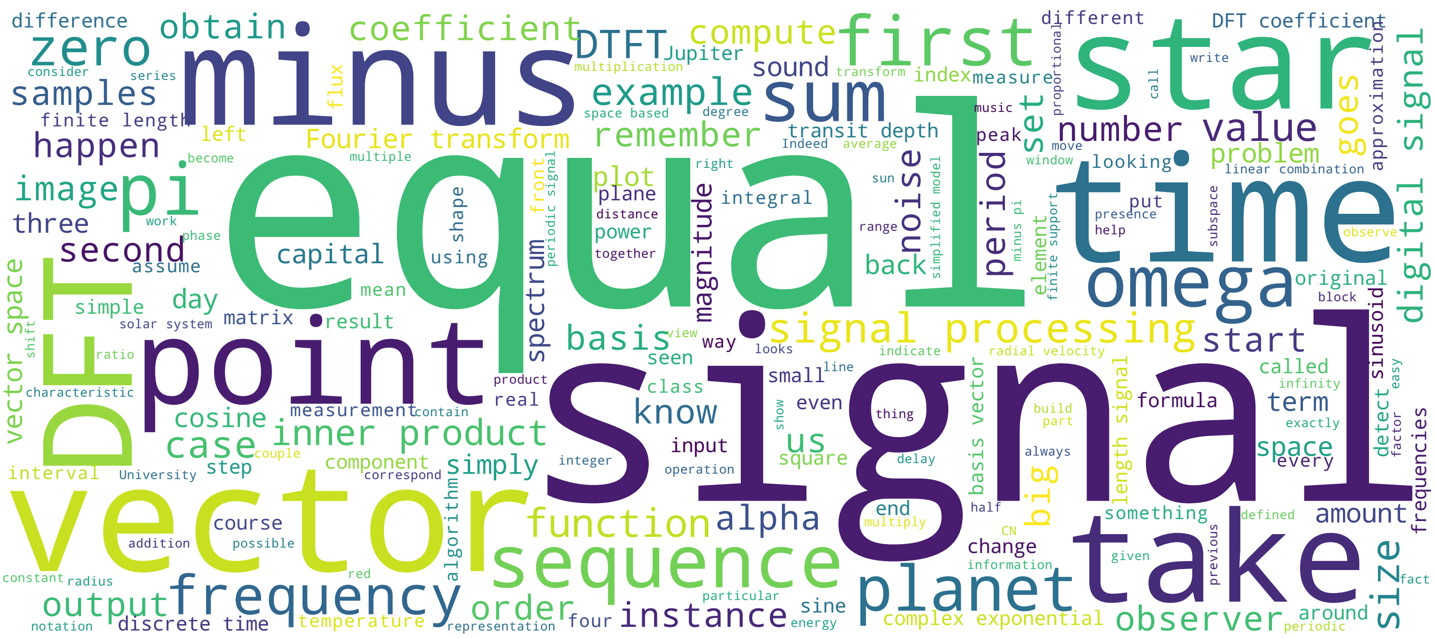
Digital Signal Processing

Signal of the Day: Exoplanet Hunting



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Hello, and welcome to this new installment of the Signal of the Day, where we will be talking about exoplanet hunting. As you will see, this is yet another cool application of digital signal processing. But before we proceed to the actual topic, we would like to acknowledge the help of the CHEOPS team from the University of Bern in Switzerland. In particular, we'd like to thank Andrea Fortier and Attila Simon who provided us with the datasets and helped us prepare this Signal of the Day. Let us start our exploration of the topic with this image of the Milky Way, our galaxy, observed from Earth. It contains between 200 and 400 billion stars, out of which the Sun, our star, is just one.

Notes

Summary

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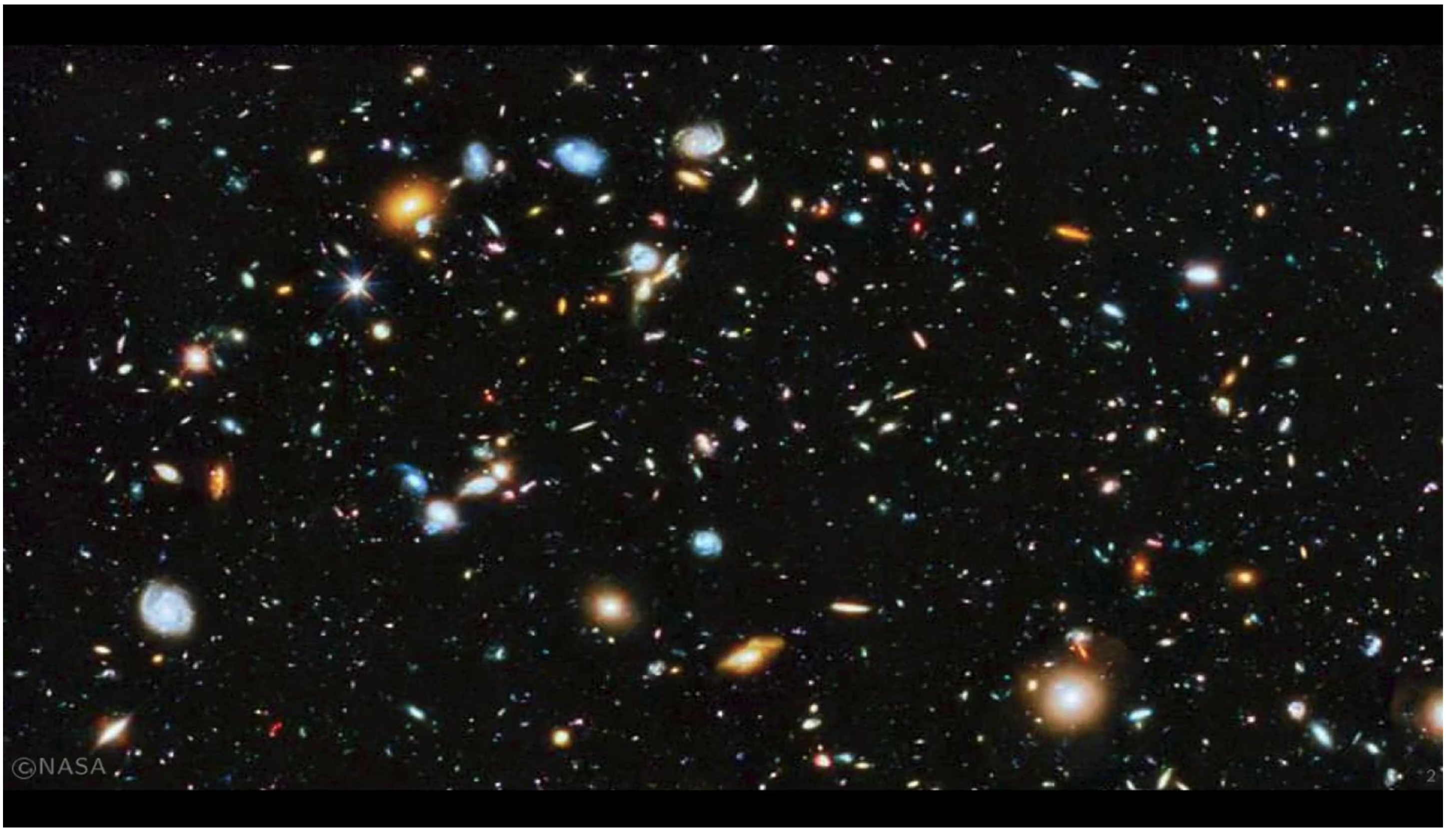

If we zoom out and look now at an image of the universe taken by the Space Telescope Hubble, the universe contains an estimated number of 100 billion galaxies, each containing hundreds of billions of stars. Hence, the likelihood is very high that another star planet system comparable to our solar system exists. But how do we look for these so-called exoplanets? Given the immensity of the universe and the number of stars, it sounds like it's worse than actually looking for a needle in a haystack. In comparison, the presence of a star is much easier to detect as a star emits its own light. Also, the characteristics of this light allow estimating characteristics about the star, like its radius, distance, or temperature at its surface. For exoplanets, we have to go one step further and use digital signal processing.

Notes

Summary

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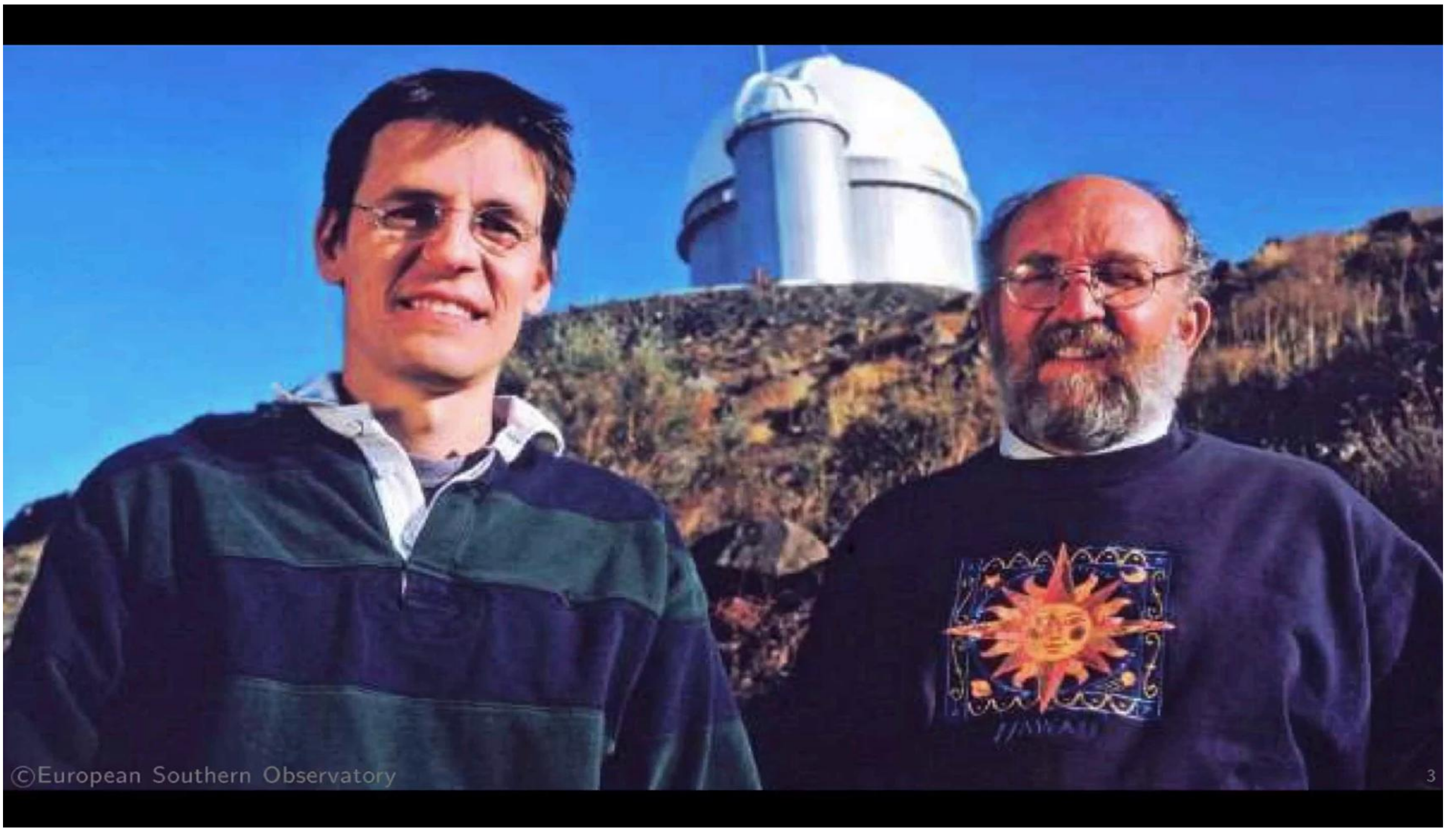

In a minute, we are going to study one method to find exoplanets, but let us first make a short historical digression. Twenty years ago, Michel Mayor and Didier Queloz from the University of Geneva discovered the first exoplanet. Didier Queloz, pictured here on the left, was then a PhD student and his aim was not to hunt for exoplanets, but to measure very precisely the radial velocity of stars. Collecting measurements and processing them using a special algorithm, he noticed that one of the stars he was observing behaved in a rather unusual way. Unlike other stars, the radial velocity of this star was varying strongly. He thought, originally, this was created by a bug in his software. But after a couple of months of further measurements and double checking, he came up to the conclusion that this variation in velocity was caused by the presence of a planet. This first discovered exoplanet, named Pegasi 51, has a radius of Jupiter, but a revolution period of only 4.2 days, that is 1,000 times smaller in comparison with Jupiter. This went against existing beliefs about planets. However, a couple of months later, this discovery was confirmed by measurements from another team and since then, hundreds of other exoplanets have been discovered.

Notes

Summary

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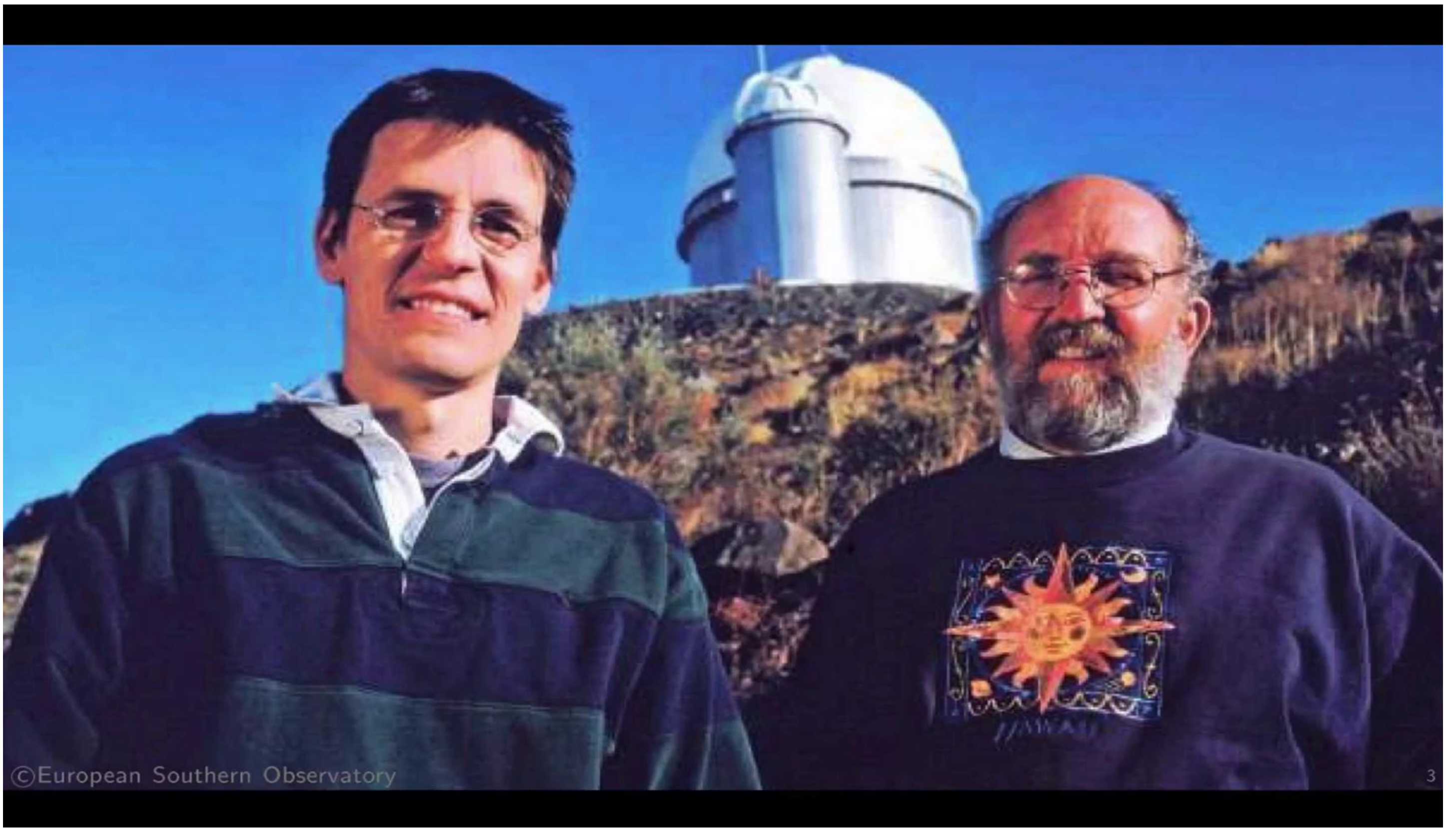


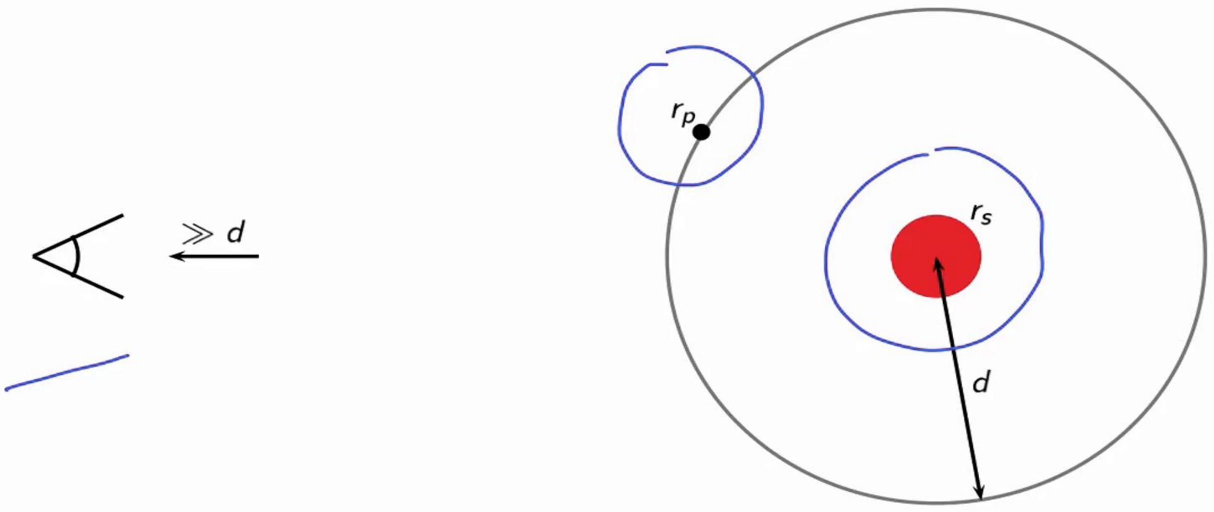
The original radial velocity method is quite involved and certainly beyond the scope of the Signal of the Day. We'll instead explain another method called the transit method.

Notes

Summary

3m 29s

Schematic Diagram



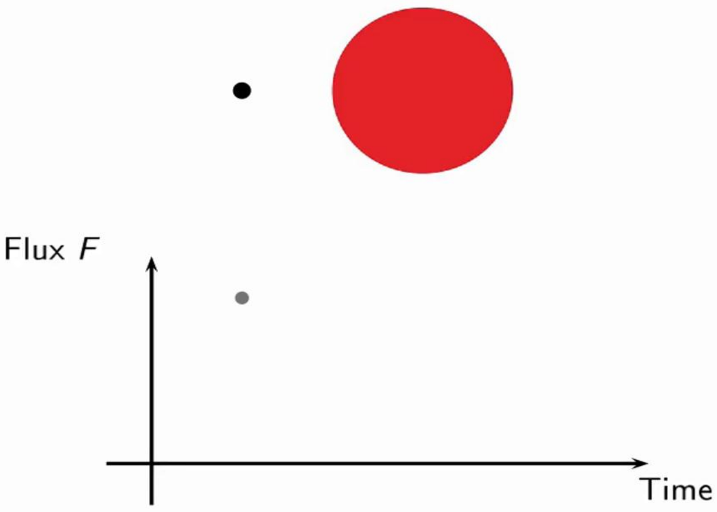
Consider the following simplified model, where a planet of radius rp revolves around a star of radius rs here in red. We also call d the distance between the planet and its star. An observer here on the left is located far away and observes the system. For the sake of simplicity, we'll also assume the observer is located in the same plane as the revolution plane of the planet around its star. This diagram is just a top view as this simplified model.

Notes

Summary

3m 42s

From the Observer



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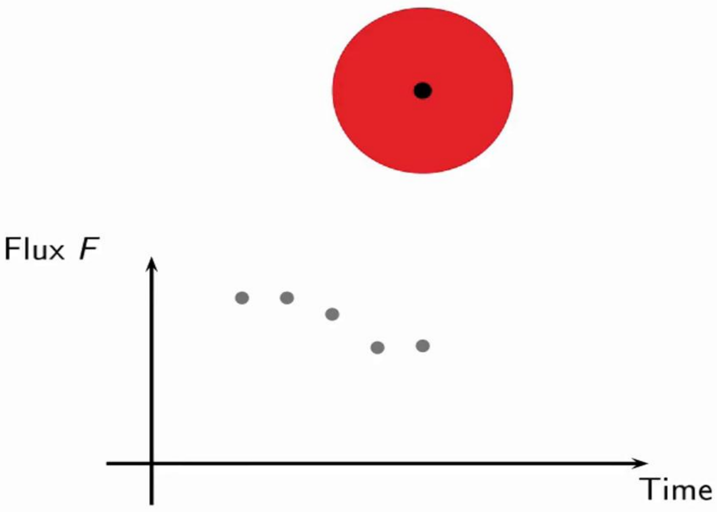
Let us now illustrate what happens when the planet passes in front of the star as seen from the observer. The top figure represents our simplified model from the point of view of the observer, with the star in red and a planet in black again. Below, we are going to plot the evolution over time of the flux of light measured by the observer, that is the amount of light emitted by the star reaching this observer.

Notes

Summary

4m 24s

From the Observer



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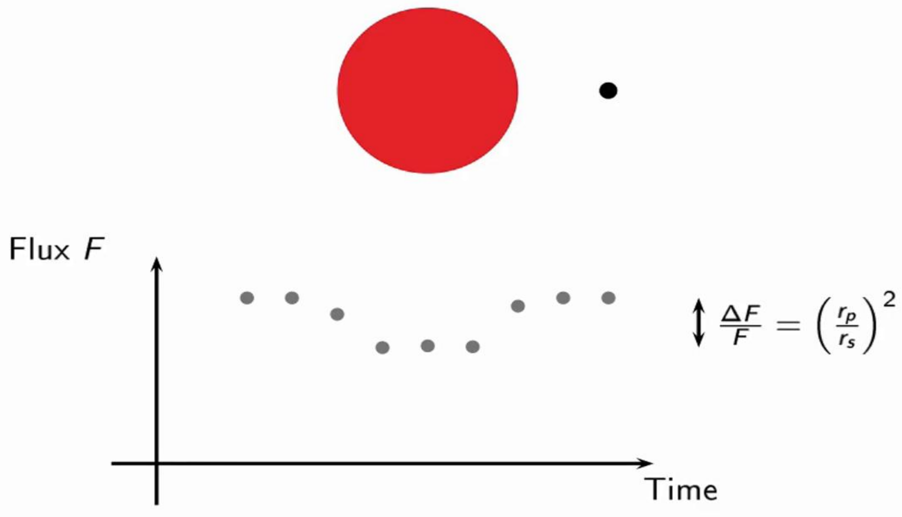
As the planet transits in front of its star, that is, it passes in front of it, the observer measures a reduction of the flux of light.

Notes

Summary

4m 54s

From the Observer



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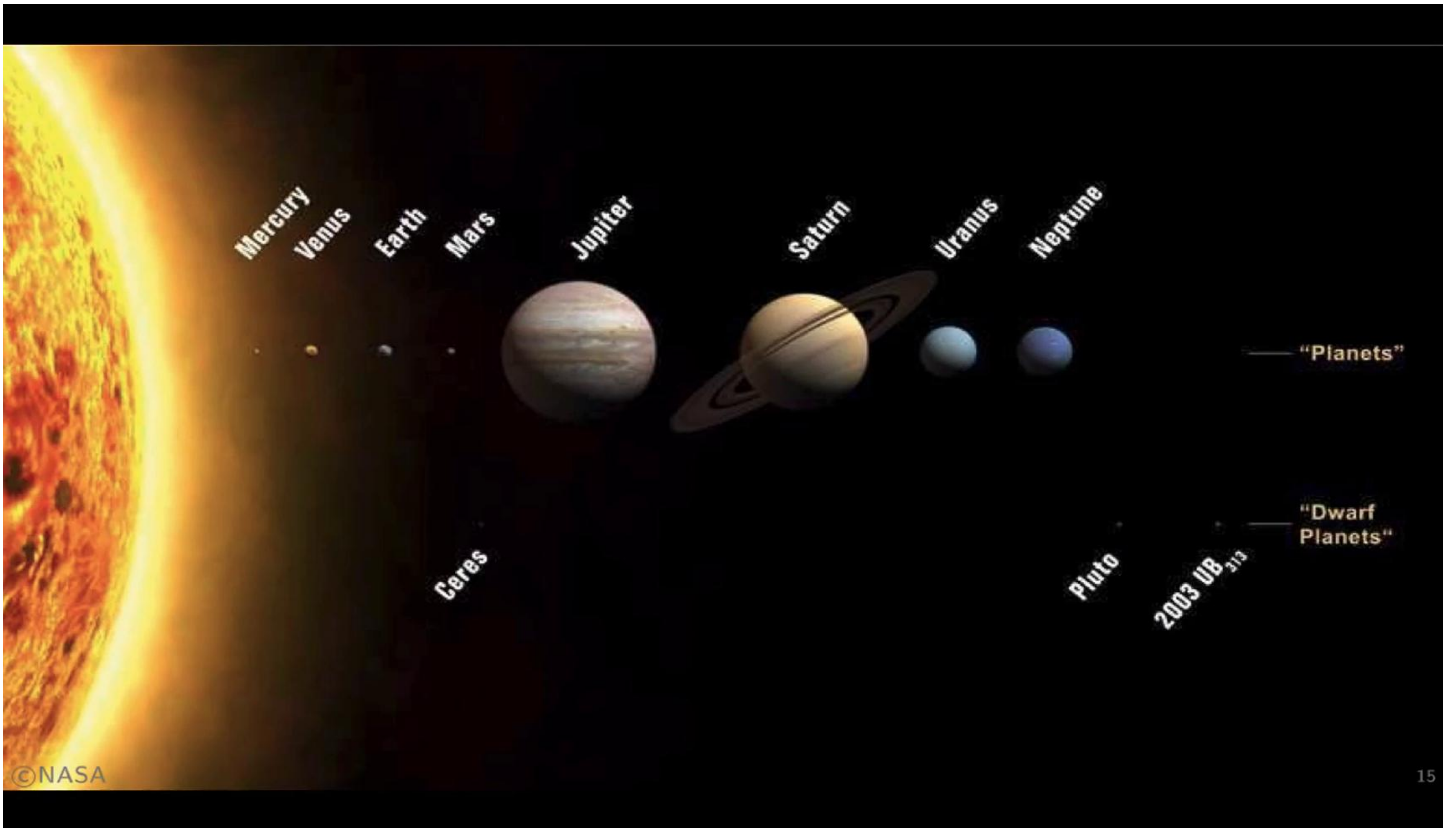
Indeed, the planet is partially masking the surface of the star, an effect similar to what happens during an eclipse. It can be shown that the relative change in the flux is equal to the ratio between the radius of the planet and the radius of the star to the square. Indeed, the masking effect of the planet is proportional to its surface, pi rp square, and the amount of light emitted by a star is also proportional to its surface, pi rs square. This relative change of flux is called transit depth.

Notes

Summary

5m 06s



What happens now if we adopt the point of view of an alien that tries to detect the presence of planets in our solar system? In this image from the NASA, we perceive the relative size of the planets in our solar system compared with the size of the sun on the left.

Notes

Summary

5m 47s

An Alien Observing the Solar System

- Earth $\frac{\Delta F}{F} = \left(\frac{r_p}{r_s}\right)^2 = \left(\frac{6{,}371}{696{,}000}\right)^2 \approx 0.01\%$
- Jupiter $\frac{\Delta F}{F} = \left(\frac{69{,}911}{696{,}000}\right)^2 \approx 1\%$
- Best telescope today can detect a transit depth of 0.1%

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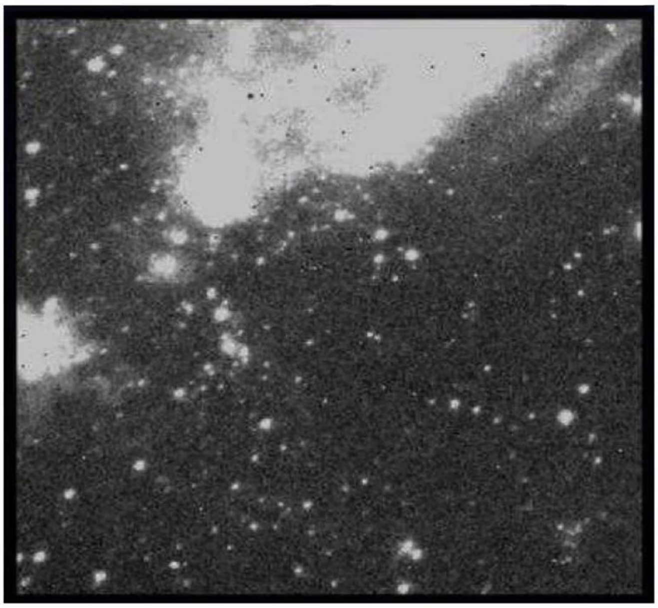
In the case of ours, applying the formula for the transit depth given before, we obtain a reduction of 0.01%. In the case of Jupiter, which is roughly 10 times bigger than us, the flux reduction is of the order of 1%. The best available telescope today has the capacity to detect transit depth of the order of 0.1%, so it has more chances to detect a planet the size of Jupiter, but virtually known to detect a planet the size of ours.

Notes

Summary

6m 07s

Original vs Denoised Images



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Let us now look at an example of an actual transit data. Scientists use either a space-based or Earth-based telescope to observe a distant star and use a CCD camera to measure the amount of light, technically, the amount of photons, from the star that reaches the observer. With a space-based or Earth-based observations, scientists need to constantly realign the telescope to track the movement of the star. This is a complex procedure, but let's assume this is properly taken care of. What we obtain is a set of images over a period of observations, like the one on the left here. The measurement process is obviously not perfect, and there are many sources of noise that corrupt this image. For example, the CCD sensor introduce various sorts of noise, but knowing the characteristic of the sensor, it is possible to remove these effects. This is where digital signal processing comes into play. The actual procedure is statistical, so it's not covered by the material you studied in class. You will need to follow another course on statistical signal processing to fully comprehend these methods. But the main lesson here is that in this seemingly unrelated field, digital signal processing plays a central role. After signal processing methods have been applied, we obtain a denoised image, like the one represented on the right here.

Notes

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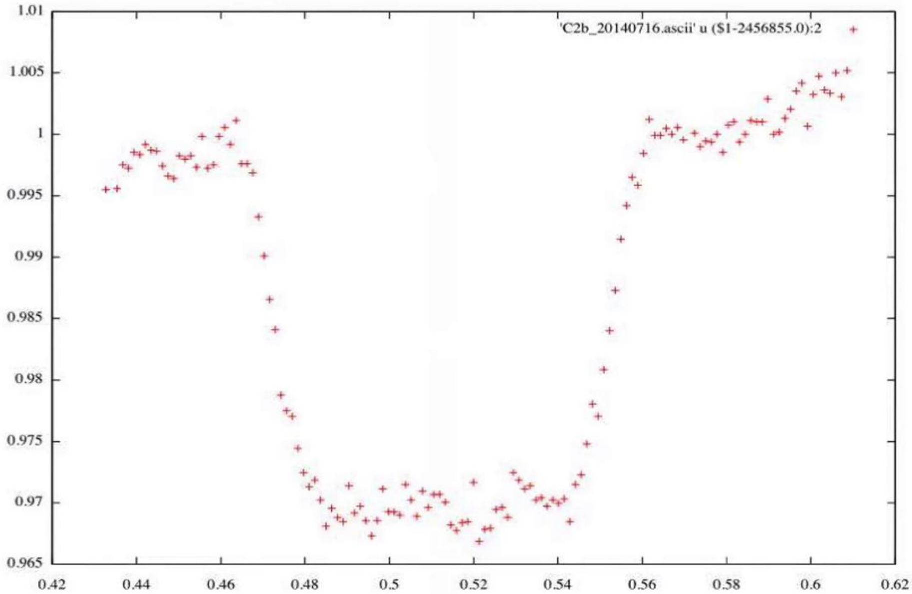
6m 46s

Example of Transit Light Curve - CoRoT 2-b



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From this series of images, we can extract the light curve, such as this example measured by the CoRoT mission. Notice that, in this case, the transit depth is approximately equal to 3%.

Notes

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8m 23s

Looking now into the near future, CHEOPS is a European mission managed by the University of Bern to build a space-based telescope. It'd be launched in 2017 and will be able to detect exoplanet with a transit depth of 0.1%. Who knows, one day, following this class, you will be able to join the CHEOPS team as a digital signal processing expert and help them detecting a new exoplanet.

Notes

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8m 39s