



Spectroscopy of V341 Arae: A Nearby Nova-like Variable Inside a Bow Shock Nebula*

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Abstract

V341 Arae is a 10th-magnitude variable star in the southern hemisphere, discovered over a century ago by Henrietta Leavitt, but relatively little studied since then. Although historically considered to be a Cepheid, it is actually blue and coincides with an X-ray source. The star lies near the edge of the large, faint H α nebula Fr 2–11, discovered by D. Frew, who showed that V341 Ara is actually a cataclysmic variable (CV). His deep imaging of the nebula revealed a bow-shock morphology in the immediate vicinity of the star. We have carried out spectroscopic monitoring of V341 Ara, and we confirm that it is a nova-like CV, with an orbital period of 0.15216 days (3.652 hr). We show that V341 Ara is remarkably similar to the previously known BZ Cam, a nova-like CV with a nearly identical orbital period, associated with the bow shock nebula EGB 4. Archival sky-survey photometry shows that V341 Ara normally varies between $V \simeq 10.5$ and 11, with a characteristic timescale ranging from about 10 to 16 days. V341 Ara lies well off-center within Fr 2–11. We speculate that either the star is undergoing a chance high-speed encounter with a small interstellar cloud, or that the nebula was ejected from the star itself in a nova outburst in the fairly distant past. At a distance of only 156 pc, V341 Ara is one of the nearest and brightest known nova-like variables, and we encourage further studies.

Key words: accretion, accretion disks – binaries: close – novae, cataclysmic variables – stars: individual (V341 Arae) – white dwarfs

Online material: color figures

1. The Variable Star V341 Arae

Variability of the 10th-magnitude star CPD –63°4037, designated HV 2969 and later V341 Arae, was discovered at the Harvard College Observatory by Henrietta Leavitt and announced by Pickering (1907). Over the ensuing century the star attracted little attention. It was noted as being blue by Hoffmeister (1956), who reported variability at a period of 11.95 days and considered V341 Ara to be a Type II Cepheid. The blue color was verified in a small number of photometric observations during a study of Type II Cepheids by Harris (1981). He suggested it may instead be an eclipsing binary.

Berdnikov & Szabados (1998) obtained extensive photoelectric photometry and also examined photometric data from the *Hipparcos* mission. They found a period of 14.11 days,

significantly longer than reported by Hoffmeister, and with considerable photometric scatter; they also verified that the $V - I$ color is relatively blue. Drilling & Bergeron (1995), based on low-dispersion objective-prism plate material, reported the star to have an OB spectral type, which is inconsistent with the Cepheid classification. Further evidence that it is not a Cepheid came from it being listed as an X-ray source, 1RXS J165743.7–631237, in the *ROSAT* All-Sky Source Catalog (Voges et al. 1999). This led Kiraga (2012) to suggest that V341 Ara is most likely a cataclysmic variable (CV). Based on photometric monitoring by the All-Sky Automatic Survey (ASAS; Pojmański 2002), Kiraga found a modulation in its brightness at a characteristic timescale of about 10 days.

Our interest in V341 Ara arose from the discovery by David Frew that the star is associated with a faint H α emission nebula, to which he gave the designation Fr 2–11. He found the large ($8' \times 6'$) nebula during a visual inspection of images from the Southern H α Sky Survey Atlas (Gaustad et al. 2001), aimed at discovering new planetary nebulae (PNe) at more than 10° from the Galactic plane. (Fr 2–11 lies at $b = -12.5^\circ$.) The H α

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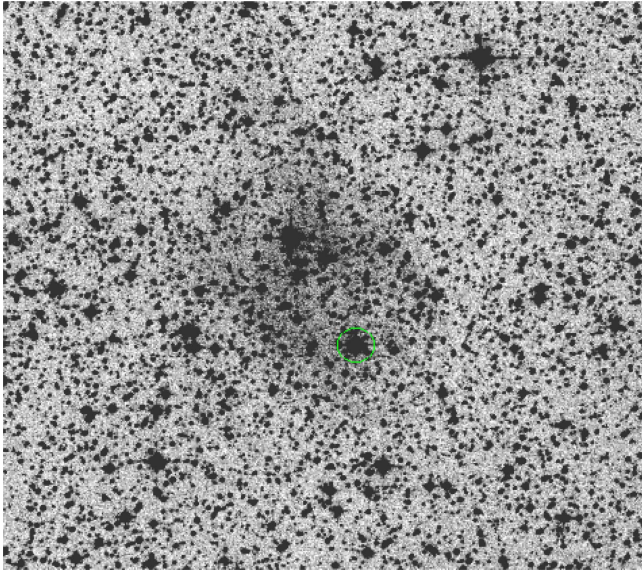


Figure 1. Digitized Sky Survey red-sensitive image of the nebula Fr 2–11 associated with the variable star V341 Ara, marked with a green circle at the south-southwestern edge of the nebula. North is at the top and east on the left, and the height of the frame is 15'. The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166.

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

nebula is actually also faintly visible in the red image of the Digitized Sky Survey,⁶ as shown in our Figure 1. However, it had not been recognized or cataloged prior to Frew’s discovery. Remarkably, V341 Ara is very far off-center in the faint nebula, lying near its southwestern edge.

Frew’s discovery was communicated to us privately, and was presented at a conference on PNe (Frew et al. 2006). Further details were given in his PhD dissertation (Frew 2008, hereafter F08), and Fr 2–11 was discussed briefly in Frew et al. (2016). Of particular interest to us was F08’s spectroscopic confirmation that V341 Ara is indeed a nova-like CV, and that his follow-up higher-resolution imaging had revealed a bow-shock morphology in the immediate vicinity of the star, distinct from the large, low-surface-brightness H α nebula.

Emission nebulae associated with CVs that have not had a known nova outburst, especially having a bow-shock structure, are extremely rare. The best-known previous case is probably the parabolic-shaped nebula EGB 4, discovered by Ellis et al. (1984, hereafter EGB). EGB found the nebula to be associated with a bright, previously unknown CV, subsequently designated BZ Cam. The EGB 4 nebula was discussed by Hollis et al. (1992), who argued that it represents a case of a source with a strong wind passing supersonically through a relatively stationary local interstellar medium (ISM). BZ Cam itself is a

nova-like variable (i.e., belonging to the “UX UMa” subclass of CVs in which there is a high rate of mass transfer from a main-sequence donor to its white-dwarf companion, producing an optically thick accretion disk around the white dwarf). This has led other authors (e.g., Griffith et al. 1995) to suggest that the nebula was ejected from BZ Cam itself and is being sculpted by an interaction with the ISM. The orbital period of BZ Cam is 0.1535 days (3.68 hr; e.g., Patterson et al. 1996; Honeycutt et al. 2013). Deep optical images of EGB 4 have been presented by Greiner et al. (2001).

More recently the nebula IPHASX J210204.7+471015 has been shown to have a bow-shock structure, which is associated with a previously unknown nova-like CV (Guerrero et al. 2018). The central star has an orbital period of 4.26 hr.

Because of our interest in binary stars associated with PNe, we undertook spectroscopic observations aimed at finding the orbital period and other properties of V341 Ara, which we report in this paper.

2. The Bow Shock Nebula and *Gaia* Astrometry

In order to illustrate the morphology of the bow shock associated with V341 Ara, we retrieved a publicly available [O III] image from the European Southern Observatory (ESO) archive.⁷ This observation was obtained with the Wide-Field Imager of the 2.2 m MPG/ESO telescope on 2004 May 27. The exposure time was 900 s and employed a narrow-band filter centered on the [O III] 5007 Å emission line. We cleaned the image of cosmic rays using LACOSMIC (van Dokkum 2001), and bad columns were interpolated over. A false-color rendition of this image is shown in the left panel of Figure 2. (F08 contains deeper images of the bow shock and surrounding nebula, together with an extensive discussion of V341 Ara itself.)

For comparison, we show in the right-hand panel of Figure 2 a rendition of an image of the EGB 4/BZ Cam nebula, obtained by H.E.B. in 1996 with the Kitt Peak National Observatory Mayall 4 m telescope. This false-color image combines H α (red) and [O III] 5007 Å (green) exposures.

Precise parallaxes and proper motions for both of these CVs are available from the recent *Gaia* Data Release 2 (Gaia Collaboration et al. 2018). The derived distances for V341 Ara and BZ Cam, respectively, are 156.1 ± 2.0 pc and 372.0 ± 5.2 pc. The respective proper motions are 97.7 mas yr⁻¹ at position angle 209°6, and 28.8 mas yr⁻¹ at PA 184°5. These correspond to moderately large transverse velocities of 72 and 51 km s⁻¹, respectively. Both nebulae are remarkably similar in showing bright rims of enhanced [O III] emission that are almost exactly in the directions of the stars’ motions relative to the ISM. Based on average *V* magnitudes of 10.75 for

⁶ Available from the Space Telescope Science Institute at http://stdatu.stsci.edu/cgi-bin/dss_form.

⁷ The archive is located at http://archive.eso.org/eso/eso_archive_main.html and the data for Fr 2–11 were originally obtained as part of program 073. D-0157(A) (PI: Q. A. Parker).



Figure 2. False-color renditions of narrow-band, emission-line images of two nova-like variables embedded in bow shock nebulae. In both frames, north is at the top and east on the left, and logarithmic stretches were used. Left: V341 Ara. This is an image in [O III] 5007 Å, obtained on 2004 May 27 with the MPG/ESO 2.2 m telescope (see the text for details and credits). Height of frame is $2''.9$. The faint vertical features are artefacts. Right: The EGB 4 nebula associated with BZ Cam. This image was obtained with the Kitt Peak National Observatory Mayall 4 m telescope on 1996 March 13. Red is H α and green is [O III]. Height of frame is $6''.1$. (A color version of this figure is available in the online journal.)

V341 Ara (see below) and 12.8 for BZ Cam (Honeycutt et al. 2013), the stars’ absolute magnitudes are also very similar, at $M_V = +4.8$ and $+4.9$, respectively. These values are quite typical of nova-like CVs, and several magnitudes brighter than the values for dwarf novae in quiescence (e.g., Ramsay et al. 2017 and references therein).

3. Light Curve Behavior

For a star as bright as V341 Ara, there is now extensive photometric time-series coverage available from all-sky monitoring surveys such as ASAS and the follow-up All-Sky Automated Survey for Supernovae (ASAS-SN; Shappee et al. 2014 and Kochanek et al. 2017).⁸ Both the ASAS data⁹ covering 2001–2009 and the ASAS-SN data from 2016 to the present show that the star generally varied between $V \simeq 10.5$ and 11.0, with occasional brief excursions to somewhat fainter

levels. There have not been any drops to deep “low” states such as occasionally shown by BZ Cam (e.g., Garnavich & Szkody 1988; Greiner et al. 2001; Honeycutt et al. 2013 and references therein), at least in the ASAS and ASAS-SN data that we examined.

As typical examples of the star’s photometric behavior, Figure 3 shows the ASAS-SN data for three 100 day intervals between 2017 April and 2018 May. In the first panel, there are peaks at $V \simeq 10.5$ recurring roughly periodically at intervals of about 14 days. However, in the second panel, the star remained mostly at its maximum brightness, but with a few drops to $V \simeq 11.5$ or fainter. In 2018 it returned to semi-periodic maxima spaced by about 15 days. There is no evidence for deep eclipses in the data.

It is this quasi-periodic behavior that led to the misclassification as a Cepheid in the historical work. The time interval between maxima appears to vary, as indicated by the 11.95 day period reported by Hoffmeister (1956) and the approximate 10-day timescale found by Kiraga (2012). These light variations are likely due to accretion-disk instabilities,

⁸ <http://www.astronomy.ohio-state.edu/asassn/index.shtml>

⁹ http://www.astrouw.edu.pl/cgi-asas/asas_variable/165742-6312.6,asas3,0,0,500,0,0

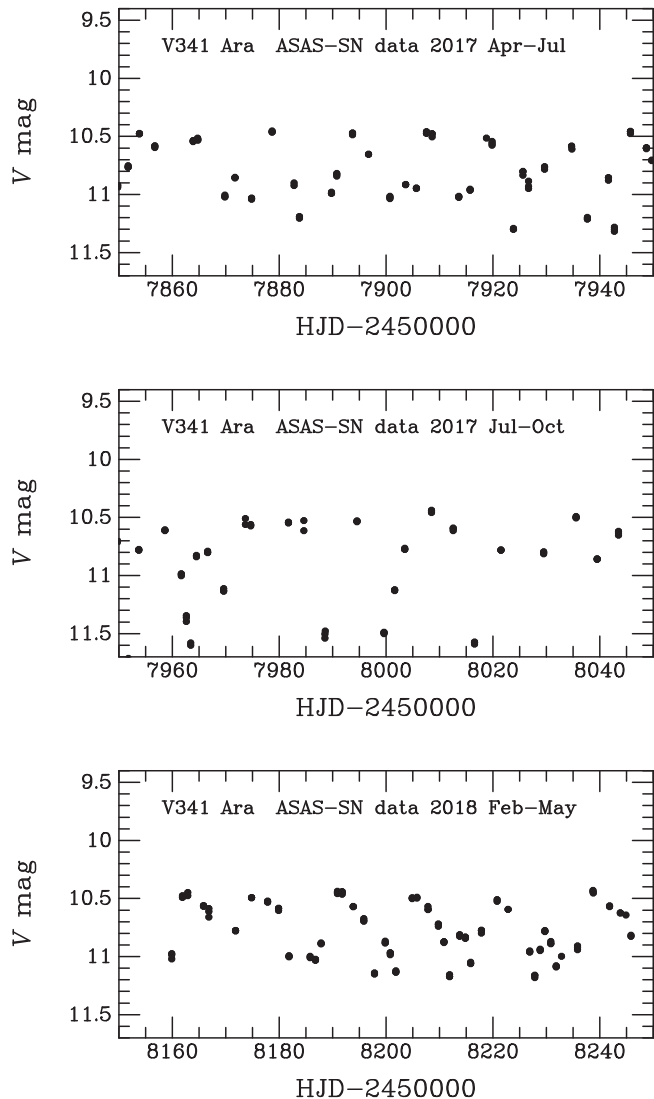


Figure 3. ASAS-SN light curves of V341 Ara for three 100-day intervals in 2017–2018. Magnitude error bars are generally smaller than the plotting symbols. In the first and third panels, the maxima tended to recur at intervals of about 14–15 days (see the text), but in the middle panel the star tended to remain bright with occasional excursions to fainter levels.

similar to those that produce the outbursts of dwarf novae, but with a smaller amplitude due to a relatively high mass-transfer rate. IX Vel is a bright, well-known nova-like variable (e.g., Linnell et al. 2007 and references therein) with many similarities to V341 Ara, apart from lacking an association with nebulosity. We examined its recent ASAS-SN light curve. IX Vel shows a light curve remarkably similar to that of V341 Ara: the peak-to-peak amplitude is a nearly identical 0.5 mag, and the spacing of maxima was about 14.2 days over the first several months of 2018.

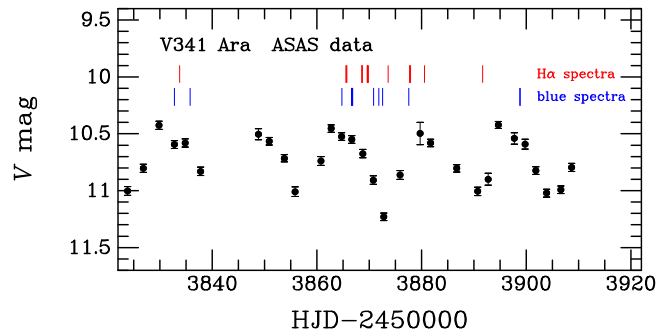


Figure 4. ASAS light curve of V341 Ara during the season of our spectroscopic observations with the SMARTS 1.5 m telescope, 2006 April–July. Red tick marks indicate the times of H α -region spectra, and blue ticks show the times of blue-region spectra.

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

4. Spectroscopic Observations

In order to study its spectroscopic behavior and determine its orbital period, we undertook observations of V341 Ara with the SMARTS¹⁰ 1.5 m telescope at Cerro Tololo Interamerican Observatory (CTIO), using its RC-focus spectrograph equipped with a CCD camera. Our observations were made in queue mode by Chilean service personnel, and took place between 2006 April 7 and July 30. To cover the red region around H α , we used the “47/Ib” grating setup, giving a wavelength interval of 5650–6970 Å with a 3 pixel resolution of 3.1 Å. With this setup we made 17 separate visits to V341 Ara on eight different nights. At each visit we obtained three individual exposures, usually of 240 s each.

For the blue region, we used several different setups, depending on the queue scheduling. These included “26/I” covering 3532–5300 Å with a spectral resolution of 4.3 Å (5 visits), “56/II” (4017–4938 Å, resolution 2.2 Å; 8 visits), and “47/IIb” (4070–4744 Å, resolution 1.6 Å; 2 visits). At each visit we obtained three exposures of 300 s each.

The CCD images were bias-subtracted and flat-fielded, and then the stellar spectrum was extracted and wavelength-calibrated, all using standard IRAF¹¹ routines. Wavelength calibration was accomplished using comparison spectra of neon (red) or helium-argon (blue) lamps, obtained immediately before and after each set of three stellar exposures without moving the telescope.

In Figure 4, we show the ASAS light curve during the interval in 2006 when the spectroscopic observations were made. At this time the spacing between photometric maxima was about 16.6 days. Tick marks—red for H α , blue for blue

¹⁰ SMARTS is the Small & Moderate Aperture Research Telescope System: <http://www.astro.yale.edu/smarts>.

¹¹ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

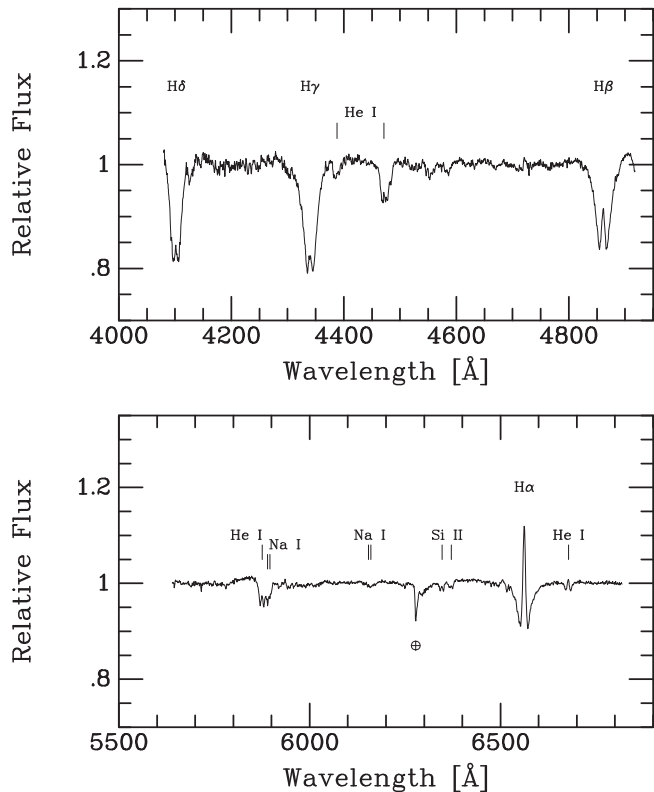


Figure 5. Plots of the averages of all of our V341 Ara spectra in the blue (top panel) and red (bottom panel) wavelength regions, normalized to a flat continuum. The spectra are typical of nova-like CVs, showing broad absorption features of the Balmer series and He I, with central emission peaks. Absorption due to Na I and Si II also appears to be present.

region—indicate the times of our spectroscopic observations, showing that both the red and blue spectra sampled the high, intermediate, and low states of V341 Ara. However, a comparison of spectra taken at different brightness levels showed no clear dependence upon the brightness of the equivalent widths or shapes of the absorption or emission features.

The top panel in Figure 5 shows a blue spectrum created by combining all of the spectra, and normalizing to a flat continuum. This spectrum is typical of a nova-like CV, showing broad absorption lines of the Balmer series and He I. There are relatively sharp emission lines in the cores of the broad absorptions.

The bottom panel of Figure 5 shows the red spectral region, averaged over all of our spectra. Again we see broad absorption features of hydrogen and He I, with central emission lines. One curiosity is the apparent presence of Si II features in absorption, at 6347 and 6371 Å, probably with weak central emission. To our knowledge the Si II features are not commonly present in nova-like CVs, although the Si II doublet near 4130 Å was seen

in absorption in the spectrum of WZ Sge by Gilliland et al. (1986)¹² (and may be present in our spectra as well, although the wavelength is slightly discrepant). The Na I doublet also appears to contribute to the broad absorption feature due to He I 5875 Å.

5. Orbital Period

The strongest emission line in the spectrum of V341 Ara is H α . We measured the centroid wavelength of the H α emission core in each of our spectra by fitting a Gaussian profile, using the BPLLOT task in IRAF. The wavelength was converted to radial velocity (RV), and corrected to the heliocentric frame. Table 1 lists the results.

We used a periodogram analysis to search for a periodic signal in the RVs, finding a strong peak at about 0.1522 days. This was then refined by computing a least-squares sinusoidal fit to the RV data, resulting in an ephemeris of $\text{HJD} = 2453833.048 \pm 0.006 + (0.15216 \pm 0.00002)E$. The center-of-mass velocity is $-33.5 \pm 1.2 \text{ km s}^{-1}$, and the velocity semi-amplitude is $32.0 \pm 2.2 \text{ km s}^{-1}$.

In Figure 6 we plot the RVs against the orbital phase, along with the sinusoidal fit. Remarkably, the orbital period of 0.15216 day (3.652 hr) is nearly identical to the 0.15353 (3.685 hr) period of BZ Cam (Section 1).

6. Nature of the V341 Ara System

In this paper, we have presented an initial exploration of the nature of the variable star V341 Ara and its surrounding nebulae. We have confirmed that the star is a nova-like CV, and we determined its orbital period. We consider two possible interpretations of the system:

1. One plausible scenario is that V341 Ara is a CV that is undergoing a chance high-speed encounter with an interstellar gas cloud, leading to the cloud being photoionized by ultraviolet radiation from the binary. In this picture, the fact that V341 Ara is located well off-center with respect to the nebula Fr 2–11 indicates that the latter was not ejected from the star itself in a previous nova explosion. The space motion of V341 Ara, of about 80 km s^{-1} (including the center-of-mass velocity), is highly supersonic relative to the gas, presumed to be stationary. It is well established from ultraviolet studies that the similar system BZ Cam is ejecting a stellar wind (e.g., Balman et al. 2014 and references therein). The “snowplowing” interaction between a wind from the accretion disk of V341 Ara and the ISM cloud would produce the bow-shock region near the star.
2. An alternative picture is that the faint, large nebula Fr 2–11 was ejected during a nova outburst of V341 Ara

¹² We thank E. M. Sion for pointing out this paper.

Table 1
H α Radial Velocities of V341 Ara

HJD-2450000	RV (km s ⁻¹) ^a	HJD-2450000	RV (km s ⁻¹) ^a	HJD-2450000	RV (km s ⁻¹) ^a
3833.7553	-64.4	3872.7729	-14.8	3872.7788	-14.1
3833.7583	-60.4	3868.6689	-18.2	3873.6027	-51.8
3833.7612	-60.2	3868.6719	-16.4	3873.6056	-46.3
3865.5671	-85.9	3869.5832	-6.9	3873.6086	-42.9
3865.5701	-80.1	3869.5857	-14.4	3877.6978	-26.5
3865.5730	-85.6	3869.5882	-5.4	3877.7007	-22.7
3865.6279	-3.9	3869.6732	-40.3	3877.7036	-16.1
3865.6308	-7.2	3869.6756	-45.7	3877.7821	-19.7
3865.6338	-15.4	3869.6781	-55.7	3877.7851	-13.9
3865.7187	-68.7	3869.7414	-8.0	3877.7880	-19.3
3865.7217	-81.7	3869.7438	-5.6	3877.8635	-44.1
3865.7246	-77.6	3869.7463	-6.2	3877.8664	-44.9
3868.5787	-46.5	3869.8067	-42.3	3877.8694	-45.9
3868.5921	-54.8	3869.8091	-49.9	3880.5310	-25.0
3868.5951	-55.3	3869.8116	-39.9	3880.5339	-11.0
3868.6250	-59.7	3872.6871	-35.2	3880.5368	-23.7
3868.6279	-58.9	3872.6901	-33.0	3891.6384	-19.9
3868.6309	-54.3	3872.6930	-42.5	3891.6413	-17.3
3868.6660	-29.9	3872.7758	-15.3	3891.6443	-19.5

Note.

^a Velocity errors are estimated at about 9.0 km s⁻¹.

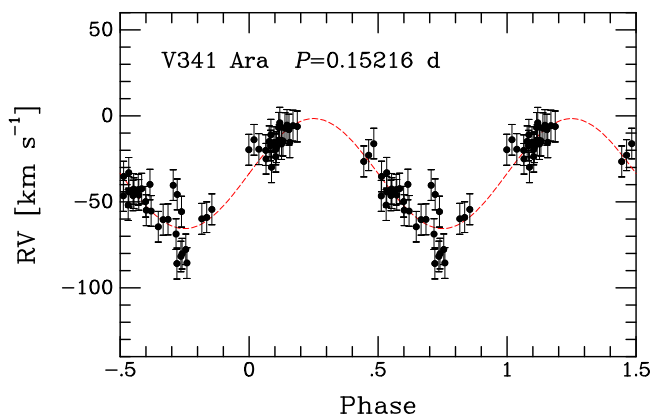


Figure 6. H α radial-velocity curve for V341 Ara. The velocities listed in Table 1 are plotted against orbital phase, calculated using the ephemeris $\text{HJD} = 2453833.048 + 0.15216 E$. The dashed red curve shows a least-squares sinusoidal fit to the data, with coefficients as listed in the text.

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

in the distant past. Over the past decade or so, faint nebulae have been discovered around several other known CVs. These include two members of the Z Cam subclass (Z Cam itself, Shara et al. 2007; AT Cnc, Shara et al. 2012), and a nova-like variable (V1315 Aql, Sahman et al. 2018). In addition, investigations of several faint nebulae have revealed associations with previously unknown CVs. These include a nova-like variable in IPHASX J210204.7+471015 (Guerrero et al. 2018) and a

dwarf nova (Te 11, Miszalski et al. 2016). As we mentioned in Section 1, IPHASX J210204.7+471015 is associated with a bow shock nebula. There is also a weak bow shock on the southwest side of Te 11. We suspect that the unusually shaped inner [O III] nebula of Te 11 may be the product of a similar mass-loss process as experienced by BZ Cam and V341 Ara, except in this case the lack of a high space motion has left the nebula relatively less disturbed.

All of these nebulae are approximately centered on the variables and thus almost certainly are ejecta from unwitnessed classical nova eruptions that occurred several hundred to a few thousand years ago. However, a particularly instructive example for our discussion comes from the recent discovery by Shara et al. (2017) of a nova shell and a CV associated with the explosion site of the historical Nova Scorpii AD 1437. The star has been classified as a DQ Her-type magnetic CV by Potter & Buckley (2018). In this case, the star is observed to lie off-center with respect to the nova shell. Shara et al. account for this by proposing that the ejecta are being decelerated through an interaction with the ISM, while the remnant star continues its motion. Theoretical investigations of such scenarios have been made by, e.g., Wareing et al. (2007), and indeed can result in nebulae with an off-center star, and eventually a star completely outside its ejected nebula.

Consistent with this picture, Shara et al. measured the proper motion of the Nova Sco remnant star, and showed that

(assuming the nebula to be stationary) the star had been located near the center of the nebula in the 15th Century. (Actually, the recent *Gaia* data release results in a smaller proper motion for the star than found by Shara et al., but nevertheless in a direction approximately consistent with their scenario, especially if the nebula itself has a smaller proper motion in the same direction as the star.) Using the proper motion of V341 Ara measured by *Gaia* (see Section 2), and assuming the H α nebula to be stationary, we find that the star was indeed closest to the center of the nebula roughly 800 years ago.¹³ The appearance of a bow shock in this scenario arises because the nebula ejected by the nova outburst has been decelerated by interaction with the ISM, but the star continues its high-velocity motion and ejects a stellar wind into the surrounding material. Arguing perhaps against this scenario, however, is the fact that the large nebula shows no pronounced evidence for a decelerative interaction with the ISM, at least in the material available to us. Also, if the Fr 2–11 nebula is only 800 years old, its expansion velocity is about 220 km s⁻¹, which should be observationally testable.

In conclusion, V341 Ara is one of the brightest nova-like variables, as well as one of the nearest—and it is a near-twin of the well-studied (but fainter and more distant) BZ Cam—yet it has remained largely unknown among the CV community. We hope that this paper will encourage further studies of this puzzling system. A useful constraint on its history would come from a determination of the expansion velocity of the H α nebula Fr 2–11: is the velocity high, indicating that it was ejected from V341 Ara, or low, indicating a chance encounter?

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Facility: CTIO:1.5m.

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¹³ At maximum brightness, a typical classical nova at a distance of ~ 150 pc would appear about as bright as Sirius. Unfortunately, V341 Ara lies so far south that it would not have been visible to astronomers in Europe, and much of Asia and North America.