The Astrophysical Journal, 578:L59–L62, 2002 October 10

CHANDRA OBSERVATIONS OF THE RECURRENT NOVA CI AQUILAE AFTER ITS 2000 APRIL OUTBURST

J. Greiner[1,2] and R. Di Stefano[3,4]

Received 2002 July 5; accepted 2002 September 4; published 2002 September 16

ABSTRACT

We report the results of two *Chandra* observations of the recurrent nova CI Aql at 14 and 16 months after its outburst in 2000 April. The X-ray emission is faint in both cases, without any noticeable change in spectrum or intensity. Although the emission is very soft, it is not luminous enough to be due to late-time H burning. This implies that the luminous supersoft phase ended even before the time predicted by the most recent calculations. The details of the X-ray spectrum, together with the fact that the observed X-ray intensity is brighter than preoutburst (1992/1993), suggest that the observed X-ray emission is either due to ionization of the circumstellar material or due to the shocks within the wind and/or with the surrounding medium.

Subject headings: binaries: close — novae, cataclysmic variables — stars: individual (CI Aquilae) — X-rays: stars

1. INTRODUCTION

Recurrent novae (RNe) are a rare subclass of cataclysmic variables, showing repeated outbursts with typical recurrence times of 50–100 yr. These outbursts are thought to be thermonuclear runaways on the surface of a white dwarf that has accreted enough material from the companion star to ignite the surface hydrogen. If the hot white dwarf could be observed directly, it would have the characteristics of a supersoft X-ray source (SSS); i.e., its luminosity would lie between $\sim 10^{36}$ and 10^{38} ergs s^{-1}, with kT on the order of tens of eV (Nomoto 1982; Fujimoto 1982; Iben 1982). The short recurrence times require either or both small envelope masses and high accretion rates on the order of $\sim 10^{-8}\ M_\odot$ yr^{-1} (Warner 1995). Since the ejecta of RNe typically are not metal-enriched, the white dwarfs in RNe are not significantly eroded but may grow in mass (Starrfield, Sparks, & Truran 1985). The fitting of RN optical light curves suggests that the white dwarf masses are high, near the Chandrasekhar limit (e.g., Hachisu & Kato 1999; Hachisu et al. 2000), suggesting that RNe may be progenitors of Type Ia supernovae (SNe Ia).

Although only eight other RNe are known, three subclasses are defined (Warner 1995) according to the nature of the companion and, consequently, the length of orbital period: the T Pyx subclass with dwarf companions ($P \sim 2$–3 hr), the U Sco subclass with evolved main-sequence or subgiant companions ($P \sim 1$ day), and the RS Oph subclass with red giant companions ($P \gtrsim 100$ days).

CI Aql was discovered when it showed a $\Delta m = 4.6$ mag outburst in 1917 (Reinmuth 1925). It was classified as a dwarf nova with long cycle length (Duerbeck 1987), but this was cast in doubt (Szkody & Howell 1992; Greiner, Alcala, & Wenzel 1996) until a second outburst, discovered in 2000 April (Takamizawa 2000), revealed CI Aql to be an RN. A subsequent search in the Harvard Plate collection led to the discovery of another outburst in 1941/1942 (Schaefer 2001b). CI Aql is an eclipsing binary system with an orbital period of 14.84 hr (Mennickent & Honeycutt 1995) and therefore belongs to the U Sco subclass.

RNe are expected to emit soft X-rays during a short interval after the ejected shell has become optically thin and before the hydrogen shell burning ceases and during an interval of cooling. During this time, the effective radius should be somewhat larger than the radius of the white dwarf, and the luminosity should therefore be larger than 10^{37} ergs s^{-1}. Thus, it should fit the profile of an SSS. The only previous RNe observed with X-ray detectors were T Pyx and U Sco. T Pyx has had its last outburst in 1967 but was argued to be a quasi-persistent SSS because optical data suggested a luminosity of $\sim 10^{36}$ ergs s^{-1} (Patterson et al. 1998). T Pyx was not detected, however, in a *ROSAT* Position Sensitive Proportional Counter observation carried out in 1998 December (J. Greiner 1999, unpublished). A *BeppoSAX* observation carried out 20 days after the U Sco outburst revealed a luminous ($\sim 10^{36}$ ergs s^{-1}) soft X-ray component with a best-fit temperature of $\sim 9 \times 10^5$ K, consistent with steady nuclear burning continuing for at least ~1 month after the nova outburst (Kahabka et al. 1999). Further observations of the evolution of the soft and hard X-ray emission in other sources are crucial to better test theoretical models and also to test the conjecture that RNe are SN Ia progenitors.

Based on the observed optical light curve of CI Aql over the first year after the 2000 outburst, Hachisu & Kato (2001) predicted that CI Aql should have been active at soft X-ray wavelengths from 2000 December until 2001 August. This motivated us to observe CI Aql using *Chandra*.

2. OBSERVATIONS AND RESULTS

We obtained two *Chandra* observations using ACIS-S. The first one was performed on 2001 June 1, for 2.15 ks, and the second one on 2001 August 1, for a total of 19.88 ks (see Table 1 for details).

During the first *Chandra* observation, we detected CI Aql with a count rate of $(6.0 \pm 2.3) \times 10^{-3}$ counts s^{-1}, collecting a total of 15 photons. In the August observation, the mean count rate was $(8.6 \pm 0.7) \times 10^{-3}$ counts s^{-1}; thus, CI Aql exhibited the same X-ray intensity as on 2000 June 1.

No single-component model fits the X-ray spectrum of CI Aql (second observation; Figs. 1–3). As a first approximation, and since the spectrum looks thermal, we have used a blackbody spectrum plus a power law and find a reasonably good fit with $kT = 50 \pm 20$ eV and a power-law photon index of 1.78 ±

[1] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany.

[2] Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse Postfach 1312, 85741 Garching, Germany; jcg@mpe.mpg.de.

[3] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; rdistefano@cfa.harvard.edu.

[4] Department of Physics and Astronomy, Tufts University, Robinson Hall, Medford, MA 02155.

TABLE 1
Observation Log

Observation Interval (UT)	Exposure Time (ks)	Sequence Number	Observation ID	Count Rate (counts ks^{-1})
2001 Jun 01 20:21–21:31	2.15	300054	2465	6.0 ± 2.3
2001 Aug 01 12:24–18:27	19.88	300056	2492	8.6 ± 0.7

0.72. Note, though, that owing to the small number of photons, the fit parameters are correlated, and therefore the reduced $\chi^2_{\rm red}$ is smaller than 1. Using a white dwarf atmosphere model (van Teeseling, Heise, & Paerels 1994) gives a similar value of $kT = 38 \pm 15$ eV. The best-fit absorbing column is 3.6×10^{21} cm^{-2} (for the blackbody model) or 5.5×10^{21} cm^{-2} (for the white dwarf atmosphere model), consistent with the foreground extinction of $E(B-V) = 0.85$ (Kiss et al. 2001) but considerably less than the total Galactic column in this $b = -0\overset{\circ}{.}8$ direction of 1.5×10^{22} cm^{-2} (Dickey & Lockman 1990). The unabsorbed luminosity of the blackbody (white dwarf atmosphere) component is $1.0 \times 10^{33}(D/1\ {\rm kpc})^2$ ergs s^{-1} [$8.0 \times 10^{32}(D/1\ {\rm kpc})^2$ ergs s^{-1}].

Physically, such a high-temperature optically thick emission at such a low luminosity is difficult to explain. The corresponding radius of the emitting area would be 40 km, a minute fraction of the white dwarf radius. We therefore turned to other spectral models (see Table 2).

In some recent X-ray grating observations of novae, the spectra show a wealth of narrow emission lines in the 0.2–2 keV range. Although most of the identifications of these lines and their origin are not settled, we considered the possibility that pure line emission at soft energies could model the spectrum of CI Aql: to model the main emission around 0.5 keV, we need only one Gaussian line with a width corresponding to the energy resolution of ACIS-S. The best-fit line energy is 0.358 keV. The spectrum at high energies (above ∼4) can similarly be fitted by models other than a power law. A Raymond-Smith model gives a best-fit temperature of $kT = 2.7 \pm 2.4$ keV; a thermal bremsstrahlung model gives $kT = 3.1 \pm 3.0$ keV. Of course, the spectrum could also be explained by a superposition of several lines, but we do not have enough photons and/or spectral resolution to resolve this issue.

The first-epoch spectrum can be fitted by the model parameters of the fit to the second-epoch observation. This is not a great surprise given the few photons in the first-epoch spectrum. Yet, we can conclude that (1) the intensity was seemingly steady and (2) no major spectral change (change in the emission mechanism) occurred between the two *Chandra* observations both in the soft as well as in the hard component—this also excludes any dramatic decrease of absorption, which is expected once the expelled shell gets optically thin for X-rays, or cooling of the soft component (although this cannot be directly proven with the 15 detected X-ray photons).

The second *Chandra* observation covers about 40% of the orbital period of CI Aql. We therefore analyzed the temporal behavior of the X-ray emission but did not find orbital variability.

3. DISCUSSION

After our *Chandra* observations occurred, more optical data became available (Schaefer 2001a), leading Hachisu & Kato (2002) to revise their modeling of the optical decay light curve of CI Aql. The important new result of their revision for the interpretation of our *Chandra* data is that the supersoft X-ray phase should have lasted only until 2001 May, thus ending even before the first of our *Chandra* observations. But the source would have remained hot and several orders of magnitude more luminous than observed had nuclear burning ended as recently as 2001 May.

The faintness of the detected X-ray emission and the fit results of a blackbody (or white dwarf atmosphere) model indeed suggest that CI Aql was not in the nova plateau phase during our *Chandra* observations. Instead, the luminosity derived for an optically thick emission model explaining the soft part of the X-ray spectrum is only on the order of $10^{33}(D/1\ {\rm kpc})^2$ ergs s^{-1}.

However, even beyond the plateau phase the system should be observable as an SSS, because the cooling of the hot white dwarf and the concordant luminosity decay is expected to last months to years. Model calculations (I. Hachisu & M. Kato 2002, in preparation) show that the temperature should have declined by a factor of ∼2 (from 55 to 30 eV) between our

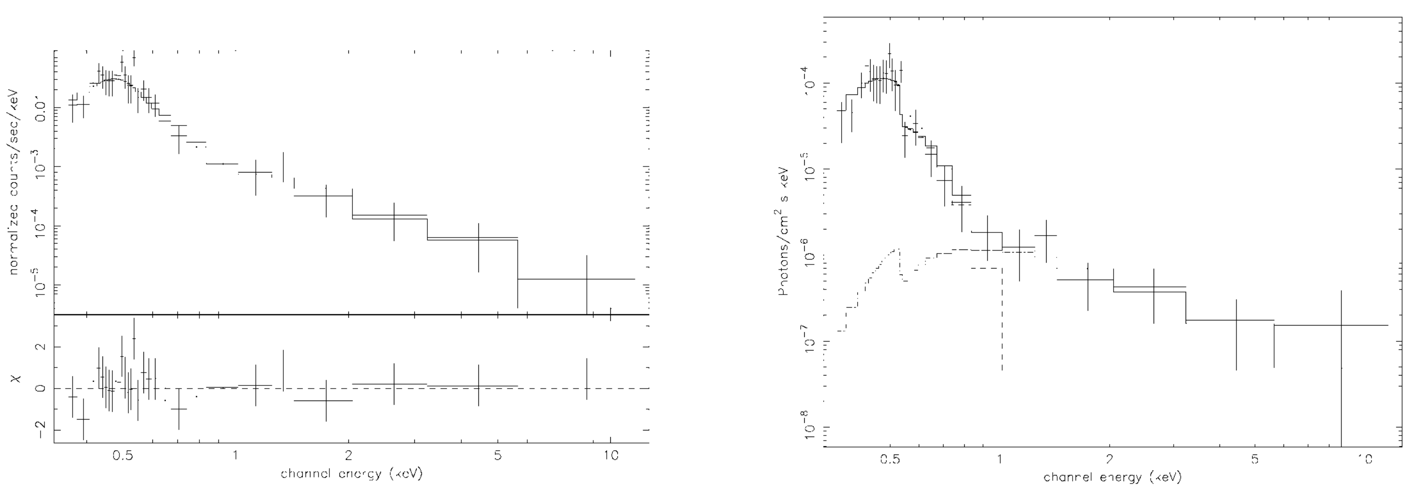

Fig. 1.—X-ray spectrum of CI Aql as measured (*left panel*) with *Chandra* ACIS-S on 2001 August 1, composed of a blackbody (*right panel*; *dashed line*) and a power law (*right panel*; *dotted line*) model.

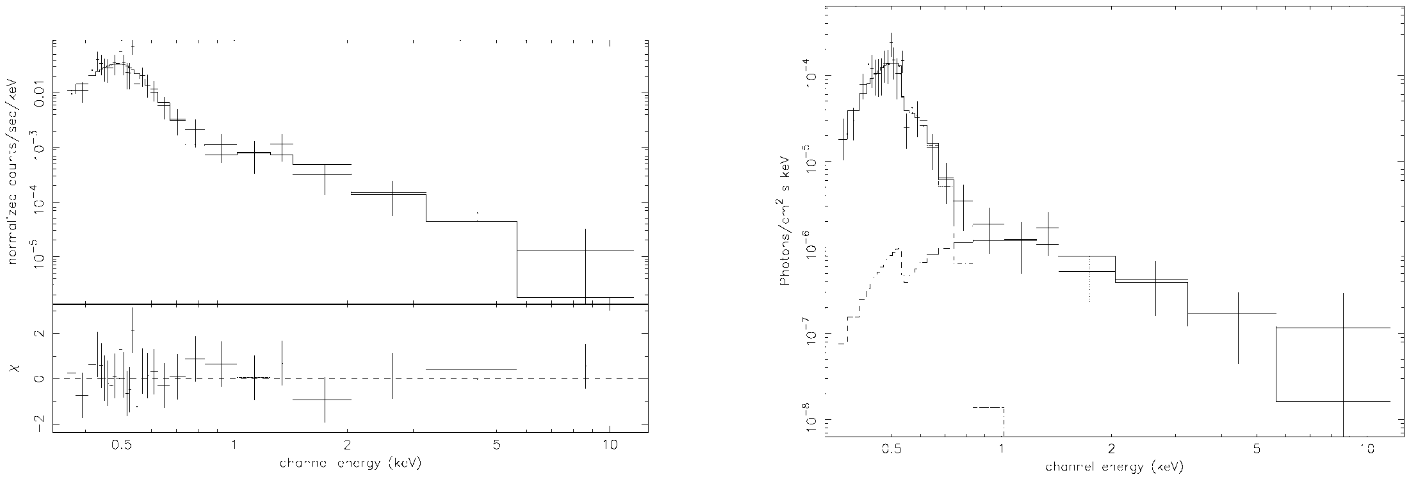

FIG. 2.—X-ray spectrum of CI Aql as measured with *Chandra* ACIS-S on 2001 August 1, composed of one Gaussian line (*right panel*; *dash-dotted line*) and a thermal bremsstrahlung (*right panel*; *dotted line*) model.

two *Chandra* observations, whereas the *Chandra* data do not allow a temperature change by more than 10 eV. These model calculations also suggest that in the 2001 June–August time frame the luminosity of the cooling white dwarf would still be in the 10^{37}–10^{36} ergs s^{-1} range, at least a factor of 1000 more than the observed X-ray luminosity. Thus, we find it very unlikely that the soft X-ray component around 0.5 keV is an optically thick component from the (cooling) white dwarf. This implies that nuclear burning ended earlier than indicated by even the revised prediction.

Alternatively, the soft component could be composed of (a) nonresolved emission line(s). After fitting a Gaussian line to the soft component, one realizes that the spectral resolution of ~100 eV makes this Gaussian line broad enough to fit perfectly the soft component, and not even a second Gaussian line is necessary to explain the X-ray emission below 0.7 keV. The best-fit line energy for this Gaussian is 0.358 ± 0.058 keV, and the unabsorbed line luminosity $2.7 \times 10^{32}(D/1\ \mathrm{kpc})^2$ ergs s^{-1}. We suggest this line to be the H-like C VI line (nominal energy at 0.3676 keV).

When we rebin the spectrum into only 1 σ confidence level bins (Fig. 3), the search for possible further excess emission above the broadband continuum emission at higher energies reveals marginal evidence for possible lines at 0.8, 1.28, and 6.3 keV. These could be interpreted as O VII, Ne IX, or Mg X and Fe XXVI lines. Given the signal-to-noise ratio of the spectrum, this is speculative.

The hard spectrum is not constrained: it could be fitted by either a power law, a Raymond-Smith model, or a bremsstrahlung model. Also the marginal Fe detection does not provide a clue for its origin (e.g., reflection off the disk or thermal plasma). Indeed, the Fe emission could be due to matter from the white dwarf, consistent with the strong Fe II lines seen in the optical spectra (Kiss et al. 2001). The small temperature on the order of 3 keV, if interpreted as thermal emission, is consistent with CI Aql having had a very slow nova outburst, and a rather low expansion velocity, a correlation that has been found already in earlier novae (e.g., Mukai & Ishida 2001 for Nova V382 Vel).

We note, on the other hand, that the unabsorbed luminosity of this hard component of $\sim10^{30}(D/1\ \mathrm{kpc})^2$ ergs s^{-1} (0.5–10 keV) is in the range of X-ray luminosities usually found in cataclysmic binaries during quiescence. However, CI Aql during quiescence is definitely fainter: *ROSAT* observations in 1992 and 1993 failed to detect CI Aql, implying an upper limit on the unabsorbed X-ray luminosity of 5×10^{29} ergs s^{-1} $(D/1\ \mathrm{kpc})^2$ in

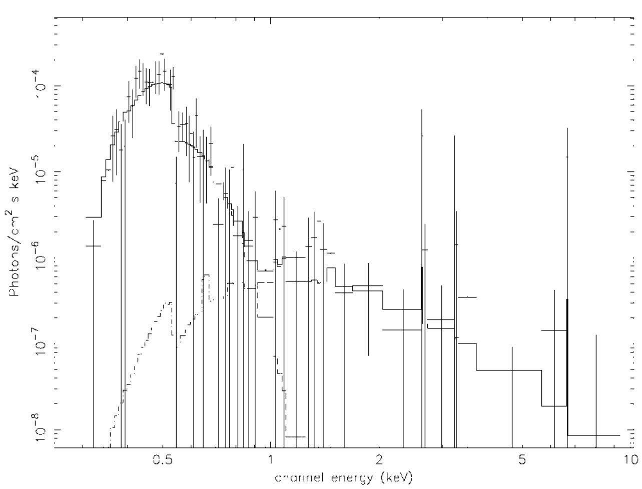

FIG. 3.—X-ray spectrum of CI Aql as measured with *Chandra* ACIS-S on 2001 August 1, composed of a blackbody and a Raymond-Smith model. The binning has been reduced to only 1 σ confidence to visualize the possible excesses at 1.3, 2.6, 3.3, and 6.6 keV (see text).

TABLE 2

PARAMETERS OF THE SPECTRAL FITS

Model Component	Parameters
Blackbody + Power Law: $N_H = 3.6 \pm 0.2$; $\chi_{red} = 0.69$	
Blackbody	$kT = 50 \pm 20$ eV, norm = 3.18E−05
Power law	$\alpha = 1.78 \pm 0.72$, norm = 2.16E−06
White Dwarf Atmosphere + Power Law: $N_H = 5.5 \pm 0.2$; $\chi_{red} = 0.72$	
White dwarf atmosphere	$kT = 43 \pm 15$ eV, norm = 1.58E−05
Power law	$\alpha = 1.86 \pm 0.95$, norm = 5.42E−06
1 Gaussian + Bremsstrahlung: $N_H = 2.9 \pm 0.2$; $\chi_{red} = 0.60$	
Gaussian 1	$E_L = 0.363$, $W_L = 0.11$, norm = 7.03E−04
Bremsstrahlung	$kT = 3.1 \pm 3.0$ eV, norm = 3.25E−06
2 Gaussians + Bremsstrahlung: $N_H = 2.9 \pm 0.2$; $\chi_{red} = 0.64$	
Gaussian 1	$E_L = 1.254$, norm = 3.59E−07
Gaussian 2	$E_L = 0.364$, norm = 7.03E−04
Bremsstrahlung	$kT = 6.1 \pm 3.0$ eV, norm = 2.45E−06

NOTE.—N_H = absorbing column ($\times 10^{21}$ cm^{-2}); E_L = line energy; W_L = line width; norm = normalization.

the 0.1–2.4 keV range (Greiner et al. 1996). Thus, 16 months after its outburst, CI Aql had not yet returned to its quiescent level of X-ray emission.

Thus, it seems clear that we observed the CI Aql system when it had ended both the phase of shell burning and cooling as well as the phase in which the wind was obscuring the soft emission. In the cases of Nova V382 Vel (Burwitz et al. 2002) and V1494 Aql (Krautter et al. 2002), it has recently been possible to observe the dramatic changes of the X-ray emission of novae from a highly absorbed spectrum during the very early times, over the development and subsequent fading of a luminous supersoft X-ray component toward a completely line-dominated spectrum with hardly any detectable continuum. While the first two stages of this evolution are physically well understood in terms of the expanding shell blocking less and less of the X-radiation of the white dwarf until burning on its surface ceases, the origin of the line-dominated spectrum is not clear. One possibility is that during the late phase of a nova, when the shell has become transparent, the medium around the system is ionized by the still UV-EUV bright white dwarf. It would require far less than one part in a thousand conversion efficiency of photoionization of the C VI line to explain, e.g., the spectrum of CI Aql as observed with *Chandra*, consistent with photoionization models around supersoft ionizers (Rappaport et al. 1994). However, because of the steep and rapidly changing density profile due to the expanding shell/wind, the recombination emission may be rapidly suppressed. Alternatively, the line-dominated spectrum could result from the interaction of the expanding shell with the circumstellar matter, shocks within the expanding shell, or shocks due to collisions of a fast wind with the interstellar matter. Detailed investigations of the complex emission-line spectra have just begun and promise a better understanding in the near future.

We are indebted to H. Tananbaum for granting director's discretionary time for the *Chandra* observations. We thank I. Hachisu and M. Kato for prompt information on their modeling of CI Aql. This material is based on work supported by the National Science Foundation under grant 9815655 and by a NASA LTSA award, NAG5-10705.

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