# Astrophysical Noise in Astrometric and RV Search for Exo-Earths

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## Abstract

As instruments get better, astrophysical noise will become the limiting factor in astrometric and radial velocity (RV) detection of exoplanets. The main source of astrophysical noise for both RV and astrometric measurements is the star itself. Both astrometry and RV deduce the presence of a planet by looking at the wobble of the star, as it orbits the star-planet center of mass. Any non-uniformity of the stellar photosphere will produce biases in both astrometric and RV measurements. Astrometry and RV measurements are affected slightly differently by various astrophysical effects. Radial pulsations, affect RV but not astrometry. One major source of noise, star spots has the same qualitative effect on RV and astrometry measurements. Quantitatively, a spot with an area of 0.1% of the area of the sun will produce a maximum bias that is 0.83 of the astrometric signature of an Earth @1AU and 11 times larger than the RV signature of the same Earth at 1 AU. One aspect of star spot noise that is particularly damaging is that the bias lasts on the order of a week. To reduce the star spot bias by a factor of 10, requies measurements spread over ~100 weeks. To detect a periodic signal with a SNR=6, on stars with 0.1% area spots implies a minimum of ~25 measurements spread over > 0.5years for astrometry and ~4000 measurements spread over 85 years for RV. A survey of nearby stars shows that approximately 85~90% of nearby stars are more active than our Sun.

## Introduction

Many types of stellar activity can bias astrometric and RV measurements. But some, such as the 5 min (P mode) oscillations have been studied (Kjeldsen 2005)and are not major problems even for detection of Earths. But star spots are a major problem. This paper describes a simulation of the astrometric and RV biases caused by star spots. The purpose of the simulation was to provide a quantitative way to relate photometric variability with RV and astrometric variability. Photometric data exists on many stars, while precise RV data at the sub 0.3m/s and astrometric data at the microarcsec (uas) level does not yet exist because the instruments are only just now getting to this precision.

With the simulation in place, we have a quantitative estimate of this component of astrophysical noise for the Sun. The question remains what fraction of nearby stars are as quiet or more quiet as the Sun, and what approximate fraction of stars nearby stars have astrophysical noise that would prevent the detection of Earth-like planets in the habitable zone by RV techniques and by astrometric techniques?

### Star Spot Bias in Astrometry and RV Measurements

It's relatively straightforward to calculate the effect of a Sunspot with 0.1% of the area of the surface of the Sun on RV and astrometric measurements. The projected area as seen by an observer is 0.1%*cos(phi). The astrometric offset is simply

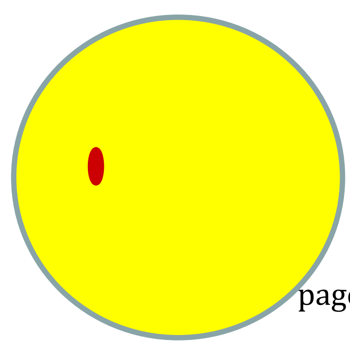
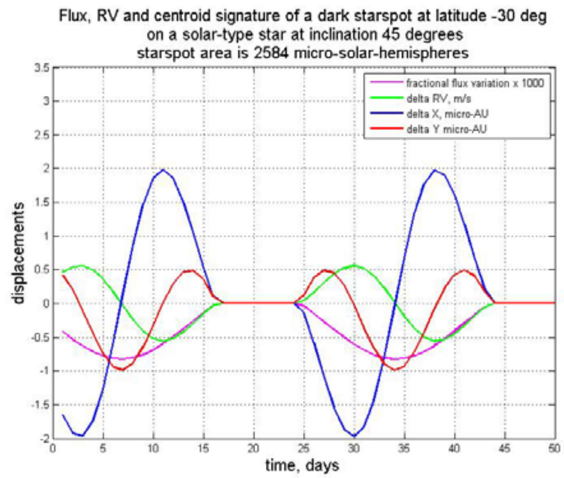


**Figure 1: Sunspot**

r*sin(phi)*projected_area, where r is the radius of the Sun, which is 0.5mas for the Sun at 10pc. The RV bias from the spot is the projected_area*V0*sin(phi) where V0 is 2km/s for the Sun. When the spot in in the middle of the Sun, there is no bias, in RV or astrometry. The maximum bias is at a phase angle of phi=45deg.




For our nominal 0.1% spot, the maximum astrometric bias is 0.25uas and RV bias is 1m/s. The amplitude of an Earth at 1AU orbit the sun by comparison is 0.3uas for astrometry and 0.09m/s in RV. Astrometry and RV have opposite sensitivity to orbit period. RV is more sensitive to short period orbits and astrometry more sensitive to long period orbits.

As a spot rotated the corresponding photometric, astrometric and RV signals are shown in figure 2.

## *Star spot model*

The star spot model generated random star spots with random life times, but with an average life time of ~10 days. The spots were placed on the star which rotated with a 30 day period. The number of spots and the size of the spots are roughly consistent with the historical data on star spot numbers and had a 11 year period. The model had a few free parameters which could be adjusted. The model of course can produce the photometric variation of the star as well as the astrometric and RV variation. The free parameters of the model were adjusted so that the photometric power spectrum matched the observed photometric power spectrum of the Sun, from 30 yrs of space observations, from ACRIM and SOHO/Virgo instruments.

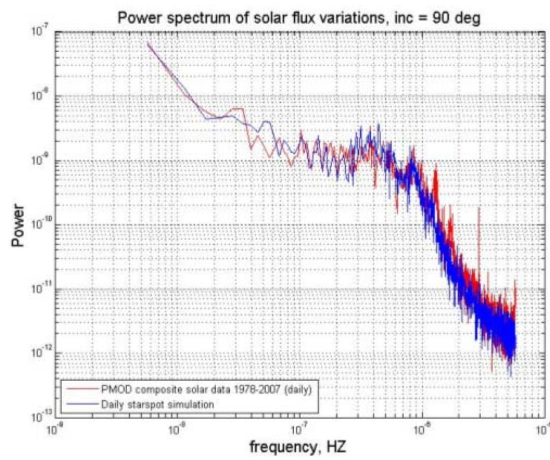



Figure 3 Photometric Power Spectrum of Sun and Model

## *Evaluating RV and Astrometric noise*

With the model, we are now able to evaluate in a quantitative way the RV and astrometric noise caused by star spots, as well as the variation in the spot number and the latitude of the spots throughout the 11 year solar cycle. Averaged over the 11 year sun spot cycle, the rms RV noise is ~ **0.5m/s** and the rms astrometric jitter is ~**0.08 uas**. The rms photometric fluctuation of the Sun over the 11 years is **4e-4**. An important characteristic of star spot noise is that it is not white noise. A quick look at the photometric power spectrum clearly shows that the photometric variation is not white noise. A steep power law in the power spectrum is call “pink” noise or 1/f noise. The implication of 1/f noise is that the accuracy of the measurement doesn’t improve as the sqrt(time). From a physical point of view this is very obvious. A star spot with a 10 day lifetime, will be on the “left” side of the star for a week. Multiple measurements during a week will see roughly the same RV and astrometry bias. Spot noise will not begin to average out until the measurements are separated in time by more than ~1 week.

The ~ 1week time scale is important when looking at the amount of time needed to detect an Earth @ 1AU. If we want a high SNR detection of the planet with say a SNR=10, then we want to have enough astrometric measurements and/or RV measurements so that the amplitude of the signal divided by the single epoch precision/sqrt(N_epochs) is ~10. For RV the signal is 9cm/s and N_epochs ~ 3000. If the 3000 measurements have to be separate by 1 week, such an observation will take ~58 years. For astrometry the signal of an Earth @ 10pc is 0.3uas and N_epochs has to be > 7 weeks.

## *Are most stars as quiet as the Sun?*

While 58 years is a long time to wait, detecting planets more massive than 1 Mearth should take much less time. A 5 Mearth mass planet has 5 times the signal and would require 25 times less observing time, when limited only by star spot noise. But are most stars as quiet as the Sun? To get a rough answer to this question we obtained photometric data of ~ 100 stars from the COROT spacecraft.

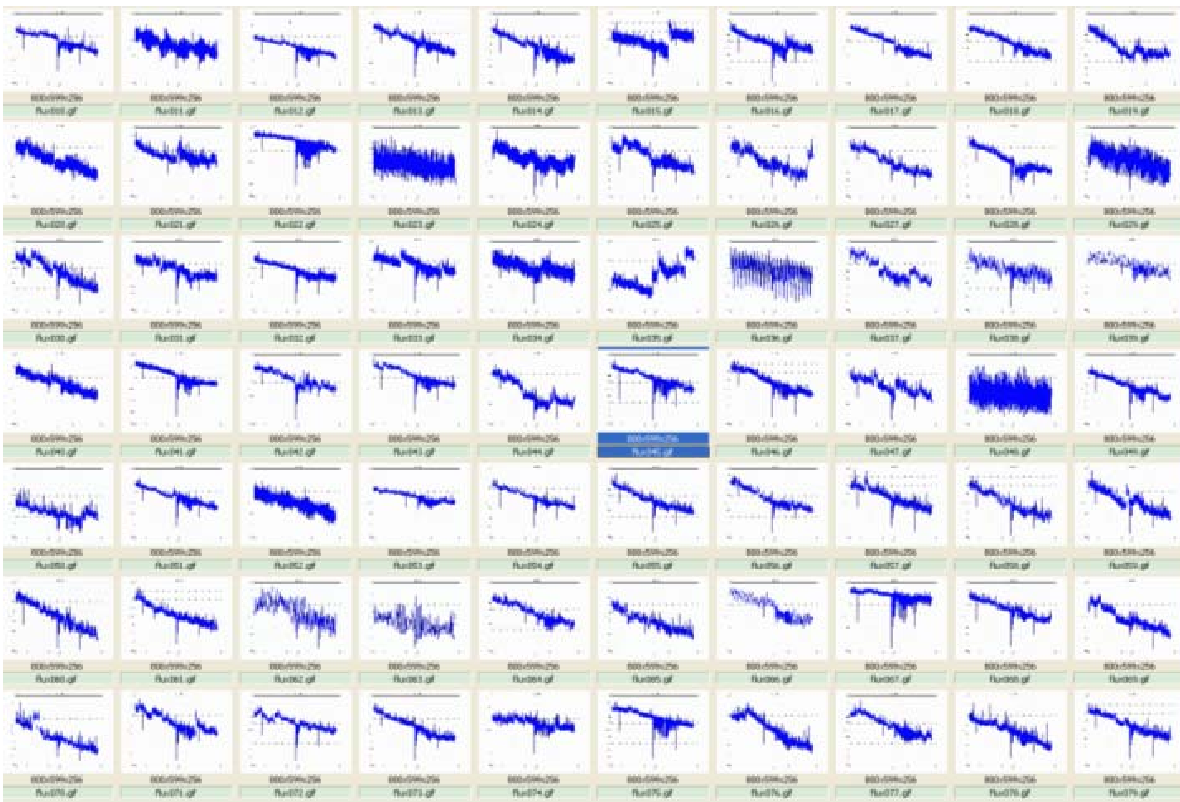


Figure 4: Light Curves for 70

COROT is a French space mission designed to look for transiting planets. On a time scale of ~10 hrs or less it has a precision of ~ 1e-4. Unfortunately the stability of the instrument on a month long time scale is not as good. Figure 4 shows the light curves for 70 of the stars. A number of artifacts are obvious and correctable, such as slight downward drift seen in all the stars. Other instrument artifacts that are correctable are single even cosmic ray glitches. The actual cosmic ray events produces a huge signal that data is flagged and not used. But often, a pixel

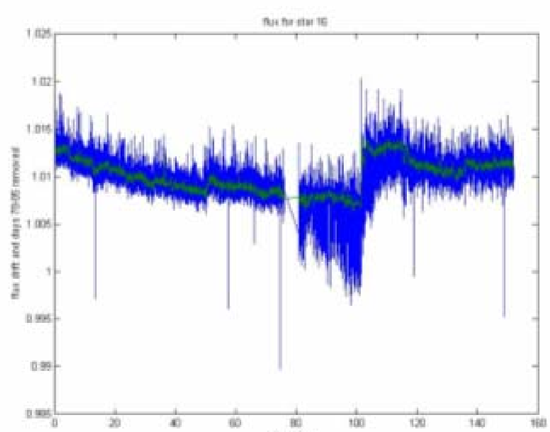


Figure 5: Slope removed Median Filtered

adjacent to the ones used for stellar photometry may have a cosmic ray hit and produce a small glitch in the photometric data. These can be removed with a median filter. Figure 5 shows the raw data (blue) and the median filtered data (green). More serious are the hot pixel events one of which can be seen in figure 5. A hot pixel occurs when a cosmic ray disrupts the silicon lattice of the CCD resulting in an increase in the dark current. On HST, hot pixels are annealed by bring the CCD back to room temperature. This option was not available for COROT. Hot pixels because they happen only once every few months, in general will not interfere with transit observations, but they do get in the way of determining long term (few month) stability of a star. The presence of hot pixels overall limit the long term photometric precision to be 1~2e-3, rather the the 1e-4 of shorter term <24 hrs time scales.

Even with this limitation, we see that ~40% of the 100 stars are variable at or more than 0.2% on a time scale of ~75 days. Our Sun is variable at ~0.02% on a time scale of 75 days. Roughly speaking 40% of stars are 10X more active than our Sun. Can we say something abut the other 60% of stars? Because of the limitations of the instrument, we can't make "hard" statements. But if we make some "reasonable" assumptions on the distribution of variability amongst stars we can calculate a rough limit of how many stars are as quiet as the Sun. Figure 6 is a histogram describing the distribution of stellar variability.

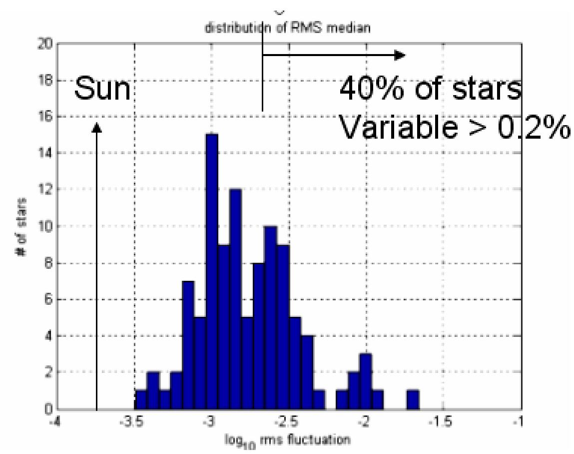



Figure 6: Distribution of Stellar Variability

If the actual distribution of stellar variability is a Gaussian function of log ( variability) or if the actual distribution is a triangular distribution would give slightly different answers as to what fraction of stars are as quiet as the Sun. But over a wide range of assumptions, as to the parent distribution of stellar variability, we find that somewhere between 7~15% of stars would be as or quieter than the Sun.

## *RV and Astrometric Searches for Earth Clones*

This analysis suggests that RV searches for Earths in a 1 AU orbit would be limited to the quietest 10~15% of stars. In fact this is the observing strategy that has been adopted by the leading RV planet finding teams(Pasquini, 2009). The Swiss team's plans for their next generation instrument (Expresso on the VLT) is to search ~50 of the quietest stars within 50pc of the Sun for signs of Earths in the habitable zone. The Expresso RV spectrometer is being designed to 10cm/s precision, quite a large factor below the "stellar" noise even for quiet stars. But even on these low noise stars, very likely stellar noise will limit the sensitivity to 4~5 Earth mass planets in a 1 yr orbit.

An astrometric search could be conducted on stars that are significantly noisier. Although it's likely that 10~15% of the stars would be too noisy even for astrometry. Astrometry does provide more information that RV, the orbit inclination can't be measured by RV and the mass of the planet has a SIN(I) ambiguity. A face on orbit would also have a reduced RV signature, the 4~5 Earth mass sensitivity would be for edge on orbits.

After finding an earth-like planet in the habitable zone, the next major step would be for a space based coronagraph or interferometer to block out the light from the star and measure the spectra from the planet. If the Earth-clone is nearby 5 or 10 pc, a modest sized TPF-C/I might be able to measure its spectra. But if the Earth-Clone is very distant 40~50pc, a truly gigantic telescope or interferometer costing many 10's of billions of dollars would be needed.

## Summary and Conclusions

Such missions are not viable unless some other mission or technique has previously found the Earths and measured their orbits.

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