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The Emergence of the Infrared Transient VVV-WIT-06*

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Abstract

We report the discovery of an enigmatic large-amplitude ($\Delta Ks > 10.5$ mag) transient event in near-IR data obtained by the VISTA Variables in the Via Lactea (VVV) ESO Public Survey. The object (designated VVV-WIT-06) is located at R.A. = 17:07:18.917, decl. = −39:06:26.45 (J2000), corresponding to Galactic coordinates $l = 347.14539$, $b = 0.88522$. It exhibits a clear eruption, peaking at $Ks = 9$ mag during 2013 July and fading to $Ks \sim 16.5$ in 2017. Our late near-IR spectra show post-outburst emission lines, including some broad emission lines (upward of FWHM ~ 3000 km s^{-1}). We estimate a total extinction of $A_V = 10$–15 mag in the surrounding field, and no progenitor was observed in *ZYJHKs* images obtained during 2010–2012 (down to $K_s > 18.5$ mag). Subsequent deep near-IR imaging and spectroscopy, in concert with the available multiband photometry, indicate that VVV-WIT-06 may be either: (i) the closest Type I SN observed in about 400 years, (ii) an exotic high-amplitude nova that would extend the known realm of such objects, or (iii) a stellar merger. In all of these cases, VVV-WIT-06 is a fascinating and curious astrophysical target under any of the scenarios considered.

Key words: binaries: close – Galaxy: stellar content – novae, cataclysmic variables – supernovae: individual

1. Introduction

The variable universe is one of the next frontiers that holds surprises as new surveys begin to massively explore the time domain. Large variability surveys frequently discover sources that remain unexplained, that are left unpublished, presumably because they fall outside of the main interests of the survey scientists, and because they are notoriously difficult to follow up. It is expected that future databases like LSST (Ivezic et al. 2008) would contain numerous such treasures.

The VISTA Variables in the Via Lactea (VVV) is a variability survey that is observing the inner bulge and southern disk in the near-IR in order to study the Galactic structure using Cepheid and RR Lyrae variables (Minniti et al. 2010). Saito et al. (2012) describe and characterize the first data release (DR1), and Hempel et al. (2017) describe and characterize the last data release (DR4) of the VVV Survey.

The VVV survey team pays special attention to some of the rare objects that defy classification. The extreme cases (generally high-amplitude variables that are not novae, microlensing events, long period variables, MNORs, etc.) are labeled as WIT objects (for What Is This?), that deserve further study. In the past years, we have discovered a few of these intriguing objects (Minniti et al. 2012; Dekany et al. 2014; Beamin et al. 2015; Saito et al. 2015, 2016). Here, we present a new case of a large amplitude near-IR transient located in the Galactic plane, that we call VVV-WIT-06.

2. VVV Survey Data and Follow-up Observations

The VVV survey observations carried out at the ESO 4 m VISTA Telescope (Emerson & Sutherland 2010), with the data reduction provided by the Cambridge Astronomical Survey Unit (CASU; Irwin et al. 2004). An initial set of single-epoch, *ZYJHKs* observations of the entire VVV survey region (540 deg^2) was acquired in 2010, followed up by multi-epoch *Ks*-band observations in 2010–2016. Another single epoch in *ZYJHKs* was acquired in 2015. The VVV images reach a limiting magnitude of $Ks = 18$ mag (3σ detection in the CASU photometry), with a median seeing of 0.9 arcsec. The coverage of the light curves is random, with no fixed cadence. In particular, VVV field d112 was observed 50 times in the *Ks* band from 2010 March 29 to 2015 July 27, with the complementary colors observed in 2010 June 25 and 2015 July 27. The VVV survey *Ks*-band light curves are regularly inspected searching for Galactic long-period variables (LPVs), microlensing events, novae (Saito et al. 2013), high-amplitude variable YSOs (Contreras Peña et al. 2017), but other rare high-amplitude near-IR transients are found, for which this

* Based on observations taken within the ESO programmes 179.B-2002 and 298.D-5048, and on observations carried out at the Magellan Telescope at LCO.

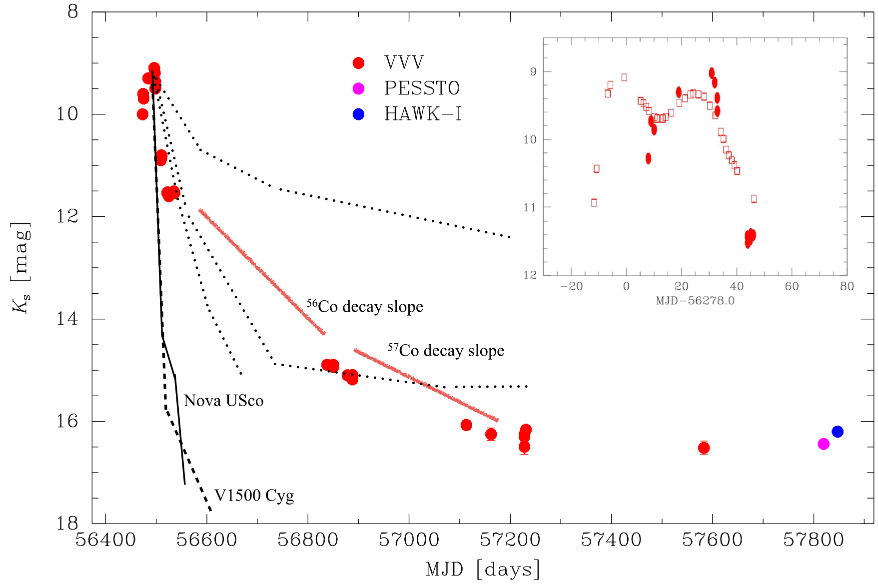

Figure 1. VVV-WIT-06 K_S-band light curve based on VVV data (red circles), compared with the light curves of novae U Sco and V1500 Cyg (with scaled optical photometry; solid and dashed lines), with classical novae observed by the VVV in the near-IR (dotted lines; Saito et al. 2013), and with the typical SN decay slopes for ^{56}Co (~1 mag/100 day), = and ^{57}Co (~0.5 mag/100 day). The insert shows the expanded peak region, compared with a double-peaked SN Ia (light squares). During the 2010–2012 seasons VVV-WIT-06 is fainter than $Ks \sim 19$ mag, so the epochs are not shown. On 2013 June the object is first detected at $Ks = 10.0$ mag reaching $Ks = 9.0$ on 2013 July 22 (MJD 56496). Since then the object fades steadily, reaching $Ks \sim 17.0$ in 2017. The list of VVV Ks measurements and dates is given in Minniti & Saito (2017). The purple point is from the ESO PESSTO Survey (Kuncarayakti et al. 2017), and the blue point from our VLT+HAWKI follow-up observations. For the brightest magnitudes ($Ks > 11.5$) the CASU photometry is based on the non-saturated PSF wings.

initial inspection does not reveal a clear classification. These objects are followed up in detail, and after discarding image reflections, border effects, blendings, and blemishes, some turn out to be our WIT objects.

VVV-WIT-06 was discovered in the VVV field d112 as a large-amplitude near-IR transient event with a clear eruption peaking in 2013 July. The object's point-source coordinates are R.A. =17:07:18.917, decl. = −39:06:26.45 (J2000), corresponding to Galactic coordinates $l = 347.14539$, $b = 0.88522$, measured from the Ks-band images. The complete VVV photometric data are listed by Minniti & Saito (2017), allowing us to draw the Ks-band light curve shown in Figure 1, that reached $Ks \sim 9$ mag. Interestingly, the shape of the light curve at maximum exhibits a double peak, as seen in the near-IR light curves of SNe Ia (Wood-Vasey et al. 2008).

Pre-eruption *ZYJHKs* VVV observations of VVV-WIT-06 obtained during years 2010 (5 epochs, March 28 to June 25), 2011 (8 epochs, May 9 to October 5), and 2012 (6 epochs, June 25 to July 6) show no detection of the progenitor at the source position. Taking into consideration that the detection limit of individual epochs in the field is of $Ks \sim 18.5$ mag, we initially inferred a total amplitude of $\Delta Ks > 9.5$ mag. When stacking all the good-seeing pre-eruption VVV Ks-band images of this field (19 background-subtracted and flux-matched images in total were median-combined between years 2010 and 2012 with seeing <1.1 arcsec and a median seeing of 0.88 ± 0.11 arcsec), we reach more than one magnitude deeper. There is still no progenitor detected in this deeper image, from which we conclude that the total amplitude of the eruption is $\Delta Ks > 10.5$ mag. An archival search for earlier data at the position of VVV-WIT-06 using SIMBAD-ADS shows no observable counterpart (within 5 arcsec) in previous images from 2MASS, GLIMPSE, *Spitzer*, *WISE*, and *MSX*.

Post-eruption multi-color images measured on 2015 July 27 (~760 days after the observed maximum in 2013 July) yield near-IR colors $(J - Ks) = 2.146$, $(H - Ks) = 0.952$, and $(J - H) = 1.194$. We also obtained deep point-spread function (PSF) photometry of this field. The color–magnitude diagram (CMD) shows a typical Galactic plane field, with two main branches: disk main sequence and red giant stars (Figure 2). Comparing the CMD of a 5 × 5 arcmin^2 field centered on VVV-WIT-06 with the CMD of the whole VVV tile d112 covering 1.5 deg^2 shows that the VVV-WIT-06 region is relatively less reddened than the rest of the field. Unfortunately, we have color information for the object only during the 2015 season, two years after the peak magnitude. Figure 2 shows that VVV-WIT-06 has a similar color to the other objects in the surrounding field. In fact, the position in the CMD at this late phase after maximum is typical of a field dwarf star.

We note that the light curve coverage is not continuous. There is a full year gap in the VVV observations, between the last 2012 observation (when VVV-WIT-06 was beyond detection in MJD = 56115.05587517) and the first 2013 observations (that show $Ks = 10.0$ mag in MJD = 56473.09881128). Therefore, if the real maximum light occurred just before 2013 June, we would have missed it.

The extinction toward the direction of VVV-WIT-06 measured from the VVV survey reddening maps (Gonzalez et al. 2012) is $A_V = 10$–15 mag, depending on the reddening law (see Nishiyama et al. 2009). Other available extinction estimates for the field are $A_V = 10.0$ (Bonifacio et al. 2000) and $A_V = 12.7$ (Schlafly & Finkbeiner 2011).

We also note that the final post-eruption object is a point source, and no nebulosity (nor any light echoes) was detected in the latter observations out to the present time (2017 April). Proper motions measured with the VVV Infrared Astrometric Catalog (VIRAC; Smith et al. 2017) are μR.A.=10.3 ± 4.1 mas yr^{-1}, μdecl. = -29.3 ± 3.9 mas yr^{-1}, being the uncertainties significantly larger than those measured for other sources at the same magnitudes. The μdecl. is significant and

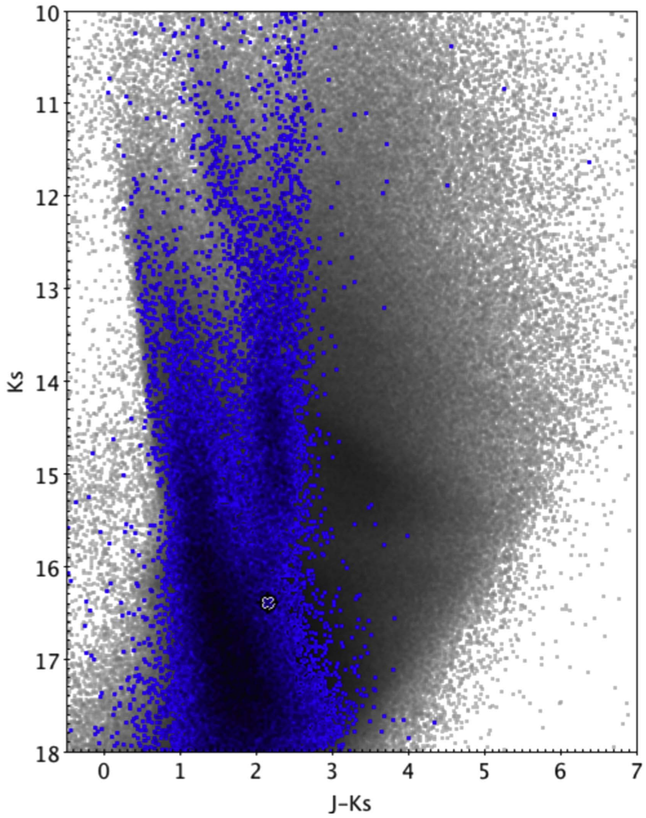

Figure 2. CMD of a 5 × 5 arcmin region (blue stars) centered on VVV-WIT-06 (black cross). The PSF photometry for whole VVV tile d112 covering 1.6 deg^2 gives 1.7 million stars that are also shown in gray as a Hess density diagram.

consistent with the motion of a Galactic disk object; however, we have found that some extreme variables can mimic a false proper motion while rising to (or fading from) a maximum in brightness (e.g., VVV-WIT-04; Saito et al. 2015).

There are no published optical observations of this object. The area has been surveyed in the I-band since 2014 May by OGLE-IV (Udalski et al. 2015), but nothing has been detected at these coordinates down to $I \simeq 20$ mag (P. Pietrukowicz 2017, private communication).

There were recent (2017 March 7) *JHKs* observations reported by Kuncarayakti et al. (2017) from the PESSTO survey (Smartt et al. 2015) that are consistent with the previous VVV observations. In particular, they show no significant fading or color changes, with $Ks = 16.44$ and $J - Ks = 1.99$. We have also acquired deep follow-up near-IR images with HAWKI at the ESO VLT on 2017 April 4, some 1350 days after eruption. VVV-WIT-06 is detected as a faint isolated point source in these images, without significant fading or color changes ($Ks = 16.20 \pm 0.7$).

In addition, from archival searches around the time of the discovery of VVV-WIT-06 (2013 March–July) we found no transient gamma-ray source in its field and listed in the *INTEGRAL*[16] (20–200 keV; Mereghetti et al. 2003), *Fermi*[17] (10–1000 keV; Bhat et al. 2016), or *Swift*[18] (15–150 keV; Lien et al. 2016) mission databases. Although upper limits on fluences of high-energy transients are difficult to place without the knowledge of proper spectral shape, duration, and exact time of the event, we can obtain values of $\leqslant 10^{-6}$, $\leqslant 10^{-7}$, and $\leqslant 10^{-7}$ erg cm^{-2}, respectively, from the three above mentioned satellites and the corresponding reported spectral ranges.

Likewise, there are no neutrino excess detections from the IceCube experiment at that time (Aartsen et al. 2017) nor from SuperKamiokande (M. Vagins 2017, private communication).

We acquired near-IR spectra with the Folded-Port Infrared Echellette (FIRE) spectrograph (Simcoe et al. 2010) at the *Magellan* telescope at Las Campanas Observatory on 2017 March 6, at about 1300 days after explosion. We also obtained optical–infrared spectra with the XSHOOTER spectrograph (D'Odorico et al. 2006) at the ESO Very Large Telescope of the ESO Paranal Observatory on 2017 April 4, some 1350 days after burst.

The high-quality FIRE and XSHOOTER spectra of VVV-WIT-06 are similar (Figure 3), and we do not detect any evolution between these spectra taken a month apart. There is a clear underlying continuum in both spectra that becomes bluer after reddening correction. The XSHOOTER spectrum covers ~0.3–2.5 μm, but shows no flux in the optical wavelengths, as expected for a highly reddened object.

The most striking VVV-WIT-06 spectral characteristics are the emission lines. Both spectra show two types of features: some are very strong and broad emission lines (FWHM ~ 3000 km s^{-1}), others are weak and narrow (FWHM < 500 km s^{-1}). The former are high excitation coronal lines sometimes seen in novae and SN, like [Co II], [Al IX], [Si VI], and [Ca VIII]. A couple of these lines are double peaked ([Ca VIII]2.3205, [Si VI]1.9641 μm), possibly indicating a material in a disk or in an expanding shell. The latter group includes lines of the H I Paschen and Brackett series that are detected but very weak. Instead, the [He II] lines (at 1.626, 1.4760, 1.4879, and 2.1885 μm) are strong, indicating high nebular temperatures.

The estimated $\mathrm{RV} = -90 \pm 20$ km s^{-1} from the emission lines in the VVV-WIT-06 spectrum is consistent with the expected velocity of a Galactic object located at a distance $D \sim 7 \pm 2$ kpc.

3. Discussion

One of the initially preferred interpretations was that VVV-WIT-06 was the closest Type I SN that is located in a nearby galaxy hidden by dust. The light curve slopes after maximum resemble the radioactive decay of a Type Ia (thermonuclear SN) or a Type Ibc SN (core-collapse event). The best match with the observed IR light curves of other SNe (e.g., Wood-Vasey et al. 2008) is with Type Ia and Type Ibc. Also, subluminous SNe Ia would give a reasonable fit, but there is less IR photometry than for SN Type Ibc. However, late evolution departs from the characteristic power-law radioactive decay because the brightness remains nearly constant during 2016 and 2017, indicating an additional energy source.

Several NIR lines trace the distribution of radioactive elements powering the light curve of Type I SNe (e.g., [Co II], [P VIII] lines). Unfortunately, there are no near-IR spectra of SN Type I observed so late after explosion that we can use to make a quantitative comparison with our late spectra of VVV-WIT-06. However, some of the emission lines seen in the VVV-WIT-06 spectrum are also seen in Type I SN spectra ([Co II], [Mg I], [Fe II]).

[16] http://www.isdc.unige.ch/integral/science/grb
[17] https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html
[18] http://www.grbcatalog.org/

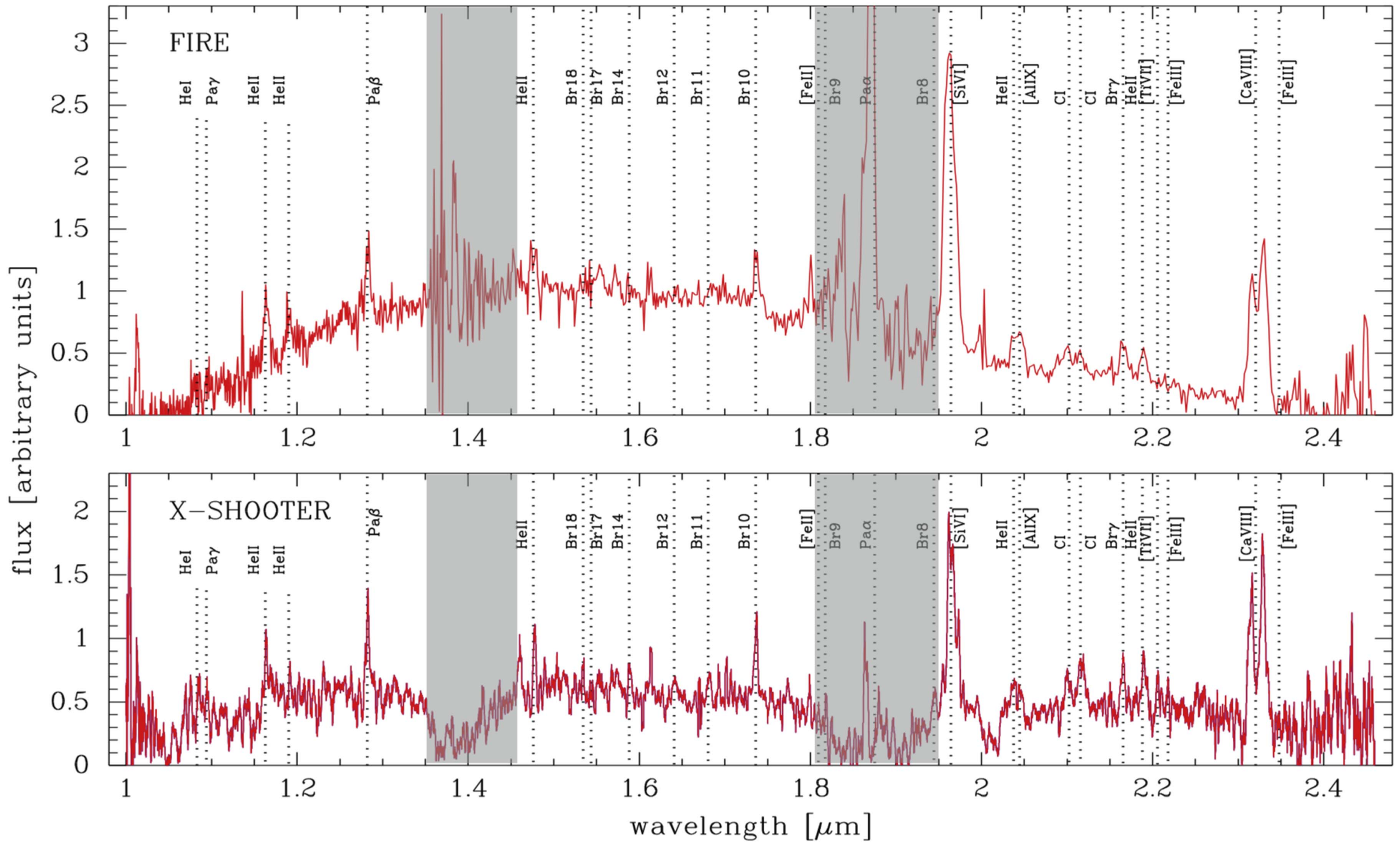

Figure 3. Top: *Magellan* FIRE spectrum of VVV-WIT-06 taken 1300 days after peak brightness. Bottom: VLT XSHOOTER spectrum of this object taken 1350 days after peak brightness. The most prominent spectral features are labeled, and the inter-band regions badly affected by the atmosphere are shaded.

Using the extinction estimate $A_V = 10–15$ mag, we can compute the distance, assuming that VVV-WIT-06 is a Type I SN. Using a range of A_K between 1.3 and 1.9 and a range of peak absolute magnitudes between -17 to -19 (which would be true for both Type Ia and Type Ib) we get a distance range between 0.7 and 2.2 Mpc, always outside the Milky Way. This rather uncertain distance places the potential SN in the outer Galactic halo or in an unknown nearby galaxy. However, the survey of McClure-Griffiths et al. (2005) shows no evidence for strong additional H I emission in that direction.

This Type I SN interpretation would explain the shape of the light curve, the maximum brightness that implies a distance between $D = 0.7–2$ Mpc, the absence of a progenitor, and the lack of gamma-rays and neutrino detection (the latter only for the Type Ia case). The distance range depends on the peak SN brightness in the near-IR and the total foreground extinction. However, the problems with this interpretation are the low probability ($<1\%$) that the host galaxy would align within less than a degree from the Galactic plane, that the light curve at later times requires an additional energy source to remain nearly constant, and that the measured kinematics (radial velocity and proper motions) favor a Galactic object.

This possibility is important because, if confirmed, VVV-WIT-06 would be the nearest Type I SN observed in 400 years. The peak apparent magnitude of VVV-WIT-06 was about 3 mag brighter than SN2011fe at maximum in the K band (Matheson et al. 2012). Given the low expected rate of Galactic SN Ia (e.g., Branch et al. 1995; Della Valle & Livio 1996), this would probably be a unique object in a lifetime that has been followed up for a few years after explosion, monitoring the low-luminosity decay slope. Also, if this is a Galactic supernova, the fact that VVV-WIT-06 was undetected in the optical reinforces the theory that even though SNe are rather frequent in the Milky Way (rate 1/50–100 years), they have not been observed because of dust extinction.

However, we stress that against this possibility are the observed peak brightness that doe not reach typical supernovae Type I absolute luminosities and the rather flat evolution of the light curve at late times (after ∼1000 days) that would require an additional energy source (like dust production or a light echo).

Another possibility to consider is a Galactic core-collapse SN of Type II. This interpretation is less likely because the spectrum is very different from the late spectrum of the atypical SN1987A at $T + 1350$ days from Fassia et al. (2002) and also because the observed light curve has a different timescale and shape from SNe Type II. The lack of progenitor is also a big problem because we can place stringent limits to the progenitor magnitude: $M_K > 3.8$ mag for reasonable distances within the Milky Way $1 < D < 18$ kpc. Also, neutrinos should be detected in Galactic core-collapse supernovae, and there were no excess neutrinos reported.

The possibility of a Galactic nova was also considered (Figure 1) since there are a few examples of novae exhibiting large-amplitude light curves (e.g., U Sco—Pagnotta et al. 2015; V1500 Cyg—Ferland 1977). The main problems here are the shape of light curve, with a decline slope that is not typical of classical novae nor of slow novae (e.g., Hachisu & Kato 2006, 2015), and the lack of progenitor down to very faint magnitudes (Figure 1). The narrow emission lines of the H I Paschen and Brackett series are very weak in VVV-WIT-06. However, in view of the spectrum that shows some other emission lines common in novae at late times, this scenario is quite likely. Indeed, the zoo of novae includes some extreme objects. The spectrum resembles the late spectrum of some novae that sometimes also exhibit broad near-IR coronal lines (Greenhouse et al. 1990) and/or He II emission lines, like fast He/N novae (Banerjee & Ashok 2013) or very slow novae (Rudy et al. 2002). Also, some novae like the C-type nova V2491 Cyg exhibit a double-peak structure in the optical light curve (Strope et al. 2010). Assuming a nova, the distance depends on the extinction and color correction and on the nova type. Comparing to the optical light curves of U Sco and V1500 Cyg corrected to the near-IR and also for extinction, the distance estimates range from about 1 to 10 kpc. Smaller distances are unlikely because of the absence of a progenitor.

This object lies in an interesting region in the classical transients diagram of Kulkarni (2013, Figure 3), beyond the classical novae. If VVV-WIT-06 turns out to be a nova, this will expand considerably the realm of this kind of transient, overlapping the location of supernovae in the amplitude–timescale diagram.[19]

There are also rare high-amplitude IR transients observed in nearby galaxies, called SPRITEs (Kasliwal et al. 2017). These appear to be intermediate between novae and SNe. Even though the shape of the light curve of VVV-WIT-06 is inconsistent with these extragalactic SPRITEs, if it is a SPRITE, it would be the first such Galactic candidate, an excellent opportunity to learn about these objects in detail.

Finally, we might be witnessing a stellar merger, which may not be an uncommon event in the Milky Way (Kochanek et al. 2014). OGLE-2002-BLG-360 and V1309 Sco are examples of two well-studied cases with high-quality long-term light curves observed by OGLE (Tylenda et al. 2011, 2012), where the eruption appears to be the result of the final merger of a contact binary star after a common envelope phase. The final product is a stellar source with a slowly declining brightness. In the case of VVV-WIT-06, the progenitor was very faint with $Ks > 19.5$, undetected in the optical and near-IR, arguing for a low-mass contact binary. Indeed, adopting $A_{Ks} \sim 1.5$ and a typical distance of $D \sim 7$ kpc yields a progenitor with $M_K > 3.8$, corresponding to a very low mass contact binary. In addition, the late position of VVV-WIT-06 in the CMD (Figure 2) is typical of a field dwarf star and would also be consistent with the interpretation of a stellar merger.

4. Conclusions

We presented the case of VVV-WIT-06, an extreme near-IR transient event in the Galactic plane. The object is located in a very reddened field, with $A_V = 10$–15 mag depending on the shape of the reddening law. We consider various possibilities for VVV-WIT-06, arguing that this could be a nearby SN Type I, a peculiar nova, or a stellar merger. While we cannot fully discard any of these possibilities, all of these scenarios are interesting in their own right.

Regarding the distance estimated for the SN scenario, based on assuming about 2 mag of extinction in Ks, and $M_K = -18$ absolute mag at peak, which is typical for both SNe Ia and Ib, we obtain $D = 0.7$ to 2.2 Mpc. Alternatively, there is still the possibility of a Galactic SN if its maximum was reached before the 2013 VVV campaign. If this is a true SN, it would be the closest SN Type I in about 400 years, and it might also pinpoint the location of a new nearby galaxy hidden by dust.

Concerning the nova scenario, this is a good option because it is supported by the late-time spectra. In this case, VVV-WIT-06 would be an uncommon He/N nova that would expand the realm of novae in the Kulkarni (2013) diagram of peak luminosity versus characteristic timescale for explosive events.

Considering the stellar merger possibility, VVV-WIT-06 would be one of the few well-observed cases. Its follow-up study is important for the long-timescale prediction of the star formation and fate of the Milky Way at the end of the stelliferous era (Adams & Laughlin 1997).

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[19] The Kulkarni (2013, Figure 3) diagram was made in the optical, and it has to be updated to the near-IR, where many obscured transients are detected that are not seen optically, as is the case of VVV-WIT-06.

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