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## AQUILA X-1 FROM OUTBURST TO QUIESCENCE: THE ONSET OF THE PROPELLER EFFECT AND SIGNS OF A TURNED-ON ROTATION-POWERED PULSAR

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### ABSTRACT

We report on the 1997 March–April *BeppoSAX* observations of Aquila X-1, which were the first to monitor the evolution of the spectral and time-variability properties of a neutron star soft X-ray transient from the outburst decay to quiescence. We observed a fast X-ray flux decay, which brought the source luminosity from  $\sim 10^{36}$  to  $\sim 10^{33}$  ergs s<sup>-1</sup> in less than 10 days. The X-ray spectrum showed a power-law high-energy tail with a photon index  $\Gamma \sim 2$ , which hardened to  $\Gamma \sim 1\text{--}1.5$  as the source reached quiescence. These observations, together with the detection by the *Rossi X-Ray Timing Explorer* of a periodicity of a few milliseconds during an X-ray burst, likely indicate that the rapid flux decay is caused by the onset of the propeller effect, which arises from the very fast rotation of the neutron star magnetosphere. The X-ray luminosity and hard spectrum that characterize the quiescent emission can be consistently interpreted as shock emission by a turned-on rotation-powered pulsar.

*Subject headings:* pulsars: general — stars: individual (Aquila X-1) — stars: neutron — X-ray: stars

### 1. INTRODUCTION

Soft X-ray transients (SXRTs), when in outburst, show properties similar to those of persistent low-mass X-ray binaries (LMXRBs) containing a neutron star (White, Kaluziński, & Swank 1984; Tanaka & Shibazaki 1996; Campana et al. 1998). The large variations in the accretion rate that are characteristic of SXRTs allow the investigation of a variety of regimes for the neutron stars in these systems that are inaccessible to persistent LMXRBs. While it is clear that, when in outburst, SXRTs are powered by accretion, the origin of the low-luminosity X-ray emission that has been detected in the quiescent state of several SXRTs is still unclear. An interesting possibility is that a millisecond radio pulsar (MSP) turns on in the quiescent state of SXRTs (Stella et al. 1994). This would provide a “missing link” between persistent LMXRBs and recycled MSPs.

Aquila X-1 is the most active SXRT known: more than 30 X-ray and/or optical outbursts have been detected so far. The companion star has been identified with the K1 V variable star V1333 Aql, and an orbital period of 19 hr has been measured (Chevalier & Ilovaisky 1991). The outbursts of Aql X-1 are generally characterized by a fast rise (5–10 days), followed by a slow decay, with an  $e$ -folding time of 30–70 days (see Tanaka & Shibazaki 1996, Campana et al. 1998, and references therein). Type I X-ray bursts were discovered during the declining phase of an outburst (Koyama et al. 1981), testifying to the presence of a neutron star. Peak X-ray luminosities are

in the  $\sim(1\text{--}4) \times 10^{37}$  ergs s<sup>-1</sup> range (for the  $\sim 2.5$  kpc distance inferred from its optical counterpart; Thorstensen, Charles, & Bowyer 1978). Close to the outburst maximum, the X-ray spectrum is soft, with an equivalent bremsstrahlung temperature of  $kT_{\text{br}} \sim 4\text{--}5$  keV. Sporadic observations of Aql X-1 during the early part of the outburst decay (Czerny, Czerny, & Grindlay 1987; Tanaka & Shibazaki 1996; Verbunt et al. 1994) showed that when the source luminosity drops below  $\sim 10^{36}$  ergs s<sup>-1</sup>, the spectrum changes to a power law with a photon index  $\Gamma \sim 2$ , extending up to energies of  $\sim 100$  keV (Harmon et al. 1996). *ROSAT* PSPC observations revealed Aql X-1 in quiescence on three occasions at a level of  $\sim 10^{33}$  ergs s<sup>-1</sup> (0.4–2.4 keV; Verbunt et al. 1994). In this lower energy band, the spectrum is considerably softer and is consistent with a blackbody temperature of  $kT_{\text{bb}} \sim 0.3$  keV.

### 2. X-RAY OBSERVATIONS

An outburst from Aql X-1 reaching a peak luminosity of  $\sim 10^{37}$  ergs s<sup>-1</sup> (2–10 keV) was discovered and monitored starting from 1997 mid-February with the *Rossi X-Ray Timing Explorer* All-Sky Monitor (*RXTE* ASM; Levine et al. 1997). Six observations were carried out with the *BeppoSAX* Narrow Field Instruments (NFIs) starting from 1997 March 8 (see Table 1), with the aim of studying the final stages of the outburst decay. Figure 1a shows the light curve of the Aql X-1 outburst as observed by the *RXTE* ASM and *BeppoSAX* Medium-Energy Concentrator Spectrometer (MECS). The first part of the outburst can be fitted by a Gaussian with  $\sigma \sim 17$  days. This is not uncommon in SXRTs (e.g., in the case of 4U 1608–52; Lochner & Roussel-Duprè 1994).

The flux decay rate changed dramatically around MJD 50,512 (1997 March 5). At the time of the first *BeppoSAX* observation (which started on 1997 March 8), the source luminosity was decreasing very rapidly, fading by about 30% in 11 hr, from a maximum level of  $\sim 10^{35}$  ergs s<sup>-1</sup>. The second observation took place on 1997 March 1, when the source, which was a factor of  $\sim 50$  fainter on average, reduced its flux by about 25% in 12 hr. In the subsequent four observations, the source luminosity attained a constant level of  $\sim 6 \times 10^{32}$  ergs s<sup>-1</sup>, consistent with previous measurements of the quiescent luminosity of Aql X-1 (Verbunt et al. 1994). The sharp

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TABLE 1  
SUMMARY OF *BEPPoSAX* NFIS OBSERVATIONS

Observation	Date	LECS/MECS-PDS			
		Exposure (s)	LECS Count Rate (counts s <sup>-1</sup> )	MECS Count Rate (counts s <sup>-1</sup> )	PDS Count Rate (counts s <sup>-1</sup> )
1	1997 Mar 8	5240/21342	0.84 ± 0.02	2.2 ± 0.01	0.87 ± 0.06
2	1997 Mar 12	3247/21225	(2.5 ± 0.4) × 10 <sup>-2</sup>	(7.4 ± 0.2) × 10 <sup>-2</sup>	≤0.19
3	1997 Mar 17	5755/17258	(5.6 ± 1.7) × 10 <sup>-3</sup>	(1.3 ± 0.1) × 10 <sup>-2</sup>	≤0.24
4	1997 Mar 20	4287/22589	(5.8 ± 1.9) × 10 <sup>-3</sup>	(1.6 ± 0.1) × 10 <sup>-2</sup>	≤0.17
5	1997 Apr 2	8440/23576	(6.2 ± 1.3) × 10 <sup>-3</sup>	(1.2 ± 0.1) × 10 <sup>-2</sup>	≤0.17
6 <sup>a</sup>	1997 May 6	11789/21703	(6.7 ± 1.1) × 10 <sup>-3</sup>	...	≤0.19

<sup>a</sup> No MECS data were obtained.

decrease after MJD 50,512 is well described by an exponential decay with an  $e$ -folding time of  $\sim 1.2$  days.

The *BeppoSAX* Low-Energy Concentrator Spectrometer (LECS), MECS, and Phoswich Detector System (PDS) spectra during the fast-decay phase, as well as those obtained by summing up all the observations pertaining to quiescence, can be fitted with a model consisting of a blackbody plus a power law (see Table 2 and Fig. 1*b*). The soft blackbody component remained nearly constant in temperature ( $kT_{\text{bb}} \sim 0.3\text{--}0.4$  keV), but its radius decreased by a factor of  $\sim 3$  from the decay phase to quiescence. The equivalent radius in quiescence ( $R_{\text{bb}} \sim 1$  km) is consistent with the *ROSAT* results (Verbunt et al. 1994). The power-law component changed substantially from the decay phase to quiescence: during the decay, the photon index was  $\Gamma \sim 2$ , while in quiescence, it hardened to  $\Gamma \sim 1$ . The two values are different with greater than 90% confidence (see Table 1). The ratio of the 0.5–10 keV luminosities in the power-law and blackbody components decreased by a factor of 5 between the first *BeppoSAX* observation and quiescence.

### 3. DISCUSSION

The *BeppoSAX* observations enabled us to follow, for the first time, the evolution of an SXRT outburst down to quies-

cence. The sharp flux decay leading to the quiescent state of Aql X-1 is reminiscent of the final evolution of dwarf novae outbursts (e.g., Ponman et al. 1995; Osaki 1996), although there are obvious differences with respect to the X-ray luminosities and spectra involved in the two cases, likely resulting from the different efficiencies in the gravitational energy release between white dwarfs and neutron stars.

Models of low-mass X-ray transient outbursts that host an old neutron star or a black hole are largely built analogous to dwarf novae outbursts. In particular, van Paradijs (1996) showed that the different range of time-averaged mass accretion rates over which the dwarf nova and low-mass X-ray transient outbursts were observed to take place is well explained by the higher level of disk irradiation caused by the higher accretion efficiency of neutron stars and black holes. However, the outburst evolution of low-mass X-ray transients presents important differences. In particular, the steepening in the X-ray flux decrease of Aql X-1 has no clear parallel in low-mass X-ray transients containing black hole candidates (BHCs). The best-sampled light curves of these sources show an exponential-like decay (sometimes with a superposed secondary outburst) with an  $e$ -folding time of  $\sim 30$  days and that extends up to four decades in flux, with no indication of a sudden steepening

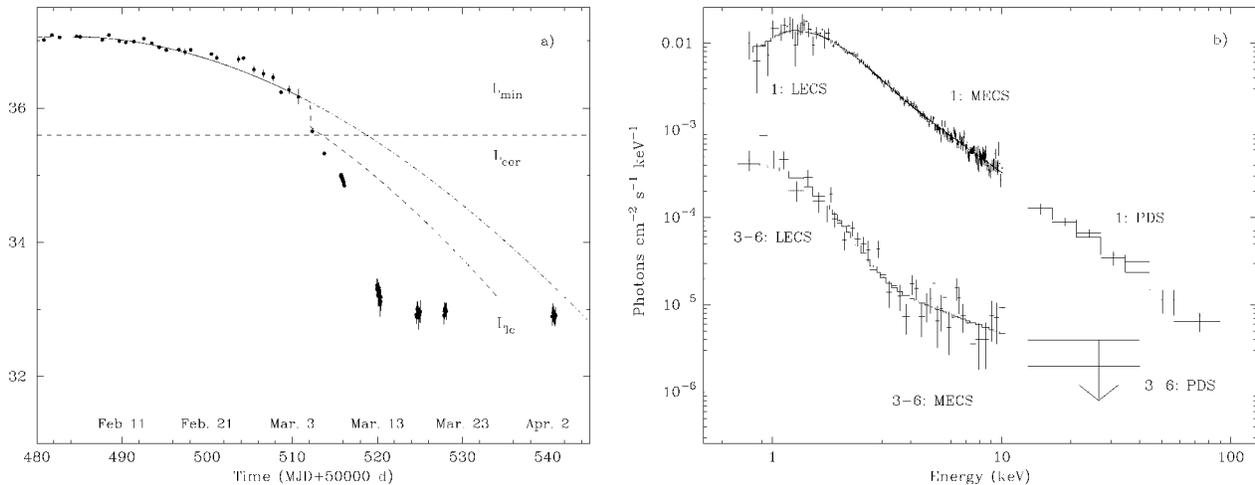


FIG. 1.—(a) Light curve of the 1997 February–March outburst of Aql X-1. The data before and after MJD 50,514 were collected with the *RXTE* ASM (2–10 keV) and the *BeppoSAX* MECS (1.5–10 keV), respectively. *RXTE* ASM count rates are converted to (unabsorbed) luminosities using a conversion factor of  $4 \times 10^{35}$  ergs s<sup>-1</sup> (before MJD 50,512) and  $2 \times 10^{35}$  ergs s<sup>-1</sup> (after MJD 50,512), as derived from *RXTE* spectral fits (Zhang et al. 1998a). *BeppoSAX* luminosities are derived directly from the spectral data (see text). The evolution of the flux from MJD 50,480 to MJD 50,512 is well fitted by a Gaussian centered on MJD 50,483.2. However, this fit does not provide an acceptable description for later times (dot-dashed line), not even if the accretion luminosity is calculated in the propeller regime (dashed line). The horizontal solid line represents the X-ray luminosity corresponding to the closure of the centrifugal barrier  $L_{\text{min}}$  (for a magnetic field of  $10^8$  G and a spin period of 1.8 ms), and the horizontal dashed line represents the luminosity gap due to the action of the centrifugal barrier,  $L_{\text{cor}}$ . The horizontal dotted line marks the minimum luminosity in the propeller regime ( $L_{\text{ic}}$ ). (b) *BeppoSAX* unfolded spectra of Aql X-1 during the early stages of the fast decline (observation 1) and during the quiescent phase (observations 3–6, summed). The best-fit spectral model (blackbody plus power law) is superposed on the data.

TABLE 2  
SUMMARY OF SPECTRAL FITS

Observation <sup>a</sup>	Blackbody $kT_{\text{bb}}$ (keV)	Blackbody $R_{\text{bb}}$ (km)	Power Law $\Gamma$	PL/BB Flux Ratio <sup>b</sup>	Mean Luminosity <sup>c</sup> (ergs s <sup>-1</sup> )	Reduced $\chi^2$
1 .....	$0.42 \pm 0.02$	$2.6 \pm 0.3$	$1.9 \pm 0.1$	3.7	$9 \times 10^{34}$	1.0
2 .....	$0.3^{+0.1}_{-0.2}$	$0.7^{+6.6}_{-0.3}$	$1.8 \pm 0.7$	1.6	$2 \times 10^{33}$	0.9
3-6 .....	$0.3 \pm 0.1$	$0.8^{+0.4}_{-0.1}$	$1.0 \pm 0.3$	0.7	$6 \times 10^{32}$	1.3

NOTE.—Errors are  $1 \sigma$ .

<sup>a</sup> Spectra from the LECS and MECS (and PDS for the first observation) detectors have been considered. The spectra corresponding to the quiescent state have been summed up, in order to increase the statistics, and an upper limit from the summed PDS data was also used to constrain better the power-law slope.

<sup>b</sup> Power-law-to-blackbody flux ratio in the 0.5–10 keV energy range.

<sup>c</sup> Unabsorbed X-ray luminosity in the 0.5–10 keV energy range. In the case of the first observation, the PDS data were included in the fit (the unabsorbed 0.5–100 keV luminosity amounts to  $2 \times 10^{35}$  ergs s<sup>-1</sup>).

(Chen, Shrader, & Livio 1997). In addition, BHC transients display a larger luminosity range between outburst peak and quiescence than neutron star SXRTs (Garcia et al. 1998 and references therein). Since the mass donor stars and the binary parameters are quite similar in the two cases, it appears natural to attribute these differences to the different nature of the underlying object: neutron stars possess a surface and, likely, a magnetosphere, while BHCs do not.

When in outburst, accretion down to the neutron star surface takes place in SXRTs, as testified to by the similarity of their properties with those of persistent LMXRBs, especially the occurrence of type I bursts and the X-ray spectra and luminosities. The mass inflow rate during the outburst decay decreases, causing the expansion of the magnetospheric radius,  $r_m$ . Thus, accretion onto the neutron star surface can continue as long as the centrifugal drag exerted by the corotating magnetosphere on the accreting material is weaker than gravity (Illarionov & Sunyaev 1975; Stella, White, & Rosner 1986). This occurs above a limiting luminosity  $L_{\text{min}} = GMM_{\text{min}}/R \sim 4 \times 10^{36} B_8^2 P_{-3}^{-7/3}$  ergs s<sup>-1</sup>, where  $G$  is the gravitational constant and  $M$ ,  $R$ ,  $B = B_8 10^8$  G, and  $P = P_{-3} 10^{-3}$  ms are the neutron star mass, radius, magnetic field, and spin period, respectively (here and in the following, we assume  $M = 1.4 M_{\odot}$  and  $R = 10^6$  cm). As  $r_m$  reaches the corotation radius,  $r_{\text{cor}}$ , accretion onto the surface is inhibited, and a lower accretion luminosity ( $< L_{\text{min}}$ ) of  $L_{\text{cor}} = GMM_{\text{min}}/r_{\text{cor}} \sim 2 \times 10^{36} B_8^2 P_{-3}^{-3}$  ergs s<sup>-1</sup> is released. After this luminosity gap, the source enters the propeller regime. If the mass inflow rate decreases further, the expansion of  $r_m$  can continue up to the light cylinder radius,  $r_{\text{lc}}$ , providing a lower limit to the accretion luminosity that can be emitted in the propeller regime,  $L_{\text{lc}} = GMM_{\text{lc}}/r_{\text{lc}} \sim 2 \times 10^{34} B_8^2 P_{-3}^{-9/2}$  ergs s<sup>-1</sup>. Below  $L_{\text{lc}}$ , the radio pulsar mechanism may turn on, and the pulsar relativistic wind interacts with the incoming matter, pushing it outward. Matter inflowing through the Roche lobe is stopped by the radio pulsar radiation pressure, giving rise to a shock front (Illarionov & Sunyaev 1975; Shaham & Tavani 1991). Clearly these regimes have no equivalent in the case of black hole accretion.

### 3.1. The Onset of the Propeller

During the 1997 February–March outburst of Aql X-1, *RXTE* observations led to the discovery of a nearly coherent modulation at  $\sim 550$  Hz ( $\sim 1.8$  ms) during a type I X-ray burst. A single QPO peak, with a centroid frequency ranging from  $\nu_{\text{QPO}} \sim 750$  to 830 Hz, was also observed at two different flux levels, when the persistent luminosity was  $\sim 1.2 \times 10^{36}$  and  $\sim 1.7 \times 10^{36}$  ergs s<sup>-1</sup> (Zhang et al. 1998b). In the presence of a single QPO peak, the magnetospheric and sonic-point beat-frequency model (Alpar & Shaham 1985; Miller, Lamb, &

Saltis 1997) interpretation is ambiguous in that the QPO peak could represent either the Keplerian frequency at the inner disk boundary or the beat frequency. Moreover, the burst periodicity at  $\sim 550$  Hz may represent the neutron star spin frequency,  $\nu_s$ , or half its value (Zhang et al. 1998b). In either case, the possibility that accretion onto the neutron star surface takes place even in the quiescent state of Aql X-1 faces serious difficulties: for a quiescent luminosity of order  $10^{33}$  ergs s<sup>-1</sup>, a magnetic field of only  $\lesssim 5 \times 10^6$  G would be required in order to fulfill the condition  $r_m \lesssim r_{\text{cor}}$ . For such a low magnetic field, Aql X-1 and, by inference, LMXRBs with kilohertz QPOs can hardly be the progenitors of recycled MSPs. More crucially, the marked steepening in the outburst decay that takes place below  $\sim 1 \times 10^{36}$  ergs s<sup>-1</sup> is accompanied by a marked spectral hardening, resulting from a sudden decrease of the flux in the blackbody spectral component. This is clearly suggestive of a transition taking place deep in the gravitational well of the neutron star, where most of the X-rays are produced. The most appealing mechanism is a transition to the propeller regime, where most of the inflowing matter is stopped at the magnetospheric boundary (Zhang, Yu, & Zhang 1998a). In Figure 1a, the luminosity at MJD 50,512 is identified with  $L_{\text{min}}$ , and the lower horizontal lines indicate the luminosity interval during which Aql X-1 is likely to be in the propeller regime.

Additional information on the neutron star magnetic field (and spin) can be inferred as follows. The observed ratio of the luminosity,  $L_{\text{QPO}}$ , when the QPOs at  $\sim 800$  Hz were detected and the luminosity,  $L_{\text{min}}$ , when the centrifugal barrier closes is  $L_{\text{QPO}}/L_{\text{min}} \sim 1.2$ – $1.7$ . At  $L_{\text{min}}$ , the Keplerian frequency of matter at the magnetospheric boundary is, by definition, equal to the spin frequency, i.e.,  $\nu_s \sim 550$  or  $\sim 275$  Hz for Aql X-1. Based on beat-frequency models, at  $L_{\text{QPO}}$ , the Keplerian frequency at the inner disk boundary can be either  $\nu_{\text{K,QPO}} \sim 800$  Hz or  $\nu_{\text{K,QPO}} \sim \nu_s + 800$  Hz, depending on whether the single kilohertz QPO observed corresponds to the Keplerian frequency or the beat frequency. In the magnetospheric beat-frequency models, simple theory predicts that the Keplerian frequency at the magnetospheric boundary is proportional to  $L^{3/7}$ ; in the radiation pressure-dominated regime relevant to the case at hand, the Ghosh & Lamb (1992) model predicts instead a frequency proportional to  $L^{3/13}$ . Therefore, we expect  $\nu_{\text{K,QPO}}/\nu_s \sim (L_{\text{QPO}}/L_{\text{min}})^{3/7} \sim 1.2$  and  $\nu_{\text{K,QPO}}/\nu_s \sim (L_{\text{QPO}}/L_{\text{min}})^{3/13} \sim 1.1$  in the two models, respectively. Such a low ratio clearly favors the interpretation in which  $\nu_{\text{K,QPO}} \sim 800$  Hz and  $\nu_s \sim 550$  Hz. In the sonic-point beat-frequency model (Miller et al. 1997), the innermost disk radius is well within the magnetosphere, implying that the Keplerian frequency at the magnetospheric boundary is less than  $\nu_{\text{K,QPO}}$ . In this case, all possible combinations of  $\nu_s$  and  $\nu_{\text{K,QPO}}$  are allowed. By using the observed  $L_{\text{min}}$ , a neutron

star magnetic field of  $B \sim (1-3) \times 10^8$  G (depending on the adopted model of the disk-magnetosphere interaction) is obtained in the case of  $\nu_s \sim 550$  Hz and  $B \sim (2-6) \times 10^8$  G in the case of  $\nu_s \sim 275$  Hz.

Once in the propeller regime, the accretion efficiency decreases further as the magnetosphere expands for decreasing mass inflow rates ( $L_{\text{acc}} \propto \dot{M}^{9/7}$ ). The  $\sim 1$  day exponential-like luminosity decline observed with *BeppoSAX* is considerably faster than the propeller accretion luminosity extrapolated from the first part of the outburst (e.g., the Gaussian profile shown by the dashed line in Fig. 1a). We note here that the spectral transition accompanying the onset of the centrifugal barrier may also modify the irradiation properties of the accretion disk, contributing to X-ray luminosity turnoff. Alternatively, an active contribution of the “propeller” mechanism or the neutron star spin-down energy dissipated into the inflowing matter cannot be excluded.

### 3.2. A Turned-on Rotation-powered Pulsar?

It is unlikely that the quiescent luminosity of Aql X-1 is powered by magnetospheric accretion in the propeller regime. As shown in Figure 1a, the quiescent X-ray luminosity is probably lower than the minimum magnetospheric accretion luminosity,  $L_{\text{ic}}$ , allowed in the propeller phase (this remains true for  $B \geq 6 \times 10^7$  G if  $\nu_s \sim 550$  Hz and for  $B \geq 3 \times 10^8$  G if  $\nu_s \sim 275$  Hz). Moreover, the *BeppoSAX* X-ray spectrum shows a pronounced decrease in the power-law-to-blackbody flux ratio, together with a flattening of the power-law component between the fast-decay phase and quiescence, suggesting that a transition to shock emission from the interaction of a radio pulsar wind with the matter outflowing from the companion star has taken place. Note that an X-ray spectrum with a slope of  $\Gamma \sim 1.5$  has been observed from the radio pulsar PSR B1259–63 immersed in the wind of its Be star companion. Models of this interaction predict that a power-law X-ray spectrum with a slope of  $\Gamma \sim 1.5$  should be produced for a wide range of parameters (Tavani & Arons 1997).

The additional soft X-ray component observed during the outburst decay (see Table 2) might be emitted at the polar caps as a result of the residual neutron star accretion in the propeller phase. Note that the equivalent blackbody radius decreases for decreasing X-ray luminosities, just as it would be expected to do if the magnetospheric boundary expanded. Alternatively, the blackbody-like spectral component observed in quiescence could be due to the streaming of energetic particles that hit the polar caps, in close analogy to the soft X-ray component observed, in MSPs, at the weaker level of  $\sim 10^{30}$ – $10^{31}$  ergs s<sup>-1</sup> (Becker & Trümper 1997).

If we assume a magnetic field in the range derived in § 3.1 [i.e.,  $B \sim (1-3) \times 10^8$  G for  $\nu_s = 550$  Hz and  $B \sim (2-6) \times 10^8$  G for  $\nu_s = 275$  Hz], we can consistently explain the  $\sim 10^{33}$  ergs s<sup>-1</sup> quiescent X-ray luminosity as being powered by a radio pulsar enshrouded by matter outflowing from the companion star, if the conversion efficiency of spin-down luminosity to X-ray is  $\sim 0.1\%$ – $10\%$ . This is consistent with the modeling and observations of enshrouded pulsars (Tavani 1991; Verbunt et al. 1996).

There are chances of observing an MSP (a simple scaling from MSPs implies a signal at 400 MHz of  $\sim 10$  mJy; see Kulkarni, Narayan, & Romani 1990), even though the emission would probably be sporadic, as in the case of the pulsar PSR 1744–24A, due to the large amount of circumstellar matter (see Lyne et al. 1990; Shaham & Tavani 1991).

In summary, Aql X-1 appears to provide the first example of an old, fast-rotating neutron star undergoing a transition to the propeller regime at first, followed by a transition to the radio pulsar regime, as the transient X-ray emission approaches its quiescent level. Therefore, Aql X-1 (and possibly SXRTs in general) likely represents the long-sought “missing link” between LMXRBs and recycled MSPs.

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