

Dying Pulse Trains in Cygnus X-1

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Dying pulse trains, created by material spiraling towards an event horizon from the last stable orbit of the inner edge of an accretion disk surrounding a black hole, exhibit pulses of decreasing intensity with diminishing intervals between them. The detection of such pulses would positively identify the existence of an event horizon. Cygnus X-1 was observed in the 2-15 keV X-ray region during the low and low-high failed transition states using the RXTE proportional counter array. No dying pulse trains were found in 2 hours of observation, although X-ray pulses were clearly detectable in the data.

Introduction

As predicted by General Relativity, a black hole is a point singularity surrounded by an event horizon. The event horizon will lie at $R_s = 2Gm/c^2 = 3 \text{ km} \cdot m/M_\odot$. Stable Keplerian orbits are able to exist when $r \geq 3 R_s$ with the innermost stable orbit having a period of $P = 0.6 \text{ ms} \cdot m/M_\odot$. The last stable orbit will define the inner edge of the accretion disk of orbiting material surrounding the event horizon (Dolan 2001).

Dying pulse trains of radiation are emitted as matter breaks off the inner edge of the accretion disk, where it is no longer able to keep a stable orbit around the black hole and spirals in to the event horizon (Stoeger 1980). Due to Doppler and aberrational effects, the orbiting matter will appear to emit a pulse of radiation each time it orbits the black hole (Cunningham & Bardeen 1972). The intensity of the pulses will decrease with each orbital revolution around the black hole, with the final pulse displaying the weakest intensity before disappearing. If the compact object were a white dwarf or neutron star, however, the final pulse would be expected to have the greatest flux, signifying the existence of a solid surface impact following acceleration from the object's gravitational field. The separation between consecutive pulses will also decrease as the orbital period decreases for both cases (Dolan 2001).

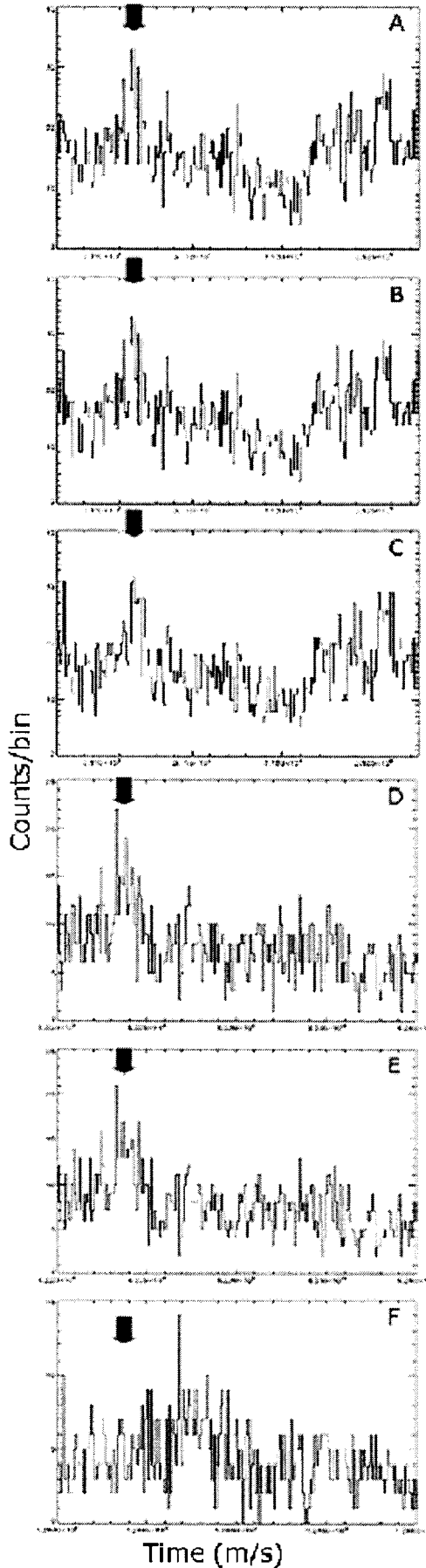
The Cygnus X-1/HDE 226868 system is a leading candidate for housing a greater than 5 solar mass black hole (Dolan 1989, 1992). Evidence of dying pulse trains in this system would signify the existence of an event horizon.

Observations and Reduction

Cyg X-1 was observed across low and low-high failed transition accretion states using the proportional counter array on the Rossi X-ray Timing Explorer. Three epochs of data were obtained from the Goddard Space Flight Center RXTE archives. The journal of observations is given in Table 1. Data from the low (~2-6 keV) and high energy bands (~6-15 keV) was combined in order to produce the entire X-ray bandpass for each epoch. After being broken down into 200 second segments (819200 data points per 200 second set), each data set was binned into time increments ranging from 10 ms-0.25 ms to produce the highest signal-to-noise ratio and separate statistical variability from actual pulse occurrence.

DATE OF OBSERVATION:	TIME OF OBSERVATION:	ENERGY LEVEL:	STATE OF CYG X-1:	TIME RESOLUTION:
2/11/2000	10:49:20-11:20:08	2.1-15.6 keV	Low-high failed transition	244 ms
2/26/2000	8:06:32-8:52:15	2.1-15.6 keV	Low	244 ms
3/26/2006	6:58:24-7:33:09	2.06-15.18 keV	Low	122 ms

Table 1: Observations of Cyg X-1/HDE 22868 using RXTE



Each 200s time segment was examined for evidence of X-ray pulses ($>3\sigma$ above mean) in series occurring across multiple time binnings. If observed, individual pulses were then examined in detail for each time binning to search for the occurrence of dying pulse trains. Various phases between time binnings were also examined in order to place each bin at the center of the FWHM and differentiate between statistical variation and actual pulses.

Data Analysis

A pulse is defined as a peak in intensity occurring at least 3σ above the average count rate that is apparent across multiple time binnings. Dying pulse trains are expected to have the following characteristics that distinguish them from a typical X-ray pulse (Dolan 2001; Stoeger 1980):

1. The pulses should occur in series of 3 or more.
2. Individual pulses should occur at least 3 standard deviations above the mean count rate.
3. The separation between pulses should have a time period given by the equation $P = 0.6 \text{ ms} \cdot m/M_{\odot}$; for an estimated mass of $>5 M_{\odot}$ for Cyg X-1 (Dolan 1989).
4. The separation between each successive pulse in the series will decrease as the orbital period decreases.
5. The FWHM of each pulse is $\sim 10\%$ of the time interval between pulses.
6. The intensity of each pulse decreases toward the end of the dying pulse train. It is possible that the last pulse in the series would fall below 3σ significance above the mean count rate, but still be part of a dying pulse train.

These characteristics of pulse trains should be detectable with a very high signal-to noise and all should be apparent for any given significant event. A pulse should occur during multiple phases of a data set with a given time resolution, as well as with multiple time resolutions (Dolan 2001).

Typically, the statistical variability of the data will cause the counts to shift when examined at various phases. Those occurring without great variation through multiple time binnings and phases show evidence of a true pulse.

Figure 1: A typical 3σ event that meets the pulse criteria, but fails to satisfy dying pulse train characteristics. Observations A-C have a 5.0 ms time resolution, D with a 2.5 ms time resolution and E -F are at 1.25 ms with variant phases for each. As evidenced, the pulses appear to break down due to statistical variability when binned at multiple time resolutions.

Although several X-ray pulses were apparent in the observed data, characteristics of dying pulse trains (i.e. 3 or more pulses of decreasing intensity at period more pulses of decreasing intensity at period P , while orbiting the inner edge

of the accretion disk) were not seen across multiple time binnings and phases.

As shown in Figure 1, the data initially appears to exhibit a series of 4 decreasing pulses across several time binnings. When examined at greater time resolution the bin counts begin to shift due to statistical variability. Although there appears to be an actual pulse occurring with more than 3σ significance, when examined across multiple phases and time resolutions the pulse breaks down and criteria for a dying pulse train is no longer met. After examining two hours of X-ray data, several of these pulse occurrences were observed, yet they all failed to meet the criteria for dying pulse trains across multiple time resolutions and phases.

Conclusions

No dying pulse trains were detected in two hours of X-ray data observed from Cygnus X-1, yet evidence of pulses were apparent. A few theories as to why no dying pulse trains were observed in the data are as follows:

1. Dying pulse trains are too faint to be seen in the X-ray region. Due to the abundance of background radiation from the accretion disk, pulse trains could be potentially difficult to distinguish from X-ray pulses given off by the accretion disk.
2. The occurrence of dying pulse trains could be more common in other states of Cyg X-1, than the states observed. Since only low and low-high failed transition states of the candidate source were observed, it would be beneficial to look at the behavior of the source in its other states, mainly high and high-low transitions for evidence of dying pulse trains.
3. Cygnus X-1 may be a poor candidate for detection of dying pulse trains. Further study of other potential black holes would be beneficial.

Although no dying pulse trains were detected in this study, further research of black holes is required to gain adequate understanding of the nature of their systems. Future work would require acquisition of additional data to include in the study of dying pulse trains. Observing other various candidate black holes, across multiple accretion states would be valuable in creating a larger overview of such systems. Additional data from various other energy levels in addition to the X-ray spectrum would be also useful for the study of this subject.

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