VVV-WIT-04: an extragalactic variable source caught by the VVV Survey

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ABSTRACT

We report the discovery of VVV-WIT-04, a near-infrared variable source towards the Galactic disk located ~0.2 arcsec apart from the position of the radio source PMN J1515-5559. The object was found serendipitously in the near-IR data of the ESO public survey VISTA Variables in the Vía Láctea (VVV). Our analysis is based on variability, multicolor, and proper motion data from VVV and VVV eXtended surveys, complemented with archive data at longer wavelengths. We suggest that VVV-WIT-04 has an extragalactic origin as the near-IR counterpart of PMN J1515-5559. The $K_s$-band light-curve of VVV-WIT-04 is highly variable and consistent with that of an Optically Violent Variable (OVV) quasar. The variability in the near-IR can be interpreted as the redshifted optical variability. Residuals to the proper motion varies with the magnitude suggesting contamination by a blended source. Alternative scenarios, including a transient event such as a nova or supernova, or even a binary microlensing event are not in agreement with the available data.

Key words: Surveys – Catalogues – Infrared: stars – Stars: individual: VVV-WIT-04 – radio continuum: galaxies – radio continuum: transients

1 INTRODUCTION

In the past years, the VISTA Variables in the Vía Láctea (VVV) survey has scanned our Milky Way (MW) galaxy in the near-infrared (near-IR) searching for variable sources (Minniti et al. 2010; Saito et al. 2012). VVV is an European Southern Observatory (ESO) variability survey, focused on unveiling the 3-dimensional structure of the Milky Way using distance indicators such as pulsating RR Lyrae and Cepheids, as well as red clump stars. In 2016 the complementary VVV eXtended Survey (VVVX, Minniti 2018) started observations, widening the survey area. It is also revisiting the original VVV footprint, thus extending the original time baseline as a result of combining both the VVV and VVVX datasets.

Besides its main goal, VVV has also contributed to the discovery and study of variable sources such as eclipsing bi-
naries, young stellar objects, planetary transits, RR Lyrae and Cepheid variables, etc. Specifically, a search for transient sources such as microlensing events and novae outbursts has resulted in the discovery of a large number of new events in the inner MW (e.g., Saito et al. 2013, 2016; Navarro et al. 2017, 2018). Among the targets found as high-amplitude transient sources in the VVV data, some caught our attention because their behaviour does not seem to fit the currently known classes of stellar variability. We named these targets as “What Is This” (WIT) objects. These rare sources include SN candidates in the MW or behind it (VVV-WIT-01 and VVV-WIT-06, Minniti et al. 2012, 2017) and a possible second example of the “Tabby’s star” (VVV-WIT-07, Saito et al. 2019).

VVV-WIT-04 is a transient source located ∼0.2 arcsec apart from the position of the radio source PMN J1515−5559 in the inner MW disk (Wright et al. 1994), discovered in a search for large amplitude objects in the VVV data (Saito et al. 2015). VVV observations during years 2010–2013 showed VVV-WIT-04 increasing in brightness by ΔKs > 2.5 mag. Based on the VVV Ks-band light-curve limited to the 2013 season, Saito et al. (2015) suggested that it was a Galactic nova or even a supernova in a galaxy behind the Milky Way.

Here we present an analysis of VVV-WIT-04 based on the VVV/VVVX variability, multicolor, and proper motion data covering 2010–2018. Complementary archive data in the mid/far infrared and radio aided in the analysis and interpretation. We suggest that VVV-WIT-04 is the near-IR counterpart of the radio-source PMN J1515−5559. The variability in the near-IR is consistent with an Optically Violent Variable (OVV), and can be interpreted by the optical variability shifted towards longer wavelengths. Alternative scens are also discussed, none of which is fully consistent with the available data.

2 OBSERVATIONS AND ARCHIVE DATA

The VVV observational strategy consists in two sets of quasi-simultaneous ZY and JHKs photometry, and a variability campaign in the Ks-band with 50 – 200 epochs car-

Figure 1. Ks-band light-curve of VVV-WIT-04 combining data from the VVV and VVVX surveys. There is a total of 111 data-points spanning from March 31, 2010 to April 3, 2018. The two epochs of WISE observations as well as the epochs for the multicolour VVV data are marked. “W1234" means WISE observations in the four filters (W1, W2, W3 and W4) while “W12" represents WISE observations only in W1 and W2.

Figure 2. VVV JHKs false-color image of VVV-WIT-04 area based on observations taken in year 2010 (see Table 1). The field size is 1.5′ × 1.2′ and oriented in equatorial coordinates. North is towards the top and East towards the left. The reticle at the centre marks VVV-WIT-04. We note that the object is the reddest source in the field.

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Table 1. Archive data for VVV-WIT-04. Observations are limited to long wavelengths. The VVV Ks epochs presented here correspond to the ones observed simultaneously with the J and H bands. WISE epochs and magnitudes are mean values over 15 (Feb 2010) and 16 (Aug 2010) observations taken within approximately 1 day interval (see Appendix B). Radio data are in mJy units. Julian dates for radio observations are mean values.

| Filter  | Survey       | $\Delta \phi$ [\mu m] | $A_{\phi}$ [mag] | Epoch [date (JD)] |
|---------|--------------|------------------------|------------------|------------------|
| Z       | VVV          | 0.878                  | 19.617 ± 0.083   | Mar 30, 2010 (2455285) |
| Z       | VVV          | 0.878                  | 20.035 ± 0.115   | May 03, 2015 (2457145) |
| Y       | VVV          | 1.021                  | 18.582 ± 0.048   | Mar 30, 2010 (2455285) |
| Y       | VVV          | 1.021                  | 18.880 ± 0.078   | May 03, 2015 (2457145) |
| J       | VVV          | 1.254                  | 17.374 ± 0.039   | Apr 01, 2010 (2455287) |
| J       | VVV          | 1.254                  | 17.843 ± 0.047   | May 28, 2015 (2457170) |
| H       | VVV          | 1.646                  | 15.934 ± 0.030   | Apr 01, 2010 (2455287) |
| H       | VVV          | 1.646                  | 16.557 ± 0.047   | May 28, 2015 (2457170) |
| Ks      | VVV          | 2.149                  | 14.732 ± 0.016   | Apr 01, 2010 (2455287) |
| W1      | WISE         | 3.35                   | 13.130 ± 0.138   | Feb 20-21, 2010 (2455249) |
| W1      | WISE         | 3.35                   | 13.843 ± 0.423   | Aug 20-22, 2010 (2455430) |
| W2      | WISE         | 4.60                   | 12.295 ± 0.119   | Feb 20-21, 2010 (2455249) |
| W3      | WISE         | 11.6                   | 9.481 ± 0.206    | Feb 20-21, 2010 (2455249) |
| W4      | WISE         | 22.1                   | 7.304 ± 0.286    | Feb 20-21, 2010 (2455249) |

Passband Frequency Flux [mJy]

| 4.8 GHz  | PMN          | 4.8 GHz                | 1990 ± 99        | June 1990 (2048057) |
| 4.8 GHz  | PMN-ATCA     | 4.8 GHz                | 1041 ± 18        | Nov 9-15, 1992 (2048938) |
| 8.6 GHz  | PMN-ATCA     | 8.6 GHz                | 815 ± 38         | Nov 9-15, 1992 (2048938) |
| 8.6 GHz  | VLBI         | 8.6 GHz                | 1463 ± 225       | Dec 12, 2009 (2451577) |

A false-color image of the VVV-WIT-04 area produced from the JHKs 2010 images is shown in Fig. 2. VVV-WIT-04 appears as a faint point source, much redder than the surrounding field stars. According to the VVV extinction maps (Minniti et al. 2018) the region has a total extinction of $A_K = 0.77$ mag, corresponding to $A_V = 6.52$ mag, assuming the law of Cardelli et al. (1989). These values are similar to those in Schlafly & Finkbeiner (2011), where $A_K = 0.73$ mag and $A_V = 6.65$ mag.

An archive search at the VVV-WIT-04 position resulted in few measurements at longer wavelengths. Two sets of observations with Wide-field Infrared Survey Explorer (WISE) were secured on February and August 2010 (Cutri et al. 2012; Cutri & et al. 2013a) the latter being simultaneous with our VVV data. In the following Sections as well as in Table 1 the WISE magnitudes are mean values over a dozen observations taken within approximately 1 day interval by this satellite (see Fig. 5). The complete WISE dataset is presented in the Appendix A. Besides the measurements in the VLBI Source Position Catalogue (Petrov et al. 2019) taken in Dec 2009 at 8.6 GHz, PMN J1515–5559 was also observed by the Parkes-MIT-NRAO (PMN) Survey (Wright et al. 1994) at 4.8 GHz in June 1990, and by the Australia Telescope PMN (ATCA-PMN) Follow-up Survey at 4.8 and 8.6 GHz in Nov 1992 (McConnell et al. 2012).

1 http://astrogeo.org/vlbi/solutions/rfc2019a/
3 DISCUSSION

VVV-WIT-04 was found serendipitously during a search for high amplitude variables in the VVV data (Saito et al. 2013, 2016). As shown in Saito et al. (2015), the $K_s$-band light-curve of VVV-WIT-04 covering 2010–2013 seasons is highly variable and increases in brightness by $\Delta K_s > 2.5$ mag during the late 2012 and the beginning of the 2013 season, peaking at $K_s = 13.4$ mag on May 2013. After this event, instead of decreasing steadily as expected for a putative outburst (or even a microlensing event), the 2013–2018 light-curve shows an irregular variability pattern, going fainter than $K_s = 16$ mag in 2014 and then presenting a second peak on May 2015 at $K_s = 15.2$ mag. On June 2017 the object is as faint as $K_s = 17$ mag, thus presenting a total variation of $\Delta K_s > 3.6$ mag over the nine years of the VVV and VVVX coverage.

The colour of VVV-WIT-04 also varies in time. In 2010, $(Y - J) = 1.21$ mag and $(J - K_s) = 2.64$ mag. Assuming the law of Cardelli et al. (1989) and $A_V = 6.52$ mag, $(Z - Y)_0 = 0.49$ mag and $(J - K_s)_0 = 1.58$ mag. Later in 2015, $(Y - J) = 1.03$ mag and $(J - K_s) = 2.52$ mag. $\Delta K_s$ vs. $(J - K_s)$ colour-magnitude diagram (CMD) and a $(Y - J)$ vs. $(J - K_s)$ colour-colour diagram (CCD) for stellar sources within 10 arcmin radii of around the target position are shown in Fig. 3. Both diagrams show that VVV-WIT-04 does not have typical star colors. In fact, the VVV colors of VVV-WIT-04 are in full agreement with a very reddened quasar, similar to the ones found behind the Magellanic Clouds by Ivanov et al. (2016) using VISTA data, when applied the extinction of $A_V = 6.52$ mag towards the position of VVV-WIT-04 (see Section 2). Its WISE colors are also consistent with an AGN (e.g., Mateos et al. 2012; Maitra et al. 2019).

Proper motions from the VVV Infrared Astrometric Catalogue (VIRAC, Smith et al. 2018) show that the residuals to the proper motion varies as a function of the magnitude for the $K_s$-band data. It suggests contamination by a blended source. When VVV-WIT-04 is in the high-stage it dominates the position while the contamination is stronger when VVV-WIT-04 is faint, moving the centroid towards the position of the contaminator.
Close to the OVVs are the BL Lac objects, which are also variable AGNs presenting a spectral energy distribution (SED) similar to FSRQs. BL Lacs and OVVs are blazar sub-types, which embrace all quasars with the relativistic jet closely aligned to the line of sight of the observer. Compared with the OVVs, BL Lac objects are generally less luminous and present a relatively featureless spectrum, with weak emission or absorption lines. In blazars both optical and near-IR variability time-scales depend on the distance from the emitting region to the central engine and range from months to hours, the latter indicating that the source is compact (Ghisellini et al. 2011a,b, and references therein).

VVV-WIT-04 is a point source located ~ 0.20 arcsec apart from the position of PMN J1515-5559. Catalogued as the quasar LQAC_228-055_001 (Souchay et al. 2015; Gattaneo et al. 2018), the archive radio data of PMN J1515-5559 are consistent with non-thermal radiation from a compact radio source as expected for an AGN. As discussed in Section 3 (see also Figures 2 and 3) the colour of VVV-WIT-04 is not a typical star colour, but rather it is in agreement with a very reddened quasar (e.g., Mateos et al. 2012; Ivanov et al. 2016; Maitra et al. 2019), leading us to suggest that VVV-WIT-04 has an extragalactic origin as the near-IR counterpart of PMN J1515-5559.

In the scenario, the near-IR counterpart is highly variable in time as shown by our VVV light-curve as well as the WISE archive data. In particular, the VVV light-curve resembles the ones obtained by Patiño-Alvarez et al. (2018, see their Fig. 3) for the OVV 3C 279. However, 3C 279 is observed to vary also at optical wavelengths, as Optically Violent Variable Quasar should behave, while no optical date are available to verify the behaviour of VVV-WIT-04 at shorter wavelengths. The absence of optical data is probably due to the high extinction. In fact, for a galaxy behind the MW, the total extinction as calculated by the VVV maps is probably underestimated.

Our source has an observed magnitude of $K_s = 16.5$ mag in its “quiescent phase”, which corresponds to a dereddened magnitude of $K_s \sim 15$ mag, assuming an extinction of $A_{K_s} = 1.5$ mag (with the caveat cited above). By comparing this magnitude to that of 3C 279 ($K=10.9$ mag from the 2MASS point source catalog; Cutri, et al. 2003b) we can infer that VVV-WIT-04 is 6.5 times more distant. Based on the WMAP nine-year model cosmology (Hinshaw 2012), and on a redshift of $z = 0.536$ (Marziani et al. 1996), the luminosity distance to 3C 279 is 3.13 Gpc. Were VVV-WIT-04 to have the same luminosity as this prototypical OVV QSO, its magnitude would imply a redshift of $z = 2.46$. Therefore, it is reasonable to assume that the variability we detect in the near infrared could simply be the optical variability shifted towards longer wavelengths due to the recessional velocity of the source.

Previous interpretations of VVV-WIT-04 as a transient event such as a nova or even a supernova (Saito et al. 2015) do not agree with the current data, especially because of the irregular behaviour during seasons 2013–2018 – as example of the secondary peak of $\Delta K_s \sim 1$ mag observed on May 2015 – since the remnant of a nova or a supernova is expected to decline in brightness slowly and steadily with time. That would not be the first case where a variable quasar is mis-interpreted as a high amplitude stellar source. For instance, J004457+4123 (= Sharov 21, Sharov et al. 1998) was first
announced as a remarkable nova in M31 and later confirmed as a background quasar with a strong UV flare (Meusinger et al. 2010).

We have also considered other kinds of sources highly variable in the near-IR. Some microlensing events, for example, can have large amplitudes. The amplitude of a microlensing event is related to the impact parameter (Paczynski 1986), therefore, a considerable increase in the brightness of a source can be explained with this effect. In this case, the curve may resemble a binary microlensing event due to the two most pronounced peaks around MJD−56400 and MJD−57200. To evaluate this scenario we fitted the light-curve using the python Light-curve Identification and Microlensing Analysis (PyLima, Bachelet et al. 2017). The fit does not follow the observational data neither in the base (which is not constant) nor during the increases in brightness. Moreover, colour changes are not expected during microlensing events, contrary to the observed in VVV-WIT-04. For these reasons we disfavor the possible explanation of this object as a microlensing event.

5 CONCLUSIONS
We have presented VVV-WIT-04, a variable source identified by the VVV survey towards the Galactic disk at the position of the radio source PMN J1515-5559. Based on VVV/VVVX variability, multicolor, and proper motion data our analysis suggests that VVV-WIT-04 has an extragalactic origin as the near-IR counterpart of the radio-source PMN J1515-5559, with characteristics of an Optically Violent Variable (OVV) quasar. The near-IR variability can be interpreted as the redshifted optical variability. Residuals to the proper motion suggest that VVV-WIT-04 is blended with a nearby source, probably a faint star in the foreground Milky Way disk. Alternative scenarios, including a transient event such as a nova or supernova outburst as proposed by Saito et al. (2015), or even a binary microlensing event have also been discussed and are not in agreement with the currently available data, including the variability pattern and colours, which disfavors all the listed hypotheses.

The absence of spectroscopic information makes difficult to unequivocally classify VVV-WIT-04 among the AGN variable sub-types, since the classification is also based on spectral features. For instance, OVV's, BL Lacs or even UltraLuminous InfraRed Galaxies (ULIRGs) could present similar variability behaviour in the optical/near-IR, despite the differences in the luminosity and spectra (e.g., Lonsdale et al. 2006; Ghisellini et al. 2011b; Dexter, & Begelman 2019; Gopal-Krishna et al. 2019).

Compact radio sources are distributed over the whole celestial sphere, including towards the Galactic plane (e.g., Petrov et al. 2019). Similar to VVV-WIT-04 (= PMN J1515-5559), other violent variable near-IR counterparts of radio sources should be present in the database of recent completed (e.g., VVV and UKIDSS-GPS, Lucas et al. 2008) and ongoing (e.g., VVVX) IR multipoch surveys of the inner Galaxy. A search for high amplitude near-IR variability at the position of radio sources in these surveys should reveal new interesting objects as is the case of VVV-WIT-04.

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**APPENDIX A: VVV-WIT-04 K_s-BAND DATA**

Here we present the PSF K_s-band data-points of VVV-WIT-04 available from VVV/VVX and used to build the light-curve presented in Fig. 1. There is a total of 111 data-points spanning from March 31, 2010 to April 3, 2018. The data-point number of data-points (111) is larger than the observed epochs (63) because the PSF photometry is performed on the individual VISTA pawprint images instead of on the final VISTA tile image (Saito et al. 2012; Sutherland et al. 2015).

**APPENDIX B: WISE DATA**

This paper has been typeset from a TeX/XeTeX file prepared by the author.
| MJD (days) | W1 (mag)     | W2 (mag)     | W3 (mag)     | W4 (mag)     |
|------------|--------------|--------------|--------------|--------------|
| 55248.1549 | 13.198 ± 0.066 | 12.275 ± 0.055 | 9.729 ± 0.121 | 7.350 ± 0.418 |
| 55248.2873 | 13.141 ± 0.055 | 12.197 ± 0.054 | 9.566 ± 0.112 | 6.889 ± 0.220 |
| 55248.4196 | 13.156 ± 0.047 | 12.572 ± 0.091 | 9.444 ± 0.121 | 7.674 ± 0.448 |
| 55248.4857 | 12.963 ± 0.061 | 12.204 ± 0.066 | —            | 7.493 ± 0.343 |
| 55248.5519 | 13.154 ± 0.054 | 12.321 ± 0.079 | 9.456 ± 0.106 | 7.187 ± 0.348 |
| 55248.6181 | 13.119 ± 0.041 | 12.130 ± 0.035 | 9.573 ± 0.133 | 7.619 ± 0.428 |
| 55248.6842 | 12.764 ± 0.045 | 12.189 ± 0.053 | 9.513 ± 0.114 | 6.848 ± 0.228 |
| 55248.7505 | 13.311 ± 0.065 | 12.277 ± 0.057 | 9.457 ± 0.095 | 6.988 ± 0.240 |
| 55248.8165 | 13.141 ± 0.055 | 12.197 ± 0.054 | 9.566 ± 0.112 | 6.889 ± 0.220 |
| 55248.8828 | 13.241 ± 0.056 | 12.268 ± 0.063 | 9.330 ± 0.112 | 7.143 ± 0.339 |
| 55249.1029 | 13.239 ± 0.050 | 12.403 ± 0.051 | 8.813 ± 0.395 | 7.372 ± 0.469 |
| 55249.0151 | 12.968 ± 0.046 | 12.180 ± 0.043 | 9.587 ± 0.118 | 7.605 ± 0.480 |
| 55249.1474 | 13.136 ± 0.041 | 12.459 ± 0.059 | 9.558 ± 0.128 | 7.566 ± 0.491 |
| 55249.2797 | 13.326 ± 0.067 | 12.411 ± 0.077 | 9.605 ± 0.112 | 7.614 ± 0.413 |
| 55249.2798 | 13.074 ± 0.038 | 12.337 ± 0.063 | 9.533 ± 0.118 | 7.318 ± 0.386 |
| 55249.4337 | 14.407 ± 0.245 | 14.006 ± 0.292 | —            | —            |
| 55249.5660 | 14.208 ± 0.103 | 13.452 ± 0.116 | —            | —            |
| 55249.6984 | 14.098 ± 0.166 | 13.225 ± 0.095 | —            | —            |
| 55249.8307 | 13.716 ± 0.134 | 13.639 ± 0.186 | —            | —            |
| 55249.8967 | 13.848 ± 0.077 | 13.898 ± 0.244 | —            | —            |
| 55249.9628 | 13.705 ± 0.085 | 13.872 ± 0.308 | —            | —            |
| 55249.9630 | 13.836 ± 0.108 | 14.104 ± 0.212 | —            | —            |
| 55300.0290 | 13.785 ± 0.079 | 13.328 ± 0.136 | —            | —            |
| 55300.0951 | 14.178 ± 0.160 | 14.037 ± 0.253 | —            | —            |
| 55300.1614 | 14.023 ± 0.170 | 13.454 ± 0.121 | —            | —            |
| 55300.2274 | 13.912 ± 0.090 | 14.336 ± 0.266 | —            | —            |
| 55300.2937 | 13.626 ± 0.061 | 14.422 | —            | —            |
| 55300.4260 | 12.456 | 14.342 ± 0.337 | —            | —            |
| 55300.5581 | 13.583 ± 0.098 | 13.987 ± 0.290 | —            | —            |
| 55300.5583 | 14.177 ± 0.172 | 14.003 ± 0.239 | —            | —            |
| 55300.6904 | 13.931 ± 0.136 | 13.990 | —            | —            |