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X-ray Observation of XTE J2012+381 during the 1998 Outburst

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Abstract. The outburst of X-ray transient source XTE J2012+381 was detected by the RXTE All-Sky Monitor on 1998 May 24th. Following the outburst, X-ray observations of the source were made in the 2–18 keV energy band with the Pointed Proportional Counters of the Indian X-ray Astronomy Experiment (IXAE) on-board the Indian satellite IRS-P3 during 1998 June 2nd–10th. The X-ray flux of the source in the main outburst decreased exponentially during the period of observation. No large amplitude short-term variability in the intensity is detected from the source. The power density spectrum obtained from the timing analysis of the data shows no indication of any quasi-periodic oscillations in 0.002–0.5 Hz band. The hardness ratio i.e. the ratio of counts in 6–18 keV to 2–6 keV band, indicates that the X-ray spectrum is soft with spectral index >2. From the similarities of the X-ray properties with those of other black hole transients, we conclude that the X-ray transient XTE J2012+381 is likely to be a black hole.

Key words. Accretion, accretion disks—black hole physics—Xrays: stars—stars: individual—XTE J2012+381.

1. Introduction

The soft X-ray transients (SXT) are low-mass X-ray binaries, where the accretion of matter takes place from the Roche lobe filling companion onto a stellar mass black hole or neutron star. The source remains in a quiescent state for a long period as the mass accretion rate is low. Outburst occurs when the mass accretion rate reaches a limit to create instability in the accretion disk, resulting in increase in luminosity of the source by many orders of magnitude in a few days. At the peak of the outburst, the X-ray luminosity of the transient sources increases from 10^{33} erg s^{-1} to 10^{38} – 10^{39} erg s^{-1} (Tanaka & Lewin 1995). The luminosity of the source declines roughly either exponentially or linearly after the outburst. Some of the soft X-ray transients show secondary outbursts during the declining phase. During the secondary outburst, the luminosity increases sharply by a factor of up to 3, followed by an exponential or linear decay (Ertan & Alpar 1998). The soft X-ray transients (SXT) possess the characteristics of fast rise in flux in a few days and a slow decay with time scale of the order of one month. Some of the SXTs are recurrent with time scale of a few tens of years.

The X-ray transient source XTE J2012+381 was discovered by Remillard *et al.* (1998) from the observations with RXTE All Sky Monitor (ASM) on 1998 May 24th. The X-ray flux of the source was 23 mCrab in 2–12 keV energy band when detected and increased to 88 mCrab on 1998 May 27.3 (Remillard *et al.* 1998). The source spectrum became softer as the brightness increased. Following its discovery, the transient XTE J2012+381 was observed with ASCA X-ray observatory from May 29.30 UT to 30.19 UT (White *et al.* 1998). The position of the source was found to be RA(2000) = $20^h\ 12^m\ 39.1^s$ and Dec(2000) = 38° 10' 50" with an accuracy of 0.5'. Hjellming, Rupen & Mioduszewski (1998) observed the radio counterpart of the source with VLA with flux densities of 2 and 1.5 mJy at 1.4 and 4.9 GHz respectively on 1998 May 31.25 (Hjellming *et al.* 1998). The radio source was well inside the error region for the RXTE ASM position. The variability of the radio source at 15 GHz was reported by Pooley & Mullard (1998) with Ryle Telescope observation. From the optical and infrared observations, Hynes *et al.* (1999) identified the optical counterpart of the source XTE J2012+381 to be a faint red star which coincides with the radio counterpart and emits weak Halpha line.

Following the discovery of the source by RXTE ASM, X-ray observations were made with Pointed Proportional Counters (PPCs) of the Indian X-ray Astronomy Experiment (IXAE) during 1998 June 2nd–10th. The X-ray light curves of the source do not show any large amplitude variability on short time scales. The power density spectrum obtained from the timing analysis of the data does not show any indication of quasi-periodic oscillation in the source in the frequency range of 0.002 to 0.5 Hz. The results of the analysis are described in this paper.

2. Instrument and observations

The observations of the soft X-ray transient XTE J2012+381 were made using Pointed Proportional Counters (PPCs) on IXAE. The IXAE includes three identical, co-aligned, multi-wire, multi-layer PPCs with effective collecting area of 1200 cm^2. A gas mixture of 90% argon and 10% methane at a pressure of 800 torr is used as filling gas. A honeycomb type of collimator is used in each PPC which restricts the field of view to 2°.3 × 2°.3. All the three detectors operate in the energy range of 2–18 keV with an energy resolution of 22% at 6 keV. The gain stability of the detectors is monitored by the irradiation of X-rays from a radioactive Cd^{109} source to the Veto cells. The event processing time for the detectors is about 50 μs in the processing electronics. For a detailed description of the PPCs, refer to Agrawal (1998) and Rao *et al.* (1998).

The IRS–P3 satellite launched on 1996 March 21st, from India, is in a circular orbit at an altitude of 830 km and inclination angle of 98°. Pointing of the detectors towards any given source is done by inertial pointing using a star tracker with an accuracy of about ≤ 0°.1. The useful observation period is limited to the latitude range from –30° S to +50° N as the high inclination and high altitude region is very background prone. The large extent of the South Atlantic Anomaly (SAA) region restricts the observation to about 5 of the 14 orbits per day. In the non-operating regions, the high voltage to the detectors is reduced and data acquisition is stopped.

Table 1. X-ray observations of XTE J2012+381 with the IXAE for 1 sec time resolution mode.

Observation day, 1998 June	M.J.D.	From (UT)	To (UT)	Counts per sec
02	50966	11:03:00	11:17:00	284
		12:38:00	12:57:00	311
		14:20:00	14:36:00	310
		16:03:00	16:20:00	290
04	50968	15:17:00	15:37:00	271
05	50969	11:32:00	11:58:00	161
		13:14:00	13:38:00	208
		14:56:00	15:19:00	192
		16:38:00	16:58:00	180
		18:19:00	18:40:00	220
06	50970	11:13:00	11:33:00	166
		12:53:00	13:15:00	171
		14:35:00	14:55:40	170
		16:16:00	16:37:52	163
		17:58:00	18:19:40	169
07	50971	12:31:00	12:53:00	173
		14:13:00	14:35:00	175
		15:55:00	16:15:00	166
		17:36:00	17:57:00	180
08	50972	12:10:00	12:32:00	165
		13:53:00	14:13:00	150
		15:34:00	15:54:00	167
09	50973	11:49:00	12:11:00	155
		13:32:00	13:52:00	175
		15:13:00	15:33:00	155
10	50974	11:28:00	11:50:00	141
		13:11:00	13:31:00	146

The soft X-ray transient XTE J2012+381 was observed by IXAE from 1998 June 2nd-10th with 1 second integration time. The log of observation is given in Table 1 with background subtracted summed count rate for the three PPCs. The total useful period of observation of the X-ray source is about 37,100 seconds.

3. Analysis and results

3.1 *The X-ray light curve*

The light curve of the source XTE J2012+381 with average count rates per orbit, for the total period of observation by the PPCs is shown in Fig. 1. The inset in Fig. 1 represents the ASM light curve for the source with one day average data for the total outburst period. The IXAE observations, made just after the peak of the outburst, are marked by two vertical lines in the inset. The intensity of the source was maximum on 1998 May 31st with about 16 ASM counts s^{-1} (Crab = 74 ASM counts s^{-1}). The flux of the source again increased to a maximum of about 12 ASM counts s^{-1} after 24 days of the first peak, followed by a linear decay.

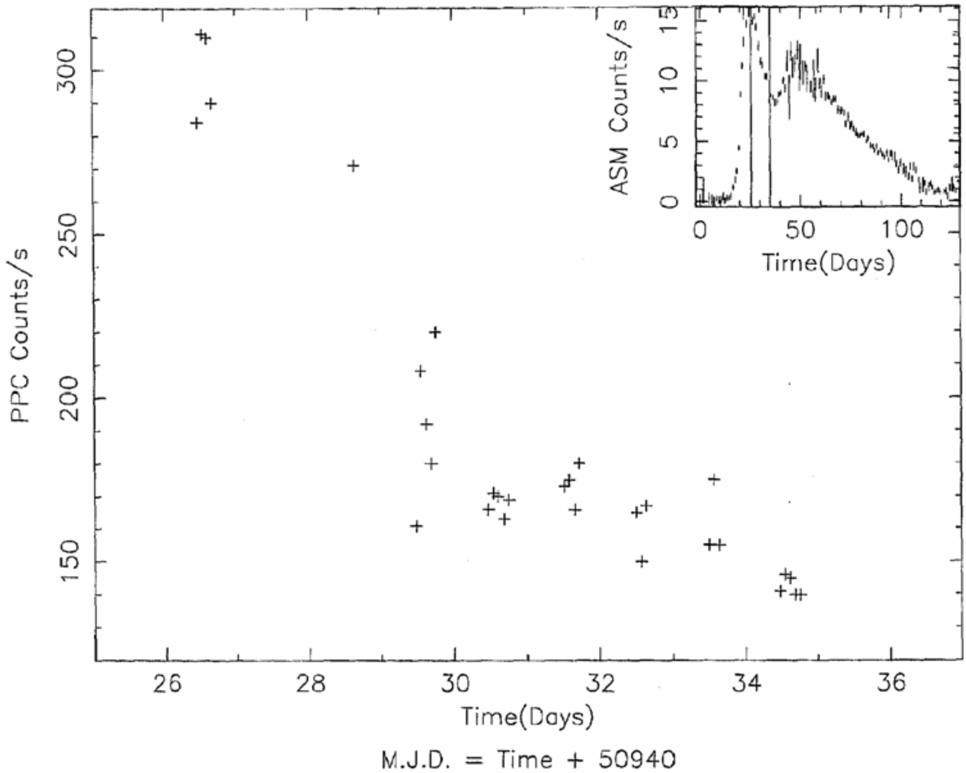

Figure 1. The count rate for XTE J2012+381 obtained from PPC observations. ASM light curve for 1-day average data is shown in the inset. The region between two vertical lines is the period of observation of the source with the PPCs.

The X-ray data for 2–18 keV and 2–6 keV energy bands are corrected for background and offset pointing. Dead time correction, which is less than 1% even at the maximum count rate of about 110 counts s^{-1} per PPC, has been neglected. The light curves were generated using the corrected data for the two different energy bands. The light curve for one of the observations on 1998 June 2nd for 1 s integration time is shown in Fig. 2. A constant intensity fit to the data gives an average count rate of 323 with reduced χ^2 of 1.4 for 498 degrees of freedom. From the light curve of Fig. 2, there is no indication of any large amplitude rapid variability or flaring of the kind seen in Cyg X–1 and some other black hole binaries. However there may be low amplitude variations which results in the large value of the reduced χ^2. Bining the same data in 5 s time bins yields a reduced χ^2 of 1.67 for 99 dof consistent with the presence of low amplitude intensity variations.

The hardness ratio i.e. the 6–18 keV counts divided by 2–6 keV counts, was computed for all the observations. A typical plot of hardness ratio for one of the observations on 1998 June 2nd is shown in Fig. 3. The ratio is found to be about 0.76 ± 0.01 with reduced χ^2 of 0.8 (260 degrees of freedom). There is no significant change in the hardness ratio during any individual observations. The hardness ratio of $0.76 + 0.01$ indicates that the X-ray flux, emitted by the source, is soft. The corresponding hardness ratio for Crab from the PPC observations is 0.85 (Mukerjee 1999), hence we conclude that the X-ray spectrum of XTE J2012+381, if represented as a

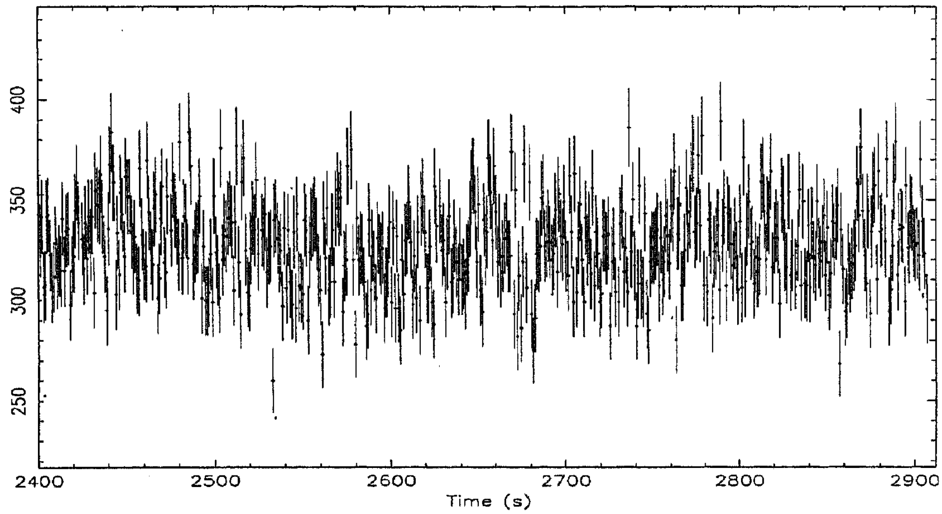

Figure 2. The light curve obtained from one of the observations of XTE J2012+381 on 1998 June 2nd for 1 s time resolution mode for all the PPCs.

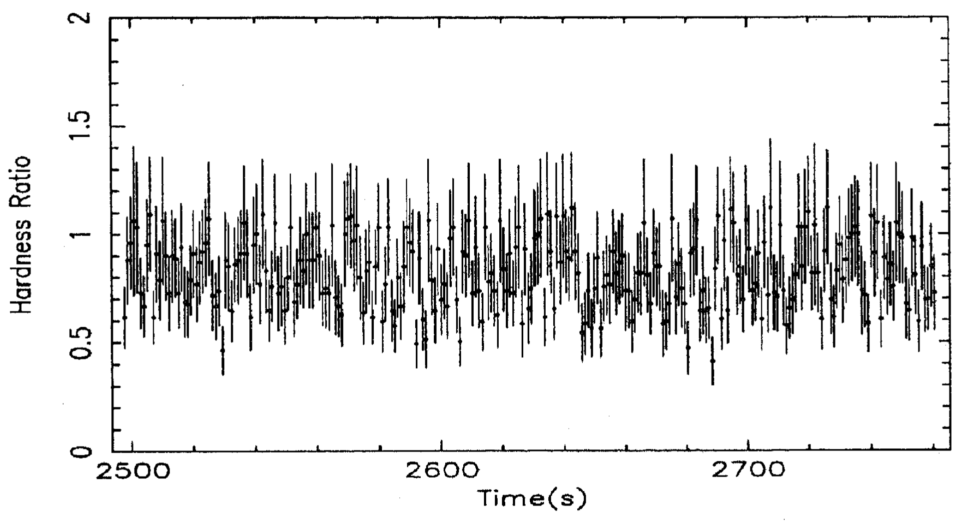

Figure 3. The hardness ratio i.e. count rate in 6–18 keV band divided by that in 2–6 keV interval, for one of the observations on 1998 June 2nd for XTE J2012+381.

power law, should have a photon index of > 2. This suggests that XTE J2012+381 is most likely to be a soft X-ray transient.

3.2 *The power density spectrum*

To study the timing behaviour of XTE J2012+381, power density spectra were generated by taking the Fourier transform of 1 s time resolution data. The light curves for 2–18 keV and 2–6 keV energy bands, generated from the data corrected for

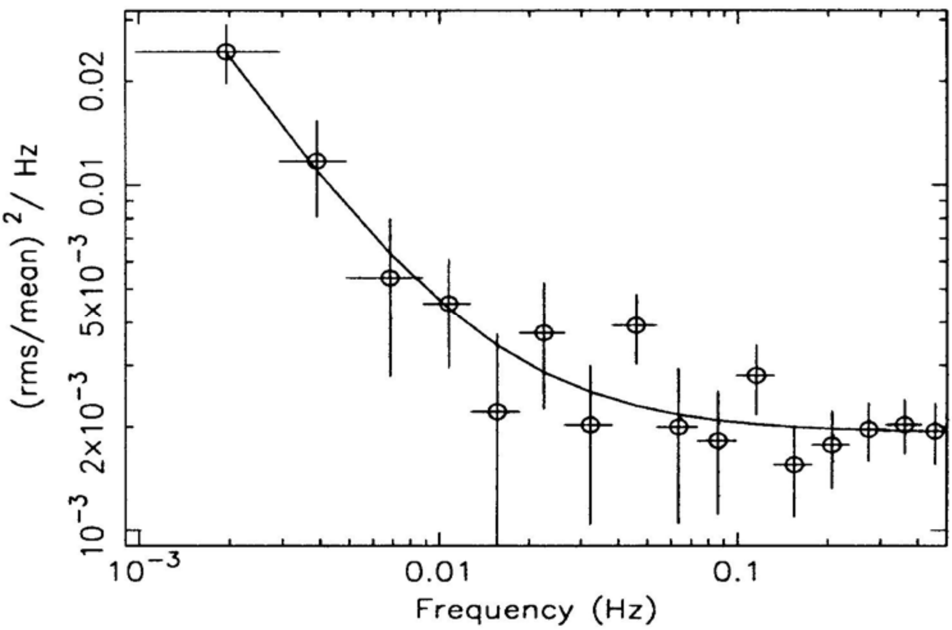

Figure 4. The co-added power density spectrum for XTE J2012+381 for the observations from 1998 June 2nd to 1998 June 10th in 2–18 keV energy band and 1 sec time resolution mode.

background and vignetting, were broken into segments of 512 seconds. The power density spectrum (PDS) was obtained for each data segment and then co-added to get the final PDS. The PDS are normalised to squared fractional rms per hertz. XRONOS software package is used for the data analysis.

Figure 4 shows the added PDS for all the observations for 1 s time resolution for 2–18 keV energy range. From the figure, it is clear that there is no indication of any QPO feature in the frequency range of 0.002 Hz to 0.5 Hz. The PDS is fitted well by a power law from 0.002 Hz to 0.02 Hz with index –1.29 and a constant in the higher frequency range with reduced χ^2 of 0.58 for 13 degrees of freedom. The rms variation of the PDS is calculated to be 2%. In the PDS, the power law represents the low-frequency noise component. The variation in the hardness ratio and percentage of rms variation for each day average data is shown in Fig. 5. The average count rate is found to be correlated with the hardness ratio of the source with a linear-correlation coefficient of 0.7 (7 degrees of freedom) corresponding to 95% of significance level. There is indication of a weak correlation between count rate and rms variation of power and hardness ratio and rms variation as indicated by correlation coefficients of 0.514 and 0.51 respectively.

4. Discussion

Many of the SXTs which contain a black hole as the compact object, show secondary outbursts. The decay time and the time scale of occurrence of the secondary maximum (t_s) in the various black hole X-ray transients are summarised in Table 2. The outburst profiles are classified as fast rise and slow decay (frsd), irregular (irr)

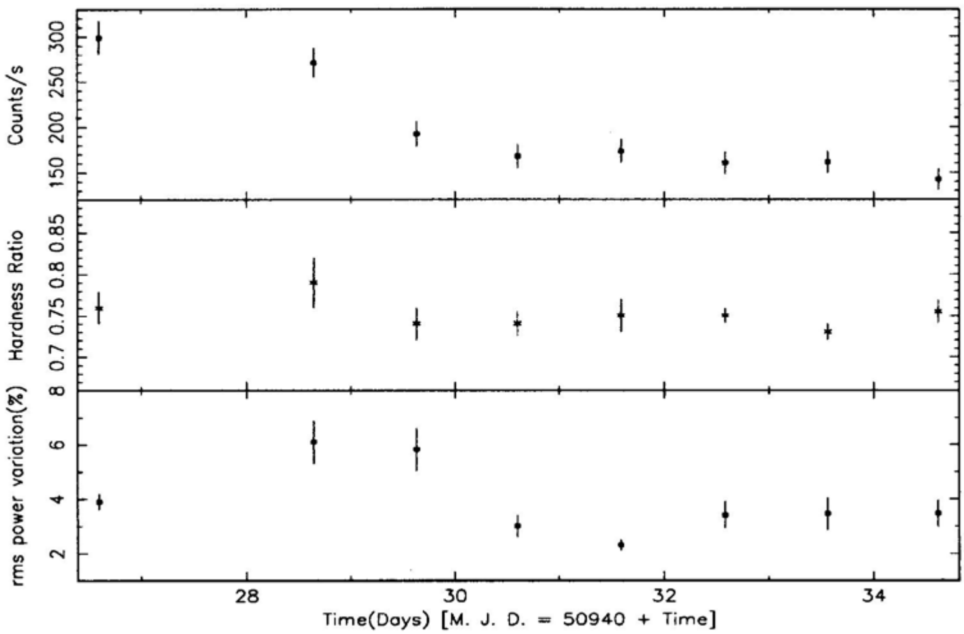

Figure 5. The observed PPC count rates for the source XTE J2012+381 averaged over one day are shown along with the corresponding variation in hardness ratio and rms variation(%) in the PDS.

Table 2. Summary of the outburst characteristics of black hole X-ray transient sources.

Source name	Overall light curve profile	t_s (days)	Decay time of primary outburst(days)	Reference
GRO J0422+32	frsd	38	40.1	Shahbaz *et al.* (1998)
A0620−00	frsd	54	26.3	Shahbaz *et al.* (1998)
GS/GRS1124−68	frsd	80	–	Ertan *et al.* (1998)
4U 1543−47	frsd	15	42.7	Shahbaz *et al.* (1998)
X1630−472	irr	–	–	Remillard (1998)
GRO J1655−40	irr	40	30.0	Remillard (1998)
GRS 1737−310	qp	–	–	Remillard (1998)
GRS 1739−278	frsd	83	34.0	Remillard (1998)
XTE J1739−302	qp	–	–	Remillard (1998)
XTE J1748−288	frsd	–	15.0	Revnivtsev *et al.* (1999)
XTE J1755−324	fsrd	–	30.2	Remillard (1998)
XTE J1856+053	fsrd	–	40.2	Remillard (1998)
GRS 1915+105	irr	–	–	Remillard (1998)
GS 2000+25	frsd	75	30.1	Shahbaz *et al.* (1998)
XTE J2012+381	fsrd	24	16.2 & 36.0	Present work
GS 2023+338	frsd	–	30–40	Zycki *et al.* (1999)

Note: frsd = fast rise and slow decay, **irr** = irregular, **qp** = quasi persistence, t_s = time of occurrence of secondary maximum from the maximum of the primary outburst.

and quasi persistent (qp) as given by Remillard (1998). For XTE J2012+381, we have determined the decay times of both the primary and the secondary outbursts by fitting an exponential to the decay profile obtained from the XTE ASM data and these values are given in the table. We have also determined the decay time for the primary outburst from the PPC data as 18.1 days using exponential fit which agrees with the value of 16.2 days obtained from the ASM light curve.

The soft X-ray transients A0620–00, GS 2000+25, GS/GRS 1124–68 and GRO J0422+32 (Ertan *et al.* 1998) show many similarities with the SXT J2012+381. The primary outburst profiles for these transients are characterised by a fast rise and slow decay. The typical exponential decay time is around one month. During decline, all the above five transients exhibit secondary outbursts. For GS 2000+25 and GS/GRS 1124–68, the secondary maxima are observed about 80 days after the main outburst while in A0620–00, it is observed 50 days after the main outburst. However for XTE J2012+381, the secondary maximum was observed 24 days after the main outburst.

The power density spectrum of XTE J2012+381 is similar to that of the black hole transient GS 2023+338 (Zycki *et al.* 1999) and XTE J1748–288 (Revnivtsev *et al.* 1999) in the frequency range 0.003 Hz to 0.5 Hz. Though the absolute value of the power for XTE J2012+381 is not exactly the same as that of XTE Jl748–288 in the high state, the fitted power law indices for the PDS are identical. The power law index for XTE J1748–288 in high state varies between 1.0 and 1.5 with 1% of fractional variability in the amplitude (Revnivtsev *et al.* 1999), which is similar to that of XTE J2012+381. There is no indication of large amplitude flux variation in XTE J1748–288 on shorter time scales ($\leq$ 5s) like the one found in Cyg X–l or GX 339–4. Though the QPOs are absent in XTE J2012+381, its PDS is similar to that of XTE J1748–288 in the high state of the 1998 outburst. Considering these similarities and the soft spectrum of the source, it is likely that the source may be in a high state during our observations. From the similarity of the decay time, the occurrence of the secondary maximum and also the similarity of the PDS with those of GS 2023+338 and XTE J1748–288, it can be infered that the soft Xray transient XTE J2012+381 is most likely a black hole.

The outburst of X-ray transients can be explained by the thermal accretion disk instability model or by instability in the accretion disk created by the enhanced mass transfer from the companion. Chen & Taam (1994) have investigated the time-dependant evolution of the thermal viscous instabilities in geometrically thin, optically thick accretion disks around black holes and neutron stars. Since the mass accretion rate for a black hole stellar source is expected to be large, the inner region of the disk is expected to be dominated by the radiation pressure. For such a disk in which the viscous stress (τ), is proportional to the total pressure (p) i.e. $\tau = -\alpha p$ where α is a constant, the disk becomes globally unstable due to the thermal and viscous instabilities (Lightman & Eardley 1974; Shakura & Sunyaev 1976). This results in burst like fluctuations of large amplitude in the disk luminosity.

It has been shown that at a given radius of the accretion disk, the stability of the disk traces a characteristic 'S' curve in the $\sum - T_{\rm eff}$ plane, where $\sum$ is the surface density and $T_{\rm eff}$ is the effective temperature at that radius (Lasota, Hameury & Hure 1995). In the middle branch of the curve, the disk is thermally unstable. No stable physical states are accessible in this region (Lasota, Narayan & Yi 1996). When the mass accretion rate falls in the range corresponding to the above unstable branch in $\sum - T_{\rm eff}$ curve, the disk becomes unstable and forced to a "limit cycle" behaviour. According to this model, the outburst in the soft X-ray transients occurs when the accretion disk makes a transition from the lower cold state to the upper hot state in the characteristic 'S' curve. The disk outburst begins when the surface mass density exceeds a critical value. For a constant mass accretion rate, the type of outburst depends on the time required for the deposition of matter on the disk to create the surface density larger than the critical value and the viscous time required for the matter to diffuse inward and cross the critical mass density region.

The main difference between the outburst light curves of SXTs and the dwarf novae is the longer decay time scale for the SXTs In the SXTs, the bolometric luminosity due to the infall of accreted matter towards the compact object is mainly emitted in X-rays. King & Ritter (1998) have explained the light curves of SXTs by the disk instability model, taking into account the irradiation by the X-ray source during the outburst. Irradiation from the X-ray source prevents the disc from coming to its cool state till the accretion rate is reduced sharply. King & Ritter (1998) have shown that the X-ray light curve of the source is roughly exponential if the irradiation is strong enough to ionize all of the disk to the edge. If the emitted X-rays from the central X-ray source are too weak to ionize the disc, the light curve should decline linearly. The X-ray light curve of the various SXTs, which are thought to contain a black hole as the compact object, are interrupted by a secondary maximum during which the X-ray flux increases by a factor of 2 or more, followed by a linear or exponential decay. According to King & Ritter (1998), when irradiation begins, the increase in viscosity is more in the outer regions compared to the inner region of the disk, causing a block of extra mass to move inwards and resulting in a secondary outburst. Chen, Livio & Gehrels (1993) have suggested that the secondary maxima (glitch) in the light curves result due to the extra mass loss from the companion when illuminated by the X-rays from the bursting primary object. Augusteijn *et al.* (1993) interpreted the secondary maximum (glitch) arising due to the enhanced mass transfer from the companion resulting from the heating by X-rays from the primary source, after the outburst. Time delay of a few months or so occurs in the similar linear flow of matter from the companion to the X-ray emitting inner disk.

More detailed studies of the characteristics of the light curves of SXTs will provide valuable insight into the mechanism of the occurrence of the outbursts in these sources.

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