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Orbital analysis of additional bodies around eclipsing binaries HT Vir and MR Del

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Abstract. We analyze the orbital characteristics of additional bodies suggested to exist around the eclipsing binaries HT Vir and MR Del by utilizing both astrometric and eclipse timing data, with recent timing data primarily from TESS and astrometric data from Gaia. Our analysis shows that the available timing data for HT Vir closely follows the ETV trend induced by the companion suggested by the astrometric solution. For MR Del, we derived an orbital solution indicating a companion with an approximate semi-major axis of 150 AU. We also updated the ETV analysis for MR Del, finding a longer-period variation compared to previous studies.

Key words: binaries: eclipsing – stars: individual (HT Vir, MR Del) – techniques: astrometry – eclipse timing

1. Introduction

The existence and properties of additional bodies around eclipsing binaries have long been a topic of debate, with various techniques proposing the presence of such companions. The combination and analysis of data from different observational techniques allow for a comprehensive parameter set to be derived, providing valuable insights into the orbital dynamics, mass distribution, and evolutionary processes within these systems. By analyzing both eclipse timing variations (ETVs) and astrometric data of two selected eclipsing binaries, we derive the properties of their companions suggested by these two observational techniques and compare the results.

HT Vir is a contact eclipsing binary system with a visual magnitude of 7.67 and an orbital period of 0.4077 days. It has a visual companion separated by 1.011 arcseconds, which is only 0.4 magnitudes fainter Gaia Collaboration et al. (2023). Zasche & Wolf (2007) combined the astrometric and timing data for HT Vir, deriving the orbital properties of a distant third body in the system, suggesting an astrometric orbit for this companion. Following this, Liao & Qian (2010) analyzed the eclipse timing variations of HT Vir and discovered a cyclic variation with a period of approximately 30 years. However, they noted that this cyclic change could stem from various causes, emphasizing the need for additional minimum timing observations to better understand the underlying mechanisms. Furthermore, Lu et al. (2001) identified the distant companion as a spectroscopic binary, establishing HT Vir as a quadruple system.

MR Del, on the other hand, is a detached eclipsing binary system with an orbital period of 0.5217 days and a visual magnitude of 9.20. The system also features a visual companion separated by only 1.654 arcseconds, as reported in Gaia DR3. Zasche et al. (2009) initially analyzed MR Del's astrometric data to investigate a resolved additional body and derived an orbital period of approximately 1996 years. However, ETV analyses of MR Del have suggested much shorter periodicities than those indicated by the astrometric data. In recent studies, both Özavcı et al. (2020) and Meng et al. (2021) identified a cyclic period variation in MR Del, with an approximate period of 18 years, likely driven by a Light-Time Effect (LiTE) caused by an additional companion.

Within this study, we aim to update the astrometric analyses for both HT Vir and MR Del, while conducting an ETV analysis exclusively for MR Del. Utilizing the latest timing data from TESS and astrometric data from Gaia, this approach provides a refined characterization of the additional bodies around these binary systems, enhancing our understanding of their orbital properties.

2. Data

2.1. Astrometry

We obtained the astrometric data, including epoch, angular separation and position angle and their associated uncertainties, from the Washington Double Star Catalogue, which includes Gaia data (Mason et al., 2001)[1]. We retrieved the parallax values used in the analysis from Gaia DR3.

2.2. Eclipse Timing

We collected the minimum timing data from various sources. For both systems, we retrieved TESS light curves from Mikulski Archive for Space Telescopes

[1]http://www.astro.gsu.edu/wds

(MAST) Portal[2]. We removed outliers and detrended the TESS light curves by dividing the data with second-degree polynomial fits to each half of each sector followed by a normalization to the median-level. We then calculated minima timings using the Xtrema software (Bahar et al., 2015) with the Kwee-van Woerden technique (Kwee & van Woerden, 1956). Additionally, we obtained eclipse timing data from the VarAstro[3], the BAV archive[4], and relevant literature. For MR Del, we conducted additional observations using the T35 telescope with a QSI 660 CCD camera at Ankara University's Kreiken Observatory and the IST40 telescope with a KAF 8300 camera at Istanbul University Observatory, from which we derived minimum timings as well.

Table 1. New timings of minima obtained for MR Del in this study

Eclipse Timing (BJD-TDB)	Error [days]	Type	Filter	Telescope
2460139.405707	0.000041	Primary	R	T35
2460525.456763	0.000057	Primary	V	IST40
2460529.369638	0.000069	Secondary	R	T35

3. Analysis

3.1. Astrometry

For the astrometric analysis, we used the ORBITIZE! code (Blunt et al., 2019) to determine the orbits and properties of the additional companions for both HT Vir and MR Del.

The parallel-tempered Affine-invariant Markov Chain Monte Carlo (MCMC) algorithm (Vousden et al., 2016) was employed in this analysis, producing a posterior distribution of orbital parameters. Some entries in the dataset lacked uncertainty values; to incorporate these entries into the analysis, we assigned the largest error present in the dataset to ensure consistent treatment. To ensure robust analysis, we utilized 100,000 posterior samples, representing plausible orbital configurations consistent with the data. The orbits and derived parameters of these companions are presented below in Figures 1 and 2, with the corresponding orbital parameters, represented as median values along with their uncertainties, listed in Table 2.

[2]https://archive.stsci.edu
[3]https://var.astro.cz
[4]https://www.bav-astro.eu

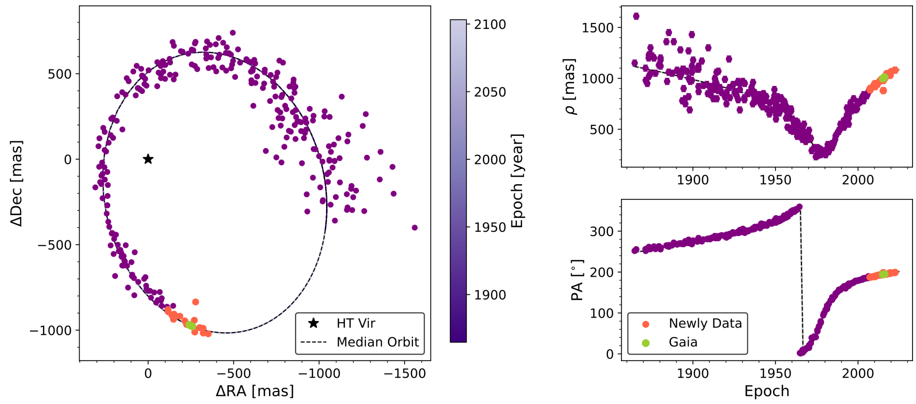

Figure 1. The left panel shows the relative orbit of the companion of HT Vir based on astrometric data, plotted using 1000 randomly selected orbits from the posterior distribution. The dashed black line represents the orbit generated using the median values of the parameters listed in Table 2. The top-right plot shows the angular separation, while the bottom-right plot presents the changes in position angle over time, in conjunction with the orbit. The yellow and orange data points represent new astrometric data added after the most recent astrometric study for this star.

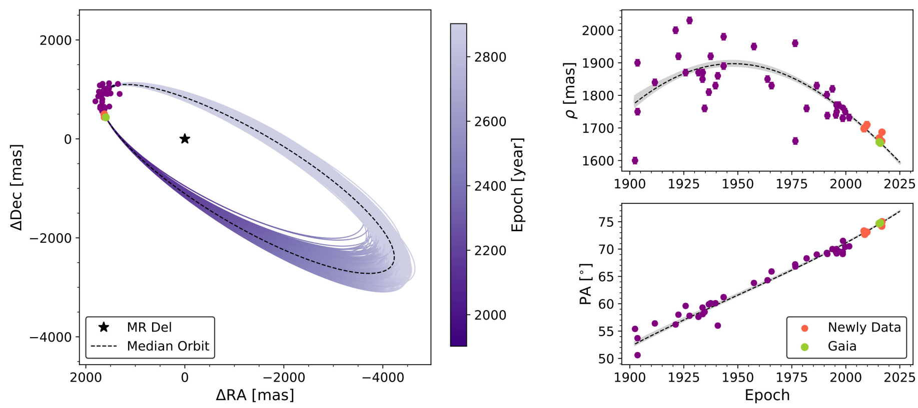

Figure 2. Relative orbit of the companion of MR Del. For a detailed description, see Figure 1.

3.2. Eclipse timing

For MR Del, we modeled the eclipse timing variation using our Python code, employing the affine-invariant MCMC algorithm developed by Foreman-Mackey

Table 2. Orbital Parameters for the visual tertiary components of HT Vir and MR Del.

Parameter	Unit	HT Vir	MR Del
Period	[yr]	238.5028 ± 0.0192	1772.7580 ± 65.1634
Semi-major axis	[AU]	64.4571 ± 0.2441	153.5693 ± 4.4432
Eccentricity	-	0.6200 ± 0.0001	0.4453 ± 0.0172
Inclination	[deg]	48.7555 ± 0.0029	72.1005 ± 0.3778
Argument of Periastron	[deg]	254.1245 ± 0.0046	352.0605 ± 3.9922
Longitude of Nodes	[deg]	176.7337 ± 0.0034	59.9052 ± 0.6592
Parallax	[mas]	15.7849 ± 0.0602	22.1742 ± 0.0230
Total Mass	[$M_\odot$]	4.7079 ± 0.0531	1.1511 ± 0.0403
Epoch of Periastron	[yr]	1976.5155 ± 0.0006	1926.8032 ± 10.1655
RMSE	[mas]	75.47	53.39
χ^2_ν ($\chi^2_{\nu,\mathrm{RA}} + \chi^2_{\nu,\mathrm{Dec}}$)	-	15.59	108.82

et al. (2013). In cases where minima timings lacked uncertainty values, we categorized the observations based on the methods used across the dataset. For each observational method such as pe:photoelectric, ccd: CCD photometry, we calculated an average uncertainty and assigned this value to entries missing error data, using the method-based average to maintain accuracy.

As a result of our analysis, we updated the ephemeris to best represent the O-C diagram, effectively mitigating the linear trend caused by accumulated uncertainties. The updated ephemeris is given by:

$$\mathrm{Min\ I}(\mathrm{BJD_{TDB}}) = 2459770.052326(256) + 0.52168927(3) \times E$$

Table 3. Orbital parameters and model fit statistics for MR Del.

Parameter	Unit	Value
P_3	[yr]	32.607 ± 1.115
e_3	–	0.389 ± 0.003
ω_3	[deg]	7.997 ± 0.011
T_0	[$\mathrm{BJD_{TDB}}$]	2465503.752909 ± 557
A	[day]	0.00353 ± 0.00001
$a_{12} \sin i$	[AU]	0.663 ± 0.004
a_3	[AU]	10.750 ± 1.341
$f(M_3)$	[$M_\odot$]	0.00027 ± 0.00003
M_3	[$M_\odot$]	0.083 ± 0.008
Model Fit Statistics		
χ^2_ν	–	13.1757
AIC	–	2161.6425
BIC	–	2183.5931

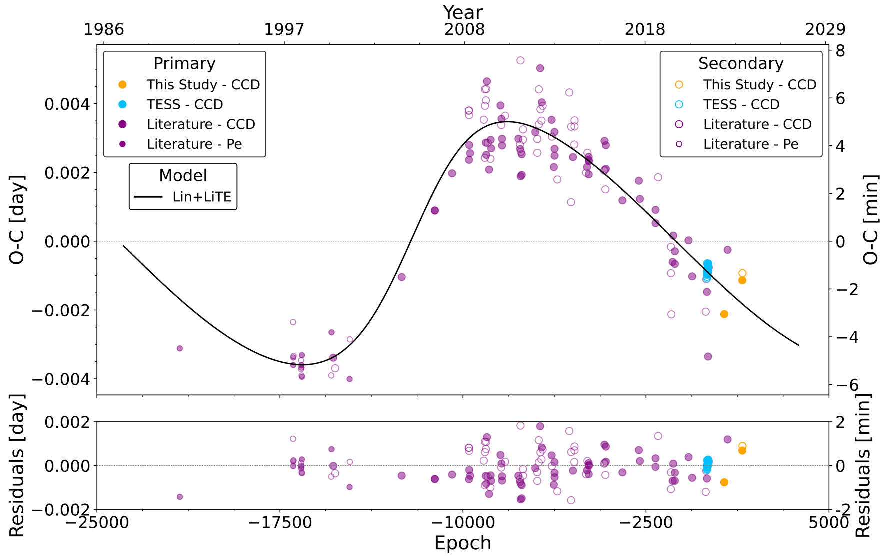

Figure 3. ETV diagram for MR Del.

4. Discussion and conclusion

In this study, we examined the orbital properties of the resolved tertiary bodies gravitationally bound to the eclipsing binary systems HT Vir and MR Del by utilizing both ETV and astrometric data. We focused on understanding how the properties derived from each dataset influence the other, particularly the effects of additional components on the observed eclipse timing variations. These findings contribute to a more refined understanding of the systems' orbital structures and dynamics.

(i) For the HT Vir system, the total mass was estimated to be approximately 4.7 $M_\odot$. Given that the combined mass of the binary system is estimated to be $M_{1,2} = 2.3M_\odot$, as determined by D'Angelo et al. (2006), the mass of the additional component can be calculated to be around 2.4 $M_\odot$. This significantly large mass is expected to cause a significant variation in the ETV diagram. By applying the REBOUND N-body simulation code (Rein & Liu, 2012) and using the orbital parameters derived for the additional component, we calculated the corresponding ETV variation. To align the observed minima timings of HT Vir with the expected ETV trend induced by this component, a slight linear correction was applied. This manual adjustment, not based on a fit, yielded $T_0 = 2448760.66470$ and $P = 0.407673$. The corrected minima timings closely followed the ETV trend caused by the additional component, highlighting its influence on the system's timing behavior.

Furthermore, the relatively large amplitude periodic variation observed in HT Vir can be partially explained by the presence of this additional componaion. However, recent observations suggest that the remaining variation does not follow the cyclic trend and might instead be linked to magnetic activity, as suggested by the O'Connell effect observed in the light curves of the systems and its F8 spectral type.

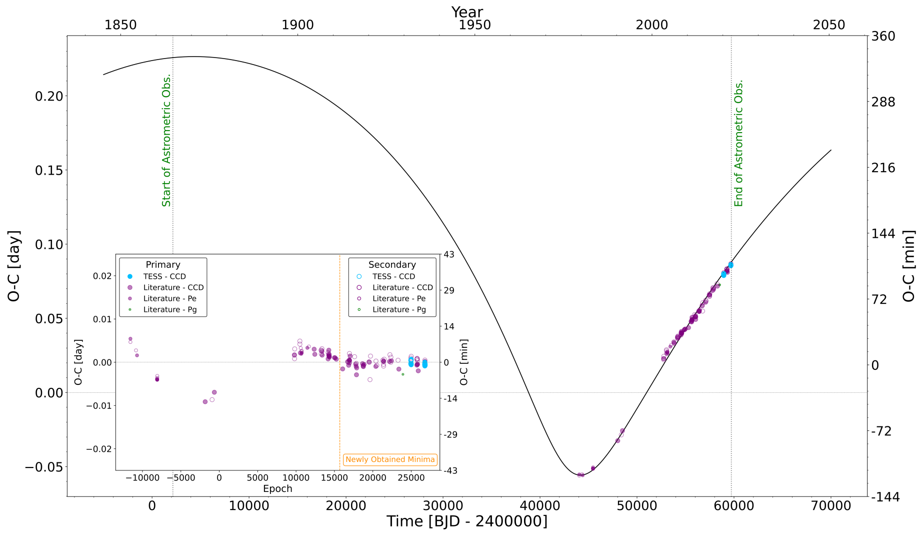

Figure 4. ETV analysis of HT Vir based on its astrometric solution. The figure shows the astrometric orbit of the companion and its corresponding ETV. The inset graph represents the O-C diagram for HT Vir itself. This diagram was generated using the ephemeris: Min I(BJD_{TDB}) $= 2448760.673345(264) + 0.40767253(1) \times E$.

(ii) For the MR Del system, the astrometric analysis revealed an orbital period of approximately 1800 years for the additional companion. Such a long period suggests that this component's effect on the ETV diagram should manifest itself as a nearly linear trend, rather than the pronounced variation observed in HT Vir. Observations from both ground-based and space-borne telescopes, combined with recent data, have extended the period of the detected ETV variation, resulting in a longer-period signal compared to previous studies. Moreover, the high eccentricity of the orbit makes alternative explanations, such as magnetic activity-induced changes less likely, further supporting the presence of a long-period companion whose influence on MR Del's timing data can now be seen more clearly. The derived mass of the third body is close to the boundary between a star and a brown dwarf, indicating a significant influence on the ETV pattern and reinforcing its role in the system's dynamical evolution.

In addition, the ETV solution suggests the presence of an additional component that is likely closer to the binary system than the visually detected companion. This raises the possibility that the MR Del system could be a hierarchical quadruple system. However, to confirm this hierarchical configuration with certainty, ETV data covering at least two full cycles would be required. Based on the currently available data, it is challenging to draw definitive conclusions about the system's architecture.

These analyses highlight how ETV and astrometric studies can together reveal the presence and characteristics of additional bodies in binary systems, even when these bodies have orbital periods extending beyond typical observational baselines. Future observations, especially long-term timing data, are essential to refine these orbital solutions and deepen our understanding of the complex dynamical interactions within such systems.

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