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OPTICAL IDENTIFICATION OF THE X-RAY SOURCE GS 2023+338 AS V404 CYGNI[1]

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ABSTRACT

On 1989 May 22 the Japanese *Ginga* Team reported the discovery of a bright new X-ray transient and cataloged the source as GS 2023+338. We have identified this X-ray source with V404 Cygni, an optical nova whose last reported major outburst was in 1938. Photometry with the fine error sensor on the *IUE* satellite on 1989 May 27.3 gave $V \sim 12.6$, ~ 6 mag brighter than the quiescent magnitude. Optical spectroscopy on 1989 May 27.4 revealed a strong and rich emission-line spectrum superposed on a reddened continuum. The outburst spectrum shows strong Balmer, He I, He II λ4686, and N III $\lambda\lambda$4634–42 emission lines as well as numerous interstellar absorption lines. The near-ultraviolet O III Bowen fluorescence lines at 3429–3444 Å and possibly the complex between 3750–3790 Å are present in these early spectra. These emission features are characteristics of the optical counterparts of various X-ray sources including X-ray bursters and two other X-ray novae: A0620−00 (V616 Mon) and Cen X-4. Photometrically, the source exhibits fluctuations of a magnitude or more on time scales of days, minutes, and possibly seconds. The optical light curve exhibits a remarkable similarity to the X-ray light curve suggesting that X-ray heating of an accretion disk plays a role in producing the optical emission. The X-ray behavior and the presence of strong optical emission lines in V404 Cygni is in contrast to that of other X-ray transients and two other well-studied X-ray novae, V616 Mon and Cen X-4. A considerably higher outburst luminosity in V404 Cygni as compared with these other X-ray novae may account for this difference.

Subject headings: stars: individual (V404 Cyg) — stars: novae — X-rays: sources

1. INTRODUCTION

On 1989 May 22 the Japanese *Ginga* Team reported the discovery of a new bright transient X-ray source in the direction of Cygnus and cataloged it as GS 2023+338 (Makino et al. 1989; Kitamoto et al. 1989). At the time of the discovery on May 21, the source intensity in the energy ranges 1–6 keV and 6–20 keV were 0.1 and 1 Crab, respectively, typical of most hard transient X-ray sources. However, 1 day later, on May 22, the intensities in the 1–6 and 6–20 keV ranges became 4 and 3.5 Crab, respectively, indicating that while the total X-ray luminosity was increasing, the source spectrum was becoming softer. After May 23, the source luminosity decreased rapidly becoming less than 80 mCrab in the energy range 1–6 keV by May 26. On May 30, the hardness ratio and intensity varied widely on time scales of seconds to minutes. The intensity varied by a factor of 500 reaching a peak intensity of 21 Crab (Kitamoto et al. 1989; Kitamoto 1990). These and subsequent X-ray observations have shown that the X-ray behavior of GS 2023+338 cannot be easily classified in terms of any previously known X-ray transient or nova.

We have identified the optical counterpart of GS 2023+338 with V404 Cyg, a 12.5 mag optical nova whose last major outburst was in 1938. An announcement of this identification was given jointly by Marsden (1989) and Wagner, Starrfield, & Cassatella (1989b). An independent identification was made by Hurst & Mobberley (1989). Following the identification, V404 Cyg was detected and observed from γ-ray to radio wavelengths. Many of these observations have shown that the 1989 outburst of V404 Cyg is the most unique of the well-studied X-ray novae.

In this contribution, we provide details concerning the identification, spectroscopy, and photometry of V404 Cyg obtained during the initial phases of the outburst. Preliminary aspects of some of this work were presented earlier (Wagner et al. 1989b; Wagner & Starrfield 1989; Wagner et al. 1989a, 1990). In a forthcoming paper (Wagner et al. 1991) we will describe in detail optical photometric and spectroscopic observations obtained from 1989 May through 1990 October and their analyses during the outburst and decline of V404 Cyg.

2. OBSERVATIONS AND RESULTS

2.1. *Identification*

After the announcement by Makino et al. (1989) of the new transient X-ray source GS 2023+338, there was an immediate attempt by some of us to identify the optical counterpart. Unfortunately, as was discovered later, the position of the object actually lay outside the initial X-ray error box. However, B. Marsden, of the Center for Astronomical Telegrams in Cambridge, Massachusetts, noticed that there was a previously known nova listed in Duerbeck (1987) and catalogued as V404 Cyg that lay $\sim 5'$ outside the western-most

[1] Observations reported here were obtained with the Perkins 1.8 m Reflector, a joint facility of Ohio Wesleyan University, Ohio State University, and the Lowell Observatory. Observations reported here also were obtained at the Multiple Mirror Telescope Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.

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boundary of the X-ray error box. Its last recorded major outburst was in 1938 when it rose to about 12th magnitude.

On 1989 May 26.4, visual inspection in morning twilight on the TV acquisition system at the Perkins 1.8 m telescope of the Ohio Wesleyan and Ohio State Universities at the Lowell Observatory revealed the object on Duerbeck's finding chart at magnitude 12–13. On May 27.3 photometric observations with the FES on the *IUE* satellite at VILSPA gave $V \sim 12.6$, ~ 6 mag brighter than the quiescent magnitude, thus confirming that V404 Cyg was indeed in an outburst. Initial *IUE* spectra were blank, presumably because of interstellar absorption.

On May 27.4, optical spectra of V404 Cyg (Fig. 1) obtained with the Perkins Telescope and Ohio State University CCD spectrograph revealed a rich emission-line spectrum, including lines of H, He I, He II, and N III, superposed on a reddened continuum. All of these emission lines are characteristics of the optical counterparts of various X-ray sources (McClintock, Canizares, & Tarter 1975) including X-ray bursters (Canizares, McClintock, & Grindlay 1979) and two other X-ray novae: A0620−00 (V616 Mon) and Cen X-4 (Oke 1977; Whelan et al. 1977; Canizares, McClintock, & Grindlay 1980); and thus they identify V404 Cyg as the optical counterpart of GS 2023+338 (Wagner et al. 1989b). The identification was ensured beyond doubt when radio emission was detected by Hjellming, Han, & Córdova (1989) coincident with the optical position of V404 Cyg. Analysis of the X-ray data obtained on May 23 when the source was an order of magnitude brighter in X-rays indicated that the X-ray error box does include V404 Cyg (Kitamoto et al. 1989).

2.2. *Astrometry*

In order to obtain an accurate position of V404 Cyg, an astrometric grid has been established from stars measured on the POSS and from a CCD frame obtained on 1989 November 2 with respect to a grid of 24 AGK3 stars. We have measured the position of V404 Cyg from this CCD frame as well as from the POSS, and our results are summarized in Table 1. Our astrometry is uncertain by no more than 0″.2 in both coordinates. For comparison, we have also included in Table 1 the optical outburst position reported by Okamura & Tanaka (1989), the radio outburst position reported by Hjellming, Han, & Córdova (1989), and the POSS position of Duerbeck (1987).

Our outburst and POSS positions agree well with the optical outburst position reported by Okamura & Tanaka and the radio position of V404 Cyg reported by Hjellming, Han, & Córdova. The Duerbeck position measured from the POSS is, however, 0ˢ.12 west and 1″.6 north of our measured POSS position. In spite of this discrepancy, we are confident that the object on the POSS is identical with the outburst object identified with V404 Cyg.

TABLE 1

ASTROMETRY OF V404 CYGNI

Source	Reference	α(1950)	δ(1950)
1989 outburst	1	20ʰ22ᵐ6ˢ.37	+33°42′16″.5
1989 outburst	2	20 22 6.30	+33 42 16.7
POSS	1	20 22 6.38	+33 42 16.7
POSS	3	20 22 6.26	+33 42 18.3
Radio	4	20 22 6.30	+33 42 16.3
Pre-outburst	5	20 22 6.36	+33 42 16.8

REFERENCES.—(1) This work; (2) Okamura & Tanaka 1989; (3) Duerbeck 1987; (4) Hjellming et al. 1989; (5) Szkody & Margon 1989.

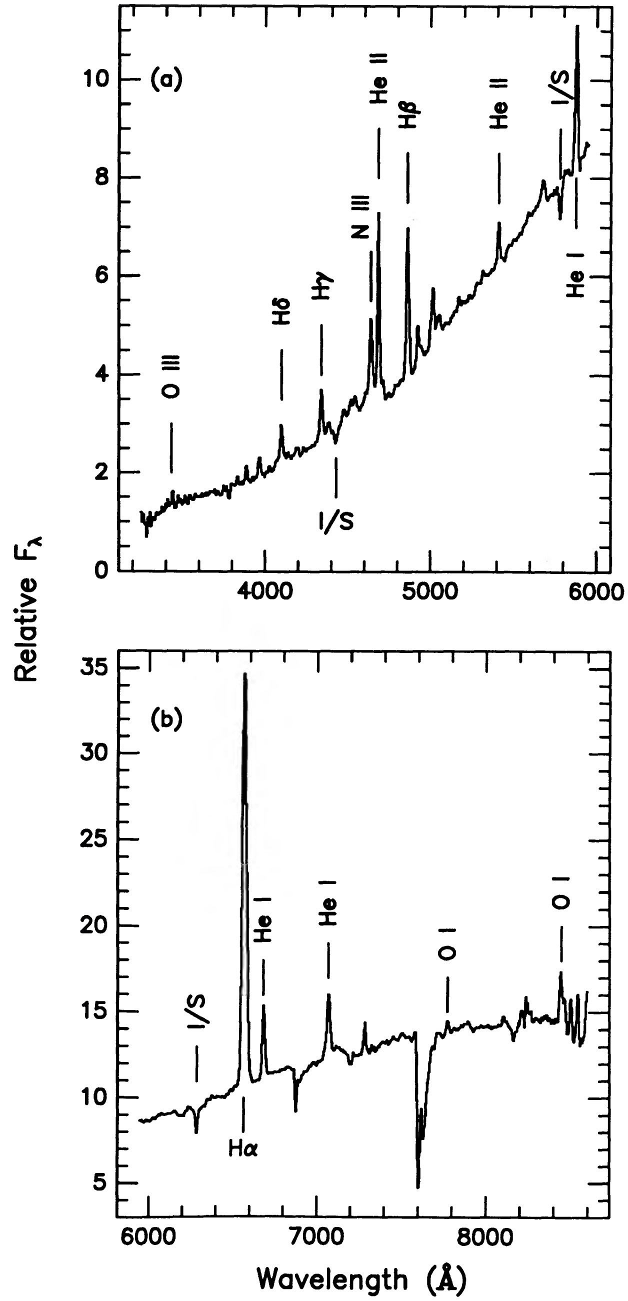

FIG. 1.—Low-dispersion optical spectra of V404 Cyg obtained on 1989 May 27.4 at the Perkins 1.8 m telescope and CCD spectrograph. (*a*) Blue spectral region. The spectrum in the blue is dominated by strong emission lines of He II λ4686 and λ5411, Hβ, Hγ, and Hδ, He I λ5876, λ5015, λ4922, and λ4471, as well as numerous Fe II lines. The interstellar bands at λ4430 and λ5780 are also prominent. (*b*) Red spectral region. The spectrum in the red is dominated by Hα, He I λ6678, λ7065, and λ7281, O I λ7774 and λ8446, and the Paschen series. The interstellar band at λ6284 is also present.

Szkody & Margon (1989) reported that a pre-outburst image of V404 Cyg was obtained on 1989 April 13, ∼40 days before the detection by *Ginga*. Dr. Paula Szkody has kindly made available to us these pre-outburst images. We have measured the position of the object corresponding to V404 Cyg and the results are also given in Table 1. This result is especially important in light of the fact that deep CCD imaging of

V404 Cyg by the Charles et al. (1989a) and ourselves has revealed the presence of a V = 19–20 star ~1".5 north of V404 Cyg. Charles et al. suggested the possibility that the star measured by Szkody & Margon was in fact not V404 Cyg but rather this fainter star. The implication of this would be that V404 Cyg was actually much fainter than the sky survey limit before the outburst and would suggest a much larger optical outburst amplitude than previously believed. The astrometric results indicate that the position of the object measured by Szkody & Margon agrees with the position inferred from the POSS, as well as with the outburst position of V404 Cyg, at which time the fainter star would have made no contribution. Spectra of V404 Cyg and of the fainter star were obtained simultaneously in 1990 July at the Multiple Mirror Telescope using the red channel spectrograph and low resolution echellette (resolution ~5 Å, range 4500–10,000 Å). At this time V404 Cyg was near its pre-outburst magnitude of ~18. We estimate that the fainter star is ~1.5 mag fainter than V404 Cyg in V, R, and I. Thus there is little doubt that pre-outburst magnitudes measured by Szkody & Margon refer primarily to V404 Cyg.

2.3. *Spectroscopy*

As can be seen in Figure 1, the spectrum early in the outburst is dominated by strong emission lines of H, He I, He II λ4686, and N III λ4640. Weaker emission features of Fe II, O I λ7774 and λ8446, and possibly C IV, N IV, Si II, and Fe III are also present. In addition, the near-ultraviolet O III Bowen fluorescence lines at 3429–3440 Å, are present near the time of X-ray maximum. An O III line at 5593 Å may also be present.

In our first low-dispersion spectrum, interstellar absorption features at 4430 Å, 5790 Å, NaD, and 6284 Å were present indicating a significant amount of interstellar extinction and reddening. The mean equivalent widths of the 4430 and 5780 Å features measured from spectra obtained on May 27, 28, and 31 are 2.3 and 1.4 Å, respectively. The 6284 Å band is contaminated by telluric O_2 and is not useable for an extinction estimate. Using the results of a study of the diffuse interstellar bands by Herbig (1975) and realizing that the 5780 Å band is blended with another interstellar band at 5778 Å, we find that for the 4430 and 5780 Å bands that $E(B-V)$ is 1.01 and 1.04, respectively, with a mean $E(B-V)$ of 1.03 mag. Assuming $R = A_V/E(B-V) = 3.2$ in the Cygnus direction (Schild 1977), we find that $A_V = 3.3$ mag. These results are consistent with those reported by Charles et al. (1989a). Correcting our spectra for this level of interstellar extinction suggests that the intrinsic continuum spectrum of V404 Cyg early in the outburst is inconsistent with a hot blackbody source or an accretion disk spectrum proportional to $\nu^{1/3}$.

In Figure 2, we show a blue spectrum of V404 Cyg obtained on May 28 with the CCDS at 3 Å resolution centered on Hγ. Emission lines visible include Hϵ, Hδ, Hγ, He I λ4026, λ4388, and λ4471, and N III $\lambda\lambda$4516–4550, as well as the interstellar absorption band at 4430 Å. Numerous other weaker emission lines are apparent in the spectrum. The profiles of the Balmer and He I emission lines appear to be asymmetric. This asymmetry may be due to the presence of weak and narrow P Cygni absorption components on their blue wings with displacements of ~1000 km s^{-1}. P Cygni absorption components are plainly visible at Hβ, Hγ, and He I λ4471 on June 1 (see Charles et al. 1989a, b). The full width at half-maximum of Hδ and Hγ is 980 km s^{-1}, corrected for instrumental resolution.

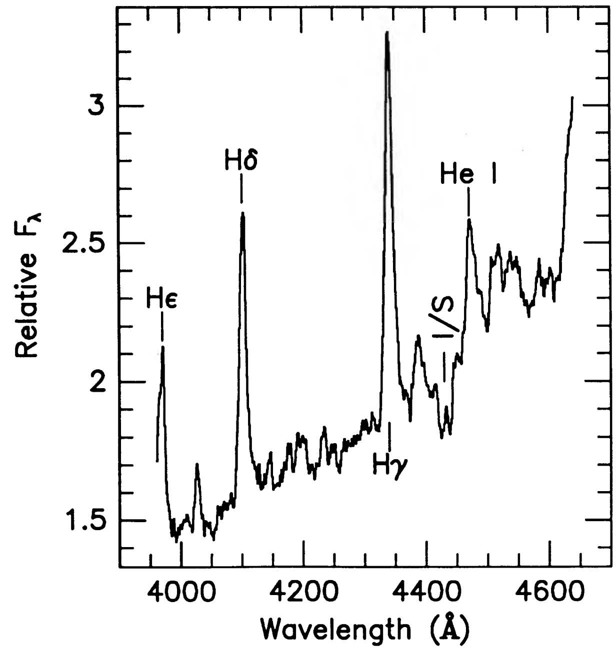

FIG. 2.—Higher dispersion spectrum of V404 Cyg obtained on 1989 May 28.4 with a spectral resolution of ~3 Å. Note the single-peaked asymmetric line profiles suggesting the presence of weak P Cyg absorption lines on the blue wings. The strongest emission line is due to Hγ.

2.4. *Light Curve*

The optical light curve of V404 Cyg from late May of 1989 through mid-June of 1989 is shown in Figure 3 where we have plotted the optical flux in magnitudes as a function of time in days since the discovery by *Ginga* (JD 2,447,668). The light curve has been assembled from the following sources: (1) visual or photographic V magnitudes reported on the IAU Circulars and to the AAVSO; (2) digital measurements reported on the IAU Circulars; and (3) V photoelectric measurements obtained with the computer-controlled 0.4-m telescope at Braeside Observatory.

Readily apparent in Figure 3 is the scatter in the light curve on individual nights reflecting the intrinsic variability of V404 Cyg on a time scale of minutes. These fluctuations have an amplitude as large as 1 mag peak-to-peak and were especially prominent during this early phase of the outburst. This flickering component is probably indicative of unstable accretion onto a compact object.

Fortunately, the identification of V404 Cyg was made prior to maximum light so that a portion of the ascending light curve was observed. Maximum light occurred on or near 1989 May 30 (day 7) at 11.5 to 12th magnitude. May 30 also coincides with the maximum 2–10 keV X-ray intensity (Kitamoto et al. 1989). Within a few days of maximum light, the light curve had fallen ~3 mag to a local minimum on day 12 (June 2; JD 2,447, 679.5). This local minimum was first noticed by Jones & Carter (1989). By day 17 (June 7), the source had brightened by ~1 mag reaching a secondary maximum and then began a steady decline. The trends evident in the optical light curve are well reproduced in the X-ray light curve reported in Kitamoto et al. (1989) and Kitamoto (1990).

2.5. *Rapid Variability*

The data in Figure 2 indicate that the optical flux of V404 Cyg varies from day to day as well as on time scales of several

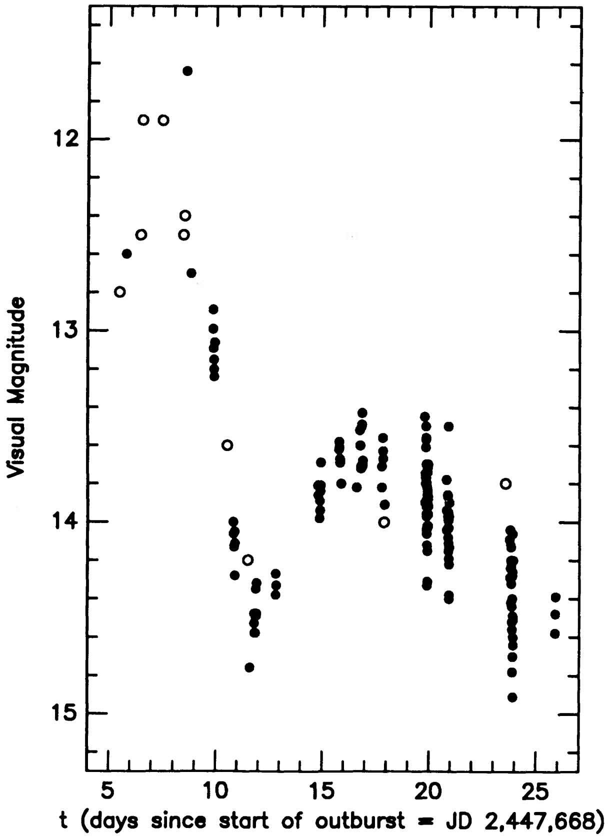

FIG. 3.—Visual light curve of V404 Cyg from the time of the identification of GS 2023+338 on 1989 May 26 through mid-June of 1989. Photographic and visual estimates from the IAU Circulars are denoted by open circles. Photoelectric and CCD measurements from our observations and those reported on the IAU Circulars are denoted by filled circles. Maximum light occurred on May 30 (day 7). Note the local minimum on June 2 (JD 2,447, 679.5, day 12) and the subsequent secondary maximum 5 days later followed by a gradual decline. The minimum on day 12 corresponds to a hardening and decrease in intensity of the X-ray spectrum.

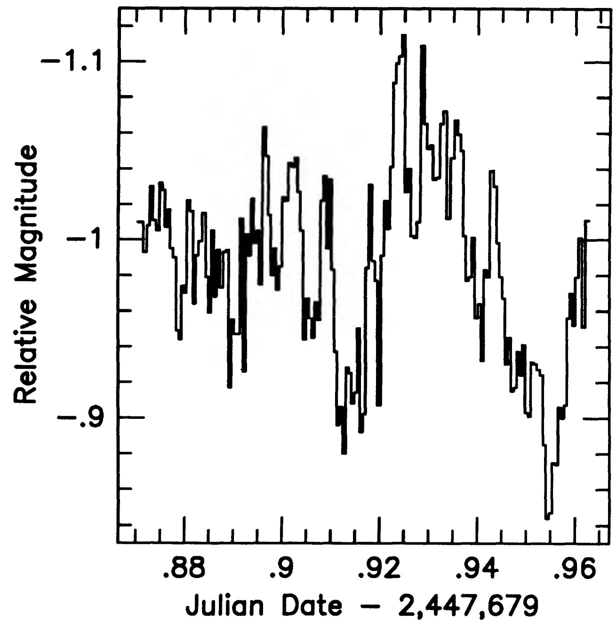

FIG. 4.—Light curve of V404 Cyg obtained with a CCD at the Perkins telescope on June 2 (day 12). Note the erratic intensity fluctuations or flickering on time scales of minutes.

minutes. On day 12 (June 2), time-resolved differential CCD photometry in *R*-band continuum light was performed using the Perkins Telescope and Lowell Observatory RCA direct imaging camera to search for more rapid variations and to investigate whether any periodic component arising from either orbital motion or rotation of a magnetized compact object was present. The integration time was 30 s with $\sim$20 s of dead time between frames. The magnitude of V404 Cyg was measured with respect to two anonymous comparison stars adjacent to V404 Cyg and the relative photometric accuracy is $\sim$0.001 mag. The light curve is shown in Figure 4. Notice the fluctuations on the order of or exceeding 0.1 mag on time scales of a minute or less. The amplitude of the flickering component on this night was considerably less than on other nights. This effect may be associated with the fact that these data were obtained during the local minimum of the mean light curve on June 2. Buie & Bond (1989) also reported photometric fluctuations of nearly a magnitude peak-to-peak on time scales of a few minutes earlier in the outburst (1989 May 30.323) as well. Flickering is seen in many cataclysmic variable stars and X-ray binaries and is thought to arise in an accretion disk surrounding a compact object. Through Fourier analysis of these data, Wagner et al. (1989) announced in 1989 June that there was evidence for a $10^{\mathrm{m}}.1$ period of amplitude 0.06 mag. However, we defer detailed discussion of possible periodic components in the time-series data until the entire photometric data set obtained from 1989 June through 1990 August can be considered.

3. DISCUSSION

The identification and outburst data reported here confirms that V404 Cyg, with a previous outburst in 1938, is the optical counterpart of the X-ray nova cataloged as GS 2023+338. In addition, these data also show that this was a unique outburst as compared to previously well observed X-ray novae. For example, neither V616 Mon (Boley et al. 1976; Gull et al. 1976; Oke & Greenstein 1977; Oke 1977; Whelan et al. 1977) nor Cen X-4 (Canizares et al. 1980) showed strong optical emission lines at maximum as did V404 Cyg. In addition, the rapid and intense fluctuations in both optical flux and X-ray spectrum and intensity (Kitamoto et al. 1989) were not found in these previous outbursts.

Nevertheless, there is no reason to abandon the accepted model for these systems, and we assume that V404 Cyg also consists of a low-mass secondary that fills its Roche lobe and is losing mass into the lobe of a compact object. At the present time, it cannot be definitely shown if the compact object is a black hole or a neutron star. In the case of V616 Mon, the mass function (McClintock & Remillard 1986) and the softness of the outburst at maximum suggest that the compact object is a black hole. For Cen X-4, the observation of a Type I X-ray burst on the decline phase of the X-ray nova outburst (Matsuoka et al. 1980) as well as recent dynamical studies (Cowley et al. 1988; McClintock & Remillard 1990) strongly suggest that the compact object is a neutron star.

For V404 Cyg, the X-ray outburst as first observed on May 21 was extremely hard, but softened over the next few days. By day 6 (June 1), the X-ray spectrum had hardened once again and thereafter showed a gradual softening (Kitamoto et al. 1989). According to Kitamoto et al., this behavior was most unusual for an X-ray transient source. During the initial stages of the outburst of V616 Mon, the X-ray spectrum was hard, but softened on the subsequent rise to X-ray maximum, in a manner very similar to V404 Cyg. The difference is that V404 Cyg exhibited a second hardening of the X-ray spectrum within the 2 days immediately following X-ray maximum. We suggest that this behavior could have been caused by the rapid expansion and cooling of the outer layers of a large accretion disk during a period of episodic or unstable accretion.

In this picture, the initial hard X-ray emission originates from the hottest inner regions of the accretion disk closest to the compact object. As further mass is accreted, the accretion disk grows rapidly and the total X-ray and optical luminosity increases, but the outer regions of the disk will be cooler resulting in a softening of the X-ray spectrum. If the X-ray luminosity is large enough, say, for example, if the accretion rate is near the Eddington limit as determined by the mass of the compact source, then one might expect to produce an enhanced radiatively driven wind. Near X-ray maximum, the optical spectrum may be very reminiscent of an Of star with strong emission lines exhibiting weak P Cyg profiles. The wind would cause the enlarged disk to expand or dissipate, thereby once again revealing the hottest inner regions of the accretion disk and thus producing a second hardening of the X-ray spectrum as was observed just after day 6 (June 1). In the optical region, the total brightness during this phase would decrease as was observed on day 7 (June 2) and shown in Figure 3. Subsequent steady accretion onto the compact source and the development of an enlarged accretion disk would then result in a second and final softening of the spectrum as was observed after day 8 (June 3).

The presence of strong optical emission lines and weak P Cyg profiles early in the outburst of V404 Cyg provides direct observational evidence for such a wind and a cool inflated accretion disk. Perhaps the difference between V404 Cyg and V616 Mon may be that the accretion rate in V404 Cyg may be comparable to the Eddington limit rather than substantially below it. Support for the idea that the compact object is a neutron star comes from radio studies which found suggestions of QPOs in the data (Han & Hjellming 1990). However, no evidence has been found for X-ray pulsations which would indicate the presence of an X-ray pulsar. Support for the idea that the compact star is a black hole comes from the rapid and random X-ray fluctuations reminiscent of Cyg X-1 (Kitamoto et al. 1989) and X-ray spectral variations analogous to V616 Mon, another black hole candidate (McClintock & Remillard 1986). Thus, the nature of the compact star remains unknown pending further observations.

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