ON THE X-RAY NOVA V404 CYGNI

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Abstract

After a search of the University of Oklahoma plate archives, we found three plates from September 1956 showing the nova V404 Cygni at about 15th magnitude. This confirms the 1956 outburst previously reported by Richter (1989). We also give an overview of the object. Using previously published observations, we present light curves of both the 1938 and 1989 outbursts and discuss recent spectroscopic data concerning the binary nature of the system and the possibility that it contains a black hole.

1. Introduction

The bright transient x-ray source GS 2023+338, a possible "black hole binary," displayed a spectacular outburst in 1989, discovered with the Ginga All-Sky Monitor (Kitamoto *et al.* 1989; Makino 1989; Makino and Ginga Team 1989). Since an optical outburst was occurring simultaneously, it was soon realized that the x-ray object had an optical counterpart, the previously-known variable star V404 Cygni. Wachmann discovered V404 Cyg in 1938 as an apparently ordinary nova. He followed the brightness variations for several months and gave a short discussion of the light curve (Wachmann 1948). The 1938 photographic light curve, taken mainly with a 30-cm astrograph in Hamburg, is reproduced here as Figure 1.

Numerous observations of the 1989 optical outburst were obtained in the B, V, and

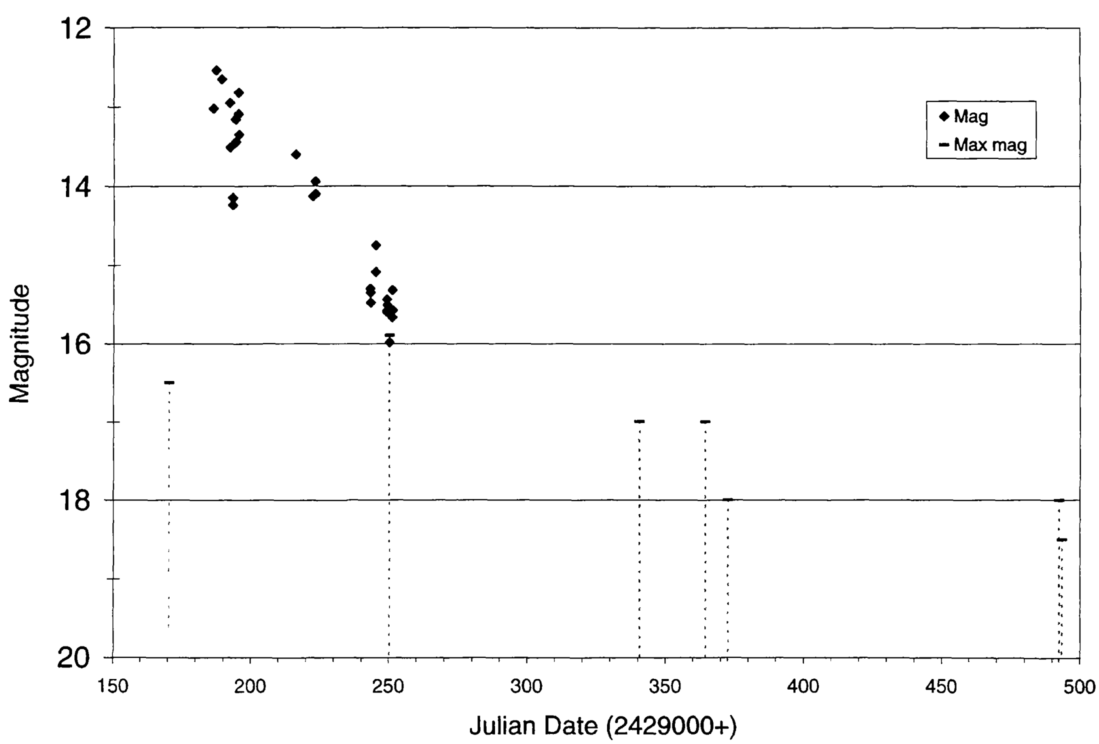

Figure 1. Light curve of V404 Cyg during its 1938 outburst. *Mag* is the photographic magnitude given by Wachmann (1948); *Max mag* is his upper limits.

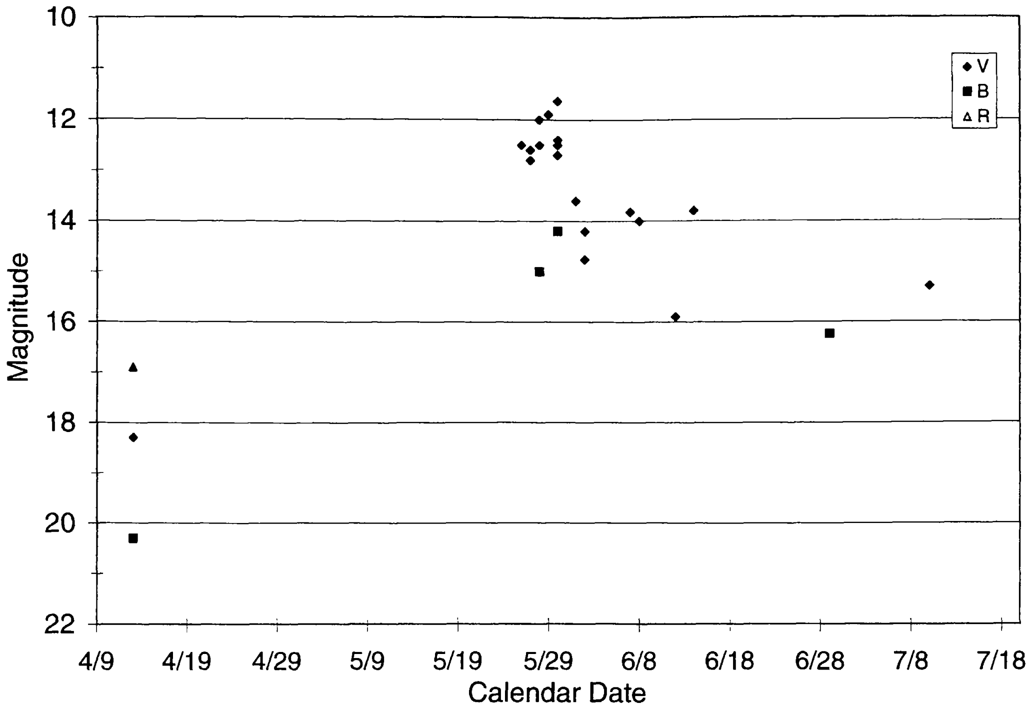

Figure 2. Light curve of V404 Cyg during its 1989 outburst. The data point at 6/29 is an average of four photographic observations from Richter (1989). Comparing the B and V magnitudes, one can readily see the large B–V of approximately +2.0 magnitudes. Some of the V magnitudes are based on visual, not photoelectric, observations.

R band passes, although the V observations are the most numerous. Photometric (and visual) data published in the *International Astronomical Union Circular* were obtained by Hjellming *et al.* (1989); Makino(1989); Okamura and Tanaka (1989); Schmeer (1989); Jones and Carter (1989); Scovil *et al.* (1989); Szkody and Margon (1989); Wagner and Starrfield (1989); and Wagner *et al.* (1989). We use these data to plot the resulting light curve in Figure 2 for comparison with the 1938 outburst. It seems, however, that V404 Cyg showed at least one other outburst between these epochs, in 1956, as was detected on a few plates from July and August 1956 preserved in the archives of the Sonneberg Observatory (Richter 1989).

Looking through the University of Oklahoma Observatory's plate archives, we found three plates from 1956 showing V404 Cyg at about photographic magnitude 15, indicating that in early September 1956 the outburst was still going on. The Oklahoma plates were taken with an 83-mm, f/4 Zeiss camera; these wide-field observations, initiated by the late Professor B. Whitney, are centered on various particularly interesting fields and do not systematically cover the whole available sky. In addition to the three plates confirming the 1956 outburst, we found two plates of particularly long exposure (56 and 60 minutes), taken on August 29, 1946, that seem to indicate the presence of the variable at an estimated magnitude 16.5. This was so close to the plate limit that we did not even try to measure them, but these plates may show V404 Cyg just above its quiescent phase. These few observations are given in Table 1.

This modest contribution may justify giving a short overview of the photometric behavior of this important object. We also discuss briefly the spectroscopic orbit, since it points, almost without doubt, to the presence in the system of an invisible secondary of significantly large mass.

2. The 1989 outburst

V404 Cygni has been identified with a 20.5-magnitude object in the Palomar Sky

Table 1. Plates from the University of Oklahoma (OU) Archive showing V404 Cyg.

The 3 plates showing the 1956 outburst of V404 Cyg:

OU Plate #	*Julian Date*	*Calendar Date*	*Exposure*
9521	2435724.677	9-7-1956	16 min
9537	2435725.823	9-8-1956	15 min
9538	2435725.841	9-8-1956	15 min

The 2 plates showing the possible quiescent phase of V404 Cyg:

OU Plate #	*Julian Date*	*Calendar Date*	*Exposure*
1856	2432062.781	8-29-1946	60 min
1857	2432062.691	8-29-1946	56 min

Survey; it is also contained in *A Reference Catalogue and Atlas of Galactic Novae* (Duerbeck 1987). A serendipitous observation on April 13, 1989, showed the star at V = 18.3 (Szkody and Margon 1989); it might already have been on a slow rise. This was followed by a sharp outburst during the last week of May, reaching a maximum brightness near May 30, at V = 11.6. The outburst peak lasted only a few days and the nova fell back to about V = ~14, followed by a slow decline (months). The optical maximum nearly coincided with the x-ray maximum, but was not double-peaked like the 1938 outburst. The color was very red, B–V = ~ 2 magnitudes; the red color was due at least partly to strong Balmer emission lines as well as to a reddened continuum. The width of the H-γ line corresponded to an expansion velocity around 1000 km/s (Wagner and Starrfield 1989). Oscillations in the nova's brightness of up to 0.7 magnitude could be observed, sometimes within a few minutes!

The very strong oscillations in the intense radio radiation bore some similarity to SS433 and Cyg X-l, and showed a much slower decay rate than other x-ray transients, such as A0620-00 (Hjellming *et al.* 1989; Schmeer 1989). The x-ray luminosity was very high, indicating that a white dwarf as the compact object in the system is almost certainly out of the question.

Detailed analyses of the optical as well as x-ray spectra may one day enable the construction of a complete model of this well-observed outburst. A rich collection of data is presented in the review article by Tanaka and Lewin (1995).

3. The likelihood of a black hole

A few years after the outburst, when the brightness of the system decreased to magnitude 18–19, crucial analysis of the orbit in the binary system became possible, thanks mainly to the efforts of two independent groups. Like most stellar x-ray sources, V404 Cygni is a binary; indeed, it is among the black hole candidates often referred to as "black hole binaries." As with A0620-00 and some other transients, the secondary component is a low-mass star of spectral type G or K. The pioneer work on the very faint spectrum was done by Casares *et al.* (1992), followed up by photometric observations and discussions by Wagner *et al.* (1992). The spectroscopic orbit has a semi-amplitude K = (211 ± 4) km/s, a period of (6.473 ±0.001) days, and a mass function of (6.3 ±0.3) $M_{\odot}$. The spectrum was classified by Casares *et al.* (1992) as probably K0III. Photometric observations by Wagner *et al.* (1992) demonstrated marked ellipsoidal variation, thereby confirming the spectroscopic period. They suggested a spectral classification for the low-mass star of K0IV, with a mass $M_1 = \sim 1 M_{\odot}$.

It is not trivial to find the photometric distance and/or the absolute magnitude of the system. The apparent brightness of V404 Cyg at quiescence is usually quoted as V= ~18, perhaps somewhat overestimated due to fluctuations and possible circumstellar radiation (accretion disk, disk corona). Taking V = ~19, one solution consistent with the K0IV spectral type is d = 2.3 kpc, A_V = 2.0 mag/kpc, yielding M_V = ~2.5, corresponding rather closely to the value for a K0IV star. However, these data seem to be perhaps on the low side. Increasing the interstellar absorption would lead to a distance d > 3 kpc and M_V near 0 or even –1, closer to luminosity class III. Nevertheless, we would expect the mass of this evolved component, even assuming a luminosity class III, to be close to $1M_\odot$.

The mass function may be written as

$$f(M) = \frac{M_1 \sin^3 i}{q(q+1)^2} , \qquad (1)$$

where M_1 is the mass of the actually observed (here less massive) component, and $q = M_1/M_2$. Choosing representative values for the inclination i, we readily obtain the value of q, and hence of M_2, the more massive component.

Using $M_1 = 1M_\odot$ for the mass of the visible component, the reasonably-well-determined mass function alone indicates a large mass M_2 for the invisible secondary. Some representative values are:

For $i = 90°$: $q = 0.125$ $M_2 = 8.0\ M_\odot$ For $i = 60°$: $q = 0.087$ $M_2 = 11.5\ M_\odot$
For $i = 45°$: $q = 0.051$ $M_2 = 19.6\ M_\odot$ For $i = 30°$: $q = 0.019$ $M_2 = 52.0\ M_\odot$,

and it is clear that M_2 cannot be less than $8.0\ M_\odot$.

Wagner *et al.* (1992) bring photometric and spectroscopic arguments that make it plausible that the inclination is such that the mass of the unseen companion is in the range 8–12 $M_\odot$. Thus the identification of this object with a stellar black hole is quite reasonable.

The orbital period being 6.47 days, the distance between the components should be (depending on M_2) in the range 15 to 25×10^6km. Thus the difference between luminosity class III and IV, i.e., the actual size of the K star, may turn out to be crucial.

The rather well-defined value of the mass function, $(6.3 \pm 0.3)\ M_\odot$, shows at once that the existence of two low-mass stars in the system is impossible. This rules out a neutron star component, at least as are found in x-ray binaries, i.e., a neutron star with a mass $M = \sim 1.5\ M_\odot$. All indications are therefore compatible with the conclusion of a stellar black hole as the more massive component in V404 Cygni. [Note added in proof: Researchers at the Harvard-Smithsonian Center for Astrophysics also voiced spectroscopic arguments for the existence of an event horizon, i.e., a black hole. See the short review in *Physics Today*, April 1997.]

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