INTRODUCTION

The black hole candidate GX 339-4 observed for the first time in 1972 with O\%2d27{"\textsuperscript{a}}95" was described by three French authors: A. H. Konig, P. A. Chamblet, E. Muller, and S. M. 2001 J.}

EXPLANATION

In the late 1980s, the black hole candidate GX 339-4 was described by three French authors: A. H. Konig, P. A. Chamblet, E. Muller, and S. M. 2001 J.

REFERENCES

A. H. Konig, P. A. Chamblet, E. Muller, and S. M. 2001 J.
X-ray fast time variability and spectral shape are consistent with that seen in the L.S (Méndez & van der Klis 1997), except that the 2–10 keV flux is at least ~ 10 times lower than in the L.S. It was concluded that the ‘off’ state is indeed an extension of the L.S, but with lower luminosity (Kong et al. 2000; Corbel et al. 2001). It is worth noting that GX 339-4 and GS 1124+683 (Elisawa et al. 1994) are the only X-ray sources observed in all these states; however, only GX 339-4 visits the different states so frequently (except for the VHS). We show in Figures 1-3 the different states of GX 339-4 in the past 30 years.

X-ray variability on long timescales (from days to years) has been found in many low-mass and high-mass X-ray binaries, but its origin is still an open question (e.g. Priedhorsky & Holt 1987; Schwarzenberg-Czerny 1992; Wijers & Pringle 1999; Ogilvie & Dubus 2001). Long-term X-ray variability has also been seen in the persistent black hole candidates Cyg X-1 (e.g. Kitamoto et al. 2000) and LMC X-3 (e.g. Paul, Kitamoto & Makino 2000). The timescales of their variability range from 100 days to 300 days. Given the similarity in X-ray properties between GX 339-4 and Cyg X-1, it is intriguing to investigate the long-term X-ray variability of GX 339-4. We therefore exploit the long-term capabilities of the all sky monitoring instruments on board the Vela 5B, Ariel 5, Ginga, Compton Gamma Ray Observatory and Rossi X-ray Timing Explorer to study the X-ray behaviour of this source on timescales of months to years.

2 LONG-TERM X-RAY OBSERVATIONS

GX 339-4 has been monitored by several X-ray missions in the last 30 years. We describe below all the instruments which contribute to the long-term X-ray light curves for this work, in addition, a new BeppoSAX observation of the source during the ‘off’ state is reported so that we can have a better understanding of the current status of the source. GX 339-4 has also been studied by other pointed observations which are summarised in the Appendix.

2.1 Vela 5B

The Vela 5B satellite (Conner, Evans & Belian 1989) monitored the X-ray sky from 1969 August to 1976 August (MJD 40367–40337) in two energy channels, 3–12 keV and 6–12 keV, the archival results of which are available from the High Energy Astrophysics Science Archive Research Center (HEASARC)1. The light curve (see Fig. 1) is made up from 508 data points using only the first channel (3–12 keV) since it has higher signal-to-noise ratio compared to the second channel (6–12 keV). Due to its limited temporal resolution and sensitivity, the data points exhibit a large scatter and only some outburst-like events were detected. It is interesting to note that there is a HS at ~ MJD 41370 and 41600 (as indicated in Fig. 1) according to the pointed observations made by satellite OSO-7 (Markert et al. 1973, see Appendix); however the intensity is not that high comparing to other data points.

2.2 Ariel 5

The Ariel 5 ASM experiment (Holt 1976) consisted of a pair of X-ray pinhole cameras with position sensitive proportional counters (3–6 keV) that covered 75% of the sky during each orbit (~ 100 mins). From the archival HEASARC Ariel 5 database, we obtained 2005 data points on GX 339-4 spanning the period from 1974 October to 1980 March (MJD 42338–44038; Fig. 1). Note that part of the Ariel 5 data was collected simultaneously with the Vela 5B (see Fig. 1) and the count rate variations are consistent with each other. As for the Vela 5B data, the light curve shows considerable scatter as well as some clear flaring episodes. No pointed observations were carried out in this period and hence the X-ray ‘state’ of the source is not clear.

2.3 Ginga ASM

The Ginga ASM (Tsunemi et al. 1989) monitored the X-ray sky in the 1–20 keV band from 1987 February to 1991 October. The effective area of the Ginga ASM was about 420 cm² with a 4° × 1° field-of-view. The sky-scanning observations were performed at intervals of a few days and covered about 70% of the sky. The typical exposure time for each scan across each observed source is about 3–18 s. During the observations from 1987 March to 1991 October (MJD 46800–48531), 215 data points were collected and it is very clear that four state transitions are seen in the light curve (Fig. 2), indicating excursions from the LS to the VHS/HS. The LS, HS and VHS state identifications were confirmed by the energy and power spectra obtained with the Ginga LAC (Miyamoto et al. 1991), Granat (Grebenyv et al. 1993) and BATSE (Harmon et al. 1994) instruments. During the LS, the corresponding flux is always below 100 mCrab (1–6 keV) and in 1988 August (~ MJD 47374), the source flux

1 http://heasarc.gsfc.nasa.gov
increased dramatically up to 1 Crab in \( \approx 10 \) days. Subsequent \textit{Ginga} LAC observations in 1988 September (\( \sim \) MJD 47405) revealed that the source was in a VHS. The flux then decreased to about 300 mCrab over 55 days, which presumably returned to the HS. By the end of 1989, the source again went to the LS until the other LS/HS transition between 1990 August and December (\( \sim \) MJD 48104–48226). The last LS/HS transition observed by \textit{Ginga} took place in 1991 August which was observed simultaneously with BATSE and will be discussed in \( \S 2.5 \).

\subsection*{2.4 RXTE ASM}

The All Sky Monitor (ASM; Levine et al. 1996) on board the \textit{Rossi X-ray Timing Explorer} (\textit{RXTE}; Bradt, Rothschild & Swank 1993) has monitored GX 339–4 several times daily in its 2–12 keV pass-band since 1996 February. The source remained at a low flux level (\( \lesssim 2 \) AS cts/s or 27 mCrab) until early 1998 January (\( \sim \) MJD 50810) although some variations were seen (see inset of Fig. 3). Extensive pointed Proportional Counter Array (PCA) observations during this period indicate that it was in the LS (Wilms et al. 1999; Belloni et al. 1999). After MJD 50806, the source flux increased dramatically to \( \approx 20 \) AS cts/s (270 mCrab) where it stayed for about 200 days before declining. Belloni et al. (1999) reported that the source underwent a LS to HS transition, probably through an IS (\( \sim \) MJD 50820). The source changed back to the LS again in 1999 February (\( \sim \) MJD 51200). After 1999 June (\( \sim \) MJD 53330), the ASM count rate dropped further and the source intensity fell below the 3-\( \sigma \) detection level. Kong et al. (2000) found that the source entered the ‘off’ state at that time from \textit{BeppoSAX} and optical observations. Note that the ASM count rate is also correlated with the hard X-rays as observed by BATSE (see next subsection). Interestingly, radio emission is also correlated with the X-ray during these different states (Fender et al. 1999; Corbel et al. 2000).

\subsection*{2.5 CGRO BATSE}

The Burst and Transient Source Experiment (BATSE) on board the \textit{Compton Gamma Ray Observatory} (CGRO) was operated continuously from April 5, 1991 (MJD 48351) until its re-entry on June 4, 2000 (MJD 51093). BATSE consists of eight identically configured detector modules with energy channels spanning from 20 to 600 keV (see Fishman et al. 1989). The GX 339–4 observations presented here were taken from the archival database which consists of data from 1991 April to 1999 August (MJD 48370–50554) in the 20–160 keV band. In constructing the light curve, the detector count rate is obtained by the Earth occultation technique (Harmon et al. 1994) and is fitted by an optically thin thermal bremsstrahlung (OTBB) model at a fixed temperature \( kT = 60 \) keV (Rubin et al. 1998), requiring in the photon fluxes presented here. The data presented in Fig. 2 were rebinned by a factor of 2.

The BATSE light curve (see Fig. 3) shows about ten hard X-ray outbursts. The first hard X-ray outburst in 1991 August (\( \sim \) MJD 48470) was accompanied by \textit{Ginga} ASM observations and two pointed observations by \textit{Granat} (inset of Fig. 3). The soft and hard X-rays are more or less correlated until the hard X-rays reached maximum. The hard X-rays then decreased sharply and the source became very soft with a much steeper power law spectrum (Grebeney et al. 1993; Harmon et al. 1994); the source changed from the LS (as observed with the \textit{Ginga} ASM) to the HS. The HS lasted for about 70 days, during which near-simultaneous radio data were available (Corbel et al. 2000) and then the source entered a possible ‘off’ state due to the non-detection of soft X-ray emission in the 3–10 keV band (Grebeney et al. 1993). The source then underwent three major hard X-ray outbursts before 1996 (MJD 50083) and a detailed energy spectral analysis of the BATSE data was presented by Harmon et al. (1994) and Rubin et al. (1998). In particular, the second one (MJD 49340–49420) is similar to the very first outburst (observed by \textit{Ginga} observations), and radio observations (Corbel et al. 2000) suggest that the duration of the HS (after the sharp decrease in flux at \( \sim \) MJD 49430) is also about 70 days. It is not clear whether there is a HS occurring between MJD 49000–49300 and MJD 49500–50100 since there is no soft X-ray and/or pointed data, but radio observations after MJD 49500 indicate that the source stayed in the LS (Corbel et al. 2000).

After the launch of \textit{RXTE}, the source was monitored regularly by both the \textit{RXTE}/ASM and BATSE and it is easily seen in the simultaneous light curves that the soft and hard X-rays are (anti) correlated in their gross behaviour, as already suggested from the simultaneous \textit{Ginga} ASM and BATSE light curves. In addition, some ‘mini’-outbursts with shorter recurrence times were also seen in the BATSE light curve. Extensive pointed \textit{RXTE} observations suggest that the source was in the LS during these periods (Wilms et al. 1999; Belloni et al. 1999). BATSE initially observed three strong outbursts with near equal intensities and separations (\( \sim 300 \) days), the subsequent outbursts clearly show that the time between outbursts was variable, with a significant correlation between outburst fluence and time since the last
outburst (Rubin et al. 1998). The source changed from the
LS to HS in 1998 January (≈ MJD 50814) according to
RXTE (ASM and PCA) observations (Belloni et al. 1999)
and the BATSE flux dropped to below significant detection
levels. Such a LS/HS transition was also accompanied by
non-detection of radio emission (Corbel et al. 2000). The
HS ended in 1999 February (≈ MJD 51210) and the return
to the LS was accompanied by the reappearance of the hard
X-rays and radio emission (Corbel et al. 2000). Following
the LS, the source entered the 'off' state (see §2.4) with a
small drop in the BATSE flux.

\[ \text{Figure 3. BATSE 20–100 keV light curve of GX 339–4 from 1991–1999. The data were rebinned by a factor of 2 for clarity. Also shown}
\text{in the insets are the simultaneous BATSE and Ginga ASM light curves (left) and simultaneous BATSE and RXTE ASM light curves}
\text{(right). The RXTE ASM data were rebinned by a factor of 2. Note that during a LS/HS transition, the BATSE flux drops to below the}
\text{detection limit, while the soft X-rays (Ginga or RXTE) increase dramatically. The arrows mark the time of pointed observations (see}
\text{Appendix) and the states are defined by the associated observations.} \]

\[ \text{2.6 BeppoSAX} \]

We observed GX 339–4 with the Narrow Field instruments
(NFI) on board BeppoSAX between March 21.9 and 24.6,
2000 UT. The NFI consist of two co-aligned imaging instru-
ments providing a field of view of 3′ × 5′: the Low-Energy
Concentrator Spectrometer (LECS; 0.1–10 keV; Parmar et
al. 1997a) and the Medium Energy Concentrator Spectrom-
eter (MECS; 1.6–10.5 keV; Boella et al. 1997). The other
two NFI, non-imaging instruments are the Phoswich Detec-
tor System (PDS; 12–300 keV; Frontera et al. 1997) and the
High-Pressure Gas Scintillation Proportional Counter (HP-
GSPC; 4–120 keV; Manzo et al. 1997).

Following the reduction procedures outlined by Kong
et al. (2000), we applied an extraction radius of 4′ centred
on the source position for both LECS and MECS images

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so as to obtain the source spectra. The MECS background
was extracted by using long archival exposures on empty sky
fields. For the LECS spectrum, we extracted the background
from two semi-annuli in the same field of view as the source
(see Parmar et al. 1999 for the reduction procedure).
Both the extracted spectra were rebinned by a factor of 3 so as
to accumulate at least 20 photons per bin and to sample
the spectral full-width at half-maximum resolution (Fiore
et al. 1999). A systematic error of 1% was added to both
LECS and MECS spectra to take account of the systematic
uncertainties in the detector calibrations (Gianinazzi et al.
1998). Data were selected in the energy ranges 0.8–1.0 keV
(LECS), 1.8–10.5 keV (MECS) and 15–220 keV (PDS) to
ensure a better instrumental calibration (Fiore et al. 1999).
A normalization factor was included for the LECS and PDS
relative to the MECS in order to correct for the NFI’s flux
intercalibration (see Fiore et al. 1999).

The source was only detected in the 1–10 keV range,
and the broad-band (1–10 keV) spectrum of GX 339–4 from
the LECS and MECS data is satisfactorily (χ^2 = 1.3 for
33 degrees of freedom) fitted by a single power-law with
photon index of 1.78 ± 0.24 plus absorption. We fixed the
N_H at 5.1 × 10^{21} cm^{-2} (Kong et al. 2000). The absorbed
flux in the 2–10 keV band is 0.60 × 10^{-12} erg cm^{-2}s^{-1}.

3 SEARCHING FOR X-RAY VARIABILITY
ON LONG TIMESCALES

From the light curves shown in the above section, GX 339–
4 underwent several state transitions and showed quasi-
periodic variability in the past 30 years. We therefore ex-
plor the data collected from different instruments to charac-
terize its overall variability. In order to search for peri-
ocdic phenomena, we used the Lomb-Scargle periodogram
(Lomb 1976; Scargle 1982; hereafter LSP), a modification
of the discrete Fourier transform which is generalised to
the case of uneven spacing. We have also employed the Phase
Dispersion Minimisation (PDM; Stellingwerf 1978) to check
the results from the LSP, as the PDM is sensitive to non-
sinusoidal modulations. For the RXTE ASM data (see inset
of Fig. 3), we first excluded the most recent HS and ‘off’
state (after MJD 50515) from the dataset as the flat-topped
HS will dominate the LSP and the data from the ‘off’ state
are not detected. By applying the LSP, a broad peak was
found at periods around 100–240 d, centered at 235 d (see
Fig. 4a). We also plotted in Fig. 4a the 99% significance level
for both white noise (Gaussian) and red noise. In determining
the white-noise confidence level, we generate Gaussian noise
datasets with the same time intervals and variance as the
time array and then perform the LSP analysis on the resulting
datasets. The peak power in each periodogram (which
must be purely due to noise) was then recorded. This was
repeated 10,000 times for good statistics. However, the noise
is not necessarily Gaussian, it can also be frequency depen-
dent with a higher power at lower frequencies. By using the
above method, strong peaks at the low frequencies might
give misleading results. In order to take into account such
a noise contribution in the data, we simulate the noise as
a power law, which is also known as red noise (e.g. Done
et al. 1992). Quantitatively, the power spectrum of the red-
noise light curve will be given by (1/\omega)^{α}, where \omega is fre-

![Figure 4. Lomb-Scargle periodograms of GX 339–4 as obtained by (a) RXTE ASM, (b) BATSE, (c) Ginga ASM, (d) Vela 5B and (e) Ariel 5, with significant peaks in the first four at 213, 227, 232 and 233d respectively. The horizontal dotted line is the 99% confidence level for white noise, while the dot-dash histogram is the 99% confidence level for red noise. The contribution of the red noise component in the Ginga, Vela 5 and Ariel 5 data is small enough (\lesssim 15\%) to be ignored since the noise level is essentially limited by the white noise.](image-url)
(Fig. 4b) which is consistent with the RXTE ASM result. The peak is very consistent and exceeds the 99% confidence level of both white and red noise. The PDM analysis also confirmed this modulation. The folded light curve of the BATSE data on 228 d is also shown in Fig. 5; T₀ is set at the time of the first data point of Vela 5B. The Ginga ASM monitored the source for 4.5 years and the four LS/HV/HS state transitions on timescales of ~ 200-400 d are seen (see Fig. 2). However, the sparse sampling prevents us from calculating a good LSP. Nevertheless, we include all the data points in searching for any variability. The strongest peak in the LSP is at ~ 232 d, although it is broad and only marginally significant (see Fig. 4c). The folded light curve of the Ginga data on 228 d is also shown in Fig. 5; T₀ is set at the time of the first data point of Vela 5B.

For the Vela 5B data, we used the whole dataset for calculating the LSP. It should be noted that two HS occurred during these observations (see Appendix; Markert et al. 1973) and hence the results should be interpreted with great caution. The strongest peak in the periodogram of the Vela 5B data is at ~ 365 days and is caused by an annual variation in the spacecraft environment (Priedhorsky et al. 1983). The LSP reveals a second peak at 232 d which is just above the 99% confidence level (see Fig. 4d). Although the sensitivity of Vela 5B is poorer than current X-ray satellites, a clear variability is seen in the light curve (Fig. 1) and the long timebase (over 10 years) increases the sensitivity to these timescales. This variability was also detected in the PDM analysis. The folded light curve on 228 days is shown in Fig. 5; T₀ is again set at the time of the first data point of Vela 5B.

The Ariel 5 ASM data do not show the variation as clearly as the RXTE ASM data, but some variability can be discerned. LS/HS transitions might occur during the Ariel 5 observations but there is no pointed observations to confirm the 'state' of the source. We here used all the data in calculating the LSP. The LSP (Fig. 4e) shows a peak near 365 days, again due to the annual variation in the count rate from soeh X-ray scattering or fluorescing from the Earth's atmosphere (Priedhorsky, Terrell & Holt 1983).

4 DISCUSSION

4.1 Long-term X-ray variability

Through the extensive dataset obtained with the CGRO/BATSE and RXTE/ASM, we find evidence of variability on timescales ~ 190-240 d in GX339-4 (it should be noted that the recent HS and off state data are excluded in both datasets and at least one HS occurred in the BATSE data). Observations from Ginga and Vela 5B also suggest a similar timescale but the data consist of state transitions. Such a variability has been noted previously by Nowak, Wilms & Dow (1999) for the RXTE ASM data. They also pointed out that the observed long-term X-ray variability is not a strict clocking phenomenon but is more likely to be a characteristic timescale. From our analysis, this timescale is also manifested in the BATSE, Ginga and Vela 5B data.

In addition, the broad peak in the LSP of the RXTE ASM data (see Fig. 4) also hints that such variability is not strictly periodic and can only be regarded as a characteristic timescale. From the folded light curves of different datasets (Fig. 5), the peaks occur almost in anti-phase, suggesting the aperiodic nature. Indeed, such quasi-periodic long-term variability (usually referred to as the super-orbital period) has also been seen in other X-ray binaries such as Cyg X-2, LMC X-3 and Cyg X-1 (see e.g. Kong, Charles & Kuulkers 1998; Paul, Kitamoto & Makino 2000; Kitamoto et al. 2000), but no clear understanding of its origin has yet been established (see Wijers & Pringle 1999). As noted by Nowak, Wilms & Dow (1999), the observed long-term X-ray variability of GX339-4 could be due to a combination of a quasi-steadily precessing disc at large radii with coronal structure changes on small radii. If this is the case, X-ray irradiation can give rise to a precessing disc (Dubus et al. 1999) and it might even explain the LS/HS transition of the source. Actually, results from the Ginga and Vela 5B data suggest that the LS/HS transitions and the outburst-like events during the low/hard state (as seen in the RXTE and BATSE data) may be due to the same mechanism, although the data is not well-sampled. Therefore, it is possible that such quasi-periodic outbursts might actually be a characteristic precursor to the LS/HS transition. In the next subsection, we will discuss the role of X-ray irradiation in the state transition and also the origin of the long-term X-ray variability.

Our BeppoSAX observations presented here indicate
that the source was fainter than the previous observation in 1999 August (see Kong et al. 2000) by a factor of 3 in half year; therefore the source is still in the ‘off’ state. The energy spectra of both observations are very similar to those obtained in the L.S. Hence, there is no doubt that the ‘off’ state is an extended L.S (see discussions by Kong et al. 2000; Corbel et al. 2000) and we may now refine the source as a transient rather than a persistent source. In fact the luminosity during the ‘off’ state is in the upper end of the quiescent luminosity of typical X-ray transients (see e.g. Kong et al. 2000). The results also further confirm that during quiescence, significant X-ray variability can be seen. Such variability in quiescence is also found in several black hole transients such as GS 2023+338 (Wagner et al. 1994; Kong et al. 2001), 4U 1630-47 (Parmar et al. 1997b) and A0620-00 (Asai et al. 1998; Menou et al. 1999).

4.2 LS/HS transition in 1998

As noted in §2.4 and 2.5, GX 339-4 underwent a LS/HS transition in 1998 (see Fig. 3; also Belloni et al. 1999) which differs somewhat from the previous ones observed with the Ginga ASM. After the source reached the peak of the HS, it spent nearly 200 days at a constant flux level of $\sim 20$ RXT ASM cts/s. Such a flat-topped X-ray light curve for GX 339-4 is different from the ‘standard’ fast-rise exponential decay profile, as observed from various X-ray transients (see Chen, Shrader & Livio 1997 for various examples of different outburst patterns). The state transition mechanism for such a persistent source is still a puzzle and observations in different states suggested that it is most likely associated with the mass accretion rate (e.g. Mendez & van der Klis 1997). A change in the mass accretion rate can be caused by a thermal instability in the accretion disc (disc instability model, or DIM) and in fact it is widely accepted that the outbursts in BHSXTs are due to this mechanism (e.g. Esin, Lasota & Hynes 2000). Interestingly, the DIM was originally developed to describe the outbursts in dwarf novae (DNS; see e.g. Cannizzo 1993 for a review) which contain a white dwarf as the compact object; it was suggested quite early that it also applies in BHSXs (e.g. van Paradijs & Verbunt 1984; Huang & Wheeler 1989; Mineshige & Wheeler 1989). In LMXBs, X-ray irradiation can influence the stability of the accretion disc (van Paradijs 1996) and thus a DIM which includes X-ray irradiation was developed (Dubus et al. 1999). It is worth noting that the recent HS spectroscopic observations of GX 339-4 obtained by Wu et al. (2001) also indicate that the accretion disc is heated by soft X-ray irradiation, suggesting that irradiation plays a role in the state transition. Irradiation of the outer disc by X-rays from the inner disc gives a stability criterion, from which the minimum mass accretion rate for a stable, steady-state accretion in an X-ray irradiated disc can be expressed as (Dubus et al. 1999):

$$\dot{M}_{\text{crit}}^{\text{irr}} \approx 2.0 \times 10^{-5} \left(\frac{M_1}{M_2}\right)^{0.5} \left(\frac{M_2}{M_0}\right)^{-0.2} \times$$

$$p_{\text{irr}}^{1.4} \left(\frac{C}{5 \times 10^{-2}}\right)^{-0.5} \text{g s}^{-1},$$

where $M_1$ is the black hole mass, $M_2$ is the mass of the companion, $P_{\text{irr}}$ the orbital period in hours. $C$ is a parameter to describe the properties of irradiation through:

$$T^{4}_{\text{irr}} = \frac{C M_t^2}{4 \pi \sigma R^4}.$$  \hspace{1cm} (2)

where $T_{\text{irr}}$ is the irradiation temperature and $\sigma$ is the Stefan-Boltzmann constant. For a stable X-ray irradiated disc during the HS, $\dot{M}_{\text{crit}}^{\text{irr}}$ can be estimated from the HS observations by Belloni et al. (1999), in which they have fitted the spectrum with a power law plus a multi-colour disc blackbody model. By using the derived inner disc radius, $R_{i n} \cos i$ of 25.4 $D_k$ km (where $D_k$ is the distance to the source in units of 4 kpc; Zdziarski et al. 1998) and the blackbody temperature, $T_{\text{bb}}$ of 0.72 keV, we can calculate the bolometric luminosity of the disc blackbody component as

$$L_{\text{bb}} = 4\pi R_{i n}^2 \sigma T_{\text{bb}}^4.$$  \hspace{1cm} (3)

The accretion rate can be estimated via the relation

$$L_{\text{bb}} = 0.5 G M_1 M/R_{\text{in}},$$

which leads to $\dot{M} \approx 1.7 \times 10^{-4} D_k^2 \text{g s}^{-1}$ if we assume an orbital inclination of about $15^\circ$ (Wu et al. 2001) for a 14.8-hr orbital period (Callanan et al. 1992). Assuming an estimated mass of the black hole of 5 $M_\odot$ (Zdziarski et al. 1998) and companion star of 0.4 $M_\odot$ (Callanan et al. 1992), we obtain $\dot{M} = 9.4 \times 10^{-4}$ from Eqn. 1, which is slightly higher than $5 \times 10^{-4}$ obtained by comparison with other results in the literature (see Dubus et al. 1999). According to the scenario outlined above, the mass of the compact object is limited to be $\sim 3-5 M_\odot$.

From the previous LS observations, the estimated mass accretion rate is about $5 \times 10^{-6}$ g s$^{-1}$ (e.g. Wilms et al. 1999; Belloni et al. 1999) which is a factor of 3 below the critical accretion rate for a stable disc and hence the disc may be subject to the DIM in order to give rise to a LS/HS transition. Since the accretion rate during the LS is very close to the critical value, a slight increase in the accretion rate by a small factor would produce a stable disc. As a result, a shorter interval to the next state transition would be expected. Unlike the SXTs in which the outburst timescale is normally longer than ten years, GX 339-4 has much more frequent state transitions, as seen in e.g. the Ginga ASM data (see Fig. 2). In fact, the 212-d variability seen in the Ginga and Vela 5B data has already hinted at such behaviour.

The most interesting behaviour of the 1998 HS is that the observed flat-topped X-ray light curve of GX 339-4 bears characteristics of Z Cam-type DN in which standstills (i.e. the brightness remains constant) occasionally interrupt the recurrent outbursts. Such a scenario can be explained by the DIM (Meyer & Meyer-Hofmeister 1983; King & Cannizzo 1998) in which the accretion rate before standstill is very close to a critical value and a sudden increase in the accretion rate (e.g. by a starspot or irradiation induced mass overflow) triggers the standstill state. The light curve of GX 339-4 is even more similar to the model proposed by King & Cannizzo (1998) in which the standstill is at a higher luminosity than the normal outbursts. For Z Cam systems, the intensity of the standstills is lower than the maximum of the outbursts (Meyer & Meyer-Hofmeister 1983), but we should note that
the models for explaining the Z Cam systems are used to account for optical light curves.

The second similarity between GX 339–4 and Z Cam systems concerns the recurrence of outbursts between standstills. From our earlier period analysis of the archival GX 339–4 data over 30 years, we find a variability timescale of ~190–240 d and we suggest this to be the recurrent outbursting behaviour seen in Z Cam systems. As pointed out by Dubus et al. (in preparation), the accretion rate can vary on timescales of 10–100 days when a viscously unstable disc is irradiated by a constant X-ray flux. If irradiation is crucial for determining the accretion rate of GX 339–4, this may explain the variability of the 'mini'-outbursts observed during the LS. There is also an indication that the accretion rate of GX 339–4 was building up before the HS in 1998 as the average intensity level of both RXTE ASM and BATSE data has an increasing trend especially after MJD 50000 (see Fig. 3). In addition, the HS occurring at MJD 48550 and 40450 (see §2.5) were just after a strong X-ray outburst in the LS (see Fig. 3). Perhaps this takes the accretion rate in the LS to be close to the critical value and finally triggers the state transition. As a result, this HS may be simply a strong, prolonged outburst in an otherwise LS. In fact, from the period analysis of the Vela 5B and Ginga data for which state transitions are included in the calculation, the timescale of variability resembles that found in the RXTE ASM data in the LS. Perhaps the LS outbursts may be excursions towards the HS but which they do not quite reach. If this is the case, we would expect similar spectral evolution during the LS outburst, just like during a state transition. However, such outbursts are usually short and therefore observations are difficult to arrange. The most likely observations available are from Wilms et al. (1999), in which an RXTE pointed observation of GX 339–4 was made near the outburst (MJD 30710) just before the LS/HS transition. Although the energy spectrum appeared to be slightly softer, it is still consistent with other LS observations within the uncertainties. It is worth noting that Cyg X–1 also shows LS/HS transitions occasionally and it has flaring activities during the LS. Moreover, the long HS of Cyg X–1 between May and August resembles that seen in GX 339–4, but with more flares during the HS (Zhang et al. 1997). Therefore, it is possible that the state transition of Cyg X–1 is due to a similar mechanism to that discussed here (see however Zhang et al. 1997; Esin et al. 1998). More recently, LMC X–3 was also shown to have recurring state transitions but the driving force is very likely to be due to other mechanisms (Boyd et al. 2000; Wilms et al. 2001). Given that the accretion rate in the LS is close to the critical value, similar LS/HS transitions would be expected in the near future and multi-wavelength observations of such transitions, particularly the correlation between the X-ray, optical and radio emissions will constrain the accretion disc structure and behaviour of the secondary star.

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APPENDIX A: PREVIOUS POINTED X-RAY OBSERVATIONS OF GX 339–4

GX 339–4 has been observed by several X-ray satellites in the past 30 years and the results from those pointed observations are crucial to determine the 'state' of the source. We compile here a list of pointed observations of GX 339–4 from the literature (see Table A1). Note that the 'state' quoted is determined by spectral and temporal analysis. Although the X-ray flux level can more or less reflect the 'state' of the source, on several occasions the X-ray flux in the LS is actually higher than the HS (e.g. 1981 May and 1984 May). Hence the X-ray intensity itself is not an accurate indicator of X-ray 'state'.

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Table A1. Previous X-ray observations of GX 339-4.

<table>
<thead>
<tr>
<th>Date</th>
<th>X-ray state</th>
<th>Flux (mCrab)</th>
<th>Satellite</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971 October to 1972 January</td>
<td>LS</td>
<td>~ 10-40 (1-6 keV)</td>
<td>OSO-7</td>
<td>1</td>
</tr>
<tr>
<td>1972 February</td>
<td>HS</td>
<td>~ 50 (1-6 keV)</td>
<td>OSO-7</td>
<td>1</td>
</tr>
<tr>
<td>1972 May</td>
<td>LS/off</td>
<td>&lt; 5 (1-6 keV)</td>
<td>OSO-7</td>
<td>1</td>
</tr>
<tr>
<td>1972 December</td>
<td>HS</td>
<td>~ 50 (1-6 keV)</td>
<td>OSO-7</td>
<td>1</td>
</tr>
<tr>
<td>1981 March</td>
<td>LS/off</td>
<td>&lt; 50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1981 May</td>
<td>LS</td>
<td>160 (0.1-20 keV)</td>
<td>Bakugo</td>
<td>2, 3</td>
</tr>
<tr>
<td>1981 June</td>
<td>LS to HS</td>
<td>~ 160-600 (3-6 keV)</td>
<td>Bakugo</td>
<td>2</td>
</tr>
<tr>
<td>1982 May</td>
<td>LS/off</td>
<td>&lt; 50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1983 May</td>
<td>HS</td>
<td>300 (3-10 keV)</td>
<td>Tevra</td>
<td>4</td>
</tr>
<tr>
<td>1984 March &amp; May</td>
<td>HS</td>
<td>90 (3-10 keV)</td>
<td>EXOSAT</td>
<td>5</td>
</tr>
<tr>
<td>1984 May</td>
<td>HS</td>
<td>120 (0.1-20 keV)</td>
<td>EXOSAT</td>
<td>3</td>
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<tr>
<td>1985 April</td>
<td>LS/off</td>
<td>1.7 (0.1-20 keV)</td>
<td>EXOSAT</td>
<td>3</td>
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<tr>
<td>1987 June</td>
<td>LS/off</td>
<td>~ 13 (1-6 keV)</td>
<td>Ginga</td>
<td>6, 7</td>
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<tr>
<td>1987 July</td>
<td>LS/off</td>
<td>~ 26 (1-6 keV)</td>
<td>Ginga</td>
<td>6, 7</td>
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<tr>
<td>1988 August</td>
<td>VHS</td>
<td>900 (1-6 keV)</td>
<td>Ginga</td>
<td>7, 8</td>
</tr>
<tr>
<td>1990 April</td>
<td>LS</td>
<td>~ 12 (1-6 keV)</td>
<td>Ginga</td>
<td>7, 9</td>
</tr>
<tr>
<td>1991 August November</td>
<td>HS</td>
<td>100-230 (3-10 keV)</td>
<td>Granat</td>
<td>10</td>
</tr>
<tr>
<td>1991 February November</td>
<td>LS to HS</td>
<td>~ 100-300 (3-10 keV)</td>
<td>Granat</td>
<td>10</td>
</tr>
<tr>
<td>1992 February</td>
<td>off</td>
<td>&lt; 17 (3-10 keV)</td>
<td>Granat</td>
<td>10</td>
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<tr>
<td>1993 September</td>
<td>off</td>
<td>&lt; 0.01 (2-10 keV)</td>
<td>ASCA</td>
<td>11</td>
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<tr>
<td>1994 August</td>
<td>LS</td>
<td>~ 30 (3-9 keV)</td>
<td>ASCA</td>
<td>12</td>
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<tr>
<td>1995 September</td>
<td>LS</td>
<td>50 (3-9 keV)</td>
<td>ASCA</td>
<td>12</td>
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<tr>
<td>1996 April</td>
<td>LS</td>
<td>70 (2-12 keV)</td>
<td>RXTE</td>
<td>13</td>
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<tr>
<td>1997 February to October</td>
<td>LS</td>
<td>~ 70 (2-12 keV)</td>
<td>RXTE</td>
<td>12</td>
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<tr>
<td>1998 January to February</td>
<td>HS</td>
<td>160-270 (2-12 keV)</td>
<td>RXTE</td>
<td>13</td>
</tr>
<tr>
<td>1998 August</td>
<td>HS</td>
<td>260 (2-12 keV)</td>
<td>RXTE</td>
<td>14</td>
</tr>
<tr>
<td>1999 August</td>
<td>off</td>
<td>0.1 (2-10 keV)</td>
<td>BeppoSAX</td>
<td>14, 15</td>
</tr>
<tr>
<td>2000 March</td>
<td>off</td>
<td>0.03 (2-10 keV)</td>
<td>BeppoSAX</td>
<td>this work</td>
</tr>
</tbody>
</table>


REFERENCES


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