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Unraveling the Infrared Transient VVV-WIT-06: The Case for the Origin as a Classical Nova*

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Abstract

The enigmatic near-infrared transient VVV-WIT-06 underwent a large-amplitude eruption of unclear origin in 2013 July. Based on its light curve properties and late-time post-outburst spectra, various possibilities have been proposed in the literature for the origin of the object, namely a Type I supernova, a classical nova (CN), or a violent stellar merger event. We show that, of these possibilities, an origin in a CN outburst convincingly explains the observed properties of VVV-WIT-06. We estimate that the absolute *K*-band magnitude of the nova at maximum was $M_k = -8.2 \pm 0.5$, its distance $d = 13.35 \pm 2.18$ kpc, and the extinction $A_v = 15.0 \pm 0.55$ mag.

Key words: infrared: stars – line: identification – novae, cataclysmic variables – stars: individual (VVV-WIT-06) – techniques: spectroscopic

Supporting material: data behind figure

1. Introduction

We analyze the enigmatic infrared (IR) transient VVV-WIT-06 discovered by the VISTA Variables in the Via Lactea (VVV) ESO Public Survey (Minniti et al. 2010). The object showed a large amplitude ($\Delta K_s > 10.5$ mag) outburst in 2013, peaking at $K_s \sim 9$ mag during 2013 July and subsequently fading to $K_s \sim 16.5$ in 2017. Analysis of its near-IR (NIR) spectra obtained by Minniti et al. (2017) almost 1300 days after the eruption showed the spectrum to be heavily reddened and having several emission lines. Based on the light curve and the spectra, Minniti et al. attempted to classify the object but a definitive classification could not be achieved. They proposed three possibilities for its nature: (i) the closest Type I supernova (SN Ia) observed in about 400 yr, (ii) an exotic high-amplitude nova belonging to a regime separate from normal classical novae (CNe), or (iii) a stellar merger event.

Our motivation to reanalyze the object was to resolve its true nature. Furthermore, peculiar objects can sometimes be flag bearers for a new or unique class of objects, e.g., as V838 Mon was for stellar mergers (Munari et al. 2002) or as V445 Puppis was a prototype for helium novae (Ashok & Banerjee 2003). In the present study, we therefore reanalyze some of the Minniti et al. (2017) data and also present two additional spectra. We arrive at the conclusion that VVV-WIT-06 is a CN whose first spectrum, however, was recorded unusually late, several years after its eruption.

2. Observations

Three NIR spectra of VVV-WIT-06 were obtained on 2017 March 7, 26, and April 21 using the Folded Port Infrared Echellette (FIRE) spectrograph on the 6.5 m Magellan Baade Telescope (Simcoe et al. 2013). The FIRE spectra were obtained in the high-throughput prism mode with a 0.6 arcsecond slit. The configuration yields a continuous wavelength coverage from 0.8 to 2.5 μm with a resolution of ~500 in the *J* band. At each epoch, an A0V telluric standard was observed close to the science target in time, angular distance, and airmass for telluric correction, as per the method described in Vacca et al. (2003). Additional details of the observation and reduction steps can be found in Hsiao et al. (2015). The log of the observations is given in Table 1. We also show NIR comparison spectra of the novae V959 Mon (Nova Mon 2012) and V5668 Sgr which were taken at $R = 1000$ (0.85–2.4 μm) using the Near-infrared Camera and Spectrograph (NICS) from the Mount Abu Observatory (Banerjee & Ashok 2012). Details of observational and data reduction procedures related to the NICS are given in Banerjee et al. (2014), Joshi et al. (2015), and Srivastava et al. (2016).

3. Results and Discussion

Figure 1 shows the three individual spectra of VVV-WT-06. Since they are reasonably similar (except for the [Ca VIII] 2.3205 μm line which is discussed later), they were coadded to increase the signal-to-noise ratio (S/N). The coadded spectrum, after continuum subtraction and normalization, is presented in Figure 2 with the lines identified. The spectrum is very typical of a nova in the nebular/coronal stage, which is reached when the central white dwarf has evolved to high enough

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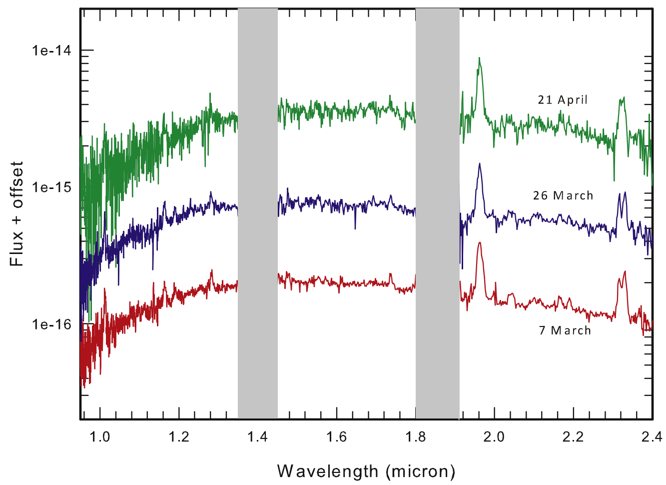

Figure 1. Un-de-reddened spectra of VVV-WIT-06 recorded on 2017 March 7, 26, and April 21, respectively. The data used to create this figure are available.

Table 1
Log of NIR Spectroscopy

Date (in 2017)	Days After Max[a].	Int. Time (s)	Std. Star	Target Airmass	Std. Airmass
Mar 7	1324	1014	HD 151075	1.03	1.02
Mar 26	1343	3170	HIP 75418	1.03	1.02
Apr 21	1369	1390	HD 151075	1.07	1.07

Note.
[a] The maximum has been taken to occur on 2013 July 22 (MJD 56496).

temperatures to emit sufficiently hard radiation to produce ions with high levels of ionization such as Si VI, Ca VIII, Al IX, etc. (the ionization potentials for these are 166.77, 127.20 and 284.66 eV, respectively). At this stage forbidden transitions dominate the spectrum together with those from permitted lines of H, He I, and He II. We also show the J- and K-band spectra of two novae (Banerjee et al. 2012, 2016) at a similar stage of ionization. These are V959 Mon, which had its outburst in 2012 June 22–24, and V5668 Sgr, which erupted on 2015 March 15. The former is a He/N nova (Williams 1992) while the latter is an Fe II type nova. As can be seen, there is a good match of the spectra and the same lines are seen in the spectra of all three objects. This strongly supports our contention that VVV-WIT-06 is a CN. Any observed difference in the relative strengths of the lines is likely due to the fact that the VVV-WIT-06 observations were made at +1300 days after outburst while those for V959 Mon and V5668 Sgr were at ∼+200 days and +350 days after outburst. The strengths of the recombination lines of H and He are proportional to the square of the electron density and are hence time-dependent and expected to weaken as the ejecta expands and dilutes. The strength of the forbidden lines is also greatly dependent on the density (and hence on the epoch of observation) since they become prominent only below a certain critical density which varies from ion to ion.

Figure 3 shows the velocity profiles for a few selected forbidden and permitted lines. The forbidden lines like [Si VI] 1.9641 μm and [Ca VIII] 2.32 μm have been recorded at reasonably good S/N, allowing us to estimate that their full width at zero intensity (FWZI) is ∼6000 km s^{-1}. However all the permitted lines are fairly weak and we had to use a three-point running average to smooth their profiles in Figure 3. Even then the FWZIs of these lines are difficult to ascertain with satisfactory accuracy, but it is clear that they are narrower than the forbidden lines and have an FWZI of ∼4000–5000 km s^{-1}. These values are satisfactorily consistent with generally observed profile velocities in novae. In the classification scheme by Williams (1992), the Fe II novae have FWZI $<$ 5000 km s^{-1} whereas the He/N novae generally have FWZI $>$ 5000 km s^{-1}. Based on this criterion alone, however, it is difficult to say whether VVV-WIT-06, if indeed a CN, is of the Fe II type or He/N type. But we would favor the former class because of the extended climb to maximum seen in the light curve and also since the line profiles are not significantly flat-topped, as expected for He/N novae.

Another argument suggesting a Fe II class for the object is its position with respect to the Galactic plane. Given that the object's Galactic latitude is $b = 0.88522$ degrees and has an estimated distance $d = 13.35 \pm 2.18$ kpc, its vertical height z above the Galactic midplane is 206 ± 33 pc. Della Valle & Livio (1998) found that novae belonging to the He/N class tend to concentrate close to the Galactic plane with a typical scale height ⩽100 pc, whereas the Fe II novae are distributed more homogeneously up to $z \leqslant 1000$ pc, or even beyond. Although a classification of the object (He/N or Fe II) is not easy, it may be noted in general that the FWZI values of ∼5000–6000 km s^{-1} observed here, though slightly large, have been similarly observed in several CNe (e.g., Harrison et al. 1991; Schwarz et al. 2011) thereby supporting our nova interpretation.

It is necessary to check whether the characteristics of the light curve are also consistent with the proposed nova classification for VVV-WIT-06 as suggested by the spectra. Figure 4 shows the K_s-band light curve from the data available in Minniti & Saito (2017) and for comparison the light curves of the novae V496 Scuti and T Pyxidis are also shown. Novae show an enormous variety in their light curve shapes as can be seen from the compilation by Strope et al. (2010). There is also a huge spread in the so-called speed class as measured by the t_2 parameter, the time for the brightness to decline by two magnitudes from maximum, which ranges from a very few days for very fast novae to several hundred days for very slow novae. The VVV-WIT-06 light curve is a typical nova light curve, with an initial rise to maximum followed by a rapid decline. The slow rise to maximum hints that this is likely a nova of the Fe II class (e.g., V1280 Sco; Das et al. 2008; V339 Del; Gehrz et al. 2015; Evans et al. 2017), where such behavior is often encountered, rather than a He/N nova where the rise and decline from maximum are much more rapid. From the light curve we estimate that t_2 is 17.5 ± 0.5 days, making this a nova of the fast speed class. This translates to an absolute K_s-band magnitude $M_k = -8.2 \pm 0.5$ using the maximum magnitude versus rate of decline (MMRD) relation of della Valle & Livio (1995). This is a very typical value of the absolute magnitude expected for a nova (Warner 1995).

We estimate the extinction and distance to the nova in the following way. If reliable extinction versus distance information is available in the nova's direction (e.g., as in the Marshall et al. 2006 data shown in Figure 5) and a valid MMRD relation for the nova is also available, then estimates of both the extinction and distance can be made simultaneously. The continuous curve in Figure 5 shows the A_k versus distance curve from the relation

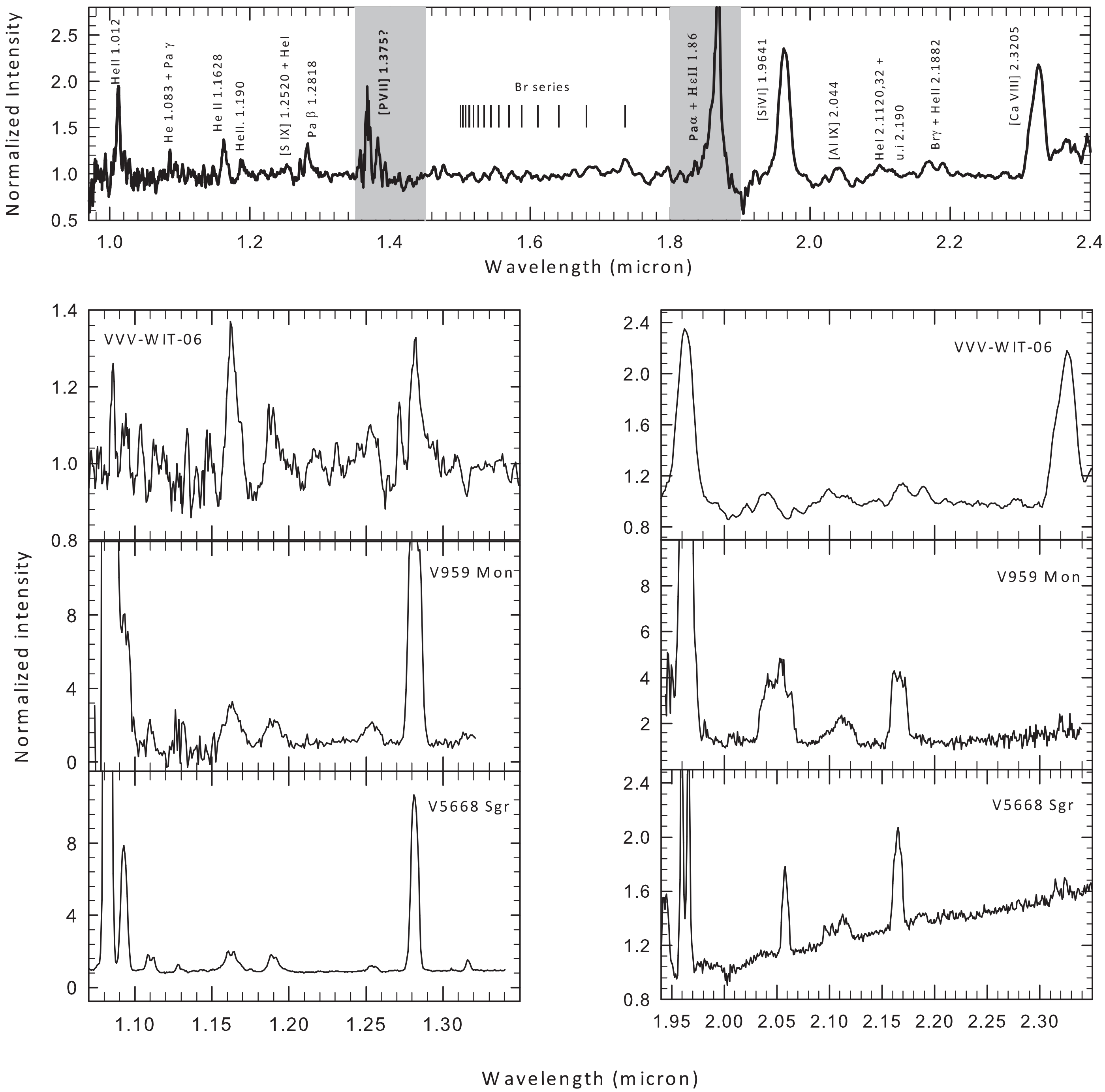

Figure 2. Top: average of the three spectra of VVV-WIT-06 from 2017 March 7, 26, and April 21 after a continuum subtraction and normalization. Regions of poor atmospheric transmission are shown in gray. Lines are marked; the unidentified line at 2.090 μm blended with He I 2.1120, 2.1132 μm has sometimes been attributed to [Mn XIV] 2092 μm (Wagner & Depoy 1996). The bottom six panels show expanded views of the J- and K-band spectra of VVV-WIT-06 and also, for comparison, the spectra of two other novae with coronal lines, namely V959 Mon (He/N type) and V5668 Sgr (Fe II type; Banerjee et al. 2012, 2016). Although the lines in the VVV-WIT-06 spectrum are weak due to the faintness of the object when it was observed, there is a good match between the spectra of all three objects. This strongly suggests that VVV-WIT-06 is a CN.

$m_k(\max) - M_k = 5\log d - 5 + A_k$ wherein we use $m_k(\max) = 9.09$ and $M_k = -8.2$. The second curve in Figure 5 shows extinction versus distance from Marshall et al. (2006) based on their modeling of Galactic extinction. The intersection of the two curves should give the nova's distance and extinction because both curves in principle correspond to the same line of sight and thus the same extinction. We obtain $d = 13.35 \pm 2.18$ kpc and $A_k = 1.68 \pm 0.18$. Using $A_k/A_v = 0.112$ and $A_v = 3.09E(B-V)$ (Rieke & Lebofsky 1985) we get $A_v = 15.0 \pm 0.55$ and $E(B-V) = 4.85 \pm 0.18$. These are in reasonably good agreement with similar estimates made by Schlafly & Finkbeiner (2011) and Schlegel et al. (1998) who find $E(B-V)$ values of 4.12 ± 0.20 and 4.80 ± 0.23 respectively in the direction of the nova. Some caveats in our calculations include the fact that the extinction estimates of Marshall et al. (2006), Schlafly & Finkbeiner (2011), and Schlegel et al. (1998) are for small regions in which both the extinction and the ratio of selective-to-total extinction could vary (e.g., Alonso-García et al. 2017), and

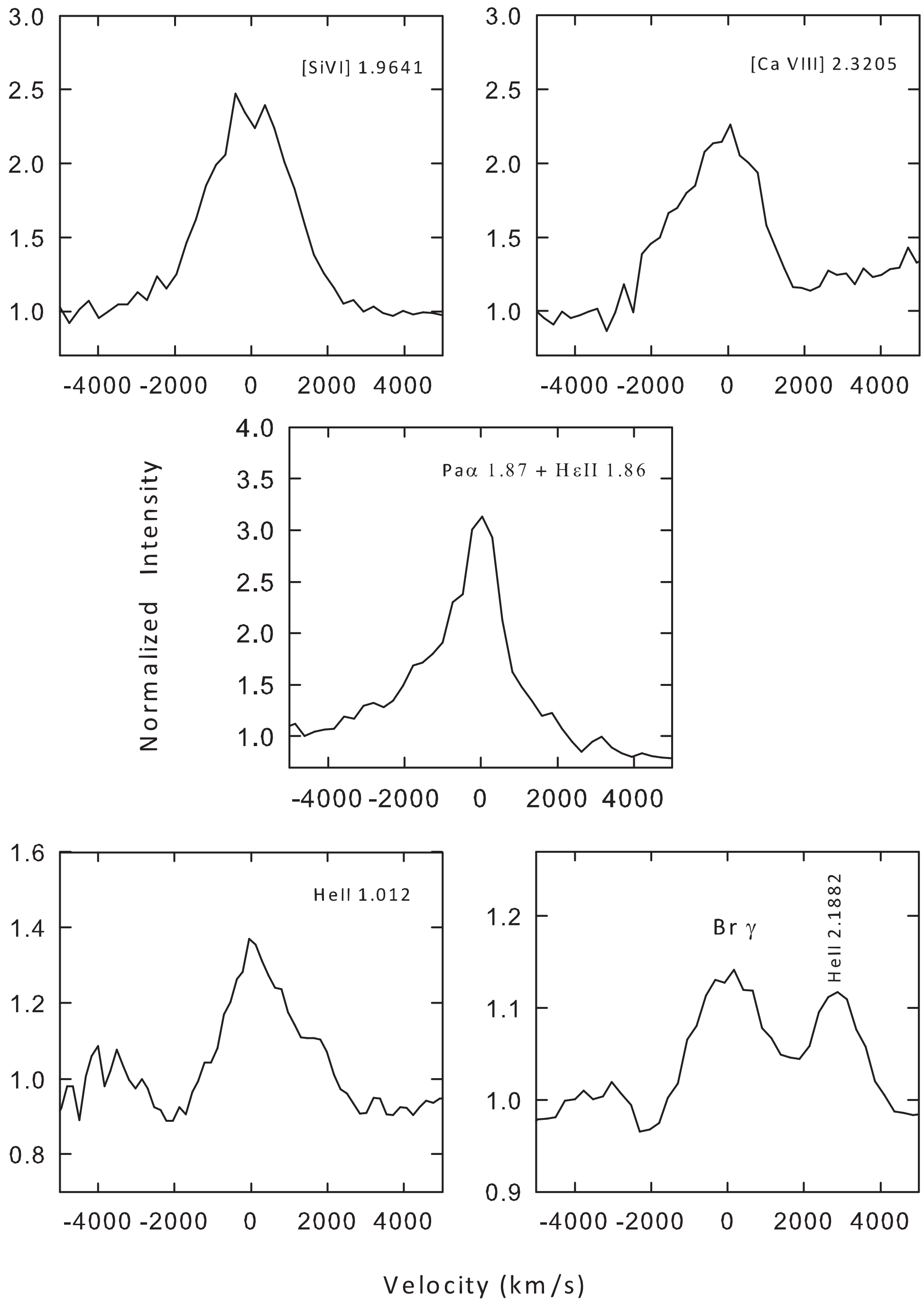

Figure 3. Velocity profiles of selected forbidden and permitted lines.

also that near the Galactic plane ($|b| < 5$ deg) the extinction value is quite uncertain.

The split profile of the [Ca VIII] 2.3205 μm line warrants some discussion. The clear splitting of the profile peak into a blue and a red component is clearly seen in Figure 1 but unfortunately gets suppressed in averaging the spectra in Figure 2. None of the other lines shows a similar pronounced double-peaked structure. The depth and presence of the splitting varies with epoch, which may partially be caused by the varying S/N of the three spectra (e.g., the April 21 spectrum is noisier and the splitting least pronounced). For understanding the origin of this profile we compare the [Ca VIII] 2.3205 μm line profile with other coronal lines. The latter are forbidden transitions that get de-excited by collisions once a critical density is exceeded. For the [Si VI] 1.9641 μm line the critical density is 10^8 cm^{-3} (see Spinoglio & Malkan 1992; Spinoglio 2014). The critical density for the [Ca VIII] 2.3205 μm line is not covered by this work. However, Ferguson et al. (1997), analyzing coronal line strengths in active galactic nuclei show that the [Ca VIII] 2.3205 μm line is not present for densities exceeding $10^{6.25}$ cm^{-3}, while the [Si VI] 1.9641 μm line is not seen beyond a density of 10^8 cm^{-3}. We thus assume the critical density of the [Ca VIII] 2.3205 μm line is $10^{6.25}$ cm^{-3}. Hence it should arise from regions of considerably lower densities compared to the [Si VI] 1.9641 μm line, i.e., from different sites within the nova which

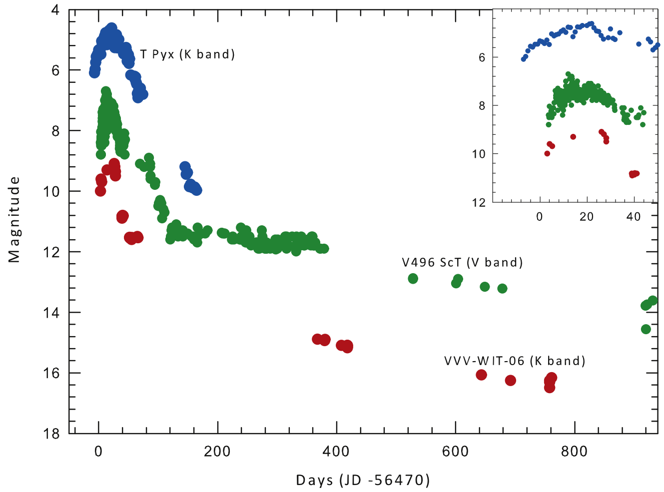

Figure 4. K_s-band light curve of VVV-WIT-06 and, for comparison, the light curves of the novae V496 Scuti (a Fe II type) and T Pyxidis (a recurrent nova). The inset, giving an expanded view of the early rise and decline stages, shows the considerable similarity between the objects.

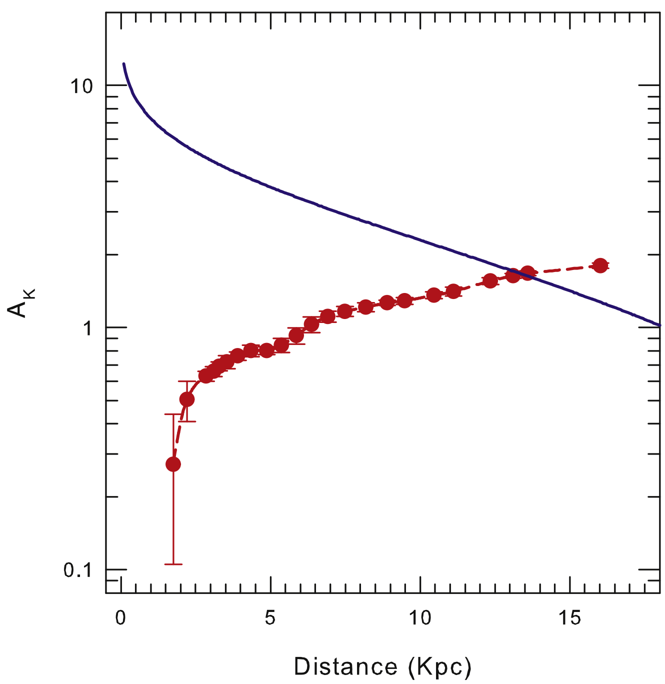

Figure 5. Variation of the extinction toward VVV-WIT-06 (curve joining the data points (red circles)) based on results from Marshall et al. (2006). The continuous straight line is a plot of extinction A_K vs. distance d from the equation $m_k - M_k = 5 \log d - 5 + A_k$ where m_k is known from observations and M_k is estimated from the MMRD relation. The intersection of the two curves allows us to simultaneously estimate the extinction and distance to the nova. More details are given in the text.

could therefore have different kinematic properties. One possibility is that VVV-WT-06 has a bipolar morphology—many novae have such a shape, as discussed in great detail in Banerjee et al. (2018). In such a geometry the material in the equatorial plane is dense and slow moving while the density in the polar regions is low since these regions expand and dilute rapidly. Thus the Si VI and other atomic emission could emanate from all over the nova including the equatorial waist whereas the [Ca VIII] 2.3205 μm would preferentially be located mostly in the polar regions. The blue and red components would then correspond to the line-of-sight velocity components from the approaching and receding polar regions of the bipolar structure. An alternative possibility for a dip in the central region of the peak is that it is caused by self-absorption since the line is fairly strong.

4. Discussion

If the observed light curve represents that of a CN, the derived quantities from it such as t_2 and the absolute magnitude are also consistent with those expected for a CN. The estimated extinction matches the observed extinction in the direction of the nova. The amplitude of outburst, from quiescence to peak brightness, of $>$10.5 mag is consistent with what is expected for a nova; the slowest novae have an amplitude around 7 and the fastest around 15 (Warner 1995; Bode & Evans 2008). The distance estimate also appears reasonable, being within the Milky Way. Thus, the evidence supports a CN classification. The spectra independently also strongly support the CN nature.

Minniti et al. (2017) have considered two alternative eruption scenarios which could produce such a high-amplitude outburst as observed in VVV-WIT-06. One possibility is that it is an SN Ia. But, as the authors admit, there are several difficulties in assigning an SN origin to VVV-WIT-06. These include the fact that the late evolution of the light curve departs from the characteristic power-law radioactive decay of SNe Ia because the brightness of VVV-WIT-06 remains nearly constant during 2016 and 2017, indicating an additional energy source. Additionally, NIR spectra of SNe Ia are not available up to $\sim$1300 days after explosion, thereby not allowing a direct comparison with the observed late spectra of VVV-WIT-06. The other problems with an SN interpretation are the low probability ($<$1%) that the host galaxy would align within less than a degree with the Galactic plane, and that the measured kinematics (radial velocity and proper motions) of VVV-WIT-06 favor a Galactic origin.

The other possibility considered is that it could be a stellar merger event. The observational realm of stellar mergers arose in 2002 with the spectacular outburst of the haloed V838 Mon. It was soon realized that two other objects, V4332 Sgr and M31-RV in Andromeda, shared similar evolutionary properties with V838 Mon, leading to the proposition that they comprised a new class of objects (Banerjee & Ashok 2002; Munari et al. 2002). However all these objects showed a common trend of evolving toward cool temperatures after their outburst (e.g., Rich et al. 1989; Banerjee & Ashok 2002; Evans et al. 2003; Lynch et al. 2004). Their post-outburst spectra resembled those of cool stars replete with molecular bands, either in absorption or emission, of many species such as CO, AlO, H_2O, TiO, ScO, CrO, etc. (Banerjee et al. 2003, 2004, 2005; Banerjee & Ashok 2004; Lynch et al. 2004; Kamiński et al. 2015). Many of them formed copious dust that exists to date (Chesneau et al. 2014; Banerjee et al. 2015). This is in complete contrast with VVV-WIT-06 whose ejecta has evolved in the opposite direction, namely toward high-ionization stages containing species such as Si VI, Al IX, etc. We thus consider the stellar merger scenario to be completely ruled out and, in view of our earlier arguments, propose a CN origin for VVV-WT-06.

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