# Chapter 7

# Conclusions and prospects

The knowledge of both the radius and the mass of an exoplanet, obtained with combined observations of the planet's transit and the star's radial velocity variations, allows the determination of the planet's density. The observed planet densities provide important constraints on planet structure and evolution models.

The uncertainties on the planet parameters need to be small in order to test the physics used in the planet evolution models, and to discriminate between different structures and compositions.

The motivation of this thesis was to derive more accurate and precise planet in a two-fold approach. The first aim was to improve the precision and accuracy of the planet parameters in the presence of stellar activity, by meticulously processing and fitting the planet's transit signal. The second aim was to improve the precision on stellar temperatures which are fundamental to derive precise stellar radii and masses. The fist aim was tackled in Chapters 2, 3 and 6, and the second in Chapter 5.

The new light curve filtering method presented in Chapter 2 also conserves all signals at the orbital period of the planet. In Chapter 4, this property was exploited by searching re-processed light curves for lower amplitude planet signals such as the planet's secondary eclipse and orbital phase variations.

## 7.1 Summary of achievements

### 7.1.1 A post-detection stellar variability filter

Stellar photometric variability on timescales of hours to days hinders the characterisation of the planet's transit signal. The frequency content of the transit signal and the stellar variability signal overlap in the timescale range of hours. Current stellar variability filters, which are used to filter the stellar variability prior to the transit detection, do not differentiate between the transit component and the stellar variability component on these overlapping timescales. This results in either filtering out some of the transit signal or not filtering out enough stellar variability. Either affects the accuracy and precision of the derived planet parameters.

In Chapter 2, we used a pre-detection filter, the non-linear iterative filter (NIF) of Aigrain & Irwin (2004), to show that such filters induce a deformation in the transit shape which can induce errors (up to 50%) in the star-planet radius ratio. A new post-detection stellar variability filter, the Iterative Reconstruction Filter (IRF), was thus developed and tested. This filter simultaneously evaluates the stellar photometric signal and the planet photometric signal. It uses the prior knowledge of the planet orbital period to estimate the transit signal, and a median filter to estimate the stellar variability.

Tests on 20 simulated CoRoT light curves showed that the IRF especially improves the shape of the transit for light curves with strong stellar variability (large amplitude and high frequency variations). Nonetheless, residual noise in the filtered transit light curve allows for transit models (with different combinations of system scale and impact parameters) to fit the data equally well. This effect limits the direct comparison of the planet parameters derived from different filtering methods.

The IRF is limited to stellar variability filtering of light curves with a precise knowledge of the planet orbital period. It evaluates the phase-folded signal of the transit and is therefore limited to the determination of mean parameters, i.e. it is not sensitive to the transit shape or timing variations due to additional planets or moons in the system.

### 7.1.2 Application to the transit of CoRoT planets

CoRoT's light curves have a photometric precision of the order of 0.2 mmag. At this level of precision most stars show intrinsic stellar variability. The first seven CoRoT space light curves with confirmed planetary transits were run through the IRF in Chapter 3. The planet parameters were derived from the IRF-filtered light curves using the analytical transit formulation of Mandel & Agol (2002) and a Levenberg-Marquardt convergence algorithm.

Compared to the values in the planet discovery papers, the planet parameters derived from the IRF-filtered light curve were consistent at the $1\,\sigma$ level. The level of stellar activity in the real CoRoT light curves is observed to be smaller than that in the simulated light curves used prior to launch. The effect of stellar variability on the planet's transit is thus limited, and the treatment by the IRF did not provide a major improvement. However, a few advantages in using the IRF were highlighted through this work. The IRF allows stellar variability to be filtered out down to timescales of 6h without affecting the transit shape, which is not the case for the NIF. Despite the more robust error analysis used, the error bars associated to the parameters from the IRF-filtered light curves were comparable to (or smaller than) those in the literature, except for CoRoT-7b, where we would argue the error bars are underestimated in the discovery paper.

This study also confirmed that the planet transit modelling is highly sensitive to the modelling of the stellar limb darkening. The evaluation of the true impact of the IRF on the planet parameters was limited by this effect.

### 7.1.3 Photons from the CoRoT planets

The IRF preserves any signal at the period of the transit. This property was investigated in Chapter 4 to search for secondary eclipses and orbital phase variations in the phase-folded IRF-filtered light curves of CoRoT-1 and CoRoT-2. These planets were chosen due to their expected strong secondary eclipse signals.

The search for a secondary eclipse was performed in the phase-folded IRF-filtered light curve, sliding a box of varying duration over the phase range 0.4–0.6 (range adapted to the low eccentricity of the planets). The search for orbital phase variations was also performed by a visual check of the phase-folded IRF-filtered light curve.

A clear detection of the secondary eclipse of CoRoT-1b was achieved in its IRF-filtered white CoRoT light curve. In addition, a low amplitude phase modulation was also observed. The detailed characterisation of the eclipse and phase variations were limited by the level of white noise in the filtered light curve. A noisier detection of CoRoT-1b's secondary eclipse in CoRoT red and green channels was made.

The detection of the secondary eclipse of CoRoT-2b in its IRF-filtered white CoRoT light curve was also made, but with a lower signal to noise ratio. The secondary eclipse of CoRoT-2b was expected to be more challenging to detect as the planet is further away from its host star and its star is more active than CoRoT-1b. The characterisation of this eclipse was limited by the level of residual systematics in the filtered light curve.

In order to improve the filtering by the IRF of the transit light curve of CoRoT-2b, the behaviour of the IRF with different minimum timescales of stellar variability was studied. This work revealed that the IRF improves the filtering of the stellar variability down to timescales of 0.25 days, below which it unintentionally reconstructs noise features along with the transit signal. The optimal stellar variability filtering timescales was found to be between 12 and 6 hours.

### 7.1.4 Precise relative stellar temperature measurement

The transit and radial velocity methods, respectively, derive the planet's radius and mass relative to the radius and mass of the host star. The precision on the parameters of large exoplanets are limited by uncertainties on the stellar parameters. The derivation of the latter, starts with estimating the stellar temperature, so a more precise temperature will help reduce the uncertainties on the stellar parameters.

This issue was tackled in Chapter 5, where a new temperature calibration was derived based on equivalent width ratios. This calibration derives relative stellar temperatures with precision down to 10 K, for $T_{\rm eff}$ within the calibrated temperature range, i.e.

between 5000 and 6100 K. This method was improved on, and published in Sousa et al. (2009).

The method was used to successfully derive an independent measurement of the temperatures of the CoRoT planet host stars with $T_{\rm eff}$<6100 K. The temperatures derived with this method are sensitive to the accuracy of the equivalent width measurements, so special care should be taken, at this step, to ensure the method derives an accurate stellar temperatures. This method is also limited by the absolute precision of the temperatures used to calibrate it, which are model-dependent. Therefore, like all other available temperature determination methods for single stars, it may suffer from systematic shifts in the absolute scale.

### 7.1.5 Joint modelling of transits and stellar temperatures

The planet's orbital inclination $i$ and system scale $a/R_\star$ are correlated in transit models, which limit the precision on the derived planet parameters. Additionally, the detailed shape of a transit depends on the stellar density, which is linked to the stellar temperature. The stellar temperature can be determined spectroscopically (e.g. as described in Chapter 5). All the above information can be taken into account when fitting the best model to the transit using a Markov Chain Monte Carlo (MCMC).

In Chapter 6, an MCMC is used to jointly model the transit shape and the stellar temperature. Transit models of Mandel & Agol (2002) with different planet parameters and stellar densities are compared to the IRF-filtered transit of CoRoT-2b, to derive the best transit model and the planet parameters most consistent with the available information on the planet and its host star.

The planet parameters derived from the MCMC (with a prior on the stellar temperature) are consistent with those derived from using the same method without this prior. These parameters are also consistent, as expected, with the transit fit derived using the Levenberg-Marquardt algorithm. All the planet parameters derived from the IRF-filtered light curve are marginally compatible ($2\sigma$ and above) with the parameters in the discovery paper (Alonso et al., 2008). The differences come from the difference in light curve processing and modelling, and from the modelling of the stellar limb darkening.

## 7.2 Conclusions

The aims of this thesis, in terms of developing new techniques to better characterise transiting exoplanets in the presence of stellar activity, were achieved. However, the absolute improvement on the planet parameters of real planets were smaller than expected, due to the smaller level of stellar activity of the first seven CoRoT planets, than previously simulated.

The techniques developed were applied to study aspects of the planets that were not originally planned, such as the the planet's emission in the visible. In general, the work undertaken in this thesis has highlighted the complexity inherent to detailed characterisation of transit light curves. The detailed analysis of planetary transits, secondary eclipses and orbital phase variations are sensitive to the light curve processing and transit fitting strategies. When characterising a planet from its transit light curve, important aspects to keep in mind are a) the correction from all contaminant fluxes in the light curve, b) the residual stellar variability and systematics on the transit light curve, c) the modelling of the stellar limb darkening, d) the chosen methods used to find the best transit model and estimate uncertainties, and e) the incorporation of all prior knowledge on the planet and its host star in the transit fit.

## 7.3 Future improvements and prospects

Some of the work presented in the thesis is still in progress and can be improved in a number of ways.

The IRF can be further tested to understand, and suppress if possible, its behaviour when filtering the stellar variability with a timescale smaller than 6h. It would also be interesting to test it further on very active stars with planetary transits, to probe the limits of its performance in reconstructing the transit signal. It may be possible to use the IRF at the detection stage to improve the detectability of borderline transits which would otherwise be masked by stellar variability. This would be computationally challenging, however, as the IRF would need to be run at each trial period. There is also a danger that it may lead to an increased rate of false alarms if the IRF parameters are not carefully chosen.

It may be possible to fine-tune the filtering of the light curve of CoRoT-2 further and to reduce the residual stellar variability at the transit period in order to improve on the detection of CoRoT-2b's secondary eclipse. The tentative detection of CoRoT-1b's orbital phase variations in the visible also deserves further attention. Generally, however, the scientific usefulness of CoRoT secondary eclipses is limited by the degeneracy, in the CoRoT bandpass, between the planet's thermal emission and stellar reflected light. This degeneracy may be lifted by combining the CoRoT measurements with other bandpasses and/or by detecting the signal in individual CoRoT channels. There is also scope for applying the IRF to other, good candidates from CoRoT and other similar surveys searching for similar signals.

The sensitivity of the ARES equivalent width measurements to the rejt parameter to evaluate the continuum needs to be better understood, as it currently limits the reliability of the stellar temperatures derived using equivalent width ratios. It would also be desirable to extend ARES to produce error bars on its equivalent width measurements, or to explore alternative automated methods to measure precise equivalent widths. The equivalent width temperature calibration may be extended by including cooler and hotter stars outside the current calibrated range in the calibration set.

Additional prior knowledge could be incorporated in the MCMC transit fits, starting with the stellar limb darkening coefficients: these can be linked to the stellar temperature using theoretical models in the same way as the stellar density. Ultimately, a homogenous detailed analysis of all the CoRoT planets using the tools presented in this thesis – the IRF, the $T_{\rm eff}$ calibration, and joint modelling of the transit light curves and the stellar temperature – would enable a more direct comparison of the planets' radii, free from the side-effects of different light curve processing and fitting methods.

As seen throughout this thesis, stellar variability is an important limitation to the precision and accuracy of planet parameters, and to the detection of the planet's secondary eclipse and orbital phase variations. It is likely to be even more important in future missions such as PLATO and TESS, and many more planets around active stars will certainly be discovered. The IRF should therefore prove increasingly useful in the future, and may be indispensable to characterise small planets around active stars.