ExTrA : Exoplanets in Transit and their Atmospheres

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Introduction

The most common way to detect exoplanets is by using the **photometric transit method** which consists in searching for dips in the stellar luminosity caused by planets passing in front of their host stars.

M dwarfs

- dominant stellar population
  $N \sim 50 - 70\%$ stars, $M_{Tot} \sim 70\%\ M_{Gal}$
- low-mass stars
  $0.07\ M_\odot \leq M_\star \leq 0.6\ M_\odot$
- low temperature
  $2100\ K \leq T_{eff} \leq 3800\ K$
- small
  $0.1\ R_\odot \leq R_\star \leq 0.5\ R_\odot$
- intrinsically faint
  $5.10^{-4}\ L_\odot \leq L_\star \leq 0.1\ L_\odot$

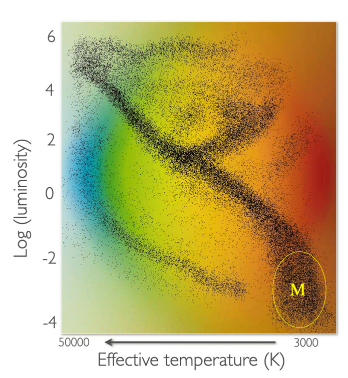

Figure 1 : Characteristics and interests of M-dwarfs

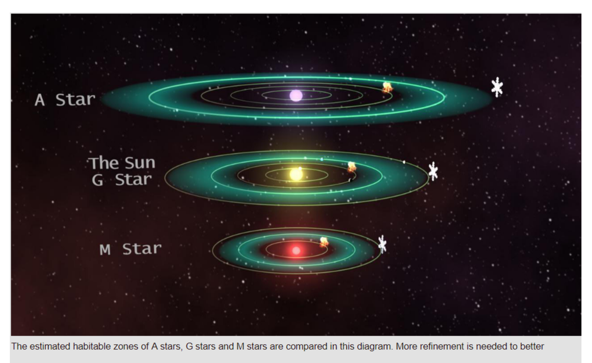

Figure 2 : Habitable zones for different spectral-type stars.

Motivation for **near-infrared observations** : M-dwarfs radiate most of their energy at infrared wavelengths.
Principal limitation of infrared sensitivity from ground-based telescopes : Earth's atmosphere and the presence of large bands of telluric lines.
Water vapor absorbs a significant amount of infrared radiation, and the atmosphere itself emits at infrared wavelengths.
For this reason, most infrared telescopes are built in very dry places at high altitude, so that they are above most of the water vapor in the atmosphere.

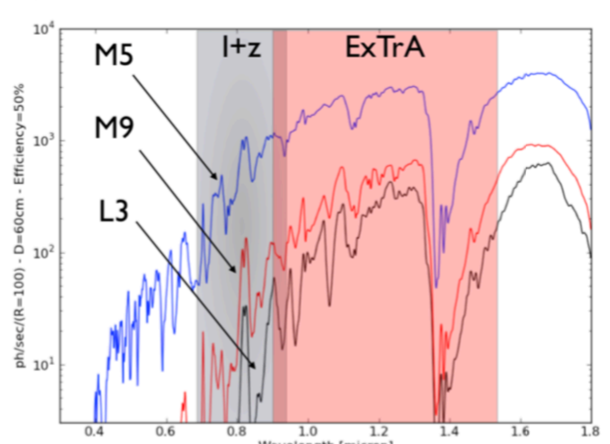

Figure 3: Photon distribution (per R=100 resolution element) for a M5@15pc, a M9@10pc, and a L3@10pc dwarfs, as would be recorded with a telescope of 60-cm diameter, with a 50% efficiency, and through the Earth atmosphere.
The gray zone labeled 'I+z' is the typical band pass of ground-based transit surveys.
The light-red zone labeled ExTrA is our spectral window.

A new concept

ExTrA is a new instrument composed of **three 60cm telescopes** that are located at La Silla Observatory. The facility is composed by the three domes and an auxiliary building that hosts the spectrograph, the main server, the weather station, an all-sky camera, and a webcam.
→ detection of Earth-like exoplanets orbiting around M dwarfs in the vicinity of our solar system.

The ExTrA facility relies on a new approach that involves **combining optical photometry with spectroscopic information** in order to mitigate the disruptive effect of Earth's atmosphere, as well as effects introduced by instruments and detectors.

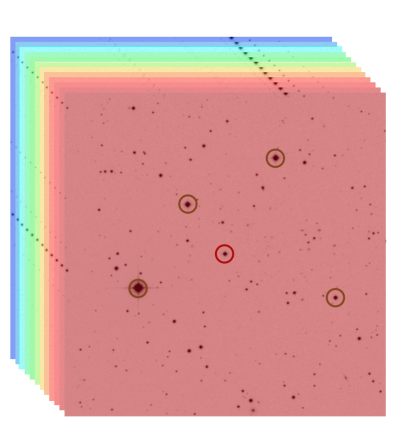

Figure 4 : The target star and 4 reference stars fluxes analyzed at different narrow bands

The three telescopes collects light from **a target star and four reference stars** for comparison.
This light is send through optical fibers into a **multi-object spectrograph** in order to analyze it in many different spectral channels.
We can then use this spectral information to create a mask for the telluric lines and remove systematics from the light curves.

Methodology

On each telescope, **5 Field Units (FUs)** are used to pick off the light from the target and the selected comparison stars. They are composed by fibers accurately positioned that feed a single **near-infrared spectrograph** with low spectral resolution (**R~200**) and that covers the **0.9-1.6 µm** range.

Although all three telescopes can observe the same field, they will most of the time observe different fields in order to maximize the transit search efficiency.

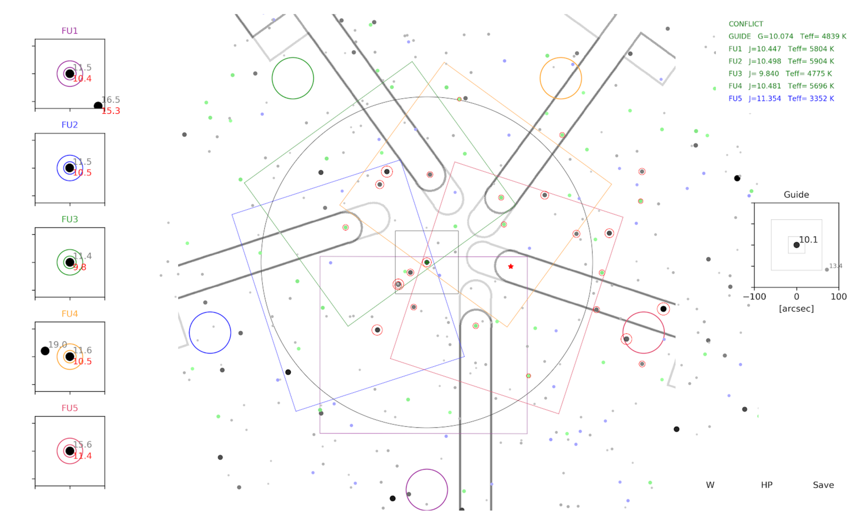

Figure 5 : Field of view of TRAPPIST-1 with the 5 arms and the guiding star in the center.

Each Field Unit is composed of two "buttons": the science button, and the centering button.
The **centering button** is composed of a bundle of 19 fibres, used to measure the position of a star accurately before any science acquisition, and then apply a relative movement to center the star in the science button.
Each **science button** is composed by two channels, one optimized for bright stars with an aperture of 8″ and a second one optimized for faint stars with an aperture of 4″ in order to reduce the background contribution.
Each channel has two fibers: one to collect the light of the star and another to collect the sky background close to the star.

The **spectrograph** allows to image the fibre bundles in centering mode, and with a different light path to disperse the science fibres using a prism.

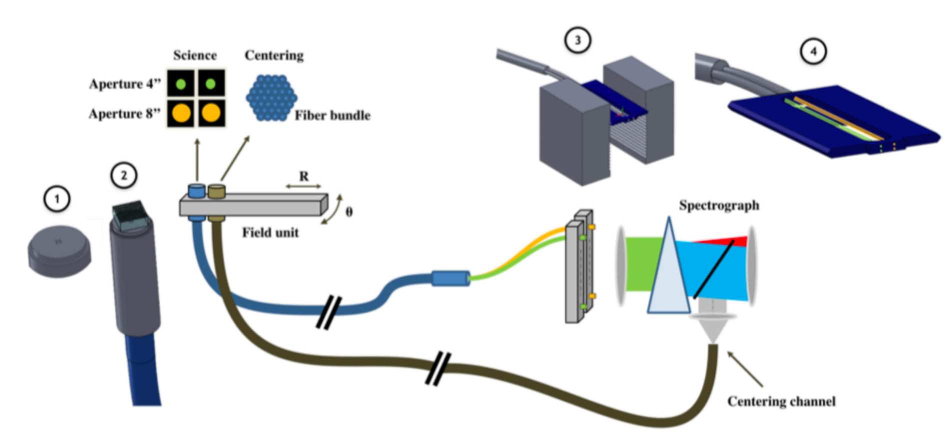

Figure 6 : Scheme of the ExTrA fiber system from the field units to the spectrograph, with the 3D implementation of some of the parts: detail of a science button (1), science button with microlens (2), drawner arrangement at the spectrograph image plane (3), and drawner detail (4).

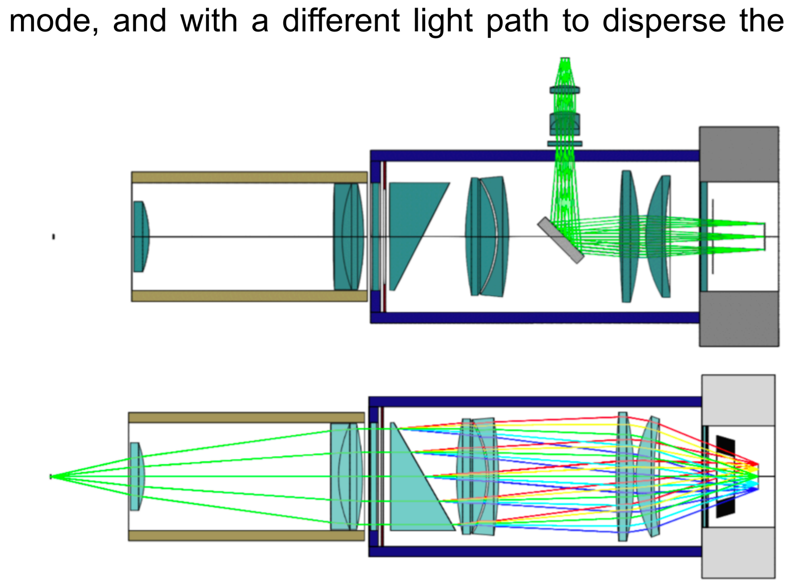

Figure 7 : The two configurations of the spectrograph: centering mode (upper panel), and science mode (lower panel).

Synergies with other missions

Besides running its own survey, ExTrA will be a valuable resources to **follow-up M dwarfs** with candidates found by both **K2 and TESS** missions.
With ExTrA, we will obtain a better precision for the coolest stars (late M) because of infrared photometry.

NIRPS will be an **infrared spectrograph** designed to detect Earth-like rocky planets around the coldest stars. NIRPS is the "red arm" of HARPS, extending its capability into the infrared and allowing astronomers to characterize planetary systems.

The exoplanets detected by ExTrA will be amenable to **atmospheric characterization** with instrument such as the **VLT**, and future instruments like the **JWST**, and **ELT**.

Analysis (example of TOI-269)

In order to evaluate the capacity and precision of ExTrA, we started by observing TOIs (**TESS Object of Interest**) to detect transits. One of them was **TOI-269** where we were able to detect the presence of a mini-neptune orbiting a M2 star (Vmag = 14.37, Jmag = 10.909, 0.398 ± 0.012 $R_\odot$ and 0.3917 ± 0.0095 $M_\odot$).
The planet was detected by the TESS pipeline and confirmed with radial velocity measurements with the spectrograph HARPS.
The target was observed during 6 sector with the TESS satellite, 3 nights with ExTrA (2 nights with 2 telescopes and one with the three telescopes) and 2 nights with LCO-CTIO (not shown).
81 spectra of TOI-269 were obtained with **HARPS** between UT January 18, 2019 and October 20, 2019.

We used the **juliet** tool (Espinoza et al. 2019) in order to model our different sets of data. juliet performs nested sampling algorithm (via dynesty, Speagle 2019) to model jointly photometric dataset with the package batman (Kreidberg 2015), and radial velocities via radvel (Fulton et al. 2018). In addition, we can add Gaussian processes via the celerite (Foreman-Mackey et al. 2017) or george (Ambikasaran et al. 2014) packages to improve our data.

The joint photometry and radial velocity analysis leads to a **mini-neptune planet** at a period of 3.7 days with a planetary radius of 2.89 ± 0.14 $R_\oplus$ and mass of 9.36 ± 1.50 $M_\oplus$.
Some results of the joint fit are presented below.

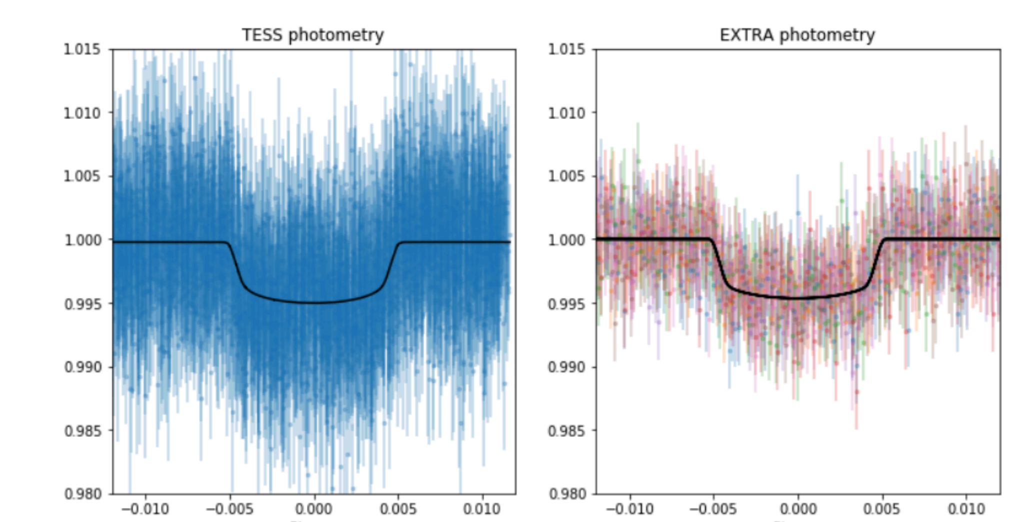

Figure 8 : Phased lightcurves from TESS (2-minute cadence, 37 transits), ExTrA (1-minute cadence, 7 transits, GPs) obtained using the juliet modeling tool.

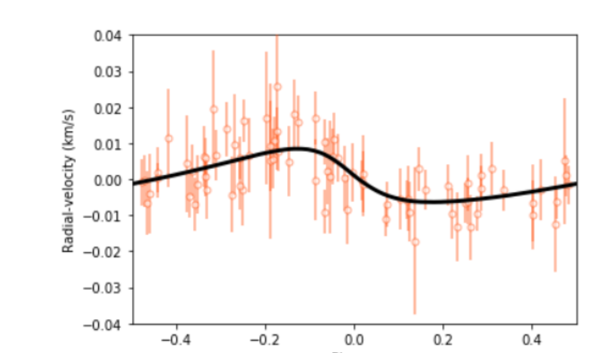

Figure 9 : Phased radial velocity measurements obtained using the juliet modeling tool. It appears that the planet may have a non-zero eccentricity.

In order to assess the precision we can obtain with ExTrA light curves, we binned the residuals of the modeling (after subtraction of the GPs and the transit) for different bin width and measure the RMS to infer the error on our measurements.

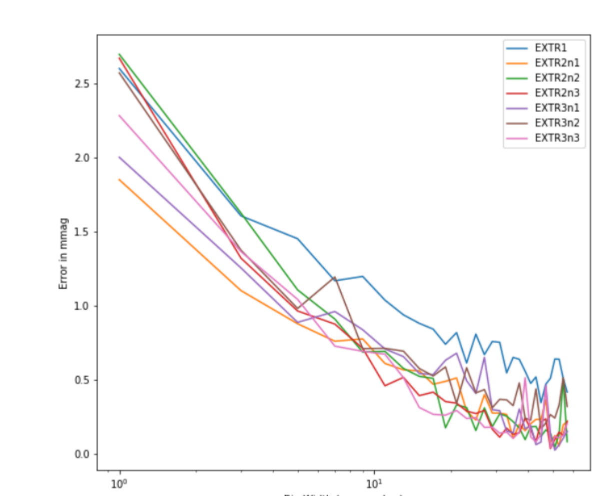

Figure 10 : Errors in mmag for different bin width (one sequence/acquisition corresponds to approximately 1 minute) for each telescope and each night of observation with ExTrA.
Floor precision for these observations was approximately 200 ppm for temporal bins larger than 30 min

Reference ExTrA : https://arxiv.org/pdf/1508.06601.pdf