P2IO research activity report

Study of the stellar activity for exoplanetary atmospheres characterisation.

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Aim of the project

The study of exoplanetary atmospheres epitomises a continuous quest for higher accuracy measurements. The stellar variability, found in all late type, solar-type and non-main sequence stars, in particular creates temporal instabilities in the transit lightcurves and it significantly hampers the ability to detect Earth size planets where the transit signal is only a few times the inferred noise on comparable timescales. An other critical aspect is that the variation of the luminosity affects the transit profile making it difficult to combine measurements obtained at different wavelengths and at different epochs, preventing us putting constraints on the atmospheric characterisation of planets.

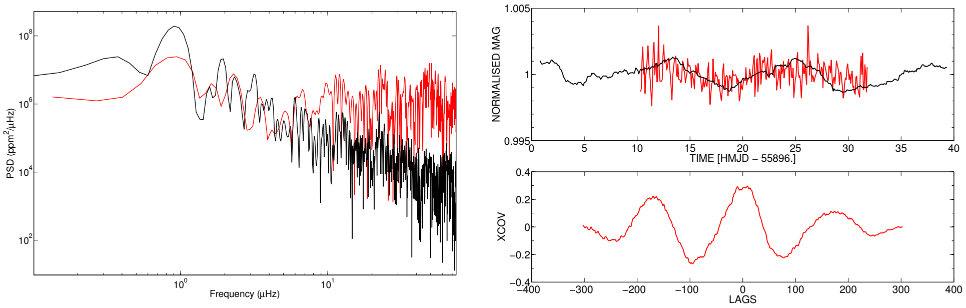
The aim of this project is twofold. First, I want to develop a better understanding of the stellar variability over a large spectral range and to study possible activity-induced correlations at different wavelengths. This would cover as much as possible the entire possible activity levels, giving information about how the variability scales from the optical to the infrared (where the planetary signal is concentrated). Second, I want to use this information to better constrain the planetary parameters and atmospheric properties.

Work achieved

Since my arrival I started a collaboration with the Osservatorio Astronomico di Palermo (Italy) from where I got 30 days optical and infrared photometric observations of a sample of 180+ mains sequence stars, recorded simultaneously with CoRot and the Spitzer Space Telescope. The sample consists of stars with visible magnitudes 11$<M_V<15$ of which majority are K0-V stars. The CoRoT data were recorded with the Exo channel (centred in the R band $\sim 0.658\ \mu$m) and a cadence of 32 s. Spitzer data were recorded with

the InfraRed Array Camera (IRAC) at 3.6 μm and 4.5 μm and a cadence of ~ 101 min. Due to different overlap of the three channels' field of view only 103 stars have data at all the three wavelengths.
To start with I developed a code to read the data and to select the photometric data points for which the flux information was considered reliable. Following I worked on the lightcurves instrumental systematics correction. CoRoT data especially needed to be corrected for south atlantic anomaly and for brightness jumps. The last are abrupt variations in the flux and they are not attributable to stellar variations. Hence, I invested time testing different correction codes on both my data and other CoRoT planetary transit lightcurves data. These codes are currently under development in the context of CoRoT N2 data pipeline.

After cleaning the lightcurves I started exploring the degree of correlation in the data. The correlation between the three spectral channels, visible and IR can be explored in different ways. One of the methods is to study the power spectral density of the stellar timeseries. The power spectral density (PSD) describes the signal power distribution as a function of frequency. It is normally used in the study of solar-like, sub-giant and red-giant stars to retrieve information about the rotational period of the star, its magnetic activity level, the timescale of the granulation noise and its oscillation spectrum.
I converted all the data to the same unit of measure and the same cadence, in order to be able to compare the same set of frequencies. This caused a cut off at ~ 140 μHz i.e. the Spitzer data Nyquist frequency. I then computed the PSD for all the available stars. The results show that the PSD at low frequencies ($\nu < 10\mu$Hz) is quite similar for both visible and infrared band-pass, while it differs at higher frequencies ($\nu > 10\mu$Hz). The infrared PSD is in fact much higher than the visible band one. This difference at high frequencies could be due to noise: the PSD of white noise would in fact appear constant over all the frequencies. I therefore made a simulation to check what the PSD level would have been if the possible signal in IR timeseries were to be completely destroyed. The results showed that astrophysical signal is present in the Spitzer data, but it does not tell at which frequency the signal is concentrated and hence it does not unequivocally identify the high frequency PSD as noise. To confirm this result I then fitted all the stellar PSDs with straight line. Previous studies have in fact showed that the slope that defines the difference in power intensity between low and high frequencies is an indicator of stellar magnetic activity. The result given by the fit showed that no PSD is completely flat and hence it proved again the presence of signal in the stellar timeseries. The slopes computed for the visible band-pass are obviously more steep than the infrared ones as we are sounding a different level in the stellar atmosphere. Figure 1 (a) shows an example of PSD for a K0-V star $M_V \sim 14.7$: in black the visible data PSD, in red the 4.5 μm PSD (for this star 3.6 μm data were not available). Both



(a) Power spectral density of visible (black) and infrared(red) data. The first peak at $\sim 1\mu$Hz represent the stellar rotational period

(b) top: visible(black) and infrared (red) time series, bottom: cross-correlation plot which shows a periodicity of 11.57 days, corresponding to the rotational period of the star.

Figure 1: Spectral analysis and time domain cross-correlation for a K0-V star.

PSD are very similar until 10 μHz; Here in particular it is possible to see correlation at $\sim 1\mu$Hz (11.57 days), which correspond to the rotational period of the star. I am currently working on the estimation of the noise level at higher frequencies.
The other way to test for correlation is by cross-correlating the timeseries in the time domain. I cross-correlated the visible with the two infrared channels as well as the two infrared channels together for all the available stars. Figure 1(b) shows the time series (top panel) and the cross-correlation (bottom panel) of the same star plotted in Figure 1 (a). The results confirmed what I saw in the spectral analysis: it is not possible to generalise a level of correlation as a function of the stellar spectral class or the magnitude. A larger stellar sample spanning a larger variety of spectral class would be needed. Correlations are although detected in some targets at both low and high frequencies. The presence of correlations at low frequencies (i.e. at time scales larger than 1 day) means that, when we observe the infrared phase curve of the planet, we need to be extremely careful and take into account the stellar variation. For shorter time-scales this needs to be tested yet, it is although of extreme importance to understand it as the variations in this frequency range, corresponds at the typical planetary transit timescale.

This Project is also part of a conjoint project at the CEA with the James Webb Space Telescope/Mid-Infrared Instrument (MIRI) team. Understanding the level of the stellar variability and how it could affect the MIRI observations in the infrared bandpass is important to fully characterise the instrument performances and the expected SNR before the launch.

Since my arrival I have presented the project I am working on at the following conferences.

- Contributed talk: *Using simultaneous visible and infrared observations to better constrain stellar activity*, at the Towards Other Earths II, Oporto, Portugal.
- Contributed talk: *Simultaneous visible and infrared observations of stellar activity.*, at the JWST-MIRI Workshop, MPIA, Heidelberg, Germany.
- Invited seminar: *Goldilocks and the 1000+ exoplanets, towards characterisation of atmospheres in the habitable zone.*, at the Osservatorio Astronomico di Palermo, Palermo, Italy.

Relevance of the project within the P2IO

The project I am working on is of incredible relevance in the context of the study of origins of planets and life. Over the past two decades primary transit and radial velocity measurements have determined the size and masses of exoplanets, putting constraints on the bulk compositions of these exotic worlds. These measurements have revealed the great variety of planets and of the systems in which planets originate and evolve. These studies have led to very important questions such as *What are exoplanets made of? How do planetary systems work? Why do we observe such exceptional diversity compared to the Solar System?* To answer these questions we require a in-depth spectroscopic knowledge of the atmospheres of a large planetary sample for which precise physical, chemical and dynamical information can be obtained. The combination of these information with estimates of planetary bulk compositions from accurate measurements of radii and masses can then be used to trace back to planetary formation, migration and evolution. It will also shed light on the structure of the Solar System, explaining why it is not a paradigm in our galaxy.

My work is developed in this context of exoplanet spectroscopy. The understanding of the stellar variability at multiple wavelengths is a key factor to break the degeneracies associated with planetary interior modelling and planetary spectrum interpretation.

Publications

C. Danielski et al. *Simultaneous optical and infrared lightcurves of field stars with CoRot and Spitzer: a study of multi-wavelength stellar activity.*, in preparation.