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GIANT, REPEATING, OPTICAL BURSTS FROM THE SOFT X-RAY TRANSIENT AQUILA X-1

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ABSTRACT

We report the detection of optical bursts during a low-amplitude, flat-topped eruption of the soft X-ray transient Aql X-1. The bursts had amplitudes between 0.17 and 0.35 mag and were variable in duration, some lasting longer than 78 s. On one night they recurred quasi-periodically at a mean interval of 1.01 hr. Regularly repeating optical bursts of this kind have not heretofore been observed from any X-ray binary. The accreting star in Aql X-1 is known to be a neutron star. We propose that the optical bursts are reprocessed type I X-ray bursts; that is, that they are thermonuclear flashes in the envelope of the neutron star.

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

1. INTRODUCTION

The properties of Aql X-1 are unusual for a soft X-ray transient (SXT) (for a review of SXTs, see Tanaka & Shibazaki 1996). Its outbursts recur at irregular intervals of roughly 1 yr, more often than most SXTs, and their peak X-ray luminosities range from 2×10^{36} to 4×10^{37} ergs s^{-1} with a mean near $\sim 7 \times 10^{36}$ ergs s^{-1}, a factor of 10–100 less than most SXTs (van Paradijs & McClintock 1995; Chen, Shrader, & Livio 1997). Its 1978 and 1997 outbursts had a fast rise and exponential decay (FRED)—a characteristic signature of SXT eruptions—but many if not most of its eruptions are low-amplitude, flat-topped, and irregular in morphology (Charles et al. 1980; Garcia et al. 1997). Its visual flux rose by 4.4 mag during the 1978 eruption but more typically rises by 2–3 mag, also less than most SXTs (Chen et al. 1997).

Aql X-1 exhibits type I X-ray bursts, which are understood to be thermonuclear flashes in the envelopes of neutron stars (Koyama et al. 1981; see Lewin, van Paradijs, & Taam 1995 for a review of X-ray bursts). The compact star in Aql X-1 is, therefore, a neutron star, again placing Aql X-1 among the minority of SXTs, most of which appear to contain black holes (Chen et al. 1997). The two X-ray bursts recorded in 1979 April were typical of type I bursts in that they rose to maximum in less than 1 s and then returned nearly to minimum in 20–30 s, but both were atypical in showing nearly constant, weak, excess flux for at least 500 s after one burst and 2500 s after the other (Czerny, Czerny, & Grindlay 1987). The X-ray light curve of the 1979 April 7 burst showed a coherent periodic modulation at 7.6 Hz that lasted ∼100 s and was attributed to rotation of the neutron star (Schoelkopf & Kelley 1991). A probable optical counterpart of a type I X-ray burst from Aql X-1 was detected in 1980. It had an amplitude of ∼0.12 mag and lasted ∼15 s (van Paradijs 1983).

The companion to the neutron star is visible between eruptions and has a K5 V spectral type (Thorstensen, Charles, & Bowyer 1978; Shahbaz et al. 1996). The radial velocity curve of the K5 V star has not been measured, and the orbital period of Aql X-1 is not definitively established, but a periodic modulation at 18.97 ± 0.02 hr has been detected in the optical light curve during low-amplitude eruptions and has been equated with the orbital period (Chevalier & Ilovaisky 1991). An orbital period of 18.97 hr would place Aql X-1 near the boundary between accretion disks that are stable and unstable to thermal-viscous instabilities in a diagram of X-ray luminosity versus orbital period, which may be relevant to the erratic properties of its outbursts (van Paradijs 1996).

In this Letter we report optical photometry of Aql X-1 obtained during its 1995 July eruption and at quiescence in 1997 June. The eruption light curves exhibit large-amplitude bursts unlike any heretofore reported in any X-ray binary star.

2. THE OPTICAL LIGHT CURVES

We measured the light curve of Aql X-1 on the nights of 1995 July 28–31 (UTC) with a CCD photometer on the 2.1 m telescope at McDonald Observatory, taking 60 s integrations separated by 9 s of dead time. We generally used an R filter but switched to a V filter for a few minutes at intervals of 30 minutes to 1 hr. The differential magnitude of Aql X-1 in individual CCD frames was measured relative to the mean of six local comparison stars, all of which were constant with respect to each other. We also observed Aql X-1 in early 1997 June, when it was at minimum light. The weather was miserable, but we salvaged 4.0 hr of usable data scattered over the nights of 1997 June 3, 4, and 9 (UTC).

The differential R-band light curve on the night of 1995 July 30 (JD 2,449,928.8) is shown in Figure 1, and the light curves on all four nights in 1995 are shown in Figure 2. The R magnitude can be obtained from the differential magnitude by the relation $R = \Delta R + 16.60$, where ΔR is the differential magnitude; the mean color of Aql X-1 in our eruption observations was $\langle V - R \rangle = +1.35$. Aql X-1 was observed at $V \approx 17.5$ on July 25 (Ilovaisky & Chevalier 1995), and its mean magnitude during our observations was $V \approx 17.7$, so this was a low-amplitude, flat-topped eruption. The eruption took place a few months before *RXTE*/ASM observations of Aql X-1 began, but there are a few high points in the *GRO*/BATSE observations of Aql X-1 between 1997 mid-July and the end of 1997 September that may be related to the eruption (Garcia et al. 1997).

During the eruption, Aql X-1 flickered by up to 0.1 mag on timescales as short as 10 minutes, and it varied from night to night by up to 0.6 mag. Figure 2, which shows the eruption light curves folded on the 18.97 hr photometric period found by Chevalier & Ilovaisky (1991), demonstrates that a modulation with a period at or near 18.97 hr is also present in our data and accounts for most of the night-to-night variability. We note in passing that it is premature to equate the 18.97 hr period with the orbital period of Aql X-1 because the physical mechanism causing the modulation is unknown. If, for example, the modulation is caused by ellipsoidal variations of the secondary

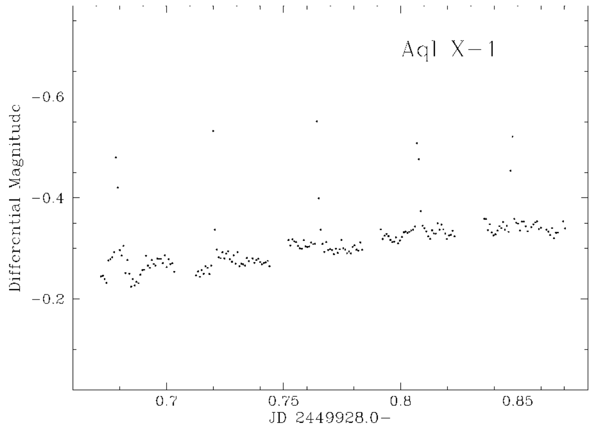

FIG. 1.—Differential R-band light curve of Aql X-1 on 1995 July 30 (UTC). The light curve was measured with 60 s integrations separated by 9 s of dead time.

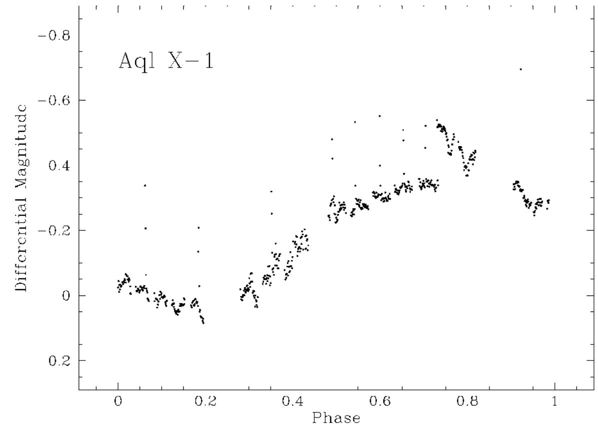

FIG. 2.—Differential R-band light curves of Aql X-1 folded at a period of 18.97 hr. The portion of the light curve between phases 0.00 and 0.20 was obtained on JD 2,449,926.8, between phases 0.25 and 0.45 on JD 2,449,927.8, between phases 0.45 and 0.73 on JD 2,449,928.8, and between phases 0.73 and 1.00 on JD 2,449,929.8.

star, the orbital period would be twice 18.97 hr, or if the modulation is caused by precession of an elliptical disk (superhumps), the orbital period would be a few percent less than 18.97 hr.

The outstanding features of the eruption light curves are the large optical bursts. We detected nine bursts, including five bursts on the third night (JD 2,449,928.8). The bursts had amplitudes between 0.17 and 0.35 mag, reaching $R_{\rm peak} = 15.9$ during the single burst on JD 2,449,929.8 (phase 0.82 in Fig. 2). The distance to Aql X-1 is poorly determined, but if we adopt a distance of 4 kpc and a reddened of $E(B-V) = 0.4$ (Charles et al. 1980; Tanaka & Lewin 1995), we find $M_R \approx 2.1$ at the peak of the brightest burst. If the spectral distribution of the bursts is similar to that of a stellar atmosphere or an optically thick accretion disk, as it would be if the energy in the optical bursts has been reprocessed from X-ray wavelengths, then, even with no bolometric correction, the peak luminosity reached $L_{\rm opt} = 2.8 \times 10^{34}(d/4\ {\rm kpc})^2$ ergs s^{-1}, where d is the distance in kpc. Adopting a mass of 1.5 $M_\odot$ for the neutron star, the ratio of the optical to the Eddington luminosity is $L_{\rm opt}/L_{\rm Edd} \approx 1.4 \times 10^{-4}$.

The five bursts detected on JD 2,449,928 were nearly periodic. The mean interval between bursts was 1.01 hr, and the intervals between individual bursts ranged from 0.97 to 1.07 hr, a variation of only $\pm 5\%$ from the mean. The intervals between bursts on the other nights were at least 1.5 hr. We see no convincing relations between the burst amplitudes, fluences, and intervals. We detected no bursts during 4.0 hr of monitoring Aql X-1 at minimum light, which suggests that Aql X-1 bursts more often during eruption than during quiescence.

The time resolution of the light curves is inadequate to determine the burst profiles but is good enough to place significant constraints on the burst durations. The single burst on JD 2,449,929 was detected in only one integration and must have lasted less than 78 s. Several bursts were detected in three successive integrations, but none were detected in four. Those bursts lasted between 78 and 216 s. The bursts durations were, therefore, variable, some lasting less than 78 s and some lasting longer than 78 s, possibly as long as 216 s.

3. DISCUSSION

Regularly recurring optical bursts have not been seen before from any X-ray binary, nor are there any reports of optical bursts lasting as long as 78 s. Some of the bursts during the 1995 eruption had durations more than 5 times longer and amplitudes (in magnitudes) up to 3 times greater than the optical burst from Aql X-1 observed in 1980 (van Paradijs 1983). Aql X-1 was undergoing a low-amplitude transient eruption when the 1980 burst was observed, and its brightness was similar to its brightness when the 1995 bursts were observed (Koyama et al. 1981). The fluence in some of the 1995 bursts was, then, more than 15 times greater than the fluence in the 1980 burst.

We assume that the optical bursts from Aql X-1 are connected with X-ray bursts, but the connection cannot be simple. Following Grindlay et al. (1978), we note that the maximum temperature of an X-ray burst with a blackbody spectral distribution and a radiating area equal to the surface area of a 1.5 $M_\odot$ neutron star is the blackbody temperature corresponding to the neutron star's Eddington luminosity, or ∼1.6 keV. The optical tail of a blackbody spectrum with this temperature and radiating area fails to reproduce the observed ratio $L_{\rm opt}/L_{\rm Edd} \approx 10^{-4}$ by a factor of $\sim 10^6$. Alternatively, if the optical bursts are produced by the tail of a blackbody with a temperature of 1.6 keV, the radius of the region producing the optical burst is $\sim 2 \times 10^8$ cm; if the spectral distribution of the optical burst is similar to that of the accretion disk, the radiating area must be comparable to the area of the disk to produce bursts with amplitudes as large as 0.35 mag. In either case, the radiating area is far larger than the surface area of a neutron star. We propose, therefore, that the optical bursts come from the accretion disk or companion star, not the neutron star, and that the optical flux has been reprocessed from X-ray wavelengths.

Because light takes time to traverse the binary system, reprocessed optical bursts begin after and last longer than the X-ray bursts that produce them. Taking 18.97 hr for the orbital period of Aql X-1 and 1.5 and 0.8 $M_\odot$ for the masses of its stars, we find that the two stars in Aql X-1 are separated by 11 lt-s. Light-travel time can stretch the duration of the optical bursts by no more than twice this amount, or 22 s. While this is a substantial stretching, it is much less than the duration of the optical bursts from Aql X-1, and, therefore, the source X-ray bursts must have lasted longer, possibly much longer than ∼60 s.

Two basic types of X-ray bursts have been identified: those caused by thermonuclear flashes in the envelopes of neutron stars (type I bursts) and those caused by accretion instabilities (type II bursts) (see, e.g., Lewin, van Paradijs, & Taam 1995). Both types can recur at regular intervals. For example, the intervals between the recurrent type I bursts from 3U 1820−30 slowly decreased over 4 days from 3.4 to 2.2 hr with only a 5% jitter about the mean interval (Clark et al. 1977). The bursts from GRO J1744−28, most of which could not have been type I bursts, recurred at regular intervals of 172 s in 1996 December (Kouveliotou et al. 1996). Although both type I and type II bursts typically last only 10–30 s, both types display an enormous variety of burst profiles, including bursts that last hundreds of seconds (see, e.g., Lewin, Vacca, & Basinska 1984; Tan et al. 1991). Nevertheless, the combination of regular recurrence with long duration appears not to have been observed before, and in this regard the bursts from Aql X-1 are unique.

Accretion instability models are not attractive for the optical bursts from Aql X-1 because there is no evidence for type II bursts from Aql X-1 at X-ray wavelengths. The data are sparse, however, and additional observations could conceivably produce support for accretion instability models. If so, nonmagnetic models for type II bursts may be worth considering. The magnetic field of the neutron star in Aql X-1 must be too weak to affect the accretion flow significantly because there is no evidence (with the possible exception of the 7.6 Hz modulation during the 1979 April 7 burst) that the neutron star is an X-ray pulsar at any accretion rate in the large range of accretion rates that prevail over an eruption cycle. Of the nonmagnetic models, those invoking thermal-viscous instabilities based on the Lightman-Eardley instability in the accretion disk (see, e.g., Taam & Lin 1984; Lasota & Pelat 1991; Cannizzo 1996; Belloni et al. 1997) are promising. The timescales of the bursts in these models depend critically on the inner radius of the accretion disk, on the magnitude of the viscosity, and on the mass accretion rate. With appropriate choices for these parameters, the burst interval and possibly the burst duration might be increased enough to agree with the burst properties of Aql X-1.

Since type I bursts have been detected from Aql X-1 at X-ray wavelengths, thermonuclear flashes must for now be the preferred explanation for the bursts from Aql X-1. Evolutionary models for type I bursts usually produce repeating bursts and commonly produce regularly repeating bursts with intervals similar to the 1 hr intervals between the bursts from Aql X-1 (see, e.g., Taam, Woosley, & Lamb 1996). As noted above, most type I bursts have short durations, but long-duration bursts have been observed (see, e.g., Lewin et al. 1984; Tawara et al. 1984). Likewise, most thermonuclear flash models produce bursts with short durations, but Bildsten & Brown (1997) have noted that type I bursts could last several minutes if the burning front propagates slowly across the neutron star. X-ray observations of the bursts from Aql X-1 would test these models.

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