THE BRIGHT X-RAY TRANSIENT GS2023+338 (=V404 CYG) IN OPTICAL OUTBURST AND DECLINE

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SUMMARY

We present the results of optical spectroscopy and photometry from La Palma of V404 Cyg, the optical counterpart of the new X-ray transient GS2023+338 recently discovered by Ginga. The overall light curve is very similar to that of the previous optical outburst of this object, which was recorded as Nova Cyg 1938 and classified as a classical nova. It is not a classical or recurrent nova, as the large range in optical brightness and intense X-ray emission at maximum indicate that the system must be a low-mass X-ray binary. The optical spectrum, however, is unlike any known LMXB or X-ray transient in that it displays strong, broad, variable and complex emission lines of H, HeI and HeII. The reddened spectrum and interstellar absorption features indicate a probable distance in the range 1-3 kpc. CCD photometry reveals that the source is variable, but gives no indication of the orbital period, there being no eclipse or regular modulation.

Keywords: X-ray transient, low-mass X-ray binary, classical nova, recurrent nova.

1 INTRODUCTION

X-ray transients can broadly be divided into 2 classes: those associated with high mass Be systems, in which the outbursts are the result of variable accretion due to a long period, highly eccentric orbit (see e.g. Ref. 1); and the soft X-ray transients (SXTs) which are associated with low-mass X-ray binaries (LMXBs), and are more akin to extreme dwarf nova outbursts in their behaviour (see e.g. Ref. 2). In both cases optical activity is also recorded, with the low-mass systems undergoing a dramatic (8 mags or greater) increase in brightness.

The All-Sky Monitor on the Ginga X-ray satellite (Ref. 3) has enabled X-ray transient events to be detected early in their outburst cycle, thereby making multi-wavelength observations possible for a significant fraction of the outburst. Using this device, the X-ray source GS2023+338 was discovered by Makino et al. (Ref. 4) on 1989 May 22, who reported that it was varying erratically and exhibited a very hard X-ray spectrum. During the following week it reached a peak of ~20 Crab, but retained its dominant characteristic of extraordinarily large variations in intensity (it once varied by a factor 200 in a matter of minutes) combined with a generally hard X-ray spectrum.

2 THE OPTICAL COUNTERPART

It was immediately noted by Marsden (Ref. 5) that the previously known variable V404 Cyg was consistent with the (poor) X-ray location of GS2023+338. V404 Cyg was the optical counterpart of Nova Cyg 1938 (Ref. 6) and had been classified as a classical nova by Duerbeck (Ref. 7). The quiescent magnitude of this star is ~19-20, but it was found by Wagner et al. (Ref. 8) and Hurst & Mobberley (Ref. 9) to be around 12th magnitude within days of the discovery of GS2023+338. This association with the X-ray transient was confirmed beyond doubt when Hjellming, Hun & Cordova (Ref. 10) reported the discovery of a transient radio source at the position of V404 Cyg. The first optical spectra of V404 Cyg during this outburst were obtained by Wagner, Staehle & Cassatella (Ref. 11), who reported a red continuum with superposed emission lines. The reddening was confirmed when they found that the source was too faint to observe with IUE. Szekody & Margon (Ref. 12) were also able to report optical photometry of V404 Cyg that they fortuitously obtained on April 13, immediately prior to this outburst. They found

B=20.3; V=18.3; R=16.9

which may be slightly above the quiescent level recorded on POSS plates. However, given the discovery of a close optical companion to V404 Cyg (see section 4.1) this result clearly requires confirmation, as the above measurements may be contaminated or not record V404 Cyg at all.

The possibilities at this stage were that the transient source was (a) a recurrent nova, (b) an accretion event in a white dwarf system (i.e. a cataclysmic variable), or (c) an accretion event in a neutron star or black hole system (i.e. an LMXB). It was, however, already displaying unusual properties for any of these possibilities and so it was of paramount importance to observe the nova throughout the early phases of the outburst.

3 SPECTROSCOPY FROM LA PALMA

Optical spectra were obtained with the 2.5m Isaac Newton Telescope and IDS/FOC combination during the period 1989 May 29 - June 11, as summarised in Table 1. (For instrumental details see Ref. 14). The first low-resolution, FOS spectra indicated the presence of strong Balmer, HeI and HeII emission lines, superposed on a red continuum (Ref. 15). These were then followed by higher resolution spectra using the IDS+IFPCS which indicated the complex and variable nature of the line profiles. A sample of the lower resolution spectra are shown in figure 1, the higher resolution spectra in figure 2.

1 Note that the Duerbeck reference to Baldwin (Ref. 13) is spurious as Baldwin refers to an object that outburst in 1937. There is no spectroscopic data for Nova Cyg 1938.
Table 1  La Palma Spectroscopic Observations of V404 Cyg

<table>
<thead>
<tr>
<th>Date</th>
<th>U.T.</th>
<th>Tel.</th>
<th>Instrument</th>
<th>$\lambda$ range</th>
<th>Spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 29</td>
<td>0512</td>
<td>INT</td>
<td>FOS</td>
<td>3400-9600</td>
<td>1</td>
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<tr>
<td>May 30</td>
<td>0520</td>
<td>INT</td>
<td>&quot;</td>
<td>&quot;</td>
<td>2</td>
</tr>
<tr>
<td>Jun 1</td>
<td>0150-0500</td>
<td>IDS+IPCS</td>
<td>3500-6800</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Jun 2</td>
<td>0225-0325</td>
<td>&quot;</td>
<td>3600-6700</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Jun 3</td>
<td>0240-0330</td>
<td>&quot;</td>
<td>3500-7500</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Jun 4</td>
<td>0310</td>
<td>&quot;</td>
<td>&quot;</td>
<td>4200-5200</td>
<td>1</td>
</tr>
<tr>
<td>Jun 5</td>
<td>0435</td>
<td>&quot;</td>
<td>&quot;</td>
<td>3500-7500</td>
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<tr>
<td>Jun 6</td>
<td>0400-0450</td>
<td>&quot;</td>
<td>4200-5200</td>
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<td></td>
</tr>
<tr>
<td>Jun 7</td>
<td>0150-0520</td>
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<td>&quot;</td>
<td>16</td>
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<tr>
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<td>&quot;</td>
<td>&quot;</td>
<td>12</td>
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<tr>
<td>Jun 11</td>
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<td>&quot;</td>
<td>&quot;</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Aug 24/5</td>
<td>2335-0025</td>
<td>WHT</td>
<td>ISIS</td>
<td>3400-9300</td>
<td>4</td>
</tr>
</tbody>
</table>

The Balmer and HeI profiles show gross variations, sometimes on short (~10 mins) timescales. Note also the transition to P Cyg profiles of Hα and HeIλ5876 in figure 1(a) over 2 nights. This suggests that there is intermittent mass-outflow from the system, such as would be expected given the enormous X-ray luminosity generated, and which might be able to mimic that seen during a "normal" nova outburst. This clearly affects the Balmer and HeI profiles, thus making them less useful as a guide to motions near the compact object. For this reason we decided to examine the higher excitation HeII profile more carefully in the hope of determining the orbital period of the system. The HeII emission consists of a broad base with two narrow velocity-separated (~300 km s$^{-1}$) peaks. The relative strengths of these two peaks are clearly variable and indicative of activity close to the X-ray emitting region, which will be less affected by any mass outflow. This technique is frequently successful in the study of cataclysmic variables.

Substantial and erratic variations in the HeII profiles (in both the relative strengths and velocities of the 2 components) were visible on timescales from 10 mins to 1-2 hours to 1 day. No periodic phenomenon was evident in either the strengths or velocities (as determined by a multi-gaussian fitting model).

4 PHOTOMETRIC VARIABILITY

Figure 3 shows the 1938 outburst light curve of V404 Cyg as reproduced from the measurements of Wachmann (Ref. 6), together with the optical measurements obtained by us with the JKT during the 1989 outburst.

The general structure of the light curves are similar, in particular, note the post-maximum "dip" (~1") that occurred in both outbursts, and at comparable times after maximum. However, it is also clear that the 1938 outburst was much brighter in B (~photographic), and given the fixed reddening (see section 5) this implies that the V to I light curves must have been both brighter and substantially longer in outburst time.

Shortly after the Ginga discovery of GS2023+338, Wagner et al (Ref. 11) announced that their CCD R band photometry indicated the presence of a low amplitude (~0.06 mags) modulation at a period of 10.0 ± 0.1 mins superposed on stochastic flaring behaviour. However, this was not confirmed by subsequent CCD observations undertaken at the INT prime focus on 1989 July 4. The INT time series data are shown in figure 4 and clearly indicate intrinsic source variability on a timescale of 10 minutes or so, but it is not periodic, nor does the data show any evidence for flares.

4.1 THE DECLINE TO QUIESCENCE

By the end of August, the visual brightness of V404 Cyg had declined to ~17, barely 2 mags above its quiescent level. We therefore decided to use the 4.2m William Herschel Telescope which was equipped with ISIS, the new double spectrograph, to study both the blue and red spectra of V404 Cyg in order to search for any indication of the secondary (red) component (e.g. TiO bands). The spectra are shown in figure 5. The blue is remarkably similar to figure 1(a), indicating the essentially simultaneous decline of the continuum and emission line spectrum. The red is dominated by (double-peaked) Paschen emission and contains no indication of any normal stellar spectrum.
Figure 3. Outburst light curves of V404 Cyg in 1938 (above) and 1989 (below).

In mid-September further CCD photometry of V404 Cyg was performed with the JKT which revealed the R image shown in figure 6. There is clearly a companion around R~20 which is 1.4 arcsec North of V404 Cyg, and this may be the star visible when the transient itself is in quiescence. This question can only be resolved by accurate astrometry of the field.

5 REDDENING AND DISTANCE ESTIMATE

Our optical spectra show a number of interstellar features that allow an estimate of the reddening and distance to be made. The diffuse interstellar band at 4430 has an E.W. of 2.4Å which, from Herbig's (Ref. 16) relation, indicates E(B-V)=1.0, and hence A_v=3.3 mags and d=1.8 kpc (Ref. 17). A rough picture of the variation of absorption A_v with distance can be drawn from the work of Neckel & Klare (Ref. 18) and Forbes (Ref. 19). The field is substantially clear to a distance of 800pc where the absorption suddenly rises to 3-4 mags. It apparently remains constant to more than 3kpc, but this could be the effect of observational selection. The field is close to the great rift in the northern milky way and the intersection of Gould's belt with the galactic plane. The Na D lines have an E.W. of 1.4Å from which a distance of 1.4 kpc would be inferred for a linear relation between E.W. and distance (Ref. 17). At a latitude of +2.09 degrees the object lies entirely within the reddening layer, but given the above discussion we can only constrain the distance of V404 Cyg to be in the range 1.5-3kpc, and it may be more.

If the object were a classical nova then we may use the Schmidt-Kaler (Ref. 20) relation (M_n = -11.75 + 2.5log(t)) which gives M_n=-7.3 for the t_3 of 60 days (time to fall by 3^m). For an A_v of 3 mags and observed maximum of m_n=12, then d=16kpc. This option can therefore be eliminated since it leads to an L_x of 10^{50} erg s^{-1}, at least 100 times the Eddington luminosity for a 1M_\odot object, and such levels have never been seen from classical novae (see Ref. 21). Only recurrent novae manage to generate X-rays early in an outburst, but that is usually quite weak and a result of shocks caused by new ejecta impacting debris from previous eruptions.

Alternatively, if the system were a dwarf nova, then it would have to be at a distance of about 100pc. This is completely excluded by the level of interstellar reddening observed.

6 DISCUSSION

Although Wagner & Starrfield (Ref. 22) drew an analogy between their optical spectra of V404 Cyg and those of A0620-00 (Ref. 23), we find that our spectra are quite distinct from those of either A0620-00 or the more recent soft X-ray transient GS2000+25. To illustrate this point we show in figure 5 a WHT FOS spectrum of GS2000+25 (Ref. 24). Both objects are reddened, but their emission line characteristics are totally different. The Balmer emission in GS2000+25 is weak and broad, being barely detectable at Bβ, as is HeII λ4686. In V404 Cyg, however, the strength of the Balmer, HeI and HeII emission is far more reminiscent of "nova-like" variables (see e.g. Ref. 25) or AM Her systems. Such objects are associated with a white dwarf compact object, which is ruled out here by the enormous X-ray luminosity, being \geq 10^{38} erg s^{-1} for the distance estimated above.

It should also be noted that CVs, which are strong emission-line
objects in quiescence, change drastically in outburst as the disc becomes optically thick, usually mimicking the atmosphere of an A star (see e.g. Ref. 26). No such effect is evident in V404 Cyg, nor does the spectrum change dramatically as it declines.

The large magnitude range from quiescence to outburst, coupled with the high $L_\alpha$, indicates that we must be dealing with a low-mass X-ray binary (LMXB) in which the compact object is either a neutron star or black hole, accreting matter from a low-mass, possibly evolved, companion. However, it is by no means straightforward to infer the nature of the compact object in V404 Cyg.

The case for a black hole in A0620-00 is a strong one (Ref. 27), and the similarity with GS2000+25 (see Callanan & Charles, these proceedings) argues that it too may harbour a black hole. However, V404 Cyg displays a tantalising set of similarities and differences with these black hole candidates. The X-ray behaviour of GS2023+338 (see Tanaka and Inoue, these proceedings) shows some remarkable similarities with Cyg X-1 in the form of its X-ray spectrum near 7keV and the power spectrum of its variability. The primary difference is the general absence of a soft component, the presence of which is occasionally cited as the hallmark of a black-hole binary (see e.g. Ref. 28) However, the Ginga observations did at times show evidence for a weak soft component, almost certainly reduced by the larger line of sight column density. The hard X-ray component out to 100 keV (see Kaniovsky, these proceedings) was certainly similar to that of GS2000+25 with a Comptonisation $kT \sim 30$keV.

But we must conclude by emphasising the unique features of V404 Cyg / GS2023+338, which once again demonstrates the importance of equipping X-ray satellites with all-sky monitors which can detect such short-term transient objects. The X-ray variability of GS2023+338 was extraordinary by any standards in its early phase (only Cir X-1 has displayed such rapid and erratic variations; see Ref. 29, 30), and yet it settled down after a week or so to decay in a manner similar to other soft X-ray transients. It has an optical spectrum unlike that of any other LMXB or X-ray transient, with strong emission lines that persisted throughout the outburst. Even the radio source stopped declining as expected for an expanding synchrotron source and became an erratic variable (Ref. 31). These properties may indicate a high inclination system in which the large variability is due initially to an enlarged disc edge which we can only just see over and intermittently obscures our view. We can also then view the optically thin line emitting regions which are partially shadowed from the X-ray source. However, at such an inclination, it is hard to understand why eclipses (or at least regular modulation) are not visible. Whether such ideas are correct or not, the relative brightness of V404 Cyg in quiescence will make it an attractive target for future study.

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References