QUIESCENT THERMAL EMISION FROM THE NEUTRON STAR IN AQUILA X-1

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ABSTRACT

We report on the quiescent spectrum measured with Chandra ACIS-S of the transient, type I, X-ray-bursting neutron star Aql X-1, immediately following an accretion outburst. The neutron star radius, assuming a pure hydrogen atmosphere and a hard power-law spectrum, is \( R_\odot = 13.4^{+0.3}_{-0.2}(d/5 \text{ kpc}) \) km. Based on the historical outburst record of the Rossi X-Ray Timing Explorer All-Sky Monitor, the quiescent luminosity is consistent with that predicted by Brown, Bildsten, and Rutledge from deep crustal heating, lending support to this theory for providing a minimum quiescent luminosity of transient neutron stars. While not required by the data, the hard power-law component can account for \( 18\% \pm 8\% \) of the 0.5–10 keV thermal flux. Short-timescale intensity variability during this observation is less than 15\% rms (3 \( \sigma \); 0.0001–1 Hz, 0.2–8 keV). Comparison between the Chandra spectrum and three X-ray spectral observations made between 1992 October and 1996 October find all spectra consistent with a pure H atmosphere, but with temperatures ranging from 145 to 168 eV, spanning a factor of \( 1.87 \pm 0.21 \) in observed flux. The source of variability in the quiescent luminosity on long timescales (greater than years) remains a puzzle. If from accretion, then it remains to be explained why the quiescent accretion rate provides a luminosity so nearly equal to that from deep crustal heating.

Subject headings: stars: atmospheres — stars: individual (Aquila X-1) — stars: neutron — X-rays: binaries

1. INTRODUCTION

Brown, Bildsten, & Rutledge (1998, hereafter BBR98) showed that the core of a transiently accreting neutron star (NS) such as Aql X-1 (for reviews of transient neutron stars, see Chen, Shrader, & Livio 1997; Campana et al. 1998a) is heated by nuclear reactions deep in the crust during accretion outbursts. The core is heated to a steady state in \( \sim 10^4 \) yr (see also Colpi, Geppert, & Page 2000), after which the NS emits a thermal luminosity in quiescence of (BBR98)

\[
L_q = 8.7 \times 10^{33} \left( \frac{\langle M \rangle}{10^{-10} M_\odot \text{ yr}^{-1}} \right) \times \frac{Q}{1.45 \text{ MeV}/m_p} \text{ ergs s}^{-1},
\]

where \( \langle M \rangle \) is the time-averaged mass-accretion rate onto the NS, and \( Q \) is the amount of heat deposited in the crust per accreted nucleon (Haensel & Zdunik 1990; see Bildsten & Rutledge 2000 for a discussion).

Aql X-1 has been detected in X-ray quiescence five times: once with the ROSAT HRI, twice with the ROSAT Position Sensitive Proportional Counter (PSPC; Verbunt et al. 1994), once with ASCA (Asai et al. 1998), and once with BeppoSAX (Campana et al. 1998b, hereafter C98). We report in this paper the detection and CCD X-ray spectroscopy of a Chandra observation of Aql X-1 in quiescence, and compare its luminosity and spectrum with most of these previous observations. We show that the quiescent X-ray spectrum is consistent with thermal emission from a pure H atmosphere on the NS (Rajagopal & Romani 1996; Zavlin, Pavlov, & Shibanov 1996), as is observed from this and other transient neutron stars in quiescence (Rutledge et al. 1999, 2000, 2001). As pointed out by BBR98, for accretion rates \( \lesssim 2 \times 10^{-13} M_\odot \text{ yr}^{-1} \), gravity stratifies metals in the NS atmosphere faster than they can be provided by accretion (Bildsten, Salpeter, & Wasserman 1992), making a pure H atmosphere the appropriate description of the NS photosphere.

Callanan, Filippenko, & Garcia (1999) recently showed that the optical counterpart to Aql X-1 is a faint star near the previously misidentified counterpart. This led to the counterpart’s identification as a late-type star (spectral type K7–M0) with a quiescent magnitude \( V = 21.6 \) at a reddening of \( A_V \approx 1.6 \) (Chevalier et al. 1999). The orbital period has been well measured at \( P_{\text{orb}} = 18.95 \) hr, via photometric observations both in outburst (Chevalier & Ilovaisky 1998; Garcia et al. 1999) and quiescence (Welsh, Robinson, & Young 2000).

Chevalier et al. (1999) estimated the distance to the binary as 2.5 kpc by assuming that the counterpart was a main-sequence star of spectral type K7, or roughly \( M_c \approx 0.6 M_\odot \) and \( R_c \approx 0.6 R_\odot \). However, the steady mass transfer and ellipsoidal variations (Welsh et al. 2000) require that the companion be Roche lobe filling, which gives \( R_c \approx 1.65 R_\odot (M_c/M_\odot)^{1/3} \), larger than Chevalier et al.’s estimate. If we use the dereddened quiescent \( V \) magnitude, we find that the distance to the binary is \( d = 4.7 \) kpc (for spectral type K7) for \( M_c = 0.5 M_\odot \) and \( 6.4 \) kpc for \( M_c = 1.0 M_\odot \). For a spectral type of M0, we find \( d = 4 \) kpc for \( M_c = 0.5 M_\odot \) and 5 kpc for \( M_c = 1.0 M_\odot \). Thus, the clear minimum distance is 4 kpc, and the current uncertainties allow for a distance as large as 6.5 kpc. The type I bursts observed by Czerny,
Czerny, & Grindlay (1987) had peak fluxes of \( \approx 7 \times 10^{-8} \) ergs cm\(^{-2}\) s\(^{-1}\), which gives a solar abundance Eddington luminosity of \( 2 \times 10^{38} \) ergs s\(^{-1}\) at \( d = 5 \) kpc. We use 5 kpc as our fiducial distance.

In § 2, we describe the Chandra observation and the constraints on variability during the observation. Section 3 shows our results on the spectral analysis and compares the Chandra observations with previous quiescent observations. We conclude § 3 with a comparison of the observed luminosity to that predicted by equation (1). We discuss these results in the context of alternate emission mechanisms in § 4.

2. CHANDRA OBSERVATIONS AND TIMING ANALYSIS

Aql X-1 was observed with Chandra (Weisskopf 1988) using the ACIS-S3 detector in imaging mode, beginning 2000 November 28, 10:51:35 UT, 7 days after the last 1 day detection (3 \( \sigma \), \( \approx 20 \) mcrab) with the Rossi X-Ray Timing Explorer All-Sky Monitor (RXTE ASM; Levine et al. 1996) during the outburst.

The X-ray source position was offset 4' from the optical axis to mitigate pileup. The observation had a total exposure time of 6627.6 s over a period of 7307.6 s (90% live time), with a time resolution of 0.44104 s and a 0.4 s exposure. One X-ray source is detected in the field, at a position (based on spacecraft pointing) of \( x = 19^h 11^m 16^s 00, \) \( \delta = 00^\circ 35' 06'' 4 (J2000) \), with systematic errors dominating the uncertainty of position (\( \pm 1' \)), consistent with the known optical position of Aql X-1 (Thorstensen, Charles, & Bowyer 1978; Callanan et al. 1999).

The data were analyzed using CIAO v2.0 \(^6\) and XSPEC v11 (Arnaud 1996). X-ray source counts were extracted within an area 10 pixels in radius about the source position, with a total of 1243 counts. At 0.075 counts per frame, the pileup fraction was <3% and could be neglected. Background was taken from an annulus centered on the source position, with radii of 13 and 50 pixels. The expected number of background counts in the source region was 8 counts, which was neglected in our analyses.

We binned the 0.2–8 keV counts into three light curves with three different time resolutions: \( \delta T = 0.44104 \) s, 10, and 100 s. In each case, the distribution of the number of counts per bin was consistent with a Poisson distribution, for an average number of counts per bin of (1237 counts)/(7308 s/\( \delta T \)). We also produced a power density spectrum (PDS), beginning with a light curve of all the counts in the source region with a time resolution of 0.44104 s, producing a 0.00014–1.13 Hz PDS. The PDS is statistically consistent with a constant power at the Poisson level, and shows no evidence of any excess variability. Fitting the PDS with a power-law component with a fixed slope (\( \propto v^{-1} \)) above a (fixed) Poisson level gives a 3 \( \sigma \) upper limit to the rms variability of <15% (0.0001–1 Hz; 0.2–8 keV). We thus find no evidence of intensity variability during the Chandra observation.

3. SPECTRAL ANALYSIS

We bin the data into 13 energy bins (0.5–8.0 keV), and fit several single-component spectral models (power-law, H atmosphere, Raymond-Smith, multicolor disk, or blackbody). We also include H atmosphere with a power law, with two fixed values for the power-law slope (\( \alpha = 1 \) and 2). Galactic absorption (\( N_H = 10^{22} N_{H,22} \) cm\(^{-2}\)) is initially left as a free parameter. The best-fit models are all statistically acceptable, and most give column densities consistent with \( A_V = 1.6 \) and \( N_{H,22} = 0.179 A_V \) (Gorenstein 1975; Predehl & Schmitt 1995); the parameters are given in Table 1.

The Raymond-Smith spectrum has a metallicity substantially below the solar value (\( Z < 5 \times 10^{-3} Z_\odot \)). In addition, Bildsten & Rutledge (2000) showed that the quiescent X-ray–to–optical flux ratio of Aql X-1 (\( \sim 10^{0.5} \pm 0.3 \) ) is much greater than the maximum observed from quiescent stellar coronae \( (F_X/F_\text{opt} \lesssim 10^{-3}) \), so we exclude the stellar coronae as a possible solution. The single power-law spectrum requires a higher column density than the optically implied value (\( N_{H,22} = 0.72 \) vs. 0.30) and is much steeper (photon slope \( \alpha = 4.1 \)) than is typically observed from nonthermal X-ray sources. We reject the model on this basis.

Standard Shakura-Sunyaev (Shakura & Sunyaev 1973) disks have largely been excluded as the dominant emission of transients in quiescence (McClintock, Horne, & Remillard 1995), although recent interest in alternative disk models (Nayakshin & Svensson 2001) suggest that it is useful to constrain parameters for a multicolor disk model. In addition, although blackbody emission does not physically describe the emergent spectrum from a transient neutron star atmosphere in quiescence (BBR98), we include these spectral parameters as well for the interested reader. Neither \( R_{\text{in}} \) of the multicolor disk model nor \( R_{\text{in}} \) of the blackbody model appear to correspond to any physically interesting values; both are smaller than canonical NS radii.

The simplest interpretation of the spectrum is thermal emission from a pure hydrogen atmosphere on the NS, and so we include the best-fit parameters in Table 1. However, previous observations have found a power-law component that dominates the quiescent spectrum at high energies in Aql X-1 (C98) and in the transient Cen X-4 (Asai et al. 1996; Campana et al. 2000; Rutledge et al. 2001), with values between \( \alpha = 1 \) and 2. We include a power-law component, with slope fixed alternately at \( \alpha = 1 \) and 2. An F-test (Press et al. 1995) shows that the additional spectral component does not significantly improve the model fit (probability = 0.07 and 0.13, respectively). The resulting values of \( R_{\text{in}} \) are systematically higher, while \( kT_{\text{eff,}} \) is systematically lower, indicating that the presence of a weak power law may be biasing the pure H atmosphere spectral-model parameters. We therefore prefer the values from the H atmosphere plus \( \alpha = 1 \) spectral model (over the H atmosphere spectral model alone) of \( R_{\text{in}} = 13.4 \pm 2.0 \) km and \( kT_{\text{eff,}} = 135 \pm 19 \) eV (see Fig. 1). These are not significantly different from those of the \( \alpha = 2 \) spectral model.

When we hold \( N_{H,22} \) fixed at its best-fit value, we obtain (for the \( \alpha = 1 \) spectrum) \( R_{\text{in}} = 13.4 \pm 2.0 \) km and \( kT_{\text{eff,}} = 135 \pm 19 \) eV, indicating that the uncertainty in \( N_{H} \) has a modest effect on the uncertainty in the H atmosphere spectral parameters.

Here \( kT_{\text{eff,}} \) and \( R_{\text{in}} \) are the effective temperature and NS radius as measured by a distant observer. They obey the relation \( L_{\text{bol}} = 4 \pi R_0^2 \sigma T_{\text{eff,}}^4 \), where \( L_{\text{bol}} \) is the luminosity measured by a distant observer. The "proper" values of \( kT_{\text{eff}} \) and \( R \) are related to those at infinity through the gravitational redshift parameter \( \zeta = [(1 - 2GM/Rc^2)]^{1/2} \) (the redshift is \( z = G \zeta^{-1} \)); for a neutron star of mass 1.4 \( M_\odot \) and radius 10 km, \( g_\gamma = 0.766 \). The gravitational field

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\(^6\) Details at http://asc.harvard.edu/ciao2.0/.
redshifts photon energies and bends their trajectories, so that \( kT_{\text{eff}} = kT_{\text{eff, x}} \Omega_0^{-1} \) and \( R = R_\infty \Omega_0 \). The observed and proper bolometric luminosities are then related by \( L_{\text{bol}}^\infty = L_{\text{bol}} \Omega_0^2 \); one power of \( \Omega_0 \) accounts for the energy redshift and the other accounts for the time dilation. The observed bolo-

![Chandra ACIS-S/Hi (0.5–8.0 keV)](image)

**TABLE 1**

| Parameter | Value |
|-----------|-------|
| \( N_{H,22} \) | \( 0.30 \pm 0.06 \) |
| \( kT_{\text{eff}} \) | \( 156 \pm 18 \) |
| \( R_\infty \) | \( 9.4^{+2.4}_{-2} \) |
| Total model flux | \( 12 \) |
| \( \chi^2/\text{dof} \) | \( 1.7/10 \) |

**H Atmosphere + Power Law (\( z = 1 \))**

| Parameter | Value |
|-----------|-------|
| \( N_{H,22} \) | \( 0.35^{+0.08}_{-0.07} \) |
| \( kT_{\text{eff}} \) | \( 135^{+18}_{-12} \) |
| \( R_\infty \) | \( 13.4^{+3}_{-4} \) |
| \( \alpha \) | \( 1.0 \) |
| \( F_{\text{X, PL}} \) | \( 2.2 \pm 1 \) |
| Total model flux | \( 14.7 \) |
| \( \chi^2/\text{dof} \) | \( 0.55/9 \) |

**H Atmosphere + Power Law (\( z = 2 \))**

| Parameter | Value |
|-----------|-------|
| \( N_{H,22} \) | \( 0.36^{+0.10}_{-0.10} \) |
| \( kT_{\text{eff}} \) | \( 131 \pm 19 \) |
| \( R_\infty \) | \( 13.8 \pm 4 \) |
| \( \alpha \) | \( 2.0 \) |
| \( F_{\text{X, PL}} \) | \( 3.1^{+1.8}_{-1.4} \) |
| Total model flux | \( 14.9 \) |
| \( \chi^2/\text{dof} \) | \( 0.66/9 \) |

**Photon Power Law**

| Parameter | Value |
|-----------|-------|
| \( N_{H,22} \) | \( 0.72 \pm 0.09 \) |
| \( \alpha \) | \( 4.1 \pm 0.3 \) |
| Total model flux | \( 52^{+13}_{-11} \) |
| \( \chi^2/\text{dof} \) | \( 1.4/10 \) |

**Raymond-Smith**

| Parameter | Value |
|-----------|-------|
| \( N_{H,22} \) | \( 0.47^{+0.05}_{-0.05} \) |
| \( Z (Z_{\odot}) \) | \( < 5 \times 10^{-3} \) |
| \( kT (\text{keV}) \) | \( 0.77 \pm 0.10 \) |
| \( \int \frac{n_e n_H}{v} \text{cm}^{-3} \) | \( (1.8 \pm 0.4) \times 10^{57} \) |
| Total model flux | \( 19.4 \) |
| \( \chi^2/\text{dof} \) | \( 1.7/9 \) |

**Multicolor Disk**

| Parameter | Value |
|-----------|-------|
| \( N_{H,22} \) | \( 0.36^{+0.05}_{-0.05} \) |
| \( T_{\text{in}} (\text{keV}) \) | \( 0.43 \pm 0.04 \) |
| \( R_{\text{in}}(\text{cos} \theta)^{1/2} \text{km} \) | \( 0.81^{+0.03}_{-0.02} \) |
| Total model flux | \( 14.0 \) |
| \( \chi^2/\text{dof} \) | \( 1.74/10 \) |

**Blackbody**

| Parameter | Value |
|-----------|-------|
| \( N_{H,22} \) | \( 0.23 \pm 0.06 \) |
| \( kT_{\text{eff}} \) | \( 330 \pm 20 \) |
| \( R_\infty \) | \( 1.9 \pm 0.3 \) |
| Total model flux | \( 10 \) |
| \( \chi^2/\text{dof} \) | \( 2.0/10 \) |

Note—X-ray fluxes are unabsorbed, in units of \( 10^{-13} \text{ergs cm}^{-2} \text{s}^{-1} \). Upper limits and uncertainties are 90% confidence. Values in parentheses are held fixed. Assumed source distance \( d = 5 \) kpc.

3.1. **Comparison to Previously Measured Quiescent Spectra**

We simultaneously fit the Chandra spectrum with three energy spectra taken in quiescence: ROSAT PSPC in 1992 October, ROSAT PSPC in 1993 March, and ASCA in 1996 October (see Table 2; see Rutledge et al. 1999 for details on these spectra). We include a 14% systematic uncertainty to allow for differing calibrations between instruments. The results of these spectral fits are in Table 3.

Fitting an absorbed, pure H atmosphere spectrum with all identical parameters produces a statistically unacceptable fit \( \chi^2/\text{dof} = 2.63/(67 \text{ dof}) \); here and elsewhere in this paper, the first number is the reduced \( \chi^2 \) value, and the second number is the number of degrees of freedom. However, acceptable fits are found if we permit either \( N_{H,22} \) (marginally), \( kT_{\text{eff, x}} \), or \( R_\infty \) to vary between the four observations. The observed 0.5–10 keV fluxes span a range of a factor of \( 1.87 \pm 0.21 \) (90% confidence). Therefore, while the spectra are statistically different, we are unable to observationally discern which spectral parameter (or combination of parameters) is changing.

We now add the power-law component. The best-fit spectrum in which all five spectral parameters are the same for the four different observations is statistically unacceptable \( \chi^2/\text{dof} = 2.80/(65 \text{ dof}); \) probability = \( 2 \times 10^{-13} \), indicating spectral variability. Acceptable fits are found if we let any of the four parameters \( (N_{H,22}, kT_{\text{eff, x}}, R_\infty, \text{ and } F_{\text{X, PL}}) \) vary independently between the four observations. The constraints on the power-law slope are very weak. Also, in the fit in which \( F_{\text{X, PL}} \) is permitted to vary, the value \( \alpha = 3.5 \pm 0.5 \) is steeper than is typical of these sources, combined with a high value of \( N_{H,22} \).
We examine the temperature decrease as a function of time since the outburst end. Table 2 gives the time delay between the quiescent observation and the end of the previous outburst; Table 3 contains the temperatures measured during the quiescent observation. For the 1993 ROSAT observation, we assume that the outburst ended 60 days after its start. A linear fit to the data finds a temperature that decreases $-50 + 90$ eV yr$^{-1}$ (consistent with no decrease), with a 3σ upper limit of $<270$ eV yr$^{-1}$. This is an uncertain measurement for a number of reasons: the number of days since the outburst start is uncertain by $\pm 7$ days, the duration of outbursts varies from outburst to outburst, and the initial temperature of the NS atmosphere may be related to the total fluence of the most recent outburst, which is unknown for two of the four outbursts. Moreover, the temperatures taken alone are not significantly different. This level of decrease is consistent with the limit on the decrease in the thermal temperature of Cen X-4, which is $-2.2 \pm 1.8$ eV yr$^{-1}$ (Rutledge et al. 2001).

### Table 2: Observation List

| Instrument       | Observation Date | Days Since Outburst Start | Days Since Outburst End | References |
|------------------|------------------|--------------------------|-------------------------|------------|
| ROSAT PSPC (1)   | 1992 Oct 15      | 110–130                  | 190                     | 1          |
| ROSAT PSPC (2)   | 1993 Mar 24      | ...                      | ...                     | 2, 3       |
| ASCA             | 1996 Oct 21      | 7                        | 130                     | 2, 4       |
| Chandra          | 2000 Nov 28      | 7                        | 7                       | 2          |

### Table 3: Multispectral Observations

| Instrument         | Observation Date | Days Since Outburst Start | Days Since Outburst End | References |
|--------------------|------------------|--------------------------|-------------------------|------------|
| ROSAT PSPC (1)     |                  |                          |                         | 1, 2       |
| ROSAT PSPC (2)     |                  |                          |                         | 3, 4       |
| ASCA               |                  |                          |                         | 5          |

**References:**  
(1) Ilovaisky & Chevalier 1992a, 1992b; (2) Rice et al. 1998; Rutledge et al. 2001.

We investigate if a variable power-law intensity could be responsible for the variations between the four observations. We hold the value of $a = 1$ fixed (the value found by C98 in observations 3–6), keep $N_T$, $kT_{\text{eff,}a}$, and $R_{\text{s}}$ constant between the four observations, and permit the power-law flux to vary between observations. The best fit is unacceptable [$\chi^2(\text{df}) = 1.64/(65 \text{ df})$; probability = $8 \times 10^{-4}$]. We conclude that the observed spectral variability cannot be explained by a variable power-law component with the slope observed by C98. The variability is caused either by a power law that changes in slope and flux, or by variability in the thermal component or column density.

### 3.3. Predicted versus Observed Quiescent Flux

Aql X-1 is one of the brightest known quiescent NSs, and combined with its frequent accretion outbursts, provides the best opportunity to test the relationship between the time-averaged outburst flux and the quiescent flux predicted by BBR98.

We use the RXTE ASM data to measure the time-averaged outburst flux $\langle F \rangle$ (which is proportional to $\langle d \rangle$). We integrate all counts with $>5 \sigma$ significance during the 5 yr period of 1996 January to 2001 January ($3.9 \times 10^8$ counts; we adopt a $\pm 10\%$ uncertainty), which includes $\approx 5$ outbursts. If the flux of Aql X-1, when not in outburst, was always just below the RXTE ASM 1 day detection limit (0.1 counts s$^{-1}$), this would increase the time-averaged outburst flux by only 4%. Using W3PIMMS, the ASM counts/flux conversion for power-law spectra $x = 0.8, 1.0, \text{ and } 2.0$ are

### Table 3: Multispectral Spectral Fits

| Parameter       | Value               | Reference     |
|-----------------|---------------------|---------------|
| $N_{\text{H,22}}$ | $1.43 \pm 0.01$     | Chandra        |
| $kT_{\text{eff,}a}$ | $10^{-12}$        | Chandra        |
| $R_{\text{s}}$   | $10^3$              | Chandra        |
| $F_X$ (PL)      | $10^{-12}$          | Chandra        |
| $F_X$ (Therm)   | $10^{-12}$          | Chandra        |
| $\chi^2(\text{df})$ |                        | Chandra        |

**Note:** Uncertainties are $1 \sigma$. Assumed source distance $d = 5$ kpc. Model fluxes are corrected for absorption, in units of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$.

* Best-fit flux for the power-law component.

b Best-fit flux for the thermal component.

* Labels refer to observations listed in Table 2.

* Value is for Chandra observation.
3.4, 3.6, and 5.0 \times 10^{-10} \text{ ergs cm}^{-2} \text{ count}^{-1} (0.5-10.0 \text{ keV}), respectively. For blackbody spectra, kT = 0.8-1.4 \text{ keV}, the conversion factors are approximately the same: 3.3 \times 10^{-10} \text{ ergs cm}^{-2} \text{ count}^{-1}. We adopt 3.6 \times 10^{-10} \text{ ergs cm}^{-2} \text{ count}^{-1} (0.5-10.0 \text{ keV}) with the realization that the spectral and bolometric uncertainties can be as large as \pm 25\%. This then gives \langle F \rangle \approx 10^{-5} \text{ ergs cm}^{-2} \text{ s}^{-1}, or roughly \langle M \rangle \approx 2.5 \times 10^{-10} M_\odot \text{ yr}^{-1} (d/5 \text{ kpc})^2.

We assume that the NS liberates \( GM/R \approx 1.8 \times 10^{20} \text{ ergs} \) per accreted baryon during the outburst. Then, from equation (1), we expect a quiescent bolometric thermal flux \( F_\text{bol} \approx \langle F \rangle /130 \), or \( F_\text{bol} = 7.7 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \), compared with \( F_\odot \approx 2.5 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \) observed during the Chandra observation. The quiescent bolometric thermal flux is uncertain by \pm 0.25 \text{ dex} (about a factor of 2 in both directions, 1\sigma), and so is consistent with this prediction (BBR98; eq. 1).

Note, on the other hand, that if one were to assume that 100\% of the emergent luminosity were from accretion, this would set \( M = 1.1 \times 10^{-12} M_\odot \text{ yr}^{-1} \), which is above the \( M \) at which gravity stratifies metals in the NS atmosphere, that is, at which metal lines would become unobservable. We do not exclude the presence of metal lines in the observed spectrum, and it is possible that, at such an implied accretion rate, metal lines may be observed.

4. DISCUSSION AND CONCLUSIONS

We have detected Aql X-1 in quiescence, at a luminosity comparable to that observed in three previous epochs. This makes Aql X-1 the second transiently accreting, type I X-ray--bursting NS (after Cen X-4; Rutledge et al. 2001) that maintains a quiescent luminosity to within a factor of a few. The stability of Cen X-4's quiescent luminosity over years, and the ability of Aql X-1 to return to the same quiescent luminosity between outbursts (in which \( M \) increases by more than a factor of 1000) are both strong support for their basal quiescent luminosity being set by deep crustal heating (BBR98). In addition, spectral evidence points to most of the quiescent emission being thermal emission from the NS surface.

While the H atmosphere spectral model implies a NS radius that is at the low end of the equation-of-state range for the adopted distance (see, for example, Lattimer & Prakash 2001), inclusion of an additional power-law component, although not statistically required, produces a systematically larger value of \( R_\odot \) and smaller value of \( kT_{\text{eff}, \odot} \), which is the expected direction of bias if the previously observed power-law component is present. We therefore quote a best-fit value of \( R_\odot = 13.4^{+2}_{-4} (d/5 \text{ kpc}) \) km and \( kT_{\text{eff}, \odot} = 135^{+18}_{-25} \text{ eV} \), which includes an \( \alpha = 1 \) power-law component, noting that these are not significantly different when we assume a value of \( \alpha = 2 \). Greater scrutiny of the distances to this and similar objects is called for. Moreover, we examined the spectrum only in a limited range (0.5–8.0 keV), since Chandra ACIS-S is not yet calibrated down to 0.2 keV.

However, puzzles remain. The quiescent X-ray luminosity of Aql X-1 has varied by a factor of 1.87 \pm 0.21 over timescales of years, while remaining constant (\(<15\% \) rms) on timescales of 1–10,000 s. This is similar to the intensity variability observed from another quiescent transient neutron star, Cen X-4, which has shown variability of a factor of \( \approx 3 \) on timescales of days to years (Campana et al. 1997; Rutledge et al. 2000), and \(<18\% \) rms variability on 1–10,000 s timescales (Rutledge et al. 2000). In addition, the power-law spectral components in some of these sources cannot be explained as thermal emission; their origin is unclear.

A variation in \( kT_{\text{eff}, \odot} \) can be attributed to either a variation in quiescent accretion onto the compact object or a changing thermal emission. Since the NS core cannot change its temperature on these timescales, any variation in the thermal emission would need to be from either previously neglected internal heat sources (Ushomirsky & Rutledge 2001) or changes in the overlying envelope.

If quiescent accretion powers the variability in Cen X-4 and Aql X-1, then we are left with the surprising coincidence that \( M_\odot \) provides a luminosity comparable to the deep crustal heating luminosity (eq. [1]) in at least two different systems. Even in its simplest form (a diminished accretion rate from a cool disk; King & Ritter 1998), it seems surprising that quiescent accretion would maintain near equality with the deep crustal heating luminosity. It seems even less likely if one invokes a magnetic propeller to regulate the accretion rate onto the NS in quiescence (Menou et al. 1999). Therefore, if the variability is due to accretion, it remains to be explained why the accretion rate provides a luminosity so nearly equal to that from deep crustal heating.

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