TIMING PROPERTIES AND SPECTRAL STATES IN AQUILA X-1

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Received 2003 July 25; accepted 2003 October 30

ABSTRACT

We have analyzed five X-ray outbursts of the neutron star soft X-ray transient Aquila X-1 and investigated the timing properties of the source in correlation with its spectral states as defined by different positions in the color-color and hardness-intensity diagrams. The hard color and the source count rate serve as the distinguishing parameters, giving rise to three spectral states: a low-intensity hard state, an intermediate state, and a high-intensity soft state. These states are respectively identified with the extreme island, island, and banana states that characterize the atoll sources. The large amount of data analyzed allowed us to perform, for the first time, a detailed timing analysis of the extreme island state. Differences in the aperiodic variability between the rise and the decay of the X-ray outbursts are found in this state: at the same place in the color-color diagram, the source exhibits more power at low frequencies (<1 Hz) during the rise, whereas during the decay the source is more variable at high frequencies (>100 Hz). The very low frequency noise that characterizes the banana-state power spectra below 1 Hz cannot be described in terms of a single power law: a two-component model is required. In two outbursts, a new 6–10 Hz quasi-periodic oscillation (QPO) has been discovered and tentatively identified with the normal/flaring branch-like oscillation observed only at the highest inferred mass accretion rates. We have compared the spectral and timing properties of Aql X-1 with those of other atoll and Z sources. Our results argue against a unification scheme for these two types of neutron star X-ray binaries.

Subject headings: accretion, accretion disks — stars: individual (Aquila X-1) — stars: neutron — X-rays: binaries — X-rays: bursts — X-rays: stars

1. INTRODUCTION

Aquila X-1 belongs to the general group of systems known as low-mass X-ray binaries (LMXB). These systems consist of a neutron star or a black hole orbiting a late-type star (later than A). The X-rays are the result of the accretion of material from the companion onto the compact star. Mass transfer is thought to occur via Roche lobe overflow and hence proceeds via an accretion disk. In Aql X-1, the compact star is a neutron star and the mass-donating companion is a \( V = 21.6 \) K7V star, located at an estimated distance of 2.5 kpc (Chevalier et al. 1999). An orbital period of 18.95 hr has been suggested (Chevalier & Ilovaisky 1991; Welsh, Robinson, & Young 2000). The high-energy radiation is characterized by 1.5–2 month transient X-ray outbursts, during which the X-ray luminosity can increase by more than 3 orders of magnitude. These are thought to be due to thermal instabilities in the accretion disk (e.g., van Paradijs 1996). Their recurrence time and duration vary, but typical values are \( \sim 200 \) days and \( 40–60 \) days, respectively (Simon 2002). The source also displays type I bursts (Zhang, Yu, & Zhang 1998) that last a few tens of seconds and are interpreted as runaway thermonuclear burning of matter on the surface of the neutron star.

Various schemes have been proposed to categorize the LMXBs: X-ray spectral behavior as a function of intensity and the requirement of a low-energy blackbody component in the X-ray spectra (Parsignault & Grindlay 1978; Naylor & Podsiadlowski 1993); cluster analysis of a large number of source characteristics (Ponman 1982); detailed X-ray spectral fits (White & Mason 1985); X-ray hardness-intensity and color-color diagrams (Schulz, Hasinger, & Trümper 1989); and aperiodic variability at very low frequencies (Reig, Papadakis, & Kylafis 2003). Most relevant for the purpose of this paper is the classification scheme in terms of the rapid aperiodic variability, and the patterns that these sources display in color-color diagrams (Hasinger & van der Klis 1989). In this scheme, LMXBs are divided into two different subclasses, Z and atoll sources.

The three spectral branches that make up the Z shape are called the horizontal branch, normal branch and the flaring branch, and the two structures that occur in atoll sources are known as the island and the banana (van der Klis 1989). At the lowest count rates, an extension of the island state is sometimes seen with a harder spectrum and stronger band-limited noise than the “canonical” island state (van Straaten, van der Klis, & Méndez 2003 and references therein). The term “extreme island state” has been used to designate such a state (Prins & van der Klis 1997; Reig et al. 2000). The spectral and timing properties of atoll sources in this state are reminiscent of those seen in the low-intensity hard state of black hole systems (van der Klis 1994a, 1994b; Berger & van der Klis 1998; Olive et al. 1998; Belloni, Psaltis, & van der Klis 2002). Both Z and atoll sources move through these patterns continuously, that is, without jumping from one branch to another, although the source motion along the spectral tracks is much slower in atoll sources when they are in the island state than in the banana state, and in Z sources in all states. The classification of Aql X-1 in this scheme was investigated by Reig et al. (2000) (see also Cui et al. 1998), who studied the correlated X-ray timing and spectral variations of Aql X-1 and presented evidence for its classification as an atoll source, exhibiting all classic atoll source states.
This scheme has been revisited by Muno, Remillard, & Chakrabarty (2002) and Gierliński & Done (2002). They reported that three transient atoll sources that display a wide dynamic range in intensity ($F_{\text{max}}/F_{\text{min}} \approx 100$), 4U 1608–52, 4U 1705–44, and Aql X-1, trace out three-branch patterns in the color-color diagram similar to those of Z sources and suggested this may be a general feature. Their study was based on the spectral properties only. However, as pointed out by Hasinger & van der Klis (1989), it is difficult to make a clear distinction between Z and atoll sources on the basis of the motion through the color-color diagram alone. Analysis of the rapid aperiodic variability, allowing study of the noise components in different regions of the color-color diagram and the actual timescales of the motion of the source through the diagram, is important to identify source type and state.

In this work, we have studied the spectral and timing properties of Aql X-1 in order to investigate whether atoll and Z sources can be unified into one classification scheme and to provide new insights into the poorly known extreme island states of atoll sources. We find that although the color-color diagram shows a branch whose topology is similar to the normal branch of Z sources, neither the timing properties nor the motion in the color-color diagram of Aql X-1 agree with those of Z sources.

2. OBSERVATIONS

The data were retrieved from the Rossi X-Ray Timing Explorer (RXTE) archive and comprise all observations of Aql X-1 available from 1997 February to 2002 May. Data taken during satellite slews and Earth occultation were removed. Likewise, all type I bursts were excluded from our analysis. The observations contain five X-ray outbursts. Although the duration and maximum intensity differ, the profiles of the outbursts are very similar and are characterized by a fast rise and a slower decay. During maximum intensity, the light curve is complex and multipeaked. The fourth outburst showed two minor outbursts (the peak intensity was 1 order of magnitude lower than the main outburst) 70 and 110 days after the main peak, respectively. The long-term light curve of the observations is shown in Figure 1.

3. THE COLOR-COLOR DIAGRAM

Background-subtracted light curves corresponding to the energy ranges 2.0–3.5, 3.5–6.0, 6.0–9.7 and 9.7–16.0 keV were used to define the soft color (SC) as the ratio between the count rates of the 3.5–6.0 and 2.0–3.5 keV energy ranges and the hard color (HC) as the ratio between the count rates of the 9.7–16.0 and 6.0–9.7 keV energy ranges. The color-color diagram (CD) of Aql X-1 was then constructed by plotting the hard color as function of the soft color (Fig. 2). During the time spanned by the observations, the response of the detectors varied because of aging. In addition, gain changes are applied occasionally, making the channel boundaries for a given energy range change with time and also slightly affecting the effective areas of the detectors. Each gain change is the start of a new “gain epoch.” We reduced the effect of the color shifts that result from these gain changes by linearly interpolating between the count rates in the two energy channels straddling the energy boundaries in each epoch. Each data point of Aql X-1 was normalized with the closest corresponding Crab pulsar point within the same gain epoch, in order to mitigate the response-change effects on the colors. The final CD was obtained by averaging the five (one for each detector) normalized CDs and rebinning into 256 s data points. We excluded data for which the resulting relative errors were larger than 5%. The total number of data points excluded from the analysis was \( \leq 10\% \). In order to recover the true values of the colors of Aql X-1, the soft color should be multiplied by 2.35 and the hard color by 0.56 (quoted values are averages of the Crab colors during the observations and for all five Proportional Counter Units [PCUs] on RXTE). The variation of the Crab colors computed as the r.m.s., i.e., the standard deviation over the mean color was 5.3% and 1.7% for

![Figure 1](image1.png)

**Fig. 1.**—Light curve of the entire set of observations showing the five X-ray outbursts. Different symbols represent different spectral states: extreme island (circles), island (stars), and banana (dots).

![Figure 2](image2.png)

**Fig. 2.**—Color-color diagram of Aql X-1. The soft and hard colors are relative to those of the Crab pulsar. Each point in the color-color diagram represents 256 s. No error bars are given, but all the points shown in this plot have relative errors smaller than 5%. Different symbols represent different outbursts as indicated. The lines separate the banana-state regions, from BS1 in the left to BS5 in the right.
the soft and hard colors, respectively (see also Fig. 1 in van Straaten et al. 2003).

3.1. Spectral States

Aql X-1 can be found in two main states: a low-intensity hard state and a high-intensity soft state. In addition, a short-lived intermediate or transition state is found displaying values of the hard color between the two main states. The aperiodic variability as a function of spectral hardness, i.e., the position in the CD of Aql X-1, was previously studied by Reig et al. (2000). With only two of the five outbursts analyzed in that work, the CD consisted of a soft branch (the banana branch) and two isolated groups of points, which were called extreme island and island states. The large amount of data now analyzed reveals a more structured CD, in which the extreme island state appears as a more stable and longer-lived branch than the island state. The high-intensity soft state corresponds to the classical banana state and the island state represents the transition between the two main states.

Outbursts 1, 4, and 5 (O1, O4, and O5) contain points in the two main states, while outbursts 2 and 3 (O2 and O3) provide points to the banana state only. Observations of O2 and O3 began and finished when the source was still at a relatively high level of emission (>1200 counts s⁻¹) and did not experience large intensity changes (I_{max}/I_{min} < 5). In contrast, outbursts 1, 4, and 5 extended over a larger dynamic range in intensity (I_{max}/I_{min} > 50). None of the points of the two minor outbursts that followed O4 (which will be termed here as O4') contributed to the banana state.

Outbursts 1, 4, 4', and 5 include points in the extreme island state. While O4 and O5 include points both during their rise and during their decay, O1 gives points during its decay only. The island state occurred only during the decay of O1 and O5. All five outbursts (except for O4') have points in the banana state, but only O3 provides banana state points during the rise.

3.2. Motion in the Color-Color Diagram

Figure 3 displays the motion of Aql X-1 in the CD for outbursts 4 and 5. Data points are ~1 day averages. Figure 4 shows the evolution of the hard color with time for those outbursts that include spectral transitions (O1, O4, O5). The 2–16 keV intensity just before the transitions is also given. All quoted intensities in this section are background-subtracted and correspond to 5 PCUs in the energy range 2–16 keV. There is a strong correlation between the position of the source in the CD and its intensity. At the onset of the outbursts, the data points distribute in the softest part of the extreme island state. The count rate is ≤100 counts s⁻¹. As the intensity increases, the source moves toward the right along the extreme island branch. The hard color (HC) slightly decreases on average. In about 6 days, the count rate increases by 1 order of magnitude and the soft color (SC) increases by ≈+0.3. Then the source seems to jump to the banana state, recovering the initial values of the soft color. The hard color decreases by ≈−0.5. The 2–16 keV intensity is ~3 or 4 times that of the extreme island state prior to the spectral transition, namely, 4000–6000 counts s⁻¹.

Fig. 3.—Track followed by the source in the color-color diagram during outbursts 4 (upper panel) and 5 (lower panel). Each data point is a 1 day average.
No intermediate points between the two states are observed during the rise of the outbursts. This can be attributed to the fast rise and the lack of good sampling of the data. Indeed, the observational gaps between the last point of the extreme island branch and the first one of the banana branch were 2.6 and 3.1 days for O4 and O5, respectively.

As the intensity continues to increase the source becomes harder, i.e., it moves to the right along the banana, with an approximately constant hard color. The peak of the outburst is characterized by flaring activity with erratic changes in the count rate. The count rate at the peak is 50–100 times the minimum detected count rate. Despite this irregular behavior, the correlation between the intensity and the colors is maintained in the sense that the lower intensity points in the flares display a lower soft color, as is illustrated in Figure 5. In other words, during the flare maxima the source lies at the right end of the banana branch, and between flares it moves to the left. Thus, the flaring variability in the light curve translates into the CD in a back-and-forth motion, which extends approximately over the right half section of the banana state. This motion is quite fast. As an example, in one of the flares in O5 the soft color changed by 0.08 in about 2.4 hr. In another flare by 0.06 in 0.55 hr. This flaring behavior is seen in all outbursts, but O2 shows it exclusively (Fig. 5). Such behavior stops once the source reaches the midpoint of the decay of the outburst, at which point the source shifts to lower soft colors (to the left along the banana branch).

As the outburst declines, the source moves back along the banana branch, abandoning it when the count rate becomes lower than \sim 800 counts s\(^{-1}\). The transition to the hard state occurs at a much lower soft color than when it entered the banana, although not necessarily at the lowest soft color. The banana state covers values of the soft color between 0.87 (O5) and 1.16 (O3). The transition to the hard state takes place at SC =0.92–0.93 (Fig. 3). The count rate at which the transition between the two main states takes place is higher when the source is in the rise of the outburst. Hard to soft transitions occur when the count rate is well above \sim 1000 counts s\(^{-1}\). Soft to hard transitions occur when the count rate is well below \sim 1000 counts s\(^{-1}\), as can be seen in Figure 4.

Rather than jumping directly to the hard branch, the source remains for a short time (\lesssim 0.1 days) in an intermediate state, the island state. Note that such a short island state episode would usually have been missed because of data gaps in the rise. The count rate in the island state is \sim 200–400 counts s\(^{-1}\). At even lower count rates the source finds itself back in the extreme island branch, moving toward the left as the intensity decreases, eventually becoming too weak to allow sufficient measurement of the colors. The source reenters this state during the decay when the count rate goes below \sim 200 counts s\(^{-1}\). The reentry point occurs at a lower soft color (SC \approx 1.05–1.10) than when the source left the extreme island state (SC \approx 1.3). As the speed of motion along the extreme island state is approximately constant, the time during which the source can be found in this state is shorter during the decay of the outburst than during its rise. A difference in the position of the source in the CD depending on whether the source intensity increases or decreases was already recognized by Reig et al. (2000).

The main result that should be stressed is that transitions between states do not occur at the same points of the spectral branches. During the rise of the X-ray outburst, the source occupies the hardest parts of the extreme island state before the spectral transition to the banana state. During the decay, it tends to occupy the softest part of the banana branch before moving into the island state. However, the points of departure and arrival are different. In the CD, this translates into a near-rectangular track (Fig. 3) along which Aql X-1 moves clockwise as the count rate first increases and then decreases.

In addition to Figure 4, Tables 1 and 2 also illustrate the timescale of the motion through the diagram. Table 1 and Table 2 give upper limits on the duration of the source in each state and the timescales of the spectral transitions, respectively. Note that the observational gap for the spectral transitions from the extreme island state to the banana state is approximately 2 times longer than that for the reverse transitions. Given the speed of motion of the soft color along the extreme island branch (roughly 0.05 day\(^{-1}\)), a 3 day gap might imply a change in soft color of about 0.15. Thus, it is possible that the actual entry point into the banana branch is at lower values of the soft color. In this case, the motion of Aql X-1 in the CD would be similar to that of 4U 1705–44 (Barret & Olive 2002), in which both the transition from the extreme island state to the banana state and the reverse transition from the banana state to the extreme island state occur at the same point of the banana branch. The motion in the CD then would then resemble an inverted triangle rather than a rectangle.

4. TIMING ANALYSIS

In order to investigate the aperiodic variability of Aql X-1, we obtained power spectra by dividing the 2–60 keV Proportional Counter Array (PCA) data of each observation into 256 s segments and calculated the Fourier power spectrum of each segment up to a Nyquist frequency of 2048 Hz. The high-frequency end (1500–2048 Hz) of the power spectra was
used to determine the underlying Poisson noise (approximated by a constant power level), which was subtracted before performing the spectral fitting. Our aim is to investigate the aperiodic variability in correlation with the spectral states, which in turn correlate with the source count rate. Thus, we divided the color-color plane into various regions and obtained a mean power spectrum for each region. The mean power spectrum was the result of averaging all the power spectra corresponding to the points enclosed in each color region. See Table 3 to find the average values of the colors and the boundaries and intensity of each region. Prior to this, we investigated whether power spectra from the same CD region taken at different outbursts shared the same properties. We found that while this was true for the banana state, some differences existed in the extreme island state depending on whether the source was in the rise or the decay of the X-ray outburst.

The extreme island state is populated with points from the rising parts of O4 and O5, the decaying parts of O1, O4 and O5 and from the extended extreme island state of O4. Consequently, the extreme island state was first separated into points pertaining to the rise, to the decay, or to O4. Each one of these groups was further divided into three subgroups according to the value of the soft color. Note that in the case of the rise and decay regions, this division implies a division in count rate as well as in hard color. On average, the extreme island states EISrise1 and EISdecay2 (see Table 3) have lower intensities and are softer than EISrise2 and EISdecay1, respectively. In turn, EISrise2 contains softer points than EISrise3. The island-state (the intermediate state) points defined another region. The timing properties of the banana state in atoll sources have been seen to vary smoothly as the soft color or, equivalently, the count rate increases, that is, from the

| TABLE 1 | DURATION AND INTENSITY (2–16 keV, 5 PCUs) OF THE SPECTRAL STATES FOR EACH OF THE FIVE X-RAY OUTBURSTS |
| States | Duration (days) | $I_{\text{min}}$ (counts s$^{-1}$) | $I_{\text{max}}$ (counts s$^{-1}$) | $I_{\text{mean}}$ (counts s$^{-1}$) |
| Outburst 1 |
| EIS | 0.14 | 56 | 63 | 60 |
| BS | 15 | 583 | 3057 | 2164 |
| IS | 0.10 | 200 | 220 | 209 |

| Outburst 2 |
| EIS | 30.96 | 1213 | 2694 | 1778 |

| Outburst 3 |
| EIS | 38.95 | 1227 | 6175 | 4656 |

| Outburst 4 |
| EIS | 6.02/2.03 | 110/70 | 1295/156 | 650/127 |
| BS | 18.05 | 368 | 4835 | 2330 |
| IS | 30.96 | 1213 | 2694 | 1778 |

| Outburst 4' |
| EIS | 63 | 77 | 530 | 340 |
| BS | 38.95 | 1227 | 6175 | 4656 |
| IS | 30.96 | 1213 | 2694 | 1778 |

| Outburst 5 |
| EIS | 6.54/1.33 | 87/128 | 1444/255 | 542/203 |
| BS | 41.53 | 810 | 8555 | 4925 |
| IS | 0.01 | 458 | 463 | 460 |

Note.—EIS: extreme island, BS: banana, IS: island. The left values correspond to the rise of the outburst, the right values correspond to the decay of the outburst.

| TABLE 2 | DURATION IN DAYS OF THE SPECTRAL TRANSITIONS |
| Transition | Outburst 1 (days) | Outburst 4 (days) | Outburst 5 (days) |
| EIS—BS | 2.63 | 4.94 |
| BS—EIS | 4.83 | 1.06 | 2.64 |
| BS—IS | 1.89 | 0.98 |
| IS—EIS | 2.84 | 1.64 |

Note.—Values in this table should be considered as upper limits since they include observational gaps.
lower (left) to the upper (right) banana branch. Therefore, the banana branch was split into five regions (BS1 to BS5) in increasing order of the soft color. Each region contains approximately the same amount of data.

There is no unanimity in the literature about the names of the power spectral noise components, nor about the mathematical functions used to fit those components. In this work we have followed the terminology of Belloni et al. (2002) and fitted the power spectra using Lorentzian functions only. Also, for displaying our power spectra we have used the power-fitted the power spectra using Lorentzian functions only. Also, for displaying our power spectra we have used the power-frequency in the rms normalization and the Fourier frequency is plotted as a function of the Fourier frequency.

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1. Spectral States: Aperiodic Variability

The extreme island state power spectrum contains, in order of increasing frequency, the low-frequency band-limited noise, \( L_0 \), the broad-peak low-frequency noise \( L_1 \), the broad version of \( L_1 \) and one more component that could be either the hectohertz QPO or a kilohertz QPO. Based on the rms and frequency correlations of the noise components seen in other atoll sources, van Straaten et al. (2002, 2003) favored the upper kilohertz interpretation. If \( L_1 \) is also interpreted as the lower kilohertz QPO, then the intervals ElSrise2, ElSrise3 and ISO4 (see Fig. 6) would represent the first detection of the two kilohertz QPO in Aql X-1. Alternatively, the fourth component could be the hectohertz QPO. Note that the narrow ~1160 Hz peak in ISO4 is not statistically significant. An \( F \)-test reveals that the probability of the improvement of the fit (in terms of a lower \( \chi^2 \)) by the addition of an extra Lorentzian happening by chance is larger than 30%. The characteristic frequencies of the noise components increase and their rms values decrease slightly as the count rate increases, i.e., the source moves toward the right in the extreme island state.

Figure 7 displays the characteristic frequency of the \( L_0 \) and \( L_1 \) components as a function of the band-limited noise component \( L_{\text{bb}} \) for Aql X-1, the atoll sources 4U 1608–52 (van Straaten et al. 2003), 4U 1728–34 and 4U 0614+09 (van Straaten et al. 2002), and the Z source GX5–1 (Jonker et al. 2002). In the case of GX5–1, the horizontal branch oscillation is plotted instead of \( L_{\text{bb}} \). Note also that the broadband noise in the Z source was not fitted with a Lorentzian but with a cutoff.

### Table 3

| States | Mean \( \nu_{\text{SC}} \) | Mean \( \nu_{\text{HC}} \) | Mean Count Rate* | Number of Power Spectra | \( \chi^2/(\text{dof}) \) |
|--------|-----------------|-----------------|-------------------|------------------------|-----------------------------|
| ElSrise1 | (0.89, 1.08) | (1.12, 1.08) | (0.89, 1.25) | (1.11, 1.26) | 1.01 1.14 185 54 122/92 |
| ElSrise2 | (1.14, 1.06) | (1.21, 1.07) | (1.14, 1.15) | (1.26, 1.14) | 1.18 1.09 925 34 105/84 |
| ElSrise3 | (1.19, 1.04) | (1.34, 1.05) | (1.23, 1.10) | (1.29, 1.11) | 1.25 1.07 1063 23 95/87 |
| ElSdecay1 | (1.01, 1.02) | (1.11, 1.03) | (1.00, 1.12) | (1.11, 1.23) | 1.05 1.07 183 37 87/92 |
| ElSdecay2 | (0.92, 1.11) | (1.11, 1.14) | (0.88, 1.43) | (1.06, 1.45) | 0.98 1.24 76 40 106/92 |

* Background-subtracted count rate for the five PCUs and a bandwidth of 2–16 keV.
power law, \( P(\nu) \propto \nu^{-\alpha} e^{-\nu/\nu_{\text{max}}} \). By differentiating \( \nu P(\nu) \) and equating the resulting function to zero, the maximum frequency of the Z-band–limited noise, \( \nu_{\text{max}} = (1 - \alpha) \nu_{\text{cut}} \), was derived. Figure 7 seems to confirm that (1) the 1–20 Hz broad feature \( L_b \) observed in atoll sources at low count rates (island states) has the same origin as the horizontal branch oscillations (HBO) observed in Z sources (Psaltis, Belloni, & van der Klis 1999; van Straaten et al. 2003) and that (2) the broad bump at frequencies 10–25 Hz is associated with the lower kilohertz QPO. The extreme island state data in Aql X-1 sample the lowest characteristic frequencies so far detected.

One interesting result from the timing analysis of the extreme island state is the differences in the aperiodic variability of the source during the rise and decay of the outbursts. Figure 8 shows three power spectra of Aql X-1 and an enlargement of the CD displaying the extreme island state. All three power spectra are associated with the same value of the colors, i.e., they occupy the same position in the CD (marked in Fig. 8). However, they correspond to different parts of the X-ray outburst: rise (diamonds), decay (stars) and when the source found itself in the extended island state of O4' (crosses). During the rise the power is concentrated at low frequencies, whereas during the decay
Fig. 6.—Power spectra and best fits for different positions in the color-color diagram (see Table 3). The lines represent the different noise components as follows: for the island states, $L_b$ (dashed line), $L_h$ (dotted line), $L_l$ (dot-dashed line), and $L_u$ (triple-dot-dashed line); for the banana state, $L_{EVLFN}$ (dashed line), $L_{HVLFN}$ (dotted line), $L_b$ (triple-dot-dashed line), and $L_{d2}$ (dot-dashed line). The second dashed line in BS1 corresponds to $L_b$. 
the source exhibits more power at high frequencies. During the extended island state of outburst O4 there is roughly equal power at all frequencies. The differences in the characteristic frequencies of the noise components are much less pronounced, and they are consistent with one another whenever the same component appears.

4.1.2. The Banana State

The low-frequency end (≤1 Hz) of the banana state power spectra is dominated by the very low frequency noise (VLFN). One single power law is normally used to fit this component. However, the power spectrum of Aql X-1 below 1 Hz cannot be described by one component only. In order to fit the VLFN, we used two zero-centered Lorentzians that were called low VLFN (LVLFN) and high VLFN (HVLFN) (Schnerr et al. 2003). The characteristic frequencies of these components are found to be independent of the position of the source in the CD: \( \nu_{\text{max}} \approx 0.01 \text{ Hz and } \approx 0.03 \text{ Hz} \), respectively. However, while the fractional rms variability of lower frequency VLFN remains approximately constant at \( \approx 3.4\% \), the higher frequency VLFN becomes stronger, increasing from \( \approx 0.9\% \) in the lower banana to \( \approx 2\% \) in the upper banana, as the count rate increases.

Above 1 Hz, the banana state power spectra contain one broad Lorentzian, describing the band-limited noise and one QPO (two in BS1). The characteristic frequency rms amplitude, and width of the broad-band–limited noise component decreases as the count rate increases (i.e., as the source moves toward the right). This component has also been seen in 4U 1608−52 (van Straaten et al. 2003), 4U 0614+09 and 4U 1728−34 (van Straaten et al. 2002). However, the lack of data precludes a more detailed comparison. Only 4U 1728−34, with just two measurements, seems to have the same behavior as Aql X-1, i.e., the frequency of this noise component decreases along the banana. Following van Straaten et al. (2003), we will refer to this component as \( L_b \). Next to, and sometimes on top of, the band-limited noise in the banana state there is a relatively narrow peak whose characteristic frequency and width do not correlate with any other parameter. This narrow QPO has a frequency between that of the hectohertz Lorentzian and \( L_h \), van Straaten et al. (2003) (see also Di Salvo et al. 2001; and van Straaten et al. 2002) argued that it is the band-limited noise component \( L_b \), which transforms into a narrow QPO above certain frequency (\( \approx 20 \text{ Hz} \) in 4U 1608−52). The appearance of \( L_b \) and this transformation of \( L_h \) occurs coincidentally. In Aql X-1, although the narrow version of \( L_b \) appears systematically in all banana-state power spectra it is always below 3 \( \sigma \).

The detection of a second kilohertz QPO in Aql X-1 is only marginal (van der Klis 2000). Based on the values of the fitting parameters and the relation between the QPO frequency and the X-ray colors, Méndez, van der Klis & Ford (2001) concluded that whenever a kilohertz QPO is detected in Aql X-1, it is always the lower kilohertz QPO. The fractional rms and characteristic frequency of the second QPO in BS1 are consistent with being the lower kilohertz QPO (Fig. 1 of Méndez et al. 2001). Also, the characteristic frequencies of the \( L_l \) and \( L_b \) in BS1 agree with the correlation of Figure 7 if an extrapolation to higher frequencies of the Aql X-1 points is done.

4.1.3. The Island State (IS)

The analysis of the transition state is hampered by poor statistics resulting from the relatively low number of points. One single Lorentzian with a peak at \( \approx 20 \text{ Hz} \) and a \( Q \)-value of 0.15 accounts for the entire 0.01−100 Hz frequency band. This noise component is identified as \( L_b \). A second, narrower Lorentzian with \( \nu_{\text{max}} \approx 710 \text{ Hz} \) and \( Q \approx 3 \) fits the noise at higher frequencies. Its fractional rms, \( \approx 17\% \), is too high to agree with the lower kilohertz QPO. In fact, the value of the frequency and rms are similar to what it is seen in 4U 1608−52 and 4U 1728−34 for the upper kilohertz QPO (Fig. 1 of Méndez et al. 2001). Nevertheless, given the relatively

![Fig. 7.—Characteristic frequency of the \( L_h \) and \( L_l \) noise components of the atoll sources 4U 1608−52, 4U 1728−34, and 4U 0614+09 (dots), and the HBO of the Z sources GX 5−1 (stars) as a function of the characteristic frequency of the band-limited noise (\( L_b \) for the atoll sources and HBO for GX5−1). Aql X-1 observations have been represented by open circles.](image-url)
noisy spectrum at high frequencies such identification should be taken with care.

4.2. The Normal/Flaring Branch-like Oscillations

A QPO with frequency 7–14 Hz has been found in at least two atoll sources, XTE J1806–246 (Wijnands & van der Klis 1999; Revnivtsev, Borozdin, & Emelyanov 1999) and 4U 1820–30 (Wijnands, van der Klis, & Rijkhorst 1999). These QPOs are detected at the highest inferred mass accretion rates only, are short-lived (a few hundreds of seconds), and are localized in a very narrow region of the CD, namely, the tip of the upper banana. They are reminiscent of those observed in Z sources in the normal and flaring branches, when the source is accreting near the Eddington limit. Thus, the detection of similar QPOs in atoll sources at significantly lower accretion rates questions the current models that explain normal branch-like oscillations (NBOs) in terms of near-Eddington accretion (Fortner, Lamb, & Miller 1989). We searched for NBO–like QPOs in Aql X-1 and tentatively found two of them at ~3 σ significance, at frequencies 10.3±0.5 Hz in O3 and 5.8±0.2 Hz in O5 (Fig. 9). They have similar rms amplitude (~0.7%) and Q-values (~3). The average values of the colors and intensity associated with these QPOs are SC = 1.11, HC = 0.52, $I_X = 5045$ counts s$^{-1}$ for O3, and SC = 1.06, HC = 0.51, $I_X = 6870$ counts s$^{-1}$ for O5. For the sake of comparison with other sources, we also give the value of the X-ray luminosity:

![Comparison of the power spectra for three different parts of the X-ray outburst. All three power spectra correspond to the same region of the CD. An enlarged view of the island state marking the color region is also plotted.](image)
As a confirmation that they occur at the highest count rates, typical luminosities in the softest parts of the extreme island and banana states are $3 \times 10^{34}$ and $2 \times 10^{36}$ ergs s$^{-1}$, respectively. The values of the luminosity are for a distance of 2.5 kpc and the energy range 2–16 keV. In the other three outbursts, the detection is only marginal. The low statistical significance of these QPOs ($P < 2.5$) can be ascribed to their extremely short life.

5. DISCUSSION

We have analyzed all the available RXTE data of Aql X-1 between 1997 February and 2002 May and investigated its spectral and timing properties in correlation. This work has been motivated by recent reports that show that if large data sets are used, the atoll sources displaying the largest amplitude variations in intensity ($I_{\text{max}} > I_{\text{quiescence}} > 1000$). Thus, a comparison between these two sources is of particular interest. 4U 1608–52 has been extensively studied by van Straaten et al. (2003). By comparing the shape of the power spectra (see Fig. 7 in van Straaten et al. 2003 and our Fig. 6) and the results of the power spectral fits (see Tables 2 and 3 in van Straaten et al. 2003 and our Table 4), one can find distinct similarities between the two sources: the power spectra of intervals A, B, and C in 4U 1608–52 resemble those of the extreme island state of Aql X-1, while interval D of 4U 1608–52 is reminiscent of the island state in Aql X-1. Likewise, the shape and number of Lorentzians appearing in the power spectra of the extreme island state of Aql X-1 are similar to those of the three low-luminosity X-ray bursters studied by Belloni et al. (2002).

It is worth noting the relevant role of the hard color in connection with the timing properties of the extreme island state. In Aql X-1, the characteristic frequencies of the timing features in the extreme island state increase from left to right. This is opposite to what it is seen in 4U 1608–52, where frequencies increase from right to left. However, in both sources the increase in frequencies occurs in correlation with an overall decrease in hard color. We therefore suggest that in the extreme island state it is the hard color, rather than the intensity, that is the main determining factor of the timing properties. We note that black hole candidates are likewise characterized by power spectral states whose occurrence seems to primarily depend on spectral hardness and which are relatively insensitive to intensity and are associated with two-dimensional motion through the color-intensity plane rather than motion along a one-dimensional track (Homan et al. 2001). It may be that in the island and extreme island states, the states in which atoll sources are most similar to black holes in any case (e.g., van der Klis 1994a; Belloni et al. 2002), possibly because in these states the inner disk radius is furthest from the neutron star surface, this two-dimensional picture better describes neutron star behavior than the one-dimensional description appropriate to the banana state and to Z sources.

Leaving aside the kilohertz QPOs, the overall shape of the banana-state power spectra of Aql X-1 presents similarities
with those of other atoll sources, namely, a strong red-noise component, the VLFN below ~1 Hz, and broad and narrow components describing the band-limited noise in the frequency range 1–100 Hz. Compared to 4U 0614+09, 4U 1608–52 and 4U 1728–34, Aql X-1 exhibits the strongest VLFN but the weakest band-limited noise. While the VLFN is normally described by either a power law with index between 1.5 and 2.0 or a zero-centered Lorentzian in the other atoll sources, it requires the use of two model components in Aql X-1, similar to the case of GX 13+1 (Schnerr et al. 2003). The broad-band–limited noise component Lb in Aql X-1 and 4U 1608–52, or equivalently the zero-centred Lorentzian in 4U 1728–34 and 4U 0614+09, have similar rms values. In contrast, Ls, which is clearly detected in these other atoll sources, is not significant in Aql X-1 in the banana state.

5.2. Is Aquila X-1 a Z Source?

Gierliński & Done (2002) suggested that the name atoll source is no longer appropriate, as these type of low-mass X-ray binaries also display a three-branch pattern in the color-color diagram when large data sets of observations are used, reminiscent of the Z pattern for which Z sources are named. This effect is more pronounced in systems exhibiting large flux variations (Muno et al. 2002), like Aql X-1. The CD of Aql X-1 (Fig. 2) does indeed show a branch (the island state) that can be interpreted as connecting the two main branches in a Z shape. In addition, the correlation between the characteristic frequency of the 1–20 Hz broad Lorentzian Lb and the band-limited noise component (Fig. 7) at low count rates, which suggests a common origin with the horizontal branch oscillations and low-frequency noise (LFN) in Z sources, and the discovery of 7–14 Hz QPO at the highest X-ray flux (Fig. 9), which is reminiscent of the Z source normal/flaring branch oscillations, strengthens the similarities between Aql X-1 and Z sources.

However, there are a number of systematic differences that clearly put Aql X-1 outside the group of Z sources. First, there is the motion in the CD. In the extreme island state, as the count rate increases the soft color increases and the hard color decreases. Then the source makes a rapid transition to the banana state and proceeds to harder colors (right) as the count rate increases further. However, after the peak of the outburst, when the intensity decreases the source does not follow the exact reverse path. As shown in Figure 3, Aql X-1 enters the banana state at a higher value of the soft color than when it leaves that state; also, Aql X-1 enters the extreme island state at a lower value of the soft color than when it leaves that state. The source moves clockwise, following a rectangle track. It should be pointed out that the entrance into the banana state at such high soft color is not caused by the time resolution used (~1 day) in Figure 3. A 256 s bin shows the same effect. However, we cannot rule out an observational origin since the time gap between the transition from the extreme island state to the banana state is ~5 days for outburst 5 and ~2.6 for outburst 4 (Table 2). If this is the case and the source entered the banana state from the left, then the pattern that it would trace out in the CD would be that of an inverted triangle, much like 4U 1705–44 (Barret & Olive 2002). In contrast, the re-entrance into the extreme island state at a low soft color is probably not caused by the lack of data, given the relatively short gap between the island state and the extreme island state (just 1.6 days in outburst 5). In either case, this behavior is not that of Z sources. In Z sources, the NB is not a fast transition between the other two branches, and the source follows the same path whether it is going up or down along the NB. In this respect, Aql X-1 is like the other two atoll sources that display high-amplitude flux variations. More detailed examinations of the motion of 4U 1608–52 and 4U 1705–44 have revealed different topologies from the classical Z-shaped track. The motion of 4U 1608–52 resembles the greek letter ε (van Straaten et al. 2003), and 4U 1705–44 describes an inverted triangle (Barret & Olive 2002). As noted above, these various topologies may simply be different aspects of two-dimensional motion through the color-intensity plane, with hard color determining the timing properties.

Second, the amplitude of the X-ray–luminosity change over the Z track is also different. In Aql X-1, the X-ray luminosity changes throughout the CD, i.e., from the left of the island state to the right of the banana state, by about 3 orders of magnitude. In Z sources, luminosity changes are typically less than a factor of 2 (Di Salvo et al. 2000, 2002).

Third, another difference is the velocity and time spent by the source in each spectral state. Jonker et al. (2002) calculated that the Z source GX 5–1 spent most of the time in the normal branch. In contrast, Aql X-1 spends the smallest percentage of the total observing time in the transition state (the analogue to the normal branch if Aql X-1 were a Z source). Wijnands & van der Klis (1997) found that Cyg X-2 moves through the Z most slowly on the HB, faster on the NB and fastest on the FB. During a typical X-ray outburst, i.e., when it is X-ray active, Aql X-1 spends most of its time in the banana branch (the analogue to the flaring branch).

Finally, the properties of the aperiodic variability of Aql X-1 also differ from those in Z sources, especially at very low count rates. We can establish the following differences:

1. The very existence of the extreme island state. Although the characteristic frequencies in Aql X-1 increase along the extreme island state as the count rate increases, as Z sources do in the HB, the latter never reach the low frequencies that are seen in atoll sources in the extreme island state, even when at the left end of the HB. Likewise, the rms amplitude of the noise components in the extreme island state is significantly higher than that of a Z source HB. The total rms amplitude of those components in Aql X-1 amounts to ~30%, while typically in Z sources it does not go above ~10%. The extreme island state power spectra are typical of atoll sources.

2. The peaked noise components, such as Lb and the upper kilohertz QPO are narrow QPOs on the HB in Z sources, with typical values of the Q-value above 3 for the upper kilohertz QPO, whereas they are considerably broader peaked noise components in the extreme island state in Aql X-1 (Q < 0.5).

3. In Aql X-1, the normal/flaring branch-like oscillation does not occur during the “normal/flaring branch,” i.e., the island or the lower banana branches, but in the upper banana branch, as in other atoll sources.

4. The strength of the kilohertz QPOs decreases as the Z source moves along the Z track from HB to NB. Typically, the kilohertz QPOs become undetectable by the time the source reaches the middle of the NB. In contrast, Aql X-1 presents kilohertz QPOs in the island and banana states.

5. The timescales of the aperiodic variability tend to decrease (hence the frequencies increase) as the Z source moves along the FB, which is the opposite behavior to that observed in Aql X-1 in the banana branch.

6. CONCLUSIONS

We have investigated the timing and spectral properties of the soft X-ray transient Aql X-1 during five X-ray outbursts
covering a period of more than 5 years. Three spectral states show up in the color-color diagram of Aql X-1: a low-intensity hard state, identified with an extreme island state, a high-intensity soft state corresponding to the classic banana state, and an intermediate state associated with the island state of atoll sources. We have found that the hard color plays a crucial role in determining the timing properties of the extreme island state. Although the overall distribution of these states in the color-color diagram may resemble a Z, neither the motion in the CD, nor the typical timescales through the different branches of the CD, nor the range of X-ray luminosities, nor the timing properties at very low count rates (i.e., the existence of the extreme island state) are compatible with the classical Z-source behavior.

P. R. is a researcher of the programme “Ramón y Cajal” funded by the University of Valencia and the Spanish Ministry of Science and Technology. P. R. also would like to thank the University of Crete for providing in part the resources needed to carry out this work. This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center.

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