Discovery of a Very Fast Optical Activity in the X-Ray Source GX 339–4

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Introduction

Most galactic X-ray sources are compact objects (white dwarfs, neutron stars and maybe black holes) in binary systems. Matter coming from a normal companion star is driven onto the surface of the compact object where the release of gravitational energy powers the X-ray emission. The energy emitted at X-ray wavelengths ranges from 10^{35} to 10^{38} erg/s and a mass transfer rate of typically 10^{-11} to 10^{-8} $M_\odot$/year is enough to explain the X-ray luminosity. In most of the cases an accretion disk is formed around the compact object due to the angular momentum carried by the matter escaping the companion star. Recent investigations have shown that the accretion disks can be very large and that the heating of their surface by the X-rays emitted by the central source can make them very luminous.

X-ray astronomers usually distinguish between massive and low-mass X-ray binaries. In the massive X-ray binaries, the companion of the compact object is a giant hot star (OB type with surface temperature of 20,000–30,000° K). Its mass (10 to 20 $M_\odot$) is large compared to the mass of the compact object (1–2 $M_\odot$), and its optical – UV luminosity is $\sim 10^{38}$ erg/s. In this case, the optical emission from the disk itself (some 10^{36} erg/s) is difficult to detect. Optical variability is small and essentially due to the changes of aspect with orbital motion of the tidally distorted companion star. In the low-mass systems, the stellar companion has a mass equal to or less than the X-ray source yielding a very different picture. The disk becomes visible and often dominates the optical emission of the system. This kind of system is the most suitable to study the accretion disks, provided that it is possible to distinguish clearly the contributions of other likely sources, as the X-ray heated hemisphere of the companion and the surroundings of the X-ray source itself.

Variability

An almost universal feature of X-ray sources is the variability of their X-ray flux. Time scales of variations ranging from years to milliseconds are observed. Strictly periodic variabilities are common and are caused by three mechanisms:

- The orbital motion (a few hours to a few days).
- The rotation of the compact object (a few seconds to a few minutes). If the neutron star or the white dwarf has a strong enough magnetic field, matter will be driven along magnetic field lines down to the polar cap where the X-ray emission will take place. If the compact object rotates, an earth observer will then see X-ray pulsations due to the periodic crossing of the line of sight by the X-ray beam.
- The precession of the disk can shadow periodically the X-ray source (about 1 month).

Unperiodic random variability can also occur on a wide range of time scales. Bursts of some tens of seconds can be explained by instabilities in the accretion process or thermonuclear flashes on the surface of the neutron star. Some sources like Sco X-1 display a variability on time scales of minutes which is not quite well understood. Long-term (months to year) variations reflect in most cases changes in the accretion rate.

Three remarkable sources, Cyg X-1, GX 339-4 and Cir X-1 show very peculiar random variability. Their time behaviour is highly erratic on a time scale of seconds, and flares as short as some milliseconds have been observed. This activity is usually mathematically described by a shot-noise random process, in which the time-dependent flux is the result of the superposition of elementary narrow pulses randomly distributed in time. Unfortunately, this description, which is useful to compare the activity of different objects, is not very helpful to understand the underlying physics. Several mechanisms have been proposed: rotating hot spot in the inner parts of the accretion disk, hydrodynamical instabilities, transient magnetic structure, etc. But in our present state of knowledge, it is impossible to rule out one of these possibilities. These three X-ray sources have another common feature: the X-ray intensity has two preferred states, high and low. During the high state the spectrum has an excess of soft X-rays (< 3 keV) with respect to the low state. Theoretical models, built under the assumption that the compact object is a black hole (as it is thought to be the case for Cyg X-1), explain this bimodal behaviour as due to changes in the density, size and plasma properties of the innermost parts of the accretion disk which are thought to be, in this case, the X-ray emitting regions.

Optical Observations

The stellar companion of Cyg X-1 is massive and optically dominates the system, making the accretion disk hardly visible in the optical. Optical studies of the two other members of this class revealed a continuous spectrum with emission lines, but failed to detect any stellar absorption lines. They also showed that the brightness of the optical counterpart is variable by 2–3 magnitudes.

These two pieces of evidence indicate that they must be low mass binaries. Cir X-1 is very far away and absorbed in the optical ($B \sim 20$) making optical studies rather time-consuming. GX 339-4 is brighter ($V = 16$ to 18) and is thus a better choice. It was indeed on our target list in March 1981, during an observing run at the 3.6-m at La Silla. At the same time, J. Hutchings, A. Cowley and D. Crampton, visiting astronomers at Cerro Tololo, had planned to take some spectra of this object, but could not find the star anymore. Some days later, on March 6, we pointed the 3.6-m telescope and had the same surprise. The object had disappeared from the sky. The following night, a Schmidt plate was taken by M. Pizarro.

The object was found to be in an unreported faint state ($B \geq 21$). We warned our Japanese colleagues who maneuvered the X-ray satellite HAKUCHO and found that on April 7, the X-ray flux of GX 339-4 was below the limit of detection. Such large variations in the X-ray and optical fluxes are not unusual among X-ray transients and novae. They are thought to be due to an increase of matter accretion and thus of X-ray emission which in turn heats the companion star and the recently built accretion disk, producing the optical brightness jump. This confirmed that GX 339-4 is a low-mass system with most of the light coming from X-ray heating.

During another run at the 3.6-m telescope in infrared on March 24, we naturally pointed the telescope toward GX 339-4. We had another surprise; the star was back to a very bright state ($V = 15.4$), also unreported in the literature (see Fig. 1).

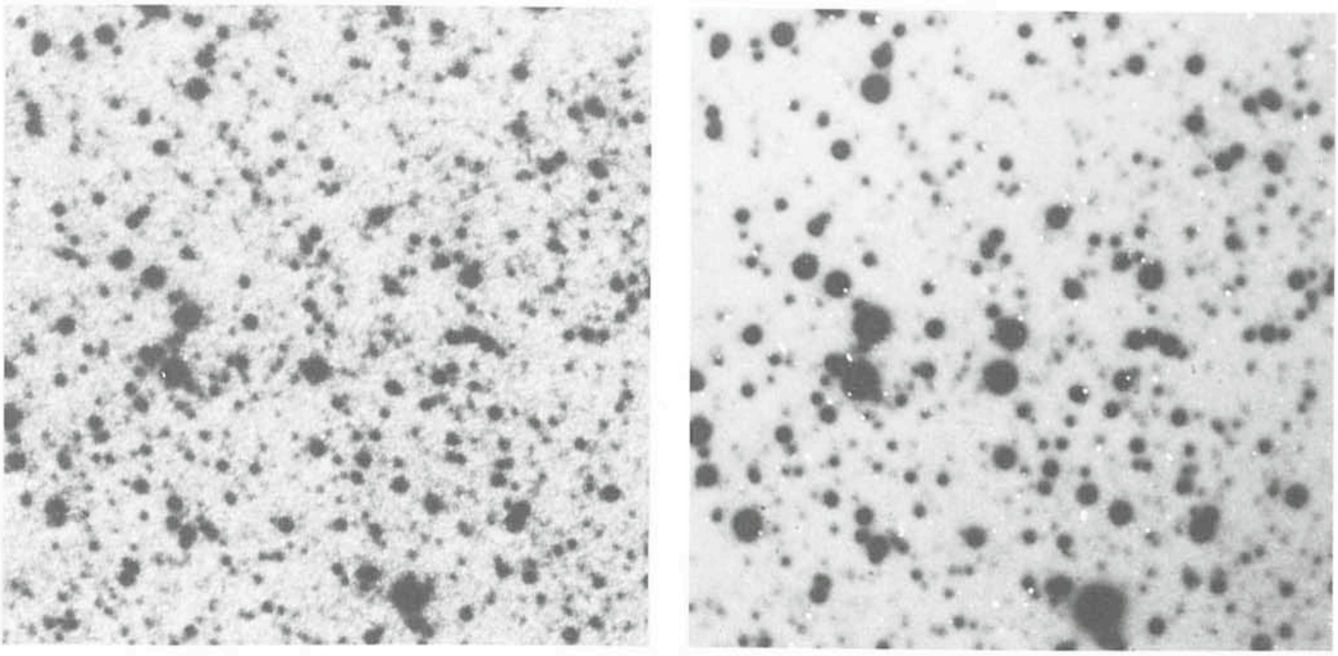

Fig. 1: *GX 339-4 field with the object at minimum (left) and at maximum (right).* Left: *enlargement from a 1-m ESO Schmidt plate (taken by G. Pizarro) in the blue (IIIa-J + GG385 filter) of a 90-min exposure taken on March 1981.* Right: *enlargement from a 3.6-m ESO prime-focus plate taken with the Triplet Adapter and the 4-cm McMullan electronographic camera with a B filter. A 90-min exposure, taken by H. E. Schuster, on 1 June 1981. The object is at the center. North is at the top, East to the left. The fainter star immediately to the NE of GX 339-4 has B = 19.5. The almost equally bright star farther South has B = 15.9.*

We undertook classical photometry and were a bit disappointed by the lack of accuracy of the measurements. The dispersion of the single integrations were far too large for the number of photons counted. We thus decided to further investigate the time behaviour of GX 339-4 making fast photometry observations.

On May 28 and 29, we used the 1.5-m Danish Telescope equipped with the Danish double beam (star/sky) photometer. We used the full response of two RCA 31034 GaAs red sensitive tubes. The star was kept centered in a 9 arcsecond diaphragm by the auto-guider system. Integration time was 10 milliseconds. These observations revealed soon the unprecedented activity of the optical flux (see Fig. 2). It took us some time to become convinced of its reality. The same observations made from time to time on an anonymous field star of similar brightness did not show any particular activity. The data from

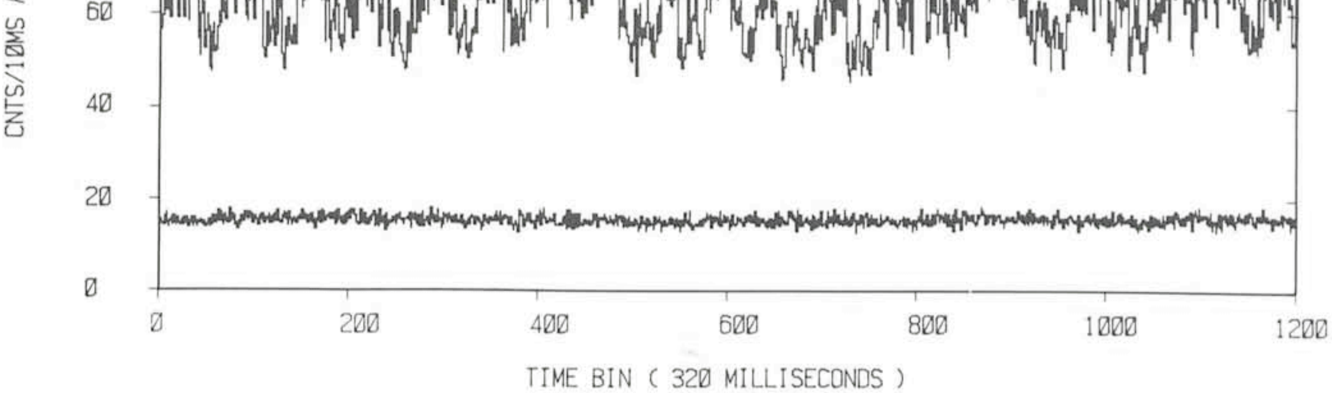

Fig. 2: *A part of the optical lightcurve of GX 339-4 in white light (3400–9000 Å). 10 millisecond data have been averaged in 320 millisecond bins. The sky background recorded by the other photometric channel is also shown. Typical error bar is indicated. The high-amplitude, 20-second quasi-periodic oscillations are clearly visible as well as the large flaring activity.*

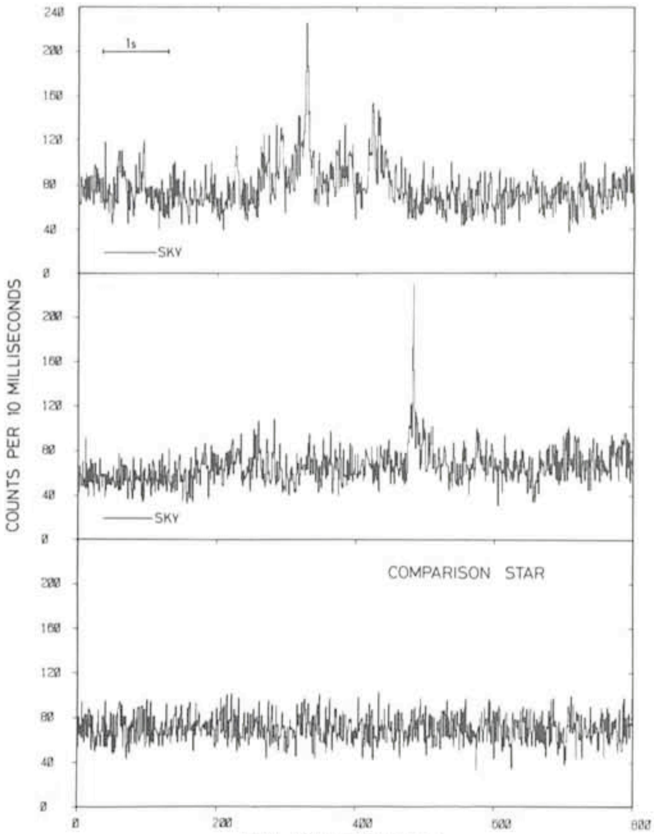

Fig. 3: *A sample of very short (10 to 30 milliseconds width) optical flares from GX 339-4. Data are shown with 20 millisecond time bins. The companion star data (of same integrated brightness as GX 339-4 in the wavelength range 3400–9000 Å) give an estimate of the actual noise. Sharp flares may occur alone or accompanied by other small ones. Two series of flares ending with a large one are shown (bottom).*

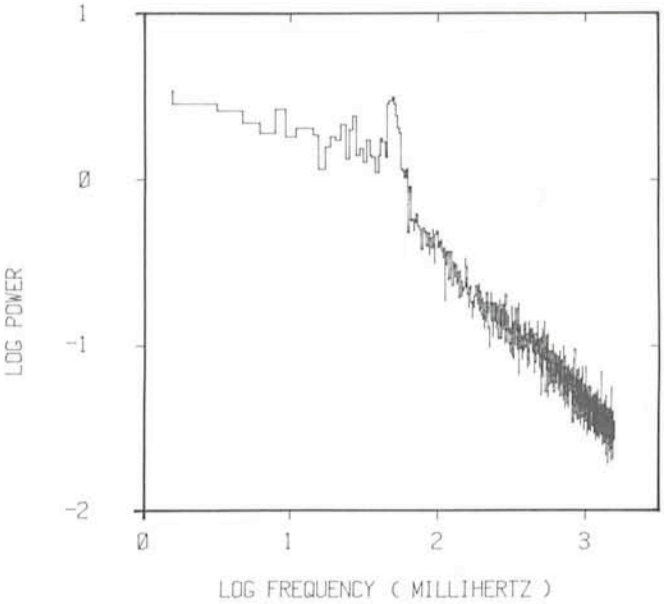

Fig. 4: *The average Fourier Transform of GX 339-4 computed on data averaged in 320 millisecond bins and plotted in log/log scale. The power spectrum is almost flat for frequencies below 0.05 hertz (P = 20 seconds) and displays a 1/f slope at high frequencies. The quasi-oscillations at P = 20 seconds clearly appear as a hump located at the knee frequency of the power spectrum.*

the other photometer channel (sky) were also normal and finally weather conditions and seeing were excellent.

The large fluctuations clearly visible on Figure 2 were readily found to be 20 second quasi-oscillations with a full amplitude of 30 to 40 %. Secondly, a careful look at the data stream with full time resolution revealed the presence of flares as short as 10 to 20 milliseconds, during which the flux of the object can be multiplied by a factor of 2 to 5! (see Fig. 3). In less than 3 hours of observations, we detected about 900 flares at a 6 σ level. Some large flares were accompanied by other smaller flares before and after, and some tend to show a decay of the total flux just after.

A statistical analysis of the data proved them to be consistent with a shot noise process. Few papers study the flaring activity of GX 339-4 and we had to compare mainly with the X-ray behaviour of Cyg X-1, also described in terms of shot-noise and widely studied. In fact, the resemblance is striking. The power spectrum shown in Figure 4 is very similar to that of the X-rays of Cyg X-1 reported by Nolan *et al.* (1981, *Astrophysical Journal* **246**, 494). They both show an almost flat part at low frequencies, a 1/f slope at high frequencies and the knee frequency is the same in both cases. Finally, the only difference is the presence of the 20 seconds quasi-oscillation in the optical of GX 339-4.

Analysis of the auto-correlation function revealed the same decay times as for Cyg X-1. The striking resemblance between the time behaviour of the opticals of GX 339-4 and the X-rays of Cyg X-1, and the fact that, at the time of the optical observations, X-ray observations made with the Ariel 6 satellite (Ricketts, private communication) showed that GX 339-4 was in a low and flaring state, prove that X-ray and optical flares have close origin. However, the sharpness of the optical flares raises some problems. A 10-millisecond time structure implies a typical dimension of 3,000 km for the optically emitting region. Assuming a Rayleigh-Jeans spectrum for the optical emission and a distance of 4 kpc, the temperature of the emitting region is found to be 5 10^9 °K. Such a high temperature cannot be due to X-ray heating, but is consistent with the electronic temperatures derived for the innermost X-ray emitting parts of the disk by theoretical models of Cyg X-1 in the low state. The optical flares probably come from this region, but the exact emitting mechanism (bremsstrahlung, cyclotron emission) is unknown.

The origin of the 20-second quasi-oscillations is not clearer. The fact that they have a mean frequency equal to the knee frequency common to GX 339-4 and Cyg X-1 indicates that the mechanism responsible for the quasi-oscillations is physically related to the one producing the random X-ray and optical flares. If the mechanism at work in GX 339-4 is similar to the one present in a dwarf nova during outbursts (nonradial oscillations of disk annuli), the large amplitude indicates that the disk is small and ring-shaped. A typical radius is 11,000 km, a size similar to the one derived from the flare time scales and consistent with the size of the outer cool parts of accretion disk models of Cyg X-1. However, instabilities of the very hot inner parts of the disk, theoretically described by Shakura and Sunyaev (1976, *Monthly Notices of the Royal Astronomical Society* **175**, 613) could also trigger the quasi-oscillations.

We have certainly witnessed during those three months the onset of mass transfer, and the reformation of an accretion disk. We plan to carry on optical studies of this very interesting object in order to see whether the remarkable time behaviour found at maximum light is also present when the star has a normal brightness and how it changes with X-ray state. Correlated optical and X-ray observations should give much insight on the physics of this peculiar class of X-ray source.