Observations of sub-millisecond bursts from Cygnus X-1

A. B. Giles* Physics Department, University of Leicester, Leicester LE1 7RH

Received 1980 August 4; in original form 1980 January 9

Summary. Cygnus X-1 was observed by a powerful X-ray rocket payload on 1976 November 4 and several sub-millisecond bursts were found. These bursts when superimposed imply a rising profile with a width of ~ 500 μs, but a high resolution autocorrelation function shows this time-scale is not characteristic of the source. The problems involved in demonstrating the existence of ms bursts are discussed and the bursts seen are then compared with the few previously reported examples. This comparison shows that all observations to date have been made with detectors that are too small in area to escape entirely from the realm of small numbers and their associated statistical problems.

Introduction

The X-ray source Cygnus X-1 has been observed by many instruments since its discovery and is remarkable for its wide range of variability both on long and rapid time-scales. The rapid fluctuations were explained in terms of a shot noise model by Terrell (1972) and the shot parameters have subsequently been specified by Weiskopf, Kahn & Sutherland (1975) using Uhuru data and by Rothschild et al. (1977) from rocket observations. The characteristic time-scale of the shots ranges from 0.1 to 1.0 s but in addition to these features very rapid intensity changes, the millisecond bursts, have been observed on a number of occasions. Rothschild et al. (1974, 1977) in fact reported such bursts on two separate flights of the same instrument and Oda et al. (1974) found evidence for a clustering effect of marginal bursts when reanalyzing the earlier data of Rappaport, Doxey & Zaanen (1971). Further bursts have been reported by Ogawara et al. (1977) and Toor (1977) has also found a ms burst from the somewhat similar X-ray source, Circinus X-1. More recently, the HEAO-1 satellite has found evidence for 10 ms flaring from Cygnus X-1 but no clear evidence of the ms bursts themselves. A similar lack of bursts has also been reported by Priedhorsky et al. (1979). The other source known to exhibit rapid bursts of < 10 ms duration is GX339-4 (Samimi et al. 1979).

The observations of such rapid features in part supports a black hole as the underlying object for these sources, but the analysis methods used to identify the ms bursts have been

*Present address: Physics Department, University of Tasmania, Box 252C, Hobart, Tasmania 7001, Australia.

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System
questioned by Press & Schechter (1974) and by Weisskopf et al. (1975). The statistical significance of the bursts is complicated by two effects. First, the bursts are aperiodic and secondly, have a small number of counts so the Poisson statistics involved are very sensitive to small changes in the parameters. They are therefore susceptible to selection bias, either due to the hardware of the experiment or the analysis technique used.

The present experiment was intended to increase by a factor of 3 the counts per bin within the previously reported bursts, decreasing their chance expectation from $10^{-2}$ to $10^{-9}$, assuming a simple upward scaling. This great increase in significance may then have revealed a distribution of weaker bursts unavailable to a smaller experiment.

Experiment

To improve upon the existing observations of millisecond bursts a very large detector was designed which incorporated a number of significant improvements over previously reported instruments. The main requirement was to increase the detector area and this was achieved by using deploying detector panels that unfolded after the nose cones were jettisoned. A specially enlarged nose cone assembly was also used which resulted in a total effective area of 3980 cm$^2$ or some three times that available to Rothschild et al. (1974, 1977). The detectors had a hexagonal honeycomb collimator with a field of view of $12^\circ \times 4^\circ$ FWHM. The multi-wire array detectors provided a useful energy range of 1.5–12 keV which was divided into eight energy channels following a roughly logarithmic scale.

This large area, however, provided such a high expected count rate that the available fixed bandwidth telemetry system might have been severely overloaded. In addition, this problem would be most severe on the occasions when the highest instantaneous count rate was observed, i.e. the millisecond bursts, and so a special electronics system was devised to minimize the loss of information. This system has been fully described by Giles & Whitford (1980) and Giles (1978) but basically consists of two main features.

First, although every detected event is processed the type of information sent back is automatically varied such that at low mean count rates all the energy data is included and at higher mean count rates is progressively reduced. This released capacity allows the full timing ability of the system to continue to $12 \times 10^3$ count s$^{-1}$ when an overflow mode occurs and counts are binned in samples of 176 $\mu$s duration (the basic time resolution is normally 2 $\mu$s). Secondly, the data package resulting from each X-ray event detected is de-randomized by being queued in an electronic memory before being transmitted. The 1536-word queue allows full time resolution data to be retained that would normally occur too rapidly for the telemetry system to cope with. As an example of this powerful feature, suppose the mean detected rate is $6 \times 10^3$ count s$^{-1}$ each event of which would have energy data, then a burst to $32 \times 10^3$ count s$^{-1}$ or some four times the previous level could occur for $\sim 30$ ms before the overflow mode was reached. During such a transient most of the energy data would also be retained since the energy rejection circuit was designed only to optimize the mean use of the telemetry system over a time-scale of several seconds.

Observations

The round was successfully fired from Woomera, Australia on 1976 November 4 at 17.45 local time (7.45 UT). The experiment was deployed and data received for the whole flight. It was, however, apparent that Cygnus X-1 had only been observed for a few seconds before drifting out of the detector field of view and the telemetry records subsequently showed that one of the attitude control jets had failed to work correctly. The 6.4 s of useful Cygnus
X-1 data have been searched for evidence of shot noise following the standard methods and they are entirely consistent with this model. The short duration of the observation is, however, unsuitable for such analysis and it has not proved possible to adequately define the shot noise parameters as others have done (Weisskopf et al. 1975; Rothschild et al. 1977). These complications are not a problem, however, when looking for more rapid variability and a careful search has been made for evidence of millisecond bursts. The count rate from Cygnus X-1 was, however, lower than expected and the shortness of the observation may have prevented the source variability from providing periods of higher mean rate. The features seen and a discussion of their significance form the remainder of this paper. A full discussion of the flight can be found in Giles (1978).

Results

The time resolution of 2 \(\mu\)s allows complete freedom in choice of bin sizes and position but an initial analysis was carried out that followed the procedure of Rothschild et al. (1974, 1977). The 6.4 s of useful data was split into 40 intervals of 160 ms with each interval having 320 bins of 0.5 ms width. The bin height \(n\) distribution within each interval was then compared with that predicted by the Poisson function based on the local mean \((\lambda)\) for the entire interval,

\[ P(n, \lambda) = \exp(-\lambda)\lambda^n/n! . \]

Following the definition of a ms burst as being an event whose expectation value by chance within each interval is \(< 0.01\) only one burst (no. 4) was found compared to a total prediction of 0.29. One further burst (no. 1) with \(E < 0.02\) (total prediction 0.56) and two selected pairings of 0.5 ms bins with \(E < 0.01\) were also found. The temporal structure of the data is clearly visible in Fig. 1 which shows three consecutive samples of 0.4 s with bin widths of 0.4 ms. Several ms bursts are visible superimposed on the relatively uniform mean count rate. The sophistication of the experiment in this case, however, provides the ability to define bin widths anywhere allowing a clustering search to be carried out. This method biases the resulting bin height distribution and Poisson statistics are no longer valid.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** This figure shows three consecutive 0.4 s intervals of data from Cygnus X-1. The counts are binned every 0.5 ms and all the prominent bursts occur within this sample. Displaying such a wide sample of the data enables the bursts to be seen in perspective to the normal rate in contrast to the smaller interval and more detailed data in Figs 2 and 3.
treatment required has been described by Press & Schechter (1974) and results in a correction factor of order

\[ K_0 \left( \frac{(1 - \gamma^{-1}) \exp (1 - \gamma^{-1})}{1 - \exp (-\gamma^{-1})} \right), \]

where \( K_0 \) = counts in bin, and \( \gamma \) = overdensity = \( K_0 \)/mean per bin (\( \lambda \)).

This factor measures the fraction of \( K_0 \) flares which are lost in \textit{a priori} binning but found in a continuous scanning (clustering search) of the data. Being lost means that an intrinsic flare of size \( K_0 \) may straddle two bins and therefore not be discovered. This ‘clustering’ search yields no more bursts once the correction factor is applied and Table 1 shows the results for the entire set of data using a bin width of 0.5 ms.

A search was also made for bursts with a bin width varying from 250 \( \mu \)s to 8 ms but little of further interest emerged except for a 4 ms burst coincident with a 0.5 ms burst. All the features of interest that were located using both \textit{a priori} binning and a clustering search during the 6.4 s of data are shown in Table 2 and indicated in Fig. 1.

In Table 2 the term ‘uncorrected’ implies that a pair of bins were selected to improve the signal to noise of the burst. These selections may well not form a regular \textit{a priori} bin set and some correction factor must therefore be necessary since this biased pairing falls somewhere between true \textit{a priori} binning and a clustering search method.

As a check for hardware related spurious bursts, a section of the background data obtained later in the flight was analysed and no bursts were found. A check was also made to see if the detected bursts were correlated with any event occurring elsewhere on the payload either electrical or mechanical in nature. No evidence of a correlation was found but several operations such as the aspect camera firing are not monitored frequently and are only located in time to within \( \sim 0.5 \) s.

The energy data is potentially useful in differentiating between true bursts or random excesses since Rothchild \textit{et al.} (1977) found the mean energy of their bursts to be 2.5 \( \sigma \)

| Table 1. |
|-----------------|----------------|--------------------|-----------------|
| Height (n) | Poisson prediction | Observed \textit{a priori} binning | Observed clustering search | Search mode corrected |
| 6 | 24.2 | 20 | 78 | 22.7 |
| 7 | 5.5 | 4 | 19 | 4.3 |
| 8 | 1.0 | 2 | 4 | 0.8 |
| 9 | 0.15 | 0 | 1 | 0.16 |

| Table 2. |
|-----------------|----------------|
| No. | Counts/0.5 ms | Expectation/320 bins |
| 1 | 8 | 0.02 |
| 2 | 6 + 6 (1 ms bin uncorrected) | 0.009 |
| 2 | 9 search | 0.003 |
| 2 | 9 corrected | 0.019 |
| 3 | 7 + 5 (1 ms bin uncorrected search) | 0.009 |
| 3 | 28 search (4 ms bin) | 0.013 |
| 4 | 8 | 0.006 |
| 5 | 7 | 0.045 |
below that of Cygnus X-1 in general with the exception of the one anomalous burst of higher energy. No such effect was apparent, however, for the bursts reported here, but this statement lacks significance since the data were heavily contaminated both by the background rate and by the presence of the calibration source flux.

Following the identification of the potential bursts, an attempt was made to define a mean burst profile as tried by Rothschild et al. (1974, 1977). The clustering search method was repeated to extract the precise arrival time of each count contributing to the a priori bursts together with those in the preceding and following few milliseconds. These counts can then be simply re-binned and summed to produce a composite burst profile since the ‘shape’ of individual bursts is obviously statistically meaningless.

Knowing the exact arrival time of each photon allows several types of superimpositions to be carried out rather than just the centroid alignment case used by Rothschild. The two other methods used were, first, a symmetrical alignment about the point midway between the first and last photon and secondly, a simple summation using the initial photon arrival time as the reference. Both methods introduce biases to the first or last bin in the profile but after correction the result matches fairly well with that obtained by the usual centroid alignment procedure. The five bursts in Fig. 1 were used to form the composite profile shown in Fig. 3. This indicates a rising pulse ~ 500 µs width rather than the 1 ms wide square profile reported by Rothschild et al. (1974, 1977).

The above analysis was then repeated but using a wider sample of ±0.5 s about each burst centre in an attempt to see any ringing or periodicity but nothing was found. Since the data
Figure 3. This composite profile has been produced from the five bursts in the data that were of height 7 or 8. These were assumed to be representative of true bursts even though several did not satisfy the $E < 0.02$ criterion.

set is short in this case and the located bursts are also grouped relatively close together it is not practical to reject from the analysis bursts closer together than 2 s as Boldt (1977) did. There was, however, no evidence for the 9.946 ms quantization period located by Boldt (1977) in the GSFC data (Rothschild et al. 1974, 1977).

HIGH TIME-RESOLUTION AUTOCORRELATION

As previously noted, the data are unsuitable for shot noise analysis using the autocorrelation method; however, no really high time resolution function has previously been published. This is possible here since the overflow mode was never entered and Fig. 5 shows an autocorrelation plot for Cygnus X-1 utilizing the high resolution of the experiment with lag parameters from 20 μs to 20 ms. A power density spectrum reveals no periodic features of significance. No dramatic features were found on the slowly decreasing level that one expects from the shot noise model.

The complete set of data was also used for an autocorrelation analysis with a basic bin width of 200 μs with a lag parameter of 200 μs to 9.6 ms and there is one interesting feature visible in Fig. 4 at about 400–600 μs that has a significance of ~2.5σ.

Figure 4. This autocorrelation function shows the marginal evidence for an excess of activity around time-scales of 0.5–0.6 ms. The maximum lag parameter $\tau$ is ~9 ms.
Discussion

In dealing with the burst phenomena there are two basic questions to ask. First, are the detected bursts real in terms of a statistical approach that allows for any selection effects and secondly, believing the features to be significant, are they the cause or effect of longer time-scale structure such as the shot pulses?

SHOT NOISE/BURST RELATIONSHIP

The concept of the bursts powering the shot noise model was strengthened by the assertion of Weisskopf et al. (1975) that bursts of the observed size and rate are a basic consequence of the shot noise model. This simulation was based on Uhuru data for which all the shot noise parameters had been unambiguously deduced using the mathematical technique of Sutherland, Weisskopf & Kahn (1978).

The prediction of this simulation could be made to agree well with the observations of Rothschild et al. (1974, 1977) by varying the values of the Uhuru parameters (rate of shots, decay time, fraction of total flux in shots) and also showed the same deficit of zero height bins. A similar simulation to that of Weisskopf has been set up by Gowan (1978, private communication) who, using the above parameters and the SL-1306 count rate, obtained the data shown in Table 3. This is compared with the simple Poisson expectation and the actual observed values. The simulation is less like the actual data than the simple Poisson prediction, probably due to the large random background contribution since the 30 per cent fraction of flux in the shots (Weisskopf et al. 1978) only represents ~ 12 per cent of the total count rate for SL-1306.

These shot simulations are normally performed with an exponential pulse profile to match the observed pulse shape although a square profile can also give reasonable results. More recently Priehorsky et al. (1979) have shown the shot profile to look more like that expected for a rising exponential than a falling exponential but their data are not consistent with either profile. All these shot simulation profiles have an instantaneous rise or fall and it is open to question that any 'high frequency spikes' in the output of the simulation may be due to the unrealistic severity of the chosen pulse profile. This provides an explanation for the bursts tendency to cluster which could be interpreted as evidence for a piling up of
Table 3.

<table>
<thead>
<tr>
<th>N(n)</th>
<th>a priori binning</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>Poisson</td>
</tr>
<tr>
<td>0</td>
<td>3616</td>
</tr>
<tr>
<td>1</td>
<td>4496</td>
</tr>
<tr>
<td>2</td>
<td>2865</td>
</tr>
<tr>
<td>3</td>
<td>1264</td>
</tr>
<tr>
<td>4</td>
<td>417</td>
</tr>
<tr>
<td>5</td>
<td>115</td>
</tr>
<tr>
<td>6</td>
<td>24.2</td>
</tr>
<tr>
<td>7</td>
<td>5.5</td>
</tr>
<tr>
<td>8</td>
<td>1.0</td>
</tr>
<tr>
<td>9</td>
<td>0.15</td>
</tr>
<tr>
<td>10</td>
<td>0.02</td>
</tr>
</tbody>
</table>

the shot pulses. This correlation can, however, also be explained by other effects outlined below. Further comment on the shot noise/burst relationship awaits observations by much larger instruments.

INDIVIDUAL BURST ASSESSMENT

The concept of multibin flares and their treatment by Press & Schechter (1974) has already been described but they also point out the great importance of the local mean estimate (λ). The probability of a burst can depend on the time variability of the source over a much longer time-scale than the actual burst since any broad small increase in λ can be statistically undetectable in the noise but will dramatically increase the local probability of a single bin excess. They give a correction factor to the normal Poisson test of

\[ \text{exp} \left[ {K_0}(1 - \gamma^{-1})\Delta\lambda \right], \]

where \( K_0 = \) bin height, \( \gamma = K_0/\lambda \) and \( \Delta\lambda = \) uncertainty in local mean.

The correction factor can become appreciable if \( \Delta\lambda \) is large but for the present ms bursts is always < 2. To minimize \( \Delta\lambda \) sufficient bins must be averaged but taking too long an interval can create other problems if the mean rate clearly changes as is the case for bursts occurring in enhancements.

Once the enhancement is within the averaging interval, varying this interval’s width has two opposing effects on the chance expectation of the enclosed burst. Averaging over more bins increases the chance expectation of the burst but at the same time reduces the mean and therefore decreases the chance occurrence. For such a sample of data there will occur an optimum averaging interval which provides the lowest chance expectation value and hence the highest probability of the burst being a real feature.

Turning now to the example of a burst in Fig. 2 it is clear that in comparison with the data obtained by Rothschild et al. (1974, Fig. 2) this feature does not occur during an enhancement. The fact that the features seen are slightly less significant than the somewhat arbitrary limit of \( E < 0.01 \) merely reflects the advantageous selection effects in this section of Rothschild’s data. If the comparison is confined to only the data in these two figures the present data become the more significant.

The above argument does not, however, apply to the remaining 10 bursts from the 1973 flight that did not occur during short enhancements. Meaningful comparison with these ‘isolated’ bursts is difficult since the present data sample is so short.
Another consideration is the overall probability of the $E < 0.01$ bursts within the entire data set. This is meaningless if the bursts are merely detectable due to a combination of source count rate and statistical method. This point is discussed below where an attempt is made to compare all the observations of ms bursts so far reported.

SENSITIVITY TO BURSTS OF DIFFERENT INTRINSIC INTENSITY

The important parameters in defining the bursts’ probability are $K_0/\lambda$, $\lambda$, and $\Delta \lambda$. The mean rate $\lambda$ from the source will be approximately proportional to the detector area as will the intensity of the bursts $K_0$. The expectation value, however, decreases very rapidly and only a modest increase in area takes bursts from being marginal cases to ‘clear’ certainties.

To identify a burst some statistical analysis must be used and this will automatically define a clear division between detectable and undetectable features for any given detector area and source state. The analysis method of Rothschild can conveniently be expressed in a diagrammatical form as shown in Fig. 6. Every burst must lie on one of the diagonal straight lines, only those above the centre dotted line being detectable as a burst at the $E < 0.01$ limit for an averaging interval of 320 bins. If the source has a characteristic burst size of a particular $\gamma$ value it is clear that small experiments with a low mean value $\lambda$ per bin and low $K_0$ are immediately at a disadvantage. A low mean per bin is inevitable since the bin size must be less than or equal to the time-scale of interest. Doubling the detector area and observing the same $\gamma$ flare with $\lambda$ and $K_0$ at twice the size may just be sufficient to cross the threshold line. In addition to the present data Fig. 6 also shows some individual bursts mentioned in the literature; however, this graph takes no account of respective detector areas, energy ranges or exposure times. The relevant data are shown in Table 4 where $A$ is the detector area and $f$ the observed X-ray intensity. The Toor (1977) result for Circinus X-1 is also included for comparison.

Cygnus X-1 will presumably emit flares of varying $\gamma$ but there may well be an actual characteristic value since large $\gamma$ flares may be very rare and low $\gamma$ flares cannot be detected with small experiments.

Figure 6. This plot shows the reported ms bursts on a plot that combines the various parameters ($K_0$, $\gamma$, $\lambda$). The dashed probability curves were obtained using an iterative computer method. Most of the bursts tend to cluster near the same probability irrespective of the experiment used.
The prominent bursts seen by several observers certainly seem real to some extent and cannot be explained away entirely by the various factors discussed previously. The tendency for clusters of bursts to occur also follows naturally from the limitations imposed by any reasonable statistical analysis. It is suggested that for a small experiment the number of bursts found simply depends on the ratio of the time the source is above the threshold statistical level (only during enhancements for small experiments) to that below. The flares seen by Rothschild (1974, Fig. 2) with $\gamma = 3$ and $K_0 = 8$ would not be seen for $K_0 = 4$ and therefore these bursts are possibly far more frequent than the observation immediately suggests and may occur all the time as has been tentatively suggested by Canizares, Laufner & Primini (1976) using SAS 3 data. The other Rothschild bursts occurring during non-enhanced periods of lower $K_0$ must have had a higher value of $\gamma$ to be detected by the $E < 0.01$ criterion and were therefore relatively less frequent during the entire observation. The above factor explains why bursts are not commonly seen from Cyg X-1 and indeed it is somewhat surprising that the relatively small detector system of Ogawara et al. (1977) located so many. This implies a higher characteristic $\gamma$ during this particular observation. If bursts power the shots, since shots are present all the time bursts will also be and many might exist just below previous detector area thresholds.

Again if we assume that burst intensity is proportional to source intensity (reasonable if bursts power the shots) then tripling the detector area can be approximately negated by halving or less the intrinsic source intensity. This is the case for SL-1306 with bursts being seen during a non-enhanced lowish intensity state.

It is interesting to conjecture that if the data had been obtained for a full 240 s then a whole series of bursts ranging from those actually seen up to several $K_0 = 27$, $\gamma = 6$ flares might have been detected. This represents a fundamental change in the certainty of the observation since the chance expectation value would decrease from $10^{-2}$ to $10^{-9}$ for bursts such as those seen by Rothschild et al. (1974). Such an observation would also enable a clear study of the reported burst periodicity (Boldt 1977) since some of the weaker preceding bursts would be individually detectable.

Conclusion

The Cygnus X-1 data obtained at binary phase 0.25 by SL-1306 is consistent with the shot noise model first proposed by Terrell (1972).

Burst no. 4 in Table 2 is significant using the unpaired Rothschild analysis method but the others are not although two more are found with $E < 0.02$ (nos. 1 and 2). Two paired bin bursts are found with ($E < 0.01$ uncorrected, nos. 2 and 3).

The SL-1306 bursts scale to an intrinsic intensity $\sim 1/3$ of those seen by Rothschild et al. (1974) who note that their analysis method would have found none of the bursts they
actually located if their detector had been only half the area (equivalent to a source of half the intensity). The aligned burst profile (Fig. 3) suggests that the latter half of the 0.5 ms bursts are more intense than the first and end sharply. This time-scale of 0.5 ms in 1976 November compares with 0.6—0.7 ms in 1975 September (Ogawara et al. 1977) and 1.0 ms in 1973/4 October (Rothschild et al. 1977). Three 0.5 ms bursts have been found when less than 0.24 are expected by chance during the 3 s in which the count rate is sufficient to detect these $\gamma \sim 6$ bursts at the $E < 0.02$ significance level. These three bursts in fact occur within a space of about 1 s in Fig. 1. This implies a rate of $\sim 1$ s$^{-1}$ which would appear to support the suggestion by Canizares et al. (1976) that aperiodic millisecond structure is a constant feature of the source. The autocorrelation function in Fig. 5, however, does not indicate the presence of a large number of individually undetected ms bursts, in agreement with the analysis by Friedhorsky et al. (1979), though there is a slight indication of an excess around 500 $\mu$s.

Further study of millisecond bursts demands both a high data rate telemetry system and a detector area of order 0.5 m$^2$ or greater. There can be no substitute for detector area and with the rapid demise of HEAO-1 no such experiment exists in the near future.

Acknowledgments

This project has benefited greatly from the advice of many members of the X-ray Astronomy Group but I wish to particularly acknowledge the assistance of C. H. Whitford and D. J. Watson. I should also like to thank the B.A.C. team who carried out the vehicle preparation and launch and the SRC who provided a Research Studentship for the early part of this work.

References