THE ASTROPHYSICAL JOURNAL, 247:L27–L29, 1981 July 1

DISCOVERY OF X-RAY BURSTS FROM AQUILA X-1

K. KOYAMA, H. INOUE, K. MAKISHIMA, M. MATSUOKA, T. MURAKAMI, M. ODA, Y. OGAWARA, T. OHASHI, N. SHIBAZAKI, Y. TANAKA, AND F. J. MARSHALL[1]
Institute of Space and Aeronautical Science, University of Tokyo, 4-6-1, Komaba, Meguro-ku, Tokyo, Japan

I. KONDO
Institute for Cosmic Ray Research, University of Tokyo, 3-2-1, Midori-cho, Tanashi, Tokyo, Japan

S. HAYAKAWA, H. KUNIEDA, F. MAKINO, K. MASAI, F. NAGASE, AND Y. TAWARA
Department of Astrophysics, Faculty of Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Japan

AND

S. MIYAMOTO, H. TSUNEMI, AND K. YAMASHITA
Department of Physics, Faculty of Science, Osaka University, 1-1, Machikaneyama, Toyonaka, Japan
Received 1980 December 22; accepted 1981 March 17

ABSTRACT

Two X-ray bursts were observed from the recurrent transient Aql X-1 during the declining phase of a nova-like flare. These bursts exhibit common characteristics of typical X-ray bursts. The observed ratio of the persistent flux to the burst peak flux was about 0.02, which is about the same as the value for the burst observed from Cen X-4 during its outburst. Combined with the optical data during the X-ray quiescent state, the discovery of X-ray bursts from Aql X-1 gives strong support for the picture of X-ray bursters as binaries composed of a late dwarf and a neutron star.
Subject headings: stars: novae — X-rays: bursts

I. INTRODUCTION

Aquila X-1 (4U 1908+00) is a recurrent, soft-X-ray transient whose X-ray intensity during flares rises to that of the Crab Nebula. Its flare interval is known to be about 12–16 months from previous X-ray observations (Kaluzienski *et al.* 1977; Charles *et al.* 1980). An apparent periodicity of 1.3 days in X-ray intensity was once reported during the decay phase of a flare (Watson 1976).

Since the discovery of the optical counterpart of Aql X-1 (Thorstensen, Charles, and Bowyer 1977), extensive studies have been made during its quiescent as well as flare episodes. The optical spectrum in the quiescent state is consistent with a spectral type between G7 and K3 with no obvious peculiarities, and the distance is estimated to be 1.7–4.0 kpc (Thorstensen, Charles, and Bowyer 1978). The optical intensity increases from $V \sim 19$ mag to $\sim$15 mag at the peak of nova-like outbursts (Charles *et al.* 1980).

We observed an X-ray flare of Aql X-1 with the X-ray astronomy satellite *Hakucho* from 1980 May 20 through June 9, following the detection of an optical flare by Margon (1980). In this observation, we discovered that Aql X-1 produced X-ray bursts in its declining phase. This fact, together with a similar event observed in the Cen X-4 outburst (Matsuoka *et al.* 1980), gives an important link between bursters and soft-X-ray transients.

[1] On leave of absence from Massachusetts Institute of Technology.

II. OBSERVATIONS

The observations were performed with the burst monitor system on board *Hakucho* (Inoue *et al.* 1979). The burst monitor system consists of a pair of coarse modulation collimators (CMC-1, 2) with a wide field of view (17°.4 FWHM) and a fine modulation collimator (FMC-1) with a smaller field of view (5°.8 FWHM). Another counter (FMC-2) with a tubular collimator of 5°.8 (FWHM) field of view is also available.

When *Hakucho* was pointed to Aql X-1 on May 20, the X-ray transient's intensity was less than one-tenth the Crab Nebula intensity in the range 1–22 keV. The intensity was decreasing rather monotonously and faded below our detection limit of $\sim$1/50 times the Crab Nebula intensity after May 28. There is little doubt that the source was indeed Aql X-1. The accuracy of location determined relative to Ser X-1 and the Sun is better than 0°.5 for a 90% confidence limit. Furthermore, a simultaneous optical flare makes the identification firm.

On May 23 and 24, we detected two intense X-ray bursts. The positions of these bursts as determined with the FMC-1 are coincident with the persistent source Aql X-1 within 5′. We have no doubt that these bursts were produced by Aql X-1 and not by the nearby burst source MXB 1906+00. As a matter of fact, three bursts were observed from MXB 1906+00 in the same observation period. They were unambiguously distinguished from those of Aql X-1.

III. RESULTS

The X-ray light curve of Aql X-1 is shown in Figure 1. Each value of the persistent flux is the average of a typical 10–15 minute observation. If the intensity variation is approximated by a simple exponential form, the decay constant is about 6 days. This decay time is shorter than those for previously observed outbursts of Aql X-1 (Kaluzienski *et al.* 1977; Charles *et al.* 1980) but similar to that for the Cen X-4 outburst in 1979 (Matsuoka *et al.* 1980). No significant periodicity, such as reported by Watson (1976), is apparent. The hardness ratio, the count rate in the range 6–10 keV to that

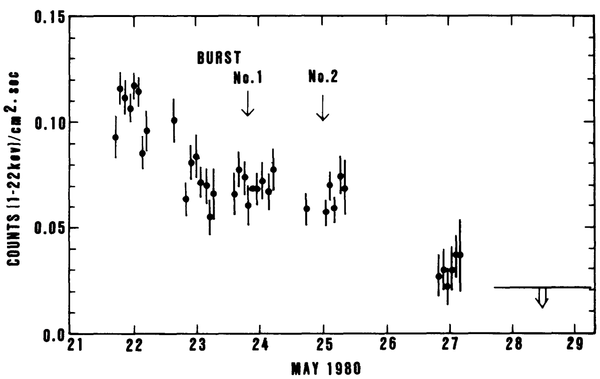

FIG. 1.—The X-ray light curve of Aql X-1 in the energy range 1–22 keV obtained with FMC-1. Arrows indicate the onset times of bursts No. 1 (May 23; $20^h53^m21^s$) and No. 2 (May 24; $23^h52^m24^s$).

in the range 3–6 keV, was about 0.5. This value corresponds roughtly to $kT = 7 \sim 8$ keV for a free-free spectrum. Hence, Aql X-1 belongs to the class of soft-X-ray transients (Cominsky *et al.* 1978).

The profiles of the two bursts observed with the CMC in two energy bands, 3–6 keV and 6–10 keV, are shown in Figure 2 together with the variation of the hardness ratio during burst. The data are corrected for the aspect and the dead time. The latter correction was necessary only for the No. 1 burst which was observed in a pulse-height sample mode involving a significant dead time. The burst profiles and the peak intensities of these two bursts are similar to each other. The peak energy flux and the integrated energy flux after the bolometric correction are approximately 10^{-7} ergs cm^{-2} s^{-1} and 10^{-6} ergs cm^{-2}, respectively. As clearly seen in Figure 2, the spectrum softens during the decay in both bursts, characteristic of type I bursts (Hoffman, Marshall, and Lewin 1978).

Further analysis is performed for the FMC-2 data which are of better statistical quality than those obtained with the CMC. On the assumption of a blackbody spectrum for the burst, the blackbody temperature and the blackbody radius can be estimated. The influence of the interstellar absorption is insignificant for $N_H \lesssim 10^{22}$ cm^{-2}, which is consistent with the estimated optical extinction $A_V \lesssim 2.0$ (Thorstensen, Charles, and Bowyer 1978; Charles *et al.* 1980). Figure 3 shows the result for the No. 2 burst. (Data for the No. 1 burst are subject to a large dead-time correction

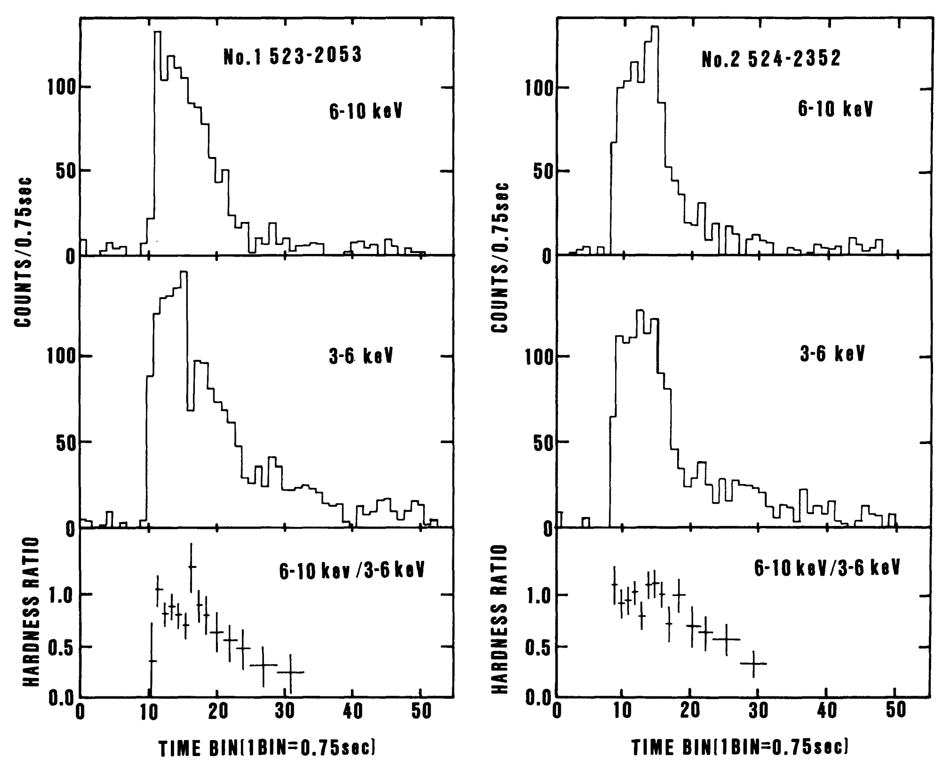

FIG. 2.—The time profile of the X-ray bursts from Aql X-1. Count rates with CMC-1 and CMC-2 are plotted for two energy bands, 6–10 and 3–6 keV. The hardness ratios for the two energy bands are given in the bottom diagrams.

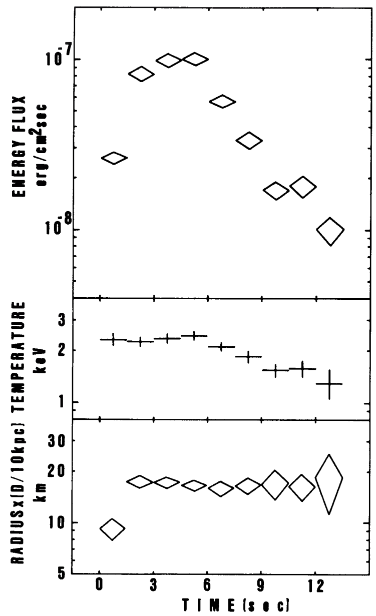

FIG. 3.—The bolometric energy flux, blackbody temperature, and radius of the emitting region at a distance of 10 kpc are plotted as a function of time for No. 2 burst.

as mentioned earlier.) The blackbody radius remains constant within statistical uncertainties from the peak through the decay and is approximately 17(D/10 kpc) km, with D as the distance to Aql X-1. For the range of the optically estimated distance, the blackbody radius becomes 3–7 km, the larger value being consistent with a typical neutron star radius.

IV. DISCUSSION

Aquila X-1 has been known to undergo recurrent nova-like outbursts with a quasi-periodicity of 12–16 months. The present outburst occurred approximately on time. Margon (1980) found from the optical observations on 1980 May 16 and 17 that Aql X-1 was in the flare state at $m_v \approx 17.5$ mag. When we started the X-ray observations on May 20, with the source's intensity at about 0.07 times that of the Crab Nebula, it was already in the declining phase. Hence, the peak intensity in the present flare is not known. It reached the Crab Nebula intensity in the previous outbursts.

The present discovery of X-ray bursts from Aql X-1 in its flare state has close similarities to the detection of a burst from Cen X-4 (Matsuoka *et al.* 1980): (i) Both of them undergo nova-like outbursts and belong to the class of sources with softer X-ray spectra or soft transients (Cominsky *et al.* 1978). (ii) They both produced type I X-ray bursts during the decay phase of the flare. (iii) Only two bursts were observed 1 day apart from Aql X-1 in 20 days or ~80 hours net observation time, while only one burst was detected from Cen X-4 in 20 days or 70 net hours. This small number of bursts seems to indicate that they produce bursts in very limited circumstances. (iv) It is significant that the γ-value (the ratio of the persistent flux to the burst peak flux) was 0.02 for both Aql X-1 and Cen X-4 when they produced bursts. These γ-values are consistent with those for other burst sources observed (van Paradijs *et al.* 1979).

Recently, Cominsky, Lawrence, and Lewin (1980) reanalyzed a single burst from Aql MXB detected by *SAS 3* on 1976 July 20 (Lewin *et al.* 1976) and found that it was consistent with being from Aql X-1. This burst indeed occurred during the decay of the Aql X-1 outburst in 1976 at a similar persistent flux level to that of the present detection of bursts, as roughly estimated from an extrapolation of the light curve (Kaluzienski *et al.* 1977; Watson 1976).

From the *Hakucho* observations thus far, three soft-X-ray transients, Aql X-1, Cen X-4, and XB 1608−522 (Murakami *et al.* 1980), have been found to produce type I X-ray bursts. These soft-X-ray transients are most likely a similar type of object as the so-called galactic-bulge sources (Lewin and Clark 1979), except for transient outbursts, because of the common characteristics such as soft-X-ray spectra, absence of pulsations and eclipses, faint blue optical counterparts, and generation of X-ray bursts. As mentioned in § I, the optical counterpart of Aql X-1 is identified with a normal star of a spectral type ~K0 during an X-ray quiescent period (Thorstensen, Charles, and Bowyer 1978). The fact of burst generation and the estimated blackbody radius indicate the presence of a neutron star in the Aql X-1 system. It is, therefore, convincing that Aql X-1 is composed of a neutron star and a late-type companion. Thus, the Aql X-1 case provides strong support for the yet unestablished picture that galactic-bulge sources, including bursters, are binaries of a neutron star and a late dwarf.

The authors wish to thank B. Margon for his prompt information on the Aql X-1 flare-up. They also acknowledge the assistance of N. Kawai in the course of data analysis.

REFERENCES

Charles, P. A. *et al.* 1980, *Ap. J.*, **237**, 154.
Cominsky, L., Jones, C., Forman, W., and Tananbaum, H. 1978, *Ap .J.*, **224**, 46.
Cominsky, L., Lawrence, A., and Lewin, W. H. G. 1980, private communication.
Hoffman, J. A., Marshall, H. L., and Lewin, W. H. G. 1978, *Nature*, **271**, 630.
Inoue, H. *et al.* 1979, *Proc. 16th International Cosmic Ray Conference*, Kyoto, Japan, **1**, 5.
Kaluzienski, L. J., Holt, S. S., Boldt, E. A., and Serlemitsos, P. J. 1977, *Nature*, **265**, 606.
Lewin, W. H. G., and Clark, G. W. 1979, X-Ray Symposium, Tokyo, Japan.
Lewin, W. H. G., Hoffman, J. A., Doty, J., Buff, J., Clark, G. W., and Rappaport, S. 1976, *M.N.R.A.S.*, **177**, 93.
Margon, B. 1980, *IAU Circ.*, No. 3478.
Matsuoka, M. *et al.* 1980, *Ap. J.* (*Letters*), **240**, L137.
Murakami, T. *et al.* 1980, *Ap. J.* (*Letters*), **240**, L143.
Thorstensen, J., Charles, P., and Bowyer, S. 1977, *IAU Circ.*, No. 3088.
———. 1978, *Ap. J.* (*Letters*), **220**, L131.
van Paradijs, J., Joss, P. C., Cominsky, L., and Lewin, W. H. G. 1979, *Nature*, **280**, 375.
Watson, M. G. 1976, *M.N.R.A.S.*, **176**, 19.