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THE COS-B X-RAY OBSERVATIONS OF X-RAY BINARIES

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Abstract. The observational information on X-ray binaries that was collected with the 80 cm² auxiliary X-ray detector onboard the COS-B gamma-ray satellite is reviewed. The results illustrate that in the study of X-ray binaries observations of long duration are extremely effective, even when using a small instrument.

1. Introduction

The aim of the COS-B mission was to study the sky in 70-2000 MeV gamma-rays. The main instrument onboard the satellite (Scarsi *et al.* 1977) was a spark chamber with a sensitive area of 50 cm² at 500 MeV. COS-B was launched from NASA's Western Test Range on 1975 August 9. To minimize interruption of the observations by Earth occultations, passage through the radiation belts and the effects of atmospheric albedo gamma-rays, the satellite was placed in a highly eccentric orbit with an initial apogee of 10⁵ km and a period of 1.5 days. After an operational life considerably in excess of its two-year planned lifetime the instrument was switched off on 1982 April 25. The satellite was operated by a consortium of research institutes calling itself the Caravane Collaboration (see Taylor and Wills 1981). Overviews of the results of the gamma-ray observations of this highly successful experiment were given by, *e.g.*, Bignami and Hermsen (1983) and Bloemen (1989). The purpose of the present paper is to provide an overview of a by-product of the mission, namely, the observations of X-ray binaries performed with a small X-ray detector that was onboard COS-B for a different purpose.

1.1. THE "PULSAR SYNCHRONIZER" PHILOSOPHY

The rationale to put a small X-ray detector onboard a gamma-ray satellite was to provide "pulsar synchronization" (Boella *et al.* 1974). The idea was that the "pulsar synchronizer" such as the COS-B X-ray detector was called would provide information on the frequency and phase of pulsations from rotation-powered pulsars simultaneously with the gamma-ray observations, thus allowing to search the gamma-ray data for the pulsar with much greater sensitivity. This "pulsar synchronizer philosophy" for the COS-B X-ray detector determined its characteristics. X-ray spectral resolution was unnecessary as the instrument was intended as a timing device, and millisecond time resolution was one of the requirements (although the duty cycle of the high time resolution data was very low, see below). As it turned out, except for the Crab pulsar, no rotation-powered pulsars were detected with

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both the X-ray and the gamma-ray instrument, so that the COS-B X-ray detector was not used for its originally intended purpose. As an instrument for studying X-ray binaries, however, it proved to be very useful.

1.2. THE COS-B X-RAY DETECTOR AS AN INSTRUMENT FOR X-RAY ASTRONOMY

The significance of the COS-B X-ray observations for X-ray astronomy can be traced back to the one aspect that at the time made them unique: their long durations. The requirements of gamma-ray astronomy, with its low photon rates, made it necessary to perform observations which lasted between about 20 days in the early days of the mission, to up to more than 100 days near the end. During these observations, the satellite, including the X-ray detector, remained pointed to the same position in the sky. It soon became apparent that the capability to perform long, pointed X-ray observations was of great significance in understanding the behaviour of the bright X-ray sources accessible to the relatively small COS-B X-ray detector. This was true even though the observations were interrupted for approximately 0.5 days once during each 1.5-day satellite orbit due to interference of charged particles in the Earth's radiation belts and Earth occultation of the X-ray source.

The technical capabilities of the COS-B X-ray detector (Boella *et al.* 1974), dictated as they were by the requirements of its use as pulsar synchronizer, were limited even by the standards at the time of COS-B's launch. The instrument, a simple collimated proportional counter, had an effective area of 80 cm^2 , an order of magnitude less than the detectors onboard the Uhuru satellite which had been used to map the entire X-ray sky five years earlier. Its collimator had a very wide field of view of 20° across (Figure 1, *left*), matched to that of the gamma-ray instrument. This meant that, especially in the crowded galactic-center region (Section 4.2), source confusion was unavoidable. The high apogee of the satellite orbit, while making it possible to monitor a given source uninterruptedly for about a day, also entailed a high background rate, caused by detections of charged particles in the X-ray instrument. After onboard rejection of these charged-particle events by the standard techniques of pulse-shape discrimination and anti-coincidence vetoing, a *residual* charged-particle background rate of about 100 counts/second had to be dealt with. This compared to typical X-ray source count rates of between a few and a few hundred counts/second.

Although the COS-B X-ray detector provided data with a time resolution of 0.2 milliseconds, this timing accuracy was only attained for the first four events (in many cases, charged particle background events) detected every 0.8 seconds. As the total (source + background) count rates were between 100 and a few 100 counts/second, the duty cycle of these data was low and variable, a few percent at most, and depended on the count rate. Therefore, the high time resolution data were in practice only useful in the study of (nearly) strictly periodic phenomena, of which many cycles could be averaged together. This was of course exactly what the instrument had been designed for. A second type of data, with a low time resolution,

Fig. 1. Photon energy response (*top*) and geometric efficiency (*bottom*) of the COS-B X-ray detector (after Bignami *et al.* 1975).

was generated simultaneously with the high time resolution data with the aim of monitoring the performance of the instrument. In a cycle with a duration of about 100 seconds, four different event rates, each integrated over about 25 seconds, were recorded. One of these four was the rate of X-ray events (contaminated with the 100 counts/second residual charged-particle background), the other three consisted of various different charged-particle rates. Consequently, these low resolution data had a duty cycle of about 25%.

The instrument was sensitive to photons in the 2–12 keV band (Figure 1, *right*), and did not provide any information about the X-ray spectrum. Consequently, all scientific results of the COS-B X-ray detector involved studies of the time variability of the X-ray intensity of the sources.

Although the constraints of the COS-B mission provided an excellent opportunity to monitor the evolution of the X-ray intensity of bright X-ray sources on time scales of days to weeks, time scales which had rarely been accessed previously, these same constraints were also the reason that during many of the COS-B “pointings” no bright X-ray source was in the field of view of the X-ray detector. In some cases, however, the very wide field of the gamma-ray instrument allowed to slightly offset the satellite from the originally intended pointing direction in order to ensure optimal detection of a bright X-ray source in the X-ray detector, without jeopardizing the prime objective of mapping the gamma-ray sky.

The main problem in the reduction of the X-ray data was the accurate removal of the high, and variable, residual charged-particle background. For this, the many observations of, from the point of view of the X-ray experiment, “empty fields”, came in good stead. Using these observations, it was possible to show that on time scales in excess of 100 seconds, and as long as the charged-particle background did not vary by large factors, there existed a good correlation between the residual background rate in the X-ray channel and the “raw” background rate as monitored by the pulse-shape discriminator. The empty-field observations were used to derive correlation formulae between the two rates, which were then employed to subtract the residual background in observations where an X-ray source *was* present in the field of view of the X-ray detector. This technique only worked when the charged-particle background was relatively steady; data obtained during charged-particle storms (related to solar events), which could last from days to weeks, were impossible to recover.

The correlation parameters used in the correction formulae showed an evolution with time through the life of the instrument, which was probably due in part to a change in the character of the charged-particle population related to the advance of the solar cycle, and partly to an evolution of the X-ray detector characteristics. The evolution of detector performance was independently monitored by observation of an onboard $^{241}\text{Am-Sr}$ calibration source in the 12–16 keV band. However, these calibration measurements were affected by the charged-particle background in a similar way as the X-ray observations themselves. Another check on the instrumental sensitivity was obtained by repeated observations of the Crab nebula,

which is a standard calibration source in X-ray astronomy, as it is assumed to emit X-rays at a constant rate.

1.3. X-RAY BINARIES

Apart from the Crab nebula, all celestial X-ray sources outside the solar system bright enough to be observed with an instrument such as the COS-B X-ray detector are X-ray binary systems, in which a more or less normal “donor” star is transferring matter to a compact object, usually a neutron star, but in some cases a black hole. The gravitational energy released when the matter accretes onto the compact object provides the energy for the emission of large amounts of X-rays (up to $\sim 10^{38}$ erg/second), which are generated by thermal processes in the $\sim 10^8$ K accreting matter.

Two broad classes of X-ray binaries can be distinguished. In *high-mass* X-ray binaries (HMXB), the donor star has an early type (OB supergiant or a B emission star) and a mass in excess of $10 M_{\odot}$. *Low-mass* X-ray binaries (LMXB) characteristically contain a companion with a mass below $1 M_{\odot}$, which may be a main-sequence star, a red giant or a white dwarf. In LMXB the mass transfer is normally caused by the companion star overflowing its critical gravitational potential surface (the Roche lobe), which can in turn be caused by either an evolutionary expansion of the star, or a shrinking of the binary orbit and the critical lobe. Matter transferred in this way carries a considerable amount of angular momentum with respect to the compact object, and forms a flat, rotating disk around it, the accretion disk, from which it gradually accretes onto the compact object. A similar process of mass transfer also occurs in some HMXB, but in these systems there exists an alternative possibility: The strong radiation-pressure-driven stellar winds characteristic of early-type stars can transfer considerable amounts of matter to the compact object. Mass accreted from a stellar wind probably has much less angular momentum with respect to the compact object and it is likely that it can be accreted without first forming an accretion disk. Combinations of the two mass-transfer mechanisms (“focused wind”) can also occur.

Periodicities which show up in the X-ray intensity of X-ray binaries are caused by the orbital motion, the neutron-star spin, and, more speculatively, by various kinds of precessional motion which might occur in these systems. Known orbital periods range from minutes to tens of days; known neutron-star spin periods (in X-ray binaries) from less than a tenth of a second to hundreds of seconds; precession periods are usually invoked to explain periodicities longer than the orbital period. The COS-B X-ray detector was particularly suited to study the orbital modulation in bright X-ray binaries on a cycle-to-cycle basis, and the pulsations in X-ray intensity caused by the neutron-star spin by averaging together relatively large numbers of cycles.

Apart from periodic phenomena, many X-ray binaries show irregular variations on a wide range of time scales. The faster of these phenomena, such as the quasi-periodic oscillations in bright LMXB (see van der Klis 1989) were beyond the

capabilities of the COS-B X-ray detector. On time scales of days to weeks, both high-mass and low-mass X-ray binaries show intensity variations (*e.g.*, the on-off cycles in Sections 3.1 and 3.2; the “dips” in Section 4), which are believed to be caused by variations in the amount of matter that is transferred from the donor star to the vicinity of the compact object. The constraints of the COS-B mission provided an excellent opportunity to closely follow the X-ray intensity evolution in X-ray binaries on these time scales as well.

2. Cygnus X-3

Cygnus X-3 was a unique and enigmatic X-ray binary at the time of the COS-B mission, and it remains so up to the present day (see Bonnet-Bidaud and Chardin 1988 for a review). The source is bright in X-rays, and shows a smooth X-ray intensity modulation with a period of about 4.8 hours which, because of its relative stability (see Section 2.3), is generally believed to be due to the binary orbital motion. Cygnus X-3 is a radio source which occasionally shows giant radio outbursts (flux densities of 20 Jy at 2.7 and 10 GHz; Gregory *et al.* 1972, Geldzahler *et al.* 1983, Spencer *et al.* 1986) and shows an axially symmetric morphology both on milliarcsecond (Molnar *et al.* 1988) and arcsecond (Strom *et al.* 1989) scales.

Much about this system is still unclear. One of the reasons for this is that, because Cygnus X-3 is located at a distance of roughly 10 kpc (Dickey 1983), and in the galactic plane, it can not be observed in the optical band so that no optical spectroscopy is possible. The source can be detected in the near infrared (Weekes and Geary 1982; it is also a far infra-red source, *e.g.*, Katz *et al.* 1984) and advances in infrared instrumentation have recently made near-infrared spectroscopy feasible. The near-infrared spectrum shows broad variable emission lines reminiscent of those of a Wolf-Rayet star (van Kerkwijk *et al.* 1992), which seem to indicate the presence of a dense stellar wind. This wind might be related to both the X-ray light curve formation (Section 2.2) and the slow increase of the orbital period of the system (Section 2.3). Another reason for Cyg X-3's enigmatic nature is that there is no other source quite like it. This of course suggests that it may be a “missing link” in X-ray binary evolution representing a short-lived stage in the development of such a system.

The nature of the companion star is unknown; from the short orbital period, it must be small ($<10^{11}$ cm): it could be a red dwarf, a white dwarf, or a helium main-sequence star. In the first two cases, Cygnus X-3 would be a LMXB, in the latter case, it could be a HMXB. The observations of van Kerkwijk *et al.* (1992) may favour the latter possibility, but the dense stellar wind might conceivably also be produced in a different manner from the standard Wolf-Rayet mechanism.

There are no firm indications as to whether the compact object is a neutron star or a black hole. Both accretion onto a compact object and rotational slow-down of a millisecond pulsar (Basko *et al.* 1974) have been proposed as the primary energy source powering the strong ($\sim 10^{38}$ erg/second) X-ray emission, and a large

Fig. 2. A sample X-ray light curve of Cygnus X-3 as obtained during one satellite orbit with the COS-B X-ray detector. Approximately 120 such light curves were obtained during four extended pointings to Cygnus X-3 (after van der Klis and Bonnet-Bidaud 1982; reprinted from *Astron. and Astrophys. Supp.*).

number of different models has been proposed for the generation of the smooth X-ray light curve. Most of these models involve scattering of the X-rays in ionized matter surrounding the X-ray source in a stellar wind (Pringle 1974, Davidsen and Ostriker 1974), a hollow shell (Milgrom 1976) or a corona associated with an accretion disk (White and Holt 1982).

There exists a large number of claims that Cygnus X-3 is a strong source of gamma-rays in the 100 MeV, and in the GeV, TeV and PeV ranges, and even of hitherto unknown particles ("cynnets") (see Turver 1987, Bonnet-Bidaud and Chardin 1988, and references therein). According to some authors (*e.g.*, Hillas 1984) the entire cosmic-ray flux in our galaxy could originate in Cygnus X-3. There is no general agreement as to the reality of these claims (see Chardin and Gerbier 1989 and Weekes 1992 for reviews). Some recent work has not confirmed earlier detections in these bands (*e.g.*, O'Flaherty 1992).

The COS-B X-ray observations of Cygnus X-3 (Bonnet-Bidaud *et al.* 1978, Manzo *et al.* 1978, Molteni *et al.* 1980, van der Klis and Bonnet-Bidaud 1981a, b, 1982, Bonnet-Bidaud and van der Klis 1981b, 1985) have provided an extensive overview of the intensity variations of the source over time intervals of months. It was possible to study the X-ray intensity variations of individual 4.8-hr cycles down to time scales of a few 100 seconds (Figure 2) as well as gradual variations in the overall characteristics of the modulation taking place on time scales of weeks to months (Figure 3). By virtue of their combination of extensive monitoring, long, uninterrupted observational windows and good time resolution, these observations constitute a unique record of the activity of Cygnus X-3.

Fig. 3. An overview of three of the observations of Cygnus X-3 with the COS-B X-ray detector. Gaps are due to satellite orbital effects; the 4.8 hour binary modulation is clearly seen (after van der Klis and Bonnet-Bidaud 1982; reprinted from *Astron. and Astrophys. Supp.*).

2.1. LONG-TERM PERIODICITIES

One type of investigation on which the COS-B X-ray observations of Cygnus X-3 had a considerable impact was that into possible periodic long-term X-ray intensity variations additional to the 4.8-hr modulation. Such a long-term periodicity is well established in, *e.g.*, Her X-1, and has been variously ascribed in that source to donor-star, accretion-disk and neutron-star precession periods, and to accretion-disk instabilities (see Ögelman and Trümper 1988). The first report of a possible long-term modulation in Cygnus X-3 was made by Holt *et al.* (1976) on the basis of the 1974–1979 Ariel V All-Sky Monitor (ASM) data. These authors reported a 16.75-day modulation with an amplitude of $\sim 18\%$ of the total X-ray flux. Later, more extensive Ariel V ASM data led Holt *et al.* (1979) to refine this to a double-peaked modulation with a period of 33.0 ± 0.2 days.

The much larger area and greater duty cycle of the COS-B X-ray detector as compared to the Ariel V ASM allowed Molteni *et al.* (1980) to make a more detailed analysis of possible long-term periods on the basis of two ~ 35 day continuous COS-B observations. They concluded, that a 34.1 ± 0.1 day period was present, the

Fig. 4. Variation in the amplitude (A_1) and mean level (A_0) of the 4.8 hour modulation of Cygnus X-3 as a function of time (adapted from Bonnet-Bidaud and van der Klis 1981b and 1985). Arrows indicate predicted maxima in 34.1 day cycle.

evidence for which was one $\sim 50\%$ -amplitude peak in each of the two observations (see Figure 4). Reports of correlations in hard X-ray and gamma-ray emission with these proposed periods appeared in the following years (Dolan *et al.* 1982, Dowthwaite *et al.* 1983). However, the further COS-B observations of Cygnus X-3 did not confirm the presence of long-term periodicities. Figure 4 summarizes the long-term behaviour of Cygnus X-3 in these four COS-B observations; the predicted times of maximum flux on the basis of the Molteni *et al.* (1980) 34.1-day period are indicated with arrows. There was no peak at the predicted epoch of maximum

flux in a 40-day COS-B observation in 1980 (Bonnet-Bidaud and van der Klis 1981b), nor did the 110-day COS-B observation of 1981–1982 (Bonnet-Bidaud and van der Klis 1985) show evidence of any periodicity. The conclusion that there is no evidence for long-term X-ray periodicities in Cygnus X-3 has been confirmed from an analysis of the 1969–1979 Vela 5B data (Priedhorsky and Terrell 1986).

2.2. LIGHT-CURVE VARIABILITY

Although the minima and maxima of the 4.8-hr modulation can practically always be identified, the light curve of Cygnus X-3 shows considerable variations from one orbital cycle to the next (Figure 2). The COS-B X-ray data provided an excellent opportunity to study this variability in a detailed manner. It proved to be useful to decompose the variability into two components: variations in amplitude and mean level of the overall light curve, and variations in its actual shape.

As suggested by Figure 3, the mean level and amplitude of the source show gradual changes, which can be distinguished on time scales of about a day and longer. The relation between the mean level and the amplitude of the modulation was studied by Bonnet-Bidaud and van der Klis (1981b), who concluded that these two quantities are **not** strictly proportional. Rather, the amplitude increases more than proportionally with overall source brightness, or, in other words, when the source gets brighter, its relative modulation depth increases. This effect was interpreted in terms of a model for the 4.8-hr modulation where a central source is periodically eclipsed by its companion, and where the entire system is surrounded by scattering material whose scattering optical depth τ_s *decreases* when the source gets brighter. In this model, the light curve has two different components: a 100%-modulated, unscattered, eclipsing component, and a much less modulated, scattered component. When τ_s decreases, the relative contribution of the scattered component becomes less, and consequently the modulation depth increases. The increase of relative modulation depth with intensity was confirmed by Molnar and Mauche (1986), who also showed that this effect is real, and not an artefact caused by the interstellar scattering affecting the X-ray flux from the source.

The variations in the shape of the light curve which occur in addition to these gradual mean-level and amplitude variations were extensively studied using the COS-B X-ray detector (van der Klis and Bonnet-Bidaud 1981b, 1982, Bonnet-Bidaud and van der Klis 1981b). The conclusion of this work was, that although the light curve shows considerable shape changes from one cycle to the next, it is remarkably stable in shape when averaged over a sufficiently long interval (typically $\gtrsim 1$ week). Figure 5 shows average light curves from the 1977 and 1978 COS-B X-ray observations in comparison to an average light curve obtained with the Copernicus satellite during 1972–1973 (Mason *et al.* 1976). The average light curve is seen to display a large shape stability, exhibiting a relatively slow rise to a broad maximum, and a steep fall to a more narrow minimum. This characteristic shape has persisted up to the present day (see, *e.g.*, van der Klis and Bonnet-Bidaud 1989 for the EXOSAT results). However, in a unique event

Bonnet-Bidaud 1981b) was used extensively in subsequent years in studies of Cygnus X-3 in high-energy gamma-ray bands (*e.g.*, Fegan and Danaher 1981, Hayashida *et al.* 1981, Weekes *et al.* 1981, Lamb *et al.* 1982, Dowthwaite *et al.* 1983, Lloyd-Evans *et al.* 1983, Baltrusaitis *et al.* 1985, 1987a, b, Battistoni *et al.* 1985a, b, Cawley *et al.* 1985a, b, Chadwick *et al.* 1985a, b, 1987, Hermsen *et al.* 1985, 1987, Lambert *et al.* 1985, Marshak *et al.* 1985a, b, 1990, Berger *et al.* 1986, Bhat *et al.* 1986, Kifune *et al.* 1985, 1986, 1987, Oyama *et al.* 1986, Alexeenko *et al.* 1985, Bionta *et al.* 1987, Chardin *et al.* 1987a, b, Czapek *et al.* 1987, Eames *et al.* 1987, Morse 1987, Resvanis 1987, Ruddick 1987, Watson 1987, Dingus *et al.* 1988, Tonwar *et al.* 1988, 1992, Li and Wu 1989, Bednarek 1990, Brazier *et al.* 1990a, b, Edwards *et al.* 1990, Gregory *et al.* 1990, Muraki *et al.* 1991, Xiaoyu *et al.* 1991). The gradual lengthening of the observed 4.8-hr period implied by the ephemeris might be the result of various different effects. The most straightforward explanation is that the orbital period of the system is increasing due to mass loss from the system as a whole, and/or mass transfer between the stellar components of the system. As pointed out by, *e.g.*, van der Klis and Jansen (1985) such a scenario is incompatible with conservative mass transfer by critical-lobe overflow from a red-dwarf companion to the X-ray source (the “standard” low-mass X-ray binary scenario), but it might very well be compatible with evaporation of a dwarf star heated by the radiation emanating from the compact object (Basko *et al.* 1974), or with a model in which a Wolf-Rayet star with a strong stellar wind is the X-ray source’s companion (van den Heuvel and de Loore 1973; this scenario has been strengthened by the detection of a Wolf-Rayet like near-infrared spectrum from Cygnus X-3, see Section 2). On the other hand, conservative mass transfer from a lobe-filling very low-mass companion ($<0.05 M_{\odot}$) to a neutron star could be compatible with the observed orbital slow-down (Molnar 1988).

An alternative possibility is that the orbital period is not really getting longer at the rate suggested by the lengthening of the observed 4.8-hr period, but that the lengthening we observe is an apparent effect caused by apsidal motion of an eccentric binary orbit with an apsidal-motion period of >10 years (Elsner *et al.* 1980) or by a third body in the system (Molnar 1988). (Obviously, the first interpretation is incompatible with a 19-day apsidal motion period such as mentioned above.) A prediction of both these models for the slow-down of the 4.8-hr period is that the rate of change of the period should gradually decrease, and eventually reverse. Recent new determinations of the X-ray ephemeris of Cygnus X-3 on the basis of 1983–1985 EXOSAT and 1989–1991 Ginga observations of the source, while completely confirming the earlier COS-B results and the gradual increase of the period over the interval 1972–1985, suggest that such a decrease may indeed be taking place (van der Klis and Bonnet-Bidaud 1989, Kitamoto *et al.* 1992).

3. Accretion-Powered Pulsars

In accretion-powered pulsars, X-rays are generated by the accretion of matter onto a strongly magnetized neutron star. The magnetic field channels the accreting plasma to the magnetic poles, and consequently most of the X-rays are emitted from two hot spots on the surface of the neutron star, located at the magnetic poles. The magnetic poles usually do not coincide with the neutron star's rotation axis, so that the star's rotation makes the hot spots periodically appear and disappear. This causes periodic, relatively smooth X-ray intensity variations which are known as X-ray pulsations. The periods range from a fraction of a second to thousands of seconds (Nagase 1989). Nearly all accretion-powered pulsars are found in HMXB, because in most LMXB the neutron-star magnetic field is much lower than in HMXB. The cause of this is uncertain (Bhattacharya and van den Heuvel 1991).

Apparent as well as true variations can be observed in the pulsation period. The former are due to the orbital motion of the neutron star around its companion, which causes Doppler shifts in pulsation frequency. The latter are caused by torques exerted by the accreting matter (and possibly the neutron-star interior) on the neutron-star crust. Consequently, careful measurements of the variations in the pulse period can provide information about both the binary orbit (and hence about the masses of the two stars) and about the angular momentum of the accreting matter.

In two accretion-powered pulsars, Centaurus X-3 and SMC X-1, the long observing times of the COS-B observations allowed to closely monitor a so-called "turn-on" of the X-rays, a phenomenon that is probably related to a change in the rate at which matter is transferred to the vicinity of the neutron star. In SMC X-1, it was the first time that such an event was observed. In Cen X-3, the COS-B observations allowed for the first time to follow the behaviour of the source for an extended period of time after the event, and to measure the pulse-period variations throughout it.

The accretion-powered pulsar Vela X-1 (4U 0900–40) has a binary period of 8.9 days, and the length of the three COS-B observations of this source proved very useful in disentangling the Doppler-induced and true variations in the pulsation period. The accretion torques in Vela X-1 were found to be very irregular in character on all time scales, which is probably related to the fact that the neutron star in this system accretes directly from a stellar wind rather than from an accretion disk.

3.1. CENTAURUS X-3

Cen X-3 is a high-mass X-ray binary with an orbital period of 2.1 days that contains an accretion-powered pulsar with a pulsation period of 4.8 seconds. The source shows periodic eclipses of the X-rays lasting about half a day which are caused by the orbiting X-ray pulsar passing behind its early-type companion.

The COS-B observation of Cen X-3 lasted from 1975 December 24 to 1976

Fig. 5. Folded light curves of Cygnus X-3. The drawn curve is a smoothed version of the Copernicus data (*top left*) for comparison (after Bonnet-Bidaud and van der Klis 1981b; reprinted from *Astron. and Astrophys.*).

lasting from 1980 May 22 to June 23 and observed with the COS-B X-ray detector (Bonnet-Bidaud and van der Klis 1981b), the average light-curve shape took on a different, much more symmetric appearance (Figure 5, *lower right*). Cygnus X-3 was exceptionally bright during this time (see also Figure 3). The change in average light-curve shape was interpreted within the framework of the two-component model for the light curve. It was argued that the effect could be attributed to an exceptionally low scattering optical depth of the material around the source, causing the symmetric unscattered eclipsing component of the light curve to dominate the asymmetric scattered component. The asymmetry of the scattered component could be due to an asymmetric distribution of the scattering material with respect to the X-ray source.

On much shorter time scales, from one orbital cycle to the next, intrinsic variations occur in the shape of the light curve such as are clearly visible in Figure 2.

These variations were described in detail by van der Klis and Bonnet-Bidaud (1982). They were found to occur primarily on time scales below ~ 3000 seconds, and were not correlated to either the source intensity or the long-term mean shape of the light curve. However, there does seem to exist a correlation with orbital phase: The cycle-to-cycle variations are less pronounced around the minimum of the light curve than elsewhere. This was attributed to an eclipse of the central X-ray source and hence a disappearance of the unscattered component of the X-ray flux during this time, in accordance with the explanation for the dependence of modulation depth and degree of light-curve asymmetry on mean X-ray intensity.

2.3. THE X-RAY EPHEMERIS

A topic of considerable interest in the study of Cygnus X-3 is the evolution of its orbital (4.8-hr) period. To detect changes in this period, it is necessary to accurately measure the arrival time of the 4.8-hr cycle at various different epochs. Evidently, in view of the variations in the shape of the 4.8-hr modulation, this is a difficult task. The first report that the 4.8-hr period might not be constant, but was in fact slowly increasing was made on the basis of the November-December 1975 COS-B X-ray data by Manzo *et al.* (1978). These authors concluded to an orbital period derivative of $\dot{P} = (2.83 \pm 0.67) 10^{-9}$ ($\dot{P}/P = (5.2 \pm 1.2) 10^{-6} \text{ yr}^{-1}$). This result was confirmed by further work by Lamb *et al.* (1979) and in particular Elsner *et al.* (1980). The latter authors reanalyzed most of the earlier data in order to obtain a homogeneous data set. However, the result was contradicted on the basis of Copernicus measurements (Mason and Sanford 1979).

Further work using the 1980 COS-B X-ray observations which took into account both the Elsner *et al.* (1980) reanalysis of the earlier data and the Copernicus results reported by Mason and Sanford (1979), strengthened the earlier conclusion that the orbital period of Cygnus X-3 was increasing. The rate of increase was measured with high confidence; its value was $\dot{P} = (1.18 \pm 0.14) 10^{-9}$ ($\dot{P}/P = (2.2 \pm 0.3) 10^{-6} \text{ yr}^{-1}$; van der Klis and Bonnet-Bidaud 1981b).

It was noted that there existed a scatter in the arrival-time measurements in excess of that expected on statistical grounds. Although this scatter could be due to uncorrected-for light-curve shape variations, a more detailed study of the arrival times (Bonnet-Bidaud and van der Klis 1981b) suggested that there might be a *periodic* variation in arrival times with a period of ~ 19 days and an amplitude of 0.002 days. A similar suggestion had previously been made by Molteni *et al.* (1980) for the 34.1 day period. Whereas Molteni *et al.* (1980) had interpreted their arrival time variations as due to orbital motion on the 34.1 day period, Bonnet-Bidaud and van der Klis (1981b) noted, that a periodic variation in the arrival times might result from apsidal motion of the 4.8-hr binary orbit on a period of 19 days. In this hypothesis, the orbit would have to be eccentric, with $e \sim 0.03$. It has not been possible to confirm either of these periodicities in the arrival-time residuals from later COS-B X-ray measurements (Bonnet-Bidaud and van der Klis 1985).

The average long-term X-ray ephemeris of Cygnus X-3 (van der Klis and

Fig. 6. Pre-eclipse dip (*profile a*) in Cen X-3 and eclipse entrance without dip (*profile b*) (after Bennett *et al.* 1976; reprinted from *Astron. and Astrophys.*).

January 23. Already on the basis of 10% of the total data set, Bennett *et al.* (1976) were able to report that during this observation the source apparently underwent a turn-on such as had earlier been seen with the Uhuru satellite (Schreier *et al.* 1976). They also reported a “mid-phase dip”, a ~ 15 minutes interval approximately midway between two eclipses during which the X-rays dropped to $\sim 50\%$ of their normal level, which they ascribed to the hypothetical “wake” (Jackson 1975) created in the stellar wind of the early-type companion star by the passage of the neutron star. In addition, another strong dip was seen during the entrance into one of the X-ray eclipses (Figure 6). This was the first time that such an event had been detected. A similar pre-eclipse dip was later observed in great detail with EXOSAT (Day 1988).

The full COS-B X-ray data set (Figure 7), as reported by Bonnet-Bidaud and van der Klis (1979), clearly shows the periodic eclipses of the X-ray source (*dashed lines*), and confirms that the character of the turn-on was similar to that previously seen with Uhuru. The lower X-ray intensity near to the eclipse transitions as compared to that at mid-phase (the so-called “eclipse shoulders”), most clearly visible in Figure 7 in cycles 1 and 2, was also seen in the turn-on observed with the Uhuru satellite. It was ascribed by Schreier *et al.* (1976) to scattering of the X-rays by a very dense stellar wind; the turn-on is, in this model, caused by the wind gradually becoming less dense.

The long duration of the COS-B observation allowed to monitor the source

Fig. 7. X-ray light curve of Cen X-3. Dashed lines indicate predicted eclipse limits (after Bonnet-Bidaud and van der Klis 1979; reprinted from *Astron. and Astrophys.*).

for a full 25 days after the turn-on, and shows a decrease in mean uneclipsed X-ray intensity ~ 15 days later, in cycles 9–10. As this intensity-decrease was not accompanied by the eclipse “shoulders” characteristic for attenuation of the X-rays by the stellar wind, it was concluded that it was caused by a drop in the mass accretion rate onto the neutron star (Bonnet-Bidaud and van der Klis 1979). This drop, in turn, was suggested to be the consequence of the rarefaction of the stellar wind that caused the turn-on ~ 15 days earlier. The less dense wind was hypothesized to have caused a lower mass-transfer rate from the companion star to the neutron star, and the 15-day time lag between the two events was interpreted as the time that the effect of the lower mass-transfer rate had needed to propagate from the edge of the accretion disk to the neutron star at the center. Therefore, it was suggested that this observation constituted a direct measurement of the disk’s radial flow time. The interpretation requires Cen X-3 to contain an accretion disk. It was argued, that even if the source is accreting from a stellar wind rather than being fed by Roche-lobe overflow, the accreting matter would contain sufficient specific angular momentum for an accretion disk to form. Later optical work (van Paradijs *et al.* 1983) has confirmed that an accretion disk is present in Cen X-3.

Using the COS-B X-ray detector’s high time resolution data, it was possible to detect the 4.8 second pulsations during this same observation (van der Klis *et al.* 1980). The average pulse period was found to have decreased much faster in the year that had elapsed since its last determination with the Ariel V satellite, than had been seen before. This was the first clear indication for the now (*e.g.*, Tsunemi 1989) well-established irregularities in the accretion-torque induced spin-up (acceleration of the rotation rate) of this neutron star, for which variations in the long-term average mass-transfer rate seem the most likely explanation.

It proved to be feasible to accurately follow the evolution of the pulsations through the entire observation. During cycles 1 to 3, the relative amplitude of the pulsations (“pulsed fraction”) was gradually increasing. This was in accordance with the idea that the scattering of the X-rays in the stellar wind was high, but decreasing, during this time. After removal of the orbital Doppler effects, the pulsation period was found to decrease at a significantly faster rate during the turn-on and the first high-intensity cycles (1 to 6; $\dot{P}/P = (-10.5 \pm 1.1) 10^{-4} \text{ yr}^{-1}$), than during the lower-intensity cycles (10 to 14; $\dot{P}/P = (-5.6 \pm 1.6) 10^{-4} \text{ yr}^{-1}$). This was interpreted in terms of a drop in accretion rate (and hence angular-momentum transfer rate) consistent with that earlier derived from the variations in X-ray intensity. During the intermediate cycles 7 to 9, when the X-ray intensity was highest, the spin-up was consistent with being intermediate between the two previously quoted values ($\dot{P}/P = (-8.3 \pm 3.6) 10^{-4} \text{ yr}^{-1}$). The two measurements of the pulse period-derivative obtained after the turn-on, in cycles 7–9 and 10–14, and the associated average X-ray fluxes, were found to be consistent with standard accretion-torque theory (Pringle and Rees 1972, Ghosh and Lamb 1978). In this theory, the amount of angular momentum transferred by the accreting matter to the neutron star is closely related to the angular momentum of the matter in the

Fig. 8. X-ray light curve of SMC X-1. Dashed lines indicate predicted eclipse limits (after Bonnet-Bidaud and van der Klis 1981a; reprinted from *Astron. and Astrophys.*).

accretion disk in Keplerian orbits just outside the region where the magnetic stresses dominate the flow of matter (the magnetosphere). Using a simple version of this theory, a constraint on the neutron star's properties could be derived which can be expressed as

$$f = 4 \left(\frac{\mu}{10^{30} \text{Gauss cm}^3} \right)^{2/7} \left(\frac{R}{10^6 \text{cm}} \right)^{6/7} \left(\frac{I}{10^{45} \text{g cm}^2} \right)^{-1} \left(\frac{M}{M_{\odot}} \right)^{-3/7} = 1.6 \pm 0.4.$$

In this expression, μ is the neutron star's magnetic moment, R its radius, I its moment of inertia, M its mass and $M_{\odot}$ the mass of the Sun ($\sim 2 \cdot 10^{33}$ g). The pulse-period derivative measured during the turn-on, and its associated X-ray flux, deviated from the predictions of the theory, in the sense expected from the fact that the X-rays were attenuated by scattering in the dense stellar wind during this time. In fact, the high spin-up during the turn-on suggested that the X-ray luminosity, before attenuation by the stellar wind, must have been higher than ever observed.

3.2. SMC X-1

SMC X-1 is a very luminous (up to $5 \cdot 10^{38}$ erg/second) eclipsing high-mass X-ray binary that is located in the Small Magellanic Cloud. It has a 3.9-day orbital period and a very fast, 0.7-second pulsation period. Due to its large distance, it is not very bright, and in the COS-B X-ray detector it produced only 3.5 to 4 counts/second. During the 38-day COS-B observation starting 1976 November 2 (Bonnet-Bidaud and van der Klis 1981a), the source was observed to undergo a turn-on similar to

those seen in Cen X-3 (see also Section 3.1.). This was the first time that such an event had been observed in SMC X-1. The characteristic lower X-ray intensity near to the eclipses is clearly visible in cycles 5 and 6 (Figure 8), as well as are the X-ray eclipses. During the first four cycles the source was undetectable, which is illustrated by the absence of any evidence for eclipses during this time. The pulsations were not detected in this COS-B observation.

3.3. VELA X-1 (4U 0900-40)

Vela X-1 (4U 0900-40) is a ~ 283 -second, accretion-powered pulsar in a slightly eccentric 8.9-day orbit around its early-type companion. This source was observed with the COS-B X-ray detector on three different occasions, in 1975, 1976 and 1979 for ~ 19 , ~ 29 and ~ 35 days, respectively.

In 1977, Ögelman *et al.* (1977) reported, on the basis of an analysis of the low time resolution (25-second integrations, 100-second intervals; see Section 1.2) data of the first observation, that the pulsational period of the source had *increased* with respect to the value previously measured with SAS-3 (Rappaport *et al.* 1976). This was a surprise, since conventional wisdom had it that accretion-powered pulsars, especially slowly rotating ones such as Vela X-1, should all be accelerating their rotation rate (be “spinning up”) on relatively short time scales, until they reached an “equilibrium period” at which they would be spinning at the same rate as the matter at the inner edge of the accretion disk just outside the magnetosphere. This discovery foreshadowed later, much more extensive spin-down episodes in Vela X-1 (Nagase *et al.* 1984, 1989). The presently most generally accepted explanation for the alternation of spin-up and spin-down episodes in Vela X-1 (and a number of similar systems) is that the neutron star in this system is not accreting from an accretion disk, but more or less directly from the stellar wind (*e.g.*, Wang 1981).

An analysis of the low time resolution data of the second and third COS-B observations was reported by Molteni *et al.* (1982). The measured pulse period of the third observation confirmed the, up to that time, unprecedented long-term spin-down reported from Hakucho observations (Nagase *et al.* 1981) that had started near the beginning of 1979.

A considerable gain in timing accuracy was attained in a later analysis of the high time resolution (0.8-second) data also obtained during these observations of Vela X-1 (van der Klis and Bonnet-Bidaud 1984a, b). The reason that it helped to use a better time resolution than was available in the low resolution data, is that the 283-sec pulse profile of Vela X-1 shows considerable structure (Figure 9), with two main, and 5 to 6 subsidiary sub-pulses, which in the low time resolution data could not be resolved. This highly structured, and rather stable, pulse profile is most likely due to a complex neutron-star magnetic-field pattern.

For each of the three observations, it was possible to measure the phase of the pulsations in 0.2–1 day subsections of the data to an accuracy of 2 to 5 secs. The resulting ~ 50 pulse-arrival times per observation, in each of the three cases covering several binary orbital cycles, were used to carefully study both the

Fig. 9. Folded 283-second X-ray pulse profiles of Vela X-1. The pulse shapes are repeated twice for clarity (after van der Klis and Bonnet-Bidaud 1984a; reprinted from *Astron. and Astrophys.*).

orbital parameters and the intrinsic pulse-period variations in each observation. As the observations in each case were much longer than the binary period, it was possible to accurately distinguish between the periodic Doppler shifts in the pulsation frequency caused by the binary orbital motion, which are reflected in an approximately sinusoidal variation (with a $\sim 10\%$ distortion due to the orbital eccentricity) in pulse arrival times (Figure 10), and the intrinsic pulse-period variations, which were found to first order to conform to a description in terms of a constant pulse-period derivative that was different in each of the three observations. These mean intrinsic variations show up as parabolic variations in the pulse arrival times (Figure 11).

Fig. 10. Best-fit orbital pulse-arrival-time delay curves of Vela X-1; the secular effects of Fig. 11 were removed from these plots (adapted from van der Klis and Bonnet-Bidaud 1984a).

Fig. 11. Best-fit parabolic pulse-arrival-time variations of Vela X-1; the orbital effect of Fig. 10 was removed from these plots (after van der Klis and Bonnet-Bidaud 1984a; reprinted from *Astron. and Astrophys.*).

Using the orbital solutions derived from the Doppler shifts in the pulse arrival times, it is possible to obtain much more accurate measurements of the orbital epoch (the time the neutron star passes a given point in its orbit) than is possible from studies of the shape of the X-ray eclipses. By combining the three measurements of the binary orbital epoch resulting from the pulse arrival-time analysis of the three COS-B observations with the six additional similar measurements available in literature, a variation in the orbital period of $(2.1 \pm 0.6) \cdot 10^{-5} \text{ yr}^{-1}$ was found. This was a surprisingly large value, and it was concluded that no satisfactory explanation existed for it.

Rapid fluctuations in the *pulsation* period, at rates of up to 10^{-6} were detected on several occasions, as illustrated by the variations in the pulse arrival times around the average parabolic trends in Figure 11. These fluctuations indicated that large torques are acting on the neutron star, and it was suggested that inhomogeneities in the accreting matter might be responsible for these torques.

Later work on the basis of HEAO-1, OSO-8 and SAS-3 observations of this source (Boynton *et al.* 1986) suggests, that these intrinsic short-term fluctuations in the pulse-arrival times are part of a general noise process that can be described in terms of “red noise”, *i.e.*, slower variations have larger amplitudes. This red noise in the pulse arrival times can cause larger uncertainties in the determined orbital parameters than expected on the basis of a standard statistical analysis (which implicitly assumes the noise to be “white”). Probably, this explains the unexpectedly large derived value of the variation in orbital period mentioned above. The COS-B measurements of the orbital parameters and intrinsic pulse-period variations of Vela X-1 continue to be used in work on this source (*e.g.*, Deeter *et al.* 1987a, b, 1989), which is a prime candidate for disentangling the internal torques exerted on the neutron-star crust by its superfluid interior from the external torques exerted by the accreting matter.

4. Low-Mass X-Ray Binaries

The COS-B X-ray observations of LMXB were much more difficult to interpret than those of HMXB. One reason for this is the absence of X-ray pulsations and eclipses in all bright LMXB; another reason is that, as work with the EXOSAT observatory has clearly shown (*e.g.*, Hasinger and van der Klis 1989), X-ray colour information is indispensable to gain an even only phenomenological understanding of the X-ray variations of these sources on time scales of hours to days. The rapid (20–200 milliseconds) quasi-periodic variations in X-ray intensity which have, also with EXOSAT, been found to occur in these objects (van der Klis *et al.* 1985, see Lewin *et al.* 1988, van der Klis 1989 for reviews) can probably not be detected with the COS-B X-ray detector due to the very low duty cycle of the high time resolution data.

An additional complication was that most of the bright LMXB are concentrated in a relatively small area in the sky, near to the galactic center, so that during any

Fig. 12. X-ray light curve of Cyg X-2. The dips (marked by vertical lines) are probably excursions into the flaring branch (see text) (after Bonnet-Bidaud and van der Klis 1982; reprinted from *Astron. and Astrophys.*).

COS-B observation of this region at least several of these sources were contained in the field of view of the X-ray detector. This problem, at least, did not occur in the case of the observation of Cyg X-2 (Section 4.1), which is located in a sufficiently remote position in the sky to avoid confusion from other bright sources. During the observations of GX 5-1 (Section 4.2), there was a considerable number of additional sources in the field of the detector.

4.1. CYGNUS X-2

Cyg X-2 has attained a certain fame over the last few years as a prototypical bright LMXB of the “Z” class (Hasinger and van der Klis 1989), clearly exhibiting the tri-modal X-ray spectral (and rapid-variability) characteristics of these sources (Hasinger *et al.* 1990). However, at the time of the 47-day COS-B observation of this source in June–July 1981 (Bonnet-Bidaud and van der Klis 1982), nothing of this was known yet.

The X-ray light curve obtained during this observation is displayed in Figure 12; it is still among the most extensive monitoring sequences of the variability of the source on time scales of minutes to weeks. The erratic variability on these time scales is clearly visible, with many intensity dips lasting from 0.25 hours to more than a day. Many of these dips are probably due to the source entering a so-called “flaring-branch” state (Hasinger 1987). The transition times into and out of the dips were short, between 8 minutes and 2 hours. It was suggested that reprocessing of the X-rays into UV radiation might explain the X-ray dips, and at the same time the UV flares known to occur on similar time scales. This suggestion could recently be tested by simultaneously observing Cyg X-2 in X-rays and UV. Indeed, the source was found to become brighter in the UV band when it entered the low

Fig. 13. Map of X-ray sources known to exist in the galactic center area in 1983. Circle shows the wide (20° across) field of view of the COS-B X-ray detector and indicates which sources could have contributed to the X-ray light curves in Fig. 14 (after van der Klis and Rappaport 1983; reprinted from *Astron. and Astrophys.*).

X-ray intensity flaring-branch state (Hasinger *et al.* 1990).

The X-ray intensity variations were searched for periodicities; none were found with upper limits ranging from 4% to 0.2% on time scales from 1.1 days to 200 seconds; some evidence could be detected of a modulation of the X-ray intensity at the 9.8-day optical spectroscopic period of the optical counterpart of the source (Cowley *et al.* 1979), but the presence of a modulation at the rival 11.2-day period (Holt *et al.* 1979) could not be excluded.

4.2. THE REGION OF GX 5-1

GX 5-1 is another example of a Z source (Hasinger and van der Klis 1989). Contrary to Cyg X-2, the source has never been observed in the flaring branch (van der Klis *et al.* 1991). Several of the brightest LMXB were in the field of view of the COS-B X-ray detector during the two observations of the region of GX 5-1 in September–October 1975 (33 days) and February–March 1977 (11 days) reported

by van der Klis and Rappaport (1983). However, from the known X-ray intensity ranges of the sources in the field of view, it could be derived that GX 5-1 must have contributed between 25% and 65%, and any one of the other sources less than 25%, of the total observed counting rate. As rapid variations in intensity were seen with amplitudes of up to 25%, it was concluded that these variations were probably mostly due to GX 5-1. Figure 13 provides a map of the region, with the field of view of the detector (*circle*) superimposed.

The character of the intensity variations observed during the two observations was reminiscent of that in the observation of Cyg X-2, with flares and dips on time scales of hours to days (Figure 14). The short (down to 0.25-hr duration) dips seen in Cyg X-2 appeared to be absent. It seems likely that the high-intensity episodes correspond to times when GX 5-1 was near the junction of its “horizontal” and “normal” branches (see van der Klis *et al.* 1991). A period search of the data did not turn up any significant periodicities, with upper limits between 3.4% and 0.2% on time scales of 1 day to 200 seconds for the integrated count rate of all the sources in the field of view.

4.3. CONCLUDING REMARKS

The experience with the COS-B X-ray detector has shown the power of long, uninterrupted observations, as well as of extended monitoring in the study of X-ray binaries, and hence the great advantage in putting X-ray satellites into high orbits, and, independently, in keeping them pointed to a given source for long periods of time. Even with the very limited capabilities of the COS-B X-ray detector, observations could be performed that contributed considerably to our understanding of the sources. The experience with EXOSAT, with its very much superior instrumentation for X-ray observations, has strongly confirmed this (White and Peacock 1988), and, surprisingly, has extended this to the case of the active galactic nuclei (McHardy 1988 and references therein).

In retrospect, the lack of spectral resolution of the COS-B X-ray detector was unfortunate. Even with a very modest spectral capability of, say, 4 spectral channels, the COS-B observations of Cyg X-2 and GX 5-1 would surely have led to the discovery of the tri-modal spectral behaviour (also called Z behaviour) characterizing these sources. As it was, this had to wait for EXOSAT.

In view of the above, it can be said that with the ever-increasing sensitivity, sophistication, and cost, of X-ray instrumentation, for which it is becoming increasingly unlikely that observations with a duration of, say, a month, would ever be approved, a bigger and bigger “hole in the market” is left for instruments with capabilities only slightly in excess of the COS-B X-ray detector (a few 10^2 cm² effective area, a few spectral bands, good background rejection, 0.1–1 second time resolution and a reasonable duty cycle) that can observe the brighter sources for extended periods of time. This hole could be filled with very simple collimated proportional counters, but even better would be wide-field camera’s or all-sky monitors that can monitor several bright sources simultaneously. Fortunately, some instruments

Fig. 14. X-ray light curve of the region depicted in Fig. 13. The top frame shows the light curve from the Crab nebula for comparison. The first three frames are contiguous in time (after van der Klis and Rappaport 1983; reprinted from *Astron. and Astrophys.*).

of these latter types are scheduled to fly within the next few years. Presently, for hard X-ray sources, the GRO gamma-ray burst detector BATSE (Fishman 1992) is fulfilling some of these requirements. From a scientific point of view, this kind of facility should be permanently available in addition to the more powerful X-ray observatories. A case can be made that their presence would enormously increase

the scientific return from the big observatories, in a similar way as small optical observatories all around the world provide the setting within which research with the big optical (and other) telescopes is performed in a much more fruitful way than would otherwise be possible. In addition to this, long term monitoring of bright X-ray binaries with a *large* area proportional counter would be an extremely fruitful endeavour. This possibility has long seemed to be a dream. However, the planned "USA" mission (NRL 801; several 10^3 cm² effective area, millisecond time resolution, month-long observing times; K. Wood, priv. comm. 1991), which could fly before the end of 1995, plans to do just this.

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