Multiband Transit Follow-up Observations of Five Hot Jupiters with Critical Noise Treatments: Improved Physical Properties

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Abstract

The most challenging limitation in transit photometry arises from the noises in the photometric signal. In particular, the ground-based telescopes are heavily affected by the noise due to perturbation in the Earth’s atmosphere. Use of telescopes with large apertures can improve the photometric signal-to-noise ratio to a great extent. However, detecting a transit signal out of a noisy light curve of the host star and precisely estimating the transit parameters call for various noise reduction techniques. Here, we present multiband transit photometric follow-up observations of five hot Jupiters e.g., HAT-P-30 b, HAT-P-54 b, WASP-43 b, TrES-3 b, and XO-2 N b, using the 2 m Himalayan Chandra Telescope at the Indian Astronomical Observatory, Hanle, and the 1.3 m J. C. Bhattacharya Telescope at the Vainu Bappu Observatory, Kavalur. Our critical noise treatment approach includes techniques such as wavelet denoising and Gaussian process regression, which effectively reduce both time-correlated and time-un correlated noise components from our transit light curves. In addition to these techniques, use of our state-of-the-art model algorithms have allowed us to estimate the physical properties of the target exoplanets with a better accuracy and precision compared to the previous studies.

Unified Astronomy Thesaurus concepts: Transit photometry (1709); Exoplanets (498); Hot Jupiters (753); Wavelet analysis (1918); Gaussian Processes regression (1930); Markov chain Monte Carlo (1889)

1. Introduction

The transit photometry serves as one of the most important methods in the context of exoplanet detection and characterization. This method helps us to determine several physical parameters of a transiting exoplanet, e.g., the radius, the inclination angle of the planetary orbit with respect to our line of sight, and the semimajor axis. However, a prior knowledge of the stellar radius is necessary for the estimation of these parameters. Modeling the transit light curves also allows us to determine the limb-darkening properties of the parent stars. Moreover, the orbital inclination angle estimated by using the transit method can be combined with the radial-velocity measurements, if available, and a prior knowledge of stellar mass to precisely estimate the mass of those exoplanets (Southworth et al. 2007; Chakrabarty & Sengupta 2019).

The photometric observations obtained from the ground-based telescopes are heavily affected by the turbulence in the Earth’s atmosphere. This significantly adds to the overall noise in the observed signal. Moreover, if the ground-based survey telescopes used for the detection of new transiting exoplanets is small, it gives rise to a poor signal-to-noise ratio (S/N) in the observed transit signals. Therefore, repeated follow-up observations are very important in order to estimate the physical properties of the confirmed exoplanets with a good accuracy and precision. Repeated follow-up observations with telescopes of larger aperture can result in high S/N in the transit light curves causing small error bars in the light curves. Further, in order to achieve an improved accuracy and precision in the values of the estimated transit parameters, application of critical noise reduction techniques is essential to reduce the fluctuations prevailing in the transit light curves. The results from transit follow ups spanning over a large period of time can be used for the studies of planetary dynamics and may reveal the presence of any undiscovered planetary mass objects in those systems (Nesvorný et al. 2012; Johnson et al. 2015; Gillon et al. 2017; Patra et al. 2017; Maciejewski et al. 2018).

Our ongoing project involves the photometric follow up of transiting exoplanets using multiple photometric bands and analysis using noise reduction techniques for an improved estimation of the physical properties. For photometric follow up, we use the 2 m Himalayan Chandra Telescope (HCT) at the Indian Astronomical Observatory, Hanle, and the 1.3 m J. C. Bhattacharya Telescope (JCBT) at the Vainu Bappu Observatory, Kavalur. Chakrabarty & Sengupta (2019) (hereafter, CS19) have reported the results from their observations of five hot Jupiters, namely WASP-33 b, WASP-50 b, WASP-12 b, HATS-18 b, and HAT-P-36 b using the same telescopes as a part of this project and have addressed to the different sources of noise to improve the accuracy and precision of the estimated parameters. CS19 have segregated the noises according to their presence and spatial scales of span, and employed different techniques for the treatment of different kinds of such noises, including wavelet denoising and Gaussian process regression.

As a continuation of this project, we have followed up five more hot Jupiters using the same telescopes but in multi-wavelength bands. These are HAT-P-30 b (e.g., Johnson et al. 2011), HAT-P-54 b (e.g., Bakos et al. 2015), WASP-43 b (e.g., Hellier et al. 2011; Esposito et al. 2017), TrES-3 b (e.g., Sozzetti et al. 2009; Christiansen et al. 2011), and XO-2 N b (e.g., Damasso et al. 2015). The multiband observations of transits enable us to estimate the wavelength dependent physical parameters, such as planetary radius, with a better accuracy corresponding to each photometric band.

One of the most prominent noise component in the photometric light curves is the time-uncorrelated noise (white noise), which consists of both photon noise and the fluctuations in the light curve due to the small spatial scale variability in the
transparency of Earth’s atmosphere (CS19), such as atmospheric scintillation (Osborn et al. 2015; Föhring et al. 2019). Most of the preprocessing techniques (such as binning and Gaussian smoothing) that can reduce the effect of these time-un correlated noise components also tend to distort the shape of the transit signal. CS19 have demonstrated that the wavelet denoising technique (Donoho & Johnstone 1994; Pan et al. 1999; Luo & Zhang 2012; del Ser et al. 2018; Cubillos et al. 2017; Waldmann 2014) can be used to reduce the time-un correlated fluctuations in the light curves without distorting the transit signal and improving the precision of the estimated physical parameters (see Tables 3 and 4 of CS19) to a great extent. Wavelet denoising technique also reduces the outliers in the light curves due to cosmic-ray events. In the present work, we have used the same technique to preprocess the transit light curves. However, while applying this technique in the present studies, we have made some appropriate upgradation. This was essential in order to handle multiband data sets and a greater number of free parameters.

Another important noise component in the photometric signals is the time-correlated noise (red noise). We have reduced the large temporal scale red noise due to various instrumental and astrophysical effects by using the baseline correction method. On the other hand, the time-correlated fluctuations in the light curves of short temporal scale are due to the small spatial scale variations that affect each object on a frame differently (CS19). The major sources of this kind of red noise is the small-scale activity and pulsation of the host stars. Following CS19, we address this red noise component by using Gaussian process (GP) regression method (Rasmussen & Williams 2006; Johnson et al. 2015; Pereira et al. 2019; Barros et al. 2020) to model it simultaneously while modeling for the transit signal.

In order to model the transit light curves, we have used the analytical formalism provided by Mandel & Agol (2002), which also incorporates the limb-darkening effect of the host star using the quadratic limb-darkening law. Following CS19, we have used the Markov Chain Monte Carlo (MCMC) method with the Metropolis–Hastings algorithm (Hastings 1970) while modeling the transit light curves simultaneously along with the GP regression of the red noise. Although the MCMC sampling technique is computationally expensive, it is extremely effective for modeling any noisy signal with a large number of free parameters.

Unlike the work by CS19, in the present work we have set the radius of a planet as a free parameter for each wavelength band corresponding to each filter used. This allows us to get a coarse estimation of the band-dependent radius of the planets. This can be helpful in characterizing the planets by studying the broad atmospheric features, if any, in those ultra-low-resolution transit spectra detected with the help of the model transmission spectra in optical and in near-infrared regions (Chakrabarty & Sengupta 2020; Sengupta et al. 2020).

For the simultaneous handling of multiple observed photometric data from different nights of observation and a smooth and streamlined implementation of all the state-of-the-art techniques for reduction, photometry, processing, and modeling of the light curves, we have used the software package developed by us. This Python-based package uses a semi-automated approach and is functionally not much different from the pipeline developed and used by CS19. All the steps in this package aim at a precise estimation of the planetary properties from the transit light curves, which are at the same time robust, accurate, and reliable.

In Section 2, we have described our observational details. In Section 3, we have detailed our analysis and modeling techniques. In Section 4, we have discussed the significance of our results and in Section 5, we have concluded our study.

### Table 1

| Sources                          | HAT-P-30 b                  | HAT-P-54 b                  | WASP-43 b                  | TrES-3 b                  | XO-2 N b                  |
|---------------------------------|-----------------------------|-----------------------------|----------------------------|----------------------------|----------------------------|
| P (days)                        | 2.810595 ± 0.000005         | 3.799847 ± 0.000014         | 0.813475 ± 0.000001        | 1.30618608 ± 0.00000038   | 2.61585922 ± 0.00000028   |
| $K_{RV}$ (m s$^{-1}$)           | 88.1 ± 3.3                  | 132.6 ± 4.9                 | 551.0 ± 3.2               | 378.4 ± 9.9               | 90.17 ± 0.82              |
| $R_m$ (R$_*$)                   | 1.215 ± 0.051               | 0.617 ± 0.013               | 0.6506 ± 0.0054           | 0.829 ± 0.022             | 0.998 ± 0.033             |
| $M_*$ (M$_*$)                   | 1.242 ± 0.041               | 0.645 ± 0.020               | 0.688 ± 0.037             | 0.928 ± 0.048             | 0.96 ± 0.05               |
| $T_{eff}$ (K)                   | 6304 ± 88                   | 4390 ± 50                   | 4500 ± 100                | 5650 ± 75                 | 5332 ± 57                 |

2. Data Reduction and Analysis

In this paper we report the follow up of five hot Jupiters, e.g., HAT-P-30 b, HAT-P-54 b, WASP-43 b, TrES-3 b, and XO-2 N b. The adopted physical properties of these exoplanets and their host stars are listed in Table 1.

Our photometric observations are conducted using the 2 m HCT at the Indian Astronomical Observatory, Hanle, and the 1.3 m JCMT at Vainu Bappu Observatory, Kavalur. At the HCT, the Hanle Faint Object Spectrograph Camera (HFOSC) was used for photometric observations in V, R, and I bands (Bessel), whereas the TIFR Near-infrared Spectrometer and Imager (TIRSPEC) was used for the observations in the J band. At the JCMT, the UKATC optical CCD and the ProEM imagers were used for the photometric observations at V, R, and I bands. We have also made simultaneous observations of a few similar magnitude stars present within the photometric field of view of the target host stars. These are used as reference stars for the differential photometry, as described in the next section. The details of our observations have been listed in Table 2. Our observations have been optimized for mid-high cadence and high S/N. As can be seen from the table, the observations from JCMT have mean S/N > 250. On the other hand, the observations from HCT/HFOSC have very-high cadence and mean S/N > 1000.

3. Data Reduction and Analysis

We have reduced the raw photometric data to obtain the transit light curves, which are then processed through several techniques to reduce the noises from various sources. We have then modeled the processed light curves in order to obtain the transit parameters. These parameters are then used to derive a few other physical properties of the exoplanets. For the whole...
process of both data reduction and analysis, we have used our software package, which is written in Python programming language and uses several open-source software libraries. A detailed explanation of our methodology is given in the following subsections.

3.1. Data Reduction and Differential Photometry

Our observational data obtained on each night consists of a large number of photometric frames, which are reduced through our automatic pipeline that uses the standard PyRAF libraries in the back end. The raw photometric data are first calibrated using the bias and flat frames obtained during the respective nights of observations. Since all the instruments used in our observations are cooled up to $-70^\circ\text{C}$, the dark noise is found to be negligible. The calibrated frames are used to obtain the flux from our target host stars and the reference field stars using aperture photometry. We have calculated the photometric noise precisely using the formula:

$$N = \sqrt{f/g + a \times s^2 + a^2 \times s^2/k},$$

where $f$ is the sky-subtracted flux of the target object, $s$ is the standard deviation of the counts on the region of the sky surrounding the object, $g$ is gain of the instrument, $a$ is the area of aperture of the object chosen in square pixels, and $k$ is number of sky pixels. We have converted the timescale to BJD-TDB using the utc2bjd online applet (Eastman et al. 2010).

The observations from the ground-based telescopes are heavily affected by the varying atmospheric transparency and air-mass effect, which can be reduced using the differential photometry method. We have used the flux of the reference field stars with the best $S/N$ and minimum differential fluctuations for the differential photometry of our target host stars and obtained the photometric transit light curves.

3.2. Baseline Correction

The red noise of the large temporal scale (i.e., more than the characteristic scale of transit durations), which is mainly due to various instrumental effects and long-term stellar variability, results in a nonflat baseline for the photometric signals. One way to address this noise component is to model it using simple polynomial fits alongside the transits and subtract from the light curves. However, it risks a potential bias in the estimated parameters due to the large scale nature of these noise components and an increment in the parameter load in the already heavily populated model parameter space for MCMC sampling (see 3.5).

We have, therefore, performed the baseline correction before modeling for the transit signals. We have used linear and quadratic polynomials of time to model the out of transit part of the light curves and chosen the one with the least Bayesian information criterion (Schwarz 1978) for the baseline correction. Use of only the out-of-transit portion of the light curves for baseline modeling removes the risk of the low-mid temporal scale variations in transit signal influencing the determination of baseline coefficients. Hence, it removes the risk of potential manipulation in the estimated transit parameters. The normalized baseline corrected transit light curves from our observations are shown in Figures 1–5.

3.3. Wavelet Denoising

The time-uncorrelated noise (white noise) in the photometric signal also consists of the fluctuations in the light curve due to the small spatial scale variability in the transparency of the Earth’s atmosphere. The presence of such fluctuations are more evident in the high-cadence photometric observations due to a better temporal resolution. They can severely affect both accuracy and precision of the estimated transit properties from those light curves. The white noise component cannot be totally

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Table 2
Details of the Photometric Observations

| Target Name | Date       | Telescope | Instrument | Filter | No. of frames | $S/N$ (Mean) |
|-------------|------------|-----------|------------|--------|---------------|--------------|
| HAT-P-30 b  | 2020-02-05 | JCBT      | UKATC      | V      | 42            | 747.92       |
|             | 2020-02-05 | HCT       | HFOSC      | I      | 315           | 2002.55      |
|             | 2020-02-22 | HCT       | HFOSC      | R      | 233           | 1508.76      |
|             | 2020-03-10 | JCBT      | UKATC      | I      | 50            | 482.48       |
|             | 2020-03-24 | JCBT      | UKATC      | V      | 22            | 747.37       |
| HAT-P-54 b  | 2020-01-15 | JCBT      | UKATC      | I      | 24            | 570.82       |
|             | 2020-02-03 | JCBT      | UKATC      | I      | 56            | 410.26       |
|             | 2020-02-03 | HCT       | HFOSC      | V      | 160           | 1001.14      |
|             | 2020-02-22 | HCT       | HFOSC      | R      | 93            | 1544.17      |
| WASP-43 b   | 2019-03-06 | JCBT      | UKATC      | V      | 85            | 379.06       |
|             | 2019-04-02 | JCBT      | UKATC      | V      | 93            | 390.22       |
|             | 2019-04-11 | JCBT      | UKATC      | R      | 54            | 606.31       |
|             | 2019-12-31 | HCT       | HFOSC      | I      | 261           | 1264.00      |
|             | 2020-02-05 | HCT       | TIRSPEC    | J      | 232           | 226.06       |
|             | 2020-02-14 | JCBT      | UKATC      | R      | 31            | 662.59       |
| TrES-3 b    | 2019-02-18 | JCBT      | UKATC      | I      | 96            | 283.19       |
|             | 2019-05-03 | JCBT      | UKATC      | R      | 50            | 337.95       |
|             | 2019-05-31 | JCBT      | UKATC      | I      | 26            | 537.23       |
|             | 2020-09-21 | HCT       | HFOSC      | V      | 203           | 1447.40      |
| XO-2 N b    | 2020-01-28 | JCBT      | UKATC      | I      | 54            | 710.21       |
|             | 2020-02-05 | HCT       | HFOSC      | V      | 292           | 1789.22      |
|             | 2020-02-18 | JCBT      | ProEM      | I      | 40            | 782.06       |
|             | 2020-02-18 | HCT       | HFOSC      | R      | 622           | 1261.56      |
|             | 2020-03-23 | JCBT      | UKATC      | I      | 27            | 699.05       |
Figure 1. Observational and modeled light curves for HAT-P-30 b. For each observed transit event (see Table 2), the observation date, the instrument, and the photometric filter used are mentioned. Top: the unprocessed light curve (cyan), light curve after wavelet denoising (magenta), and the best-fit transit model (orange). Middle: the residual after modeling without GP regression (magenta), the mean (orange), and 1-σ interval (cyan) of the best-fit GP regression model. Bottom: mean residual flux (orange).
removed from a signal and should be only reduced cautiously without distorting the informative part of the signal. Hence, instead of smoothing the light curves with a low-pass filter, we used a more robust technique; namely the wavelet denoising (Donoho & Johnstone 1994; Pan et al. 1999; Luo & Zhang 2012). Although wavelet based denoising techniques have been widely used in image processing and remote sensing in various fields of science and engineering, it is a recent addition in the context of transit photometry and other light-curve analysis (e.g., Waldmann 2014; Cubillos et al. 2017; del Ser et al. 2018). CS19 applied this technique on the light curves obtained from their observational data and demonstrated that this technique produces no distortion in the transit light curves, but yields better MCMC posterior distributions for the fitted transit parameters.

Wavelet denoising consists of mainly three steps: deconstruction of the original signal into wavelet coefficients using discrete wavelet transform, thresholding, and reconstruction of the signal from the thresholded coefficients. We have used the PyWavelets (Lee et al. 2019) python package to perform the single-level discrete wavelet transform of our photometric light curves. In this process, we have used the Symlet family of wavelets, which are the least asymmetric modified version of Daubechies wavelets. A single-level transform removes the risk of excess denoising. We have calculated the threshold value using the universal thresholding law (Donoho & Johnstone 1994),

**Figure 2.** Same as Figure 1, but for HAT-P-54 b.
Figure 3. Same as Figure 1, but for WASP-43 b.
where \( \sigma = \left| \text{median}(D_x) \right| / 0.6745 \), and performed the hard thresholding, where the wavelet coefficients with absolute values less than the threshold value are replaced with it. The advantage behind universal threshold is that the risk of thresholding is small enough to satisfy the requirement of most applications. The threshold coefficients are then used to construct the denoised signal. The transit light curves after wavelet denoising are shown in Figures 1–5.

3.4. Gaussian Process Regression

The small-mid temporal scale red noise, which is correlated in time, forms the major source of the remaining reducible noise components in our transit light curves after the wavelet denoising. This noise is primarily due to the small-scale activity of the host stars. To reduce this noise component, we have used
Figure 5. Same as Figure 1, but for XO-2 N b.
We have modeled the time-correlated noise in the transit light curves using GP regression alongside modeling for the transit signals, using the MCMC technique (see Section 3.5). In order to treat the photometric noise in our observed light curves while modeling for time-correlated noise, we have followed the regression formalism as given by Rasmussen & Williams (2006) for noisy observations. In this process, we have used the Matérn class covariance function with parameter of covariance, $\nu = 3/2$, and two free parameters, e.g., the signal standard deviation $\alpha$ and the characteristic length scale $\tau$, which are used as model parameters in the MCMC sampling.

### 3.5. MCMC Sampling

In the final phase of our analysis of the transit light curves, we modeled them to the analytical transit formulation following Mandel & Agol (2002), which also incorporates the limb darkening effect of the host star using the quadratic limb-darkening law given by

$$I(\mu) = 1 - C_1(1 - \mu) - C_2(1 - \mu)^2.$$  

We used the MCMC sampling technique for this modeling, and simultaneously modeled for the time-correlated noise in the signal using the GP regression method as explained in Section 3.4. The model parameters in the MCMC include the transit parameters: (i) midtransit time $T_i$; (ii) the impact-parameter $b$; (iii) the scaled stellar radius $R_p/R_*$; (iv) the ratio of planet to stellar radius $R_p/R_*$; (v) the out-of-transit flux $f_0$; (vi) the limb darkening coefficients $C_1$ and $C_2$; and (vii) the GP regression coefficients $\alpha$ and $\tau$. The orbital periods have been kept constant and are adopted from previous studies as given in Table 1. We have followed Sing (2010) for the prior values of the quadratic limb-darkening coefficients.

We have modeled all the transit light curves corresponding to each of our target exoplanets simultaneously keeping the transit independent parameters the same for all transit events of the same target and keeping the wavelength dependent parameters same across those transit events observed using the same photometric filters. We have used the Metropolis–Hastings algorithm (Hastings 1970) in the MCMC sampling and used the modified marginal likelihood function due to the inclusion of the GP regression technique (Rasmussen & Williams 2006). In MCMC sampling for each of our targets, we used 30 walkers and 100,000 iterations for each independent walker. Such a large volume of sampling is done in order to handle the large number of model parameters and high volume of photometric data under simultaneous modeling of multiple transit events. The aim has been to assess the robustness of the convergence of the sampling parameters such that a high accuracy in the derived parameters is achieved. Such a large computation is practically impossible without the incursion of parallel computing. For this purpose, our software package for modeling and data analysis has been facilitated with parallel computing using the Python-based multiprocessing library. We have used the high-performance computing facility (NOVA) at the Indian Institute of Astrophysics (IIA) for our numerical computation. We have discarded the first 10,000 iterations for each walkers as burn-in and accepted the rest 90,000 iterations for obtaining the posterior distributions.

We have shown the corner diagrams depicting the posterior distributions of the transit parameters and the GP regression coefficients from our MCMC sampling in the Figures A1–A5 in the Appendix.

We present the best-fit transit models, best-fit GP regression model, and the mean residual fluxes in Figures 1–5. The estimated values of the physical properties for our target exoplanets with $1\sigma$ error have been given in Tables 3–7 and the estimated values of midtransit times along with the GP regression coefficients for each transit light curves have been given in Table 8.

### 3.6. Derived Parameters

The posterior distribution of the transit parameters from the MCMC sampling along with the adopted physical properties of the target exoplanets and the host stars, as given in Table 1, are used to estimate the values of some other physical parameters.

We have estimated the transit duration $T_{14}$ for each of our targets at each photometric band using the relation (CS19)

$$T_{14} = \frac{P}{\pi} \sin^{-1} \left( \frac{(1 + R_p/R_*)^2 - b^2}{\sqrt{(a/R_p)^2 - b^2}} \right).$$  

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**Note.**

* Value does not corresponds to the mentioned wavelength filter.

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**Table 3**

**Estimated Values of Physical Parameters for HAT-P-30 b**

| Parameter | Filter | This work | Johnson et al. (2011) |
|-----------|--------|-----------|----------------------|
| Transit parameters | | | |
| $b$ | 0.854$^{+0.008}_{-0.010}$ | 0.854$^{+0.008}_{-0.010}$ | |
| $R_p/a$ | 0.143$^{+0.010}_{-0.013}$ | 0.1348 $\pm 0.0047$ | |
| $R_p/R_*$ | V | 0.1075$^{+0.0165}_{-0.0102}$ | 0.1134 $\pm 0.0022$ |
| $I$ | 0.1134$^{+0.0105}_{-0.0093}$ | 0.1168$^{+0.0010}_{-0.0004}$ | |
| Limb-darkening coefficients | | | |
| $C_1$ | V | 0.329$^{+0.020}_{-0.020}$ | 0.1975$^a$ |
| $R$ | 0.329$^{+0.020}_{-0.020}$ | 0.329$^{+0.020}_{-0.020}$ | |
| $I$ | 0.329$^{+0.020}_{-0.020}$ | 0.329$^{+0.020}_{-0.020}$ | |
| $C_2$ | V | 0.280$^{+0.020}_{-0.020}$ | 0.3689$^a$ |
| $R$ | 0.280$^{+0.020}_{-0.020}$ | 0.280$^{+0.020}_{-0.020}$ | |
| $I$ | 0.279$^{+0.021}_{-0.019}$ | 0.279$^{+0.021}_{-0.019}$ | |
| Derived parameters | | | |
| $T_{14}$ (hr) | V | 2.180$^{+0.025}_{-0.022}$ | 2.129 $\pm 0.036^a$ |
| $R$ | 2.180$^{+0.025}_{-0.022}$ | 2.180$^{+0.025}_{-0.022}$ | |
| $I$ | 2.223$^{+0.024}_{-0.021}$ | 2.223$^{+0.024}_{-0.021}$ | |
| $a/R_*$ | 6.994$^{+0.060}_{-0.062}$ | 7.42 $\pm 0.26$ | |
| $i$ (deg) | 82.982$^{+0.082}_{-0.087}$ | 83.6 $\pm 0.4$ | |
| $M_p(M_j)$ | 0.713$^{+0.031}_{-0.031}$ | 0.711 $\pm 0.028$ | |
| $M_p(M_\odot)$ | 226.2$^{+9.8}_{-9.7}$ | 226.0 $\pm 8.9$ | |
| $T_{eq}(K)$ | 1686$^{+24.8}_{-24.7}$ | 1630 $\pm 42$ | |
| $a$ (au) | 0.0394$^{+0.00170}_{-0.00169}$ | 0.0419 $\pm 0.0005$ | |
| $R_p(R_\odot)$ | V | 1.2995$^{+0.0482}_{-0.0481}$ | 1.340 $\pm 0.065^a$ |
| $R$ | 1.3720$^{+0.0505}_{-0.0495}$ | 1.3720$^{+0.0505}_{-0.0495}$ | |
| $I$ | 1.4122$^{+0.0482}_{-0.0480}$ | 1.4122$^{+0.0482}_{-0.0480}$ | |
| $R_p(R_\odot)$ | V | 14.566$^{+0.549}_{-0.539}$ | 15.02 $\pm 0.73^a$ |
| $R$ | 15.379$^{+0.546}_{-0.535}$ | 15.379$^{+0.546}_{-0.535}$ | |
| $I$ | 15.829$^{+0.541}_{-0.538}$ | 15.829$^{+0.541}_{-0.538}$ | |

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* Value does not corresponds to the mentioned wavelength filter.
The inclination angle of the planetary orbit $i$ is estimated using the relation

$$i = \cos^{-1}\left(\frac{bR_p}{a}\right).$$

We have estimated the mass $M_p$ and the equilibrium temperature $T_{eq}$ of the target exoplanets using the relations (CS19),

$$M_p = M_\star^{2/3}\left(\frac{P}{2\pi G}\right)^{1/3} \frac{K_{RV}}{\sin i}$$

and

$$T_{eq} = T_{eff}\sqrt{\frac{R_p}{2a}}.$$

For all the cases, we have assumed circular orbits, zero Bond albedo, and full recirculation of the incident stellar flux over the planetary surface. The estimated values of all the derived physical properties for each of our targeted exoplanets are given in the Tables 3–7.

### 4. Results and Discussion

Our study involves the photometric follow-up observations of five hot Jupiters using 1.3 m (JCBT) and 2 m (HCT) class telescopes. Table 1 shows that the observations from the HCT have a better S/N and time cadence. This can be attributed to the large aperture of HCT, the short readout time of the new CCD installed at the back end (HFOSC2), and the good observational condition at the site of the IAO. However, the observations from JCBT also show the good S/Ns and have been extremely useful in complementing the observations from the HCT. Since the number of nights allocated at each telescope is limited, we use both the telescopes for our observations.

Figures 1–5 demonstrate that the wavelet denoising technique is a useful tool for the reduction of the time-un correlated noise components and outliers from the transit light curves. Also, we have avoided excessive smoothing of the light curves by cautiously choosing the decomposition levels and threshold levels while using this denoising technique.

The GP regression method has very effectively modeled the correlated noise components in the transit signal as shown in Figures 1–5. The origin of this correlated noise component is not only attributed to the low-scale variability of the exoplanet host stars, but also to that of the reference stars used for differential photometry. Since, the reference stars are different in most of the cases, due to various observational reasons, the amplitude of the correlated noises are different for the same target host star. Similarly, the correlated noise components are negligible for some of the low-cadence observations from

| Parameter | Filter | This work | Bakos et al. (2015) |
|-----------|--------|-----------|---------------------|
| $b$       |        | 0.7591±0.0060 | 0.741±0.010        |
| $R_p/a$   |        | 0.07175±0.00098 | 0.0697±0.0018 |
| $R_p/R_\star$ | $V$   | 0.15616±0.00024 | 0.1572±0.0028  |
| $R_p/R_\star$ | $I$   | 0.16898±0.00082 | 0.1572±0.0028 |
| $I$       |        | 0.17516±0.00165 | 0.1572±0.0028  |

Limb-darkening coefficients

$C_1$

$V$ | 0.627±0.043 | 0.4324* |
$R$ | 0.685±0.017 | 0.4324* |
$I$ | 0.630±0.028 | 0.4324* |

$C_2$

$V$ | 0.080±0.007 | 0.2457* |
$R$ | 0.080±0.007 | 0.2457* |
$I$ | 0.079±0.006 | 0.2457* |

Derived parameters

$T_{14}$ (hr)

$V$ | 1.819±0.021 | 1.797±0.017* |
$R$ | 1.855±0.020 | 1.797±0.017* |
$I$ | 1.872±0.021 | 1.797±0.017* |

$a/R_\star$ | 13.94±0.14 | 14.34±0.22 |
$i$ (deg) | 86.87±0.046 | 87.040±0.084 |
$M_p(M_\star)$ | 0.761±0.032 | 0.760±0.032 |
$M_p(M_J)$  | 241.8±10.1 | 242±10 |
$T_{eq}(K)$ | 832.0±10.8 | 818±12 |

$a$ (au) | 0.03994±0.00098 | 0.04117±0.00043 |

$R_p(R_\odot)$

$V$ | 0.9796±0.0130 | 0.944±0.028* |
$R$ | 1.0611±0.0133 | 0.944±0.028* |
$I$ | 1.0997±0.0137 | 0.944±0.028* |

$R_p(R_\odot)$

$V$ | 10.980±0.330 | 10.6±0.3* |
$R$ | 11.894±0.374 | 10.6±0.3* |
$I$ | 12.327±0.401 | 10.6±0.3* |

Note.

* value does not correspond to the mentioned wavelength filter.
Table 5

| Parameter | Filter | This work | Esposito et al. (2017) |
|-----------|--------|-----------|------------------------|
| Transit parameters | | | |
| b | 0.681(±0.0054) -0.0038 | 0.689 ± 0.013 |
| R_p/a | 0.2188(±0.0018) -0.0013 | 0.2012 ± 0.0057 |
| R_p/R_⊕ | V 0.1644(±0.00132) -0.00126 | 0.1588 ± 0.004 |
| | R 0.1626(±0.00127) -0.00142 | |
| | I 0.1621(±0.00123) -0.00121 | |
| | J 0.1375(±0.0013) -0.0033 | |
| Limb-darkening coefficients | | | |
| C_1 | V 0.627(±0.041) -0.026 | 0.66a |
| | R 0.635(±0.041) -0.029 | |
| | I 0.680(±0.036) -0.021 | |
| | J 0.645(±0.037) -0.029 | |
| C_2 | V 0.079(±0.007) -0.007 | |
| | R 0.079(±0.007) -0.006 | |
| | I 0.081(±0.006) -0.007 | |
| | J 0.080(±0.007) -0.006 | |
| Derived parameters | | | |
| T_14 (hr) | V 1.3046(±0.0090) -0.0084 | 1.164 ± 0.24a |
| | R 1.3016(±0.0090) -0.0089 | |
| | I 1.3010(±0.0091) -0.0094 | |
| | J 1.2583(±0.0102) -0.0118 | |
| a/R_⊕ | 4.584(±0.036) -0.037 | 4.97 ± 0.14 |
| i (deg) | 81.46(±0.12) -0.11 | 82.109 ± 0.088 |
| M_p (M_⊕) | 1.994(±0.072) -0.073 | 1.998 ± 0.079 |
| M_p (M_⊕) | 633.9(±27.7) -23.1 | 635.0 ± 25.1 |
| T_eq (K) | 1486.3(±33.3) -33.3 | 1426.7 ± 8.5 |
| a (au) | 0.01387(±0.00016) -0.00016 | 0.01504 ± 0.00029 |
| R_p (R_⊕) | V 1.1000(±0.0590) -0.0594 | 1.06 ± 0.017a |
| | R 1.0900(±0.0590) -0.0594 | |
| | I 1.0857(±0.0587) -0.0586 | |
| | J 0.9195(±0.0546) -0.0530 | |
| R_p (R_⊕) | V 12.336(±0.671) -0.660 | 11.61 ± 0.21a |
| | R 12.218(±0.667) -0.664 | |
| | I 12.169(±0.657) -0.658 | |
| | J 10.31(±0.612) -0.604 | |

Note. 
^a value does not correspond to the mentioned wavelength filter.

JCBT. Our analysis shows the efficiency of GP regression technique in reducing the correlated noise components irrespective of their origin and amplitude.

Our MCMC sampling includes a large number of sampling points, which is helpful to remove any bias from the choice of prior values in the MCMC, thereby resulting in an more accurate estimation of the free parameters. This is evident from the near-normal distribution of most of the model-parameter posterior distributions as shown in the Figures A1–A5 in the Appendix. As can be seen from the estimated values of the midtransit times of our observed transit events, the independently estimated midtransit times for the same transit event observed from the two different telescopes (HCT and JCBT) in three different instances [2020-02-05 for HAT-P-30 b, 2020-02-03 for HAT-P-54 b, and 2020-02-18 for XO-2 N b] are in perfect agreement with each other, with the error bar in the estimated value from the HCT observation being small due to a better S/N. This proves the robustness of our analysis method in the estimation of these properties.

Due to the multiband observations of the transit events, we have been able to estimate the wavelength dependent radii of our target exoplanets with good accuracy at each band. Even though the site conditions at IAO allows observation in the infrared wavelengths, the S/N of the data observed using the TIRSPEC instrument at the back end of the HCT is significantly low, especially in the context of transit photometry. However, we managed to observe one frame in the J band for WASP-43 b. Apart from this, all of the targets have been observed in V, R, and I bands. We will further analyze these results to check if any information can be excavated about the atmospheres of these planets with the help of the models we have developed for transmission spectra (Chakrabarty & Sengupta 2020; Sengupta et al. 2020).

We have compared the estimated values of the physical parameters for the target exoplanets in our study with those from the previous studies (given in Tables 3–7) to understand the effectiveness of the critical noise reduction and modeling algorithm used in our study, and the improvement in the
accuracy and precision in the parameter estimation. While for most of the parameters, the estimated values are in good accordance with those from previous studies, small differences in a few parameter values can be attributed to the improvement in the quality of the transit signals due to the use of noise reduction algorithms; thereby improving the accuracy in parameter estimation. Also, the precision in the estimated values of the transit parameters and the parameters which are directly derived from them have been improved up to four values of the transit parameters and the parameters which are parameter estimation. Also, the precision in the estimated values are in good accordance with those from previous studies, small differences in the quality of the transit signals due to the use the noise reduction algorithms; thereby improving the accuracy in parameter estimation. Also, the precision in the estimated values of the transit parameters and the parameters which are directly derived from them have been improved up to four values of the transit parameters and the parameters which are directly derived from them have been improved up to four times compared to the previous studies, which is significant in the context of transit photometric studies of exoplanets. This improvement in the uncertainties in estimated parameters is due to a better S/N in our follow-up observations and further reduction of various noise components. On the other hand, the estimated values of other derived parameters, which are dependent upon the stellar properties of the host stars for their estimation (adopted from the previous studies and given in Table 1), have seen no significant improvements in their precision. This is due to the large uncertainties embedded with those adopted values of stellar parameters.

### 5. Conclusion

In this study, we have performed a new multiband transit photometric follow up of five hot Jupiters, HAT-P-30 b, HAT-P-54 b, WASP-43 b, TrES-3 b, and XO-2 N b, using the 2 m HCT at IAO, Hanle and the 1.3 m JCBT at VBO, Kavalur. Taking the advantage of the larger apertures of these telescopes compared to those used for previous studies of these exoplanets, we have obtained transit light curves with a better S/N.

Our critical noise treatment analysis employs the wavelet denoising technique for the reduction of time-uncorrelated noise components from the photometric light curves without potential loss of signal due to transit origins and the Gaussian process regression technique to effectively model and compensate for the time-correlated noise in the photometric signal simultaneously along with the transit modeling. We have used the MCMC sampling technique by adopting the Metropolis–Hastings algorithm.

Due to the high S/N photometric follow-up observations as well as the adopted highly optimized noise reduction and analysis techniques, the estimated physical parameters from our study have a better accuracy and overall precision. Also, the follow up using multiple photometric bands has enabled us to estimate accurately the wavelength dependent physical properties that can be used as an outset for the high-resolution atmospheric characterization of these exoplanets in future.

Our ongoing project of follow-up studies of the exoplanets can be extended for the study of other existing exoplanets in

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**Table 6**

Estimated Values of Physical Parameters for TrES-3 b

| Parameter          | Filter | This work          | Sozzetti et al. (2009) |
|--------------------|--------|--------------------|------------------------|
| Transit parameters |        |                    |                        |
| $b$                |        | 0.831$^{+0.0040}_{-0.0047}$ | 0.84 ± 0.01            |
| $R_p/a$            |        | 0.1681$^{+0.0021}_{-0.0020}$ | 0.1687 ± 0.0016        |
| $R_p/R_s$          | $V$    | 0.16483$^{+0.0081}_{-0.0092}$ | 1.655 ± 0.002*        |
|                    | $R$    | 0.17226$^{+0.0015}_{-0.0014}$ |                        |
|                    | $I$    | 0.16704$^{+0.0017}_{-0.0017}$ |                        |
| Limb-darkening coefficients |        |                    |                        |
| $C_1$              | $V$    | 0.454$^{+0.024}_{-0.027}$ | 0.4378                 |
|                    | $R$    | 0.447$^{+0.026}_{-0.025}$ |                        |
|                    | $I$    | 0.445$^{+0.027}_{-0.026}$ |                        |
| $C_2$              | $V$    | 0.251$^{+0.013}_{-0.013}$ | 0.2933                 |
|                    | $R$    | 0.249$^{+0.014}_{-0.014}$ |                        |
|                    | $I$    | 0.250$^{+0.013}_{-0.013}$ |                        |
| Derived parameters |        |                    |                        |
| $T_{14}$ (hr)      | $V$    | 1.387$^{+0.015}_{-0.015}$ |                        |
|                    | $R$    | 1.405$^{+0.016}_{-0.016}$ |                        |
|                    | $I$    | 1.393$^{+0.014}_{-0.015}$ |                        |
| $a/R_s$            |        | 5.948$^{+0.123}_{-0.073}$ | 5.926 ± 0.056          |
| $i$ (deg)          |        | 81.96$^{+0.113}_{-0.013}$ | 81.85 ± 0.16           |
| $M_p (M_J)$        |        | 1.955$^{+0.085}_{-0.084}$ | 1.91$^{+0.075}_{-0.080}$ |
| $M_p (M_E)$        |        | 621.1$^{+6.9}_{-7.6}$ | 607.030$^{+24.83}_{-24.825}$ |
| $T_{eq}$ (K)       |        | 1638.3$^{+241.4}_{-240}$ |                        |
| $a$ (au)           |        | 0.02293$^{+0.0016}_{-0.0016}$ | 0.02282$^{+0.00023}_{-0.00022}$ |
| $R_p (R_J)$        | $V$    | 1.4881$^{+0.0770}_{-0.0768}$ | 1.336$^{+0.0514}_{-0.0517}$ |
|                    | $R$    | 1.5555$^{+0.0830}_{-0.0823}$ |                        |
|                    | $I$    | 1.5100$^{+0.0796}_{-0.0796}$ |                        |
| $R_p (R_{Jup})$    | $V$    | 16.680$^{+0.360}_{-0.360}$ | 14.975$^{+3.478}_{-4.15}$ |
|                    | $R$    | 17.434$^{+0.922}_{-0.922}$ |                        |
|                    | $I$    | 16.935$^{+0.899}_{-0.899}$ |                        |

**Note.**

* value does not correspond to the mentioned wavelength filter.
### Table 7
Estimated Values of Physical Parameters for XO-2 N b

| Parameter                  | Filter | This work | Damasso et al. (2015) |
|----------------------------|--------|-----------|-----------------------|
| Transit parameters         |        |           |                       |
| b                         | 0.199±0.023 | 0.287±0.043 |
| R_p/a                     | 0.120±0.010 | 0.1261±0.0017 |
| R_p/R_s                   | 0.1070±0.0064 | 0.1049±0.0063 |
| R                         | 0.0979±0.0082 | 0.1016±0.0160 |
| i                         | 0.0039±0.0019 | 0.196±0.014 |
| Limb-darkening coefficients |       |           |                       |
| C_1                       | 0.503±0.030 | 0.474±0.038 |
| C_2                       | 0.466±0.011 | 1.019±0.031 |
| C_3                       | 0.194±0.015 | 1.019±0.370 |
| Derived parameters        |        |           |                       |
| T_{t4} (hr)               | 0.262±0.016 | 2.7024±0.0066 |
| R                         | 2.606±0.016 |                       |
| i                         | 2.615±0.017 |                       |
| a/R_s                     | 8.308±0.072 | 7.928±0.0099 |
| i (deg)                   | 88.63±0.21 | 87.96±0.43 |
| M_p (M_J)                 | 0.595±0.021 | 0.597±0.021 |
| M_p (E_{L1})              | 189.1±0.7 | 189.737±0.674 |
| T_{E} (K)                 | 1308.3±144 |                       |
| a (au)                    | 0.0385±0.0013 | 0.03673±0.00064 |
| R_p (R_J)                 | 0.9996±0.0052 | 1.019±0.031 |
| R                         | 0.9155±0.0046 | 1.019±0.370 |
| i                         | 0.9492±0.0059 | 1.019±0.370 |

Note.

*a* value does not correspond to the mentioned wavelength filter.

### Table 8
Midtransit Times and GP Regression Parameters for Each Observed Transit Event

| Target Name | Date     | Instrument/Filter | Midtransit time (BJD-TDB) | α       | γ       |
|-------------|----------|-------------------|---------------------------|---------|---------|
| HAT-P-30 b  | 2020-02-05 | UKATC/V           | 2458855.401561±0.002181 | 0.00054±0.00002 | 0.0582±0.0574 |
|             | 2020-02-05 | HFOSC/1           | 2458855.40116±0.00099   | 0.00158±0.00009 | 0.0263±0.0010 |
|             | 2020-02-22 | HFOSC/R           | 2458902.26518±0.00121   | 0.00159±0.00011 | 0.0240±0.0070 |
|             | 2020-03-10 | UKATC/K           | 2458919.12814±0.00182   | 0.00358±0.00042 | 0.0650±0.0402 |
|             | 2020-03-24 | UKATC/V           | 2458933.17581±0.000176  | 0.00030±0.000021| 0.0825±0.0992 |
| HAT-P-54 b  | 2020-01-15 | UKATC/V           | 2458864.20161±0.00411   | 0.00035±0.00021 | 1.007±0.0437 |
|             | 2020-02-03 | UKATC/1           | 2458833.20451±0.00427   | 0.0009±0.00059 | 0.0642±0.0122 |
|             | 2020-02-03 | UKATC/3           | 2458833.20455±0.00415   | 0.0015±0.00017  | 0.0711±0.0069 |
|             | 2020-02-22 | HFOSC/R           | 2458902.203596±0.00031  | 0.00091±0.00011 | 0.0564±0.0048 |
| WASP-43 b   | 2019-03-06 | UKATC/V           | 2458549.296039±0.00034  | 0.00112±0.00022 | 0.0581±0.0127 |
|             | 2019-04-02 | UKATC/V           | 2458576.140878±0.000294 | 0.00150±0.00022 | 0.0613±0.0123 |
|             | 2019-04-11 | UKATC/R           | 2458585.087944±0.00096  | 0.00096±0.00043 | 0.0848±0.0521 |
|             | 2019-12-31 | HFOSC/1           | 2458849.468659±0.00106  | 0.00171±0.00010 | 0.0235±0.0009 |
|             | 2020-02-05 | TIRSPEC/3         | 2458885.259449±0.00091  | 0.00407±0.00025 | 0.0276±0.0017 |
|             | 2020-02-14 | UKATC/R           | 2458894.207888±0.000365 | 0.00675±0.00026 | 0.0744±0.0022 |
|             | 2020-02-18 | UKATC/1           | 2458533.473769±0.00040  | 0.00223±0.00025 | 0.0281±0.0042 |
|             | 2019-05-03 | UKATC/R           | 2458607.351900±0.000409 | 0.0005±0.00022  | 0.0582±0.0246 |
|             | 2020-03-31 | UKATC/1           | 2458940.426286±0.0000317| 0.00301±0.00022 | 0.0854±0.0052 |
|             | 2020-09-21 | HFOSC/V           | 2459114.150846±0.000214 | 0.00105±0.000010 | 0.0327±0.00010 |
|             | 2020-10-21 | UKATC/1           | 2458877.220952±0.000580 | 0.00151±0.000431 | 0.0653±0.0088 |
|             | 2020-02-05 | HFOSC/V           | 2458879.207010±0.000290 | 0.00101±0.00006 | 0.0288±0.0008 |
|             | 2020-02-18 | ProEM/I           | 2458989.149337±0.000431 | 0.00126±0.00029 | 0.0896±0.0120 |
|             | 2020-02-18 | HFOSC/R           | 2458989.149390±0.000297 | 0.00180±0.00005 | 0.0238±0.0003 |
|             | 2020-03-23 | UKATC/1           | 2458932.154930±0.000721 | 0.00110±0.00032 | 0.1501±0.0413 |

Note. The midtransit times for the same transit event observed by two different telescopes in three different instances (2020-02-05 for HAT-P-30 b, 2020-02-03 for HAT-P-54 b, and 2020-02-18 for XO-2 N b) have been calculated independently.
future. Also, the critical noise analysis algorithm can be used for the analysis of transit light curves from the existing and upcoming global exoplanet survey missions, such as the TESS (Transiting Exoplanet Survey Satellite) for the estimation of physical properties of the detected exoplanets with better accuracy.

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Appendix
Posterior Distributions from MCMC Sampling

Figure A1. Corner diagram depicting the posterior distributions of the transit parameters and the GP regression coefficients from MCMC sampling for HAT-P-30 b.
Figure A2. Same as Figure A1, but for HAT-P-54 b.
Figure A3. Same as Figure A1, but for WASP-43 b.
Figure A4. Same as Figure A1, but for TrES-3 b.
Figure A5. Same as Figure A1, but for XO-2 N b.

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