

*Hydrogen-Deficient Stars*  
*ASP Conference Series, Vol. 391, © 2008*  
*K. Werner and T. Rauch, eds.*

## On the Evolved Nature of CK Vul

M. Hajduk,<sup>1</sup> A. A. Zijlstra,<sup>2</sup> P. A. M. van Hoof,<sup>3</sup> J. A. Lopez<sup>4</sup>, J. E. Drew<sup>5</sup>, A. Evans,<sup>6</sup> S. P. S. Eyres,<sup>7</sup> K. Gesicki,<sup>1</sup> R. Greimel,<sup>8</sup> F. Kerber,<sup>9</sup> S. Kimeswenger<sup>10</sup>, and M. G. Richer<sup>4</sup>

<sup>1</sup>*Centrum Astronomii UMK, ul. Gagarina 11, PL-87-100 Torun, Poland*

<sup>2</sup>*University of Manchester, School of Physics & Astronomy, P.O. Box 88, Manchester M60 1QD, UK*

<sup>3</sup>*Royal Observatory of Belgium, Ringlaan 3, Brussels, Belgium*

<sup>4</sup>*Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 877, 22800 Ensenada, BC, México*

<sup>5</sup>*Imperial College of Science, Technology and Medicine, Blackett Laboratory, Prince Consort Road, London, SW7 2BW, UK*

<sup>6</sup>*Department of Physics, School of Chemistry and Physics, Keele University, Staffordshire ST5 5BG, UK*

<sup>7</sup>*Centre for Astrophysics, University of Central Lancashire, Preston PR1 2HE, UK*

<sup>8</sup>*Isaac Newton Group of Telescopes, Apartado de correos 321, E-38700 Santa Cruz de La Palma, Tenerife, Spain*

<sup>9</sup>*European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching, Germany*

<sup>10</sup>*Institut für Astrophysik, Universität Innsbruck, Technikerstr. 25, 6020 Innsbruck, Austria*

**Abstract.** CK Vul was classified as the oldest observed nova. Recent studies have proven however, that CK Vul cannot be unambiguously classified as any known kind of eruptive variable. We present the optical and radio observations of the remnants of the eruption of CK Vul in the year 1670 in order to discuss possible scenarios for this object. We have measured the proper motion which proves that the nebula is attributed to the star observed during its 1670–1672 brightening. A large bipolar nebula of 70 arcsec is discovered in a deep H $\alpha$  image. Radio observations reveal a barely resolved source placed in the expansion center of the ejecta.

## 1. Introduction

CK Vul was discovered at 3rd magnitude by P ere Dom Anthelme and independently by Hevelius in June/July 1670. The observed eruption lasted for two years (1670–1672). During this time the star experienced fadings and re-brightenings on a timescale of  $\sim 100$  days and eventually faded below visual limits (magnitude 6) in May 1672 (Shara et al. 1985). The star has not been recovered since. Shara et al. (1985) have successfully searched for the remnant of CK Vul. They discovered several nebulosities on their H $\alpha$  image, the spectra of which present reddened emissions of [N II], H I, [O III] and [S II]. The flux of

[N II] 6584 Å is three times more intense than the H $\alpha$  line, indicating an evolved, and perhaps hydrogen deficient chemical composition. No obvious central star was found in the field of CK Vul. A central star candidate suggested by Shara et al. (1985) was shown to be misidentified as such by Naylor et al. (1992); the latter authors were unable to identify, among the stars visible on their R image, an alternative central star candidate.

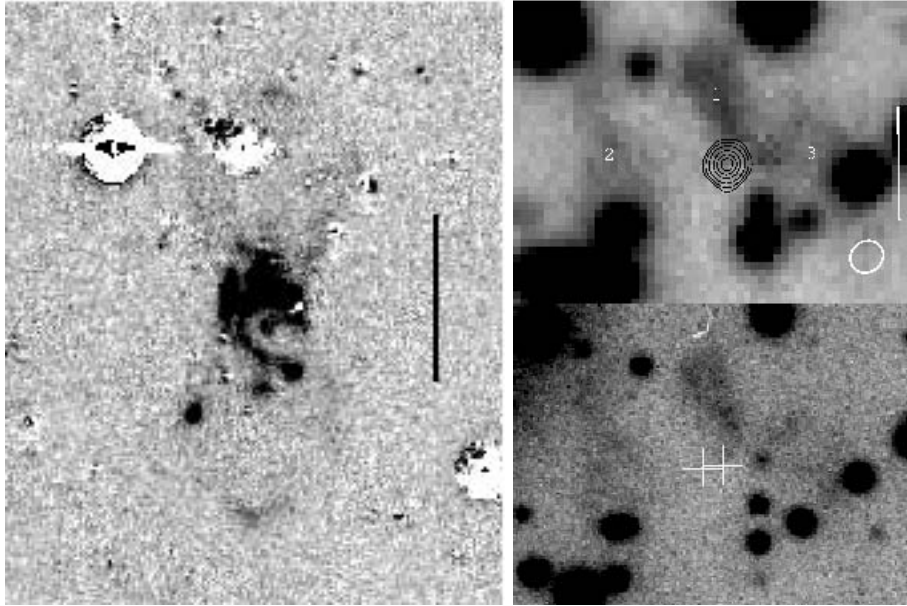


Figure 1. The image of the nebula around CK Vul. Left: the INT H $\alpha$  image of the large, newly discovered bipolar nebula. The bar is 30 arcsec long. Right up: the radio contours superposed on the r' INT image of the center of the nebula with the radio contours (0.075, 0.15, 0.3, 0.6, 0.9 and 1.2 mJy/beam) superposed. The interferometer beam and the bar of 10 arcsec are also plotted. Right down: the r' WHT image of the nebula. The crosses mark the position of the expansion centre. North is up, east is left.

## 2. Observations

The field of CK Vul was observed by the Isaac Newton Telescope (INT) on La Palma on 2004 August 4 and 2005 July 12. The H $\alpha$  and r' filter were used for the 2004 and H $\alpha$ , r' and i' filters for the 2005 observations. Earlier H $\alpha$  images have been obtained by Naylor et al. (1992) with the William Herschel Telescope (WHT) on La Palma, on 1991 August 10. The H $\alpha$  filter covers the [N II] lines for the WHT and INT observations. Long-slit echelle spectra were obtained with the 2.1 m SPM telescope on 2006 July 12 at four slit positions. VLA observations were performed on 2005 April 5 at 5 GHz and on 2006 April 9 at 5 and 8 GHz. The details of the observations are given in Hajduk et al. (2007).

The 1-cm (30 GHz) observations were made on 2007 March 25 and 27 with the OCRA-p (One Centimeter Receiver Array), mounted on the 32-m radio tele-

scope in Torun. The position calibrator was 1950+2519 and the flux calibrator was NGC 7027 (5.45 Jy). The FWHM of the instrument is 72 arcsec.

### 3. Discussion

Comparison of the 1991 and 2004 H $\alpha$  observations brought evidence for the expansion of the nebula, consistent with an explosion in 1670. The brightness of the nebula remained constant within  $\sim 10\%$  between 1991 and 2004, indicating that the recombination timescale of  $\tau$  must be  $\gtrsim 130$  yr. Conversely, the recombination timescale for [N II] for  $n_e \approx 100 \text{ cm}^{-3}$ , derived by Shara et al. (1985), is 75 yr. Naylor et al. (1992) found an even higher density of the observed part of the nebula of  $n_e \approx 10^3 \text{ cm}^{-3}$  indicating an even shorter recombination timescale. This indicates that shock ionization may occur in the ejecta.

The deep image reveals the 70 arcsec bipolar nebula (Fig.1). Shara et al. (1985) have observed part of this nebula. Rough comparison with our observations indicates that the outer nebula expands with a rate corresponding to an ejection in 1670.

VLA observations reveal a compact radio source. The position of the radio emission is consistent with the position of the expansion centre measured from the optical images and also with the symmetry center of the outer, bipolar nebula. The radio source appears to be resolved at 8 GHz (deconvolved FWHM of  $\approx 0.1$  arcsec), although this is uncertain due to the faintness of the emission. If it was indeed resolved, this would imply a thermal origin of the emission. The 5 GHz flux is  $1.27 \pm 0.16$  mJy, 8 GHz is  $1.53 \pm 0.18$  mJy and the 30 GHz flux is  $5.4 \pm 1.7$  mJy. The positive spectral index of the radio spectrum implies that the ionized gas has a non-uniform density distribution. The position of the radio emission suggests that it originates from the vicinity of the central star.

We have not found any counterpart of the radio emission at other wavelength ranges. The near-infrared candidate for the central star proposed by Harrison (1996) is clearly placed off the radio emission. The upper limits for the optical counterpart of the radio source obtained from the INT image are  $r' > 23$  mag and  $i' > 20$  mag. Neither ROSAT, IUE, 2MASS, MSX nor Spitzer/GLIMPSE counterpart of the radio emission was found. Evans et al. (2002) analysed the IRAS 12, 25 and 60  $\mu\text{m}$  and their 450 and 850  $\mu\text{m}$  observations. They modelled the infrared SED with two dusty shells, one of them may correspond to the material seen in the radio. However, these infrared observations have too low spatial resolution to find a direct confirmation that they originate from the same source as the radio emission. The radio emitting material has a very short recombination timescale, of the order of one year, and thus must be continuously ionized by the radiation from central star. The upper limit for the luminosity of the central star is of the order of  $1 L_{\odot}$ . The lack of the optical/NIR counterpart suggests the presence of a very high extinction. We have modelled the radio emission with the Cloudy photoionization code, last described by Ferland et al. (1998). For the luminosity of  $0.5 L_{\odot}$ , the central star temperature is 65 kK.

The nebula seen in the radio has a very small size. Its expansion velocity is of the order of  $1 \text{ km s}^{-1}$ . Probably it is a part of a stable structure, such as a rotating disc which could predate the eruption. The presence of the disc could influence the shaping of the ejecta observed in optical.

#### 4. The possible scenarios

The light curve of CK Vul is unlike any catalogued novae, raising doubts on its status. The apparent high amplitude of the 1670–1672 outburst is even more troublesome to explain. The very low luminosity of the object seen in the radio may correspond to a pulsar. However, pulsars have high proper motions. The radio emission is not circularly polarized. The expansion velocity of the ejecta is too small for a supernova, we detect no X-ray emission expected from a SN remnant and the morphology of the nebula does not resemble supernova remnants.

The luminosity of the central star of CK Vul is much lower than the luminosity of any known born-again star. Also the theoretical models (though very uncertain) do not predict a drop of the luminosity of the central star down to  $\sim 1 L_{\odot}$  lasting only for a few centuries. CK Vul cannot be regarded as a born-again object unless explained in terms of binary evolution. The morphology of the ejecta shows similarities to evolved binary systems. Very late thermal pulse could be triggered by accretion from the old circumbinary disc, which could manifest itself in the radio. Lawlor (2005) proposed a model of V838 Mon with a born-again episode. Changes of the accretion rate could modulate the optical light curve such that it could simulate the observed light curve of CK Vul.

A light nova is another possible explanation. Prialnik & Kovetz (1995) computed a set of models covering a wide parameter space. The model for  $M_{\text{WD}} = 0.65 M_{\odot}$  and  $T_{\text{WD}} = 3 \times 10^7$  K yields an accretion velocity of  $200 \text{ km s}^{-1}$ , eruption magnitude of 16 mag, mass-loss timescale of 480 d and a very high peak luminosity of  $L = 8 \times 10^4 L_{\odot}$ . These values are consistent with the values observed for CK Vul.

**Acknowledgments.** We thank Marcin Gawronski for carrying out and reducing the OCRA-p observations. The VLA is part of the National Radio Astronomy Observatory, operated by AUI inc on behalf of the NSF. The INT is part of the ING group of telescopes. OCRA-p operates on the 32-m radio telescope in the Center for Astronomy of Nicolaus Copernicus University, Torun, Poland. This project was supported by a NATO grant for collaborative research, and by PPARC through a rolling grant, PvH acknowledges support from the Belgian Science Policy Office through grant MO/33/017. JAL and MGR acknowledge financial support from CONACyT grant 43121 and UNAM-DGAPA grants IN108506-2, IN108406-2, and IN112103. MH and KG acknowledge financial support by MNiSW of Poland through grant No. N 203 024 31/3879.

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