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A SINGLE-STAR INTERPRETATION OF NOVA CYGNI 1975

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ABSTRACT

Observational evidence has revealed that Nova Cygni 1975 is not a typical nova event. We suggest that Nova Cygni is to be understood, not in terms of a canonical close binary system, but essentially as a single star undergoing a thin-shell thermonuclear explosion.
Subject headings: stars: binaries — stars: novae — stars: supernovae — stars: white dwarfs

I. THE OBSERVATIONAL EVIDENCE

On 1975 August 29, Nova Cygni reached an apparent magnitude of $\sim$1.8, establishing it as the brightest nova since CP Pup 1942. It quickly became clear that no object could be found at its location on either the red or blue Palomar Sky Survey prints down to the plate limit of $\sim +20$ to $+21$ (Gallagher and Ney 1976; hereafter GN). Nova Cygni thus exhibited the largest range yet observed for any bright nova, the previous record (17 mag) having been set by CP Pup. The light curve of Nova Cygni has a rounded maximum and a remarkably rapid early decline from maximum of 0.7 mag per day (GN; Lockwood and Millis 1976; Neff, Ketelson, and Smith 1976), similar to that of CP Pup (Payne-Gaposchkin 1957). In fact, the shape of its light curve was more like that of a Type I supernova than of an ordinary very fast nova which generally has a spike at maximum (Payne-Gaposchkin 1957).

Its infrared behavior was also remarkable. On 1975 August 30 it exhibited a blackbody spectrum with $T \sim 5 \times 10^3$ K. Twenty-four hours later its energy distribution was characteristic of free-free emission and resembled RR Tel. Since then (1975 September 1) its infrared luminosity has declined steadily following the decline in visual light (GN). So far it has not developed the strong infrared blackbody emission observed in Nova Serpentis (1970) by Geisel, Kleinmann, and Low (1970) and by Hyland and Neugebauer (1970).

Spectroscopically, Nova Cygni has evolved as follows: When first observed, it had a broad weak absorption line spectrum, with perhaps a trace of broad H emission. At some time on 1975 August 30, it developed P Cygni profiles in hydrogen and helium lines, and during the next 2 days its spectrum evolved to one showing predominantly emission lines. However, while results of the Steward Observatory monitoring program indicate that Hα had become very strong, with a great deal of structure (Weymann 1975; see also Leparskas 1976); observations made with the *Copernicus* satellite did not detect Lα (Jenkins *et al.* 1976). This could be attributed to interstellar absorption or possible Lα trapping in the surrounding nebula. Furthermore, Nova Cygni has so far failed to develop any of the broad, blueshifted absorption features (the diffuse-enhanced and Orion systems) which are characteristic of all previously observed novae. Judging from the optical light curve, Nova Cygni is well past the point at which such features would normally appear.

II. ENERGETICS OF THE OUTBURST

Nova Cygni lies directly in the galactic plane in Cygnus ($l^{II} \approx 90°$; $b^{II} \approx -0\overset{\circ}{.}1$) in a region of generally high extinction and is reddened by $\lesssim$0.3 mag (GN). On the basis of normal interstellar reddening this would imply a distance of about 1 kpc, a value which is consistent with the infrared blackbody parallax determination (GN). The low reddening value is also supported by the *Copernicus* observations in the near-ultraviolet (Jenkins *et al.* 1976).

If we accept an extinction of $\sim$1 mag and a distance of 1.5 kpc, then Nova Cygni reached an absolute visual magnitude of -9.5 mag, which is bright for a nova but certainly not unique; for example, CP Pup 1942 may have reached -10.5 mag (Payne-Gaposchkin 1957). The rounded maximum and exponential decay are similar to a Type I supernova light curve. However, the time scale associated with the light curve is much faster (by a factor $\lesssim 5$) than that associated with a Type I supernova. This implies that much less material was ejected by Nova Cygni than is thought to be ejected in a supernova outburst (Lasher 1976). In fact, the infrared observations suggest that $10^{-4}\ M_{\odot}$ of material was ejected (GN), which is quite compatible with nova behavior. The range of observed velocities ($\sim$1300–2500 km s^{-1}) is also typical of a fast nova. We therefore conclude that Nova Cygni is a rather unusual classical nova. In this regard, we note that the prenova absolute visual magnitude of Nova Cygni has to be fainter than $M_v \approx +10.5$ on the basis of the above distance estimate. This is typical of a white dwarf but is at least 5 mag fainter than a normal nova at minimum (Warner 1976). The unusually large amplitude of the outburst in Nova Cygni is thus due to the low initial luminosity, not to an anomalously bright maximum.

III. THEORY OF THE NOVA OUTBURST

In our view an explanation of the unusual behavior of Nova Cygni is to be found in a modification of current theories of the nova phenomenon. A long-held belief, dating from Struve (1955), is that all novae occur in close binary systems in which mass transfer from the companion star results in a hydrogen-rich envelope on the white dwarf component sufficient to trigger a thermonuclear runaway. The hydrodynamic evolution of such runaways has been described in a recent series of papers (Starrfield, Sparks, and Truran 1976 [hereafter SST] and references therein). It has been demonstrated that a thermonuclear explosion which results in ejection of material and production of a nova-like light curve can occur only under certain restrictive conditions. In particular, it was found that thermonuclear runaways in matter of solar composition could not give rise to mass ejection; this is a consequence of restrictions imposed upon the CNO reactions when they proceed on a hydrodynamic time scale. It was found, however, that an enhancement of the abundances of the CNO nuclei by a factor $\sim$5 relative to solar system matter was sufficient to allow mass ejection and hence to produce a nova-like outburst on the white dwarf. CNO abundance enhancements are thus a prerequisite for ejection in these models; an increasing body of observational evidence now exists that shows such overabundances to be characteristic of nova ejecta (Sparks, Starrfield, and Truran 1976). A further prerequisite is that the initial luminosity of the white dwarf be low—typically $\sim 10^{-3}$–$10^{-2}\ L_{\odot}$. The corresponding initial temperature is low enough both to permit the accumulation, in a cooling time, of the $\sim 10^{-4}$ to $10^{-3}\ M_{\odot}$ of hydrogen-rich matter necessary to produce an outburst and also to ensure a degenerate configuration at the base of the envelope capable of producing a flash. The models indicate that, after the runaway, the white dwarf can become a relatively stable, shell-burning star with a large radius ($r \gtrsim 10^{11}$ cm) and a high temperature ($T_e \gtrsim 30{,}000$ K). The prediction of such a constant luminosity phase can be reconciled with the observed rapid decline in visible brightness. The energy will be emitted at progressively shorter wavelengths as direct radiation from the remnant begins to dominate over the energy reradiated by the shell. The existence of a constant luminosity phase has been documented in the case of Nova Serpentis by Gallagher and Code (1974) using direct ultraviolet measures from OAO-A2. Its existence for other novae can be inferred from the appearance of high-ionization emission lines and a hardening of the continuum spectrum in the nebular stage of nova evolution (cf. Gallagher and Starrfield 1976 and references therein).

IV. THE IMPLICATIONS FOR NOVA CYGNI

The predictions of the SST models concerning the appearance of the nova following thermonuclear runaway have important implications for Nova Cygni. First, the luminosity increase ranges from $\sim$15 to 18 mag for models with low CNO enhancements up to $\sim$24 mag for models with the most extreme enhancements (Starrfield, Truran, and Sparks 1975). This range is significantly larger than the 12–14 mag typical of novae, but is consistent with the 20 mag rise of Nova Cygni. Furthermore, the theoretical light curves (particularly those of the most extreme models of Starrfield, Truran, and Sparks 1975) exhibit a rounded maximum and rapid decline very similar to that exhibited by Nova Cygni but unlike a normal fast nova. We note, however, that most novae are thought to be binaries whereas the calculations refer to essentially single stars. The brightness of Nova Cygni at minimum is consistent with a single white dwarf of intrinsic luminosity $\lesssim 10^{-3}$ to $10^{-2}\ L_{\odot}$, and its light curve is similar to that predicted from single-star models. We therefore suggest that Nova Cygni is to be interpreted as a nova-like event occurring on an essentially isolated white dwarf. Furthermore, we claim that the apparent disagreement between the model predictions and the behavior of normal novae may plausibly be explained as due to the influence of a close companion. If this interpretation is accepted, it further strengthens the case for a single-star model of Nova Cygni.

The major differences between Nova Cygni and other novae are (i) the lower luminosity of the prenova, (ii) the rounded peak to the light curve, and (iii) the absence of shallow, high-velocity absorption lines during the early decline and transition phases (i.e., the diffuse-enhanced and Orion absorption spectra). The higher preexplosion luminosities of normal novae may be ascribed to energy radiated in accretion disks during the process of mass transfer in a close binary system. The "spike" in the light curve could well result from the interaction of the ejected material both with the companion star and with material in the process of mass transfer. The origin of the diffuse-enhanced and

Orion systems is still unclear, but it is plausible that it might arise in interaction between the expanded envelope of the white dwarf and the companion. If indeed Nova Cygni is an essentially single star, no such secondary ejections of material would be expected. While this discussion is speculative, it does appear to offer a reasonable explanation that the difference in behavior between a normal nova and Nova Cygni is the difference between binary and essentially single stars.

The appearance of high-ionization lines such as [Ne v] in Nova Cygni, together with the shift in spectral energy distribution to the blue, suggests that Nova Cygni has developed a hot expanded envelope and shell-burning source as predicted by the models. On the single-star hypothesis there would, however, be no interaction with a second star to complicate the comparison with model calculations. We note that the relatively long drop in visual luminosity before the onset of the "ultraviolet phase" suggests that a rather efficient mass ejection event took place, leaving a somewhat smaller than usual shell-burning remnant.

Perhaps the most serious problem with the isolated white dwarf interpretation is that in the absence of mass transfer from a binary companion, some other source for the hydrogen envelope must be found. One alternative which has been reexplored recently is whether interstellar material can be accreted in sufficient amounts during a white dwarf cooling time to trigger a nova event. Truran *et al.* (1976) have found that there is a reasonable probability (1:10^2) that the time scale for accretion of an envelope of $\sim 10^{-4}\ M_\odot$ from interstellar clouds, sufficient to trigger a runaway on a solar mass white dwarf of luminosity $\sim 10^{-3}\ L_\odot$, can be as short as a few billion years for an individual white dwarf. This is comparable with the time required for a 1 $M_\odot$ pure carbon white dwarf to cool down to a luminosity of $\sim 10^{-3}\ L_\odot$ (Lamb and Van Horn 1975) and develop a carbon convection zone near the surface. It has recently been demonstrated (Colvin *et al.* 1976) that hydrogen accreted onto the surface can be mixed throughout the entire convective region, a process which may represent the mechanism of CNO enhancement required to cause a thermonuclear runaway to develop into a full-fledged nova outburst. It appears, therefore, that all the conditions necessary for a nova eruption can, with reasonable probability, be realized on an isolated white dwarf and that the association of nova-like events with close binary systems may not be unique.

Our arguments do not, of course, exclude the possibility that Nova Cygni is indeed a binary; in fact, the observations of quasi-periodic, short-time-scale variability may argue for duplicity. However, periodic behavior has been seen during the decline of previous novae (for example, V603 Aql and GK Per), yet the observed periods were not those of the underlying system. Some of us have recently suggested that they are caused by oscillations of the remnant object (Sparks, Starrfield, and Truran 1976). The pre-nova limits to the brightness impose the constraint that any companion must be faint ($M_v > 10$ mag) and be transferring matter at a low rate ($\lesssim 10^{-12}\ M_\odot\ \mathrm{yr}^{-1}$). For example, the possibility that Nova Cygni consists of a white dwarf with a very low-mass ($\lesssim 0.3\ M_\odot$) main-sequence companion remains. We nonetheless believe that the single-star hypothesis offers the most attractive explanation of Nova Cygni 1975.

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