The Astrophysical Journal, 688: L21–L24, 2008 November 20

A PLANETARY NEBULA AROUND NOVA V458 VULPECULAE UNDERGOING FLASH IONIZATION

R. Wesson,[1] M. J. Barlow,[1] R. L. M. Corradi,[2,3] J. E. Drew,[4] P. J. Groot,[5] C. Knigge,[6] D. Steeghs,[7,10] B. T. Gaensicke,[7] R. Napiwotzki,[4] P. Rodriguez-Gil,[2,3] A. A. Zijlstra,[8] M. F. Bode,[9] J. J. Drake,[10] D. J. Frew,[11] E. A. Gonzalez-Solares,[12] R. Greimel,[13] M. J. Irwin,[12] L. Morales-Rueda,[5] G. Nelemans,[5] Q. A. Parker,[11] S. E. Sale,[14] J. L. Sokoloski,[15] A. Somero,[16,17] H. Uthas,[6,16] N. A. Walton,[12] B. Warner,[6,18] C. A. Watson,[19] and N. J. Wright[1,10]
Received 2008 September 10; accepted 2008 October 1; published 2008 October 23

ABSTRACT

Nova V458 Vul erupted on 2007 August 8 and reached a visual magnitude of 8.1 a few days later. Hα images obtained 6 weeks before the outburst as part of the IPHAS Galactic plane survey reveal an 18th magnitude progenitor surrounded by an extended nebula. Subsequent images and spectroscopy of the nebula reveal an inner nebular knot increasing rapidly in brightness due to flash ionization by the nova event. We derive a distance of 13 kpc based on light travel time considerations, which is supported by two other distance estimation methods. The nebula has an ionized mass of 0.2 $M_\odot$ and a low expansion velocity: this rules it out as ejecta from a previous nova eruption, and is consistent with it being a ~14,000 year old planetary nebula, probably the product of a prior common envelope (CE) phase of evolution of the binary system. The large derived distance means that the mass of the erupting WD component of the binary is high. We identify two possible evolutionary scenarios, in at least one of which the system is massive enough to produce a Type Ia supernova upon merging.
Subject headings: ISM: abundances — novae, cataclysmic variables

1. INTRODUCTION

Classical novae occur when the mass transferred from a Roche-lobe-filling companion onto a white dwarf in a close binary system triggers runaway thermonuclear burning of hydrogen on the surface of the white dwarf. The energy released causes the system to brighten by ~10 mag and ejects ~10^{-4} solar masses of material at speeds of a few hundred to a few thousand km s^{-1} (Prialnik & Kovetz 1995). It is thought that massive WDs in some nova systems may eventually produce Type Ia supernovae (Hillebrandt & Niemeyer 2000).

Planetary nebulae (PNe) are formed when low to intermediate mass stars reach the end of their lives, and thermal pulsations driven by extremely temperature-dependent helium burning cause the ejection of the stellar envelope during the asymptotic giant branch (AGB) phase (Iben & Renzini 1983). The exposed core, which will become a white dwarf, then ionizes the ejecta, which moves away from the star at typical velocities of ~20 km s^{-1}. The nebula eventually fades and merges with the interstellar medium after a few tens of thousands of years. It has been proposed that PNe can only be produced by close binary systems, during their common envelope stage of evolution (Moe & De Marco 2006). In this picture, some novae should occur inside PNe but until now the only known example was GK Per in 1901 (Bode et al. 1987).

Nova Vul 2007 (V458 Vul) was discovered on 2007 August 8 at magnitude 9.5 (Nakano et al. 2007). It reached a maximum brightness of $V = 8.1 \pm 0.1$, fading by 3 mag within 21 days, thus being classified as a fast nova. Its decline was interrupted by two rebrightenings during the first 20 days after maximum. In the spectral classification scheme of Williams et al. (1994), V458 Vul has been classified as a hybrid nova (Poggiani 2008): early postoutburst spectra indicated a Fe II nova while later spectra showed nitrogen lines dominating over iron lines, indicating a He/N type. X-ray emission from the nova has been observed since 2007 October, and the nova is currently a supersoft source (Drake et al. 2008), indicating that the nova ejecta have become optically thin, revealing very hot material beneath.

2. OBSERVATIONS

The nova lay in a part of the sky which had been imaged 6 weeks before the outburst, on 2007 June 27, in Hα, r', and i' filters by the IPHAS survey (Drew et al. 2005). The IPHAS Hα images reveal a wasp-waisted nebula surrounding a central star with magnitudes in the Vega system of $r' = 18.34 \pm 0.02$, $i' = 18.10 \pm 0.03$, and Hα = 18.04 ± 0.02, having J2000.0

[1] Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK.
[2] Isaac Newton Group, P.O. Ap. de Correos 321, 38700 Sta. Cruz de la Palma, Spain.
[3] Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain.
[4] Centre for Astrophysics Research, STRI, University of Hertfordshire, College Lane Campus, Hatfield AL10 9AB, UK.
[5] Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, Netherlands.
[6] School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK.
[7] Department of Physics, University of Warwick, Coventry CV4 7AL, UK.
[8] Jodrell Bank Center for Astrophysics, School of Physics and Astronomy, University of Manchester, Oxford Street, Manchester M13 9PL, UK.
[9] Astrophysics Research Institute, Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead CH41 1LD, UK.
[10] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[11] Department of Physics, Macquarie University, Sydney 2109, Australia.
[12] CASU, Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK.
[13] Institut für Physik, Karl-Franzen Universität Graz, Universitätsplatz 5, 8010 Graz, Austria.
[14] Imperial College London, Blackett Laboratory, Exhibition Road, London SW7 2AZ, UK.
[15] Columbia University, Department of Physics, New York, NY 10027.
[16] Nordic Optical Telescope, Apartado de Correos 474, 38700 Sta. Cruz de La Palma, Spain.
[17] University of Helsinki Observatory, P.O. Box 14, 00014 University of Helsinki, Finland.
[18] Department of Astronomy, University of Cape Town, Rondebosch 7700, Cape Town, South Africa.
[19] Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK.

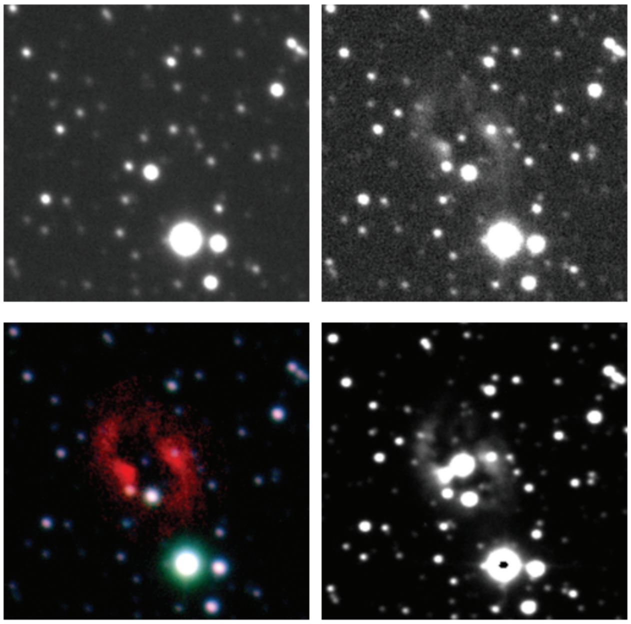

FIG. 1.—Isaac Newton Telescope WFC images of the field of V458 Vul. *Top left*: 2007 June 27 IPHAS r' image. *Top right*: 2007 June 27 IPHAS Hα image, which reveals the nebula. *Bottom left*: Color composite image made from the IPHAS r', i', and Hα images. *Bottom right*: 2008 May 20 INT WFC Hα image. Each image is 70″ on a side. North is up and east is to the left. The faint central star visible in the 2007 June images was in its postnova decline phase by the time of the 2008 May image, while the inner edge of the knot to the SE of the central star has brightened.

coordinates of $19^h54^m24.62^s$ and $+20°52'52.2''$ that are coincident within the measurement uncertainties with the position reported for the nova (Henden & Munari 2007). Figure 1 shows the IPHAS r' and Hα images, as well as a color composite image made from the three IPHAS bands to bring out the nebular structure. The main nebular ring has a semimajor axis of ∼13.5″, corresponding to a physical length of $0.065D$ pc, where D is the distance to the nebula in kpc. A bright nebular knot 4.5″ to the southeast of the central star is prominent in the IPHAS Hα image and absent in the r' and i' images.

In 2007 September we obtained intermediate-resolution long-slit optical spectra of the nebula from the 2.5 m Nordic Optical Telescope (NOT), and high-resolution optical echelle spectra from the 6.5 m Magellan-Clay telescope in Chile. A number of narrow nebular lines were detected in our spectra, and their intensities are listed in Table 1, along with line intensities predicted by a photoionization model (discussed below).

Hα images were obtained during 2008 May with the NOT and the INT, and showed the SE knot to be increasing rapidly in brightness; the 2008 May 20 INT image is shown in Figure 1, below the 2007 June 27 pre-outburst INT image. Figure 2 shows our 2008 May 12 NOT Hα image, obtained in excellent seeing conditions.

3. ANALYSIS

The $F(\text{H}\alpha)/F(\text{H}\beta)$ ratio of 5.34 measured from a 2008 May 14 spectrum of the SE knot corresponds to a reddening by interstellar dust of $E(B-V) = 0.63$ mag, assuming an intrinsic Hα/Hβ intensity ratio of 2.72 for the derived nebular physical conditions. For comparison, the maximum value of $E(B-V)$ predicted for the Galactic sight line toward V458 Vul ($l = 58.63°$, $b = -3.62°$) is 0.61 (Schlegel et al. 1998).

TABLE 1
OBSERVED AND MODELED RELATIVE INTENSITIES

λ (Å)	Species	I_λ: NOT 2007 Sep 3/4	I_λ: Magellan 2007 Sep 18	I_λ: Model
4959	[O III]	245	…	306
5007	[O III]	857	…	913
6548	[N II]	171	141	137
6563	Hα	285	285	286
6584	[N II]	504	428	419
6716	[S II]	90	79	58
6731	[S II]	90	62	61

NOTES.—Observed and modeled relative intensities of emission lines from the southeast knot of the nebula surrounding V458 Vul, normalized so that $I(\text{H}\beta) = 100$. Observed intensities have been dereddened by $E(B-V) = 0.63$ using a Galactic reddening law (Howarth 1983).

Lynch et al. (2007) derived $E(B-V) = 0.6$ from infrared observations of nova O I lines in 2007 October. For our subsequent analysis we adopt $E(B-V) = 0.63$, equivalent to a visual extinction A_V of 1.95 mag.

A crucial parameter in understanding V458 Vul is its distance. The distance to novae is often estimated using maximum magnitude versus rate of decline (MMRD) relations (Warner 1995). Taking $V = 8.1$ at maximum light from the AAVSO light curve[20] and a time to decline 3 mag from peak, t_3, of 21 days, then for $A_V = 1.95$, a "super-Eddington" MMRD (Downes & Dürbeck 2000) gives $D = 11.6$ kpc. Using a t_2 relationship from Downes & Dürbeck (2000) with $t_2 = 8$ days gives $D = 13.5$ kpc. The unusual form of the light curve makes the definition of t_2 and t_3 difficult in this case. Alternatively, one can use the t_{15} relationship (Downes & Dürbeck 2000), where the absolute mag-

[20] See http://www.aavso.org.

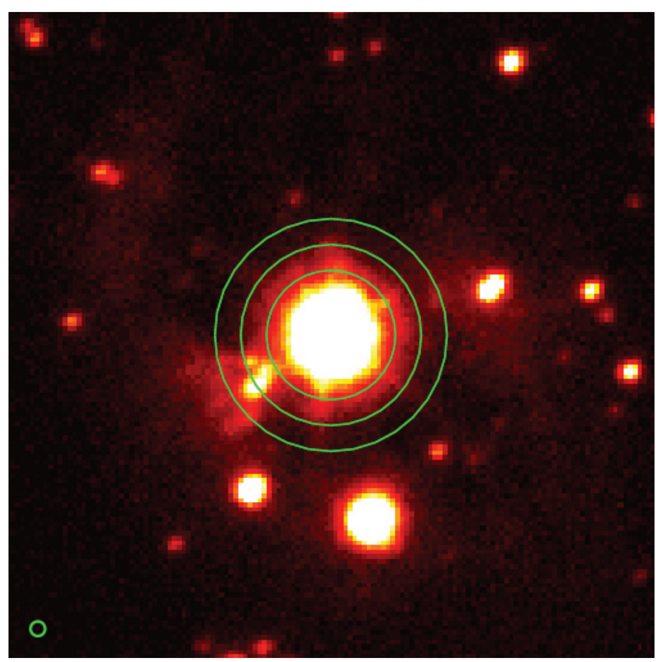

FIG. 2.—Hα image of the V458 Vul nebula obtained on 2008 May 12 in 0.57″ seeing, 278 days after the nova outburst, using ALFOSC on the 2.5 m Nordic Optical Telescope. The superposed circles centered on the nova system have angular radii of 2.5″, 3.5″, and 4.5″. The circle at the lower left corresponds to the seeing FWHM of 0.57″.

nitudes of classical novae are assumed to be the same at 15 days postmaximum. This gives $D = 10.0$ kpc.

Another estimate for the distance to nova V458 Vul can be obtained by assuming that our measured mean radial velocity of $v_{LSR} = -60.6 \pm 4.3$ km s^{-1} for its nebula is due to Galactic rotation alone. If we adopt a distance to the Galactic center of 7.6 ± 0.3 kpc (Eisenhauer et al. 2005) and 220 km s^{-1} for the Galactic rotation speed, independent of Galactic radius (Brand & Blitz 1993), a distance of 13.1 ± 0.5 kpc from the Sun is obtained. Allowing that up to 30 km s^{-1} of v_{LSR} may be due to random motion (Veltz et al. 2008), the corresponding distance uncertainty would be ± 3 kpc.

Finally, we estimate the distance to the nova from the time taken for the nova flash to reach the SE nebular knot—the first time it has been possible to determine the distance to a nova in this way. The pre-outburst 2007 June 27 IPHAS WFC Hα image (obtained in 1.4″ seeing) showed the peak brightness of the SE knot to lie 4.5″ ± 0.3″ from the central star (CS). Our 2008 May 20 WFC Hα image, obtained in 1.6″ seeing 286 days after the nova outburst (Fig. 1), shows the region of peak emission from the SE knot to have significantly increased in brightness and to have moved closer to the CS, peaking 3.5″ ± 0.3″ from the CS. A NOT Hα image obtained in 0.57″ seeing on 2008 May 12 (Fig. 2) shows the peak emission from the knot to lie 3.6″ ± 0.1″ from the CS. For the latter separation, the light travel time of 278 days from the nova to the knot implies a distance of 13.4 kpc to V458 Vul, if the line joining the knot and nova lies in the plane of the sky. The radial velocities of the SE knot and its fainter counterpart on the opposite side of the nova differ by only 3.0 ± 2.5 km s^{-1}, indicating that their motions do indeed lie close to the plane of the sky. Allowance for the line joining nova and knot being up to $\pm 30°$ out of the plane of the sky would give a corresponding distance uncertainty of ± 2 kpc.

We adopt a distance of 13 kpc to nova V458 Vul, corresponding to a Galactocentric distance of 11 kpc and to a depth of 0.8 kpc below the midplane of the Galactic disk. Fast novae are concentrated toward the Galactic plane ($z < 100$ pc) (Della Valle et al. 1992), so V458 Vul appears to be unusually situated in the Galaxy given its class. The absolute B magnitude of V458 Vul at maximum (-9.3) corresponds to a thermonuclear runaway on a white dwarf of mass 1.3 $M_\odot$ (Livio 1992).

The emission lines from the spatially resolved nebula surrounding V458 Vul are much narrower than those typically found in old nova shells. From our 2007 September Magellan echelle spectra (9.2 km s^{-1} instrumental resolution), we measure a full width at half-maximum of 13.7 ± 1.0 km s^{-1} for the [N II] lines at several nebular positions, fully 2 orders of magnitude smaller than the line widths normally associated with nova ejecta.

We measured the total Hα flux emitted by the nebula prior to the nova event from the IPHAS Hα image, correcting for the contribution of foreground stars in the field and for [N II] emission caught by the ~95 Å wide filter. We obtain a flux of $(1.0 \pm 0.25) \times 10^{-13}$ erg cm^{-2} s^{-1}. Correcting for our measured interstellar extinction gives a dereddened Hα flux of $(4.3 \pm 1.1) \times 10^{-13}$ erg cm^{-2} s^{-1}. From the [S II] line ratio in the Magellan spectra, we infer a mean electron density of 155 cm^{-3}. Adopting $N(\mathrm{He})/N(\mathrm{H}) = 0.11$, the total nebular ionized mass implied by this Hα flux is 0.2 $M_\odot$. Novae typically eject $\sim 10^{-4}$ $M_\odot$ of material (Yaron et al. 2005). The symmetry of the nebula surrounding Nova Vul and its wasp-waisted shape strongly suggest that it is not simply ionized interstellar medium. Instead, it is likely to be an old planetary nebula. Its low expansion velocity and large ionized mass both indicate a slow ejection of material by a red giant, and are in the range observed for planetary nebulae (Gussie & Taylor 1994; Barlow 1987; Boffi & Stanghellini 1994), while both its bipolar morphology and spectral characteristics of strong [N II] and [S II] emission relative to Hα indicate that it is a Type I planetary nebula, originating from a relatively high-mass progenitor (Torres-Peimbert & Peimbert 1997).

The centroid of the SE bright knot, 4.5″ from the central star in 2007 June, corresponds to a projected distance from the central star of 0.28 pc. The adoption of a median planetary nebula expansion velocity of 20 km s^{-1} (Gussie & Taylor 1994) would imply that the SE knot was ejected about 14,000 years ago. Parts of the main nebular ring have projected separations from the central star that are up to 3 times larger, implying significantly larger expansion ages unless their expansion velocities are also proportionately larger. Such self-similar expansion is generally observed in planetary nebulae (Corradi 2004).

4. DISCUSSION

The first object to be described as a planetary nebula around a nova was GK Per, which erupted in 1901 and was later found to be surrounded by a very large (>40′) bipolar-shaped region of dust and ionized gas, interpreted as a 10^5 year old massive planetary nebula (Bode et al. 1987, 2004). V605 Aql was not of this type, even though its 1919 eruption occurred inside the 70″ diameter planetary nebula A58; instead, its slow outburst and relatively low velocity ejecta fit better to a very late thermal pulse rather than to a classical nova event (Pollacco et al. 1992). The high ejection velocities (1500–2000 km s^{-1}), fast speed class, and outburst amplitude (~10 mag) of V458 Vul's 2007 eruption are all consistent with its classification as a classical nova.

The observed IPHAS $r' - i'$ and $r' - \mathrm{H}\alpha$ colors of V458 Vul before the nova event (0.245 ± 0.023 and 0.305 ± 0.018, respectively) deredden to match those of a hot O-type star with an Hα emission line equivalent width of 7–10 Å [for $E(B - V) = 0.63$]. Its dereddened r' magnitude of 16.69 corresponds to an r' absolute magnitude of $+1.1$, approximately 2.5 mag brighter than typical absolute magnitudes for classical nova systems in quiescence (Warner 1995). However, 5 out of 11 novae with good pre-eruption coverage showed slow rises of 0.3–1.5 mag in the 1–15 yr before eruption (Warner 1995). The USNO A2.0 and B1.0 catalogs give R magnitudes for V458 Vul of 18.1 in 1950.542 and 17.87 in 1975.1, while the STScI GSC2.2 catalog gives an R magnitude of 18.31 in 1991.688, offering no clear evidence of brightening during the 60 years leading up to its 2007 August eruption.

Using the 3D photoionization code MOCASSIN (Ercolano et al. 2003, 2005), we constructed models of the SE knot. We find that the preflash line intensity ratios can be well matched by a model in which the knot is inhomogeneous, with an electron density in the hemisphere nearest the star of 800 cm^{-3} and in the far hemisphere of 50 cm^{-3}. The modeled knot abundances were solar for oxygen, 3 × solar for nitrogen and 1.5 × solar for sulfur, and the central source yielding the best match to the observed intensities had a temperature $T_{\rm eff} = 90{,}000$ K, a radius R_* of 0.23 $R_\odot$, and a luminosity $L_* = 3000$ $L_\odot$. For H-burning central star evolutionary tracks (Vassiliadis & Wood 1994), this corresponds to a core mass of 0.58 $M_\odot$ and an age since leaving the AGB consistent with a nebular expansion age of ~14,000 yr.

Standard models for classical novae envisage the transfer of material from a main-sequence or slightly evolved red dwarf star onto the surface of a degenerate white dwarf (WD), leading to a thermonuclear runaway at infrequent intervals. The GK Per system has a K1 IV secondary (Morales-Rueda et al. 2002) and it has been proposed that its massive extended nebula originated from this evolved secondary star during a common envelope phase. Roche Lobe overflow onto the white dwarf with sufficiently high mass transfer rates then converted the WD into a "born again" AGB star which lost material at low velocities, producing over 10^5 yr the $40'$ nebula seen around GK Per today (Dougherty et al. 1996). When the transfer rate dropped below 10^{-7} $M_\odot$ yr^{-1}, the matter accreting onto the WD eventually produced a nova outburst, the first being in 1901. A similar scenario could be invoked for V458 Vul, in which case the high-luminosity hot central source needed to maintain the ionization of its nebula (which would otherwise recombine in less than a thousand years) must come from the accretion disk around the WD. A 1.3 $M_\odot$ WD of radius 2.9×10^8 cm accreting at $\sim 10^{-7}$ $M_\odot$ yr^{-1} should produce an accretion luminosity of a few thousand $L_\odot$, similar to that required. The maximum disk temperature would then be ∼270,000 K, and the temperature corresponding to the luminosity-weighted average disk radius would be comparable to the ∼90,000 K required to maintain the observed degree of nebular ionization.

An alternative scenario for V458 Vul is one whereby the star that dominated the pre-outburst light was a 90,000 K 0.6 $M_\odot$ PN central star, as deduced from our photoionization model, with the nova outburst taking place on a 1.3 $M_\odot$ WD companion. The nebula would also be the product of a common envelope phase. In this scenario it is unclear if the nova mass can be accreted after the common envelope phase, as the rapidly shrinking radius of the PN central star during its post-AGB evolution would make it difficult to maintain contact with its Roche lobe and continue mass transfer. More likely, and more interesting, is the possibility that the material was accreted before, or even during the common envelope phase. In this scenario, the combined mass of the two (proto) white dwarfs is above the Chandrasekhar limit and if the current orbital period is below 0.5 days, the system will merge within a Hubble time and is a potential Type Ia supernova progenitor.

Until V458 Vul has been studied much more thoroughly, these ideas about the prior evolution of the binary are necessarily schematic. Modeling of the common envelope phase proposed under each of the above scenarios could help elucidate whether either model can account for all of V458 Vul's unusual characteristics, while a determination of an accurate orbital period for the postnova system would provide crucial additional information. But it is already clear that V458 Vul and its nebula have the potential to become a very important challenge to our understanding of the common envelope phase in close binary evolution.

This Letter makes use of data obtained as part of the INT Photometric Hα Survey of the Northern Galactic Plane (IPHAS), carried out by the Isaac Newton Telescope at La Palma Observatory. All IPHAS data are processed by the Cambridge Astronomical Survey Unit, at the Institute of Astronomy in Cambridge. D. S. acknowledges an STFC Advanced Fellowship.

Facilities: ING:Newton(WFC), NOT(ALFOSC), Magellan: Clay(MIKE), ING:Herschel(ISIS)

REFERENCES

Barlow, M. J. 1987, MNRAS, 227, 161
Bode, M. F., O'Brien, T. J., & Simpson, M. 2004, ApJ, 600, L63
Bode, M. F., Roberts, J. A., Whittet, D. C. B., Seaquist, E. R., & Frail, D. A. 1987, Nature, 329, 519
Boffi, F. R., & Stanghellini, L. 1994, A&A, 284, 248
Brand, J., & Blitz, L. 1993, A&A, 275, 67
Corradi, R. L. M. 2004, in ASP Conf. Ser. 313, Asymmetrical Planetary Nebulae III: Winds, Structure, and the Thunderbird, ed. M. Meixner et al. (San Francisco: ASP), 148
Della Valle, M., Bianchini, A., Livio, M., & Orio, M. 1992, A&A, 266, 232
Dougherty, S. M., Waters, L. B. F. M., Bode, M. F., Lloyd, H. M., Kester, D. J. M., & Bontekoe, T. R. 1996, A&A, 306, 547
Downes, R. A., & Duerbeck, H. W. 2000, AJ, 120, 2007
Drake, J. J., et al. 2008, ATel 1721
Drew, J. E., et al. 2005, MNRAS, 362, 753
Eisenhauer, F., et al. 2005, ApJ, 628, 246
Ercolano, B., Barlow, M. J., & Storey, P. J. 2005, MNRAS, 362, 1038
Ercolano, B., Barlow, M. J., Storey, P. J., & Liu, X.-W. 2003, MNRAS, 340, 1136
Gussie, G. T., & Taylor, A. R. 1994, PASP, 106, 500
Henden, A., & Munari, U. 2007, Inf. Bull. Variable Stars, 5803, 1
Hillebrandt, J., & Niemeyer, J. C. 2000, ARA&A, 38, 191
Howarth, I. D. 1983, MNRAS, 203, 301
Iben, I., & Renzini, A. 1983, ARA&A, 21, 271
Livio, M. 1992, ApJ, 393, 516
Lynch, D. K., Russell, R. W., Rudy, R J., & Woodward, C. E. 2007, IAU Circ. 8883
Moe, M., & De Marco, O. 2006, ApJ, 650, 916
Morales-Rueda, L., Still, M. D., Roche, P., Wood, J. H., & Lockley, J. J. 2002, MNRAS, 329, 597
Nakano, S., Kadota, K., Waagen, E., Swierczynski, S., Komorous, M., King, R., & Bortle, J. 2007, IAU Circ. 8861
Torres-Peimbert, S., & Peimbert, M. 1997, in IAU Symp. 180, Planetary Nebulae, ed. H. J. Habing & H. J. G. L. M. Lamers (Dordrecht: Kluwer), 175
Poggiani, R. 2008, NewA, 13, 557
Pollacco, D., Lawson, W. A., Clegg, R. E. S., & Hill, P. W. 1992, MNRAS, 257, 33P
Prialnik, D., & Kovetz, A. 1995, ApJ, 445, 789
Schlegel, D. J., Finkelbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Vassiliadis, E., & Wood, P. R. 1994, ApJS, 92, 125
Veltz, L., et al. 2008, A&A, 480, 753
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge: Cambridge Univ. Press), 16
Williams, R. E., Phillips, M. M., & Hamuy, M. 1994, ApJS, 90, 297
Yaron, O., Prialnik, D., Shara, M. M., & Kovetz, A. 2005, ApJ, 623, 398