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HIGH-SPEED PHOTOMETRY OF V404 CYGNI IN OUTBURST

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ABSTRACT

We present high-speed photometric observations of the optical counterpart of the X-ray transient GS 2023+338 (V404 Cygni) obtained during the decline from a major outburst. We confirm the low-frequency flickering previously reported in X-rays, optical, and radio waves. From four nights' coverage in 1989 September, we find no evidence in the light curve for a unique coherent period. However, we observe transient broad features in the power spectra at periods in the range of 3–10 minutes. Similar features are commonly seen in the optical light curves of erupting dwarf novae; they may be a characteristic signature of disk accretion onto any type of compact star.

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

1. INTRODUCTION

V404 Cygni has been identified (Marsden 1989; Wagner, Starrfield, & Cassatella 1989) as the optical counterpart of the X-ray transient GS 2023+338 discovered on 1989 May 22 by the All-Sky Monitor aboard the *Ginga* X-ray satellite (Makino et al. 1989; Kitamoto et al. 1989). Nova Cygni 1989 increased in optical brightness from a quiescent 20th mag (Duerbeck 1987) to a peak brightness of $m_v \sim 12$ (Jones & Carter 1989). Spectroscopy revealed strong emission lines of H, He I, and He II superposed on a highly reddened optical continuum (Wagner et al. 1989). An earlier outburst in 1938 was described by Wachmann (1948), and a recent examination of the Sonneberg plates finds that additional outbursts occurred in 1956 and possibly 1979 (Richter 1989).

During early monitoring of the X-ray nova, *Ginga* witnessed erratic intensity fluctuations in the 2–20 keV bandpass over time scales spanning seconds to days. The intensity in this bandpass reached up to 17 Crab, with a maximum variability of more than a factor of 500. Following the first month, the longer period fluctuations died out while the rapid variability persisted (Kitamoto et al. 1989). This variability was echoed in the radio behavior with its rapid fluctuations and quasi-periodic oscillations (Hjellming, Han, & Córdova 1989; Han & Hjellming 1989). In the optical band, initial high-speed photometry on May 31 by Buie & Bond (1989) showed strong, rapid flickering up to 0.7 mag (peak-to-peak). Two days later Wagner et al. (1989) reported a tentative 10 minute periodicity in *R*-band photometry. Subsequent photometry by Howell (1989) and Charles et al. (1989a) did not confirm this period.

The observed characteristics, especially the high X-ray luminosity ($\sim 10^{38}$ ergs s^{-1} for the likely distance of 2–3 kpc), strongly suggest that V404 Cyg is a low-mass close binary system with an accreting neutron star or black hole. The X-ray outburst is then almost certainly due to a sudden accretion event onto the compact star. But as remarked by Kitamoto et al. (1989) and Charles, Hassall, & Sahu (1989b), there seems to be no close resemblance to any previously known object of this kind. The X-ray source, detected all the way to 300 keV (Sunyaev et al. 1989), is the "hardest" among all known X-ray transients. The huge amplitude of the X-ray variations, and the extreme variability of the X-ray spectrum (with N_H varying in the range 5–60 × 10^{21} cm^{-2}), are also unprecedented in this class. The optical properties bear some resemblance to V616 Mon (the counterpart of A0620−00), but V404 Cyg showed a substantially faster decline rate (0.04 compared to 0.015 mag day^{-1}), a shorter outburst interval (~20 compared to 60 yr), and an optical spectrum with much stronger emission lines at maximum.

In response to the early reports of periodic and quasi-periodic signals which might reveal an underlying binary orbital period, we carried out high-speed optical photometry of the star in 1989 September. No coherent signal, which might signify an orbital period, was found, but rather quasi-periodic oscillation with periods in the range 200–600 s. Signals of comparable period and coherence time are rare among the X-ray binaries; the known examples are GX 339−4 (= V821 Ara), 4U 1626−67 (= KZ TrA), and, in X-rays only, Cyg X-3. However, they are quite common among cataclysmic variables; they may represent an instability characteristic of disk accretion onto any sort of compact star. We speculate that they may represent magnetic reconnection events in the accretion disk.

2. OBSERVATIONS

Four nights of high-speed differential CCD photometry of V404 Cyg were obtained with the 1 m Anna Nickel telescope at Lick Observatory, using the high-speed photometer described by Stover & Allen (1987). The observational log is presented in Table 1. All observations were acquired in unfiltered light with a bandpass determined by the CCD response function ($\lambda_{eff} \sim$ 6000 Å). The first three nights' observations were made under

TABLE 1

OBSERVATION LOG

Date (1989 UT)	Start Time (UT)	Integration Time (s)	Run Duration (s)	Mean Count Rate (DN s^{-1})[a]
Sep 22........	05:25:14	15	13740	307
Sep 23........	04:17:12	15	17530	304
Sep 24........	03:43:50	15	9015 }	281
	06:18:23	15	7710 }	
Sep 25........	03:37:36	30	21000	273

[a] DN = CCD digital number (5.4 counts per DN).

clear sky conditions with good seeing (typically 1″–2″), while clouds were intermittently present on the last night.

2.1. *Data Reduction*

As described by Stover & Allen (1987), the CCD data acquisition system preprocessed each integration in real time by subtracting the baseline bias and by flat-fielding. The sky contribution to each stellar image on the CCD frame is then subtracted by interpolating the surrounding CCD pixels using a biquadratic function. Finally, the sky-subtracted data were fitted to a running average seeing profile to provide optimal background rejection and to correct for seeing and/or guiding errors. Along with V404 Cyg, a nearby comparison star was imaged on the CCD and used to divide out the atmospheric attenuation from the V404 Cyg light curves. Except for one interval of dense clouds on September 25, the errors introduced by this division were determined to be negligible. Simultaneous flux-calibrated observations on the Lick 3 m telescope showed the star to be at $V \sim 16.3$.

The reduced light curves are shown in Figure 1. The mean intensity decreased by 0.1 mag over three nights, consistent with the long-term rate of decline. The light curves exhibit variability on many time scales with a total RMS fluctuation of 7.5%. This fluctuation is a factor of 5 higher than that of the sky and at least a factor of 2 larger than expected for comparison star data of comparable brightness. The resulting signal-to-noise ratio is 14 and the intrinsic variability of V404 Cyg is $>5.7\%$ RMS.

2.2. *Power Spectrum Analysis*

The reduced light curves were analyzed for periodicity, both individually and as a set, by means of discrete Fourier transforms (DFTs). Most of the power is confined to a broad region with periods greater than 100 s. The power spectrum shows no sharp feature, as would be produced by a coherent signal, but rather an erratic rise toward lower frequencies. In contrast, Fourier transforms of comparison stars produce power spectra consistent with "white noise" as expected for Gaussian-distributed noise. The semiamplitude upper limit on a *strictly* coherent signal in V404 Cyg is ~ 0.003 mag for frequencies above 0.005 Hz but worsens at lower frequencies.

To search for transient coherent and quasi-periodic phenomena, we subjected short overlapping segments of the light curve to fast Fourier transforms (FFTs). We searched the light curves on 32 and 64 minute time scales using 50% overlapping segments. These segments exhibit transient oscillations at several frequencies. Figure 2 displays power spectra of overlap-

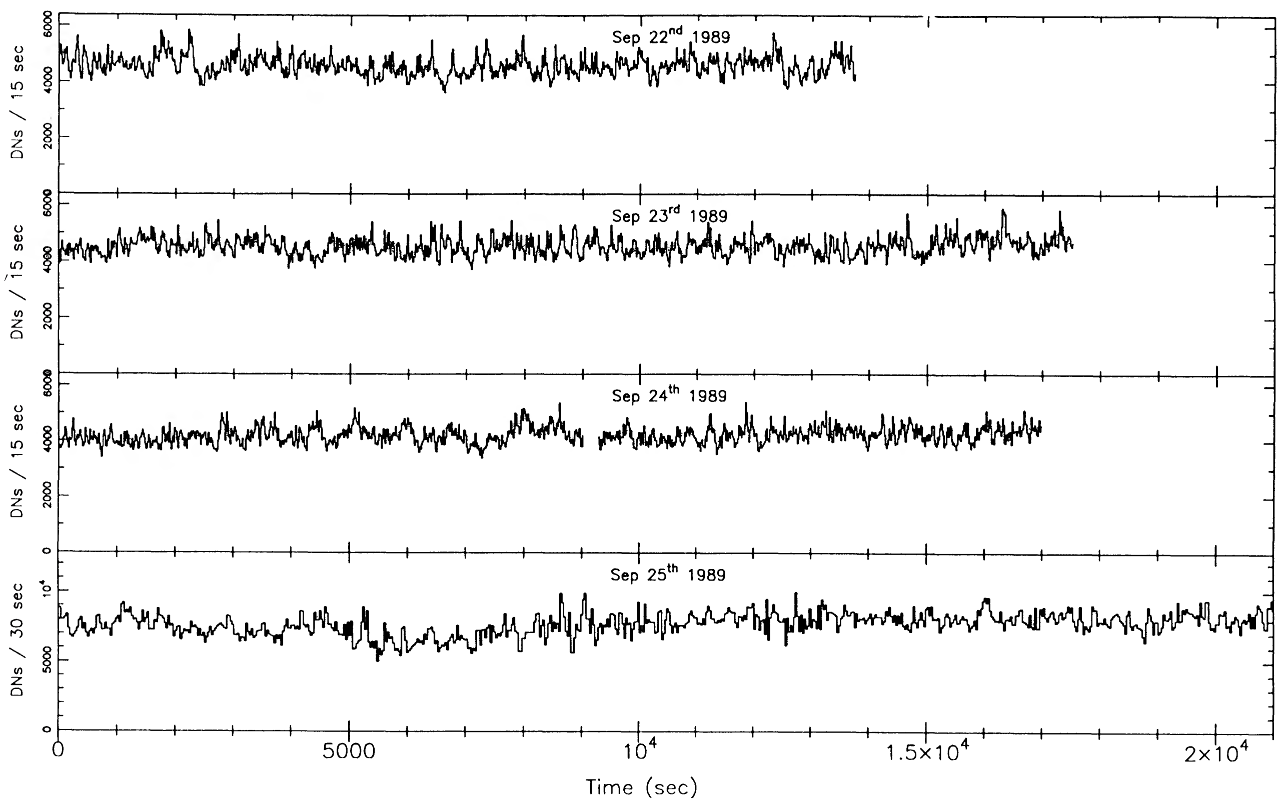

FIG. 1.—V404 Cygni normalized light curves. The count rates are in CCD digital numbers (5.4 counts per DN). The integration time is 15 s for the first three nights and 30 s for the last night. The September 24 observation contains 4.3 minutes of computer-related interruption.

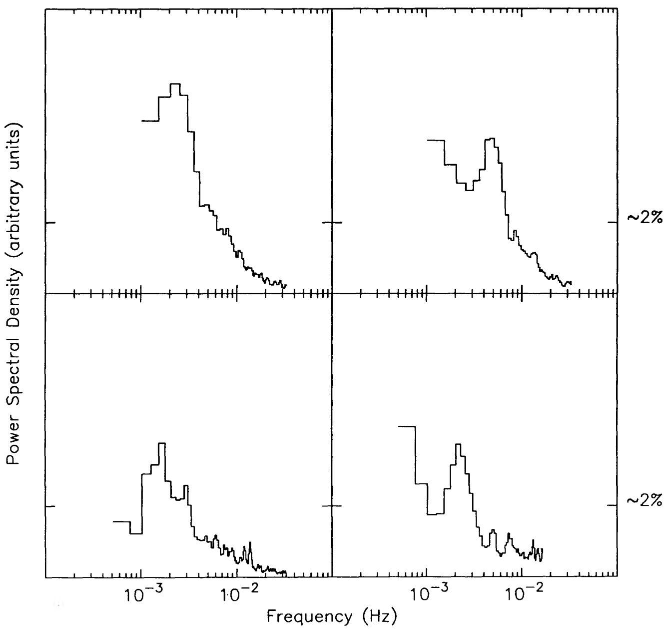

FIG. 2.—Summed power spectra from FFTs of 50% overlapping segments of the light curve for each night, displayed using an abscissa logarithmic in frequency. All plots are smoothed with a three-bin boxcar filter and displayed to the same scale. The tick mark on the ordinates denotes the power of an injected sine signal with ~2% modulation (semiamplitude/mean). In each plot, a QPO is found riding on the low-frequency flickering.

ping segments for each night's observation. All plots are smoothed with a three-bin boxcar filter. The plots are shown on the same scale (approximately) with the tick mark on the ordinate denoting the power of an injected sine signal with ~2% modulation (semiamplitude per mean). "White noise" is evidenced by a constant offset in power, while the characteristic flickering shows up as power rising toward lower frequencies (approximately as ν^{-1}).

Each night's plot shows evidence for quasi-periodic oscillations (QPOs). The September 22 plot, made up of 13 × 32 minute segments, reveals a signal of considerable power but only barely resolved (if at all) amid the flickering. The September 23 plot, comprising 17 × 32 minute segments, shows a prominent QPO with $P = 210^{+70}_{-50}$ s. The September 24th run was divided into halves: before and after a computer-related interruption of the data flow. Each half was analyzed in three 64 minute overlapping segments; the six power spectra were then summed together. The resulting smoothed spectrum displays a probable QPO centered on 500 s. The noise level in the last night's plot results in a higher offset in power, but nevertheless, a fairly well defined QPO ~150 s wide is found around $P = 450$ s, using 9 × 64 minute segments.

3. DISCUSSION

3.1. *A Stable Period: Still Elusive*

Our search has failed to reveal evidence of a stable period in the optical photometry, nor is one seen in X-rays (Kitamoto et al. 1989). Probably the best hope for finding the orbital period of the underlying binary star lies in optical spectroscopy, because the emission lines show a distinctly doubled-peaked structure—thought to arise from a moderately edge-on accretion disk. We did obtain radial velocity data simultaneous with the photometry reported here, but preliminary analysis has yielded only an upper limit: $K \leq 40$ km s^{-1} for periods in the range 0.1–6.0 hr. Details will appear in a future paper (Gotthelf, Halpern, & Patterson 1991).

3.2. *The QPOs*

The quasi-periodic oscillations we have found are essentially ubiquitous in the light curve, although of varying amplitude. In short data segments, the semiamplitude is typically ~0.02–0.04 mag. The coherence time is difficult to state, as it depends on adopting a specific mathematical model of the oscillation. We do note, however, that there are intervals in our data as long as 60–90 minutes in which the power spectrum peak was consistent in width with a signal of constant phase. This should be considered an approximate *upper limit* to the coherence time.

Were these oscillations also present near maximum light? We suspect that the answer is *yes*, since (1) the radio flux appears to show QPOs in the range 5–20 minutes, as early as 1989 July 22 (Han & Hjellming 1989); and (2) the 10.0 minute signal detected by Wagner et al. (1989) on 1989 June 2 could easily have arisen from a QPO, since the observation length was only 2 hr.

Further analysis of data sets obtained near maximum light should help clarify this issue.

3.3. *Analogies*

Do any other accreting neutron stars or black holes show such QPOs? Among the objects usually classified as "X-ray transients," no such signals have yet been found, at any wavelength. Among the low-mass X-ray binaries, quasi-periodic oscillations are commonly seen (e.g., van der Klis 1989), but at X-ray wavelengths and at much shorter periods (0.02–0.10 s). These do not appear to resemble the QPOs of V404 Cyg. One exception is Cyg X-3, whose X-ray light curves display QPO behavior on the longer time scales (van der Klis & Jansen 1985), but for which no optical data are available.

A closer comparison can be made to the ~1000 s QPOs of KZ Tra = 4U 1626−67 (Li et al. 1980; McClintock et al. 1980). These have the right time scale and are observed at optical (as well as X-ray) wavelengths. For this star, we know beyond doubt that the period is not a rotation period, since the star also exhibits a stable X-ray period of 7.7 s.

But in the zoo of X-ray binaries, probably the specimen most closely resembling V404 Cyg is V821 Ara = GX 339−4. This source is difficult to classify; its long-term light curve and X-ray/optical corrections are unlike those of any other object (Grindlay 1979; Motch et al. 1983). During its only known major outburst in 1981 May, the star displayed large-amplitude ~20 s QPOs in the optical and possibly in the X-ray as well (Motch, Ilovaisky, & Chevalier 1982; Motch et al. 1983; Maejima et al. 1984). These stars are related in other ways as well, which may or may not have any bearing on the periodicity:

1. They show X-ray fluctuations on time scales as short as ~40 ms;
2. They show X-ray spectra with a low-energy cutoff varying by a factor of 10 in N_H, suggesting either absorption at the source, or a highly variable soft X-ray component, or (most likely) both; and
3. They both show in outburst L_x (2–10 keV)/L_{opt} (3000–6000 Å) ~10, by far the lowest value for any LMXB, aside from edge-on systems in which it is believed that the direct line of sight to the compact star is totally obscured by the accretion disk itself.

These resemblances are noteworthy, but we do not yet know how to interpret them, because GX 339−4 is itself a poorly understood system. On the basis of rapid X-ray variability and a soft X-ray component, White & Marshall (1984) considered it to have good credentials as a black hole candidate, but no mass determinations exist to test this suggestion.

3.4. *Models*

What is the nature of the QPOs in V404 Cygni? The lack of good coherence tends to rule out the two natural short-period clocks in the underlying binary: orbital motion, and the rotation of the compact star. A more promising possibility is the accretion disk presumed to surround the compact star. The dynamical time scale in a disk around a 1 $M_\odot$ star would match the observations at a radius $R \sim 10^{10}$ cm.

At this great a distance from the central object, the accretion disk is probably largely unaware of whether it surrounds a black hole, neutron star, or white dwarf. And we note that among white dwarfs accreting through a disk (the dwarf novae), there are *dozens* of known cases where the star sports an optical QPO while in eruption (for reviews, see Robinson & Nather 1979, Patterson 1981). It is possible that the QPO in V404 Cyg is another example of this process which often accompanies episodes of unstable mass transfer through a disk, regardless of the nature of the compact star.

Unfortunately, it is not yet possible to specify what this process is. Several studies (Kato 1978; Van Horn, Wesemael, & Winget 1980; Livio & Shaviv 1981; Carroll et al. 1985) have suggested that the disk can be pulsationally unstable, but because the disk is supported by rotation and not pressure, the instability tends not to propagate. The " blobby disk " model of Bath (1973) and Bath, Evans, & Papaloizou (1974), in which the modulation arises from bright or dark blobs orbiting in the disk, is also a contender; but it only works at a high binary inclination, where the disk is at least somewhat self-obscuring. In addition, it is puzzling that a model of this type would yield a quasi period sensibly constant as the accretion rate varies by $\sim$10–100 X (as probably happened between 1989 late May and late September).

However, it remains to be explained why the *radio* flux should exhibit QPOs. The apparently nonthermal nature of the radio emission requires fast electrons and magnetic fields, and since the time scale of the variability is quite short, the emitting region must be small. An interesting possibility is the suggestion by Tajima & Gilden (1987) that magnetic reconnection events in an accretion disk can display oscillatory behavior. The ingredients seem very plausible: the secondary star is certainly capable of providing the seed magnetic field, differential rotation and turbulence in the disk can amplify the field, and reconnection can produce the fast electrons. Finally, the period depends on the magnetic Reynolds number, which has no obvious relation to the accretion rate. This is a promising avenue for further research.

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