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Studying of exoasteroids orbiting around WD 1145+017

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Abstract. WD 1145+017 is the first white dwarf known to be orbited by disintegrating exoasteroids. It is a helium-dominated white dwarf with lines of metals in spectra and variable asymmetric transits. The analysis of WD 1145 light curve allowed us to identify at least 8 bodies which periodically eclipse the star, showing periods ranging from 4.490 to 4.493 hours. Waterfall diagram shows that some of these periods are not stable. Estimating transit depths gave us possibility to assess the disintegration rate. We have estimated the lower limit of dust masses associated with these bodies, which exhibits time-varying characteristics, fluctuating within the range of approximately $2 - 3 \times 10^{14}$ kg.

Key words: exoplanets – circumstellar dust – exoasteroids

1. Introduction

The star known as WD 1145+017 (or WD 1145) is a white dwarf situated approximately 154 parsecs away from Earth. This object holds the distinction of being the first white dwarf ever observed with a planetary-mass entity in transit around it (Vanderburg et al., 2015). Vanderburg's team documented their observations of a white dwarf undergoing transits by, at the very least, one disintegrating planetesimal, and quite likely, multiple such objects. These transits exhibited periods ranging from 4.5 hours to 4.9 hours, which translates to an approximate distance of $1R_{\odot}$ from the central star. The transit profiles displayed asymmetrical shapes and varying depths, with some transits reaching depths of up to 40% in flux. These observations strongly suggest the presence of small celestial bodies with cometary tails composed of dusty materials (Izquierdo et al., 2018).

The photosphere of WD 1145 is polluted by metals originating from disintegrating bodies, thus its spectra show strong lines of heavy elements like magnesium, aluminum, silicon, calcium, iron, and nickel (Xu et al., 2016). The star is surrounded by dusty debris disc which causes substantial infrared excess in the spectra. Hallakoun et al. (2017) and Xu et al. (2019) also revealed that UV transit depths are always shallower than those in the optical.

We aim to revise number of planetesimals and their orbital parameters.

2. Observations

The task of revising the number of planetesimals is challenging because the light curve of white dwarf is constantly and rapidly evolving with time. Photometric observation we use in the analysis come from several observatories during 2016 - 2020 years. In our research we mostly focus on data obtained during 2017 because they are the most complete and precise. They were all obtained in the framework of a campaign organized by the Astronomical Institute of Slovac Academy of Sciences. Several medium and small size telescopes around the world participated with their observations. They are all listed in the Tab. 1 . This data was complemented by observations obtained by Bruce Gary during 2016-2020 years with 14" telescope in Hereford, Arizona.

All the data were reduced in a uniform way using standard procedures and IRAF package. Observations from SAO had relatively short exposure times so they were binned in time to achieve about 60 second cadence. We follow Vanderbourg et al. (2015) and also use Lomb-Scargle periodogram(Scargle, 1982) to find periodicities in more recent data. Our periodogram is displayed on Fig. 1. It differs from one obtained by Vanderburg - some peaks are missing or shifted. This is an evidence of rapid evolution of the system. Preliminary results show that the strongest peak is at 4.48 hours.

Table 1. Telescopes participated in observation campaign of WD 1145

Location	Aperture [m]
Devastal, India	3.6
RATIR, Mexico	1.5
Skalnaté Pleso, Slovakia	1.3
Nizhnij Arkhyz, Russia	1
TSAO, Kazakstan	1
Gaomeigu China	0.7
PROMPT-8, Cerro Tololo Inter-American Observatory	0.6
Stará Lesná, Slovakia	0.6
TNO, Narit, Thailand	0.5
Australia	0.4
Tenerife, Spain	0.4

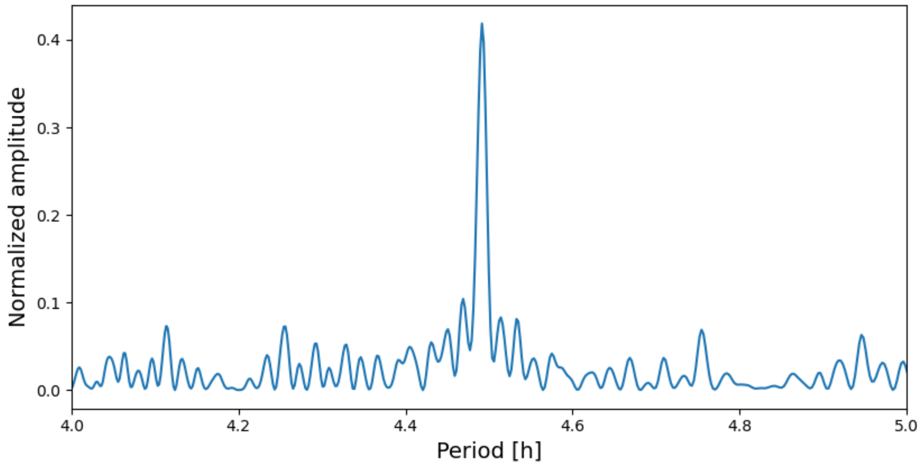

Figure 1. Periodogram of the data used in this work

3. Modelling lightcurve

To estimate orbital parameters of exoasteroids, we fit the light curve with combination of 8 asymmetric hyperbolic secants, following Croll et al. (2017):

$$M(t) = m_0 + \sum_{i=1}^{N} \frac{C_i}{e^{\frac{-(t-t'_i)}{\tau_{1i}}} + e^{\frac{(t-t'_i)}{\tau_{2i}}}} \quad (1)$$

$M(t)$ is the total magnitude, $N = 8$ is the number of transiting bodies, m_0 is the out-of-transit magnitude, $C_i/2$ is approximately the transit depth of i-th body, t'_i is the closest transit midpoint for time t, and τ_{1i} and τ_{2i} are the characteristic durations of the ingress and egress, respectively. We have to take into account the fact that exoasteroids can loose their masses as well as dust clouds surrounding them. This means that the transit depth C depends on time. We approximate it with sixth degree polynomials:

$$C = \sum_{j=0}^{6} a_j (t - t_0)^j \tag{2}$$

where t_0 is the first transit mid-point and a_j are independent parameters. To calculate t' we need to know the number of epochs passed from the start of observations:

$$n = \left[\frac{t - t_0}{P} \right] \tag{3}$$

where P is the orbital period and t_0 is the midpoint of first transit. Then we find

$$t' = t_0 + nP \tag{4}$$

Totally the equation describing the light curve has $N \times 11 + 1 = 89$ parameters (seven polynomial coefficients, time of ingress and egress, periods, transit midpoints (11 in total) of N = 8 bodies). To optimise them we use Powells method(Powell, 1964). The observations overplotted with the best fit are displayed in Fig. 2. Periods vary around 4.48 hours and differ by 10 seconds. However, long-term stability of these periods is under question. We follow Rappaport et al. (2018) and use waterfall diagram as a reliable method of monitoring trends in optical activity over large timespan. Waterfall diagram(Fig. 3) displays the magnitude as a function of the orbital phase (x-axis) for different dates of observations (y-axis). Values of individual pixels correspond to brightness of the given object at given phase and date (darker ones correspond to higher magnitudes, lighter corresponds to lower magnitudes). Thus, periodic transits form clear traces in waterfall diagram. If the data is phase-folded with the correct orbital period, the trace is represented with straight vertical line. Other shape of trace may indicate changing or incorrect period. We construct our waterfall diagram as an image of 120120 pixels. The most challenging task is to take into account significant gaps in data. We followed Rappaport and handle missing observations as follows. The flux from each observation was placed into the appropriate [x, y] bin according to the phase of the 4.5-h period and the date of the observation. For each point in the image, if there exists a data point, we leave it as it is. If a pixel is initially blank, we draw a circle around that point which is 5 pixels in radius, and take a distance weighted average of all the points within which there are data. The weighting was done according to d^{-2}, where

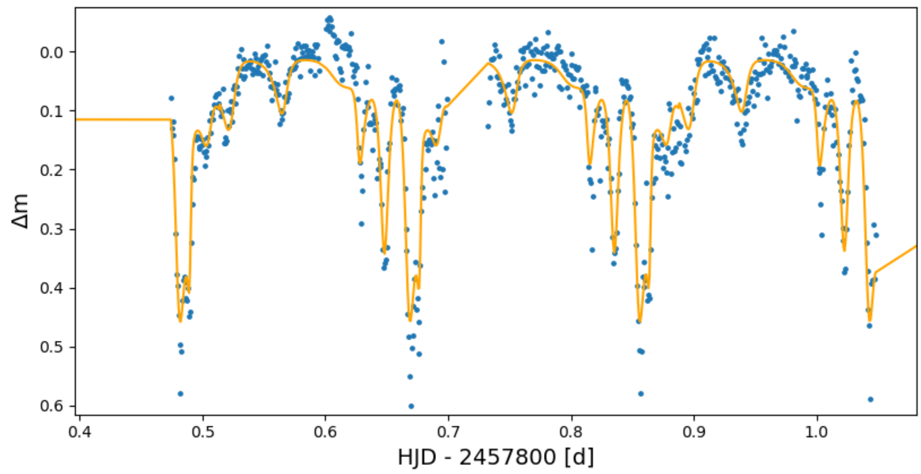

Figure 2. The observations overplotted with the best fit by Eq. 1.

d is the distance between the point being filled and the data points (in units of pixels). So the flux used to fill the blank bin is given by

$$F = \frac{\sum_{points} F_{point} d^{-2}}{\sum_{points} d^{-2}} \tag{5}$$

where we sum fluxes F_{point} within 5 pixels of blank bin, weighted with distance d from the center of blank bin to the point. The result is displayed in Fig. 3.

As one can notice, many objects have stable period, but at least two (number 3 and 5) show significant curvature. This may indicate that some periods change with time. An intriguing observation is that certain trajectories intersect. Our goal is to determine whether these intersections are indicative of genuine collisions between exoasteroids or simply the result of overlapping dusty tails.

4. Estimation of dust mass

Knowledge of the light curve helps us to estimate the dust mass. We operate on the following assumptions. First of all, we ignore the solid core of exoasteroid and suppose that the dust almost covers the whole disc of the star. Properties of the dust were determined by Budaj et al. (2022):it is composed mostly of silicates and mean grain size is about 5 microns. We also use dust opacities calculated by Budaj et al. (2015). We calculate the dust mass as follows.

$$I = I_0 e^{-\tau} \tag{6}$$

Here I_0 is constant out-of-transit intensity (we observe it when the disc is not covered by dust), I is total intensity, which varies with time, and τ is optical

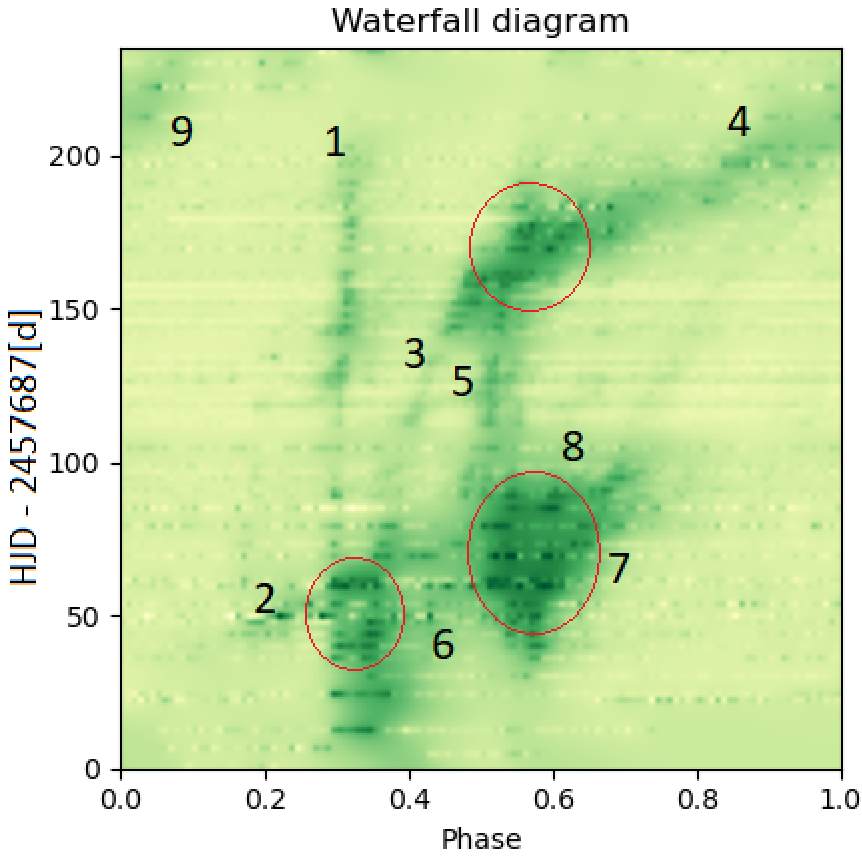

Figure 3. WD 1145 waterfall diagram for 2016 year. We can identify 8 or 9 objects. Intersections of trajectories are marked with red.

depth of the dust:

$$\tau = \kappa \rho z \tag{7}$$

where κ stands for opacity, ρ is dust density and z is geometric depth. Now we can calculate differential of mass

$$dM = \rho z dS,\ dS = 2R_{\star} v dt \tag{8}$$

where $R_{\star}$ is radius of white dwarf and v is orbital velocity. Thus, total mass of eclipsing dust is an integral over orbital period T:

$$M = -2 \int_0^T ln \frac{I}{I_0} R_{WD} v \kappa^{-1} dt \tag{9}$$

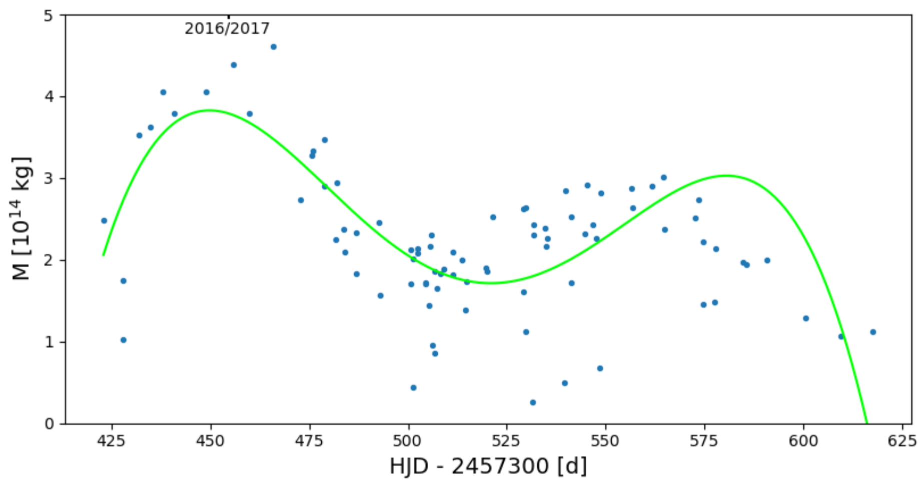

Figure 4. Variations of dust mass over 2017 year. One point corresponds to one epoch.

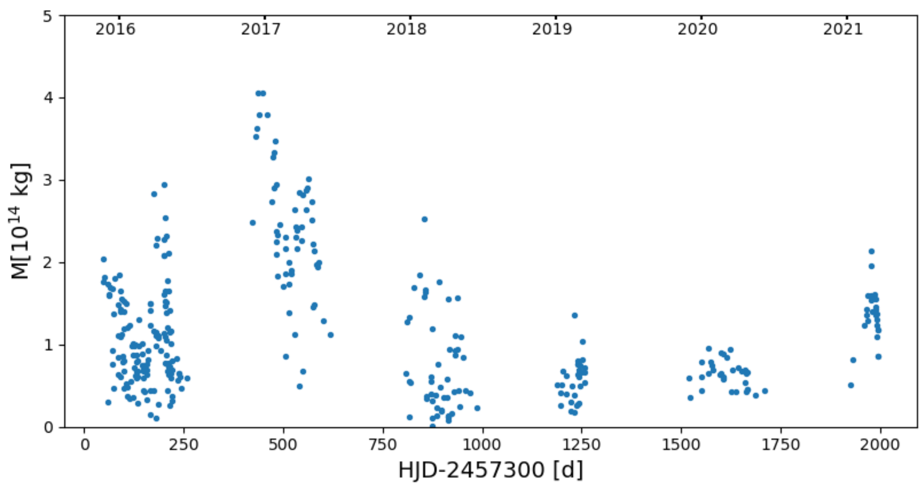

Figure 5. Variations of dust mass over 2016-2021 years. One point corresponds to one epoch.

Our results for year 2017 are displayed on Fig. 4. We can see that eclipsing dust mass does not remain stable during our observation campaign. Observed peaks at HJD = 2457750 and 2457850 correspond to intersections on waterfall diagram, marked with red circles(Fig. 3), which indicates that real collisions between exoasteroids occur. We also use unpublished data obtained by Bruce Gary to observe dust mass dynamics during 2016 - 2021 years. These results are displayed on Fig. 5 We observe significant variations every year.

5. Conclusions

In our study, we have detected a minimum of eight celestial bodies in orbit around WD 1145. These bodies exhibit orbital periods ranging from 4.4915 to 4.4932 hours. Our analysis, based on periodograms and waterfall diagrams, reveals that these orbital periods evolve over time. Furthermore, we have estimated the lower limit of dust masses associated with these bodies, which exhibits time-varying characteristics, fluctuating within the range of approximately 2-3$\times 10^{14}$ kg. Accordingly to Shestakova et al. (2019), estimated dust accretion rate is 3.2×10^{9} g s^{-1}, which means that the material of dust ring should be updated every 3 years.

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