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DISCOVERY OF A LARGE X-RAY BURST FROM AN X-RAY NOVA, CENTAURUS X-4

M. MATSUOKA, H. INOUE, K. KOYAMA, K. MAKISHIMA, T. MURAKAMI, M. ODA,
Y. OGAWARA, T. OHASHI, N. SHIBAZAKI, AND Y. TANAKA
Institute of Space and Aeronautical Science, University of Tokyo

I. KONDO
Institute for Cosmic Ray Research, University of Tokyo

S. HAYAKAWA, H. KUNIEDA, F. MAKINO, K. MASAI, F. NAGASE, AND Y. TAWARA
Department of Astrophysics, Faculty of Science, Nagoya University

AND

S. MIYAMOTO, H. TSUNEMI, AND K. YAMASHITA
Department of Physics, Faculty of Science, Osaka University
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ABSTRACT

The X-ray satellite *Hakucho* detected an X-ray burst from a nova-like transient Cen X-4 on 1979 May 31. The time profile and the spectral softening of the burst show the same properties as those of a type I X-ray burst. The peak intensity of ~25 times the Crab in the energy range 1.5–12 keV is the strongest X-ray burst observed so far. The burst occurred during a nova-like outburst which is similar to one observed in 1969. The present discovery suggests that a soft transient source such as Cen X-4 comprises a neutron star and a late dwarf and can be an X-ray burster.
Subject headings: stars: novae — X-rays: bursts

I. INTRODUCTION

A very intense X-ray burst was observed in the decline phase of the X-ray nova Cen X-4 by the *Hakucho* satellite (Oda 1979). This is clear evidence that an X-ray nova such as Cen X-4 is an X-ray burster. The *Ariel 5* All-Sky Monitor (ASM) discovered an X-ray flare-up from a source in Centaurus which appeared between 1979 May 11 and 13 (Kaluzienski and Holt 1979*a*, *b*). The position of the source was consistent with that of Cen X-4, which had been an extremely bright nova observed in 1969 July (Conner, Evans, and Belian 1969; Terrel *et al.* 1979). The X-ray intensity reached a peak value of ~4 times the Crab on May 17 (Kaluzienski and Holt 1979*a*). Soon afterward an optical counterpart was discovered at $\alpha = 14^h55^m19^s.6$ (1950), $\delta = -31°28'07''$ (1950) by Canizares, McClintock, and Grindlay (1979*a*, *b*). It brightened to $V \sim 13$ mag from $\gtrsim 19$ mag on the Palomar Sky Survey.

Hakucho pointed at Cen X-4 from May 28 through June 16 and detected X-rays therefrom until June 11, when the source faded away below the detection limit. A typical type I X-ray burst of very large size was observed from Cen X-4 on May 31. This supports an intimate relationship between the X-ray nova and the X-ray burster.

In this *Letter*, we present observations of the X-ray burst and the light curve of the decline phase of Cen X-4 observed with *Hakucho*.

II. INSTRUMENTATION

Cen X-4 was observed by four sets of scaled proportional counters covering the energy range 1.5–30 keV. Two of the counters (CMC-1 and CMC-2), with a field of view of 17°.6 (FWHM) centered in the *z*-direction, are equipped with two-layer modulation collimators with a pitch angle of 4°.7. These counters have an opposite phase of modulation with respect to each other, so that the sum of the counting rates gives unmodulated signals. The third counter (FMC-1) is equipped with a modulation collimator with a pitch angle of 0°.5, and the fourth one (FMC-2) has the same field of view (5°.8 FWHM) as that of FMC-1. There is also a NaI (Tl) scintillation counter (HDX) with a field of view 4°.4 × 10° FWHM, the center of which is offset with respect to the *z*-axis, covering the energy range 10–100 keV.

There are two kinds of observational modes: (1) a pulse-counting mode (PC) with one and/or two energy channels; and (2) a pulse-height mode (PH) with 15 energy channels. The energy ranges of the detectors are controlled within the aforementioned ranges by command signals.

Further details of the instrumentation and performance of *Hakucho* are described elsewhere (Inoue *et al.* 1979).

III. RESULTS

a) *X-Ray Burst*

An X-ray burst from the direction of Cen X-4 started at $14^h09^m28^s.07$ on 1979 May 31. Its intensity reached the peak value at 1.5 s after the onset, with a peak intensity of about 25 times that of the Crab nebula. The burst time profile observed by CMC-1 and CMC-2 in a single energy channel of 1.5–12 keV is shown in Figure 1. Since Cen X-4 was 8° away from the z-axis, it was out of the field of view of the FMC detectors. It was only partly inside the field of view of HDX, and consequently the source counting rate was considerably spin modulated. The hardness ratio, the ratio of the counting rate in the energy range 14–30 keV to that in the energy range 10–14 keV, was obtained from HDX data for about 5 s including the peak A softening of the spectrum is apparent, as is seen in the insert of Figure 1. Therefore, we classify this event as a type I burst, according to the classification scheme of Hoffman, Marshall, and Lewin (1978). If we assume a blackbody spectrum for the burst, the temperature around the burst peak is roughly estimated as $kT_{bb} = 2.5 \pm 0.8$ keV with the uncertainty including statistical and systematic errors.

The positions of the X-ray nova and the burst were obtained independently by means of rotating modulation collimator analysis (Tawara 1980), where a Sun sensor and a horizon sensor were used to determine the counter axis because no known X-ray sources were in the field of view of the CMC detectors. These two positions agree with one another within the statistical and systematic error of 0°.5, and their error boxes contain the optical nova identified with Cen X-4 (Canizares, McClintock, and Grindlay 1979*a*, *b*). Thus we conclude that the same nova emitted both X-rays and optical light, and that the burst was emitted from the nova. The position obtained above also coincides with that for the X-ray nova Cen X-4 discovered in 1969 July by Conner *et al.* (Conner, Evans, and Belian 1969; Terrel *et al.* 1979). Hence we conclude that the present outburst is a recurrence of the 1969 nova.

The ratio (γ) of the persistent flux (72 ± 2.7 counts s^{-1}) to the peak burst flux (4086 ± 100 counts s^{-1}) is $\gamma = 0.018$, which is consistent with the values of γ obtained for active type I X-ray bursters by van Paradijs *et al.* (1979). The total number of X-ray counts in the burst is $28{,}000 \pm 260$, which corresponds to a flux of about 7×10^{-6} ergs cm^{-2}, if we assume a blackbody spectrum of $kT_{bb} = 2.5$ keV. This is the largest type I burst observed so far.

b) *X-Ray Light Curve*

The X-ray light curve of Cen X-4 observed with *Hakucho* is shown in Figure 2. Almost all the data were obtained by CMC-1 and CMC-2, using the amplitude of modulation and the Earth occultation of the source. However, some of the data were obtained with FMC-1 and FMC-2. The intensities derived by means of these methods are consistent with each other. The data points plotted in Figure 2 display the intensity variation in the energy range 1.5–12 keV, corrected for both collimator response and exposure time. The error bars shown reflect both the statistical errors and the error introduced via the collimator response correction due to the uncertainties in the aspect of the satellite. The observation time is variable with durations of between

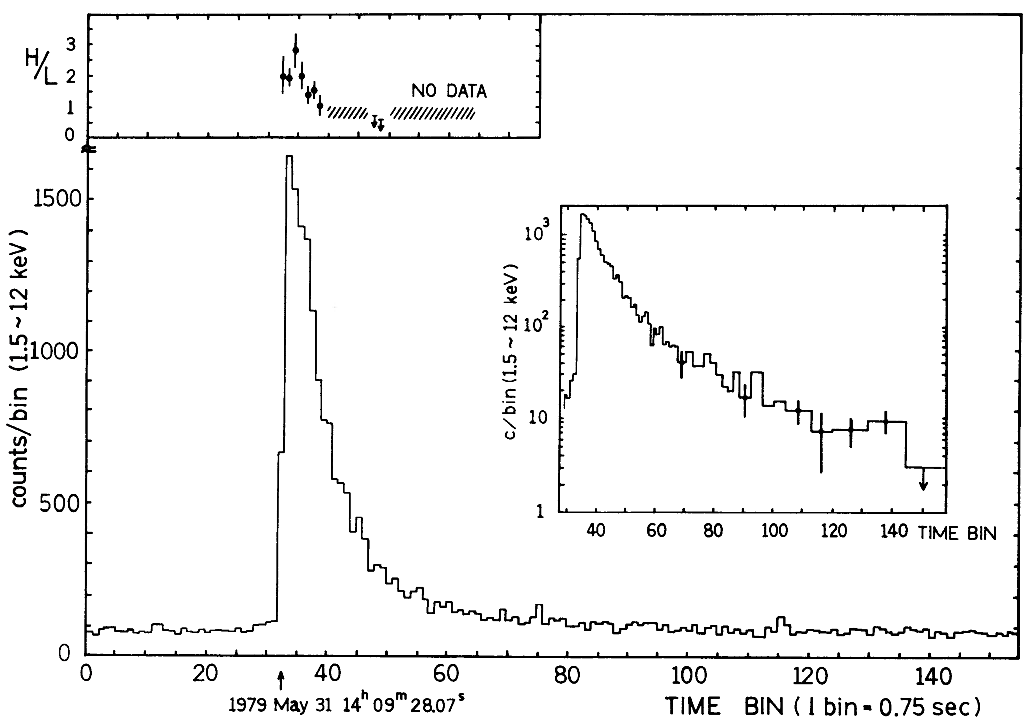

FIG. 1.—Time profile of the X-ray burst from Cen X-4. Plotted are the counts per bin (1 bin = 0.75 s) of two proportional counters (CMC-1 and CMC-2) in the energy range 1.5–12 keV. The onset of the burst is $14^h09^m28^s.07$, 1979 May 31 UT. The insert at the right is the counts per bin after subtracting the steady component and background. The upper insert gives the hardness ratio (14–30 keV)/(10–14 keV) obtained with a scintillation counter (HDX).

6 and 50 minutes, and the integration time of the analysis for these points (one point per each period) is selected in the range 10–15 minutes, depending on the observational mode of the experiment. When *Hakucho* pointed at Cen X-4 on May 28, the intensity was nearly that of the Crab nebula and after that decreased gradually with considerable fluctuations. It appears to have increased on June 4 and then gradually faded away below the detection limit of *Hakucho* after June 11. Some other X-ray novae exhibit similar variability in the decay phase (Matilsky *et al.* 1976; Watson, Ricketts, and Griffiths 1978). During the period from June 11 to 16 when it was able to observe the source, the intensity below 1 keV was already below the detection limit ($\sim 2 \times 10^{-2}$ photons cm^{-2} s^{-1}, 0.1–1 keV) of the soft X-ray counter on board *Hakucho*.

The time constant (τ) of the exponential decay is estimated as $\tau \sim 3.5$ days for the period May 28 to June 11. This time constant is consistent with that of the light curve in the decline phase of Cen X-4 in 1969 (Evans, Belian, and Conner 1970), but it is different from that of the X-ray nova, A0620−00, i.e., $\tau \sim 9$ days (Kaluzienski *et al* 1977) in the final phase.

c) *Spectrum and Hardness Ratio*

The energy spectrum of Cen X-4 was observed from May 28 to 31 by real-time telemetry. A reliable energy spectrum was not obtainable after June 1 because of the low source intensity. The curves of energy spectra measured between May 28 and 31 remained the same in shape within statistical errors and they are in essential agreement with the spectrum measured in 1969 by Kitamura *et al.* (1971). The spectrum is well fitted to a free-free spectrum gE^{-1} exp $(-E/kT_{\rm ff} - N_{\rm H}\sigma)$ or a power-law spectrum $E^{-\alpha}$ exp $(-N_{\rm H}\sigma)$, where σ is the Brown and Gould (1970) absorption cross section and g is the Gaunt factor. However, fitting parameters for a blackbody spectrum were not acceptable because of the less than 10% significance level on a $(T_{\rm bb}, N_{\rm H})$-plane. Figure 3 depicts the inferred spectrum with best-fitting parameters for the free-free spectrum, i.e., $\chi^2_{\rm min} = 3.9$ (8 degrees of freedom), $kT_{\rm ff} = 4.8 \pm 2$ keV, and $N_{\rm H} = 1.2(+4.5, -1.2) \times 10^{22}$ H atoms cm^{-2}. On the other hand, the best-fitting parameters for the power-law spectrum $\chi^2_{\rm min} = 5.0$ (8 degrees of freedom) are given as $\alpha = 2.7(+0.9, -0.6)$ and $N_{\rm H} = 4(+7, -4) \times 10^{22}$ H atoms cm^{-2}, where the errors of parameters represent the 90% confidence limits. Thus the observed spectral characteristics lead to the conclusion that Cen X-4 belongs in the category of soft transient X-ray sources (Kaluzienski *et al.* 1977; Cominsky *et al.* 1978; Fabbiano and Branduardi 1979).

The hardness ratio of intensities (6–10 keV)/(3–6 keV) was measurable until June 5, as shown in Figure 2, exhibiting a nearly constant value over the

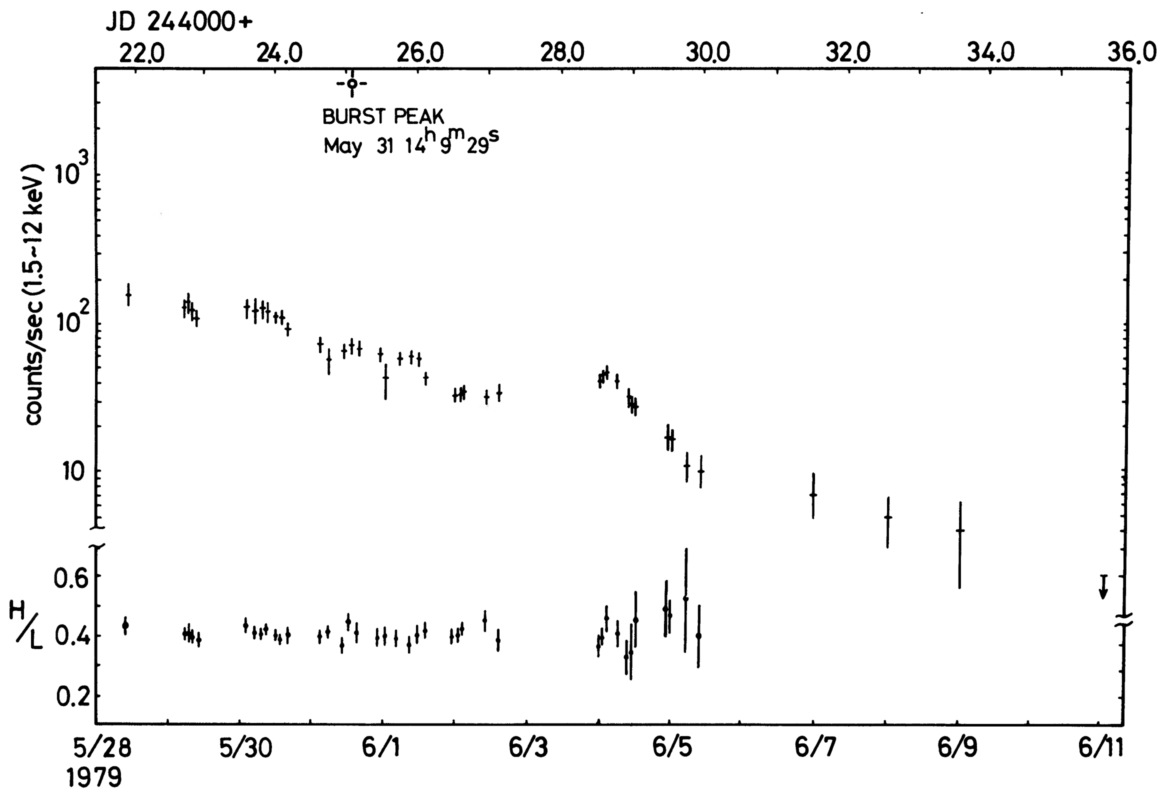

FIG. 2.—The X-ray light curve for the energy range 1.5–12 keV and the hardness ratio (6–10 keV)/(3–6 keV) of Cen X-4 obtained with two proportional counters (CMC-1 and CMC-2). One Crab intensity corresponds to about 161 counts s^{-1} in the energy range 1.5–12 keV.

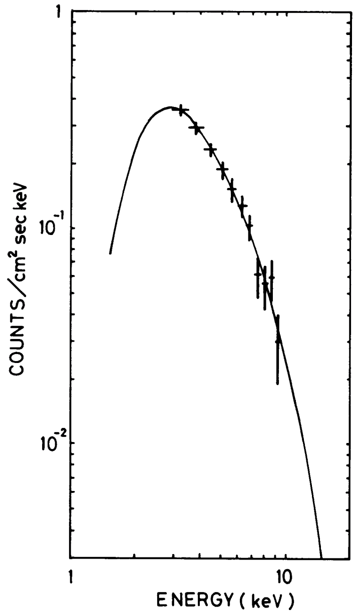

FIG. 3.—The energy spectrum of a persistent component obtained by the CMC counters on 1979 May 30. The solid curve is the free-free spectrum with the best-fitting parameters; $kT_{ff} = 4.8$ keV and $N_H = 1.2 \times 10^{22}$ H atoms cm^{-2}.

observation period. The constancy of the corresponding hardness ratio during the flare-up in 1969 was noted by Evans, Belian, and Conner (1970). There was no significant change in hardness ratio of the persistent component just before and after the X-ray burst.

IV. DISCUSSION

The fact that X-ray bursts are considered to be associated with accreting neutron stars (see Lewin and Clark 1979, and references therein) suggests that Cen X-4 is also a close binary system with a neutron star. No regular pulsation was detected in the persistent flux; the upper limit of the pulsating component is found to be 6% in the range 0.1–1000 s. Nonetheless, if we assume the validity of the thermonuclear flash models for type I X-ray bursts (Joss 1978, and references therein), the present discovery of a type I X-ray burst is clear evidence that Cen X-4 is accompanied by an accreting neutron star which exhibits no observable pulsation.

If the observed peak burst intensity of $\sim 1.0 \times 10^{-6}$ ergs cm^{-2} s^{-1} is due to the Eddington limit for a 1.4 $M_\odot$ object, the distance of Cen X-4 is not larger than ~ 1.2 kpc. If the X-rays are emitted uniformly over the spherical surface of a star with a blackbody temperature of $kT_{bb} = 2.5 \pm 0.8$ keV, its radius is not larger than about 11 km, which implies a size consistent with a neutron star. On the other hand, for a distance of 1.2 kpc, the magnitude of the prenova star ($\gtrsim 19$ mag) corresponds to a dwarf of type K or later. We note further that the optical companion is faint except during nova activity and that optical pulsations were not detected (Canizares, McClintock, and Grindlay 1979*b*). Thus it is a reasonable conclusion that Cen X-4 consists of a binary system of a K or later dwarf and a neutron star.

After this work was substantially complete, we learned of the analysis of the *Ariel 5* ASM that suggests a probable binary nature of Cen X-4 with a period of 8.2 ± 0.2 hours (Kaluzienski, Holt, and Swank 1980). The amplitude of the modulation, expressed as a percentage of the mean flux value of the decline phase data, is about 10% for a sinusoidal modulation. Although we reexamined the data, we do not obtain significant evidence for a periodic modulation around a period 8.2 hours, possibly resulting from the intermittent source sampling and large intensity fluctuations. The upper limit of the amplitude is about 15% in the energy range 1.5–12 keV according to the same definition as above.

The optical luminosity was high while the X-ray nova was observed. For example, on May 29 the X-ray flux was $\sim 1.7 \times 10^{-8}$ ergs cm^{-2} s^{-1} and the optical flux was 14.5 mag in the B band (Takagishi 1979). Taking account of the observed small interstellar reddening (Canizares, McClintock, and Grindlay 1979*b*), we estimate the ratio of the X-ray to optical luminosity L_x/L_o at about 200. This is similar to those of A0620−00, A1524−61 (Murdin, Griffiths, and Pounds 1977), and H1705−25 (Griffiths *et al.* 1978), implying that the X-ray emitting plasma becomes optically thick in the infrared. The soft transient sources thus far discovered, including these three, seem to belong to the same class as Cen X-4 and may similarly produce X-ray bursts. The present observations thus support the picture of a significant association between X-ray bursters and soft transients (Fabbiano and Branduardi 1979).

Hakucho observed Cen X-4 intermittently for 67 hours over 19.7 days, excluding periods of Earth occultation period of Cen X-4 and the transits of the South Atlantic Anomaly. Only one X-ray burst was detected from Cen X-4 during the entire 67 hour observation period. This suggests that the apparent burst frequency of Cen X-4 is appreciably smaller than that of other typical bursters. In contrast, 22 bursts were observed from the nova-like burster XB 1608−522 during a total coverage time of about 180 hours (Murakami *et al.* 1980). It has been suggested that type I bursts occur when the accretion rate is within critical values and the corresponding persistent luminosity is between $L_u \approx 0.1\, L_{Ed}$ and $L_l \approx 0.001\, L_{Ed}$, where L_{Ed} is the Eddington luminosity (van Paradijs *et al.* 1979, and references therein). *Hakucho* observed Cen X-4 for a total time of 40 hours during which the persistent luminosity $L_p \approx (0.04\text{–}0.001) L_{Ed}$, and for 27 hours during which $L_p \lesssim 0.001\ L_{Ed}$, respectively, where we assume the Eddington luminosity for the peak luminosity of the May 31 burst. Thus the observation of only one burst from Cen X-4 suggests that the source did not maintain a sufficiently large accretion rate long enough to produce X-ray bursts. In contrast, the persistent luminosity of XB 1608−522 probably can stay within the critical limits for a long time.

One might think that a precursor reported by Belian, Conner, and Evans (1972) in the previous flare-up of Cen X-4 was a burst. Its peak flux was about 1.4×10^{-6}

ergs cm^{-2} s^{-1}, the blackbody temperature at the peak was about 3×10^7 K, and the temperature decreased with time. Although these properties are similar to those of a type I burst, the decay time is longer than the present burst by an order of magnitude and it occurred before nova activity. The total energy of $\sim 5 \times 10^{39}$ ergs for an assumed distance of 1.2 kpc is roughly 5 times greater than that estimated for the present type I burst. Therefore, if this precursor was associated with Cen X-4, it and the present X-ray burst would imply differing conditions in the thermonuclear flash mechanism; for example, much more fuel gas might have been accreted during the dormant period before the 1969 precursor.

Further optical study and a search for weak X-ray intensity in the quiescent state will be needed in order to postulate a system and an explosion mechanism for Cen X-4.

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S. Hayakawa, H. Kunieda, F. Makino, K. Masai, F. Nagase, and Y. Tawara: Department of Astrophysics, Faculty of Science, Nagoya University, Chikusa, Nagoya 464, Japan

H. Inoue, K. Koyama, K. Makishima, M. Matsuoka, T. Murakami, M. Oda, Y. Ogawara, T. Ohashi, N. Shibazaki, and Y. Tanaka: Institute of Space and Aeronautical Science, University of Tokyo, Meguro, Tokyo 153, Japan

I. Kondo: Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188, Japan

S. Miyamoto, H. Tsunemi, and K. Yamashita: Department of Physics, Faculty of Science, Osaka University, Toyonaka, Osaka 560, Japan