Optical characterization and Radial velocity monitoring of Exoplanet and Eclipsing Binary candidates*

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Abstract: In recent times, many new exoplanet and eclipsing binary candidates are reported, particularly from the archival data produced by the Kepler space mission destined to detect exoplanets in the Cygnus-Lyra region of the sky. In the framework of Belgo-Indian Network for Astronomy & Astrophysics (BINA) project, we also initiated a long-term programme "Optical characterization and Radial velocity monitoring with Belgian and Indian Telescopes *(ORBIT)*" which aims at collecting ground-based photometric and high-resolution spectroscopic observations of exoplanet candidates as well as low-mass eclipsing binary candidates using the Indo-Belgian telescopes. We initially focus our study on a few bright candidates for which high-precision radial velocity and photometry could be possible from the available facilities within the BINA network. Our aim is to determine the physical parameters of these candidate stars in order to derive their true nature. Having a large enough sample of low-mass objects from this survey as well as from those reported in the earlier surveys, we intend to understand the mass-radius relation which is still debated for the low-mass regime of the main-sequence stars.

Keywords: binaries: eclipsing – binaries:exoplanets – stars: low-mass – technique: photometric – technique: spectroscopic

1 Introduction

The detection of extrasolar planets (or exoplanets) is one of the most fascinating scientific field as their study gives us the opportunity to improve our knowledge in the field of planetary science i.e. provide clues about their formation, evolution, the presence of water content, existence of life, etc. A few thousands exoplanets and exoplanet candidates have been reported by ground and space-based missions mostly by means of transit and radial velocity methods[1]. In particular, the Kepler space

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mission has completely revolutionized the exoplanetary field by detecting large number of exoplanets with unprecedented quality through its uninterrupted high-precision photometry. Currently, there are around 4000 confirmed and about 2500 candidate exoplanets known through various surveys as well as hundreds of low-mass eclipsing binary candidates after mining the archive data produced by these surveys (e.g., Coughlin et al. 2011, Burke et al. 2014, Foreman-Mackey et al. 2015, Barros et al. 2016, Vanderburg et al. 2016). The sample of the confirmed exoplanets shows that the bulk of the discoveries are smaller planets with a radius in the range between 1.25 and 5 $R_{\oplus}$, normally called Super-Earths (Burke et al. 2014).

Follow-up observations of these exoplanetary and other low-mass objects are very crucial in order to reveal their true nature. As more and more exoplanets are detected with a wide range in mass, density, orbital parameters, etc, they allow a better understanding of the formation of planetary systems. Moreover, studying the exoplanets at different stages of their life will provide further details on the formation and evolution of our own solar system. Further, the identification of a larger sample of low-mass eclipsing binaries offers an opportunity to probe the mass and radius relation which is still uncertain towards the lower branch of the main-sequence.

2 ORBIT Project

The programme *Optical characterization and Radial velocity monitoring with Belgian and Indian Telescopes (ORBIT)* is a long-term project under the framework of BINA collaboration which was formed with the aim to optimize the scientific exploitation of the observations of galactic and extra-galactic celestial objects carried out by the Indo-Belgian telescopes. *ORBIT* aims at collecting the ground-based photometric and spectroscopic observations of few selected exoplanet and low-mass eclipsing binary candidates needed to understand an in-depth characterization in order to understand their physical nature. The scientific objectives of the project are twofold:

1. Confirmation and characterization of exoplanets: We plan to do transit photometry of some of the exoplanet candidates discovered by the Kepler mission. We intend to characterize the exoplanets detected by the transit method using high-precision (multi-colour) photometry and high-resolution spectroscopy from the ground. By comparing stellar properties (like colour, effective temperature, and luminosity) with the theoretical stellar evolution models, we may be able to constrain the planet mass, radius, orbital inclination and some other physical parameters.

2. Study of Low-mass Eclipsing Binaries: Although low-mass eclipsing binaries (LMEBs) are sources of false alarm in the detection of exoplanets as their shallow eclipses mimic hot Jupiter transits, they are ideal objects for the determination of the fundamental parameters of very low mass stars (Chew et al. 2014). Hence, in addition to search for exoplanets, we also aim to study LMEBs. The characterization of low mass stars in the binary systems can help us to improve the stellar models in the low mass regime. In general, the critical evaluation of stellar evolution models cannot be done when the uncertainty level is too high (Torres et al., 2010). Ribas et al. (2008) and others show a 10 to 20% difference in the radius and a 5 to 10% difference in the temperature of M dwarfs when compared to predictions by the present stellar models. Cruz et al. (2018) collected many such LMEBs from literature as well as through their own observations, and once again found anomaly in the mass-radius diagram in the mass range 0.3-0.7 $M_{\odot}$ as illustrated in Figure 1. They suggested that this anomaly can be caused due to stellar magnetic activity induced by stellar rotation, starspots or the dependence of the radius on the metallicity. Unfortunately, only a few tens of well-characterized LMEBs are known so far (e.g., Table A1 of Cruz et al. 2018). Hence, the detection and characterisation of more such binary

systems comprising a low-mass companion are important to address the issue of radius inflation and its effect on the evolution of low-mass stars.

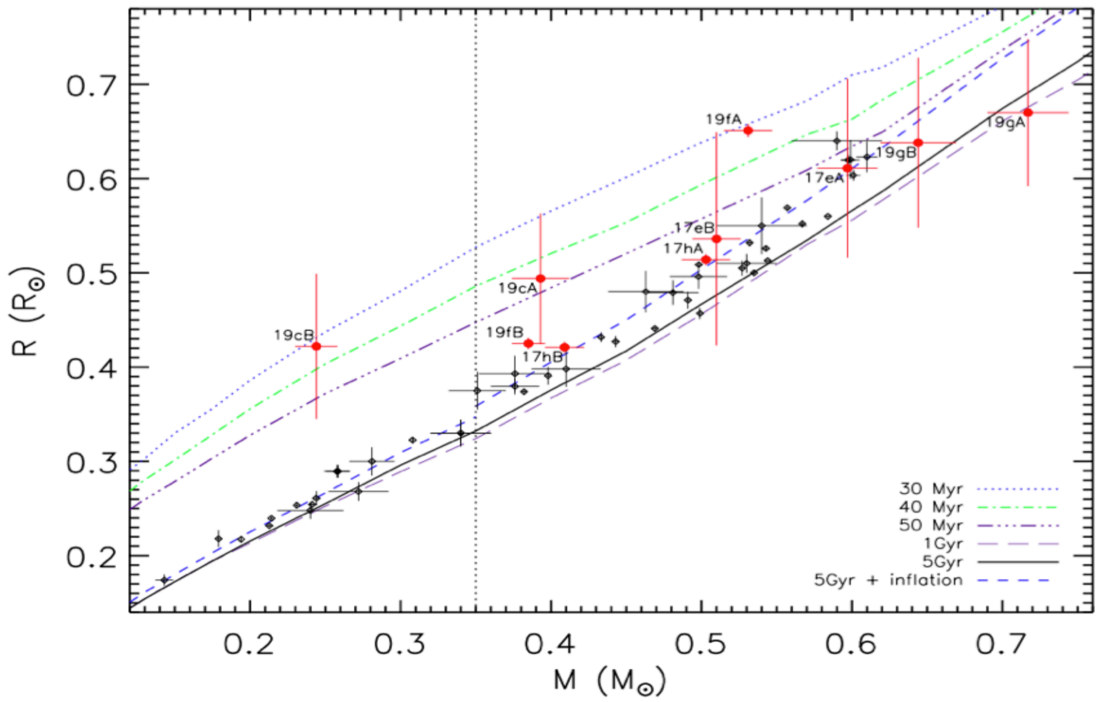

Figure 1: The plot shows the mass-radius diagram for selected well-studied LMEBs along with the theoretical isochrones of various ages (see, Cruz et al. 2018 for detail). Assuming a typical 5 Gyr age for the low-mass stars, it is evident that the stars in the mass range 0.3 to 0.7 $M_{\odot}$ do not fit in the mass-radius relation as described by the present stellar models but show inflated radii.

3 Techniques to detect Exoplanets and LMEBs

3.1 Transit Method

When a planet passes in front of the disk of its host star along our line of sight, there is a dip in the brightness of the star. While the periodic dip reveals the orbital period of the exoplanet, the amplitude of the dip depends upon the relative size of the planet with respect to the star. During the transit, the planet also passes behind the host star when its bright phase is eclipsed which results in a very small flux change in the total light of the star-planet system. This secondary eclipse gives an idea of the planet's brightness hence its temperature. However, the amplitude variation during the primary transit itself is very small (less than 1% level or <10 millimag) most of the time, and we need very high-precision photometry which is not always possible from the ground, particularly for fainter stars or smaller exoplanets. Due to this limitation, such a detection is limited to bright stars only.

3.2 Radial-Velocity Method

When a planet orbits a star, the star moves in its own orbit around the center of mass and in the process, the star moves away or towards us which can be observed by monitoring the Doppler shifts in the stellar spectral lines. The periodic radial velocity variation in a star generated either due to its planetary companion or that of a secondary star in case of a binary system. By measuring precise radial velocity variations, one can obtain the accurate orbital parameters of the system, as well as derive the fundamental parameters such as the minimum mass of the components of the system (due to the coupling with the orbital inclination).

However, it is the combined analysis of photometric light curves and radial velocity variations that provides the individual masses and radii of the exoplanets and components of the LMEBs along with many other physical parameters of the observed systems.

4 Observing Candidates

Several catalogues of exoplanet and LMEB candidates discovered in the Kepler/K2 mission have been published during last few years e.g., Coughlin et al. (2011), Barros et al. (2016) and Vanderberg (2016). A majority of these Kepler candidates are not fully characterized. Hence a follow-up photometric and spectroscopic observations of these candidates are necessary. As most of the reported planetary candidates are not bright enough to be observed with the high-resolution spectroscopic instruments currently available to us, we focus only on the objects brighter than 10.5 mag. Since we tentatively know the period (P_{orb}) and the mid-transit time (Epoch), transit depth and total duration of the primary eclipse/transit for each of these candidates, we can plan the observations during the times of their transits/eclipses.

5 Observing facilities under the project

5.1 1.3-m Devasthal Fast Optical Telescope

At the Devasthal Observatory, Nainital, the 1.3-m Devasthal Fast Optical Telescope (DFOT) is operational in an excellent site with the main objective to monitor optical and near-infrared flux variability in astronomical sources such as transiting exoplanets, stellar variables (pulsating, eclipsing and irregular), etc. To demonstrate the observing capability of DFOT, we show a differential light curve of the known transiting exoplanet WASP-12 along with the model fit in Figure 2 (see detail in Maciejewski et al. 2013). Though individual magnitudes have a typical photometric accuracy of 2 mmag for about 12 mag star in a 5-sec exposure, the accuracy has gone down to better than 1 mmag when 20 continuous frames are co-added to construct the final light curve. It clearly shows that science programs such as exoplanet study which require a photometric accuracy of few mmag on a time scale of a few hours could be possible under good photometric conditions.

5.2 3.6-m Devasthal Optical Telescope

At the Devasthal Observatory, we also have a 3.6-m Devasthal optical telescope (DOT) which is equipped with a number of instruments providing high resolution spectral and imaging capabilities at visible and near-infrared bands e.g. 4kx4k back-illuminated CCD imager, ARIES Faint Object Spectrograph and Camera (FOSC), TIFR-ARIES Near Infrared Spectrograph (TANSPEC) and TIFR Near Infrared Imaging Camera (TIRCAM) (see, Kumar et al. 2018). We shall use this telescope to confirm some of the most interesting objects resulting from the 1.3-m DFOT observations. Furthermore, any transit or eclipse variations of low-mass cool stars will be prominently detected in the infrared using 3.6-m DOT equipped with high-sensitive instruments. A high-resolution ARIES spectrograph capable of giving continuous spectral coverage (380 nm to 900 nm) in a single exposure is also planned for the 3.6-m DOT. It is expected to measure the stellar spectrum with a stability of 2-10 m/s down

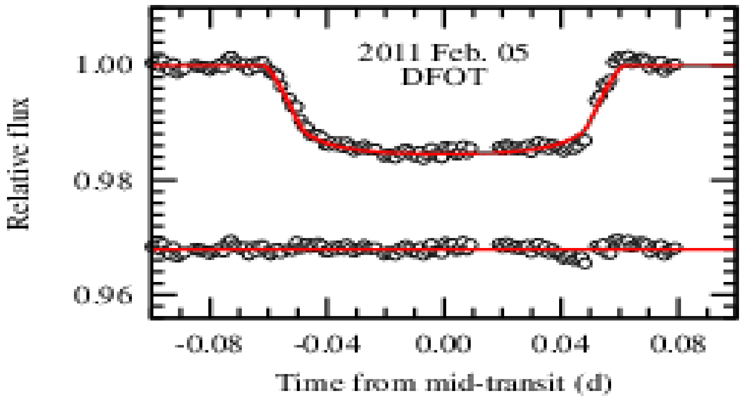

Figure 2: The R-band differential light curve of the transiting exoplanet WASP12 observed with the 1.3-m DFOT at Devasthal, Nainital. Each single data point in the light curve represents flux from twenty co-added frames. A typical error in each data point is of the order of 1 mmag. The best fit model is also overplotted with a continuous line (for detail, see Maciejewski et al. 2013).

to 14 mag and function in two modes of resolution 80,000 and 40,000. Once commissioned, this instrument shall be very helpful in the precise determination of elemental abundances in stars as well as radial velocity study of bright exoplanet and LMEB candidates.

5.3 HESP on 2-m Hanle Chandra Telescope

Hanle Echelle Spectrograph (HESP) is a fibre-fed, high-resolution (R = 30,000 and 60,000), spectrograph for the 2-m Hanle Chandra Telescope (HCT). The spectrograph has a large wavelength coverage (350-1000 nm) in a single exposure and high throughput ($\sim$ 20%). One can achieve a radial velocity accuracy of around 20 m/s in ThAr reference mode. The instrument is already operational and capable of monitoring about 11 mag stars with S/N = 15 at R = 60,000 with an hour exposure time. The high mechanical stability and double fibre mode allow the measurement of precise radial velocities, essential for programs such as exoplanet studies, asteroseismology and the determination of chemical abundances of low-mass stars.

5.4 HERMES on 1.2-m Mercator telescope

HERMES (High Efficiency and Resolution Mercator Echelle Spectrograph) is a high-resolution fibre-fed spectrograph installed at the Nasmyth focus of the 1.2-m Mercator telescope at the Spanish Roque de los Muchachos observatory where high resolution spectra ($R = 85000$) in the wavelength range from 380 to 900 nm in a single exposure can be obtained. It has an excellent throughput with a peak efficiency of 28%. The spectrograph routinely observes $V \sim 10$ mag stars having S/N of 100 within an hour of integration time (in HRF mode) which can go down to $V \sim 13$ mag stars with S/N of 20 in a similar time scale. A detail description can be found in Raskin et al. (2011).

It should be noted here that we have already acquired some observing time on DFOT, HESP and HERMES to monitor four of our target stars to do the photometric and spectroscopic observations under this programme. Once enough data is accumulated, we will analyse our data for any exoplanetary or LMEB signature in the selected objects.

6 Expected Scientific Output

6.1 Exoplanet detection

To fully characterize the possible exoplanetary systems, we need both photometric as well as spectroscopic observations of the candidate stars.

1. Photometry will allow us to determine the size ratio of the transiting body to the host star. Knowledge of the radius of the host star will yield the size of the transiting body while transit light curve fitting will provide more accurate values of parameters like transit time and duration than those provided by the Kepler photometry only.

2. The radial velocity curves determined from the multi-epoch spectra will be used to determine the orbital parameters that also includes an accurate determination of the stellar parameters (effective temperature, surface gravity, metallicity, projected rotational velocity) and abundances. We can also determine the minimum mass limit and the spin-orbit alignment through Rossiter-MacLaughlin effect that tells whether the transiting body is in a retrograde or prograde orbit at the time of transit.

It is known that while the transit method provides a good estimate of the radius of exoplanet along with the orbital inclination, the radial velocity method provides estimates of the masses coupled with the inclination, and together they provide a robust estimate of both mass and radius of the exoplanet hence its density. Only after acquiring both photometric and spectroscopic observations, we can figure out whether these systems are exoplanet-hosting stars or LMEBs mimicking planetary signatures. The estimate of their density will enable us to characterize these systems e.g., to distinguish between rocky and gas giant planets.

6.2 LMEBs detection and Mass-Radius relation

Since the photometric light curve of an LMEB is similar to that of a transiting hot Jupiter (Triaud et al. 2017), their photometric variation creates a false alarm of exoplanet detection. Continuous observations of such objects are particularly important because the eclipse geometry severely constrains the orbital inclination, and this, in turn allows their masses and radii to be precisely derived. The precise mass and radius determinations of significant number of LMEBs provide data for the study of the mass-radius relation of the low-mass stars. Since the number of such stars with detailed knowledge is still small, the study of these kind of systems can be extremely useful.

After the completion of the *ORBIT* project, we hope to substantially increase the number of LMEBs with accurate masses, radii and metallicities which will be tools to characterize the mass-radius relation towards the low-mass regime. This will, in turn be helpful in the development of low mass binary evolution models.

6.3 Atmospheric study of exoplanets

The transit method is very important to study the exoplanets atmospheres because during the phases of ingress and egress, the light from the star passes through the atmosphere of the exoplanet which can be revealed through the molecular absorption features of the host star. One can use high-resolution spectroscopic observations to study exoplanetary atmospheric properties by comparing the spectra of the host star during in-transit and out-of-transit period. However, it is not trivial to do this kind of transmission spectroscopy for the fainter stars or low-mass planetary companions as it is mainly limited to brighter Jovian planets, mostly carried out through spaced-based telescopes like Hubble and

Spitzer (Sing et al. 2016). Though challenging, one could explore to study the planetary atmosphere using the available (or upcoming) instruments on 3.6-m DOT located at such an excellent observing site.

7 Summary

In the *ORBIT* project, we aim to study many exoplanets and LMEB candidates that have been reported from the analysis of archival data produced by the Kepler space mission. The combined high-precision photometric and high-resolution spectroscopic observations are required to infer the true nature of exoplanetary signature. Furthermore, it would tell whether such variations are generated by the stellar signatures like stellar spots or other magnetic activities which otherwise may generate radial velocity variations of the order of few m/s that can overshadow the true radial velocity variations from the exoplanetary companions.

One persistent issue in the study of low-mass stars is whether inflated radii are caused by enhanced stellar rotation resulting from the magnetic activity. Having a larger number of LMEBs observed in the *ORBIT* project, we should be able to look into the cause of this phenomenon in the low-mass regime. Along with precise masses, radii and temperatures, these systems could yield valuable insights into the scenarios of binary formation in the low-mass regime. With an expected accuracy of 2-10 m/s in the proposed high-resolution instrument for the 3.6-m DOT, we may also be able to detect the Rossiter-McLaughlin effect in some of these systems in order to understand stellar rotation and their spin-orbit angle distributions.

Our long-term goal is to increase the number of exoplanets and LMEBs. The BINA network can offer access to the observational facilities which are in much demand to pursue the scientific objectives described in the ORBIT project.

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