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SHORT-TERM X-RAY VARIABILITY OF GX 339−4

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ABSTRACT

A black hole candidate GX 339−4 (4U 1659−48) was observed in 1981 and 1982 with the X-ray astronomy satellite *Hakucho* for more than 50 days in total. In 1981 April and 1982 May, the source was in the X-ray OFF state ($\lesssim$15 mCrab units), while the optical counterpart was also very faint. Through a substantial part of 1981 June, GX 339−4 was in a 0.1–0.2 Crab intensity state with a relatively hard spectrum. On this occasion, it exhibited a persistent, aperiodic intensity variation with ~35% rms amplitude on time scales of a fraction of a second to tens of seconds. In the 1–22 keV range, the characteristics of the fluctuation were independent of X-ray energy. In late June of 1981, the source made a transition into a much brighter (~0.5 Crab intensity) state, with a significant spectral softening. After the transition, the short-term X-ray variation disappeared. We discuss the similarity between GX 339−4 and Cyg X-1.

Subject headings: black holes — stars: individual — X-rays: binaries

I. INTRODUCTION

Although intensity variation is a common feature of compact galactic X-ray sources, a persistent, aperiodic variability on subsecond time scales has been observed only in a few of them (e.g., Bradt, Kelley, and Petro 1979). Two outstanding examples are Cyg X-1 (e.g., Ogawara *et al.* 1977; Canizares and Oda 1977; Sutherland, Weisskopf, and Kahn 1978, Priedhorsky *et al.* 1979; Nolan *et al.* 1981; for a review see Oda 1977) and Cir X-1 (Jones *et al.* 1974; Sadeh *et al.* 1979; Dower, Bradt, and Morgan 1982; Robinson-Saba 1983). Since Cyg X-1 is a well-known black hole candidate, such rapid variability draws our attention as a possible manifestation of physical processes occurring around a black hole.

A third example of such a source is GX 339−4 (4U 1659−48), which is the subject of this paper. This X-ray source was discovered with *OSO 7* (Markert *et al.* 1973). It exhibits three typical intensity states ("high," "low," and "off"), involving intensity changes of a factor $\gtrsim$60 on time scales of months, with a very soft spectrum during the high state (Markert *et al.* 1973; Jones 1977; Doxsey *et al.* 1979; Chiapetti 1981; Ricketts 1983). Nolan *et al.* (1982) detected a hard X-ray component from this source, which persisted even during the off state. These general properties of GX 339−4 would be sufficient to indicate the peculiarity of this source among compact galactic X-ray sources. A still more exciting discovery came from the *HEAO 1* observation: Samimi *et al.* (1979) detected rapid X-ray fluctuation from GX 339−4 (up to a factor ~3 intensity changes in as short as 40 ms) during a low state in 1977. While, Li, Clark, and Rappaport (1978) reported that such a rapid fluctuation was absent during a high state of GX 339−4. (See also Forman, Jones, and Tananbaum 1976.) It is hence suggested that the rapid X-ray variation of GX 339−4 occurs in the low state.

GX 339−4 was identified optically with a ~16.6 mag, reddened, emission line object (Doxsey *et al.* 1979; Grindlay 1979). In 1981, a series of fascinating results came of the optical observations of GX 339−4 (Motch, Ilovaisky and Chevalier 1982). The source was unusually faint ($B \sim 20$ mag) in February–March (Hutchings, Cowley, and Crampton 1981; Ilovaisky and Chevalier 1981). It came back to its normal brightness ($V \sim 16.3$ mag) by May 7, and the brightness further increased in late May ($V \sim 15.4$ mag; Motch, Ilovaisky, and Chevalier 1981) exhibiting a high optical activity on time scales down to 20 ms (Motch, Ilovaisky, and Chevalier 1982). During this state of high optical activity, a short, simultaneous X-ray coverage was available from the *Ariel 6* satellite (Motch *et al.* 1983), which showed an interesting anticorrelation between the optical and X-ray intensities.

In 1981 and 1982, we observed GX 339−4 with the X-ray astronomy satellite *Hakucho* (Kondo *et al.* 1981; Hayakawa 1981) for more than 50 days in total. We encountered three distinct intensity states. We witnessed a source transition from a hard-spectrum (low) state into a much brighter state with a very soft spectrum. During the low state, a random, persistent X-ray variability with ~1 s characteristic time scale was observed. This variability disappeared after the transition. The present observation provides a self-contained description of the essential X-ray features of this fascinating object.

II. OBSERVATIONS

Following the optical report in 1981 March of unusual faintness of the GX 339−4 counterpart (Hutchings, Cowley, and Crampton 1981; Ilovaisky and Chevalier 1981), we pointed the X-ray detectors of *Hakucho* to GX 339−4 on 1981 April 7–9, but failed to detect any significant X-ray flux above an upper limit of ~15 mCrab (Oda and *Hakucho* team 1981*a*). We encountered another OFF state of this source on the occasion of a coordinated optical/X-ray observation in 1982 May 22–26. We obtained a similar upper limit in X-rays, while the optical counterpart was also extremely faint ($B = 18.6$ mag; Ilovaisky, private communication). The optical and X-ray brightnesses are thus positively correlated on a large scale, which gives direct evidence that the substantial part of the optical emission from GX 339−4 is due to mass accretion onto the X-ray emitting object rather than arising from the companion star.

During 1981 June 5–July 17, GX 339−4 was continuously in the 17°.6 (FWHM) field of view of the *Hakucho* CMC-1 detector (a proportional counter with a wide-field coarse rotating modulation collimator). We used the CMC-1 data to obtain the intensity of GX 339−4 in two spectral bands (3–6 and 6–10 keV), through modulation-pattern analysis. In Figure 1, we present the resulting two-color X-ray light curve of GX 339−4. Each data point has a typical integration time of about 20 minutes. The X-ray hardness ratio (the event-rate ratio in 6–10 to 3–6 keV bands) is also shown. Note that the Crab Nebula gives ~33 counts s^{-1} and ~16 counts s^{-1} in 3–6 and 6–10 keV, respectively, with the hardness ratio ~0.47. Figure 1 shows that the source was in an 0.1–0.2 Crab intensity state until around June 24. This X-ray intensity falls in between the low and high states according to the previous classification (Markert *et al.* 1973; Doxsey *et al.* 1979). However, we conventionally call it a low state. The source subsequently made an evident transition, in about a week, into a brighter state (Oda and *Hakucho* team 1981*b*). By early July of 1981, it had reached a peak intensity around a half Crab flux in 3–10 keV. Probably this is one of the brightest levels of this source in soft X-rays ever observed. Thus we call it a high state. We notice that the transition was accompanied by a significant spectral softening: the 3–6 keV photon flux increased by a factor ~3, whereas the 6–10 keV flux was almost halved. Thus X-ray absorption cannot be the principal mechanism for producing the low state (see also Ricketts 1983).

On one occasion (June 5–15) during the low state and on another occasion (July 7–16) during the high state, the source was also in the 5°.8 (FWHM) field of view of the *Hakucho* FMC detectors (FMC-1 and FMC-2). These two periods are indicated in Figure 1. The data from the FMC-1 (a proportional counter with a fine rotating modulation collimator) were used to determine accurate spacecraft aspect relative to the source as well as to derive the background information. The data from the FMC-2 (a proportional counter with a tubular field of view) were used to study the short-term X-ray variation and the spectral characteristics of the source. The FMC-2 count rates were acquired in four spectral channels (1–9, 3–6, 6–10, and 9–22 keV). The highest time resolution of the FMC-2 data was 93.75 ms in most cases, and was 11.72 ms (8 times higher) for the small fraction (~15%) of the data obtained during real-time contact between the spacecraft and the ground station. The analysis methods for the short-term variability and the results are presented in § III.

Figure 2 shows the X-ray light curve based on the FMC-2 data. It is generally consistent with Figure 1, and provides X-ray intensities of GX 339−4 more accurately than Figure 1. One remarkable feature is a very small (at most ±15%) X-ray variation on time scales of minutes to a day, during both the low and high states. This confirms previous reports by Chiapetti (1981) and Ponman (1982) that GX 339−4 showed little medium-time-scale X-ray variations.

We fitted the FMC-2 data (in four spectral bands) and the CMC-1 data (in two bands) simultaneously with three conventional model spectra; thin thermal, blackbody, and power law. Because of rather limited spectral information, we did not attempt to distinguish among these models, but instead tried to obtain some quantitative measure for the spectral hardness. The neutral hydrogen column density was fixed at $N_H = 5 \times 10^{21}$ cm^{-2}. This value is based on the very soft X-ray measurements from *Hakucho* in 1979 June–July (Hayakawa 1981). The results of fitting are presented in Table 1. The low state spectrum we observed is significantly harder than the *HEAO 1* low state result ($kT = 4$ keV assuming a thin-thermal model; Doxsey *et al.* 1979), but agrees reasonably with the *Ariel 6* results (Motch *et al.* 1983; Ricketts 1983) obtained immediately before our observation. Our high-state spectrum is very soft, being in general agreement with the previous high-state measurements (Markert *et al.* 1973; Jones 1977; Chiapetti 1981; Ricketts 1983).

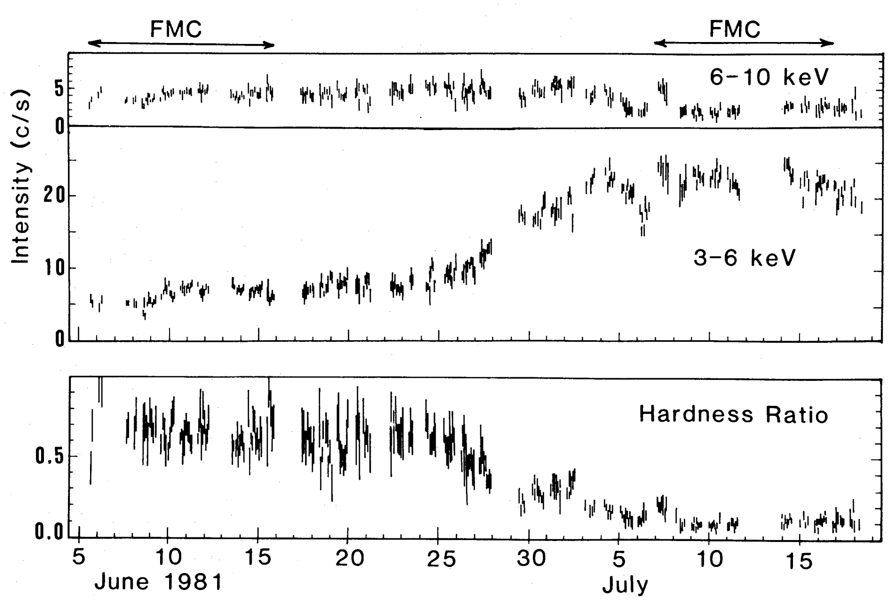

FIG. 1.—X-ray light curves (in 3–6 and 6–10 keV bands) and the spectral hardness ratio of GX 339−4 in 1981 June–July, observed with the *Hakucho* CMC-1 detector. The hardness ratio refers to the ratio of observed photon fluxes in 6–10 keV to 3–6 keV. A source transition, from a low state to a high state, is seen around June 25. Data with a higher time resolution were obtained from the FMC detectors during the indicated periods (see text).

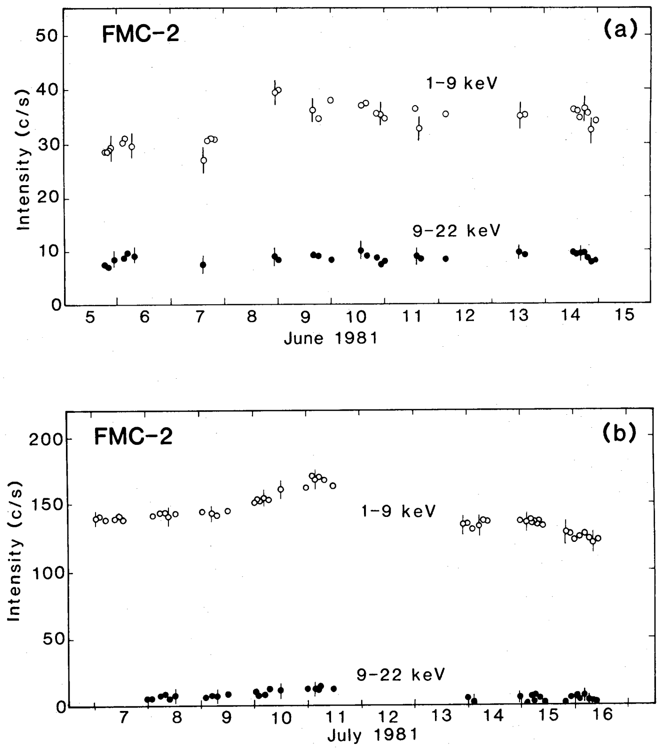

FIG. 2.—X-ray light curves of GX 339−4 in 1–9 annd 9–22 keV bands observed with the *Hakucho* FMC-2 detector. Fig. 2*a* is for the low state and Fig. 2*b* for the high state. Each data point refers to an integration time of 5–20 minutes. The background flux and the persistent component from 4U 1636−53 were subtracted using the FMC-1 data. The Crab Nebula gives ~193 FMC-2 counts s^{-1} in 1–9 keV and ~31 counts s^{-1} in 9–22 keV.

As indicated so far, the X-ray intensity of GX 339−4 during our observation was inversely correlated with the spectral hardness. This becomes still clearer when we arranged the CMC-1 data in the correlation plot of Figure 3. There data taken before and after the transition form two distinct clusters. Similar behavior has been reported previously (Markert *et al.* 1973; Ricketts 1983). The energy flux quoted in Figure 3*b* may be a reasonable measure of the soft X-ray luminosity. However, because of our ignorance of the hard X-ray flux, it does not necessarily represent the total luminosity. The total luminosity may well be comparable between the two states (e.g., Ricketts 1983).

TABLE 1

MEASURE OF THE SPECTRAL HARDNESS OF GX 339 − 4 FOR THE LOW AND HIGH STATES IN 1981 JUNE–JULY[a]

Model Spectrum	Low State (June 5–15)	High State (July 7–16)
Power law:		
Photon index	1.74 ± 0.04	4.3 ± 0.2
Chi square[b]	1.8	8.0
Free-free:		
Temperature (keV)	16.1 ± 1.2	1.65 ± 0.10
Chi square[b]	2.9	5.6
Blackbody:		
Temperature (keV)	No reasonable	0.78 ± 0.08
Chi square[b]	fit obtained	8.9

[a] The CMC-1 data (in two spectral bands) and the FMC-2 data (in four spectral bands) were fitted simultaneously.

[b] For 2 degrees of freedom. Fairly large values of χ^2 for the high-state data may be due to small uncertainties in the relative performance of the two detectors, in combination with a very steep source spectrum.

Finally, Motch *et al.* (1983) reported that the X-ray transition was accompanied by the optical darkening by ~1.5 magnitudes. This suggest that there may be a certain range of the mass accretion rate in which the optical and soft X-ray intensities are inversely correlated.

III. SHORT-TERM VARIABILITY

a) Detection of Variation

Using the FMC-2 data taken on the two occasions in 1981 June–July (Fig. 2), we studied X-ray variations of GX 339−4 on time scales of 0.01 s to minutes. Figure 4 shows examples of raw count rate data from the low and high states. Though it would be difficult to tell immediately from Figure 4 whether there was any nonstatistical fluctuation, the standard chi-square test revealed $\chi^2 = 951$ and 277 (both for 255 degrees of freedom) for Figures 4*a* and 4*b*, respectively. Thus there was indeed an intrinsic variation in Figure 4*a* with a high ($\gtrsim$ 99.9%) statistical significance, which was undetectable in Figure 4*b*. We found that the above situation applies not only

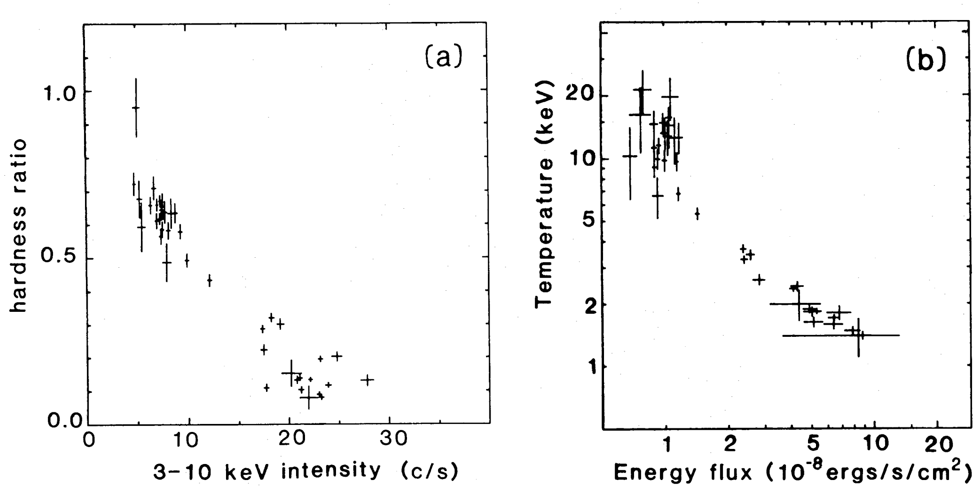

FIG. 3.—(*a*) The CMC-1 data (daily average from Fig. 1) arranged in a correlation plot between the X-ray intensity and the spectral hardness ratio. Data points for the low and high states form two distinct clusters. (*b*) Same as panel (a), converted into the 1–22 keV energy flux and the temperature assuming a thin-thermal model spectrum with $N_H = 5 \times 10^{21}$ cm^{-2}.

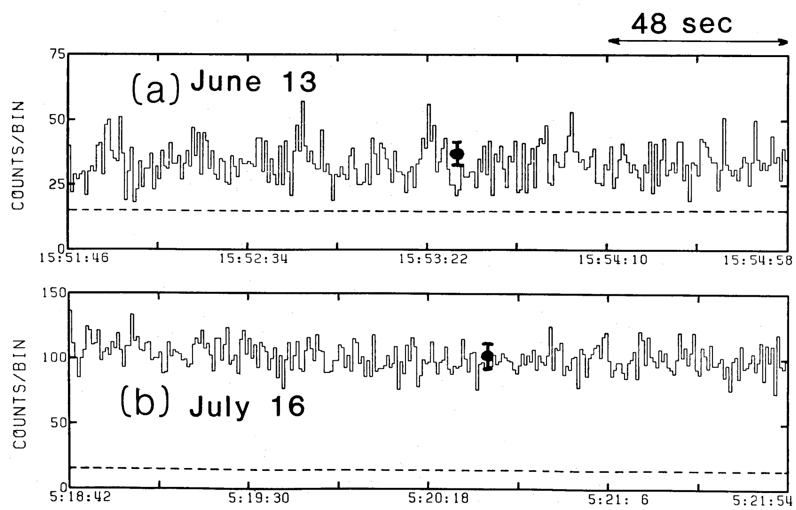

FIG. 4.—Examples of the 1–22 keV X-ray count rate data (counts per 0.75 s) of GX 339−4, observed with the FMC-2. (*a*) The low state; (*b*) the high state. The dashed line indicates the background level. The error bar stands for the ±1 sigma of the photon counting statistics.

to the particular case of Figure 4, but also to all the FMC-2 data; variations are present in the low state, and are undetectable in the high state.

During the FMC observations, there was often another X-ray source, 4U 1636−53, in the FMC field of view; the typical aperture efficiency of the FMC was ~60% for GX 339−4 and ~15% for 4U 1636−53. We concluded, however, that the observed fluctuations were in fact from GX 339−4, for the following reasons. First, the fluctuation amplitude would be too high (≳100%) if it were coming from 4U 1636−53. Second, no such fluctuation was observed on a number of occasions in 1979–1982 when 4U 1636−53 alone was in the FMC field of view. (One such occasion took place for 1981 June 19–July 2, during the very present observational span.) Finally, we have never observed intrinsic subsecond X-ray variation, either in the background data, or from other bright "bulge" sources including GX 5−1, GX 349+2, GX 340+0, GX 17+2, 4U 1705−44, etc.

b) *Variation Function Analysis*

Now that the intrinsic X-ray fluctuations were confirmed, we next studied its nature in a more quantitative way through the variation function technique. This method was introduced into X-ray astronomy by one of the authors (Doi 1978*a*), and has been applied successfully to the Cyg X-1 data (Ogawara *et al.* 1977; Doi 1980). It is above all suited to analysis of aperiodic, stationary time variabilities: it is simple in formalism (as shown below), quick in calculation, straightforward in interpretation, stable against statistical noise and data-sampling irregularities.

The variation function (VF), denoted $\eta(t_b)$, is a dimensionless statistical quantity defined for a discrete time series as a function of the time-bin width, t_b. For each value of t_b, $\eta(t_b)$ is defined as a square root of the data variance due to intrinsic (non-Poisson) source variation, normalized to the average source flux;

$$\eta(t_b) = \frac{[V(t_b) - x(t_b)]^{1/2}}{x(t_b) - y(t_b)} ,$$

where $x(t_b)$ is the mean X-ray counts per bin including background, $y(t_b)$ is the average background counts per bin, and $V(t_b)$ is the total data variance. The second term in the square root represents the subtraction of Poisson-noise component. Note that the VF is expected to vanish if there is no intrinsic variability, and to increase in general with decreasing t_b under the presence of random intrinsic variations. It shows a significant slope over a time-scale range on which the source is varying. In particular, $\eta(t_b) \propto t_b^{-1/2}$ is expected if the variation power spectrum can be regarded as white. In short, $\eta(t_b)$ is a measure of the source power spectrum integrated over the time scales $\gtrsim t_b$. In the Appendix, we derive its relation to the autocorrelation function and the Fourier power spectrum.

We have calculated the VF for each data stream of the FMC-2 (of ~20 minutes typical duration). The background flux and contributions from the persistent component of 4U 1636−53 were subtracted using the CMC-1 and FMC-1 data. The shape of $\eta(t_b)$ was essentially the same for all the FMC-2 data streams acquired during the low state, with η = 30–40% at $t_b \sim 0.1$ s and decreasing gradually toward the longer time scales. Making use of this fact, we superposed individual VFs incoherently over ~100 data streams (covering June 5–15) to reduce the statistical uncertainty. Figure 5*a* shows the resultant composite VF for the 1–9 keV band. It indicates that the preferred time scale of variation is from a fraction of a second to tens of seconds. The variation seems not prominent on a 10–100 ms time scale range, although not conclusive since the information below ~0.2 s is based on a small amount of real-time data. In Figure 5*b* we present the composite VFs for other energy bands of the FMC-2. (The real-time data were omitted due to poor statistics.) No significant energy dependence is observed over the 1–22 keV range.

We also present in Figure 5*a* the composite VF in 1–9 keV covering the high state (July 7–16). No intrinsic variation is seen above an upper limit of ~2%. Considering that the 1–9 keV photon flux increased by a factor ~4 on the transition (Fig. 2), we conclude that the absolute fluctuation amplitude in the high state is less than ~1/4 of that observed in the low state. This rules out the possibility that a persistent X-ray component exhibiting variability is simply masked in the high state by another brighter component. Some fundamental change, therefore, must have taken place in the source during the transition.

Figure 5*c* represents the VFs for several other X-ray sources. The VFs for Cyg X-1 (taken from Ogawara *et al.* 1977) show a remarkable resemblance to those of GX 339−4. This subject

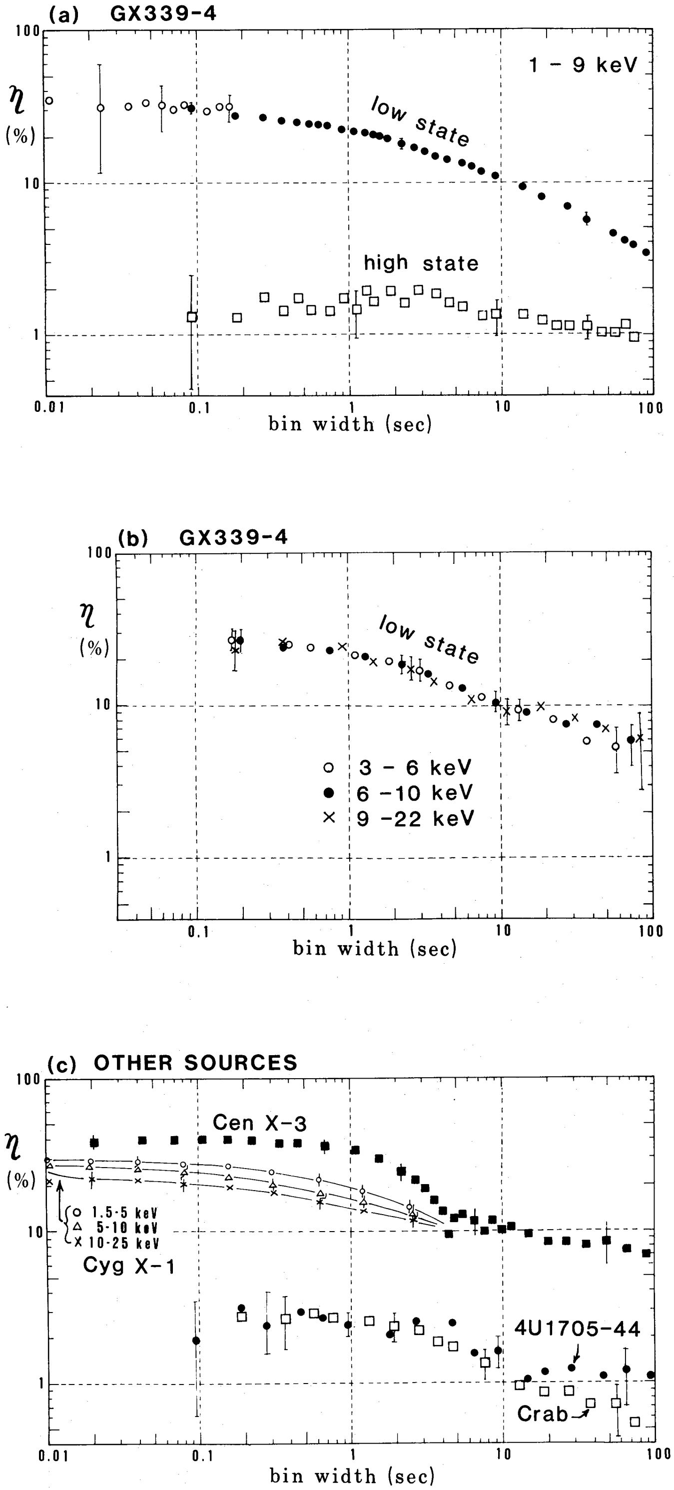

FIG. 5.—The variation functions (VFs) for GX 339 − 4 and other sources. (*a*) The 1–9 keV VFs for GX 339 − 4 in the low state (averaged over 1981 June 5–15) and the high state (averaged over July 7–16). The open circles (for the low state only) are based on the "real-time" data of a higher time resolution. The small residual variations of the high state data are attributable to the spin modulation of source flux by the FMC-2 collimator. (*b*) Results for GX 339 − 4 during the low state in the other three energy bands of the FMC-2. (*c*) Results for several other X-ray sources. Those for Cyg X-1 are taken from Ogawara *et al.* (1977). All the other VFs are from the *Hakucho* FMC-2 in 1–9 keV; Cen X-3 (*filled squares*, observed on 1982 March 24); 4U 1705 − 44 (*filled circles*, 1981 July 18), and the Crab Nebula (*open squares*).

will be discussed again in § IV. The VF for the regularly pulsating Cen X-3 exhibits a steeper fall toward its pulsation frequency (4.8 s), which is characteristic of the VF for periodic variations. In contrast, the variation is at most a few percent for the Crab Nebula and for a bright "bulge" source 4U 1705 − 44. In these cases, the main contribution to the VF comes from the spin modulation (at about 6 rpm) of the source flux by the hexagonal FMC-2 collimator.

c) Search for Periodicity

We searched the FMC-2 data for X-ray periodicities by the standard Fourier transform with 2^{18} data bins. From the low-state observation, we obtained 10 Fourier power spectra, each covering a period range of 0.375–24,576 s (0.041 mHz–2.7 Hz). In order to examine the significance of candidate periodicities under the presence of non-Poisson intensity fluctuation, we compared the power of each Fourier component with the locally averaged power density. The most significant Fourier power was observed on June 8 at a period of 6.177 s, which was ∼11 times higher than the mean power density averaged over the 2.5–50 s period range. The corresponding half-peak amplitude was ∼4% of the average 1–9 keV X-ray flux from GX 339 − 4. The probability of observing such a high power by chance is $\sim 2 \times 10^{-5}$, while the number of independent Fourier components in the 2.5–50 s period range we studied was $\sim 3 \times 10^4$ (taking into account data sampling gaps). Therefore, this periodicity can be attributed to the chance occurrence during the random variation. No enhancements were observed at ∼6.177 s in the other nine spectra. Any other Fourier component in these 10 spectra was less significant than this particular one.

We next performed a dynamic Fourier power-spectrum analysis in a search for possible transient (low-Q) periodicities. That is, we subdivided each FMC-2 data stream into non-overlapping segments of 192 s length, and computed the Fourier power spectrum for each of them. We thus obtained 196 spectra, each covering the 0.1875–192 s (5.2 mHz–5.3 Hz) period range. None, however, contained any oscillation component of real statistical significance. For any Fourier component in this period range, we estimate the upper limit amplitude in each segment to be ∼10% of the mean flux.

From these results, we conclude that the rapid variation of GX 339 − 4 is primarily of aperiodic nature.

d) Average Power Spectrum

In order to see the average power spectrum, we superposed the 196 dynamic spectra (as obtained above) incoherently, from which we subtracted the white-noise component due to the photon counting statistics. The result is shown in Figure 6. (We did not apply any kind of window, or correction for the finite bin width.) It is clear from Figure 6 that the variation indeed exhibits a broadly distributed power spectrum without any indication of preferred frequencies.

It would be instructive to confirm that the variation function and the power spectrum are consistent with each other. The power spectrum in Figure 6 is roughly white up to a characteristic frequency ("knee frequency"), $f_k \sim 0.2$ Hz, beyond which the power falls off roughly as (power density) ∝ (frequency)$^{-\alpha}$ with $\alpha \sim 1.7$ ("decay slope index"). Then, according to the Appendix, $\eta(t_b)$ is expected to behave roughly as $\eta \propto t_b^{-1/2}$ for $t_b \gtrsim (2f_k)^{-1} \sim 2.5$ s, and the slope of $\eta(t_b)$ to decrease gradually toward the shorter time scales. These features are exactly what is observed in Figure 5.

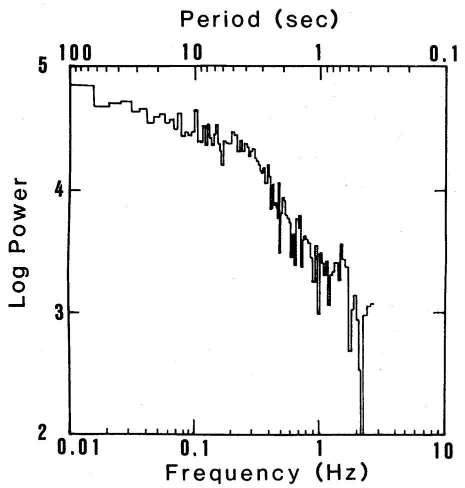

FIG. 6.—The ensemble-averaged Fourier power spectrum of GX 339−4 in 1–22 keV calculated from the entire low-state FMC-2 data. The white-noise component due to photon statistics has been subtracted. The knee frequency is around 0.2 Hz, and the decay slope index is about 1.7.

e) Autocorrelation and Cross-Correlation Functions

Figure 7 represents the 1–22 keV autocorrelation function (ACF) for the low state data. It was obtained by the inverse Fourier transform of the average power spectrum in Figure 6. This ACF is free from the white-noise component (at lag = 0) since Figure 6 was already corrected for it. The present ACF exhibits a roughly exponential decay with a characteristic time scale (denoted τ) which is quite consistent with $(2\pi f_k)^{-1} \sim 0.8$ s. According to the Appendix, the corresponding VF is expected to start bending downward at about $t_b = \tau$; This is actually seen in Figure 5. Thus we have confirmed that the three methods—variation function, power spectrum, and autocorrelation—in fact lead to the same answer.

In a similar way, we calculated the cross-correlation function (CCF), averaged over the low-state FMC-2 observation, for several combinations of the four FMC-2 energy channels. The results are shown in Figure 8, where we see no noticeable time delay in fluctuation between different energy bands within the 0.1875 s time resolution. In addition, the overall shapes of these CCFs are similar to each other, as well as to that of the ACF (Fig. 7). Considering these facts and Figure 5*b*, we infer that the short-term variation of GX 339−4 exhibits little energy dependence at least in the 1–22 keV energy range.

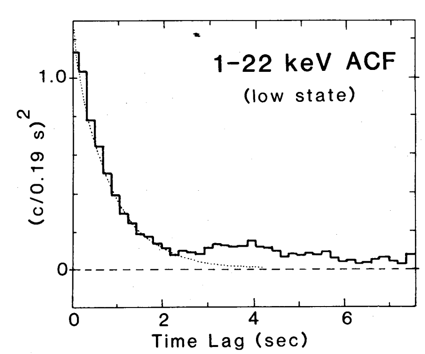

FIG. 7.—The 1–22 keV autocorrelation function (ACF) for the X-ray counting rate of GX 339−4, averaged over the low state. This has been obtained as an inverse Fourier transform of the power spectrum in Fig. 6. The Poisson noise component (at time lag = 0) has been removed. The ACF exhibits a roughly exponential decay with a characteristic time scale $\tau \approx 0.8$ s. The nonzero value at lags $\gtrsim 2$ s is mainly due to the spin modulation of the source flux by the hexagonal-shaped FMC-2 collimator.

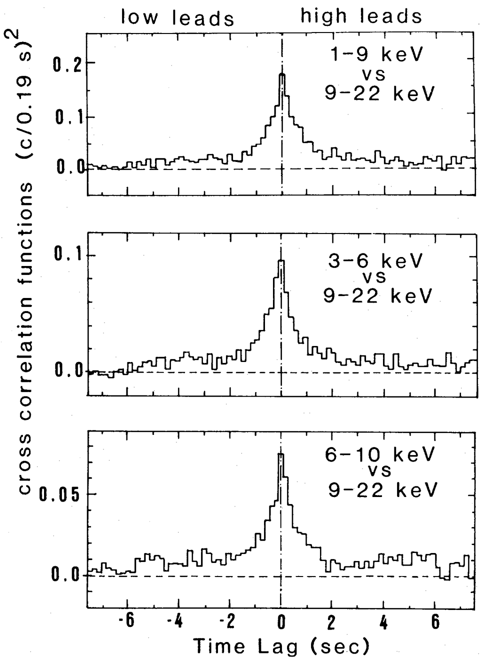

FIG. 8.—The cross-correlation functions (CCFs) of GX 339−4 calculated for several combinations of the four FMC-2 spectral bands.

f) Comparison with Previous Observations

The present observation, a long continuous one with a relatively small detector area (82 cm^2 for the FMC-2), is in many respects complementary to the *HEAO 1* observation (Samimi *et al.* 1979) with a large detector area and a short ($\sim$200 s) integration time. Nevertheless, the two observations are consistent as far as they overlap: in fact, Samimi *et al.* (1979), employing an analysis method similar to the variation function, concluded that the source was not significantly variable on 5–50 ms time scale range, and that the variation increased toward the longer time scales (up to 160–1600 ms). This is just what we have observed.

Comparison with the *Ariel 6* results (Motch *et al.* 1983) would be still more important since the *Ariel 6* and *Hakucho* observations almost certainly took place within the same low state. The two observations are consistent in many respects, such as the hardness of average spectrum, the amplitude of variation (30–40%), the characteristic time scale of variation including the knee frequency ($f_k \sim 0.2$ Hz), and the decay slope index ($\alpha \sim 1.7$) in the average power spectrum. The *Ariel 6* power spectrum (as well as the optical one by Motch, Ilovaisky, and Chevalier 1982) shows 10 and 20 s quasi-oscillation components, which are absent in our Figure 6. However, this does not seem contradictory, since Motch *et al.* (1983) report that these components waned after about June 2. The *Ariel 6* results indicate somewhat different X-ray behavior below and above 13 keV, in disagreement with our results (e.g., Fig. 8). Some qualitative change may have taken place in the source around the end of May through the beginning of June.

The shot-noise model (e.g., Sutherland, Weisskopf, and Kahn 1978) has often been employed in the literature to describe the random variation. However, we will not invoke it since it has little physical significance and gives no better physical insight into the present problem, as pointed out previously (Doi 1978*b*).

g) Summary

Through the data analysis so far presented, we have achieved the following characterization of the rapid variation of GX 339−4:

i) It is probably specific to the low state. This reconciles all the positive detections (Samimi *et al.* 1979; Motch *et al.* 1983; this work) with the negative ones (Forman, Jones, and Tananbaum 1976; Li, Clark, and Rappaport 1978).

ii) It is predominantly of random and aperiodic nature. The variation time scales range from a fraction of a second to tens of seconds.

iii) Its rms amplitude is 30–40% of the mean X-ray flux.

iv) The variation is quite persistent and stationary at least on a one-week time scale during the low state.

v) The variability shows no significant dependence on the X-ray energy.

IV. DISCUSSION

A previous viewpoint, that GX 339−4 has a low-mass primary (Doxsey *et al.* 1979; Grindlay 1979), has in fact been confirmed by the large optical variation observed in 1981, as well as by the association of optical faintness with X-ray off states. At a suggested distance of $D \sim 4$ kpc (Doxsey *et al.* 1979; Grindlay 1979), GX 339−4 has an X-ray luminosity of the order of 10^{37-38} ergs s^{-1} (Fig. 3; and Ricketts 1983). This is quite typical for an accretion-driven galactic X-ray source.

Nevertheless, GX 339−4 differs markedly in the following respects from a majority of binary X-ray sources involving neutron stars;

i) The long-term bimodal behavior in X-rays involving a distinct anticorrelation between the soft X-ray intensity and the spectral hardness (Figs. 1–3).

ii) The persistent, aperiodic X-ray variation on a subsecond time scale during the low state (Figs. 4–8).

iii) The extremely soft X-ray spectrum (typically measured in 2–10 keV range) during the high state (Table 1).

iv) The hard X-ray spectrum extending up to ~ 100 keV (Nolan *et al.* 1982). In fact, GX 339−4 is one of the few galactic X-ray sources detected with a high significance (e.g., $\gtrsim 3$ sigmas) in the 80–180 keV range by the *HEAO* A4 hard X-ray general survey (Levine *et al.* 1983).

v) High optical variations on both long and short time scales (Motch, Ilovaisky, and Chevalier 1982).

vi) Absence of noticeable X-ray variations on medium time scales during both high and low states (Fig. 2). This makes a contrast to the significant long-term variability (Markert *et al.* 1973; Li, Clark, and Markert 1979), and the rapid fluctuation during the low state.

It would be instructive to consider, in comparison, a typical X-ray source involving a low-mass primary and a neutron star secondary (Lewin and Joss 1981; Bradt and McClintock 1983). Such a source would exhibit irregular X-ray variations on time scales of days to minutes (sometimes down to seconds; Bradt, Kelley, and Petro 1979), a moderately soft spectrum with its hardness positively correlated with the X-ray intensity (Parsignault and Grindlay 1978; Ponman 1982), and often an almost twofold intensity change in 1–2 hours. The optical intensity of such a source would vary typically by ~ 1 mag on time scales of hours (e.g., Pedersen, van Paradijs, and Lewin 1981), possibly in positive correlation with the X-ray intensity as evidenced by the presence of simultaneous X-ray/optical bursts (Lewin and Joss 1981). These X-ray and optical properties are clearly alien to those of GX 339−4.

These arguments for the peculiarity of GX 339−4 at the same time highlight the fundamental similarity between GX 339−4 and Cyg X-1. In fact, the above properties (i)–(iv) of GX 339−4 apply as well to Cyg X-1 (e.g., Forman, Jones, and Tananbaum 1976; Oda 1977). The peculiarity they share, in spite of the clear difference in the optical primaries, must then be attributed to the nature of the collapsed objects involved. This, in combination with the black hole candidacy of Cyg X-1 (see, e.g., Oda 1977), argues in a natural way for the black hole model of GX 339−4 (Samimi *et al.* 1979; Fabian *et al.* 1982; Motch *et al.* 1983). This viewpoint is further reinforced by the recent discoveries of massive secondaries in LMC X-3 (Cowley *et al.* 1983) and in LMC X-1 (Hutchings, Crampton, and Cowley 1983), both of which show an ultrasoft spectrum comparable to that of the high-state GX 339−4 (White and Marshall 1984). Probably Cir X-1, with its rapid variability (Dower, Bradt, and Morgan 1981) and a very soft X-ray component (Jones 1977; Robinson-Saba 1983), also belongs to the same class of objects.

The lack of rapid variation in the high state, evidenced in GX 339−4, may be generalized to the other black hole candidates. Cyg X-1 seems less variable in the high state than in the low state (Oda 1977; Canizares and Oda 1977; Sutherland, Weisskopf, and Kahn 1978). LMC X-3 showed no short-term variation in a soft-spectrum state (White and Marshall 1984). Cir X-1 was found to be unusually quiet in a bright state with a soft spectrum (Dower, Bradt, and Morgan 1981), although its overall behavior appears significantly more complicated than that of the others.

We believe that the black hole candidacy of GX 339−4 has become significantly firmer through the recent optical and X-ray observations. GX 339−4 now occupies a very important position in studies of black hole candidates, because its optical information is essentially free from contamination by the companion, and because it seems to have comparable duty ratios for high and low states. (Note that Cyg X-1 prefers to reside in the low state.) Future observations of GX 339−4, in coordination with optical, soft X-ray, and hard X-ray frequencies, is strongly recommended.

There have been many theoretical attempts, with partial success, to explain the observed properties of Cyg X-1 in terms of an accreting black hole. It is, however, beyond the scope of this paper to review them. The readers may refer to the reference summaries in Nolan *et al.* (1981) and White and Marshall (1984). Now such theories should be able to explain as well the observed properties of GX 339−4: recently Fabian *et al.* (1982) proposed that the optical radiation from GX 339−4 may be emitted as a cyclotron emission from very hot plasma surrounding the black hole, and interpreted the hard X-rays as resulting from the Comptonization of these optical photons by the hot plasma. This model is in general agreement with the observations, and seems to give a comprehensive working hypothesis to understand GX 339−4.

Finally, we remark that the transition of GX 339−4 has been witnessed for the first time. As shown in Figures 1 and 3, the flux increased and the spectrum softened rather continuously on a time scale of about a week (although we lack the information on the rapid variation). These facts may give some constraints on the theoretical models.

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APPENDIX

RELATION AMONG VARIATION FUNCTION, AUTOCORRELATION FUNCTION, AND FOURIER POWER SPECTRUM

Let $x(t)$ be a statistical quantity which is a continuous function of time t. We assume $x(t)$ is ergodic, and we denote its average by angular brackets $\langle\ \rangle$. Let $\rho(s) \equiv \langle x(t)x(t+s)\rangle$ be the autocorrelation function (ACF) of $x(t)$, and $P(\omega)$ be the Fourier power spectrum (FPS) of $x(t)$, with ω the angular frequency. Since the variation function (VF), $\eta(t_b)$, as defined in the text, involves only the first and second order statistics of $x(t)$, there must hold simple relations among $\rho(s)$, $P(\omega)$, and $\eta(t_b)$. To see this, let us define the binning of $x(t)$ as

$$x_j = \int_{jt_b}^{(j+1)t_b} x(t)dt \qquad (j = 0, 1, 2, \ldots, N)\,, \tag{A1}$$

and let us put $\tilde{x} \equiv x - \langle x\rangle$. The variance of $[x_j]$ is then calculated as

$$V[x_j] \equiv V(t_b) = \langle \tilde{x}_j^{\,2}\rangle = \left\langle\left(\int_{jt_b}^{(j+1)t_b} \tilde{x}(t)dt\right)^2\right\rangle . \tag{A2}$$

Utilizing the assumption that $x(t)$ is ergodic, and using the fact that $\int$ and $\langle\ \rangle$ are commutative, we can easily perform the double integral of (A2) to obtain

$$V(t_b) = 2\int_0^{t_b} (t_b - s)\cdot \rho(s)ds\,. \tag{A3}$$

This, in combination with the definition $\eta(t_b) \equiv [V(t_b)]^{1/2}/\langle x_j\rangle$, gives the relation between the ACF and the VF. In particular, if $\rho(s)$ virtually vanishes for $|s| > s_1$ and if $t_b \gg s_1$, (A3) is then approximated as

$$V(t_b) \approx 2t_b \int_0^{s_1} \rho(s)ds \propto t_b\,. \tag{A4}$$

This leads to $\eta(t_b) \propto t_b^{-1/2}$ since $\langle x_j\rangle \propto t_b$.

To search for the relation between $V(t_b)$ and $P(\omega)$, we may either substitute the Fourier transform of $x(t)$ directly into (A1) and use Parseval's relation, or apply the theorem of Wiener-Khinchin to (A3). In any way we get, apart from a numerical constant,

$$V(t_b) = \text{const} \times t_b^{\,2}\int_0^{\infty} P(\omega)\cdot\frac{\sin^2(\omega t_b/2)}{(\omega t_b/2)^2}\cdot d\omega\,. \tag{A5}$$

In short, $V(t_b)$ is the Fourier power spectrum integrated from $\omega = 0$ up to approximately $\omega = \pi/t_b$. We also see from (A5) that the relation (A4) is recovered when the FPS is *white*.

Finally, we choose one of the simplest examples and assume $\rho(s) \propto \exp(-s/\tau)$, where τ is the characteristic time scale of the ACF. The corresponding FPS has a Lorentzian form:

$$P(\omega) \propto [1 + (\omega\tau)^2]^{-1}\,. \tag{A6}$$

Note that this roughly represents the actually observed FPS of GX 339−4 (Fig. 6), and the "knee frequency" is given as $f_k = \omega_k/2\pi = (2\pi\tau)^{-1}$. While, the VF is calculated readily from (A3) to be

$$\eta(t_b) \propto \{t_b[1 - 2\exp(-t_b/\tau)] + [1 - \exp(-t_b/\tau)]\}^{1/2}/t_b\,. \tag{A7}$$

As plotted in Figure 9, this VF is almost *flat* for $t_b \lesssim \tau = (2\pi f_k)^{-1}$, and behaves as $\propto t_b^{-1/2}$ for $t_b \gtrsim \pi\tau = (2f_k)^{-1}$. If we take $\tau \sim 0.8$ s (i.e., $f_k \sim 0.2$ Hz), the observed VF's (in Fig. 5) are well explained by (A7).

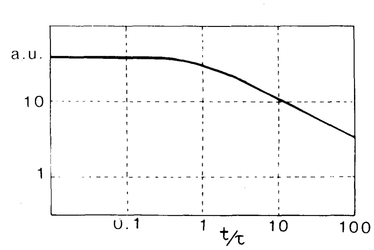

FIG. 9.—The variation function calculated for a time series, whose autocorrelation function has an exponential decay with a characteristic time scale τ

REFERENCES

Bradt, H. V., Kelley, R. L., and Petro, L. D. 1979, *Proc. NATO Advanced Study Institute on Galactic X-ray Sources*, Cape Sournion, Greece, 1979 June.
Bradt, H. V., and McClintock, J. E. 1983, *Ann. Rev. Astr. Ap.*, **21**, 13.
Canizares, C. R., and Oda, M. 1977, *Ap. J. (Letters)*, **214**, L119.
Chiapetti, L. 1981, *Space Sci. Rev.*, **30**, 447.
Cowley, A. P., Crampton, D., Hutchings, J. B., Remillard, R., and Penfold, J. E. 1983, *Ap. J.*, **272**, 118.
Doi, K. 1978*a*, Ph.D. thesis, University of Tokyo; ISAS research Note No. 55.
———. 1978*b*, *Nature*, **275**, 197.
———. 1980, *Nature* **287**, 210.
Dower, R. G., Bradt, H. V., and Morgan, E. H. 1982, *Ap. J.*, **261**, 228.
Doxsey, R., Grindlay, J., Griffiths, R., Bradt, H., Johnston, M., Leach, R., Schwartz, D., and Schwartz, J. 1979, *Ap. J. (Letters)*, **228**, L67.
Fabian, A. C., Guilbert, P. W., Motch, C., Ricketts, M., Ilovaisky, S. A., and Chevalier, C. 1982, *Astr. Ap.*, **111**, L9.
Forman, W., Jones, C., and Tananbaum, H. 1976, *Ap. J.*, **208**, 849.
Grindlay, J. E. 1979, *Ap. J. (Letters)*, **232**, L33.
Hayakawa, S. 1981, *Space Sci. Rev.*, **29**, 221.
Hutchings, J. B., Cowley, A. P., and Crampton, D. 1981, *IAU Circ.*, No. 3585.
Hutchings, J. B., Crampton, D., and Cowley, A. P. 1983, *Ap. J. (Letters)*, **275**, L43.
Ilovaisky, S. A., and Chevalier, C. 1981, *IAU Circ.*, No. 3586.
Jones, C. 1977, *Ap. J.*, **214**, 856.
Jones, C., Giacconi, R., Forman, W., and Tananbaum, H. 1974, *Ap. J. (Letters)*, **191**, L71.
Kondo, I., *et al.* 1981, *Space Sci. Instr.*, **5**, 211.
Levine, A. M., *et al.* 1983, preprint, CSR-HEA-83-11, MIT.
Lewin, W. H. G., and Joss, P. C. 1981, *Space Sci. Rev.*, **28**, 3.
Li, F., Clark, G., and Markert, T. 1979, *Nature*, **275**, 724.
Li, F., Clark, G., and Rappaport, S. 1978, *IAU Circ.*, No. 3609.
Markert, T. H., Canizares, C. R., Clark, G. W., Lewin, W. H. G., Schnopper, H. W., and Sprott, F. 1973, *Ap. J. (Letters)*, **184**, L67.
Motch, C., Ilovaisky, S. A., and Chevalier, C. 1981, *IAU Circ.*, No. 3609.
———. 1982, *Astr. Ap.*, **109**, L1.
Motch, C., Ricketts, M. J., Page, C. G., Ilovaisky, S. A., and Chevalier, C. 1983, *Astr. Ap.*, **119**, 171.
Nolan, P. L., *et al.* 1981, *Ap. J.*, **246**, 494.
Nolan, P. L., Knight, F. K., Levine, A. M., Lewin, W. H. G., and Primini, F. A. 1982, *Ap. J.*, **262**, 727.
Oda, M. 1977, *Space Sci. Rev.*, **20**, 757.
Oda, M., and *Hakucho* team. 1981*a*, *IAU Circ.*, No. 3594.
Oda, M., and *Hakucho* team. 1981*b*, *IAU Circ.*, No. 3616.
Ogawara, Y., Doi, K., Matsuoka, M., Miyamoto, S., and Oda, M. 1977, *Nature*, **270**, 154.
Parsignault, D. R., and Grindlay, J. E. 1978, *Ap. J.*, **225**, 970.
Pedersen, H., van Paradijs, J., and Lewin, W. H. G. 1981, *Nature*, **294**, 725.
Ponman, T. 1982, *M.N.R.A.S.*, **201**, 769.
Priedhorsky, W., Garmire, G., Rothschild, R., Boldt, E. A., Serlemitsos, P., and Holt, S. 1979, *Ap. J.*, **233**, 350.
Ricketts, M. 1983, *Astr. Ap.*, **118**, L3.
Robinson-Saba, J. L. 1983, preprint, Goddard Space Flight Center Tech. Memo. No. 85095.
Sadeh, D., Meidav, M., Evans, W., Byram, E., Chubb, T., and Friedman, H. 1979, *Nature*, **278**, 436.
Samimi, J., *et al.* 1979, *Nature*, **278**, 434.
Sutherland, P. G., Weisskopf, M. C., and Kahn, S. M. 1978, *Ap. J.*, **219**, 1029.
White, N. E., and Marshall, F. E. 1984, *Ap. J.*, **281**, 354.

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