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ROSAT OBSERVATIONS OF THE BLACK HOLE CANDIDATE V404 CYGNI IN QUIESCENCE[1]

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ABSTRACT

V404 Cyg was detected with the *ROSAT* PSPC in a 16 ks observation 1265 days after the 1989 May outburst. This is the first unambiguous detection of a soft X-ray transient or X-ray nova black hole candidate in quiescence. The observed X-ray spectrum is extremely soft and can be described equally well by either a blackbody, power-law, or a thermal bremsstrahlung continuum. The best-fit blackbody spectrum is characterized by a temperature of 0.2 keV. A significant amount of absorption, both along the line of sight and intrinsic to the V404 Cyg system, is required to understand the observations. The 0.2–2.4 keV light curve of V404 Cyg exhibits substantial variability on timescales of less than a day. Assuming a distance of 3.5 kpc, the quiescent X-ray luminosity of V404 Cyg is 8×10^{33} ergs s^{-1}, nearly two orders of magnitude larger than the upper limit for the X-ray nova and black hole candidate A0620−00, but comparable to neutron star X-ray novae such as Cen X-4. The lack of a significant hard X-ray luminosity in quiescence, the presence of a large and cold neutral region in the accretion disk, and a low-mass accretion rate suggests that an accretion disk instability might account for the outburst of V404 Cyg.

Subject headings: accretion, accretion disks — binaries: close — black hole physics — stars: individual (V404 Cygni) — X-rays: stars

1. INTRODUCTION

X-ray novae are a subclass of low-mass X-ray binaries (LMXBs) which undergo brief episodic outbursts during which their X-ray luminosity can increase by factors of $\sim 10^6$ relative to long intervals of quiescence. During their outbursts, the X-ray and optical properties of X-ray novae are similar to those of bright persistent LMXBs. The outburst of an X-ray nova is thought to be caused by a sudden increase in the mass accretion rate onto a neutron star or black hole. After the peak of the outburst, the X-ray flux declines exponentially to a nearly nondetectable level. The optical light of the system between outbursts and in quiescence is dominated by the spectrum of the donor or secondary star. Mass transfer (Hameury et al. 1986) and accretion disk instability (Huang & Wheeler 1989) models as well as combinations thereof (Chen, Livio, & Gehrels 1993) have been proposed to modulate the mass transfer rate. Recent optical observations of X-ray novae in quiescence indicate that these objects may represent the most promising source of new galactic black hole candidates (for a recent review see Cowley 1992).

The X-ray nova V404 Cyg (GS 2023+338) has emerged as the leading black hole candidate. Spectroscopic observations by Casares, Charles, & Naylor (1992) demonstrated that V404 Cyg consists of a compact object and a late-type secondary star in a binary system with an orbital period of 6.47 days. The mass function implied by their observations is $6.3 \pm 0.3\ M_\odot$ and can be considered a lower limit to the mass of the compact object. The discovery of ellipsoidal light variations by Wagner et al. (1992) not only confirmed the spectroscopic ephemerides, but also suggested that the mass of the compact object might be as high as 19 $M_\odot$ and that the secondary star must be evolved (see also King 1993). The dynamical and photometric properties taken together imply that the mass of the compact object is constrained to be in the range 7–29 $M_\odot$ (Casares & Charles 1994). The spectroscopic and photometric results imply that the compact object in V404 Cyg must be extremely massive and probably a black hole for any reasonable orbital inclination or mass of the secondary star. Thus V404 Cyg provides the best evidence so far for the existence of a stellar mass black hole.

Among the major observational questions regarding these systems are the shape of the X-ray spectrum and the X-ray luminosity during their long periods of quiescence. This information is critical to mass transfer instability models which require a substantial amount of hard X-rays during quiescence to efficiently penetrate and heat the companion star in order to initiate a mass transfer instability and thus produce an out-

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burst. The X-ray luminosity in quiescence for the recurrent X-ray nova Cen X-4 has been measured to be $(1.5–4.2) \times 10^{33}$ ergs s^{-1} (van Paradijs et al. 1987), but this system contains a neutron star and thus may not be characteristic of black hole X-ray novae. The quiescent soft X-ray luminosity of the black hole X-ray nova A0620−00 (McClintock & Remillard 1986) has been measured to be below 10^{32} ergs s^{-1} (Long, Helfand, & Grabelsky 1981). This result suggested that the X-ray luminosities of black hole X-ray novae could be very low in quiescence.

In this *Letter*, we describe the results of X-ray observations of V404 Cyg in quiescence. Our observations provide the first measurement of the emergent X-ray spectrum of a X-ray nova black hole candidate in quiescence.

2. OBSERVATIONS AND RESULTS

On 1992 November 6–7, we obtained X-ray observations of V404 Cyg (1265–1266 days after the outburst) in the 0.2–2.4 keV energy band with the *ROSAT* satellite and Position Sensitive Proportional Counter (PSPC). V404 Cyg returned to its preoutburst or quiescent optical brightness in 1990 July ~400 days after the outburst, and thus our X-ray observations were obtained well after the activity associated with the 1989 outburst subsided. A total on-source integration time of 16.111 ks was achieved with the PSPC in an unfiltered mode. Our observations cover spectroscopic phases 0.40–0.57 (Casares, Charles, & Naylor 1992), where phase zero corresponds to inferior conjunction of the secondary star. Thus, these observations were obtained near inferior conjunction of the accretion disk. V404 Cyg was detected easily and was found to be coincident with the optical and radio positions (Wagner et al. 1991) to within 1".5 in right ascension and 3".5 in declination. A total of 389 ± 21 net counts or an average count rate of 0.024 ± 0.001 counts s^{-1} were obtained for V404 Cyg.

The 0.2–2.4 keV light curve of V404 Cyg during our observations is shown in Figure 1. For this analysis, the data have been averaged into 600 s bins in order to achieve sufficient signal-to-noise ratio. Our observations show that at this time the source decreased in intensity by a factor of 10 over an interval of ≤ 0.5 day. The light curve resembles the decay of a flaring event that began sometime just before the start of our observations or, possibly, indicates an anisotropy of the disk X-ray surface brightness that is modulated by the orbital motion. Our X-ray observations follow a range of orbital phase which is characterized by large residuals from the mean ellipsoidal optical light curve. (Wagner et al. 1992; P. A. Charles, private communication). In addition, inspection of the highest intensity bins shows variability of factors of ~2 on timescales of ~30 minutes. The sampling of the data and faintness of the source precludes further time series analysis.

The observed 0.2–2.4 keV spectrum of V404 Cyg is shown in Figure 2. The spectrum at energies below ~1.3 keV is strongly attenuated by the interstellar medium. The neutral hydrogen absorption column density in this direction has been estimated to be $\log N_H(\mathrm{cm}^{-2}) \simeq 21.7$ as determined by continuum fitting of our optical spectra, the strength of several interstellar absorption lines (Casares et al. 1991; Wagner et al. 1991), and the results of a 21 cm neutral hydrogen absorption experiment at the VLA (Han & Hjellming 1992). The effects of interstellar absorption and the small energy range covered by the spectrum make detailed analysis of the intrinsic shape difficult. We have, however, modeled these data assuming either a blackbody, power law, or thermal bremsstrahlung continuum.

In our initial set of models, we assumed that $\log N_H$ was given by the optical and radio measurements. With this assumption, fits of the data to blackbody and power-law continuua were poor and resulted in relatively large values of the reduced χ^2 (2.7). The largest systematic discrepancy occurred between 0.9 and 1.5 keV in both cases. Thermal bremsstrahlung fits did not converge for any reasonable value of the temperature.

In our second set of models, we varied the absorbing column

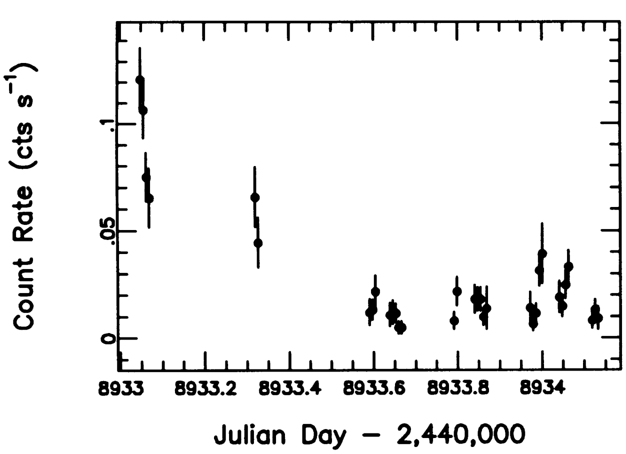

FIG. 1.—X-ray light curves of V404 Cyg obtained 1992 November 6–7 with *ROSAT* in the 0.2–2.4 keV band. Substantial variability on timescales of ≤ 0.5 day is evident. Variations on timescales of 0.5 hr may also be present in the highest intensity bins.

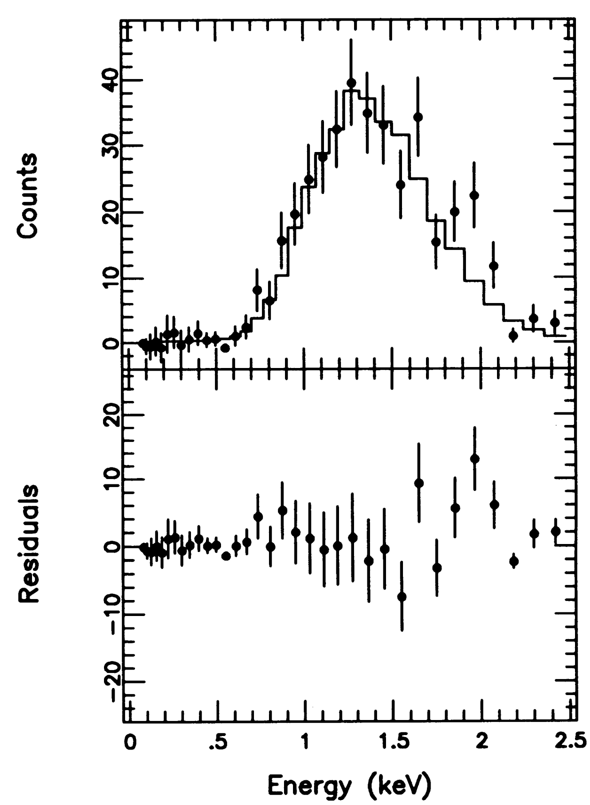

FIG. 2.—*Upper panel:* Observed X-ray spectrum of V404 Cyg (*filled circles*) and the best-fit blackbody model which is characterized by $kT = 0.2$ keV and $\log N_H = 22.1$. *Lower panel:* Residuals of the data and the best-fit blackbody spectrum.

density as well as the continuum parameters during the fitting. We found that these models continuua could fit the observed data equally well in a statistical sense, with a reduced $\chi^2 \simeq 1.7$. All of these models required an absorbing column density in excess of log $N_H \simeq 22.1$. The best-fit blackbody spectrum is shown in Figure 2, and it requires $kT = 0.21 \pm 0.05$ keV and log $N_H = 22.17 \pm 0.15$. The best-fit thermal bremsstrahlung model requires at temperature of 0.33 keV and log $N_H = 22.24$. A fit to a power law requires an energy index of 6 and an absorbing column density of log $N_H = 22.36$. If the interstellar absorption in this direction is characterized by log $N_H = 21.7$ then we require an intrinsic absorption of log $N_H \simeq 22$, in the case of the blackbody fit, to describe the observations.

The total unabsorbed 0.2–2.4 keV flux was 5.53×10^{-12} ergs cm^{-2} s^{-1}. Assuming a distance of 3.5 kpc (Wagner et al. 1992) and the blackbody spectrum described above, we derive a total 0.2–10 keV luminosity of $\simeq 8 \times 10^{33}$ ergs s^{-1} for V404 Cyg in quiescence. If nearly all of the X-rays are produced near the inner edge of the accretion disk and assuming an efficiency for converting mass to radiative energy of 10%, then our X-ray luminosity corresponds to an accretion rate onto the black hole of $\simeq 10^{14}$ g $s^{-1} = 1.4 \times 10^{-12}$ $M_\odot$ yr^{-1}. Given the formal errors in the description of the source spectrum, the luminosity and accretion rate that we have derived are uncertain by factors $\simeq$ 3–4.

3. DISCUSSION

The region containing V404 Cyg was scanned by the Japanese X-ray satellite *Ginga* on 1990 August 15–16, 442 and 443 days after the X-ray peak recorded on 1989 May 30 (Mineshige et al. 1992). These observations were performed nearly 1 month after V404 Cyg had returned to its quiescent optical brightness. However, the source position derived by Mineshige et al. was 0.13 ± 0.10 degree (90% confidence level) away from the position of V404 Cyg (Wagner et al. 1991). They point out that the observed source might have been V404 Cyg if the X-ray luminosity was fluctuating during the scan. Our results demonstrate that V404 Cyg is highly variable in quiescence and thus the positional accuracy of the *Ginga* observations could certainly have been affected by variability. Assuming the source observed by *Ginga* was V404 Cyg, Mineshige et al. derive a 1.2–37.1 keV luminosity (90% confidence) of $(2.8 \pm 1.4) \times 10^{34}(D/3\ \mathrm{kpc})^2$ ergs s^{-1} [assuming log $N_H(\mathrm{cm}^{-2}) = 21.5$]. Our combined results suggest that the X-ray luminosity of V404 Cyg reached or nearly reached its quiescent level in 1990 August and has remained at or near that level ever since.

We note that the quiescent X-ray luminosity we have derived for V404 Cyg is nearly two orders of magnitude larger than the upper limit for the X-ray nova and black hole candidate A0620−00 in quiescence ($\leq 10^{32}$ ergs s^{-1}: Long et al. 1981). On the other hand, its X-ray luminosity is comparable to Cen X-4 (1.5–4.2×10^{33} ergs s^{-1}), but perhaps greater than that of Aql X-1 ($\leq 3 \times 10^{33}$ ergs s^{-1}), both neutron star X-ray transients (van Paradijs et al. 1987). Given these results, it appears that we cannot distinguish between neutron star and black hole systems based solely on their X-ray properties in quiescence.

However, there are many properties of V404 Cyg that distinguish it from other X-ray novae and which make comparisons difficult to interpret. In particular, its 6.5 day orbital period is the longest known among X-ray novae, and its secondary star must be evolved (Casares et al. 1992; Wagner et al. 1992; King 1993). In addition, the X-ray, optical, and radio light curves of V404 Cyg were characterized by a power-law decay proportional to t^{-1} (Han & Hjellming 1992), whereas other X-ray novae, such as A0620−00 and GRO J0422+32 (Shrader et al. 1994 and references therein), exhibited exponentially decaying light curves. The X-ray spectrum of V404 Cyg during the 1989 outburst did not exhibit the strong soft component (Tanaka 1989; Kitamoto et al. 1989) which characterized the outbursts of other X-ray novae such as A0620−00, GS 2000+25, and Nova Muscae 1991. Recently, Sunyaev et al. (1993) reported that GRO J0422+32 did not exhibit the soft component as well.

The observed X-rays from V404 Cyg in quiescence are most likely due to continued accretion onto the compact object at a rate of $\sim 10^{-12}$ $M_\odot$ yr^{-1}. If the compact object is a black hole, neither X-ray radiation from a boundary layer or thermal emission from the surface of the compact object itself can give rise to the observed X-rays. For comparison, the accretion rate at the peak of the 1989 outburst has been estimated to be 3–9×10^{-7} $M_\odot$ yr^{-1} assuming a Schwarzschild black hole (Casares et al. 1993). We emphasize that the rate we have derived is not necessarily equal to the mass flow rate through the disk at an arbitrary radius or even the mass-loss rate from the companion star.

Most important, our observations indicate that the emergent X-ray spectrum of V404 Cyg is soft during quiescence. This suggests that the 1989 outburst was not initiated by a mass transfer instability. A mass transfer instability model requires a substantial hard X-ray ($kT \geq 7$ keV) flux from the accretion disk in quiescence with a strength greater than the surface flux from the companion star in the vicinity of the inner Lagrangian point L1 (Hameury et al. 1986). For a 10 $M_\odot$ black hole and either a low-mass K0 IV or stripped giant companion star (Wagner et al. 1992; King 1993), we find that a hard X-ray luminosity exceeding 2×10^{36} ergs s^{-1} in quiescence is required to initiate a mass transfer instability for V404 Cyg. This hard X-ray luminosity does not appear to be present in our data.

However, a mass transfer instability might still remain a viable model to explain the outbursts if the system undergoes a transition to a higher state with the required hard X-ray luminosity while in quiescence or perhaps just before an outburst. A scan of the region containing V404 Cyg was performed by *Ginga* 320 days before the 1989 May 21 outburst (Mineshige et al. 1992). They found that V404 Cyg was not detected and derived a 2 σ upper limit to the 1.2–37.1 keV luminosity of $5.2 \times 10^{34}(D/3\ \mathrm{kpc})^2$ ergs s^{-1}. Thus, the X-ray luminosity just prior to the outburst was not larger than our measurement 1260 days after the outburst and therefore a preoutburst high state seems unlikely. We stress, however, that V404 Cyg has been observed only three times in quiescence, and in the relatively short time interval between 1988 and 1992, while the interval between outbursts is $\simeq 50$ yr (Duerbeck 1987). Continued monitoring of V404 Cyg at X-ray wavelengths over the next several decades may be worthwhile.

Thus, the lack of a significant hard X-ray flux, the probable presence of a large, extended, and cold neutral region in the accretion disk, and a low mass accretion rate suggest that an accretion disk instability is a more likely model for the outburst of V404 Cyg than a mass transfer instability. Disk instability models have been very successful in accounting for the outbursts of dwarf novae and nova-like systems (see Wheeler, Kim, & Mineshige 1992 and references therein). Disk instability models predict low X-ray luminosities during quiescence because the temperature in the inner regions of the accretion disk is low. We note that the accretion rate onto the compact object that we derive for V404 Cyg falls within the thermally unstable region (Mineshige & Wheeler 1989). The lower X-ray luminosities and accretion rates of other X-ray novae which contain black hole candidates, such as A0620−00, suggest that their outbursts may also be caused by accretion disk instabilities (Huang & Wheeler 1989; Mineshige & Wheeler 1989).

A temperature of 0.2 keV is high enough to produce highly ionized emission lines in the optical spectrum of V404 Cyg. However, the optical spectrum of the accretion disk in quiescence is dominated by the Balmer series of hydrogen, which exhibits a standard case B recombination decrement (although the errors are large) appropriate for a gas with an electron temperature $\sim 10^4$ K (Casares et al. 1993), and weak He I $\lambda\lambda$4471, 5876 emission lines; He II λ4686 emission is very weak or absent (Fig. 3; Fig. 1 of Casares et al. 1993). From these data, we estimate its strength (corrected for reddening) to be ≤ 0.2 I(Hβ). Weak or absent He II emission lines in quiescence seems to be typical of other X-ray nova black hole candidates as well (A0620−00: Marsh, Robinson, & Wood 1994; Nova Muscae 1991: Remillard, McClintock, & Bailyn 1992). Evidently, the production of these emission lines depends critically on the geometry of the accretion disk and the angular distribution of the emitted X-rays. Given our results and a given disk geometry, a photoionization model could be constructed in an effort to predict the optical spectrum and continuum and thus study the ionization and excitation of the emission lines.

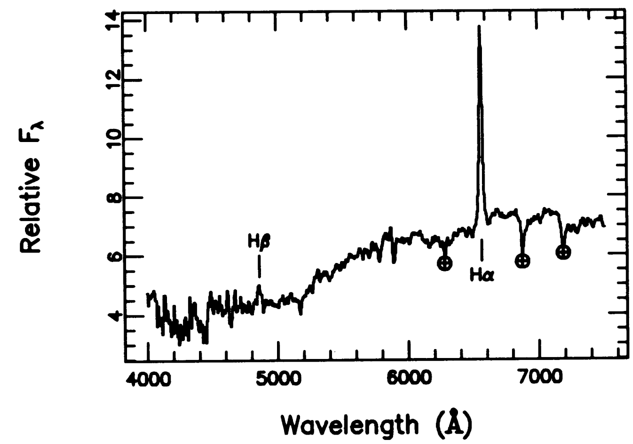

FIG. 3.—Average unreddened ($A_V = 3.3$ mag) optical spectrum of V404 Cyg in quiescence obtained at the MMT in 1991 and 1992. The spectrum of the accretion disk is dominated by the Balmer series of hydrogen. The FWHM of the Balmer lines is $\simeq 1100$ km s^{-1}. He II λ4686 and other high-ionization emission lines are weak or absent. The absorption line spectrum of the late-type K0 companion star is also evident.

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