

A Bow-Shock Nebula Around the Z Camelopardalis-type Cataclysmic Variable FY Vulpeculae*

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ABSTRACT

We present deep images of the faint nebulosity StDr 90, which we have discovered surrounds the cataclysmic variable (CV) star FY Vulpeculae. Archival photometric and spectroscopic observations, and a new optical spectrum, confirm that FY Vul belongs to the Z Camelopardalis subclass of CVs. Our imagery, obtained by accumulating long exposures with amateur telescopes equipped with CMOS cameras, shows a prominent bow shock in the light of [O III] $\lambda 5007$, collisionally excited in front of the star as it passes through a relatively dense region in the surrounding interstellar medium (ISM). FY Vul also lies near the edge of an extended faint H α -emitting nebula, which we interpret as a “recombination wake,” i.e., a Strömgren zone recombining after being photoionized by the star’s ultraviolet radiation. FY Vul joins five other CVs known to be associated with optical bow shocks and off-center nebulae. All of them are characterized by luminous accretion disks, which drive fast winds into the ISM that produce the bow shocks.

1. INTRODUCTION

1.1. *Faint Nebulae Around Cataclysmic Variable Stars*

This is the fourth in a series of papers that present deep optical images, obtained by amateur astronomers, which reveal faint nebulae around cataclysmic variables (CVs).

For reviews of CVs, see Warner (1995), Osaki (1996), Szkody & Gaensicke (2012), and Sion (2023). In summary, CVs are close binaries in which a Roche-lobe-filling star transfers mass to a compact companion, usually a white dwarf (WD). In most CVs, the transferred mass forms an accretion disk around the WD; from there the material eventually falls primarily onto the WD, but some of it is ejected from the accretion disk as a fast wind. There are several subclasses of CVs, defined according to their variability behavior. For our studies the most relevant are: (1) dwarf novae (DNe), in which the mass-transfer rate is low and the accre-

tion disk is usually optically thin, but becomes optically thick and brighter during occasional outbursts; (2) nova-like variables (NLVs), where the mass-transfer rate is so high that the accretion disk remains optically thick and bright most or all of the time; and (3) classical novae (CNe), where the hydrogen accumulated on the surface of the WD ignites nuclear fusion, producing a nova explosion. Following their eruptions, CNe generally behave similarly to NLVs.

In Paper I (Bond et al. 2024a) we reported the discovery of a faint nebula associated with the CV SY Cancri. This nebulosity had been noticed first in the course of searches aimed at finding new faint planetary nebulae (PNe; see, for example, Jacoby et al. 2010, Le Dû et al. 2022, and Ritter et al. 2023). These investigations, mainly carried out by amateurs, are based on inspection of publicly available wide-field sky-survey images. However, a literature search revealed that this particular nebula surrounds a known CV, SY Cnc, and thus is not likely to be a classical PN. Following up on this serendipitous discovery, several members of our team obtained deep narrow- and broad-band images of the nebula, accumulating long integration times on small telescopes equipped with modern low-noise detectors. This imagery revealed a bow-shock morphology, especially bright in the light of [O III] $\lambda 5007$, as well as the fact that the CV and bow shock lie off-

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* Based in part on observations obtained with the Hobby-Eberly Telescope (HET), which is a joint project of the University of Texas at Austin, the Pennsylvania State University, Ludwig-Maximilians-Universität München, and Georg-August Universität Göttingen. The HET is named in honor of its principal benefactors, William P. Hobby and Robert E. Eberly.

center within a surrounding large and faint $H\alpha$ -emitting nebula. We interpreted the SY Cnc nebula as the result of a random high-speed encounter between a CV with a fast stellar wind and an interstellar cloud. The off-center $H\alpha$ -emitting nebula is ionized material that is recombining following the passage of the ultraviolet-luminous star.

SY Cnc is classified as a Z Camelopardalis variable (ZCV; see the review by [Simonsen et al. 2014](#)). ZCVs are a subset of CVs that share properties of both DNe and NLVs. They exhibit eruptions similar to those of DNe, but can occasionally remain in “standstills” at an intermediate brightness level, for intervals of a few days up to many years. The majority of the time, however, SY Cnc itself exhibits regular outbursts; these occur at intervals of about 3.5 to 4 weeks, with an amplitude of about 2 mag (see Paper I for details).

Discoveries and follow-up deep imagery of two more cases of faint bow shocks and off-center $H\alpha$ nebulae around NLVs were presented in our Paper II ([Bond et al. 2025a](#)). These nebulae, surrounding LS Pegasi and ASASSN-V J205457.73+515731.9, have morphologies remarkably similar to the nebula associated with SY Cnc. They join two further NLVs that had found earlier to be associated with bow shocks: BZ Camelopardalis and V341 Arae (see Paper II for details and references, and Table 3 at the end of the present paper).

In Paper III ([Bond et al. 2025b](#)) we presented the discovery, with follow-up imagery, of yet another faint and previously unknown nebula around a CV. This time the star is a little-studied ZCV, ASASSN-19ds, in the southern constellation Antlia. Unlike the objects discussed above, the nebula is approximately centered on the star, and no bow shock is detected. These findings make the ASASSN-19ds nebula reminiscent of the faint nebulosities discovered around Z Cam itself ([Shara et al. 2007, 2012b, 2024](#)) and the ZCV AT Cancrī ([Shara et al. 2012a](#)). These nebulae are plausibly attributed to ejection from CN outbursts of the central binaries that occurred several centuries to more than a millennium ago.

1.2. The Faint Nebula StDr 90 around the Cataclysmic Variable FY Vulpeculae

For the past several years, H.E.B. and colleagues have been carrying out a spectroscopic survey of central stars of faint PNe. The spectroscopy is obtained with the queue-scheduled (see [Shetrone et al. 2007](#)) second-generation “blue” Low-Resolution Spectrograph (LRS2-B; [Chonis et al. 2016](#)) on the 10-m Hobby-Eberly Telescope (HET; [Ramsey et al. 1998; Hill et al. 2021](#)), located at McDonald Observatory in west Texas, USA. Details of the spectrograph and data reduction are given below (Section 2.4), as well as in a series of papers resulting from the PN survey. The two most recent of these are [Bond et al. \(2024b\)](#) and [Reindl et al. \(2024\)](#).

A major source of newly discovered and faint PNe, whose nuclei are targeted in this survey, is the PlanetaryNebulae.net website,¹ maintained by amateurs located primarily in France. In 2025 July, in the course of inspecting a list of candidate PNe identified by X. Strottnner and M. Drechsler, H.E.B. noticed that the nebula StDr 90 appears to have a relatively bright (14th-mag), blue central star. This object proved to be a known CV, FY Vulpeculae. Strottnner and Drechsler found StDr 90 on images from the Isaac Newton Telescope Photometric H-Alpha Survey (IPHAS; [Drew et al. 2005](#)), and they reported the nebula to have a diameter of 2.5. StDr 90 is only marginally visible on photographic imagery from the Space Telescope Science Institute Digitized Sky Survey.² For further information about this little-studied nebula, see its listing in the online Hong-Kong/AAO/Strasbourg/ $H\alpha$ Planetary Nebulae (HASH) database³ ([Parker et al. 2016; Bojičić et al. 2017](#)).

The presence of a CV inside the nebula indicated that StDr 90 is likely not a PN, but is instead probably similar to the objects discussed above. H.E.B. communicated the discovery to the amateur co-authors of this paper, who immediately responded by collecting the deep imagery that is presented and discussed below.

2. FY Vulpeculae

2.1. Discovery and Classification

Variability of FY Vul was discovered in 1940 at the Sternwarte Sonneberg by C. Hoffmeister, and the star was given a designation of AN 122.1940. A finding chart was published some years later ([Hoffmeister 1957](#)). Based on the Sonneberg photographic data, FY Vul was classified as a DN by [Richter \(1961\)](#). This was refined to a ZCV classification by [Meinunger \(1965\)](#), where the object is designated CSV 4779, because of standstills in its light curve. This conclusion was questioned by [Simonsen et al. \(2014\)](#), who investigated data obtained by members of the American Association of Variable Star Observers, and saw no standstills. However, subsequent work (see below) has reconfirmed its membership in the ZCV class, although the standstills occur only rarely.

Table 1 lists astrometry and photometry of FY Vul from *Gaia* Data Release 3⁴ (DR3; [Gaia Collaboration et al. 2016, 2023](#)). The bottom row gives the star’s nominal absolute magnitude in the *Gaia* system, based on the photometry and the star’s trigonometric parallax.⁵ Here we have adopted an

¹ <https://planetarynebulae.net/EN/index.php>

² https://archive.stsci.edu/cgi-bin/dss_form

³ <http://hashpn.space/>

⁴ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/355/gaiadr3>

⁵ A Bayesian analysis of *Gaia* data by [Bailer-Jones et al. \(2021\)](#) gives a distance of $573.0^{+6.7}_{-5.2}$ pc.

Table 1. *Gaia* DR3 Data for FY Vul

Parameter	Value
RA (J2000)	19 41 39.933
Dec (J2000)	+21 45 58.36
l [deg]	57.90
b [deg]	−0.61
Parallax [mas]	1.7078 ± 0.0179
μ_α [mas yr ^{−1}]	$−7.417 \pm 0.018$
μ_δ [mas yr ^{−1}]	$−18.827 \pm 0.018$
G [mag]	14.38
$G_{BP} - G_{RP}$ [mag]	0.47
M_G [mag]	+5.3

interstellar extinction of $A_G = 0.32$ mag at the distance of the star, obtained using the online *GALEX*Extin tool⁶ and based on the 3D extinction map of Chen et al. (2019).

FY Vul has been the subject of only a few studies. In this paper we are primarily concerned with its surrounding nebula. However, in the following subsections we briefly review the main photometric and spectroscopic properties of the star. The cited papers should be consulted for further information about FY Vul itself.

2.2. Long-Term Light Variations

Photometric variability of FY Vul was studied by Kato (2019). He investigated data obtained by the sky patrol of the All-Sky Automated Survey for SuperNovae (ASAS-SN; Kochanek et al. 2017), which measures optical magnitudes in the V or g bands at intervals generally of a few days. Based on the ASAS-SN observations, Kato placed FY Vul into a subclass of ZCVs called “IW And variables,” defined as ZCVs that increase in brightness after a standstill (see, for example, Szkody et al. 2013). This behavior is opposite to that of most ZCVs, which decline at the ends of their standstills.

The IW And phenomenon was discussed in more detail by Kimura et al. (2020), and an updated ASAS-SN light curve of FY Vul was included. It shows that the star is often in a mode where it shows repeated outbursts on a timescale of roughly 35 days, but at other times it drops into a state lacking such eruptions.

We investigated the most recent photometric behavior of FY Vul by downloading⁷ the ASAS-SN data for the past four yearly seasons, 2022 to the present. These data are plotted in Figure 1. Here the seasonal light curves are shifted down

successively by 1.5 mag from year to year. During the 2022 season, the star showed a few outbursts, but was fairly constant most of the time, apart from small-amplitude flickering. About a half-dozen outbursts were seen in 2023, and these became regular events in 2024, recurring at intervals ranging from ~ 23 to 39 days. “Sawtooth” variations like this are commonly seen in ZCVs (see, for example, the light curves displayed in Shafter et al. 2005). On a few occasions in 2024, sharp transient dips in brightness occurred immediately after the outbursts, a behavior occurring in several other IW And-type ZCVs (e.g., Kato 2019). In 2025, the outbursts largely disappeared, and a new behavior appeared. The overall brightness level was seen to fade to lower than it had been in the three previous years—an apparent standstill—and then the mean brightness started a slow increase. This increase continued to the end of the plotted data, interrupted by a single outburst of the type seen in previous years.

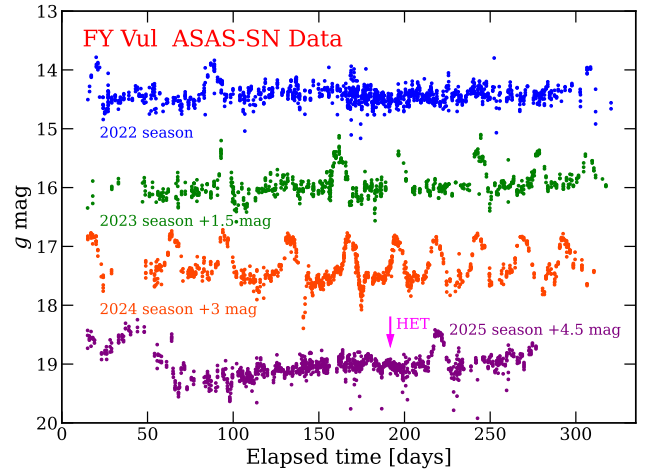


Figure 1. Seasonal g -band light curves of FY Vul based on data in the ASAS-SN archive. Blue points are for 2022 February 9 to December 12; green points (offset by +1.5 mag) are for 2023 February 12 to December 12; orange points (offset by +3 mag) are for 2024 February 17 to December 9; and purple points (offset by +4.5 mag) are for 2025 February 3 to October 23. The star sometimes shows a “sawtooth” light curve, typical of Z Cam variables, with a variable time interval between successive brightness maxima; but at other times these outbursts subside, sometimes for extended intervals. The magenta arrow above the 2025 light curve marks the date of the HET spectrum shown below in Figure 3.

2.3. Time-Series Photometry

Turning to high-cadence photometry, Bruch (2024) investigated FY Vul using data from the *Transiting Exoplanet Survey Satellite* (*TESS*; Ricker et al. 2015) mission. He calculated power spectra for the continuous measurements collected in four *TESS* “Sectors” with durations of ~ 27 days each, obtained in 2019, 2021 (two Sectors), and 2022. Two dominant photometric periods were seen, one with a period

⁶ Amôres et al. (2021); <http://www.galexextin.org/>

⁷ from <https://asas-sn.osu.edu>

of 0.2014 days (4.83 hr, present during two of the four Sectors), and the other having a shorter period of 0.1910 days (4.58 hr, present during three Sectors). During one Sector, both periods were detected in the power spectrum.

To our knowledge, the orbital period of FY Vul is unknown. Bruch suggests, however, that the longer photometric period corresponds to the orbital period, and that the period shorter by $\sim 5\%$ is that of a “negative superhump.” This phenomenon is seen in the light curves of SY Cnc (Paper I), and of LS Peg (Paper II), where the orbital periods are known. The superhump periods are shorter than them by 5% and 2%, respectively. See our previous papers for references to astrophysical interpretations of negative superhumps.

FY Vul was observed again by *TESS* in 2024 July, during the Sector 81 run. We obtained its light curve using the online *TESSExtractor* tool.⁸ A representative 2.5-day segment of this light curve is shown in Figure 2. Variations with a peak-to-peak amplitude of ~ 0.03 mag⁹ are seen, with a period corresponding to the longer period detected in the earlier *TESS* data by Bruch (2024).

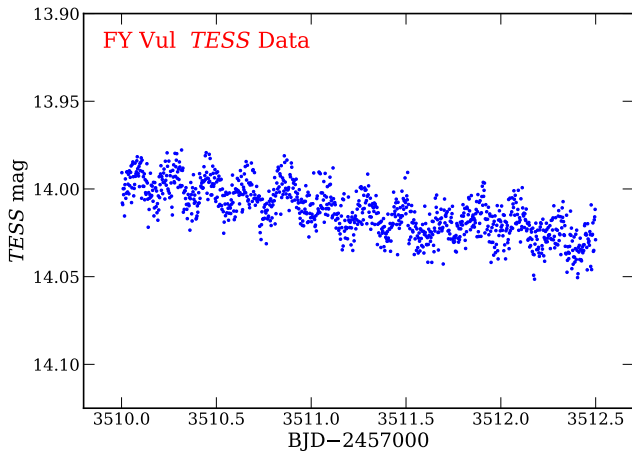


Figure 2. A representative *TESS* light curve for FY Vul, covering a 2.5-day interval in 2024 July at a 200 s cadence. A low-amplitude variation with a period of 0.2014 days is seen, possibly corresponding to the orbital period of the binary (see text).

2.4. Spectroscopy

To our knowledge, the only published (until now) spectroscopy of FY Vul was presented by Downes et al. (1995). Their spectrum, obtained in 1992, showed a very blue continuum with $H\alpha$ in emission. There were broad weak absorption features at He I $\lambda 5875$, $H\beta$, and $H\gamma$, with superposed

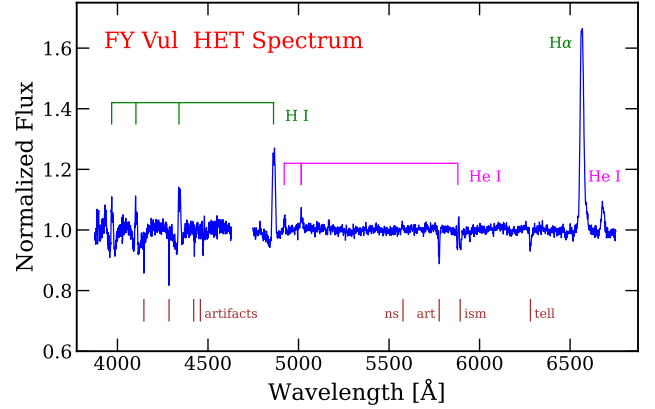


Figure 3. Normalized HET LRS2 spectrum of FY Vul on 2025 July 30, showing emission lines of hydrogen and He I. Higher members of the Balmer series, and He I $\lambda 5875$, exhibit surrounding shallow broad absorption wings. Several features due to instrument artifacts (“artifacts” and “art”), night-sky emission (“ns”), and interstellar Na I and telluric absorption (“ism” and “tell”) are marked.

faint emission cores.¹⁰ Such a spectrum is typical of a CV near maximum light.

Inspired by our recognition of its surrounding nebulosity, we obtained a spectrum of FY Vul on 2025 July 30, using the LRS2-B spectrogram on HET (see Section 1.2). Briefly, LRS2-B employs a dichroic beamsplitter to send light simultaneously into two units: the “UV” channel (covering 3640–4645 Å at a resolving power of 1910), and the “Orange” channel (covering 4635–6950 Å at a resolving power of 1140). Data reduction is carried out by co-author G.R.Z., using the *Panacea*¹¹ and *LRS2Multi*¹² packages. Further details of the LRS2-B spectrograph and data-reduction procedures are given, for example, in Bond et al. (2023).

Our spectrum is plotted in Figure 3, where it is normalized to a flat continuum. The Balmer series is seen in emission, superposed on broad absorption at $H\beta$ and higher members of the series. Several lines of He I are also in emission, with $\lambda 5875$ superposed on broad absorption wings. Here the Balmer and He I emission lines are much stronger than in the 1992 spectrum of Downes et al. (1995). This enhancement is consistent with the appearance of a ZCV’s spectrum near minimum light. A magenta arrow in Figure 1 marks the date of the LRS2-B spectrum, which indeed was obtained at a time when the star was near its baseline magnitude. The spectrum is very similar to those we obtained for the NLV ASASSN-V J205457.73+515731.9, presented in Paper II.

¹⁰ An unpublished spectrum obtained in the late 1970s in a spectroscopic survey of CVs described by Bond (1979) was, although noisy, similar to that described by Downes et al. (1995).

¹¹ <https://github.com/grzeimann/Panacea>

¹² <https://github.com/grzeimann/LRS2Multi>

⁸ Serna et al. (2021); <https://www.tessextractor.app>

⁹ Note that, because of the low spatial resolution of *TESS*, the image of FY Vul is blended with several neighboring stars, and the true amplitude of the variations is likely higher.

To summarize the photometric and spectroscopic material, FY Vul is well established as a typical ZCV, belonging to the IW And subclass. Beyond this, the available information, unfortunately, is fairly limited. In particular, the orbital period proposed by Bruch (2024) lacks definitive confirmation.

3. DEEP IMAGING

3.1. Observations

We imaged StDr 90/FY Vul and its surrounding field using six different telescopes, located at sites in California, Mis-

issippi, and Texas in the United States, and in Spain. Exposures were obtained between 2025 July 22 and August 3. Telescope apertures ranged from 6 to 20 inches. Details of these instruments, including the optical filters and CMOS cameras, are given in Paper II. Long exposures were accumulated in H α and [O III] λ 5007 filters in order to image the very faint nebulosity, and shorter exposures were taken in red, green, and blue filters to show the stellar field. Table 2 lists the exposure times. The telescope numberings in column 1 are the same as in Paper II, Table 4. Grand total exposure time was 174.8 hr.

Table 2. Exposure Times [s] on StDr 90/FY Vul

Telescope ^a	Aperture	Observer(s)	H α	[O III]	R	G	B
1	20 in	Coles	47 $\times$ 600	69 $\times$ 600	22 $\times$ 600	23 $\times$ 600	35 $\times$ 600
2, 3	Twin 6 in	Goodhew	488 $\times$ 300	339 $\times$ 300	29 $\times$ 300	29 $\times$ 300	29 $\times$ 300
4	14 in	Goodhew	192 $\times$ 300	207 $\times$ 300	...	...	...
5	6 in	Talbot	59 $\times$ 1200	...	...	...	...
6	13.8 in	Carter & Talbot	79 $\times$ 480	...	54 $\times$ 60	50 $\times$ 60	50 $\times$ 60
Total exp. [hr]			94.70	57.00	6.98	7.08	9.08

^aTechnical details for the telescopes and instrumentation are given in Table 4 in Paper II.

3.2. Imagery and Interpretation

Pre-processing of the frames was done using CCDStack,¹³ PixInsight,¹⁴ and Photoshop.¹⁵ The large number of frames was combined using AstroPixelProcessor.¹⁶

Figure 4 displays a color picture of the nebula, in a rendition created by combining all of the frames listed in Table 2. For this presentation, an “HOO” palette was employed, with H α assigned to the red channel, and [O III] λ 5007 to the green and blue channels. The orientation and angular scale are indicated at the lower right, along with the conversion to a linear scale at the known distance of FY Vul.

Figure 4 shows that the low-Galactic-latitude field surrounding StDr 90 is overlain with extensive faint H α emission (except in a region of high extinction to the west and southwest). The StDr 90 nebula itself has the appearance of being a location of enhanced H α surface brightness, covering a region with a physical scale of about 0.5 pc, lying within this network of faint emission (although, of course, much of it may be at different distances than FY Vul).

In Figure 5 we zoom in on the image of the StDr 90/FY Vul nebula, in order to show its morphology more clearly. Superposed is a blue arrow with its base located at FY Vul itself, and oriented to show the direction of the star’s proper motion. Here the position angle has been adjusted by +7.9, relative to the absolute *Gaia* value of 201.5, in order to correct for the effect of differential Galactic rotation.¹⁷ The direction shown is thus made relative to the local standard of rest (LSR) at the distance of the star. The transverse space velocity of FY Vul, relative to this LSR, is 50.6 ± 0.5 km s⁻¹.

Figures 4 and 5 clearly show the morphology of a bow shock, in the form of a bright parabolic rim to the southwest of FY Vul. As discussed in our previous papers, and as is well known, a bow-shock morphology is the signature of a fast wind from the star, colliding with the interstellar medium (ISM) as the star passes through it at high velocity. The arrow in Figure 5 shows that the motion of the star is in a direction consistent with the interpretation as a bow shock.

The two panels in Figure 6 show narrow-band images of the nebula separately in H α (top) and [O III] (bottom). This imagery shows that the bow shock is prominent in the light of [O III], but is very faint in H α . Our interpretation is that

¹³ https://ccdware.com/ccdstack_overview

¹⁴ <https://pixinsight.com>

¹⁵ <https://www.adobe.com/products/photoshop.html>

¹⁶ <https://www.astropixelprocessor.com>

¹⁷ For details of this correction, see our discussion in Paper II. To calculate the correction, we used a `python` code created by S. del Palacio, along with the Oort constants, referenced in Paper II.



Figure 4. Color image of the nebula StDr 90 around the cataclysmic variable FY Vul, created from 174.8 hours of exposure time in RGB, $H\alpha$, and $[O III] \lambda 5007$ filters, as described in the text. $H\alpha$ is assigned to the red channel, and $[O III]$ to the green and blue channels. Orientation and scale of the image (including a conversion to linear size at the distance of the star) are indicated at the lower right. FY Vul is identified in Figure 5.

the $[O III]$ emission is collisionally excited as the stellar wind plows into the ISM. The surrounding $H\alpha$ emission nebula is primarily photoionized by UV and X-ray emission from the star. This material has a patchy distribution, with the highest density lying to the northwest of the star. A more subtle detail is that the $[O III]$ emission along the bow shock is brightest to the west and northwest of the star, which is where the $H\alpha$ -emitting material is densest. Note that the bow shock is not symmetric around the star, but is bent back on the northwest side, likely due to the stellar wind colliding with the densest ISM material at this location.

FY Vul is located well off-center with respect to the $H\alpha$ nebulosity, which lies mostly behind the path of the star's proper motion as well as to the north and northwest. These off-center $H\alpha$ -emitting nebulae are seen in all of the CVs associated with bow shocks, as discussed below and in Papers I and II; they are likely to be ionized material that is recombining following passage of the star.

4. SUMMARY AND FUTURE WORK

In this paper we present deep imaging of the nebula StDr 90, which surrounds the Z Cam variable star FY Vul. The imagery was obtained by advanced amateur

astronomers, using small telescopes and accumulating extremely long exposure times. The images reveal that FY Vul is associated with a bow shock, bright in the light of collisionally excited $[O III]$. The bow shock is located in front of the star, in the direction of its supersonic motion with respect to the relatively stationary ISM at its location. The star also lies near the front edge of a faint $H\alpha$ -emitting nebula.

FY Vul thus joins the five ZCVs and NLVs discussed in our Paper II and papers cited therein; all of the nebulae around the stars show bow shocks, and the stars lie off-center in faint $H\alpha$ -emitting nebulae. In Table 3 we update a table presented in Paper II that lists these objects, by adding FY Vul. Objects are listed in order of discovery dates for the nebulae. The nomenclature used in column 1 for four of the nebulae is that of the HASH PN catalog (see Section 1.2), although none of the nebulae are actually classical PNe.

As the table shows, all six CVs have similar absolute magnitudes, lying in the narrow range $+5.3 > M_G > +4.5$. These relatively high luminosities (among CVs) indicate the presence of luminous accretion disks around the systems' WD components, due to high mass-transfer rates from their donor stars. These accretion disks launch fast winds into the surrounding space. This situation provides especially favor-



Figure 5. Close-up of the StDr 90 nebula. The arrow that extends from the position of FY Vul is oriented in the direction of the star’s proper motion relative to the Galactic-rotation standard of rest at the star’s location.

Table 3. Nova-like Variables Associated with Bow Shocks and Off-Center H α Nebulae

Nebula	Star	Distance	P_{orb}	G	$E(B-V)$	M_G	References ^a
		[kpc]	[hr]	[mag]	[mag]	[mag]	
EGB 4	BZ Cam	0.37	3.69	12.97	0.11	+4.8	(1,2)
Fr 2-11	V341 Ara	0.16	3.65	10.81	0.02	+4.8	(3,4)
PaEl 1	SY Cnc	0.41	9.18	12.69	0.04	+4.5	(5,6)
...	ASASJ2054 ^b	0.55	...	13.67	0.11	+4.6	(7,8)
...	LS Peg	0.29	4.19	11.89	0.03	+4.5	(9,10)
StDr 90	FY Vul	0.57	4.83	14.38	0.12	+5.3	(11,12)

^aFirst reference for each star is for discovery of the nebula, and the second is for determination of the orbital period: (1) Ellis et al. (1984); (2) Patterson et al. (1996); (3) Frew et al. (2006); (4) Bond & Miszalski (2018); Castro Segura et al. (2021); (5) Paper I; (6) Casares et al. (2009); (7) Bond (2020); (8) Period unknown; (9) Paper II; (10) Taylor et al. (1999); (11) X. Strottner & M. Drechsler; see Section 1.2; (12) Listed period is photometric and a possible orbital period; see Section 2.3.

^bFull designation is ASASSN-V J205457.73+515731.9; see Paper II.

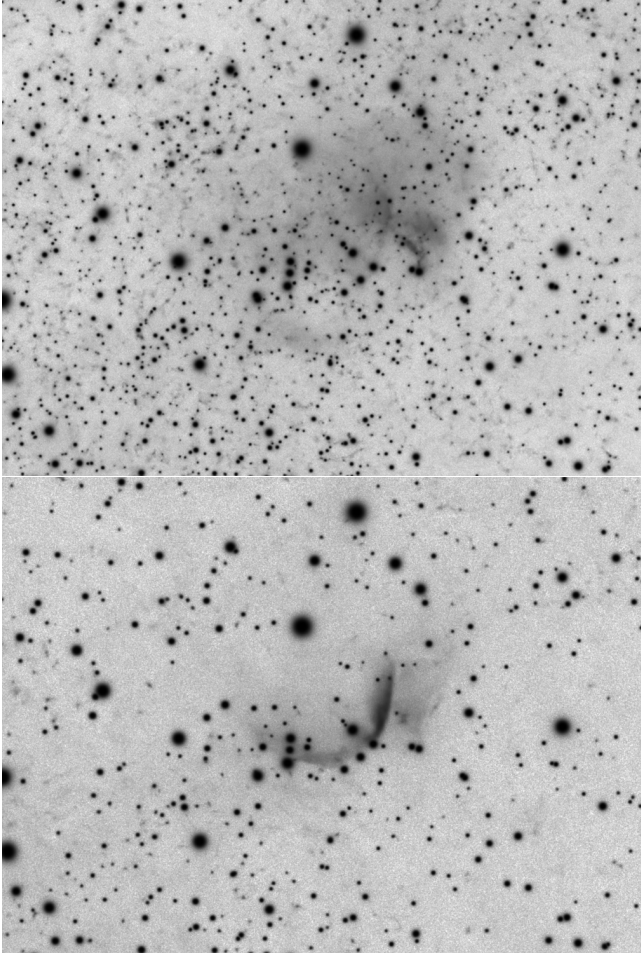


Figure 6. Narrow-band images of the StDr 90 nebula in $H\alpha$ (top) and $[O\ III]\ \lambda 5007$ (bottom).

able circumstances for the formation of bow shocks, in cases where the star happens to be passing at high speed through a relatively stationary interstellar cloud. We interpret the faint off-center $H\alpha$ nebulae as “recombination wakes,” i.e., Ström-gren zones that are recombining behind the paths of the stars after being photoionized by their ultraviolet and X-ray radiation.

As we discussed in Paper II, we hope our findings encourage deep imaging of larger samples of NLVs. Amateurs are equipped to reach deeper surface-brightness levels than many existing surveys, as shown in our series of papers, and they have access to large amounts of observing time.

We urge spectroscopic monitoring of FY Vul with large telescopes, in order to determine definitively its orbital pe-

riod. As shown in Table 3, the other five ZCVs associated with bow shocks all have periods of 3.6 to 4.2 hr (except for the longer 9.2 hr period of SY Cnc, due to its donor star being a G-type star, rather than the usual low-mass main-sequence donor). The orbital period of FY Vul is likely to be 4.83 hr, based on photometric observations, but this has not been proven directly.

The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions.

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