

## NSV 11749, AN ELDER SIBLING OF THE BORN-AGAIN STARS V605 Aql AND V4334 Sgr?

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### ABSTRACT

We argue that NSV 11749, an eruption observed in the early twentieth century, was a rare event known as “very late thermal pulse” (VLTP). To support our argument we compare the light curve of NSV 11749 with those of the two bona fide VLTP objects known to date, V4334 Sgr and V605 Aql, and with those predicted by state-of-the-art stellar evolution models. Next, we explore the INT Photometric H-Alpha Survey (IPHAS) and Two Micron All Sky Survey (2MASS) catalogs for possible counterparts of the eruption. Our analysis shows that the VLTP scenario outperforms all other proposed scenarios as an explanation of NSV 11749. We identify an IPHAS/2MASS source at the eruption location of NSV 11749. The derived colors suggest that the object is not enshrouded in a thick dust shell as V605 Aql and V4334 Sgr. Also, the absence of an apparent planetary nebula at the eruption location suggests differences with known VLTP objects which might be linked to the intensity of the eruption and the mass of the object. Further exploration of this source and scenario seems desirable. If NSV 11749 was a born-again star, it would be the third event of its kind to have been observed and will strongly help us to increase our understanding of the later stages of stellar evolution and violent reactive convective burning.

*Key words:* novae, cataclysmic variables – stars: AGB and post-AGB – stars: individual (NSV 11749, V4334 Sgr, V605 Aql)

*Online-only material:* color figures

### 1. INTRODUCTION

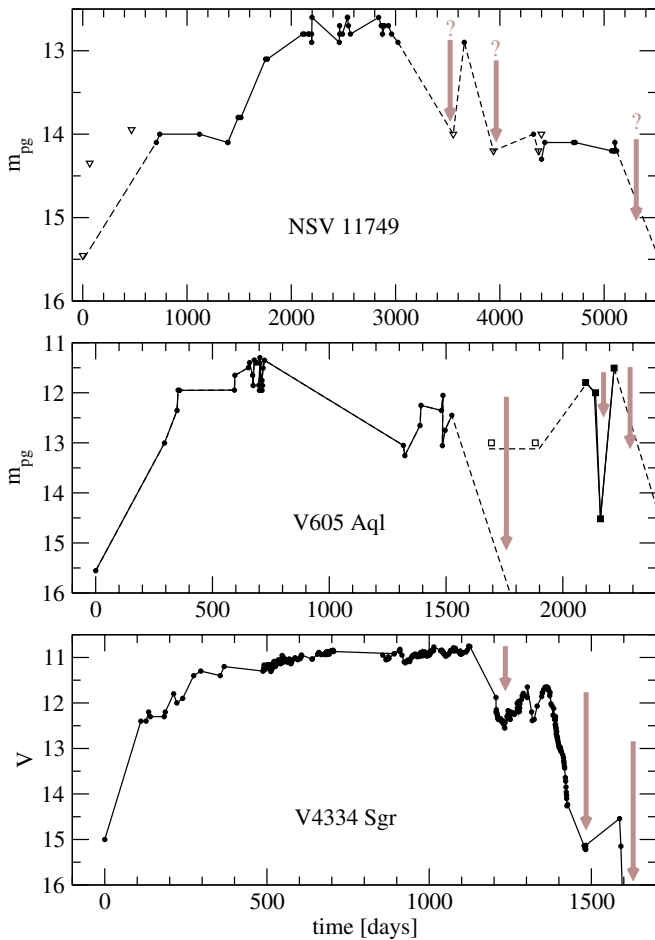
About a fifth of the stars departing from the asymptotic giant branch (AGB) are expected to undergo a final thermal pulse during their post-AGB evolution (Iben 1984). When this happens, the pre-white dwarf is predicted to be temporarily reborn as a yellow giant (Schoenberner 1979) in the so-called Born-again AGB scenario (Iben 1984). The transition from the pre-white dwarf to the giant configuration is expected to be very rapid, being of a few years in the very late thermal pulse (VLTP) flavor (Iben & MacDonald 1995) and of the order of a century in the late thermal pulse (LTP) case (Schoenberner 1979). Due to the short duration of these events, although 10% of post-AGB stars are expected to undergo a VLTP, they are extremely rare from an observational perspective. Indeed, only two objects (V605 Aql and V4334 Sgr) have been identified as stars undergoing a VLTP (see Duerbeck et al. 2000, 2002), while a third has been identified with the LTP flavor of the scenario (FG Sge; see Jeffery & Schönberner 2006 and references therein). Although observationally rare, individual VLTP stars are extremely valuable as they are key to understand the formation of C-rich H-deficient stars, such as [WC]-CSPNe, PG1159, and RCrb (see Werner & Herwig 2006 and Clayton 1996 for a review) and the formation of H-deficient white dwarfs—which comprise about ~20% of known white dwarfs. In addition, born-again star events are a key test for our understanding of the *s*-process during the thermal pulse phase of the AGB (Asplund et al. 1999; Jeffery & Schönberner 2006) and also for understanding of reactive convective burning in the interior of stars (Herwig et al. 2011).

A rough estimate suggests that the birth rate of planetary nebulae (PNe) in our galaxy is about ~1 every year (Zijlstra

2002). If 10% of their central stars become VLTP giants, then we should expect such events in our galaxy to take place at a rate of about one per decade. Due to their high intrinsic brightnesses ( $M_v \sim -2 \dots -4$ ) these objects can be easily detected at large distances within our galaxy. Hence, it should not be strange if some born-again eruptions are waiting to be identified in old and new star surveys. This could be the case for the object NSV 11749. After an excellent systematic study of all useful Harvard plates, Williams (2005) was able to reconstruct the outburst light curve of this star. The plates show that the object was fainter than  $m_{pg} \sim 15.5$  on 1897.6, became visible for the first time at  $m_{pg} \sim 14$  on 1899.5, and reached maximum at  $m_{pg} \sim 12.5$  on 1903.4. Then, it remained at about maximum brightness until 1907.6 when it started to decline, becoming undetectable after 1911.6—with four possible detections at  $m_{pg} \sim 17$  some decades later. Finally, during the declining phase, the star showed three sudden disappearances (fainter than  $m_{pg} \sim 14$ ) before finally fading into oblivion. In this Letter we argue that NSV 11749 was a VLTP event and explore possible counterparts in the INT Photometric H-Alpha Survey (IPHAS) and Two Micron All Sky Survey (2MASS) catalogs.

### 2. THE LIGHT CURVE OF NSV 11749

The light curve of NSV 11749 bears a strong resemblance to those of VLTP-objects (V4334 Sgr and V605 Aql). As can be seen in Figure 1, NSV 11749 increased its brightness by more than 2.5 mag in the first 2000 days of its eruption (i.e.,  $dm_{pg}/dt > 0.45^m \text{ yr}^{-1}$ ), stayed at a maximum brightness of  $m_{pg} \sim 12.6^m$  for about 1000 days, and then started to experience sudden dimmings (of more than  $1^m$ ) after finally disappearing from view ~13 yr after its eruption. These three



**Figure 1.** Light curves of NSV 11749, V605 Aql, and V4334 Sgr. Thick downward arrows indicate RCrB-like sudden drops in brightness.

(A color version of this figure is available in the online journal.)

sudden disappearances of the star are particularly worth noting as they are very similar to those observed in the born-again stars (Duerbeck et al. 2000, 2002). At least in the best studied born-again star (V4334 Sgr; Duerbeck et al. 2000), it is clear that these sudden dimmings are caused by carbon-dust ejection episodes similar to those observed in R Coronae Borealis Stars (RCrB stars). In Figure 1 we compare the light curve of NSV 11749 with those of the two known fast born-again stars (V4334 Sgr and V605 Aql). The three light curves share the same main features: namely, in a period of years they show an outburst stage, a steady stage at maximum brightness, a phase of RCrB-like declines, and finally a complete disappearance from view. These similarities alone are strong argument in favor of a similar explanation for all three stars, and thus for a born-again (VLTP) explanation of the light curve of NSV 11749. However, quantitatively, there is a significant difference in the timescales of NSV 11749 and both V4334 Sgr or V605 Aql. In both V4334 Sgr and V605 Aql the sequence of events happened at a faster pace, increasing more than  $3.5^m$  during the first year. Also, V4334 Sgr (V605 Aql) disappeared from view much faster, only  $\sim 4.4$  yr ( $\sim 6.3$  yr) after the eruption.

Then, the main question is to know if some born-again stars could evolve a few times slower than observed in V4334 Sgr or V605 Aql. Stellar evolution models (Herwig 2001; Miller Bertolami & Althaus 2007) suggest that, indeed, that is the case.

### 3. THEORETICAL VLTP LIGHT CURVES

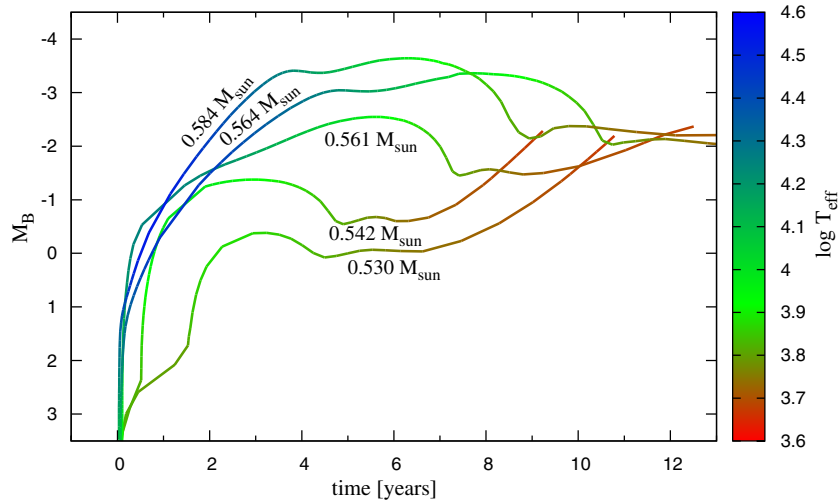
According to stellar evolution models, VLTP eruption light curves and temperatures are dependent on the mass of the erupting star. Thus, a direct comparison of the NSV 11749 light curve with those of the two known VLTP objects (V605 Aql and V4334 Sgr) might be misleading.

In order to compare theoretical eruptions in VLTP models with the observed light curve of NSV 11749, it is necessary to construct theoretical  $B$  and  $V$  light curves. In the absence of bolometric corrections for H-deficient stars in the wide range of temperatures covered by VLTP eruptions, we have relied on theoretical model atmospheres to predict the expected  $B$  and  $V$  magnitudes of the stellar evolution models. Stellar atmospheres have been computed within the assumption of plane-parallel geometry and LTE, including the opacities of all relevant major atoms (although without molecules or dust). Although plane-parallel geometry is not justified at the very low surface gravities attained by the models some years after the eruption, it is reasonable during the first years of the eruption, i.e., before the development of the RCrB stage in real stars. Abundances in stellar atmosphere computations have been chosen to reflect those predicted by VLTP models (Miller Bertolami & Althaus 2007), but tests show that light curves would be very similar if we had chosen abundances like those observed in V4334 Sgr (Asplund et al. 1999). Light curves computed with these model atmospheres and the stellar evolution sequences of Miller Bertolami & Althaus (2007) are shown in Figure 2. Also shown are the effective temperatures predicted by the models during the eruption.

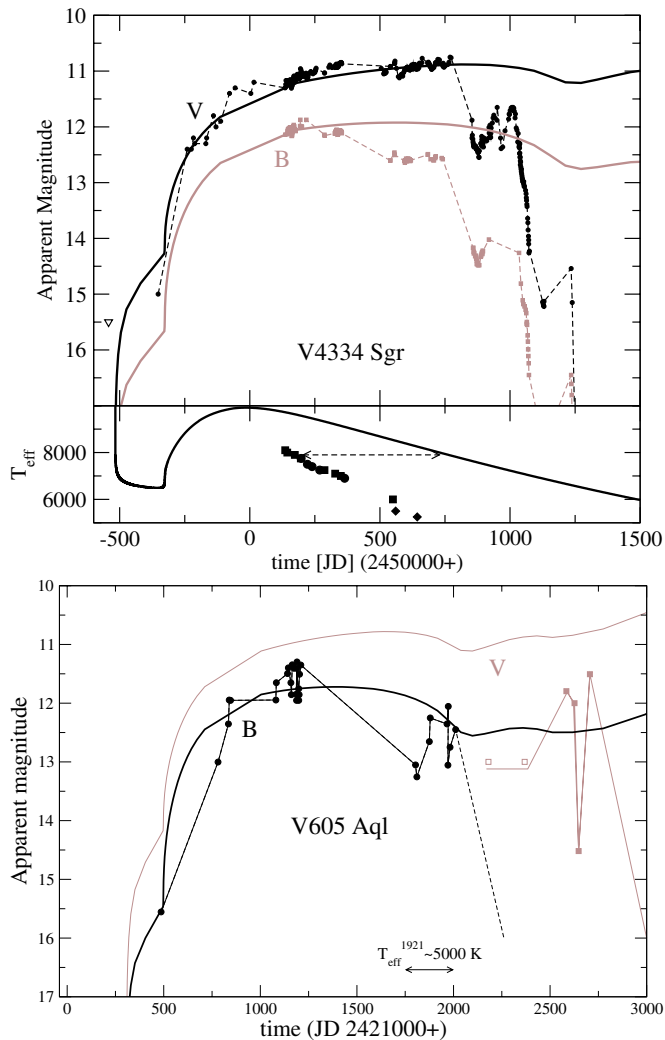
As shown in Figure 2, our models predict different light curves depending on the mass of the remnant that undergoes the eruption. In particular, note that after the fast initial rise, the light curves either stall or slightly diminish. After reaching a plateau in a few years, the theoretical light curves start to rise again as the sequences increase their luminosities without a strong change in temperature. However, this happens after the temperature falls below  $\log T_{\text{eff}} \sim 3.7$  and then we expect RCrB-like events to develop. In fact, the three identified born-again stars (FG Sgr, V605 Aql, and V4334 Sgr) have shown RCrB extinction episodes after the temperature fell below  $\log T_{\text{eff}} \sim 3.7$  (Jeffery & Schönberner 2006; Clayton & De Marco 1997; Duerbeck et al. 2000). Thus, synthetic light curves will not reflect the observed behavior from this point onward. Then, the intrinsic maximum brightness of fast-VLTP sequences, after the fast rise in brightness, spans a wide range from  $\sim -1$  to  $-4$  both in  $V$  and  $B$  bands.

#### 3.1. Test: Comparison with V605 Aql and V4334 Sgr

In order to understand to what extent our light curves can be trusted when comparing with real stars, we now compare our light curves with those of the two bona fide VLTP objects, V605 Aql and V4334 Sgr. In Figure 3 we compare the light curve of our best-fit model light curve ( $0.542 M_{\odot}$ ) with the visual light curve of V4334 Sgr (Takamizawa 1997; Duerbeck et al. 1997, 2000) and with the photographic light curve of V605 Aql published by Duerbeck et al. (2002). To compare  $B$  and  $m_{\text{pg}}$  magnitudes, we adopt  $m_{\text{pg}} = B + 0.11$  as in Clayton & De Marco (1997). The similarities between the predicted and observed light curves are apparent. It is worth noting that no tuning of the theoretical models has been carried out in order to fit the observed light curves. Figure 3 just displays our sequence with the most similar aspect to the observed ones.



**Figure 2.** Theoretical  $M_B$  light curves for the fast-VLTP sequences of Miller Bertolami & Althaus (2007). (A color version of this figure is available in the online journal.)



**Figure 3.**  $V$  and  $B$  light curves of V4334 Sgr (upper panel) and V605 Aql (lower panel) compared with our most similar light curve (sequence  $0.542 M_{\odot}$  of Miller Bertolami & Althaus 2007).

(A color version of this figure is available in the online journal.)

Assuming the interstellar extinction model of Hakkila et al. (1997), we find for V4334 Sgr ( $V - M_V \sim 12.7^m$ , for our

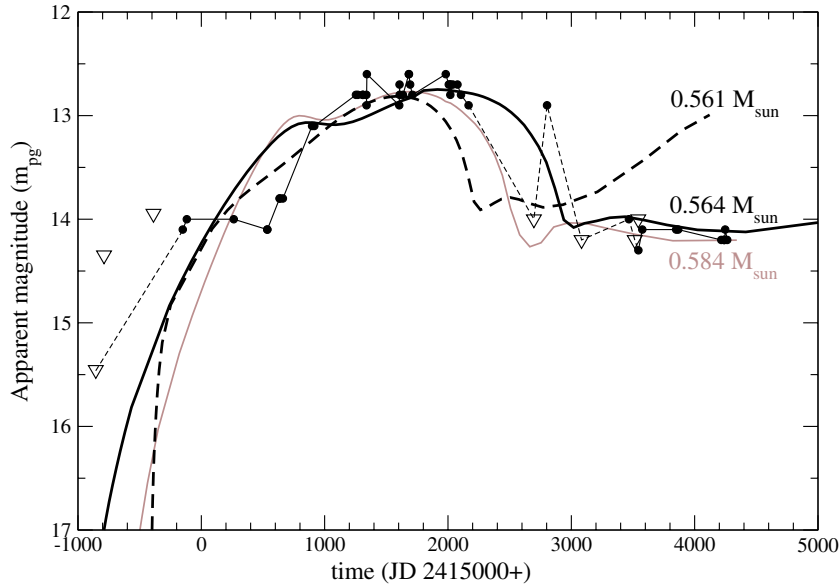
most similar light curve) a distance of  $d \sim 1.6$  kpc and  $A_V \sim 1.9^m$ . Interestingly enough, this value is within the recommended values by Kimeswenger (2002),  $d = 2_{-0.6}^{+1}$  kpc, on the basis of several independent distance determinations. Thus, our  $0.542 M_{\odot}$  light curve not only predicts a correct light-curve shape for V4334 Sgr but also a correct absolute magnitude. Also, at the distance of  $d \sim 1.6$  kpc, and a derived value of  $A_B \sim 2.5^m$  our model also predicts the maximum brightness in the  $B$  band (see Figure 3). On the other hand, it is clear from Figure 3 that our model is not able to predict simultaneously the correct luminosity and temperature evolution (although its cooling speed,  $dT_{\text{eff}}/dt$ , is very similar to that of V4334 Sgr). Also the  $0.542 M_{\odot}$  pre-outburst location in the H-R diagram might be at variance with a possible pre-discovery detection of V4334 Sgr’s progenitor in 1976 (see Miller Bertolami & Althaus 2007).

For the case of V605 Aql ( $B - M_B \sim 13.1^m$ , for our most similar light curve) we obtain a distance of  $d \sim 1.9$  kpc (and  $A_B \sim 2^m$ , assuming  $R = A_V/(A_B - A_V) = 3.1$ ), a value significantly lower than derived in previous works,  $2.7 \text{ kpc} < d < 6.0 \text{ kpc}$  (Clayton & De Marco 1997). However, it has to be kept in mind that larger distances would have been obtained if the extinction is not as high as suggested by Hakkila et al. (1997) in that particular direction of the sky ( $30^\circ < \lambda < 40^\circ$ ).

From these comparisons we conclude that our theoretical light-curve shapes are very similar to those observed in real born-again stars and can be used to identify born-again star candidates. We notice, however, that theoretical models are not able to fit, simultaneously, all observed features. This is most probably due to the uncertainties in the treatment of the violent reactive convective burning of H in the models, something that is still badly understood (Herwig et al. 2011).

### 3.2. Comparison with NSV 11749

In Figure 4 we compare  $B$  light curves of our  $0.561$ ,  $0.564$ , and  $0.584 M_{\odot}$  sequences with the photographic light curve reconstructed by Williams (2005). As can be seen, the theoretical light curves account for the brightening speed observed in NSV 11749 of about  $\sim 0.5 \text{ mag yr}^{-1}$ . Also, our light curves predict that the star will stay at maximum brightness for a few years. More interesting NSV 11749 has shown three sudden



**Figure 4.** Light curve of NSV 11749 compared with some theoretical  $B$  light curves.  
(A color version of this figure is available in the online journal.)

extinctions between 1907 and 1910 before disappearing from Harvard plates in 1912. These extinctions occur when our sequence shows a temperature of  $\log T_{\text{eff}} \lesssim 3.8$  and thus when real born-again stars have shown us that RCrB-like extinction events are expected to occur. Thus, our sequences not only reproduce the eruption light curve but also agree with the interpretation of the three drops in brightness observed in NSV 11749 as being caused by RCrB-like events. Then, our models show that while NSV 11749 has increased its brightness by a factor of about two to four slower than V4334 Sgr or V605 Aql, its light curve is well within the expected behavior for VLTP eruptions of different masses. Comparing the absolute magnitudes of the theoretical models with those observed in NSV 11749,  $B - M_B \sim 16^m$  for our  $0.564 M_{\odot}$  sequence, we roughly estimate a distance of  $d \sim 3.2$  kpc and  $A_B \sim 4.2$ . Had we compared with our  $0.561 M_{\odot}$  ( $0.584 M_{\odot}$ ) sequence, for which  $B - M_B \sim 15.25^m$  ( $B - M_B \sim 16.3^m$ ), we would have estimated a distance of  $\sim 2.3$  kpc ( $\sim 3.6$  kpc) and  $A_B \sim 4$  ( $A_B \sim 4.3$ ). It must be noted that these distance estimates are very uncertain as they not only depend on the accuracy of born-again models but also distances could be much larger if  $A_B$  is overestimated by Hakkila et al. (1997).

#### 4. POSSIBLE PRESENT COUNTERPART OF NSV 11749

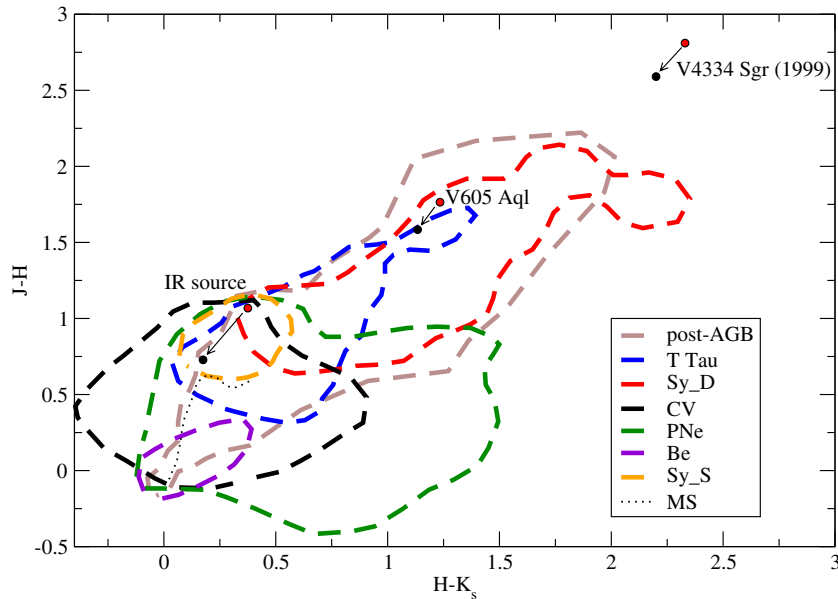
Prompted by the strong resemblance of NSV 11749 with born-again light curves (real and theoretical), we looked into 2MASS (Cutri et al. 2003) and IPHAS (González-Solares et al. 2008) catalogs for possible counterparts. If NSV 11749 experienced a born-again event  $\sim 100$  yr ago we would expect it to be, by now, either enshrouded in a thick dust shell similar to post-AGB stars or reheating as a new central star of a PN (as seen in V605 Aql). In order to constrain our search for present counterparts coordinates for NSV 11749 have been redetermined by the Digital Access to a Sky Century at Harvard (DASCH; Grindlay et al. 2009) team from six plates from the Harvard College University plate archive. These plates were scanned and analyzed with the DASCH photometry pipeline, which yielded coordinates  $\alpha = 19^{\text{h}}07^{\text{m}}42^{\text{s}}.41$  and

$\delta = 00^{\circ}02'51''.4$  with an rms error of  $\sigma \sim 1''$ .<sup>5</sup> Their photometry was also consistent with that presented by Williams (2005).

Only one infrared source (from now on IRS) very near to the location of NSV 11749,  $\alpha = 19^{\text{h}}07^{\text{m}}42^{\text{s}}.4$  and  $\delta = 00^{\circ}02'51''.0$ , is within  $3\sigma$  from the derived coordinates. The IRS is included in both 2MASS and IPHAS catalogs with magnitudes  $J = 10.794$ ,  $H = 9.726$ ,  $K_s = 9.351$  (2MASS) and  $r' = 14.509$ ,  $i' = 13.053$ ,  $H_{\alpha} = 12.994$  (IPHAS). As shown in Figure 5, 2MASS colors for the IRS are consistent with those of symbiotic stars, T-Tauri stars, cataclysmic variables, post-AGB stars, and PNe. Also, dereddened colors (Rieke & Lebofsky 1985; assuming  $d = 3.2$  kpc) fall very close to main-sequence stars. Fortunately, IPHAS colors for NSV 11749 fall above the cut defined by Viironen et al. (2009a) to isolate emission line objects (Zone 2, see Figure 1 of Viironen et al. 2009a) and we can discard a main-sequence star. Also, IPHAS colors fall in a region of the color-color diagram populated by symbiotic stars, T-Tauri stars, and PNe but away from post-AGB stars (the IRS has higher  $H_{\alpha}$  brightness). Note, however, that despite the similar IPHAS and 2MASS colors, an FU Ori (i.e., T-Tauri) or symbiotic nova (i.e., symbiotic star) explanation for NSV 11749 is unlikely (see the next section). In Figure 5 we also compare the 2MASS colors of the IRS with those derived for V4334 Sgr and V605 Aql—dereddened assuming recommended distances of  $d = 2$  kpc and  $d = 3.5$  kpc, respectively. As it is apparent, the 2MASS colors for the three objects are very different. The IRS is bluer than dust enshrouded symbiotic stars (Sy\_D) and dust enshrouded VLTP objects. Thus, 2MASS colors suggest that the IRS is not strongly enshrouded by dust. Also, the IRS is much brighter than the present state of V605 Aql, which is suspected to be completely hidden behind a thick dust torus (Clayton et al. 2006) but similar to the brightness of V4334 Sgr before the beginning of dust extinction events ( $J \sim 9.5 \dots 7$ ; Tatarnikov et al. 2000).

<sup>5</sup> These coordinates are remarkably close to those suggested by Williams (2005) which are several arcminutes away from those recorded in the NSV catalog. This is because NSV coordinates correspond to Luyten's published discovery position that was only estimated from grids traced over the plate (D. B. Williams 2010, private communication).





**Figure 5.** 2MASS color-color diagram for the source at coordinates of NSV 11749 compared with the 2MASS colors of known VLTP objects. Also shown are sketches of the location expected for different types of objects according to Viironen et al. (2009a, 2009b). Red dots indicate observed colors and black dots indicate dereddened colors.

(A color version of this figure is available in the online journal.)

Finally, an old PN would be expected within the born-again scenario, as all previous born-again objects (FG Sge, V605 Aql, and V4334 Sgr) show such PNe. Inspection of UK Schmidt Telescope (UKST) and IPHAS images around NSV 11749 do not reveal any PN around the eruption. However, as the formation of a PN depends on the evolutionary speed of its central star, the absence of a PN could be just the consequence of a different mass of the erupting star (as already suggested by its light curve). Finally, note that material ejected during the eruption (assuming  $100 \text{ km s}^{-1}$  as in V605 Aql; Clayton & De Marco 1997) would be smaller than  $1''$  and, thus, not resolved. If NSV 11749 had been a VLTP, the progenitor star had to be different from those of V605 Aql and V4334 Sgr as the object does not seem to be now surrounded by a PN or enshrouded in a thick dust shell.

## 5. DISCUSSION AND FINAL REMARKS

Based on its photometric light curve, Williams suggested two possible scenarios to explain NSV 11749: either a slow nova or an FU Ori type star. In particular an FU Ori event would be consistent with the 2MASS colors of the IRS that show it similar to T-Tauri stars. However, as already mentioned by Williams (2005) these scenarios are unable to account for both the brightness increase and dimming. While slow novae decline in timescales of the order of a year (Harman & O’Brien 2003) in qualitative agreement with NSV 11749, their rising is much faster, increasing more than 5 mag in a few days. The opposite happens with the FU Ori scenario. While typical FU Ori stars increase their brightness in a period of the order of a year their dimming is extremely slow, declining only a few magnitudes in decades (Hartmann & Kenyon 1996). Then, both scenarios fail to match the observed behavior of NSV 11749 with both rising and dimming taking place on timescales of years.

A third alternative scenario suggested by the slow rising light curve is that of a symbiotic nova (also known as very slow novae; see Mikolajewska 2010 for a review). Symbiotic novae are thermonuclear novae that take place in symbiotic

binary systems that would allow a natural link with the IRS identified in the previous section. The eruption period of these objects can last from month to years, thus naturally accounting for NSV 11749’s observed eruption light curve. However, the decline of these eruptions is extremely slow lasting for decades and even centuries (e.g., PU Vul). Thus, as in the case of the two previous scenarios, no simultaneous agreement with the eruption and declining timescales can be achieved.

Clearly, the born-again scenario outperforms all other proposed explanations for NSV 11749. In fact, as discussed in Section 2, the qualitative agreement between the light curves of NSV 11749 and known VLTP objects is very good. The most significant quantitative difference is that NSV 11749 eruption was a few times ( $\sim 5$  times) slower, with the rising taking place in about five years. However, we have shown in previous sections that these differences can be expected from differences in the mass of the star and, even better, that the NSV 11749 light curve can be quantitatively reproduced by VLTP models. In fact, differences in the mass of the star could be related with the absence of a PN around the eruption.

With the aid of synthetic born-again light curves, we have presented strong arguments in favor of a VLTP explanation for NSV 11749. If this is so, then NSV 11749 has some differences with both V4334 Sgr and V605 Aql (no PN, probably not enshrouded by dust). This finding will strongly increase our understanding of the late stages of stellar evolution. In particular, it will boost our understanding of the formation of H-deficient stars and of the reactive-convective burning phases of stellar evolution.

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A-plates around the time of the outburst and deriving magnitudes and the stellar position presented here. DASCH is supported by NSF grant AST-0909073 and the *Cornel and Cynthia K. Sarosdy Fund for DASCH*. This research has made an extensive use of NASA's Astrophysics Data System.

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