No. 23 – March 1981

Simultaneous Optical/X-ray Bursts

Jan van Paradijs, Astronomical Institute, University of Amsterdam

Introduction

The majority of the bright galactic X-ray sources are mass-exchanging binary stars in which a normal companion star is transferring matter to its compact companion, in most cases a neutron star. A neutron star is an extremely dense concentration of matter: a mass equal to that of the sun (diameter 1.4 million km) is concentrated in a sphere with a diameter of only about 20 km. The gravitational force near such a star is very strong, and, upon falling on the neutron star surface, the infalling matter reaches a velocity of about half that of light. The kinetic energy of this matter is transformed into heat (the temperature reaches values in excess of 10 million degrees) and radiated in the form of X-rays.

Almost all bright X-ray sources belong to one of the following two groups:

- Massive X-ray binaries. The companion star of the neutron star is more massive than about 10 $M_\odot$. These systems are young. The (rotating) neutron star has a (non-aligned) strong magnetic field, which shows up in pulsations of the X-ray emission.
- Low-mass X-ray binaries. The mass of the companion star is less than 1 $M_\odot$. Many of these systems emit X-ray bursts, which are the result of thermonuclear runaway processes in the freshly accreted surface layers of a neutron star.

X-ray pulsations and X-ray bursts have never been observed from the same source. This agrees with the theoretical expectation that a strong magnetic field inhibits unstable nuclear burning.

During simultaneous observations of X-ray burst sources (using X-ray satellites and optical telescopes) it was discovered that coincident with X-ray bursts a sudden increase of the optical brightness takes place.

In this article I will discuss these coincident X-ray and optical bursts, and show that such events contain information on the structure of low-mass X-ray binaries.

Observations of Optical Bursts

The first simultaneous X-ray and optical observations of X-ray bursters were made during the summer of 1977. The X-ray observations were made with the SAS-3 X-ray satellite by a group of astronomers at MIT (W. Lewin, J. Hoffman and co-workers). Optical astronomers from many countries participated in this "burstwatch", and in some cases X-ray bursts were discovered from the source 4U1837+05 (Serpens X-1) during optical coverage. (A "hit" in burster jargon). In none of these cases was there any significant increase of the optical signal during the X-ray burst, and only upper limits to the amount of energy in a possible optical burst could be given. Astronomers at the observatories of Asiago (Italy), Crimea (Soviet Union) and Kagoshima (Japan) found that less than one part in ten thousand of the X-ray burst energy was emitted in a possible optical burst.

During the summer of 1978, J. Grindlay (Harvard) and J. McClintock and C. Canizares (MIT) made a new attempt using a very sensitive photometer at the 1.5 m telescope at Cerro Tololo. The X-ray observations were again made by the MIT group using SAS-3. On June 2, 1978, the first simultaneous optical/X-ray burst was detected from the source 4U/MXB 1735–44 (see Fig. 1).

The amount of energy in the optical burst was much smaller than the upper limit found during the 1977 observations. The ratio f of the amount of energy in the optical and X-ray bursts was 2×10^{-5}. An extremely important result of this observation was that the optical signal was delayed with respect to the X-ray burst by 2.5 to 3 seconds.

Later in the summer of 1978 an optical burst was detected from Ser X-1 by J. Hackwell, D. Gehrz, and G. Grasdalen of the University of Wyoming, using a 90 inch telescope (which was built for infrared observations). An X-ray burst was detected simultaneously with SAS-3. The ratio f turned out to be even smaller than for MXB 1735-44: only 3×10^{-6} of the X-ray burst energy turned up in the optical burst. This optical burst also was delayed, by ~ 1.5 seconds, relative to the X-ray burst.

After it was known that optical bursts do exist it was worthwhile to make a large scale observational attack, to get a better insight in their properties. Since X-ray bursts occur at intervals of hours, but sometimes do not show up for much longer periods, many nights of observing time are needed for a reasonable chance to have a "hit". During the summer of 1979 the Danish astronomer H. Pedersen of ESO spent 20 nights of observing time with the Danish 1.5 m telescope on La Silla on observations of optical bursts (*The Messenger* No. 18, 1979, p. 34).

SAS-3 hat reentered the earth's atmosphere in April 1979, but fortunately a new Japanese satellite, "Hakucho", had been launched, with which the X-ray observations were performed. The Japanese team was headed by M. Oda of the Tokyo Institute for Space Research. The X-ray and optical observations were coordinated by the SAS-3 group at MIT (L. Cominsky, G. Jernigan, W. Lewin and J. van Paradijs).

These observations were very successful: 15 optical and 16 X-ray bursts were detected from the source MXB 1636-53; in five cases a "hit" occurred.

To finish this chapter: during the summer of 1980, H. Pedersen, C. Motch and J. van Paradijs observed 25 optical bursts, four of which were detected in two or three colours simultaneously. In 6 cases there was a "hit" with Hakucho. It is still too early to give details on these most recent results.

In the following we will see how these optical burst observations can be used as probes of the structure of low-mass X-ray binary systems.

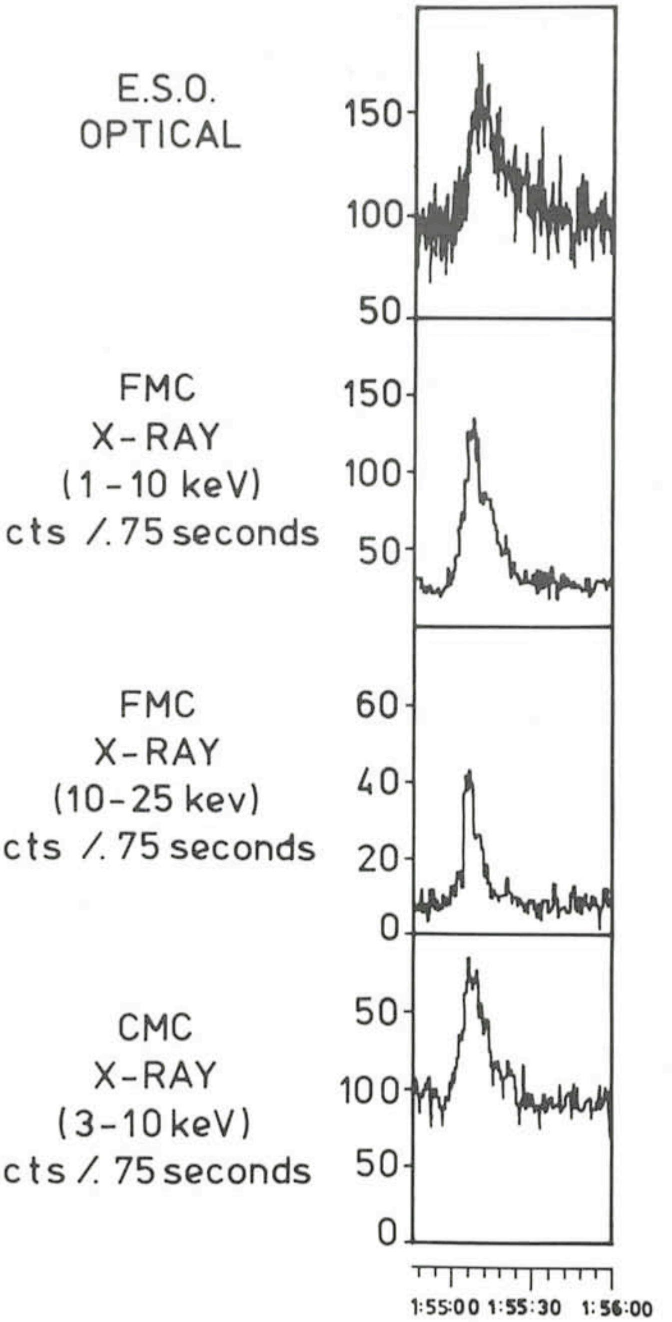

Fig. 1: *Simultaneous optical/X-ray burst observed on June 28, 1979 from MXB 1636-53. The optical burst (upper panel) was observed by Holger Pedersen with the Danish 1.5 m telescope at ESO. The X-ray burst was observed in several X-ray detectors on board the Japanese satellite Hakucho. The Hakucho team is headed by Minoru Oda. Time given is UT.*

Interpretation of Optical Burst Observations

Optical bursts contain only a very minute fraction (~ 10^{-5}) of the energy emitted in X-ray bursts. Yet this small amount is many thousand times larger than what is expected from a simple extrapolation of the observed X-ray spectrum in the burst towards the longer wavelengths in the optical passband. In combination with the observation that all observed optical bursts are delayed, this leads to the idea that they are the result of a transformation of part of the X-ray burst energy into optical radiation. The basic picture is that matter in the vicinity of the X-ray burst source absorbs a fraction of the infalling X-rays, is thereby heated, and as a consequence emits radiation at longer wavelengths.

The total pathlength for the X-rays which first travel to the absorbing matter, and of the subsequently emitted optical photons is longer than that of the X-rays which reach the observer directly. The delay of the optical signal is a natural consequence. A further contribution to the delay may be expected because the absorption of the X-rays and the reappearance of the optical photons from the absorbing medium takes a finite time. Detailed calculations show that this contribution to the delay is probably a few tenths of a second only.

Because of the finite size of the absorbing body, the optical emission from different parts of it will suffer different delays. Therefore the optical signal is not only delayed, but also smeared out. The precise values of the delay and the smearing depend on the size and shape of the region where the X-rays are reprocessed. From the observed values of delay and smearing of the optical signal one may, in turn, hope to obtain information on the location of the absorbing matter.

A method to extract this information consists of calculating synthetic optical bursts for several assumed distributions of the absorbing matter, and comparing these with the observed optical and X-ray data. In order to calculate a theoretical optical burst, a network of small surface elements is defined on the surface of the reprocessing body. Each element reflects part of the infalling X-rays and absorbs the rest. The resulting temperature of the surface element depends on the X-ray luminosity, the distance of the surface element to the X-ray source and the angle under which the X-rays reach the element. The fraction of the absorbed X-ray energy which reappears as optical photons depends on the temperature T of the surface element and on the wavelength of the photons. For high values of T most of the radiation is reemitted in the ultraviolet part of the spectrum, which cannot be observed with ground-based instruments.

By arranging the contributions of all surface elements according to their delayed arrival times we can reconstruct the profile of an optical burst as it is expected for an infinitely sharp X-ray burst. Since a real X-ray burst has a finite duration, the shape of the optical burst will be a convolution of this calculated optical response profile with the profile of the X-ray burst.

Within the framework of a low-mass X-ray binary model, obvious locations for the production of an optical burst are the surface of the companion star and an accretion disk. The latter is formed around the neutron star, because the matter which leaves the companion cannot reach the neutron star directly. Due to the rotation of the binary system, this gas flows in almost circular orbits around the neutron star. Because of mutual friction, the gas slowly spirals inward, creating a disk-shaped configuration.

The radius of the companion star is much smaller than its distance to the neutron star. Therefore the differences in the pathlength of absorbed X-rays and subsequently emitted optical photons are relatively small. Thus one expects that for optical bursts originating at the companion star, the smearing will be small compared to the average delay. For a disk, on the other hand, one expects that the smearing and delay are approximately equal. This gives us a possibility to decide where in the binary system the optical burst originates.

Detailed calculations by London, McCray and Auer (JFLA, Boulder) have shown that the optical reemission can be closely approximated by a Planckian radiation curve. For a fixed wavelength the brightness then only depends on the temperature of the radiating body. This temperature, in turn, depends on the intensity of the infalling X-rays. In this way a relation can be derived between the brightness of the X-ray source and the optical brightness of a surface element. If we wish to apply such a relation in a comparison of the observed optical and X-ray bursts, we have to realize that the temperature in the Planck function is an average over the different parts of the absorbing region.

Tentative Time-table of Council Sessions and Committee Meetings in 1981

May 4	Committee of Council
May 7 – 8	Finance Committee
May 7	Scientific Technical Committee
May 8	Users Committee
May 21 – 22	Observing Programmes Committee
June 4	Council, Stockholm
November 10	Scientific Technical Committee
November 11 – 12	Finance Committee
November 13	Committee of Council
Nov. 30 – Dec. 1 – 2	Observing Programmes Committee
December 3 – 4	Council

All meetings will take place at ESO in Garching, unless stated otherwise.

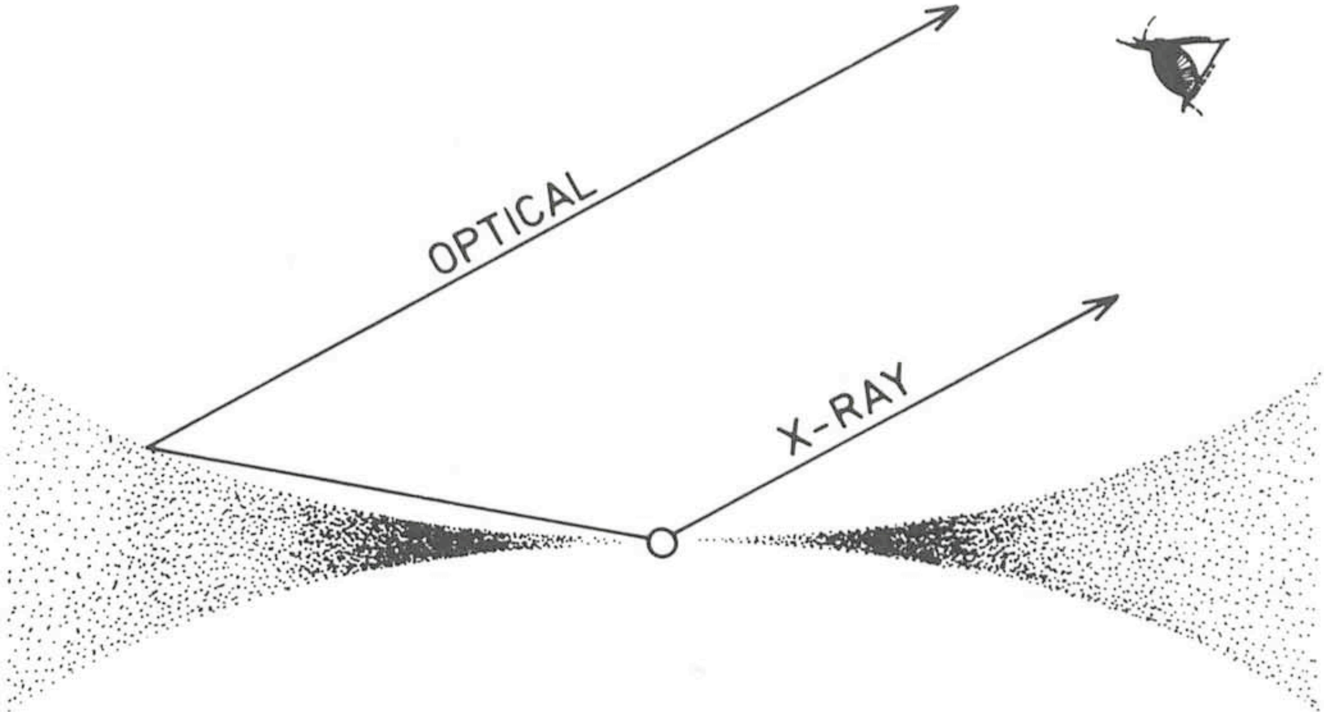

Fig. 2: *Schematic representation of the optical burst as originating from reprocessing of X-rays in an accretion disk surrounding the X-ray source.*

In an analysis procedure devised by G. Jernigan (MIT) the optical burst is considered a deformed, delayed and smeared version of the X-ray burst. The smearing is assumed to have a rectangular time dependence. The above described calculations of synthetic optical bursts indicate that this is a reasonable first approximation. The deformation is the result of the different relation of the X-ray and optical brightness to the (average) temperature of the reprocessing body.

Results

For one of the coincident optical/X-ray bursts observed in 1979 (Fig. 1), the data are of sufficient quality to determine the delay and smearing, and the temperature variation through the optical burst. For the delay and smearing, values of 3.2 ± 0.1 sec and 3.2 ± 0.4 sec were found, the maximum temperature of the reprocessing body equals 56,000 K. For two other bursts from this series, only the delay could be determined. These two optical bursts show the same delay.

These results, in particular the large value of the smearing relative to the delay, indicate that *the optical bursts originate in an accretion disk.* This is supported by the fact that all three analysed bursts yield the same value of the delay. This is expected for a circular disk: viewed from the observer such a disk always has the same location relative to the neutron star, independent of the orbital position of the companion star (Fig. 2). For optical bursts from the surface of the companion star one would expect a variable delay because of the changes in the relative positions of the observer and the binary components (unless we happen to view the binary star from a direction perpendicular to its orbital plane, or if the bursts would have occurred at the same part of the orbit).

The value of the delay is related to the size of the disk, and – indirectly – to the size of the binary system. For a given diameter of the disk the delay will be determined by the radial dependence of the contributions to the optical burst intensity (and on the angle under which the disk is seen by the observer). If the contributions from the outer parts of the disks dominate (the disk is then more nearly a ring) the delay will be maximal. The other way around, for a given delay D we may conclude that the radius of the disk is at least 0.5 D light seconds. For MXB 1636–53 this yields a minimum disk radius of 1.8 light-seconds.

The size of the disk is related to the distance between the binary components, since the disk is located inside the Roche lobe around the neutron star. This Roche lobe is a critical surface in the binary system, consisting of two separate parts, one around each of the binary components, touching each other in one single (Lagrangian) point. Particles inside this surface are unambiguously related to one of the stars, particles on or outside this surface can freely move around both stars. It is because the companion star fills its Roche lobe that matter can be transferred (through the Lagrangian point) towards the neutron star. The extent to which the accretion disk fills the Roche lobe around the neutron star is uncertain; probably its radius is between 70 and 100 per cent of that of the Roche lobe. Thus the radius of the neutron-star Roche lobe of MXB 1636–53 will be larger than 1.8 light-seconds.

The size of the Roche lobe relative to the distance between the stars depends only on the mass ratio q of the two components. For a given value R_x of the neutron-star Roche lobe the size of the Roche lobe of the comparison star is therefore a function of q only.

Mass determinations of neutron stars in massive X-ray binaries and in the binary radio pulsar show that it is reasonable to take for the neutron star mass a value of 1.4 $M_\odot$. Then for given R_x a choice of q fixes both the mass M_c of the companion and the radius R_c of its Roche lobe; stated differently, a fixed value of R_x defines a relationship between M_c and R_c.

Very probably the companion of the neutron star is a late-type main-sequence star. (In a few cases the companion of a burst source became visible after the X-rays – which dominate the optical brightness through heating – went off. In all cases the companion star turned out to be a K-type main-sequence star.) As mentioned above, in order to keep the mass transfer going, the companion has to fill its Roche lobe. Since main-sequence stars obey a well-defined mass-radius relationship, we find for a given value of R_x just one value of the companion star mass for which this is the case.

Optical burst observations only provide a lower limit to R_x, therefore we can only estimate a lower limit to M_c. For MXB 1636–53 the companion star turns out to be more massive than 0.4 $M_\odot$.

From the ratio of optical to X-ray burst energies one can, in principle, determine which fraction of the X-rays is intercepted by the disk. This would provide an estimate of the thickness of the disk, as seen from the neutron star. A problem here is that the observed optical brightness has to be corrected for the effect of interstellar extinction. If we adopt the interstellar extinction as observed for stars in the same general direction as MXB 1636–53, we find for the thickness of the disk an (uncertain) value of ~ 10 degrees.

An independent estimate of the diameter of the disk can be made from a comparison of the observed optical brightness and the surface brightness of the disk, which is determined by its (average) temperature T. (Here again we face the problem of interstellar extinction.)

Let us assume, for simplicity, that the apparent area of the disk is a circle with radius R. The optical luminosity L_{opt} of the disk is then given by

$$L_{opt} = 4\pi d^2 f_{opt} \qquad \text{and also by}$$
$$L_{opt} = \pi R^2 B_{opt}(T).$$

Here d is the distance between the observer and the X-ray source, f_{opt} is the observed optical flux, and B_{opt} (T) is the surface brightness of the disk (Planck function). These two expressions determine the angular diameter of the disk as seen from the earth.

There are good indications that the average maximum burst luminosity is the same for all bursts, and is approximately equal to the so-called Eddington limit. Therefore the distance to MXB 1636–53 can be estimated from the apparent maximum flux of its X-ray burst; we then get for the distance a value of ~ 5 kpc, and for the radius R of the apparent projected disk area ~ 0.5 light-seconds. This reasonably agrees with the size estimated from the delays of the optical bursts.

Applications for Observing time at La Silla

PERIOD 28

(October 1, 1981 to April 1, 1982)

Please do not forget that your proposals should reach the Section Visiting Astronomers **before April 15, 1981.**