# Chapter 8

# Conclusions

The detection and study of planets outside the solar system is one of the most active areas of astrophysics today. Amongst the detection methods currently implemented from the ground, the transit method has a number of advantages, the most notable being the simultaneous monitoring of many thousands of stars and the possibility of measuring the planet radius and inclination directly from the light curve. In combination with the radial velocity method, it yields mass measurements free of the mass-inclination degeneracy, and a direct probe of the planetary mass-radius relation. The first few detections thus made have recently received confirmation, and many more are expected in the coming years. From space, the transit method is expected to be the first to allow the detection of terrestrial and habitable planets.

## 8.1 Data analysis tools for planetary transit searches

The detection of planetary transits in stellar light curves poses a number of challenges due to the rarity of the transits, their brief and shallow nature, the many thousands of light curves that have to be searched, and the noise sources that affect them, in particular intrinsic low amplitude stellar variability on timescales of tens of minutes to weeks, which all stars are expected to display to some extent.

In response to these challenges, a number of data analysis tools have been developed. These include pre-processing filters to minimise the impact of stellar micro-variability and a transit search algorithm based on chi-squared minimisation with a box-shaped transit model. An empirical micro-variability model was also developed to test these tools and assist in the selection of the best target stars for transit searches, by allowing the simulation of realistic light curves for stars of different spectral and activity level.

## 8.2 Applications

The micro-variability model, filters and transit search algorithms were applied to estimate the impact of stellar micro-variability on transit detectability in *Eddington* and COROT data by exploring the star-planet parameter space in a systematic manner and identifying promising areas. The results of these simulations have already had some influence on some aspects of the observing strategy and design of these missions. I am planning to carry out more detailed and extensive simulations when the target fields have been selected and more fully characterised, and the instrument models are at a more advanced stage.

These tools were also applied in the context of a large collaboration within the COROT Exo-planet Working Group, as part of the first COROT blind exercise. This exercise helped identify detection limits for COROT. It has also shown that the performance of our filters and transit search algorithm compares well with that of other published methods, and also highlighted areas where room for improvement remain and where either alterations to the existing tools or the development of additional ones are desirable.

A transit search was also run in a 5 night dataset from the the University of New South Wales (UNSW) program on the 0.45 m Automated Patrol Telescope in Siding Springs Observatory. This analysis, though very preliminary, helped bring to light a number of issues not foreseen when testing the tools developed in this thesis on simulated space-based data, in particular the importance of systematics removal and the difficulty of obtaining stable light curves in the presence of daily interruptions and variable atmospheric extinction. Several interesting transit candidates with depths consistent with a planetary orginin were also identified, and though will be followed up in the near future.

This work is ongoing, additional data from the APT and from the SuperWASP project begin under investigation at present. These tools will also be applied to a novel ground based transit search project, which aims to find transiting planets orbiting pre-main sequence stars by monitoring star forming regions. The first target for this study is the Orion Nebula Cluster (ONC), using the Wide Field camera on the Isaac Newton telescope (INT), for which the data collection will start in November 2004. In the longer term, the methods will be applied to data from COROT, *Kepler* and if applicable *Eddington*. Their applicability to data from other missions such as GAIA, which will provide high precision photometric monitoring of an even larger number of stars but with much sparser time sampling, will also be investigated.

The micro-variability model will also be used to study and improve our understanding of the causes of stellar micro-variability by comparing it with upcoming space-based data, in the context of a collaboration within the COROT Additional Program Working Group, focused on understanding the causes of hours-timescale stellar variability.

## 8.3 Future improvements

There is room for improvement of the aforementioned tools in several areas. This is true in particular for the stellar micro-variability model, where empirical constraints are currently so scarce. This situation is about to change, as data from the MOST satellite starts to become public from the fall of 2004. These data will be used to provide additional constraints and make adjustments to the model as they becomes available, but it will be limited to a few stars. From 2006, COROT data will provide constraints for a much larger number and wider variety of stars. At the high activity end, the amplitude of variations is larger, and ground-based monitoring, such as the project targeting the ONC from the INT, will provide useful constraints. The possibility of simulating light curves in different bandpasses will also be investigated. Data from the Spectral Irradiance Monitor (SIM) on the SORCE satellite (launched last year), which provides 6-hourly measurements of the irradiance of the Sun as a function of wavelength from the IR to the UV, will be used for this purpose as soon as it becomes available.

Improvements to the filters will include a fuller investigation of the least-squares fitting plus matched filter approach, focusing on the application to particularly active stars and the reconstruction of the stellar signal, and refinements to the way the filter width is chosen in relation to the trial transit duration for the iterative non-linear filter. However, we will have to wait for the COROT data to become available to know how well these filters will perform on real data.

The performance of the transit detection algorithm itself has been investigated relatively thoroughly on model data. The next step will be to perform Monte Carlo simulations in which artificial transit signals are added to real data (to conserve the noise properties). These will be useful in particular to adjust the candidate selection process, which seems to be the area in which most progress can be expected.

## 8.4 Additional tools

The applications investigated to date have highlighted a number of areas where the natural progression is to develop a new, additional `stage' in the modular framework established for the analysis of transit search data.

Light curves from transit search projects constitute a treasure trove of information on stellar variability. A very simple procedure for the identification of periodic variable stars using sine-curve fitting was used in the context of the COROT blind exercise, but much more could be done. At the very least, a procedure should be developed to flag potentially interesting variables – on the basis of a global parameter such as the reduced chi-squared of the light curve – for further study using dedicated tools. The next step is variable star classification, for which a variety of methods are available: comparison to templates, clustering algorithms, self-organising maps, neural networks etc. . . In the first instance, a study of the published literature on these methods will be undertaken to identify the most promising for transit search data.

Another area which has only briefly been touched upon in the present thesis is the detailed analysis of the light curve and the characterisation of transit candidates. It is the first step in the follow up of the candidates, allowing the exclusion of a number of 'impostor' signals as well as the derivation of the physical parameters of the system. Measuring the transit parameters in the presence of non-white noise is a non-trivial problem. If filters are used to remove the noise, one must ensure that they do not modify the transit shape. An alternative may be to attempt to reconstruct the transit signal directly from the noisy light curve using prior knowledge of the transit period and epoch.

To summarise, a set of data analysis tools for transit searches has been developed and tested on simulated data. The next step is to apply them to real data. Each new application will no doubt raise new problems and prompt improvements to the existing tools or further developments, as well as hopefully leading the discovery of exo-planets and variable stars. By the time data from the space-based missions which originally motivated this work becomes available, it is hoped that as many as possible of the potential problems will have been identified and dealt with, so that the data may be analysed as speedily and efficiently as possible.