VVV-WIT-07: another Boyajian’s star or a Mamajek’s object?⋆

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ABSTRACT

We report the discovery of VVV-WIT-07, an unique and intriguing variable source presenting a sequence of recurrent dips with a likely deep eclipse in July 2012. The object was found serendipitously in the near-IR data obtained by the VISTA Variables in the Vía Láctea (VVV) ESO Public Survey. Our analysis is based on VVV variability, multicolor, and proper motion (PM) data. Complementary data from the VVV eXtended survey (VVVX) as well as archive data and spectroscopic follow-up observations aided in the analysis and interpretation of VVV-WIT-07. A search for periodicity in the VVV $K_s$-band light curve of VVV-WIT-07 results in two tentative periods at $P \approx 322$ days and $P \approx 170$ days. Colors and PM are consistent either with a reddened MS star or a pre-MS star in the foreground disk. The near-IR spectra of VVV-WIT-07 appear featureless, having no prominent lines in emission or absorption. Features found in the light curve of VVV-WIT-07 are similar to those seen in J1407 (Mamajek’s object), a pre-MS K5 dwarf with a ring system eclipsing the star or, alternatively, to KIC 8462852 (Boyajian’s star), an F3 IV/V star showing irregular and aperiodic dips in its light curve. Alternative scenarios, none of which is fully consistent with the available data, are also briefly discussed, including a young stellar object, a T Tauri star surrounded by clumpy dust structure, a main sequence star eclipsed by a nearby extended object, a self-eclipsing R CrB variable star, and even a long-period, high-inclination X-ray binary.

Key words: Surveys – Catalogues – Infrared: stars – Stars: individual: VVV-WIT-07 – Stars: individual: KIC 846282 – Stars: individual: J1407

⋆ Based on observations taken within the ESO Public Surveys VVV and VVVX, Programme IDs 179.B-2002 and 198.B-2004, respectively, and on observations obtained at the Southern Astrophysical Research (SOAR) telescope, which is a joint project of the Min. da Ciência, Tecnologia, Inovações e Comunicações (MCTIC) do Brasil, the U.S. National Optical Astronomy Observatorvatory (NOAO), the University of North Carolina at Chapel Hill (UNC), and Michigan State University (MSU).
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1 INTRODUCTION

In recent years, a number of variable stars have been identified in ongoing wide-field variability surveys, which have given rise to new classes of variability and expanded our views about the variable Universe. Examples of that are the Slowly Pulsating B-type stars (SPBs; Mowlavi et al. 2013), the Blue Large-Amplitude Pulsators (BLAPs; Contreras Peña et al. 2017) and the McNeil’s Nebular Objects (MNors; Pietrukowicz et al. 2017). Some of these objects are rare/unique in their nature, such as KIC 8462852 (the Boyajian’s star, Boyajian et al. 2016) and J1407 (= V1400 Cen, Mamajek et al. 2012). Synoptic surveys are major contributors to these discoveries and much more will certainly come out with the advent of LSST (Ivezic et al. 2008) and the next generation of time-series space missions, including TESS (Ricker et al. 2015) and PLATO (Rauer et al. 2014).

The VISTA Variables in the Vía Láctea (VVV) is an ESO variability survey of the inner Milky Way, which mapped about 562 sq. deg in the bulge and southern Galactic disk (Minniti et al. 2010; Saito et al. 2012). Focused on unveiling the 3-D structure of the Milky Way using pulsating RR Lyrae and Cepheid variables as distance indicators, the VVV data are also being mined on the search for microlensing events, eclipsing binaries, pre main sequence (MS) variables, etc. In 2016 a complementary survey to VVV called VVV eXtended Survey (VVVX, Minniti 2018) started observations, including revisiting the original VVV area thus expanding the original time baseline and increasing the photometric depth, in addition to affording improved proper motion (PM) measurements, as a result of combining both the VVV and VVVX datasets.

Among the targets found as variable sources in the VVV data, some are specially important since their behaviour does not seem to fit any currently known class of stellar variability. These objects are labeled as “What Is This” (WIT) objects. Most of VVV-WIT objects found up to now are high amplitude variables, including a transient of unknown character, proposed to be a nearby supernova, a rare Galactic nova, or a stellar merger (VVV-WIT-007, Minniti et al. 2017). Here we present the case of VVV-WIT-07, an intriguing variable source and unique in its nature found in the current VVV data.

2 OBSERVATIONS AND ARCHIVE DATA

VVV data consist of two sets of casi-simultaneous $Zy$ and $JHK_s$ photometry, and a variability campaign in the $K_s$-band with 50 ~ 200 epochs carried out over many years (2010 ~ 2016). The strategy of the VVVX Survey is similar to the VVV and consists of $JHK_s$ photometry plus 3 to 10 epochs in $K_s$-band. In particular for the field where VVV-WIT-07 is located, and combining VVV and VVVX data, 2 sets of $Zy$ and 4 sets of $JHK_s$ images have been observed. In addition, 85 $K_s$-band epochs were taken from May 10 2010 to May 25 2018 with irregular cadence. The VVV and VVVX data presented here are based on the default “aper3” photometry provided by the Cambridge Astronomical Survey Unit (CASU) on the stacked VVV tile images (for details see Saito et al. 2012). The set of 85 $K_s$-band epochs from VVV and VVV-X available for VVV-WIT-07 is presented in Appendix A.

VVV-WIT-07 is a stellar source located in the Galactic plane at coordinates RA, DEC (J2000)=17:26:29.387,−35:40:56.20, corresponding to l, b=−7.8580,−0.2357 deg. Figure 1 shows that the object is a relatively isolated point source (i.e. not blended), and seems to be bluer than the surrounding fainter field stars, which appear to be more affected by reddening. This object was found serendipitously in a search for large amplitude objects in the VVV data (e.g. novae and LPVs). It stood out in our search because it had a large amplitude dip in 2012. The VVV-WIT-07 $K_s$-band light curve presents an irregular behaviour with a main deep, narrow eclipse/dip of $\Delta K_s \sim 1.8$ mag delayed with respect to a broad and shallower dip around July 2012 (see Fig. 2). The narrow eclipse/dip lasts by ~11 days while the broad dip is seen with a width of ~48 days. The variation in magnitude from the median $<K_s>$=14.35 mag measured over the other epochs implies that ~80% of the flux in $K_s$ is missing during the event on July 2012.

Archive search at the VVV-WIT-07 position shows several measurements in different wavelengths spanning from Gaia data in the optical (Gaia Collaboration et al. 2018) to GLIMPSE observations in the mid-IR (Spitzer Science 2009) . Gaia, DECaPS (Schlafly et al. 2017) and VPHAS+ (Drew et al. 2016) observations are contemporaneous with our VVV/VVVX data, however epochs for Gaia observations will be released only with the final catalogue, as described in cosmos.esa.int/web/gaia/release

Figure 1. VVV $JHK_s$ false-color image of VVV-WIT-007 area. The field size is 60$''$ × 50$''$ and oriented in equatorial coordinates. North is towards the top and East towards the left. The reticle at the centre marks VVV-WIT-007.

Individual epoch data for the Gaia observations will be released only with the final catalogue, as described in cosmos.esa.int/web/gaia/release

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Figure 2. VVV $K_s$-band light curve of VVV-WIT-007. There is a total of 85 data-points covering the 2010-2018 seasons, including data from the VVVX survey. Epochs of contemporary multiwavelength observations as well as of spectroscopic observations are marked. The insert shows an expanded view around the event in July 2012.

Both data sets were data reduced using standard IRAF tasks. The resulting spectra are basically flat, with a continuum without prominent lines in emission or absorption (see Fig. 3). The only likely features seem to correspond to weak H, C and Mg absorption lines, suggesting the spectrum of a stellar source.

3 DISCUSSION

3.1 Colour data and the problem of the distance

Figure 4 shows the $Y$ vs. $(Z-Y)$ and the $K_s$ vs. $(J-K_s)$ color-magnitude diagrams (CMDs) for a 10 arcmin radius region around the position of VVV-WIT-07. According to the VVV extinction maps (Gonzalez et al. 2012) this region has an extinction of $A_K = 1.85$ mag (integrated along the entire line of sight), corresponding to $E(J-K) = 3.51$ mag, assuming the law of Nishiyama et al. (2009). The CMDs suggest that VVV-WIT-07 is a Galactic object located in the foreground disk region. The VVV colors are roughly constant over time (see Table 1 for the observed epochs) and consistent either with a reddened MS star (spectral type G or earlier, e.g. Alonso-García et al. 2018) or a pre-MS star, but the surroundings do not show evidence of an active star formation region (see Fig. 1).

The proper motion (PM) of VVV-WIT-07 as measured by the VVV InfraRed Astrometric Catalogue (VIRAC, Smith et al. 2018) is $\mu = 2.826 \pm 0.863$ mas yr$^{-1}$ ($\mu_\alpha, \mu_\delta = 2.469, 1.374$ mas yr$^{-1}$). Those values are as expected for disk field stars, that show an asymmetric drift. Even though the distance of VVV-WIT-07 is uncertain, the VIRAC PM significantly different from zero is an indication that the object is relatively nearby. While photometric data for VVV-WIT-07 are available in Gaia DR2 (source ID 597496295291907584, Gaia Collaboration et al. 2018) no PM or parallaxes measurements are reported yet for the object in Gaia DR2. The lack of motion measurements in Gaia may suggest a minimum distance for VVV-WIT-07, for instance, in Poggio et al. (2018) Gaia data are used to map the MW disk, including towards the position of VVV-WIT-07, to distances of up to $r \sim 7$ kpc, close to the Galactic center. On the other hand, VVV-WIT-07 ($G=20.56$ mag) is near the limiting magnitude of Gaia and an archive search in the region around VVV-WIT-07 shows that only a small fraction ($\lesssim 1/4$) of sources at similar magnitude ($G > 20.5$ mag) present measured PMs and parallaxes in Gaia DR2.

For a foreground disk object, the total extinction as
The VVV $K_s$ epochs presented here correspond to the ones observed simultaneously with the $J$ and $H$ bands. Gaia, DECaPS and VPHAS+ observations are contemporaneous with the VVV/VVVX data, however, epochs for Gaia observations are not yet publicly available (see Section 2).

| Filter | Survey | $A_C$ $\mu$m | Mag [mag] | Epoch [JD] |
|--------|--------|--------------|-----------|------------|
| $G$    | Gaia DR2$^1$ | 0.532       | 20.565 ± 0.016 | NA         |
| $r$    | DECaPS$^2$    | 0.638       | 21.293 ± 0.044 | 2457805    |
| $BP$   | Gaia IGSL$^3$ | 0.673       | 17.545 ± 0.500 | NA         |
| $i$    | VPHAS+ $^4$   | 0.770       | 20.25 ± 0.09   | 2456155    |
| $i$    | DECaPS$^2$    | 0.777       | 19.442 ± 0.018 | 2457805    |
| $RP$   | Gaia IGSL$^3$ | 0.797       | 17.545 ± 0.500 | NA         |
| $Z$    | VVV          | 0.878       | 18.366 ± 0.040 | 2455766    |
| $z$    | DECaPS$^2$    | 0.911       | 18.105 ± 0.007 | 2457805    |
| $Y$    | DECaPS$^2$    | 0.985       | 17.574 ± 0.022 | 2457805    |
| $Y$    | VVV          | 1.021       | 17.125 ± 0.021 | 2457667    |
| $J$    | DECaPS$^2$    | 1.240       | 18.930 ± 0.003 | 2451035    |
| $J$    | DENIS$^6$     | 1.221       | 15.666 ± 0.230 | 2451062    |
| $J$    | VVV          | 1.254       | 15.804 ± 0.061 | 2455326    |
| $J$    | VVV          | "           | 15.777 ± 0.011 | 2455411    |
| $J$    | VVVX         | "           | 15.707 ± 0.011 | 2457279    |
| $H$    | 2MASS$^3$     | 1.664       | 14.839 ± 0.094 | 2451035    |
| $H$    | VVV          | 1.646       | 14.953 ± 0.013 | 2455326    |
| $K$    | 2MASS$^3$     | 1.240       | 14.838 ± 0.004 | 2455326    |
| $K_s$  | VVV          | 1.240       | 14.961 ± 0.017 | 2455411    |
| $K_s$  | VVVX         | "           | 14.912 ± 0.017 | 2457279    |
| $K_s$  | VVV          | "           | 15.707 ± 0.011 | 2457279    |
| $K_s$  | VVVX         | "           | 14.338 ± 0.175 | 2453742    |

$^1$Gaia Collaboration et al. (2018); $^2$Schlafly et al. (2011); $^3$Smart & Nicastro (2013) $^4$Drew et al. (2016); $^5$Cutri et al. (2003); $^6$DENIS Consortium (2005); $^7$Spitzer Science (2009); $^*$upper limit.

calculated by the VVV maps is certainly overestimated. $A_{K_s} = 1.85$ mag corresponds to $A_V > 15$ mag in the optical, turning the slope of the isochrones of VVV-WIT-07 presented in Fig. 3 to peak at $J < 0.5 \mu$m, translating to a black-body temperature higher than $T = 5400$ K, 3-D extinction maps (Schultheis et al. 2014) show that the extinction increases linearly with the distance up to $D < 8$ kpc in the VVV-WIT-07 direction, making the interpretation of the extinction limits. Moreover, a photospectra for VVV-WIT-07 using multi-epoch data taken at different epochs over almost a decade must be seen with caution since the object is clearly variable over time.

Both SoFI and SOAR near-IR spectra are featureless, having no prominent lines in emission or absorption, excluding the possibility of VVV-WIT-07 as an emission line object such as a cataclysmic variable (CV) or a Nova star. The absence of $H\alpha$ data in VPHAS+ would confirm this interpretation. The shallow absorption features are interpreted as H, C and Mg absorption lines, that reinforces the hypothesis of a main sequence stellar source.

We fit the photospectrum using the Virtual Observatory SED Analyzer (VOSA, Bayo et al. 2008) with the disclaimer that the photometry was collected over nearly a decade and may be affected by the source’s variability. In this analysis we masked out Gaia, 2MASS K-band and VPHAS+ data, since 2MASS K-band magnitude is at the limit of detection of Gaia and VPHAS+ are close to their detection limits.

We made use of Kurucz and BT-Settl models (Castelli et al. 1997; Allard et al. 2012) with solar metallicity, $T_{\text{eff}}$ between 3500 and 15000 K and $\log g$ between 0 and 5, and assuming $A_V$ between 1 – 12 mag ($A_{K_s} \lesssim 1.4$ mag). For this exercise we obtained either $A_V = 5$ and $T_{\text{eff}} = 3,500$ K and $\log g = 5$ which is unlikely because that would mean a nearly red dwarf ($d < 300$ pc for a M1 dwarf). The position on the CMDs, the spectra, the PM and lack of a parallax do not support this result. The other solution was $A_V > 9$ mag with a best fit in $T_{\text{eff}} \sim 10,000$ K and $\log g \sim 3$, slightly high for an A0V star. If that is the case and we assume a regular A0V star the distance will be $\geq 3.5$ kpc.

Allowing for even higher extinction of $A_V = 15$ mag (corresponding to $A_{K_s} \sim 1.8$ mag) leads to $A_V > 9$ mag, with $T_{\text{eff}} > 9,000$ K and $\log g \sim 2.5 – 3$. This implies the presence of a nearby ($d \leq 3.5$ kpc) dust cloud with extinction, contrary to the 3-D extinction maps that show a smooth, linear increment of $A_{K_s}$ with the distance in this line of sight (e.g. Schultheis et al. 2014).

### 3.2 To be or not to be periodic?

The light curve of VVV-WIT-07 presented in Fig. 2 shows a sequence of dips, with a likely deep eclipse in July 2012. While these are certainly recurrent, the presence of a regular periodicity is not obvious. A search for periodicity using a fast Lomb-Scargle algorithm (VanderPlas & Ivezić 2015) results in two tentative periods at $P \sim 322$ days (score 0.462).
and $P \sim 170$ days (score 0.400). Figure 5 shows the periodogram and the phase-folded light curves for both periods. Despite its higher significance, a period of $P \sim 322$ days breaks the shape of the main eclipse/dip of July 2012 by including a data point at $K_s \sim 14.7$ mag at the ingress of the event ($\phi \sim 0.48$), moreover data points seen to spread out near phase $\phi \sim 0.65-0.70$. On the other hand, for the period of $P \sim 170$ days a couple of outlier data points are seen prior ($\phi \sim 0.3$) and after ($\phi \sim 0.75$ and 0.75) the main eclipse/dip. Thus, we are not able to conclusively establish a period for VVV-WIT-07. If the $P \sim 170$ days is correct, an ephemeris for the object can be calculated to predict that VVV-WIT-07 should fall down to $K_s \geq 14.7$ mag and possibly become fainter than 16 mag in $K_s$-band, three times in the next year, at around January 21, July 10, and December 27, 2019. In the case of $P \sim 322$ days another eclipse/dip should occur around August 7, 2019.

4 POSSIBLE INTERPRETATIONS

The features found in the light curve of VVV-WIT-07 are similar to those seen in J1407 (= V1400 Cen, Mamajek et al. 2012). J1407 is consistent with a pre-MS K5 dwarf with a ring system eclipsing the star. Its light curve has a main eclipse of $>3.3$ mag and multiple dimming events of $>0.5$ mag. During the main eclipse the object fades from $V \sim 12.4$ to $V \sim 15.8$, or a decrease of $\sim 95\%$ in the flux, compared with $\sim 80\%$ of VVV-WIT-07 in the near-IR. The main eclipses are similar in shape, with a smooth ingress and a shouldered in the egress, typical for the eclipse of an extended object such as a disk or ring, which is the preferred explanation in the case of J1407. If VVV-WIT-07 has the same nature of the Mamajek object, which has a lower limit on the period of 850 days, the absence of a firm period determination of VVV-WIT-07 can be explained by the irregular cadence of our light curve, which presents large windows of no coverage, especially in the last 2 years.

Another object that is possibly similar to VVV-WIT-07 is KIC 8462852 (Boyajian’s star, Boyajian et al. 2016). The object is a F3 IV/V star showing irregular and aperiodic dips, however the dips are shallow at 20% of the normalized flux, compared with $\sim 80\%$ of VVV-WIT-07. Boyajian’s star has been followed up since its discovery and the most accepted hypothesis for its dips is the occultation by orbiting material (e.g. uneven rings of dust, dusty planetesimals or even a swarm of comet-like bodies Boyajian et al. 2016; Neslušan & Budaj 2017). A possible period for Boyajian’s star is still unknown, with some recent works suggesting the presence of a likely recurrence ranging from $P \sim 1600$ days up to $P \sim 12$ years (Bourne & Gary 2017; Sacco et al. 2017; Ballesteros et al. 2018).

Alternative scenarios for VVV-WIT-07 include a “dipper” T Tauri star with clumpy dust structures orbiting in the inner disk that transit our line of sight (e.g. Rodriguez et al. 2017), or even a long period, high-inclination X-ray binary. The deep, narrow eclipse delayed with respect to a broad and shallower dip is reminiscent of the morphology seen in high-inclination low-mass X-ray binaries (LMXB, e.g. Parmar et al. 1986; Baptista et al. 2002). However, LMXBs are restricted to orbital periods of less than a few days while high-mass x-ray binaries (HMXB) can be found at $P_\text{orb}$ up to hundreds of days (e.g. X1145-619 has $P_\text{orb} = 187.5\,$d, Watson et al. 1981). Moreover, in this scenario optical and IR spectra would be dominated by the mass-donor companion star, and should show rotationally-broadened hydrogen absorption lines at epochs of no mass ejection episodes, which is not seen in the spectra of VVV-WIT-07.

An R Coronae Borealis (R CrB) classification could be also suggested, but the light curve of VVV-WIT-07 does not resemble what is typically observed in other R CrB systems in the near-IR, specially because of the fast dimming episode in July 2012. Moreover, the position in the CMD is unlikely for an R CrB. In particular, if this were a high-luminosity R CrB star undergoing unusually fast dimming episodes, VVV-WIT-07 would be located well beyond the Milky Way disk, which is inconsistent with the measured PM and amount of foreground reddening. For instance, if VVV-WIT-07 has the same absolute magnitude of the R CrB class prototype.
\(M_K \approx -6 \text{mag}\)\(^2\) that would translate to a distance to VVV-WIT-07 of \(d \gtrsim 50\) kpc (using \(n_K = 14.35\) mag and \(A_K = 1.85\) mag, see Sections 2 and 3).

5 CONCLUSIONS

We have presented the discovery of VVV-WIT-07, a unique variable source located in the Galactic disk, identified in the VVV Survey. VVV-WIT-07 is a Galactic object located in the foreground disk. Its light-curve shows dimming episodes, resembling the features seen in Boyajian’s star and in Mamajek's object. Other possibilities also relate to the young stellar zoo or the eclipse of extended bodies in a MS star. At present, with the information at hand, none of the proposed scenarios can be conclusively established. In any case, all of these possibilities are interesting in their own right.

If this is another Mamajek object, it means that these objects are likely more common than previously realized, as is shown by the example of the discovered of OGLE LMC-ECL-11893 (Scott et al. 2014), an eclipsing B9III star (\(P_{\text{orb}} = 468\) days) consistent with a dense circumstellar disk structure; and PDS 110, an eclipsing system with likely transits by a companion with a circumsecondary disc (Osborn et al. 2017). Indeed, near-IR surveys like VVV and UKIDSS-GPS (Lucas et al. 2008) have only recently, after a deliberate search, been found to contain a number of intriguing large-amplitude YSOs (Contreras Peña et al. 2017; Lucas et al. 2017). Thus, surveys like ours, apart from course of its irregular cadence, may perhaps not have found objects like WIT-VVV-07 more often primarily because they were not looking specifically for this kind of variability. The next generation of synoptic surveys such as LSST, WFIRST and PLATO will certainly be major contributors to this field, yielding many other interesting discoveries.

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\(^2\) simbad.u-strasbg.fr/simbad/sim-id?Ident=R+Coronae+Borealis
Here we present the 85 $K_s$-band data-points of VVV-WIT-07 available from VVV/VVV-X and used to build the light curve presented in Fig. 2. The photometric flag in all measurements is $-1$, corresponding to a stellar source as described in Saito et al. (2012).

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| MJD (days) | $K_s$-band (mag) |
|------------|------------------|
| 55326.3237 | 14.356 ± 0.022  |
| 55387.2660 | 14.402 ± 0.026  |
| 55411.1085 | 14.384 ± 0.021  |
| 55484.0358 | 14.446 ± 0.026  |
| 55690.3995 | 14.377 ± 0.025  |
| 55696.3680 | 14.381 ± 0.024  |
| 55697.3311 | 14.336 ± 0.022  |
| 55795.9691 | 14.700 ± 0.034  |
| 55807.0662 | 14.923 ± 0.041  |
| 55825.1012 | 14.974 ± 0.041  |
| 55684.1562 | 14.630 ± 0.027  |
| 56089.2537 | 14.716 ± 0.028  |
| 56094.2113 | 14.760 ± 0.030  |
| 56096.0677 | 14.781 ± 0.037  |
| 56099.1924 | 14.884 ± 0.054  |
| 56112.2212 | 14.917 ± 0.036  |
| 56114.1422 | 14.899 ± 0.035  |
| 56122.1067 | 15.171 ± 0.048  |
| 56123.0269 | 15.235 ± 0.060  |
| 56124.0031 | 16.164 ± 0.132  |
| 56124.9651 | 15.690 ± 0.087  |