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UNRAVELING THE OLDEST AND FAINTEST RECOVERED NOVA: CK VULPECULAE (1670)

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ABSTRACT

A narrow-band Hα + [N II] CCD image of the field of Nova CK Vul (1670) shows nebulosity with a morphology (suggestive of equatorial ejection) with several bright subcondensations, and a central star. The net Hα image also reveals a faint jet leading to an Hα-bright knot, suggestive of polar ejection.

Spectra of the equatorial and polar ejecta are similar to each other and to spectra of the shell of the recurrent nova T Pyx, but with lower excitation. Nitrogen appears enhanced, and the nebular density is low enough that its recombination time scale equals or exceeds the time since outburst.

The reconstructed light curve of CK Vul shows it to have been a very slow nova, with large oscillations near maximum. Constraints on its distance place it at 550 ± 150 pc from the Sun, near the far side of, or perhaps within, an intervening obscuring cloud. The implied nebular expansion velocity is extraordinarily low, $v_{exp} = 59 \pm 16$ km s^{-1}, and may not represent the true extent of the ejecta.

The present absolute magnitude of the central star, $M_R = +10.4$, is 6 mag fainter than canonical old novae, and requires a very low-mass secondary star (Sp. $\gtrsim$ M3 V), short orbital period ($P \lesssim 3^h.6$), and negligible mass transfer rate ($\dot{m} \lesssim 10^{-11.5}\ M_\odot$ yr^{-1}). If CK Vul represents a typical state for novae between outbursts, then published survey-based values of the space density and lifetimes of cataclysmic binaries may be seriously underestimated.

Subject headings: stars: individual (CK Vul) — stars: novae

I. THE LIGHT CURVE AND HISTORY OF NOVA CK VUL

Since 1900, no fewer than 10 classical novae (eight of them easily visible from the Northern Hemisphere) have reached apparent magnitude $m_v = 3$ or brighter at maximum, bright enough to be conspicuous to the naked eye. In the dynastic chronicles of China, Korea, and Japan, references to nearly 100 probable naked-eye novae are found between 200 B.C. and A.D. 1700 (e.g., Ho 1962; Xi and Bo 1965; Pskovskii 1972). Yet until Nova V841 Ophiuchi (1848), the only true classical nova observed in Europe having more than a single surviving Western account of its appearance was Nova CK Vulpeculae (1670), and it remains by far the best documented of ancient novae.

CK Vul[11] is listed in Flamsteed's (1725) catalog as 11 Vulpeculae, although he evidently did not himself observe it. It was in fact first discovered by Père Dom Anthelme, a Carthusian monk in Dijon, France. An account of his discovery was published by the Académie Royale des Sciences, Paris (1671):

> As this person contemplated the Heavens at night, *June* 20th of the last year, desirous to discover that admirable Star, which hath appear'd and disappear'd twice since the beginning of this Century in the Constellation of the *Swan* (which is that in *Pectore Cygni* [i.e., P Cyg]); he perceived a Star of the *Third Magnitude*, which he had never yet observed. He presently signified it to the Company which assembleth in the Library of the King: And divers of that Assembly having beheld the Heavens about the end of *June* and the beginning of *July*, took notice, that there was indeed about the *Beak* of the *Swan* a *New Star* of the *third magnitude*, not to be met with in any Catalogue of Astronomers, although many other neighbouring Stars, that are much smaller, be exactly marked by them.

Scarcely a month after Anthelme's discovery, CK Vul was found independently by Johannes Hevelius (1670*a*) on 1670 July 25, at his observatory in what is now Gdansk, Poland, and it is in fact Hevelius who gave the first published account of its appearance (see Fig. 1).

There seems no way of determining how long the nova may already have been at or near maximum when first discovered. A description of its color at that time might have provided a clue to its stage of development, but none exists. However, in view of the two independent discoveries within little more than a month, both by observers who were thoroughly familiar with that neighborhood in the sky from having monitored P Cyg nearby (Acad. Roy. Sci. 1671; Hevelius 1670*a*, 1677), it is unlikely that the nova was apparent to the naked eye during the previous observing season. Hevelius (1670*a*) states with certainty that it was not visible when he catalogued that region of the sky in 1659–1661, nor during his observations of P Cyg in 1666.

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FIG. 1.—The chart of Nova Vulpeculae and its surroundings first published by Hevelius (1670*a*). The nova is the star marked *a* in the lower left section of the chart, and is described in his accounts as the *"Nova sub capite Cygni."* The constellation Vulpecula (*"Vulpecula cum Ansere"*—"the small fox with the goose") was a later invention of Hevelius. "Nova 1600" marked on the chart is now referred to as P Cyg.

CK Vul was followed throughout its decline in the late summer and early fall of 1670 both by Hevelius (1670*a*, *b*, 1677, 1679) and by various members of the Académie Royale des Sciences (1671), until it faded from visibility in October of that year. The following year, on 1671 March 17, Anthelme recovered the nova and found it again at 4th magnitude (Acad. Roy. Sci. 1671). It continued to grow in brightness until it reached $m_v \approx 2.6$ on or about 1671 April 30 (JD 2,331,500), when it was more brilliant than had ever been observed the previous year. Giovanni Cassini (Acad. Roy. Sci. 1671) and Hevelius (1671, 1677, 1679) observed it extensively through the late spring and summer of 1671 as it once more slowly declined, finally disappearing from view late in the month of August. In March of 1672, Hevelius (1672, 1677, 1679) found it yet a third time visible to the naked eye. It never recovered its former splendor, however, remaining only barely perceptible for about two months and a half. On 1672 May 22 it was last seen.

The light curve of Nova CK Vul, shown for the first time in Figure 2 and documented in Table 1, is outstanding among classical novae. No nova recorded before or since has been of such sustained visibility to the naked eye. And while large fluctuations in brightness are not uncommon among very slow novae near maximum, no other example is known with so great a range, or with so long a time scale ($\tau \approx 320$ days) characterizing those fluctuations. The closest counterparts to CK Vul among well-observed modern novae are Nova RR Pic 1925 (cf. Spencer Jones 1931) and novae no. 29 and no. 30 observed by Arp (1956) in M31; if the analogy is appropriate, it seems likely that CK Vul never much exceeded its observed peak magnitude at any time during its development.

Apart from descriptions of its brightness, little is recorded of the appearance or color of the nova. On three occasions (1670 July 25, 1671 April 30, and 1671 May 17), Hevelius describes it as dull or blurred ("*obtusior*") in comparison with other nearby bright stars (β Aql; β, ϵ, and γ Cyg; and β Cyg and γ Aql respectively), and in the second instance he describes it as ruddier ("*rubicundior*") as well. The color is scarcely surprising, considering the great time elapsed since the nova first appeared. As for the dull or blurred appearance that Hevelius notes, the interpretation of this remark is more problematic. All of Hevelius' observations were made with the naked eye, even though he did have a telescope at his disposal. Certainly he could not have resolved a nova shell visually, and it is quite unlikely even that such a shell could have reached sufficient angular extent so early as to suppress atmospheric twinkling. It is possible that this difference in appearance is physiological rather than physical in origin, but we will return to this observation below.

The position of CK Vul was measured by Jean Picard

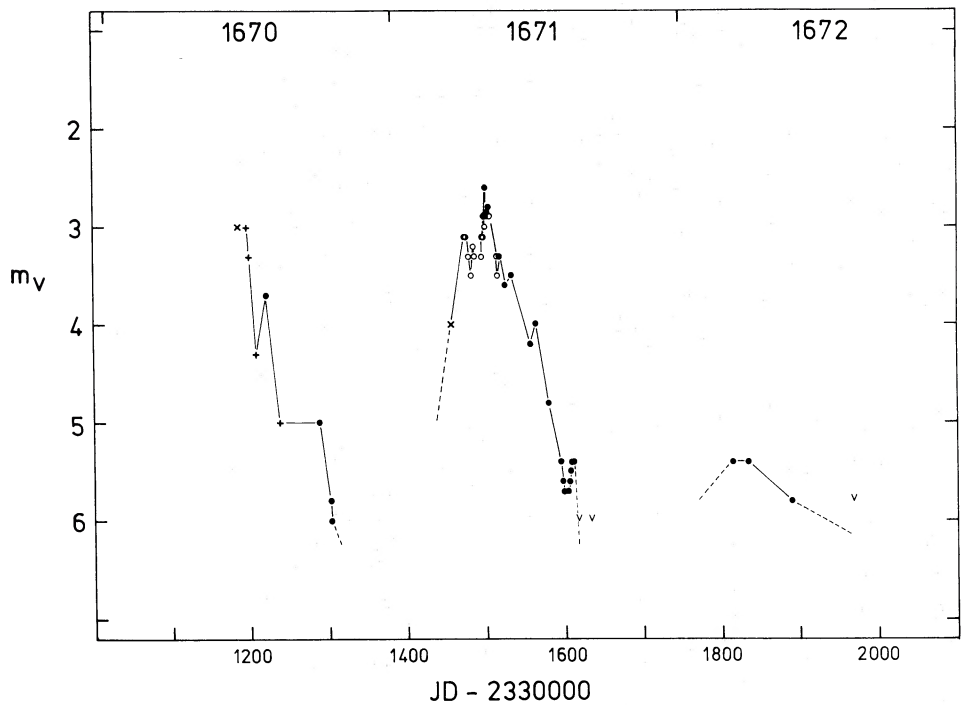

FIG. 2.—The outburst light curve of CK Vul. The individual magnitude estimates have been placed on a modern photometric scale by the adoption of photoelectric (V) magnitudes for the comparison stars, and by calibration of Hevelius' (1670*a*) magnitude scale with photoelectric photometry of nearby stars. Different symbols identify different observers: ×, Anthelme; +, various (anonymous) members of the Académie Royale des Sciences, Paris; ○, Cassini; ●, Hevelius; v, brightness limit (Hevelius).

(Acad. Roy. Sci. 1671; Le Monnier 1741) and Hevelius (1670*a*, 1671, 1679) by triangulation with other bright stars, with as great an accuracy as was then possible. We have reduced anew these raw observations (two transits and angular distances to three stars by Picard, 12 measurements of angular distances to five stars by Hevelius, all of which are weighted equally), to find the mean position:

$$\alpha_{1950} = 19^h45^m32^s.41 \pm 1^s.20 \quad \text{(mean epoch 1670.79)} ,$$
$$\delta_{1950} = +27°11'22''.6 \pm 20''.4 \quad \text{(mean epoch 1671.10)} .$$

(The mean epochs differ slightly because only α can be deduced from a few of the observations.) For comparison, Hevelius' (1690) catalogued position, brought up to the same equinox, is $\alpha_{1950} = 19^h45^m30^s.1$, $\delta_{1950} = +27°11'37''$, whereas Hind's (1861) reduction of Picard's observations gives $\alpha_{1950} = 19^h45^m32^s.6$, $\delta_{1950} = +27°11'11''$. These positions are accurate enough for the recovery of CK Vul, but not for precise astrometry (see § IV).

For three centuries following its disappearance in 1672, CK Vul eluded numerous attempts at its recovery by a long succession of observers: Hevelius (1679), Kirch (1715), Maraldi (1717), Halley (1715), Heinsius (1748), Pigott (1786), Piazzi (1814), Hind and Baxendell (Hind 1861; Anonymous 1875), Knott (1885), Pickering and Wendell (1890), Zinner (Müller and Hartwig 1920), Barnard (1914), Steavenson (1934, 1947), Humason (1938), Wachmann (1962), Walker (1963), and Becker and Marshall (1981). However, with the discovery of the nebulosities (Shara and Moffat 1982), central star, and ejected knots described in this paper, the nova has at last been identified.

In § II we present new CCD narrowband and broadband images which unambiguously locate the central star. Spectra of the brightest of the ejected nebulosities are described in § III. We discuss the reddening and derive a distance and luminosity for CK Vul in § IV. The implications of the extraordinarily low derived luminosity and possible alternative interpretations of CK Vul are briefly discussed in § V, and our findings are summarized in § VI. A later paper will discuss in detail the implications of the present and related work for the space density and long-term evolution of cataclysmic binaries.

II. CCD IMAGERY OF CK VUL

A narrow-band (50 Å FWHM) Hα image tube plate taken with the 3.6 m Canada-France-Hawaii telescope (Shara and Moffat 1982, hereafter SM) revealed three nebulous knots within $\sim 50''$ of the mean position of Nova 1670 measured by Picard (rather than LeMonnier, erroneously credited by SM) and Hevelius (see § IV). A stellar-like condensation in the northeast part of the brightest knot (labeled 1 in the finding chart of SM) was tentatively identified with the star responsible for the outburst.

The discovery plate of CK Vul was taken in poor seeing ($\sim 4''$) with a first-quarter Moon above the horizon, and is far from dark-sky–limited. We have now obtained deep narrow-band and broad-band CCD images of CK Vul. These not only reveal a wealth of detail about this oldest recovered nova, but also raise serious doubts about the canonical picture of novae between eruptions.

On 1983 August 13/14, the RCA CCD camera at the prime focus of the Cerro Tololo Inter-American Observatory 4 m telescope was used to image CK Vul. Twenty-minute exposures were taken through a broad-band R (FWHM $\approx$ 900 Å) and a narrow-band Hα filter (FWHM $\approx$ 40 Å, with both central wavelength and width corrected for the telescope's f/2.7 beam). The images were trimmed, debiased, and flat-fielded using mountain software routines.

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TABLE 1

OUTBURST OBSERVATIONS OF NOVA CK VUL (1670)

Gregorian Date	JD −2,330,000	m_v	Description[a]	Observer	Lunar Phase	Reference
1670 Jun 20	1186.6:	3.0	*de la troisiéme* [sic] *grandeur*	Anthelme	0.11	1,[b] 2
1670 Jun/Jul	1196±	3.0	*de la troisiéme grandeur*	Acad. Roy. Sci.	0.4±	2
1670 Jul 3	1199.5:	3.3	*de la troisiéme grandeur, mais sa lumiere ètoit sensiblement affoiblie*	Acad. Roy. Sci.	0.55	2
1670 Jul 11	1207.5:	4.3	*à peine de la quatriéme* [sic] *grandeur*	Acad. Roy. Sci.	0.82	2
1670 Jul 25	1221.38	3.7	*minor quidem restro Cygni* [β Cyg], *sed aequalis in Collo Aquilae* [β Aql]	Hevelius	0.29	3, 8
1670 Aug 10	1237.4:	5.0	*n'ètoit plus que de la cinquiéme* [sic] *grandeur*	Acad. Roy. Sci.	0.83	2
1670 Sep 29	1287.3:	5.0	*ut vix major illâ durarum informium Caput Cygni praecedentium Superiori* [3 Vul]	Hevelius	0.52	7,[c] 8
1670 Oct 13	1301.3:	5.8	*vix ac ne vix videbatur*	Hevelius	0.99	7, 8
1670 Oct 14	1302.3:	6.0	*adeò exilis & debilis extitit, ut nulla ratione*	Hevelius	0.03	4, 7, 8
1671 Mar 17	1456.7:	4.0	*de la quatriéme grandeur*	Anthelme	0.24	2
1671 Apr 3	1473.6:	3.1	*plus grande que les deux Etoiles de la troisiéme grandeur qui sont au bas de la Constellation de la Lyre* [β Lyr ($\phi = 0.19$), γ Lyr], *mais un peu plus petite que celle du bec du Cygne* [β Cyg]	Cassini	0.82	2
1671 Apr 4	1474.6:	3.1	*presqu'aussi grande, & beaucoup plus brillante que celle du bec du Cygne* [β Cyg]	Cassini	0.85	2
1671 Apr 9	1479.6:	3.3	*un peu diminuée, & presqu'ègale à la plus grande de deux Etoiles qui sont au bas de la Lyre* [γ Lyr]	Cassini	0.02	2
1671 Apr 12	1482.6:	3.5	*egále à la plus petite de ces deux Etoiles* [β Lyr ($\phi = 0.85$)]	Cassini	0.12	2
1671 Apr 15	1485.6:	3.2	*qu'elle croissoit, & ... ègale pour la seconde fois à la plus grande de ces deux Etoiles* [γ Lyr]	Cassini	0.23	2
1671 Apr 16–26	1486.6:–1496.6:	3.3	*Depuis le 16 jusqu'au 27 elle parut de differentes grandeurs, ètant tantot ègale à la plus grande de ces deux Etoiles* [γ Lyr], *tantot ègale à la plus petit* [β Lyr ($\phi = 0.24$–0.02], *& quelquefois moyenne entre les deux*	Cassini	0.26–0.60	2
1671 Apr 27	1497.6:	3.1	*aussi grande que l'Etoile du bec du Cygne* [β Cyg]	Cassini	0.63	2
1671 Apr 28	1498.6:	3.1	*aussi grande que l'Etoile du bec du Cygne* [β Cyg]	Cassini	0.67	2
1671 Apr 29	1499.43	2.9	*major aliquanto Rostro Cygni* [β Cyg]	Hevelius	0.70	5,[d] 7,[d] 8
1671 Apr 30	1500.45	2.6	*Major extitit Rostro Cygni* [β Cyg], *imo etiam ferè illâ in ancone inferioris alae Cygni* [ϵ Cyg]; *sed paulò minor illâ in pectore* [γ Cyg]	Hevelius	0.73	5,[d] 7,[d] 8
1671 Apr 30	1500.6:	3.0	*un peu plus claire* [than β Cyg]	Cassini	0.74	2
1671 May 1–6	1501.6:–1506.6:	2.9	*plus grande* [than β Cyg]	Cassini	0.77–0.94	2
1671 May 4	1504.6:	2.8	*major erat illâ in Rostro Cygni* [β Cyg]	Hevelius	0.87	8
1671 May 15	1515.6:	3.3	*plus petite que cette même Etoile* [β Cyg]	Cassini	0.25	2
1671 May 16	1516.6:	3.5	*ètoit moyenne entre les deux Etoiles qui sont au bas de la Lyre* [γ Lyr, β Lyr ($\phi = 0.53$)]	Cassini	0.28	2
1671 May 17	1517.6:	3.3	*aliquanto minor videbatur Rostro Cygni* [β Cyg], *& illâ in Humero Aquilae* [γ Aql]; ... *major tamen quàm illâ in Cuspide Sagittae* [γ Sge]; *aequalis ferè ille seq. in Jugo Lyrae* [β Lyr ($\phi = 0.61$), γ Lyr]	Hevelius	0.32	7, 8

TABLE 1—*Continued*

OUTBURST OBSERVATIONS OF NOVA CK VUL (1670)

Gregorian Date	JD −2,330,000	m_v	Description[a]	Observer	Lunar Phase	Reference
1671 May 25	1525.6:	3.6	*Minor jam erat Rostro Cygni* [β Cyg], *nec non illâ in ancone Alae Austr. Cygni* [ϵ Cyg]; *etain minor illis in Jugo Lyrae* [β Lyr ($\phi = 0.23$), γ Lyr] *& Humero Aquilae* [γ Aql]; *vix major apparuit minori duarum in pede Cygni* [ν Cyg ξ Cyg], *& illâ in pectore Aquilae* [β Aql]	Hevelius	0.59	7, 8
1671 Jun 1	1532.6:	3.5	*vix major visa est, quàm Die 25 Maji*	Hevelius	0.83	8
1671 Jun 26	1557.5:	4.2	*minor apparuit illâ in Collo Cygni* [η Cyg]	Hevelius	0.67	7, 8
1671[e] Jul 3	1563.5:	4.0	*ferè minor illâ in Collo Cygni* [η Cyg]	Hevelius	0.88	7, 8
1671 Jul 18	1579.4:	4.8	*vix Stellae 5 magnitudinis aequabatur*	Hevelius	0.42	7, 8
1671 Aug 2	1594.4:	5.4	*vix Sextae magnitudinis apparuit, imò minor adhuc, quàm reliquae omnes circa Caput & Collum Cygni* [of which the faintest he catalogues is 3 Vul]	Hevelius	0.93	7, 8
1671 Aug 6	1598.4	5.6	*adeò decreverat, ut vix in oculos incurreret, caelo licet admodùm sereno*	Hevelius	0.07	7, 8
1671 Aug 7	1599.4:	5.7	*vix in oculos incurrebat, ut ut omnes oculorum nervos in eam intenderim*	Hevelius	0.10	7, 8
1671 Aug 12	1604.4:	5.7	*vix deprehendebatur*	Hevelius	0.27	7, 8
1671 Aug 14	1606.5:	5.6	*vix animadvertere potui*	Hevelius	0.34	7, 8
1671 Aug 15	1607.4:	5.5	*vix ampliùs animadversa*[f]	Hevelius	0.37	7, 8
1671 Aug 16	1608.4:	5.4	*vix ampliùs deprehensa*[g]	Hevelius	0.41	7, 8
1671 Aug 17	1609.43	5.4	*vix ac ne vix videbatur*	Hevelius	0.44	7, 8
1671 Aug 25	1617.4:	>6.0	*non ampliùs apparuit*[h]	Hevelius	0.71	7, 8
1671 Sep 11/12	1634.4:	>6.0	*haud ampliùs conspecta*	Hevelius	0.29	7, 8
1672[e] Mar 7	1812.65	5.4	*denùo nudis oculis & 12 ped. Tubo observata 6 magn.*	Hevelius	0.29	6, 8
1672[e] Mar 28	1833.55	5.4	*vix sextae magnitudinis apparuit*	Hevelius	0.00	7, 8
1672 May 22	1888.6:	5.8	*vix ac ne vix videbatur*	Hevelius	0.88	8
1672 Aug 9	1967.4:	>6.0	*nusquam hoc anno affulsit*	Hevelius	0.56	7
1677 Aug 22	3806.45	>6.0	*nulla planè fulsit*	Hevelius	0.82	8
1677 Aug 26	3810.45	>9:	*nusquam affulsit* [observed with the 12 foot telescope]	Hevelius	0.96	8

[a] The photometric phases ϕ quoted for β Lyr are extrapolations of the quadratic ephemeris of Klimek and Kreiner 1973.
[b] In reference (1), the date is erroneously given as 1669 Dec 20.
[c] In reference (7), the date is erroneously given as 1670 Sep 8.
[d] In references (5) and (7), the description for 1671 Apr 29 is that identified in reference (8), and quoted here, for 1671 Apr 30.
[e] According to reference (8), the observations were made on the morning of the published date.
[f] In reference (7), the description is "*vix ampliùs conspecta.*"
[g] In reference (7), the description is "*vix ampliùs visa.*"
[h] In reference (7), the description is "*non ampliùs fuit conspicua.*"
REFERENCES.—(1) Acad. Roy. Sci. 1670. (2) Acad. Roy. Sci. 1671. (3) Hevelius 1670*a*. (4) Hevelius 1670*b*. (5) Hevelius 1671. (6) Hevelius 1672. (7) Hevelius 1677. (8) Hevelius 1679.

Figures 3 and 4, respectively, depict the R and Hα images of the field of CK Vul. Even though the original *R* image (Fig. 3) resolves stars fainter than does the Hα image, no trace of an ejected shell is seen in Figure 3. *A ring with a symmetrically-located central star is clearly seen in the* Hα *image Figure 4; this is the long-sought nova of 1670 and its ejecta.* The measured position of the central star is

$$\begin{aligned}\alpha_{1950} &= 19^{\rm h}45^{\rm m}34\overset{\rm s}{.}97 \pm 0\overset{\rm s}{.}07\\ \delta_{1950} &= +27°11'10\overset{''}{.}6 \pm 0\overset{''}{.}9\end{aligned} \quad \text{(mean epoch 1983.62)}\,.$$

Figures 5 and 6, respectively, are 4× enlargements of the central parts of Figures 3 and 4. Comparison of Figure 6 with Figure 1*c* of SM shows that the stellar-like condensation in knot 1 (of SM) is *not* the central star, but merely the brightest part of the brightest ejecta of CK Vul. The faint central star is indicated in the *R* image (Fig. 5). It is considerably fainter than in the Hα image, indicating that it is itself an emission-line object. This fact together with the symmetric position within the nebular ring strongly supports our contention that this is the central star.

The images were further interactively processed at the Space Telescope Science Institute. A VAX 11/780 computer running IDL software routines was used to align, scale, and perform arithmetic operations on the images, which were monitored on a Gould/De Anza image display system.

The subtracted image (Hα − *kR*) is shown in Figure 7*a*. The empirically determined constant *k* scales the two images so that non-Hα emission objects vanish (except the grossly oversaturated image of one nearby star). The dramatic gain in image clarity of Figure 7*a* over Figure 6 is due to the suppression of background light and stars. In particular, a nebulous jet ending on a knot is seen extending southeast of the central star and ring of Figures 6. The features revealed in Figure 7*a* are further delineated in an isointensity map (Fig. 7*b*) and in a

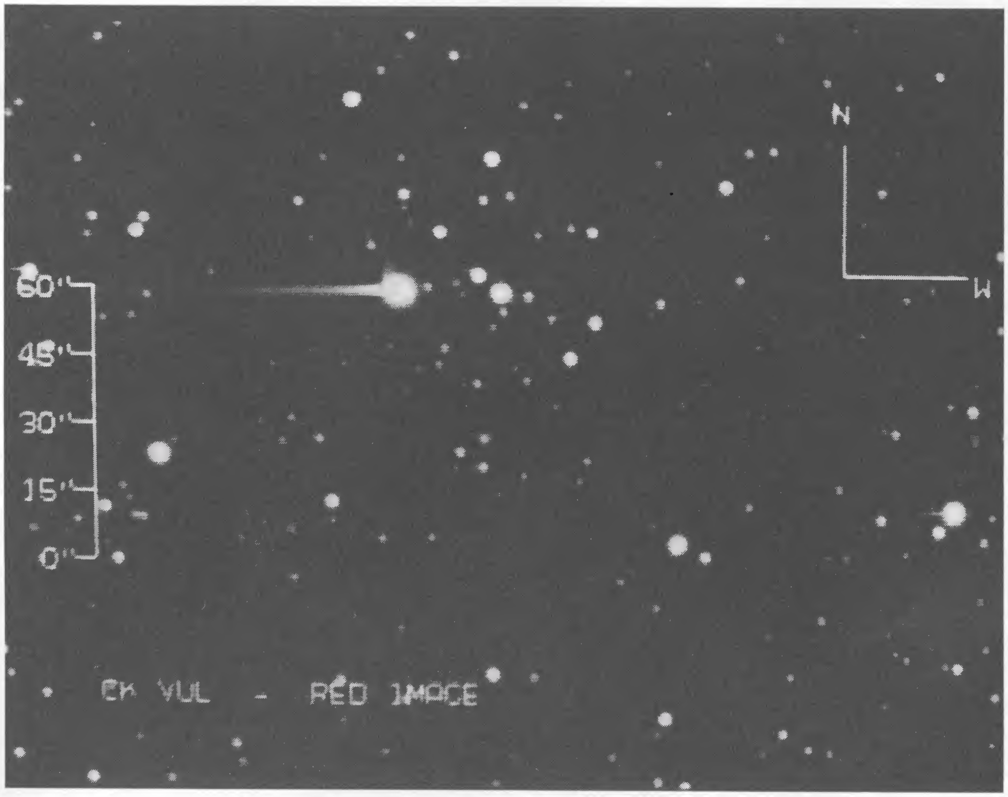

FIG. 3.—A 20 minute CCD frame of a 3′ × 5′ field around CK Vul taken through a broadband *R* filter. Neither the nova nor its ejecta are distinguishable from the background stars. This large field and Fig. 4 can be compared with the image tube plates of SM and direct plate of Humason (1938).

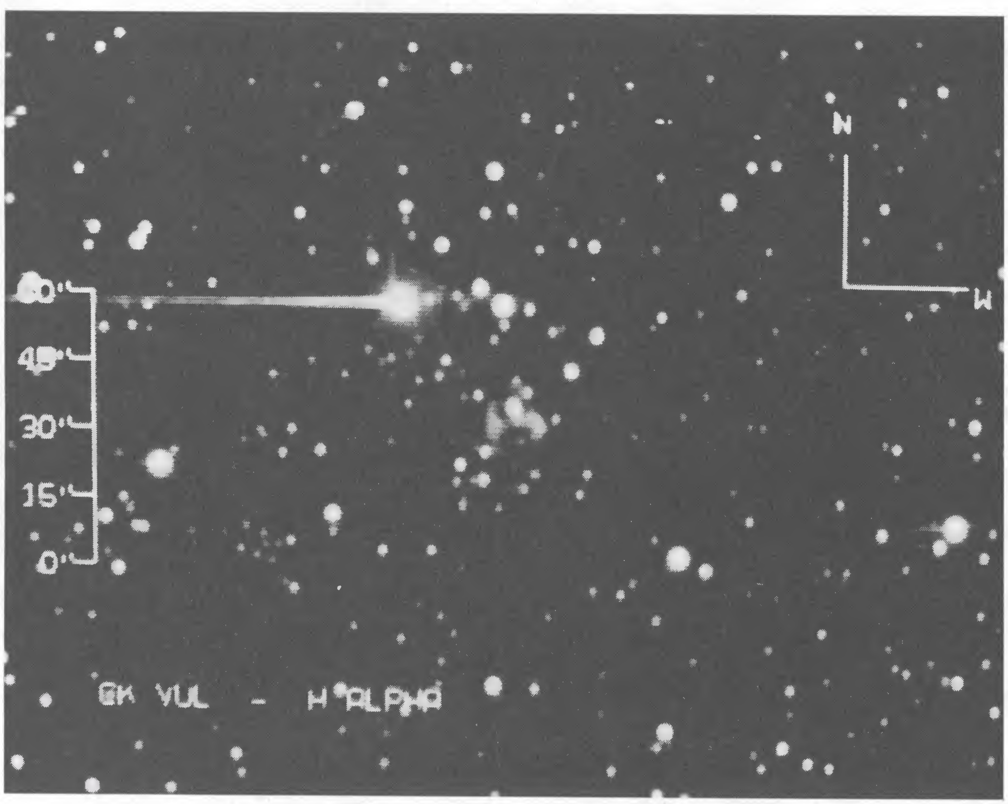

FIG. 4.—A 20 minute CCD frame of the same 3′ × 5′ field in figure 3, but taken through a 40 Å FWHM Hα filter. A U-shaped nebulosity enclosing a star stands out clearly.

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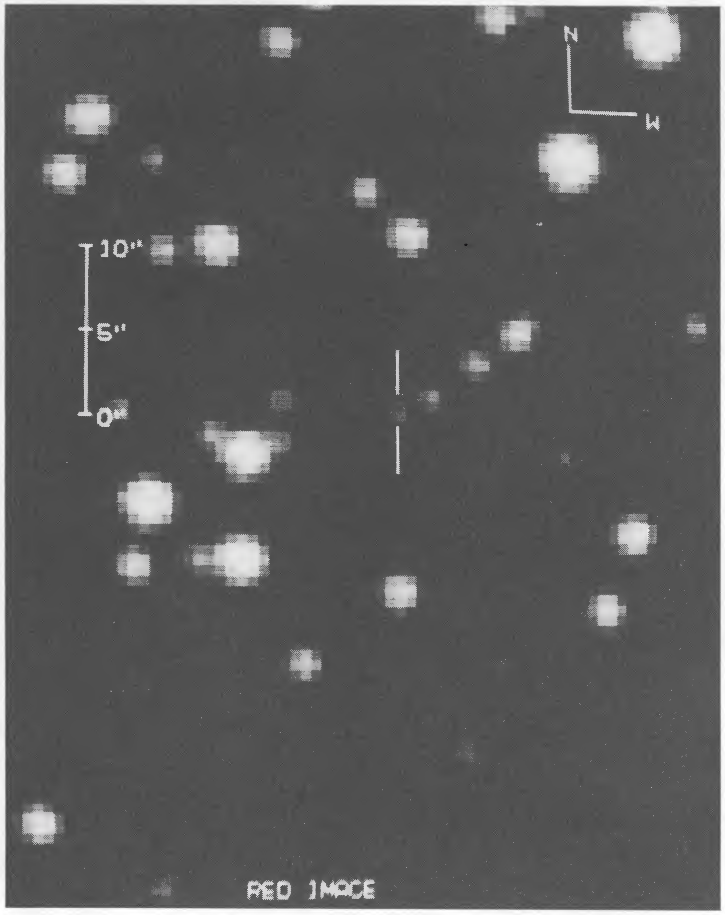

FIG. 5.—A 4 × enlargement of the central part of figure 3 (R image). The central star candidate is indicated.

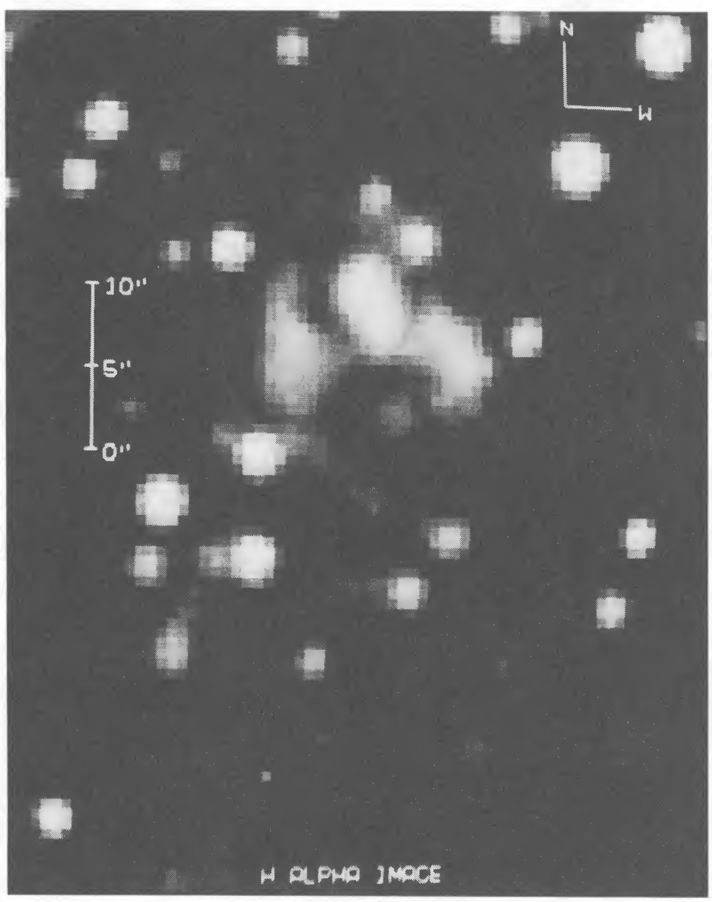

FIG. 6.—A 4 × enlargement of the central part of figure 4 (Hα image)

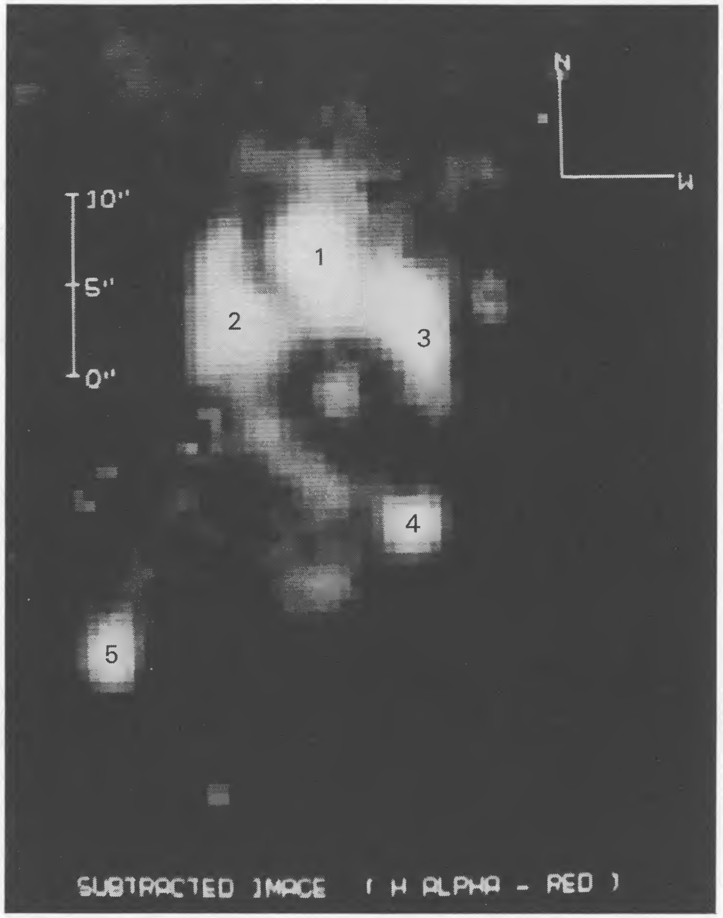

FIG. 7*a*

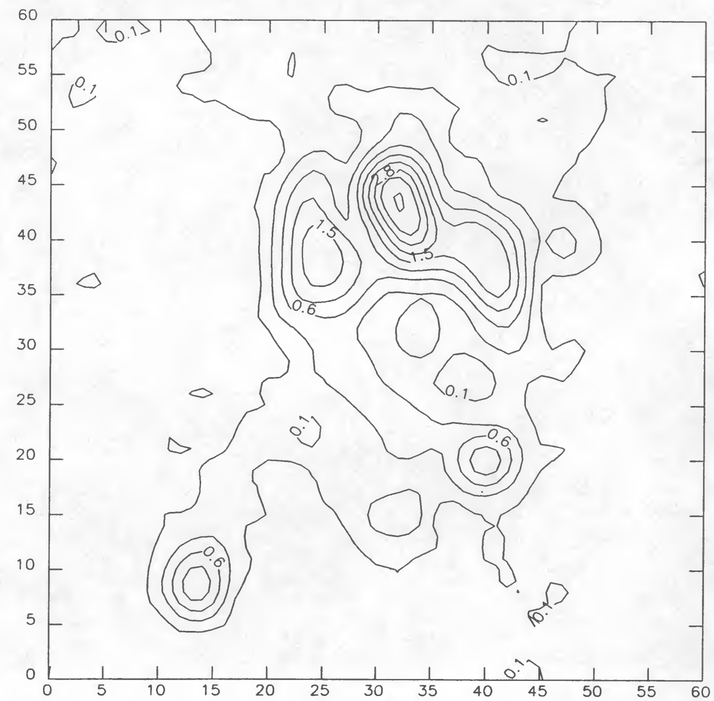

FIG. 7*b*

FIG. 7.—(*a*) The difference between Figs. 6 and 5 (Hα − kR). The empirically determined constant k scales the two images so that non–Hα emission objects vanish. A ring is clearly seen to encircle a central star; also seen is a faint jet extending to the southeast ending on an Hα-bright knot (no. 5). Five knots are numbered and referred to in the text; SM identified knots 1–3. (*b*) An isointensity map of CK Vul's net Hα emission. Contours are drawn at relative intensity levels of 0.1, 0.3, 0.6, 1.0, 1.5, 2.1, 2.8, 3.5, and 4.4. North is up, east is left, and 5 pixels (the intervals marked on the axes) correspond to 3″.

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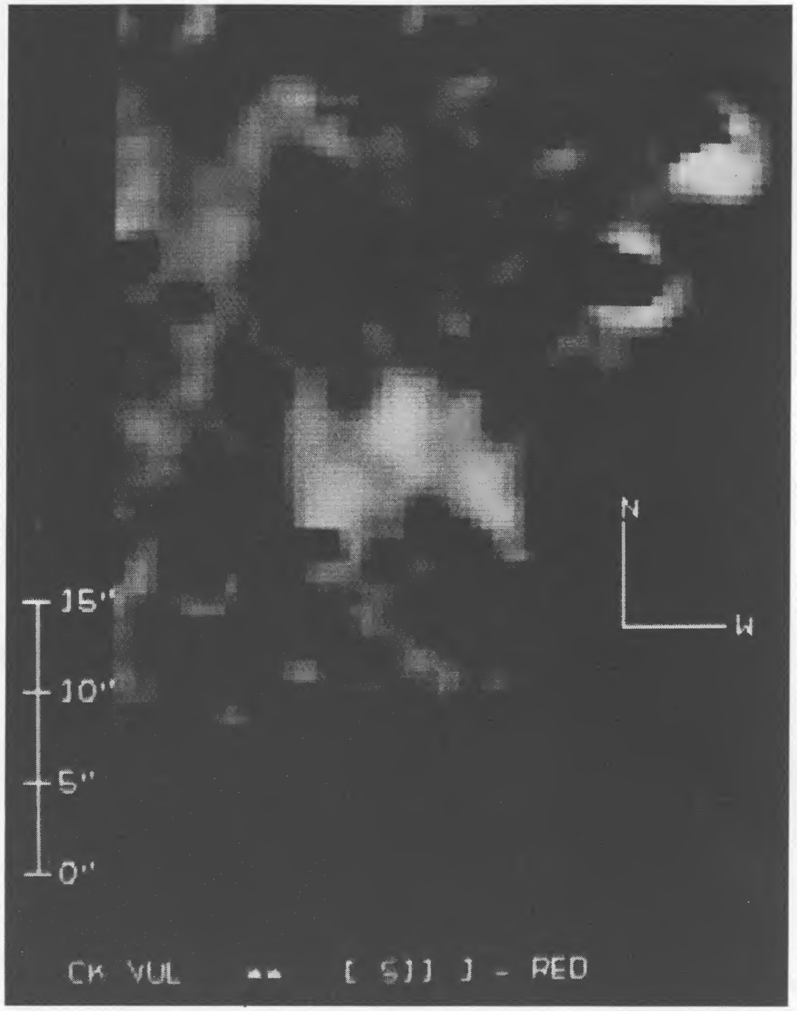

FIG. 7c

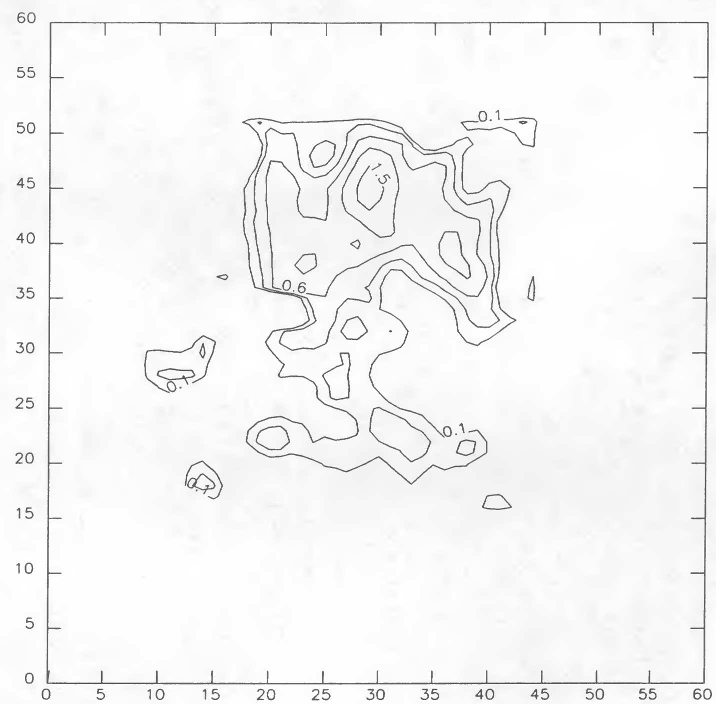

FIG. 7d

FIG. 7.—(c) A net [S II] emission image of CK Vul. See also Fig. 8b. (d) An isointensity map of CK Vul's net [S II] emission. Relative intensity levels of contours, orientations, and scale are the same as in Fig. 7b. The 0.6 contour has been chosen in each image to be that one which surrounds knots 1, 2, and 3 without large spurs. The central star and knot 5 are strikingly absent in [S II], while knot 4 is much weaker in [S II] than in Hα.

false-color net Hα image of CK Vul (Fig. 8*a*), which are designed to show the large brightness variations within the nebula, and even within individual condensations.

On 1984 June 8/9, we obtained narrowband [S II] and *R* images of CK Vul with the TI CCD camera at the Cassegrain focus of the University of Hawaii 2.2 m telescope. The [S II] image (central wavelength = 6730 Å, FWHM = 45 Å) was processed in the same fashion as the Hα image to produce the net [S II] images in Figures 7*c* and 8*b*. Note that the central star does *not* emit [S II]; lack of [S II] emission is expected in an accretion disk, a much denser environment than nova ejecta. This further supports our identification of the central star. What is surprising is that the knot labeled 5 in Figure 7*a* is *not* seen in [S II], implying that it, too, is a region of high density, despite its great distance from the central star.

The overall impression one gains from Figures 4–8*b* is one of an underlying symmetry in the geometry of the ejecta, but with a very marked asymmetry in emission measure. Blobs 1, 2, and 3 (see Fig. 7*a*) form a semicircular arc lying to the north of the central star, which sits at the focus of the arc. They emit most of the nebular light. The diametrically opposed knot 4 is weak by comparison. In addition, the net Hα-emission images (Figs. 7*a*, 7*b*, and 8*a*) clearly resolve a jet extending away from the central star toward the southeast and ending in a bright condensation or "polar cap" (labeled 5 in Fig. 7*a*). There is also some hint of a "counter-jet" in Figure 8*a* (Plate 4) extending a few arc seconds to the northwest of knots 1 and 3, along a line joining knot 5 with the central star, but it is very weak in comparison with the opposing jet.

The interpretation of this geometry will be discussed below, but it appears to be one of an equatorial ring plus polar jets. The marked asymmetry in emission measure could reflect genuinely asymmetric ejection, or inhomogeneities in the ambient medium with which the ejecta may be interacting. This point also will be taken up below.

III. SPECTRA OF THE EJECTA

We obtained spectra of the three brightest nebulosities (nos. 1, 2, and 3 in Fig. 1*c* of SM and the present Fig. 7*a*) with the Multiple Mirror Telescope (MMT) spectrograph and intensified Reticon on 1981 October 3. With the 300 lines mm^{-1} grating, useful spectra were secured in 10 minutes each for nebulosities 2 and 3 and 20 minutes for the brightest part of nebulosity 1. The instrumental resolution has a FWHM of ~8 Å.

We also obtained a spectrum of knot 5 with the Kitt Peak National Observatory 2.1 m telescope and IIDS on 1984 April 2. A 300 lines mm^{-1} grating was used to obtain the 64 minute–duration spectrum. Each nebulosity and adjacent sky were observed simultaneously in twin diaphragms (3".4 diameter at KPNO, 2" × 3" at the MMT) separated by ~30". Source and sky were switched every several minutes. First we divided out the flat-field source, normalized to relative flux from spectrophotometric standard observations, and co-added all spectra of a given object. Then we convolved them with a Gaussian smoothing filter having a FWHM of 8 Å (for the MMT data) and with a box filter of width 10 Å for the KPNO data to obtain the spectra shown in Figures 9–13.

In each of the four spectra, [N II] λ6584 is the strongest line, followed by (blended) Hα and [N II] λ6548. Also remarkably strong is the [S II] blend at λ6716/6730, which rivals Hα in intensity. In the better exposed spectra, lines of [O III] are also visible. The weaker spectra are noise-limited because of the extreme faintness of the nebular condensations. However, there do not appear to be significant variations in relative line intensities from one position to another.

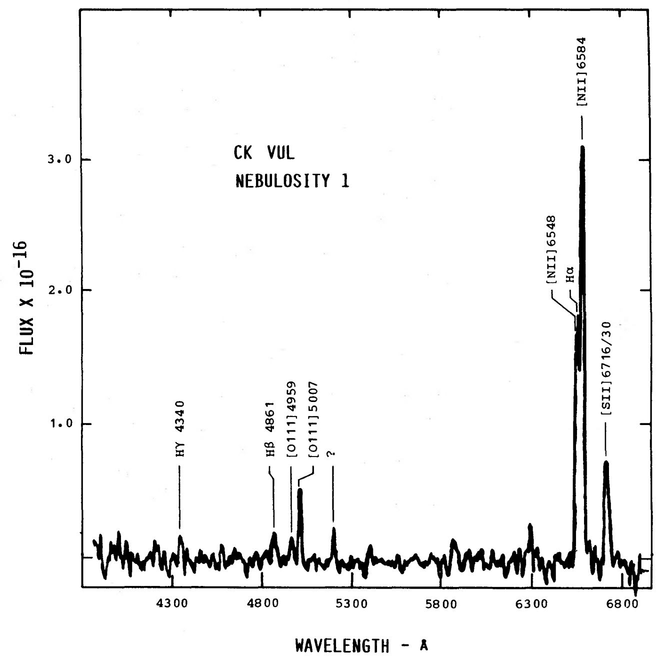

FIG. 9.—MMT Reticon spectrum of the brightest part of the nebulosity labeled 1 in Fig. 7*a*.

The measured integrated line fluxes for knot 1 (Figs. 9 and 12) are listed in Table 2. Despite the fact that the stronger lines are all badly affected by blending, and that the weaker line strengths are uncertain due to photon statistics, a number of important conclusions are still possible:

a) CK Vul is strongly affected by reddening. This is already clearly suggested by Figures 1*a* and 1*b* of SM, where many more stars are seen on the red than on the blue images of the Palomar Sky Survey of the field of CK Vul. The observed Balmer decrement, Hα:Hβ ≈ 9, implies a reddening $E_{B-V} \approx 1.0$ if we adopt case B recombination (Brocklehurst 1971), while Hα:Hγ ≈ 14 gives $E_{B-V} \approx 0.5$.

b) The apparent [S II] λ6716/6730 ratio exceeds the low-density limit, implying that $n_e \lesssim 100\ cm^{-3}$. If the oxygen-to-sulfur ratio is normal, then an electron temperature of order

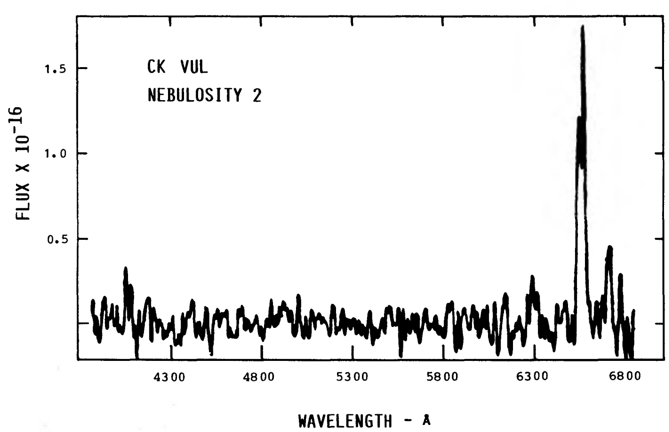

FIG. 10.—MMT Reticon spectrum of the nebulosity labeled 2 in Fig. 7*a*

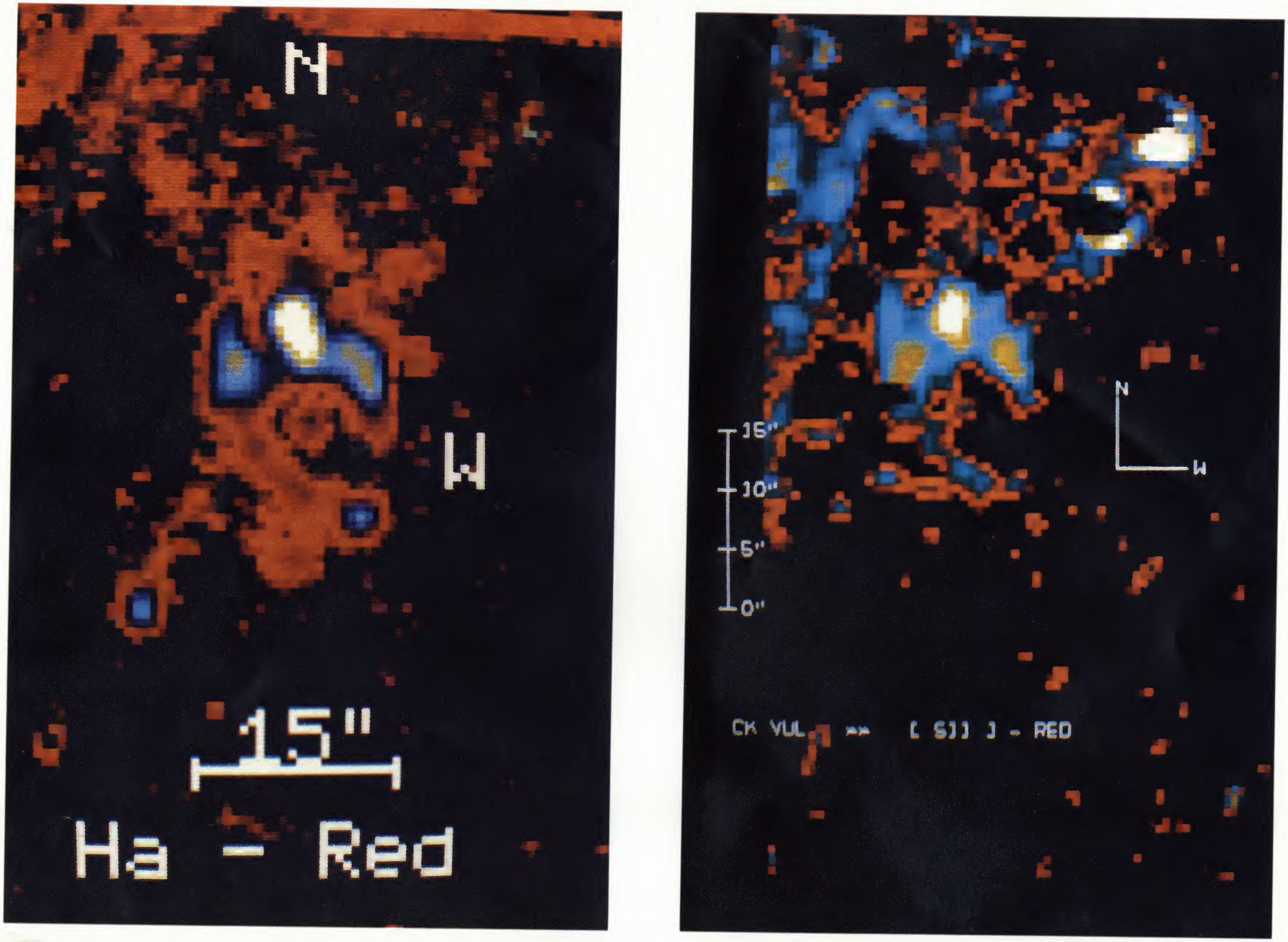

FIG. 8.—(*a*) A false-color net Hα emission image of CK Vul, showing the large brightness variations from ejecta to ejecta, and even within individual ejected knots. (*b*) A false-color net [S II] emission image of CK Vul. The central star's accretion disk and the polar knot are not seen, presumably because the nebular density is higher in these regions than in the arc north of the star.

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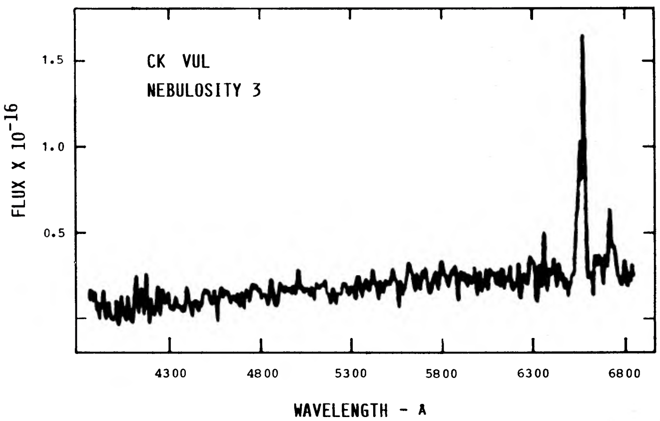

FIG. 11.—MMT Reticon spectrum of the nebulosity labeled 3 in Fig. 7*a*

$T_e \approx 10{,}000$ K is indicated by the strengths of the [O III] and H lines. Under these conditions, the recombination time scale of the nebula equals or exceeds ~300 yr, the time since outburst of CK Vul. No continuing ionization source is required.

c) For normal O/S, the great strength of the [N II] lines implies a roughly threefold enhancement of nitrogen relative to oxygen, compared to solar abundances. This clearly indicates the evolved nature of CK Vul.

No significant radial velocity differences as large as 120 km s^{-1} were observed between knots 1, 2, and 3 from the measurements of the centers of the [O III] λ5007 line. This is not too surprising, as these three objects are expected to possess mostly transverse velocities as seen from Earth, based on the ejecta geometry. Unfortunately, this does not strongly constrain the deduced distance of CK Vul (see § IV). Also as noted in SM, we determined the positions of the three brightest ejecta on the red Palomar Sky Survey plates (epoch 1950) and the CFHT plates (epoch 1981). No repeatable differences as large as 1″ were measured; the poor resolution and faintness of the ejecta on the Palomar Schmidt plates makes more accurate determinations impossible. Motions of the order of 31 yr/313 yr × 7″ = 0″.7 are expected in 31 yr, and significantly larger motions (≳2″) are observationally excluded.

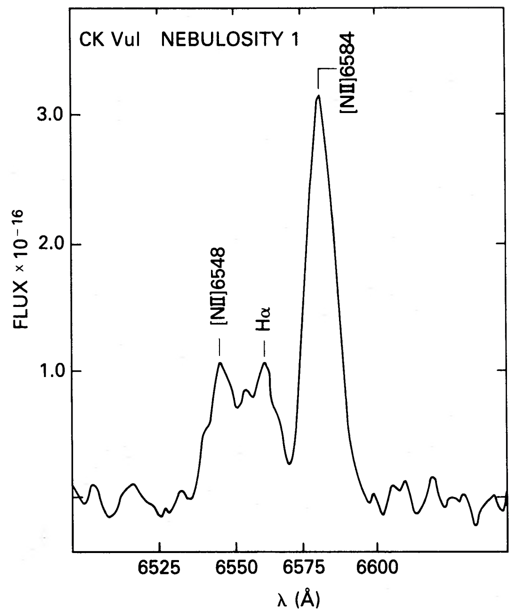

FIG. 12.—Expanded portion of Fig. 9 in the Hα region

IV. THE DISTANCE AND PRESENT LUMINOSITY OF CK VUL

An important constraint on the distance to CK Vul follows from the reddening estimated above from the nebular Balmer

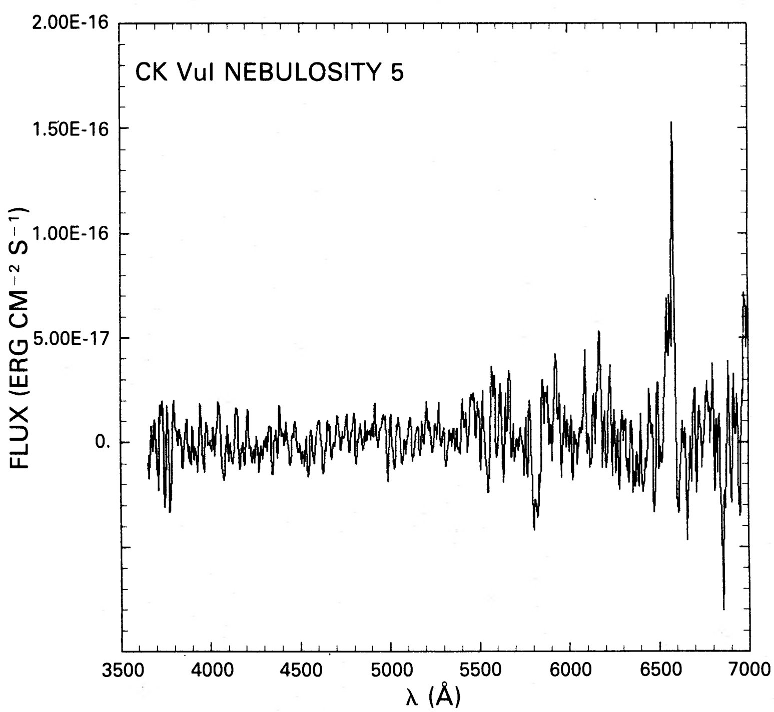

FIG. 13.—Kitt Peak 2.1 m and IIDS spectrum of the ejected Hα-bright knot (labeled 5 in Fig. 7*a*) at the end of a faint jet

TABLE 2

EMISSION LINE FLUXES FROM NEBULOSITY 1

Rest Wavelength (Å)	Identification	Observed Flux (10^{-15} ergs cm^{-2} s^{-1})
4340	Hγ	0.23 ± 0.1
4861	Hβ	0.35 ± 0.1
4959	[O III]	0.27 ± 0.1
5007	[O III]	0.87 ± 0.1
6548	[N II]	2.5 ± 0.1
6563	Hα	3.2 ± 0.1
6584	[N II]	8.7 ± 0.1
6716	[S II]	1.5 ± 0.1
6730	[S II]	0.87 ± 0.1

series. At galactic coordinates $(l, b) = (63°38, +0°99)$, CK Vul lies in a corner of region 271 of the galactic-plane-extinction map of Neckel and Klare (1980), near the boundaries with regions 269 and 267. All three of these regions show the existence of a heavy extinction layer roughly 550 ± 150 pc from the Sun in this direction. Beyond this layer there is negligible further extinction out to at least 3.5 kpc. The mean reddening through this extinction layer amounts to $E_{B-V} = 1.10$, 0.97, and 0.46 for regions 271, 269, and 267 respectively. In the mean, $E_{B-V} = 0.84 \pm 0.34$ (s.d.); these do not differ significantly from the weighted mean reddening $\bar{E}_{B-V} = 0.82 \pm 0.23$ (s.e.) derived from the nebular spectrum of CK Vul, indicating that it lies near the far side or beyond this extinction layer.

A direct estimate of the optical thickness of the extinction layer in the direction of CK Vul may be made from the measured color and magnitude of the A0 star (Humason 1938) 30″ north of CK Vul. Using Space Telescope photoelectric standards on the Palomar Sky Survey plates containing CK Vul (B. Lasker and P. Garnavitch, private communication), we find $m_B = 15.4 \pm 0.4$. A spectrum of this star obtained at the MMT just after those of Figures 10–12 yields $B-V = 0.7 \pm 0.1$. Assuming an absolute magnitude of $M_V = +0.7$ and color $(B-V)_0 = 0.0$ for an A0 star (Allen 1973), we derive, with $R \equiv A_V/E_{B-V} = 3.10$ (Savage and Mathis 1979), $E_{B-V} = 0.7 \pm 0.1$, $(m-M)_0 = m_B - M_B - A_B = m_B - M_V - (B-V)_0 - (R+1)E_{B-V} = 11.8 \pm 0.6$ for this star, corresponding to a distance of 2.3 ± 0.6 kpc. This places the A0 star well beyond the extinction layer. In the remaining discussion, we shall therefore adopt $A_V = 2.2 \pm 0.3$ (a mean of this determination and the derived extinction for the nebula) for CK Vul.

For reasons which will become clearer in the following section, we refrain here from predicating our distance estimate to CK Vul on its properties as a nova. Rather, we derive an approximate upper bound to its distance by the following heuristic argument: An astrophysical object of mass m can sustain a super-Eddington luminosity only over intervals less than or of the order of its free-fall (dynamical) time scale, $\tau_{ff} = |\ddot{r}/r|^{-1/2} = (r^3/Gm)^{1/2}$, (where G is the universal gravitational constant). For an object close to the Chandrasekhar mass radiating at the solar temperature, this time scale is of order 100 days, i.e., of the same order as the duration of individual peaks in the light curve of CK Vul (see Fig. 2). However, the fact that CK Vul maintained roughly the same *mean* brightness level for more than a year then argues that the mean magnitude over that interval could not much have exceeded the Eddington limit. For a Chandrasekhar-mass object, this limit corresponds to $M_{bol} = -7.2$, whereas the observed *mean* magnitude of CK Vul for 1670–1671 is $\bar{m}_V \approx +4.1$. Neglecting any bolometric correction (which can only reduce the deduced true distance modulus), we infer that the distance to CK Vul is $\lesssim 630$ pc.

A somewhat weaker upper limit follows from comparing the inferred nebular expansion rate, $\sim 0''.02$ yr^{-1}, with the upper limit of < 120 km s^{-1} for radial velocity differences among different nebulosities. This gives a distance < 1100 pc, the precise value depending on the (unknown) line-of-sight distribution of these nebulosities with respect to the central star.

It is clear that CK Vul must lie barely, if at all, beyond the intervening extinction layer. All the above constraints are consistent with it having essentially the same distance as that layer, 550 ± 150 pc, which we therefore adopt for CK Vul. The corresponding apparent visual distance modulus is $m_V - M_V = 10.9 \pm 0.7$.

There are in fact some intriguing reasons for placing CK Vul actually within the far side of this obscuring gas and dust layer. The presence of an ambient density gradient could account for the asymmetry in emission measure of the ejecta with respect to the central star. Such an effect is seen, for example, in the ejecta of Nova GK Per (Oort 1951; Williams 1981). The gas/dust complex adjacent to that nova also produced a well-observed light echo during its 1901 outburst (see Couderc 1939 and references therein). A similar effect in CK Vul could have produced an image in outburst more extended than a normal-seeing disk. This would suppress atmospheric twinkling and might explain Hevelius' peculiar comment, noted above, that CK Vul appeared "dull" or "blurred" in comparison with bright nearby stars.

Given the above estimate of the distance to CK Vul, we can estimate its present luminosity. The observed continuum R magnitude of the central star on 1983 August 13/14 was $m_R = 20.7 \pm 0.5$. Adopting an extinction ratio $A_B/A_V = 0.75$ (Savage and Mathis 1979), we obtain

$$M_R(\text{CK Vul}) = 10.4 \pm 0.8 ,$$

or $L_{\text{CK Vul}} \approx 10^{-2}\ L_\odot$, assuming a bolometric correction of 0.

Aperture photometry of the Hα and R CCD images of field stars and CK Vul itself (§ II) have been compared to yield the magnitude difference $m(\text{H}\alpha) - m(R) = -0.49 \pm 0.04$ mag for CK Vul. This implies an equivalent width EW(Hα) ≈ -60 Å (the exact value depends on the FWHM of the Hα emission line). Then a rough value of $M_V \approx 10$–11 for the disk of CK Vul (if Hα and Hβ equivalent widths are comparable) follows from the EW $- M_V$ relation of Patterson (1984) (Fig. 6).

As we shall see in the following section, the very low luminosity deduced above is an important constraint on the nature of CK Vul itself.

V. DISCUSSION

The very low luminosity is comparable to those of the intrinsically faintest cataclysmic variables known in their quiescent states (see, e.g., Patterson 1984), and is certainly far fainter than the visual luminosities generally regarded as typical of old novae, $M_V \approx +4.5$ (Warner 1976; Patterson 1984). The observed continuum luminosity at R estimated above could be entirely accounted for by a normal M3–M5.5 main-sequence dwarf (cf. Lacy 1977), with no additional contribution from the white dwarf companion or an accretion disk. On the other hand, it could as easily be entirely accounted for by an accretion disk with a mass-accretion rate of only $10^{-12.0 \pm 0.5}$ $M_\odot$ yr^{-1}. These are then upper limits to the allowed range of cool components and mass-accretion rates. They demand, in effect, that CK Vul have a very short orbital period, $P \lesssim 3^h.6$, if the cool star is to be nearly lobe-filling, and also that *mass transfer has, for all practical purposes, stopped entirely*.

This is a rare but not unprecedented event among cataclysmic variables. For example, MV Lyr (orbital period $3^h.2$) has been observed to turn off and on (Schneider, Young, and Shectman 1981; Robinson *et al.* 1981). A very low luminosity obtains for the low-mass-transfer state of MV Lyr: $M_V = +10.2$, powered by an M5 V secondary with $M \approx 0.17\ M_\odot$ (Schneider, Young, and Shectman 1981). CK Vul could then be a similar, possibly even fainter object. *But as an old nova, CK Vul would be by far intrinsically the faintest example known of its class.*

A second troubling feature of CK Vul is the apparent compactness of its ejected shell. At our deduced distance of 550 ± 150 pc, a shell of $\sim 7''$ radius implies a mean expansion velocity over the 313 yr since outburst of only $v_{\rm exp} \approx 59 \pm 6$ km s^{-1}. This is far below the expansion velocity of any other nova shell (see, e.g., McLaughlin 1960; Cohen and Rosenthal 1983). Even the slowest novae (e.g., HR Del, RR Pic) typically show expansion velocities of 400–500 km s^{-1}

Although we have speculated above that CK Vul lies near or within an obscuring cloud, it seems very unlikely that the ejecta could have swept up enough material to account for the low apparent expansion velocity. If we take the density limit inferred for knot 1 as typical of the entire shell, the deduced nebular mass is $\lesssim 2 \times 10^{-4}\ M_\odot$. This is typical of nova ejecta masses (see, e.g., Gallagher and Starrfield 1978). But in order to produce a sevenfold reduction in the mean expansion velocity, the ejected shell would need to have swept up ~ 24 times its initial mass, and we should therefore expect a much larger nebular mass at present. Furthermore, it is difficult to see how the geometrical symmetry of the shell could have been preserved in this case.

An alternative is that the observed nebular emission does not reflect the true dimensions of the expanding shell. If, for example, the shell density were to increase outward, the outer part of the shell could have recombined and disappeared long ago, leaving only the inner shell, with its frozen ionization, visible in emission. Alternatively, the visible emission could arise from a reverse shock propagating upstream in the outflowing ejecta, as seen in GK Per (J. S. Gallagher, private communication).

In the light of these anomalies—the extreme faintness of the central star and the compactness of the observed shell—is it possible that CK Vul was not a nova at all, but a fundamentally different type of object? A casual perusal of Kaler's (1976) "Catalog of Relative Emission Line Intensities Observed in Planetary and Diffuse Nebulae" reveals examples among both planetary nebulae and Herbig-Haro objects which resemble, at least superficially, the nebular spectrum of CK Vul.

The interpretation of CK Vul as a very young planetary nebula is not without its attractions. The nebular spectrum is virtually identical with that obtained by Kwitter, Jacoby, and Lawrie (1983) for YM 29 = Abell 21 (which is, however, a far more extended object), and the observed nitrogen enhancement is not unusual for such objects. The deduced expansion velocity is only marginally greater than those observed for normal planetaries ($v_{\rm exp} \lesssim 50$ km s^{-1}: Robinson, Reay, and Atherton 1982; Sabbadin and Hamzaoglu 1982), but this is not necessarily surprising in view of the much younger age (i.e., time since outburst) of CK Vul compared to planetaries. Furthermore, it is widely believed that planetary nebulae are descended from Mira-like variables (e.g., Wood and Cahn 1977). The ~ 320 day oscillation of CK Vul is typical of the periods of these variables (and, to some extent, of the forms of their light curves); it would be necessary to speculate further that the final few oscillations of the proto-planetary Mira variable carried it to increased effective temperature as its envelope dissipated, thereby producing the brighter maxima responsible for its appearance in the first place. However, the apparent nebular mass is at least two orders of magnitude smaller than is typical of planetary nebulae (compare, e.g., Seaton 1968; Cahn and Kaler 1971). Furthermore, even assuming a value as small as $10^{-2}\ R_\odot$ for the radius of the central star, the bolometric correction at R can never be made large enough to avoid the conclusion that the central star is extraordinarily faint: $M_R = +10.4 \pm 0.8$ implies that $\log L/L_\odot = -2.2 \pm 0.8$ at this radius. This is more than two orders of magnitude fainter than any known planetary nebula nucleus, despite the fact that CK Vul is a much younger object. Estimates of white-dwarf cooling time scales (Lamb and Van Horn 1975; Iben and Tutukov 1984) indicate that $\gtrsim 10^7$ yr are required to reach such low luminosities. We therefore conclude that the outburst of CK Vul was not a planetary nebular ejection event.

There are other, equally intriguing parallels between CK Vul and the Herbig-Haro (HH) objects (see, for example, the review by Schwartz 1983). The nebula of CK Vul is of higher excitation than is typical of HH objects, but examples can be found among the latter (e.g., HH 1: Böhm 1956; Böhm, Perry, and Schwartz 1973) which show similarly strong [N II] + Hα and [S II] emission line systems. HH objects are associated with gas/dust complexes, as we have done for CK Vul, although in the latter case the obscuring cloud appears nowhere near as compact, dense, and opaque as for typical HH objects. The apparent expansion velocity of the shell of CK Vul is not atypical of the measured apparent velocities of HH objects (Cantó 1980), which are associated as well with jetlike outflows from an obscured star (e.g., Snell, Loren, and Plambeck 1980), recalling the jet in CK Vul. Could the outburst of CK Vul then have corresponded to the birth of an HH-like object? We think not, for several reasons: First, there is no evidence of star formation occurring in its vicinity, as is typical of HH objects. Second, HH objects appear to be powered by a continuing strong energy source (Schwartz and Dopita 1980), which we would expect to be detectable now as a strong infrared source; at this writing, none has been detected (Gezari, Schmitz, and Mead 1984*a*, *b*). Finally, the nitrogen overabundance in CK Vul clearly points to an evolved object, in contrast with the primordial compositions which appear to characterize HH objects (e.g., Böhm and Brugel 1979).

We conclude that CK Vul was indeed a slow classical nova, despite its peculiarities. The nebular mass and anomalous composition strongly support this conclusion. Its spectrum, although of still lower excitation, resembles that of the nebular shell of the recurrent nova T Pyx (Williams 1982). Among classical nova shells, that of RR Pic (Williams and Gallagher 1979) is its closest parallel, but RR Pic shows significantly higher excitation.

The morphology of the ejected shell of CK Vul is similar in form to the "equatorial rings"[12] and "polar caps" deduced

[12] A spherical shell in projection produces a circular ring; the elliptical shape of the bulk of the emission nebulosity in Fig. 8*a* is much more suggestive of an ejected ring seen in projection.

spectroscopically by Hutchings (1972), Malakpur (1973), Weaver (1974), and Solf (1983) for several other novae. The physical causes of this type of morphology remain obscure, however. Localized nuclear burning (Shara 1982), red dwarf–nova wind interactions (MacDonald 1980), accretion disk–nova wind interactions (Sparks and Starrfield 1973), and magnetic localization (Mitrofanov 1980; Livio, 1983) have all been discussed in this regard, but detailed calculations and simulations are lacking for each of these mechanisms. Progress in obtaining a detailed understanding of the nova ejection process is more likely to come from further high-resolution deep imaging of nova shells.

Excluding symbiotic-like objects such as RR Tel and AG Peg, which contain giant components (cf. Kenyon and Truran 1983), CK Vul was the slowest nova ever observed. From our apparent visual distance modulus, it reached an absolute magnitude $M_V = -8.3 \pm 0.7$ at maximum, a magnitude or more brighter than one would expect from its very slow rate of decline, which would indicate $M_V \approx -6.5 \pm 0.5$ (Duerbeck 1981; Shara 1981; Cohen and Rosenthal 1983). The difference may be due in some measure to the large oscillations CK Vul displayed at maximum. The mean visual magnitude over the interval between the maxima of 1670 and 1671, $m_V \approx 4.1$, corresponds to $M_V = -6.8 \pm 0.9$, in good agreement with expectations.

If CK Vul is at all typical or representative of classical novae in the millennia between eruptions, then such objects are obviously very difficult to find; we may be overlooking the vast majority of old novae, and nova space densities and lifetimes (Patterson 1984) may be grossly underestimated. We defer a detailed discussion of the observations of other old novae, and implications for cataclysmics' evolution, to a subsequent paper.

VI. CONCLUSIONS

Our conclusions can be summarized as follows:

1) The light curve of Nova CK Vul (1670), gleaned from old European records, shows it to be a very slow nova, with large oscillations at maximum.

2) A narrow-band Hα + [N II] CCD image of the field of CK Vul shows a ring with several bright subcondensations and a central star. The ring may reflect equatorial plane ejection.

3) The net Hα image also reveals an ejected jet leading to an Hα bright knot. This may be interpreted as "polar ejection," i.e., ejection perpendicular to the system's equatorial plane.

4) Spectra of three "ring" knots and the "polar" knot are similar to each other and to spectra of the ejecta of the recurrent nova T Pyx. A threefold nitrogen enhancement is deduced. The nebular recombination time scale equals or exceeds the age of the shell, obviating the need for a continuing excitation source.

5) A reddening along the line of sight to the nova, corresponding to $A_V = 2.2 \pm 0.3$, is derived from the nebular spectrum and photometry of a field star.

6) A distance to the nova of $D = 550 \pm 150$ pc is derived, placing the nova near, or just within, the far side of an intervening obscuring cloud.

7) The low deduced luminosity of the central star, $M_R = 10.4 \pm 0.6$, is ~ 6 mag fainter than canonical old novae, and limits the spectral type of the secondary star to M3 V or later (if it is a normal main-sequence star), the orbital period to $P \lesssim 3^{h}.6$, and the present mass-transfer must practically have stopped in the system, as in the case of MV Lyr in its low state.

8) Alternative interpretations of the nature of CK Vul result in serious inconsistencies with observational constraints; CK Vul appears to have been a genuine classical nova. If it is typical of novae between eruptions, then present estimates of the space density and lifetimes of cataclysmics may be in serious error.

Observing time on the Multiple Mirror Telescope, CTIO 4 m telescope, KPNO 2.1 m telescope, and University of Hawaii 2.2 m telescope are gratefully acknowledged by M. M. S. and A. F. J. M. Astrometric measurements were carried out with the KPNO 2 axis Grant measuring engine. R. F. W. wishes to thank Dr. William B. Ashworth for supplying copies of the relevant pages from Hevelius' *Machina Coelestis* and *Annus Climactericus*, Dr. Karen B. Kwitter for valuable assistance in the nebular abundance analysis, and Drs. Jay Gallagher, Owen Gingerich, James Kaler, and James Truran for useful discussions. M. M. S. is grateful to Joseph Patterson for critical scrutiny of the paper's conclusions. M. Potter's careful image alignment was essential in bringing out faint features in the images of CK Vul. We also thank J. Barnes for instructions in reducing IIDS spectra, and R. Lamontagne for help in reducing MMT spectra. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada, and by National Science Foundation grants AST 79-21073 to Arizona State University and AST 80-18859 and AST 83-17916 to the University of Illinois.

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