Correlation Between Spectral States and Dynamical States of Cygnus X-1

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Abstract

The prototype black hole candidate (BHC) Cygnus X-1 is the brightest visible x-ray source, displaying two distinct spectral states. Cygnus X-1 is presumed to emit x-ray due to the accretion of matter onto an accretion disk where it is heated to temperatures on the orders of millions of degrees leading to x-ray and gamma ray emission. These emissions have two characteristic spectral states, determined by the number of photons detected per unit time. In addition, Cygnus X-1 displays distinct dynamical states. These dynamical states are most likely determined by the behavior of the accretion disk. Searching for the existence of a correlation between the spectral and dynamical states of this black hole candidate is the focus of my study.

Introduction

Speculation about 'dark stars' dates back centuries. With the birth of Einstein's theory of relativity, the black hole eventually evolved in to an object of serious scientific study, rather than a theoretical notion. Study of the black holes' x-ray emissions has become the primary method of analysis of these stellar bodies. Cygnus X-1 has remained the leading black hole candidate, while others have eventually been proven to be neutron stars or white dwarfs, the black hole's closest relatives in the evolution of the life of a star.

With the advent of ballistic missile technology in the 1950's, detection of astrophysical x-rays became possible. When strong signals persisted from the region of Cygnus, scientists delved in to the study of this strange new discovery. Of the variety of sounding rockets, balloons or satellites that have monitored the x-ray emissions from Cygnus X-1 since the 1960's, the European X-ray Observational Satellite, or EXOSAT[1], had the most eccentric orbit (eccentricity of 0.93). This allowed an orbital period of 90.6 hours and 76 hours of continuous observation (Rebull 1992). This data was chosen for my study because of the long time series. Figure 1 shows a schematic diagram of EXOSAT satellite.

[1] EXOSAT was operational from 1983 through 1986.

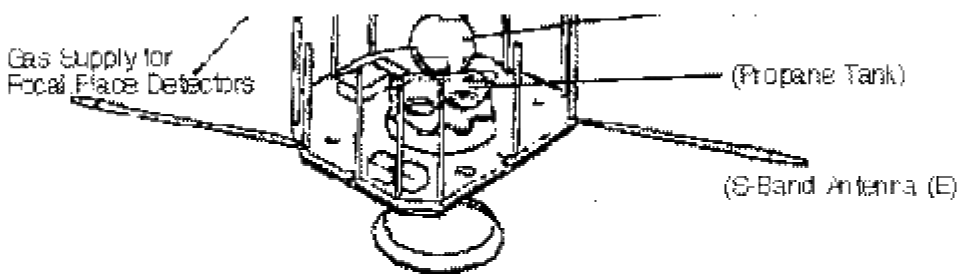


Figure 1 Schematic diagram of EXOSAT

History

The earliest speculation about ‘dark stars’, now known as black holes, dates back to 1783. British astronomer John Mitchell proposed that there could be a star so massive that its gravitational pull would be strong enough to draw light waves back to its surface. This creates the illusion of a ‘dark star’ for a sufficiently distant observer (Hawking 1988). Indeed, light waves leaving a gravitational body as massive as a black hole become trapped and are dragged back to the star faster than they can escape (Harrison 1981). Escape velocity from a planet or star (from Newton’s laws) is

$$v_e = \sqrt{\frac{2GM}{R}}, \tag{1}$$

where G is the universal gravitational constant, M is the mass of the object and R is the radius of the object (Harrison 1988).

In the case of a black hole, the escape velocity is dependent on the coordinate value from which escape is attempted. Outside the event horizon, while escape is still possible, the sheer mass of the hole increases the value of the escape velocity (as seen by the mass dependence in Equation 1). Close to the event horizon of a black hole, Equation 1 no long applies and the general theory of relativity must be used[2].

[2] Newton’s laws apply to a black hole, to a good approximation, outside the event horizon up to a few Schwarzchild radii.

Einstein's theories of relativity made stars of virtually infinite gravitational pull a scientific reality. Prior to Einstein's discoveries, Mitchell's 'stars' had not been convincing to all astronomers. Despite the great success of his theories, Einstein considered the idea of these 'dark stars' preposterous (Thorne 1994). In 1916, he published his theories of relativity and gravitation to prove the impossibility of the existence of black holes. Ironically, those same theories are now used to argue the inevitability of the demise of a massive star into a black hole (Scientific American 1996).

With this sound mathematical basis, the next step was to attempt to observe a black hole. Because direct optical observation is very difficult, methods of observing outside of the visible spectrum were devised. These objects having the greatest intensity and visibility in the x-ray range. X-ray astronomy began with the launch of the NASA's Uhuru satellite, the first to provide continuous observation of x-ray sources with good time resolution and sensitivity (Gursky 1975). In 1964, the strong x-ray source in the vicinity of the constellation Cygnus (Figure 2) was named Cygnus X-1 (Figure 3) and three years later in 1967, John Wheeler named these stellar objects "black holes" (Thorne 1994). Since then, black holes[3] have become mainstream and are now considered the most likely explanation for the energy source of quasars and active galactic nuclei. Cygnus X-1 was the first x-ray binary considered to be the most probable site of a black hole; it has successfully maintained this title. Since its initial discovery, similar sources have claimed the title of black hole, only to be proved to be either one of the black holes' closest relatives – a neutron star or a white dwarf (S&T 1996).

[3] The existence of "black holes" is still circumstantial, although the accumulated evidence is convincing to some astronomers. Their existence is maintained as a working hypothesis and used with this understanding in this report.

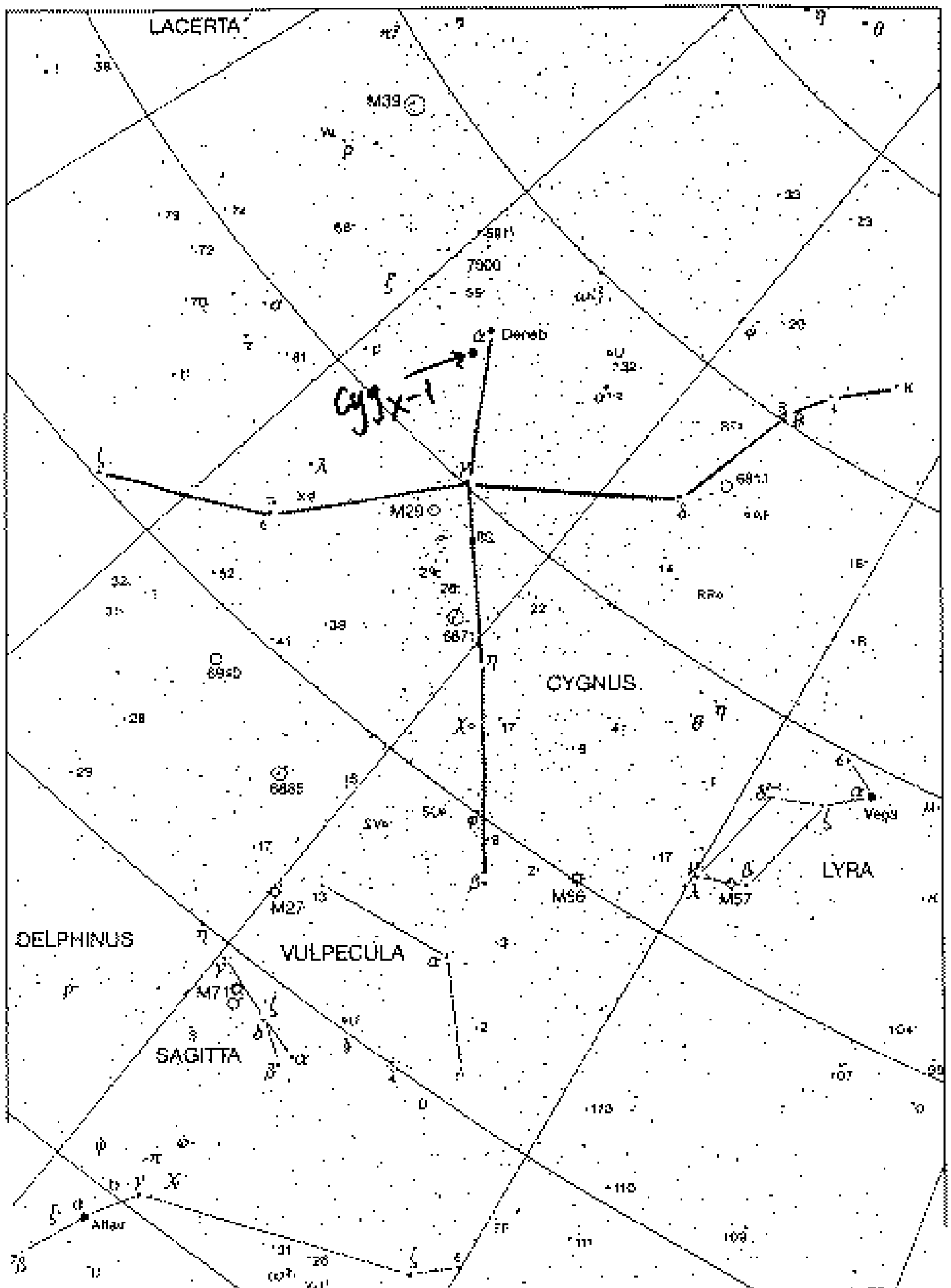
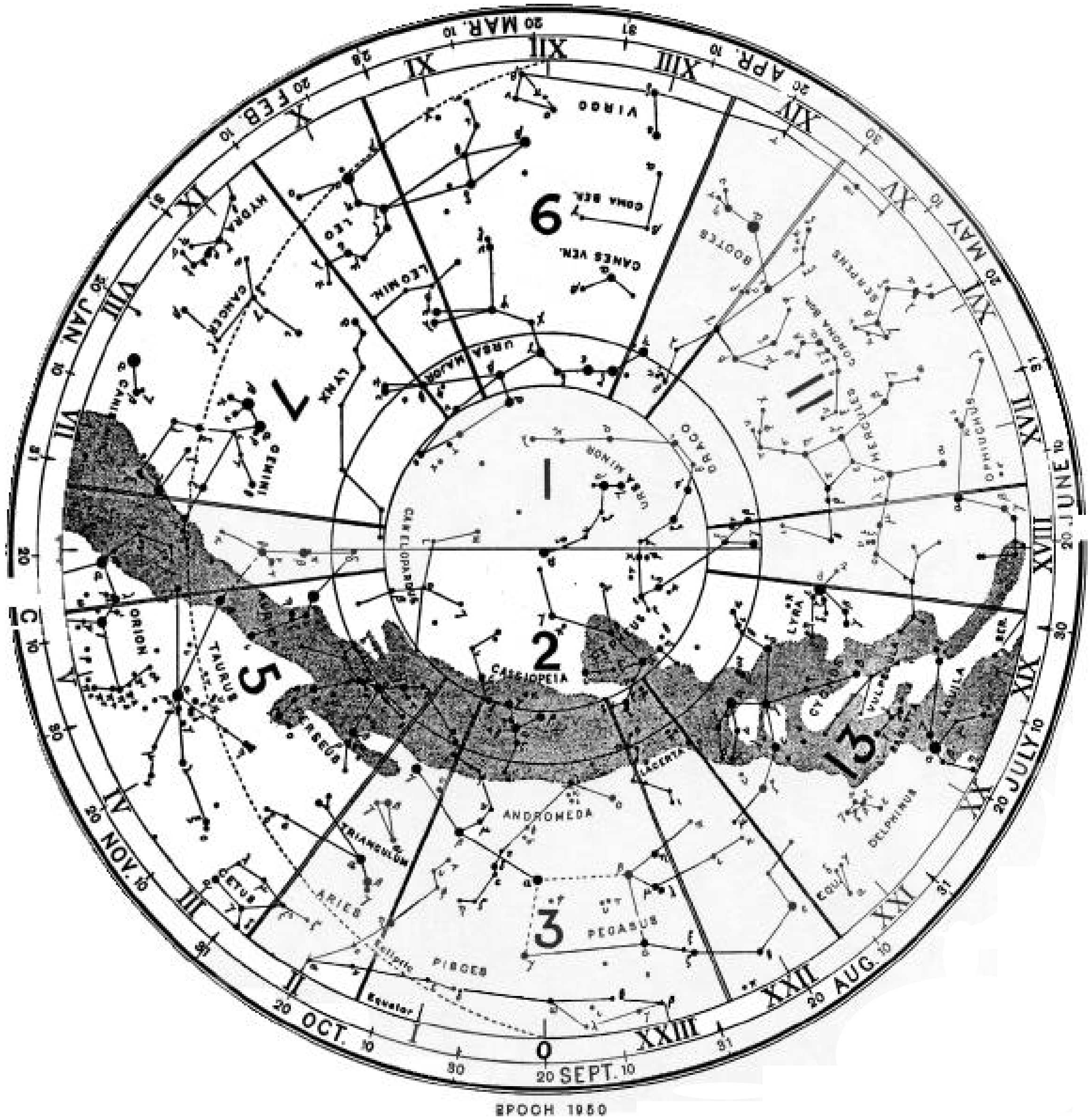


Figure 2 Constellation Cygnus and approximate location of Cygnus X-1


EPOCH 1950
ANDROMEDA
PEGASUS
PISCES
ARIES
TRIANGULUM
CASSIOPEIA
ORION
TAURUS
GEMINI
LYNX
LEO
LEO MIN.
URSA MAJOR
CANES VEN.
COMA BER.
VIRGO
BOOTES
CORONA BOR.
HERCULES
OPHIUCHUS
LYRA
AQUILA
DELPHINUS
CAMELOPARDUS
URSA MINOR
DRACO
LACERTA
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HYDRA
CANCER
Equator
Ecliptic
20 SEPT.
20 OCT.
20 NOV.
20 JAN
20 FEB.
20 MAR.
20 APR.
20 MAY
20 JUNE
20 JULY
20 AUG.

Figure 3

Formation and Structure

The Origins

Formation of a compact stellar object occurs when a massive star that has exhausted its fuel and can no longer maintain static pressure collapses under its own gravity. The immense gravitational force causes the collapse to continue until all that is left of the former star is an extremely compact collection of matter where light is trapped (Silk 1989). Depending on the size of the star before collapse, the new compact star can form one of three objects – a white dwarf, a neutron star, or a black hole (Figure 4). A white dwarf is the more distant relative, formed by the collapse of a low-mass star on the order of the mass of the sun. Many of the physical characteristics of the neutron star, however, are shared by the black hole to the point where they are almost indistinguishable. Determining whether an x-ray source is a neutron star or a black hole is made by studying the spectrum; a neutron star and black hole have uniquely distinguishing spectral graphs (Begelman 1996).

A method of determining what a star will becomes after collapsing was developed by Subrahmanyan Chandrasekhar in 1930. White dwarfs originally more massive than 1.4 solar masses will continue collapsing into a singularity. This is known as the Chandrasekhar limit (Scientific American 1996). In black holes, this core is known as the singularity. All the mass from its former stellar state is compacted in this singularity, which takes up no more space than the size of single nucleus of an atom (Hawking 1988).

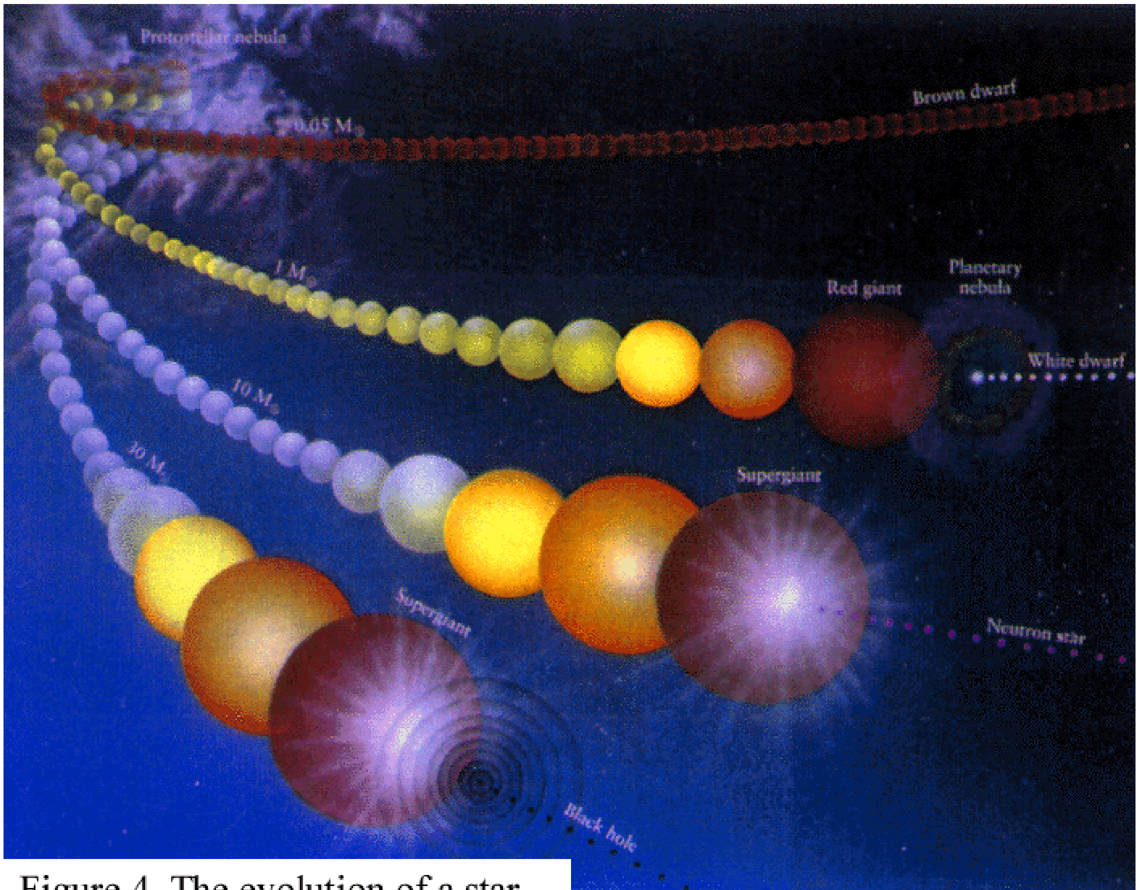


Figure 4 The evolution of a star

Another way black holes might have formed is during the Big Bang. The intense chaotic and inhomogeneous state of the early universe may have caused the collapse of matter in a local region (Silk 1989). In this way, collapsing stars or clusters of matter of mass less than the critical value (< 3.2 Solar masses) can gain enough kinetic energy to tunnel through the neutron star equilibrium, compacting down to a singularity (Ruffini 1975).

The Central Structure

The structure of a basic black hole consists of two parts, one, the above mentioned singularity, and two, the event horizon. The event horizon is an invisible surface from which particles on the outside with sufficient escape velocity could still evade the clutches of the hole's gravity. One step inside the event horizon is impending doom for any matter or light. No hope of escape exists. The radius of a black hole is defined as the coordinate value of the event horizon[4]. Cygnus X-1 has a "radius" of 15km (Pickover 1996); the sun, in comparison, is $7x10^5$ km in radius (Harrison 1991). Within its small radius, Cygnus X-1 has a measured mass of 10 to 15 solar masses (Sky and Telescope 1997). A summary of masses and radii of a number of stellar objects is shown in Table 1.

Table 1 A summary of masses and radii of Cygnus X-1, the Sun, and a neutron star.

Object Name	**Radius (km)**	**Mass (solar masses)**
Cygnus X-1 (BHC)	15 #	12 *
Sun	$7x10^5$ *	1 **
Hercules X-1 (neutron star)	10 ##	1.4 ##

*Source from ASCA 1999 # Source from S&T 1996
** Source from Tipler 1991 ##Source from http://hea-www.harvard.edu/~bboroson

Figure 5 illustrates the evolution of a star in mass vs. radius. When bodies contract they move down toward to black hole line, the region shown in dark. Black holes, despite all their mass, do not differ greatly in radius from white dwarfs and pulsars, both of which are much less massive.

[4] The radius of the event horizon is a relative term due to the severity of space-time warp around the black hole. "Coordinate value" is the more accurate term for these purposes.

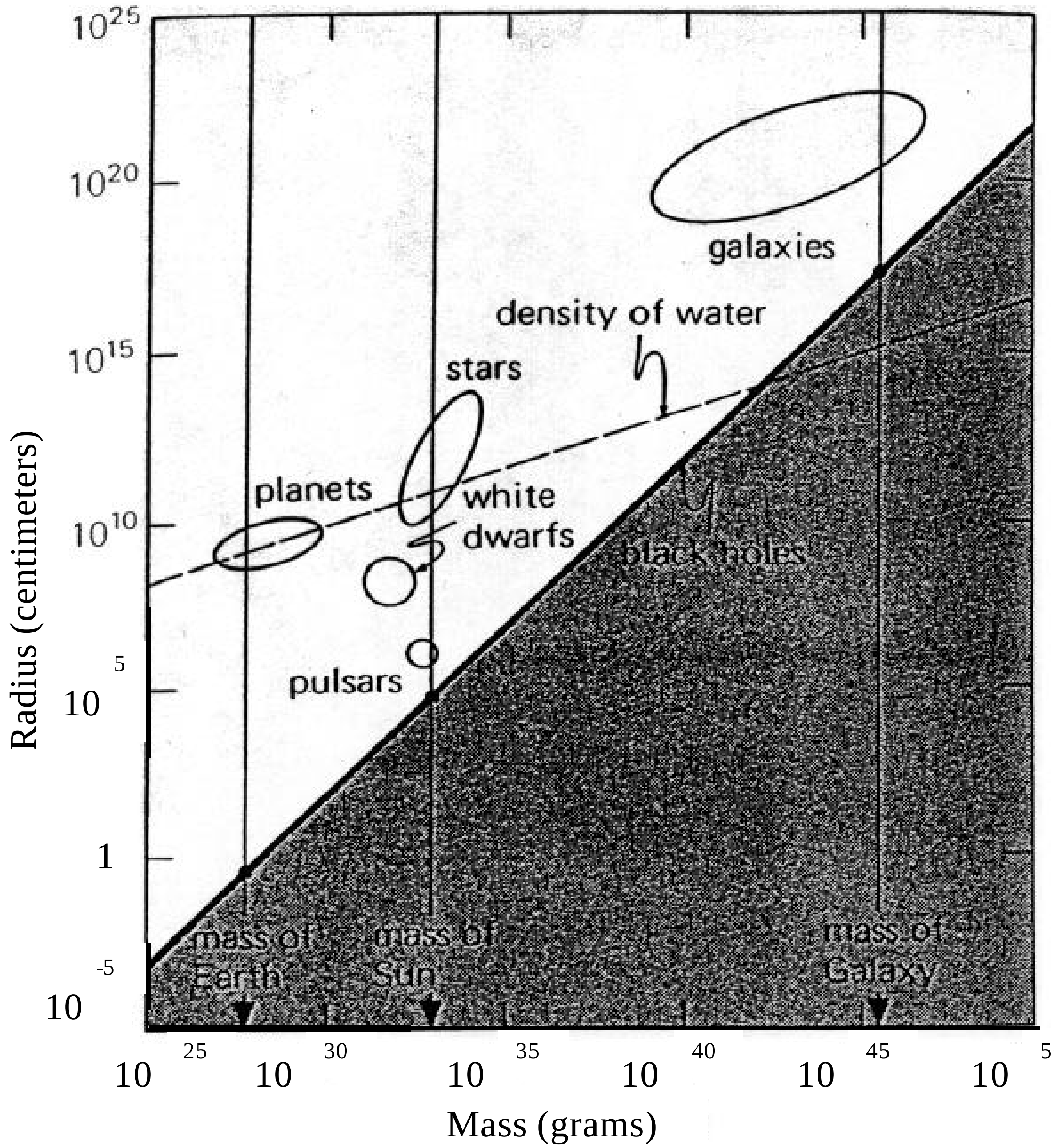


Figure 5 Mass and Radius of Black Holes

The Accretion Disk

One of the most spectacular side effects of a stellar body of significant mass is the effect of its gravity on particles of dust and gas. A body, such a black hole, draws in interstellar particles from its surrounding space. As these particles come in to the black hole's orbit, they are drawn into the shape of a disk. Twirling around the black hole, the highly ionized particles fall in to orbit with angular momentum (Moche 1993). Due to the successive layers of matter orbiting the black hole, viscous forces are produced. Forces on inner particles due to outer particles cause the outer particles to lose momentum, whereby the outer particles begin to spiral inward. The multitude of layers of inner and outer particle interaction results in a steady stream of particles falling in to the black hole, while the supply of particles is maintained by the continual accretion of matter from the surrounding regions or the companion star of a black hole (Begelman 1996).

These accretion disks, although presumably pretty sights from a distance, are actually violent furnaces. The release of gravitational energy into kinetic and thermal energy during the accretion process is the source for the energetics of the system. An accretion disk around a black hole extends inward to the closest stable orbit corresponding to a period of about one thousandth of a second. As a result, the in-fall time of matter is some 100 times this period, leading to energy pulsations at periods on the same order as the disk's stable orbital period (Gursky 1975). The heat generated by the viscous dissipation climbs to the order of 10^8 Kelvin. Temperatures of this magnitude lead to strong x-ray emission (Begelman 1996). Due to the intensity of the heat in an accretion disk, astronomers detect black hole candidates by searching for intense x-ray sources. Table 2 lists characteristic temperatures of the electromagnetic spectrum and associated wavelengths of peak emission for blackbodies. Because of the high intensity of the x-rays, the relative temperature range of the accretion disk can be determined.

Table 2 The Electromagnetic Spectrum of Blackbody Radiation.

Type of Radiation	**Wavelength Range (nm)**	**Temperature Range (K)**
Gamma Rays	< 0.01	$> 10^8$
X-Rays	0.01 – 20	$10^6 – 10^8$
Ultraviolet	20 – 400	$10^5 – 10^6$
Visible	400 – 700	$10^3 – 10^5$
Infrared	10^3 - 10^6	$10 – 10^3$
Radio	$> 10^6$	< 10

From “Astronomy Today” by Chaisson and McMillan

In detailed numerical studies of the structure of the accretion disk, astronomers found the ‘disk’ is not as flat as it seems (http://image.gsfc.nasa.gov/poetry.astro.q1766/html). Twist and ripples cover the plane of the disk, possibly due to gusts of ‘wind’ from the disk itself. These predicted phenomena in the disk have never been observed.

The Roche Lobe

Roche lobe is formed around binary systems and is defined as the theoretical shape in which all points along the lobe are at the same gravitational potential. Figure 6 shows a diagram of a system of two bodies in orbit and the associated Roche lobes (Ruffini 1975).

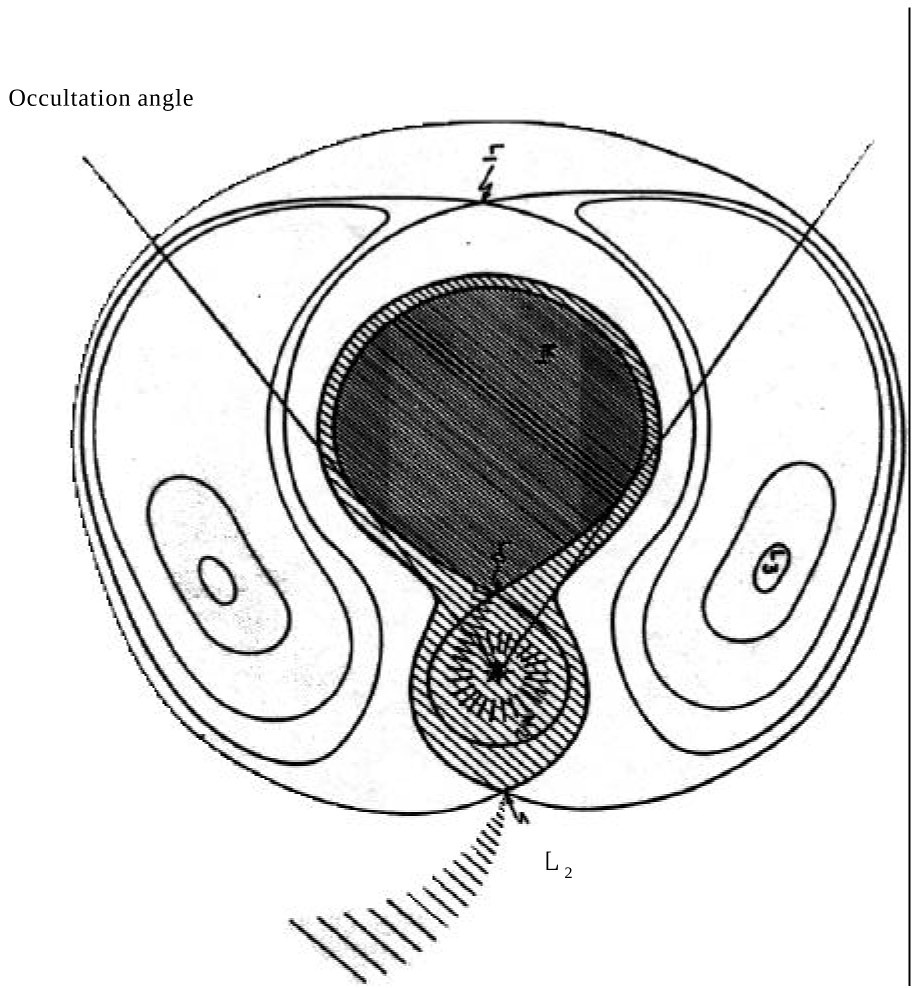


Figure 6 A binary system, its equipotential lines and the Roche lobes

Points L_0, L_1 and L_2 are the Lagrange points of the system, where the potential field lines cross and the forces of the two bodies are equal. The less dense companion, M_1, becomes elongated as it compensates for the difference in forces, filling its Roche lobe (Pickover 1996). When the tidal forces become stronger than the star can withstand, material spills over through L_0 into the Roche lobe of M_2, the black hole. It is within the limits of the Roche lobe of M_2 that the mass transfer occurs. Due to the angular momentum of the infalling matter, a disk forms around M_2. Radial viscous dissipation spreads the disk out to fill the limits of the lobe; the successive rings of accreted matter than begin rotating at different orbital speeds, leading to particle - particle friction and loss of momentum (Ruffini 1975).

Unlike neutron stars, x-ray binary sources draw energy from the gravitational binding energy of the infalling material (Ruffini 1975). The equation for constant equipotential bodies is defined as (Marion 1995),

$$\Phi = GM\left(\frac{1}{r_1} + \frac{1}{r_2}\right) = \text{constant}, \tag{2}$$

The first line of equipotential is the Roche limit, or the critical radius, which is determined by the mass of the black hole (Pickover 1996). This gravitational potential energy is given by[5]

[5] Source from Tipler 1991.

$$U = \frac{GM_1M_2}{r}, \qquad (3)$$

where the product of the masses of the two bodies is directly proportional to the potential, whereas the distance, r, between them is inversely proportional to the potential. The potential energy is converted into kinetic energy as matter falls in to the black hole, which gradually heats up to very high temperatures (Peterson 1997).

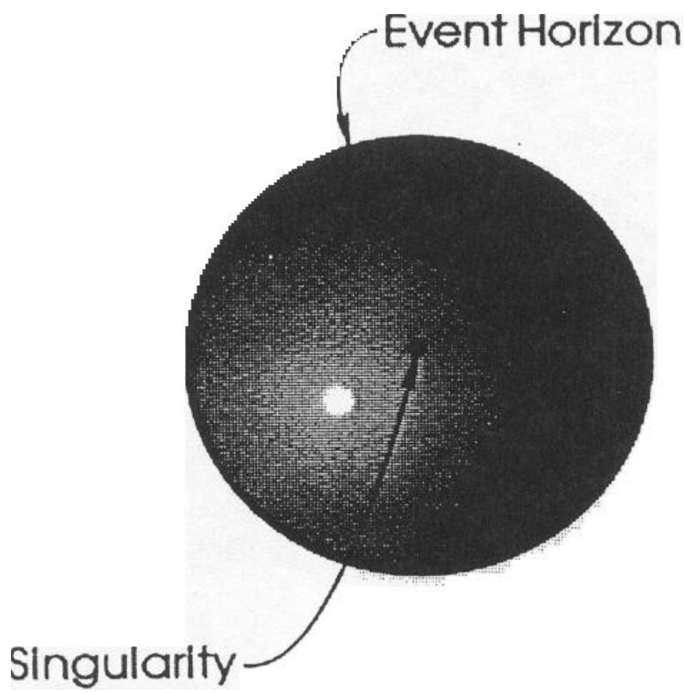


Figure 7 A Schwarzchild (static) black hole.

The Types

After collapse, the only distinguishing characteristics a black hole maintains are its mass, charge and angular momentum. Because no trails of the matter that made up the former star – whether matter or anti-matter, for example - are left, a black hole is said to have “no hair.” No other identifiable characteristics make one black hole any different from another (Thorne 1994). The simplest type of black hole, known as the Schwarzchild black hole, is composed of an event horizon and a singularity as illustrated in Figure 7. This static black hole neither rotates nor has an electric charge.

The Reissner-Nordstrom black hole is non-rotating and charged. Charged black holes consist of three parts: the singularity, the inner event horizon and the outer event horizon (Figure 8). The Kerr black hole is a rotating, non-charged hole and is considered the most common type. These rotating black holes consist of many parts. The singularity, instead of a single point, is doughnut shaped (if travel through space-time were possible, having survived the journey to the singularity one would be able to travel through its center to what could possibly be another dimension of the universe or another universe all together). This particular type of black hole houses two event horizons, the inner and the outer. Beyond the outer event horizon lies a region called the ergosphere, a region of violent rotation bounded by the outer event horizon and the outermost layer, the static limit (Figure 9). The forth type of black hole embodies both charge and angular momentum. This is the Kerr-Newman black hole (Pickover 1996).

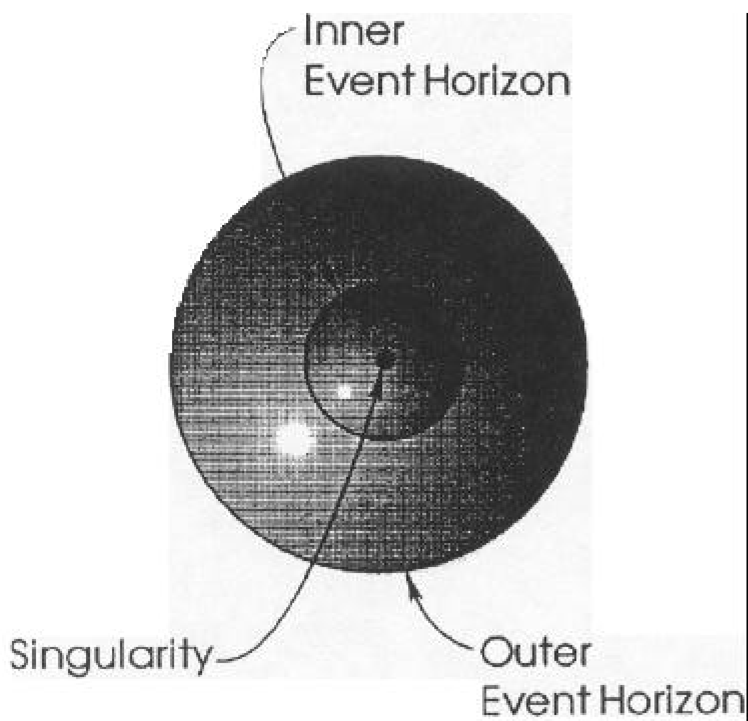
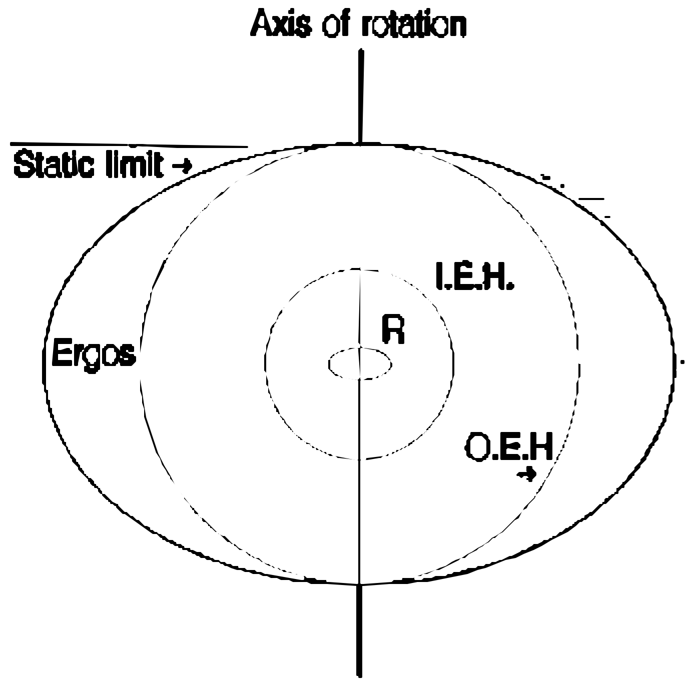


Figure 8 Artistic representation of a charged black hole.



Cross-section of a rotating black hole. (I.E.H. = inner event horizon; O.E.H. = outer event horizon; R = ring singularity)

Figure 9

Black holes radiate

In conjunction with the understanding of the different types of black holes came the understanding of their relation to pulsars and jets from active galactic nuclei. Energy extracted from rotating black holes causes them to become dynamos. This is called the Penrose process, where the extracted energy comes from the rotational energy of the rotating black hole (Pickover 1996). A black hole endowed with angular momentum and or charge can give up a finite amount of its total mass-energy. As a particle coming from infinity penetrates the ergosphere of a Kerr black hole, it decays into two particles. The negative elements of angular momentum and energy are lost in to the hole, while the positive elements are returned back out to infinity. The interesting property of this process is that the ejected element leaves with more energy than it went in with, effectively reducing the total rest mass of the black hole (Ruffini 1975). In this way, these rotating black holes can eventually stop spinning and become static black holes. Due to this radiation, black holes have been theorized to center active galactic nuclei, producing cosmic jets, as well as being the source of the highly energetic pulsars (Moche 1996).

Further evidence that black holes are not invincible is found in studying their entropy. In accordance with the First Law of Thermodynamics, a black hole neither creates nor destroys energy but merely converts the energy in to other forms. The Second Law concerning a system's entropy, however, is violated. Entropy is the measure of a system's disorder and should not decrease within a closed system (Halpern 1992). As matter is accreted, the accumulation of new particles leads to greater disorder and the system's entropy increases. Within the system of a black hole, matter accretion suggests a growth in the horizon. This cannot occur without the entropy also increasing (Hawking 1988). If, however, energy can be carried away from a black hole, its entropy would then decrease, violating the Second Law. The behaviors of a black hole cannot be explained without it having its own entropy. Subject to the black holes own laws, a new Second Law of Thermodynamics was created, allowing black holes to have entropy. Having entropy means a black hole also has a temperature and can emit light and heat, thus energy, and is susceptible to decay. Thus, black holes do radiate energy (Halpern 1992).

Observation

Due to the nature of black holes optical detection is extremely difficult. Although the distance of Cygnus X-1 from the Earth is shortest of the other black hole candidates, one of the only signs of existence of Cygnus X-1 is the strong, highly localized x-ray source. For comparison, distances of Cygnus X-1, other black hole candidates and other stellar bodies in relation to the Earth are summarized in Table 3. Around the time of its discovery, long looks at the source were difficult to obtain to produce any conclusive data. Spectral, temporal and spatial resolutions were all insufficient. The data acquired, nonetheless, led astronomers to the speculation that this bizarre object was a different type of stellar phenomenon than they had ever encountered. Contrary to Einstein's predictions, evidence continued to mount in favor of the existence of black holes and, further, that Cygnus X-1 might be one.

Table 3 Examples of distances of selected objects from Earth.

Object (type)	**Distance from Earth**
Cygnus X-1 (BHC)	8150 light years *
LMC X-1 (BHC)	175,000 ly ***
V404 Cygni (BHC)	11,000 ly ***
Sun (star)	1.6×10^{-4} ly **
Hercules X-1 (neutron star)	6520 ly – 19,560 ly *

*Source from Rebull 1992
**Source from Harrison 1981
***Source from "S&T" 1996

Most recently acquired data on Cygnus X-1 has allowed better spectral resolution, which has led scientists to pin point its location and to describe its properties and structure in more detail. Cygnus X-1 is part of an eclipsed x-ray binary, whose companion is a blue supergiant (Figure 10). The angle of precession of this binary system causes the companion star to be periodically eclipsed (Zeilik 1982). The black hole's peculiar spectral readings positively identify it as something other than a neutron star. Since Cygnus X-1 was first discovered, scientists could detect no periodicity, unlike pulsars of similar x-ray intensity. Its highly variable emission strongly suggested a black hole (Seitter 1994). Due to the extreme density of a neutron star, it shares the characteristics with a black hole of being dark, compact, and a strong x-ray source. Bursts of rays from these stars are the keys to their identities. Cygnus X-1, for example, exhibits a regular orbital period of 5.6 days, with rapid bursts of x-ray variations on time scales shorter than a millisecond. The duration of these outbursts set an upper limit on the size of the source producing the bursts. Cygnus X-1 is inferred to be about 15 kilometers in size, a rather small area for the signals to come from, thus suggesting a highly compact object (S&T 1996). The spectrum of a black hole peaks at a frequency around 10^{18} Hz, which corresponds to the x-ray region in the black body spectrum. These x-rays are emitted primarily from the inner parts of the accretion disk (Peterson 1997).

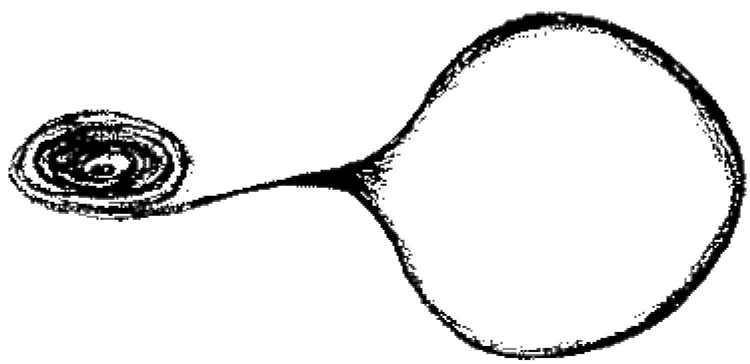


Figure 10 A binary system similar to that of Cygnus X-1 consisting of a supergiant and the black hole

These findings alone, however, are not enough to positively identify a source as a black hole. Flickering of this nature is also a property of neutron stars, which have radii much less than 300 km across. Further investigation of the x-ray spectrum yields a peculiar shape. Cygnus X-1, in particular, exhibits two distinct spectral states. The “soft” state consists of a high intensity of low energy x-rays and is thought to originate from an optically thick accretion disk (S&T 1996). The "hard" state is denoted by a smooth power law spectrum, probably originating from an optically thin region close to the center of the disk and the black hole (Ebisawa 1997). Intensity of the hard state is lower than that of the soft state by a factor of three (Gursky 1975). Transitions between these states are considered to be the best signature of a black hole candidate (S&T 1996).

Cygnus X-1 is usually found to be in the hard spectral state and transitions to the soft state are rather rare. In May 1996, Cygnus X-1 exhibited a rare hard-soft transition for the first time since 1980. From the observations, astronomers were able to limit the range of Cygnus X-1's mass, further securing it to be beyond the upper bound for the mass of a neutron star (2.9 Solar masses). The characteristic temperature of the soft component is significantly lower than that of neutron star binaries. Spectral graphs of the two states and that of a neutron star are shown in Figure 11 (S&T 1996). As the red line of Aquila X-1 shows, distinctions between neutron stars and black holes are evident by examining the spectra.

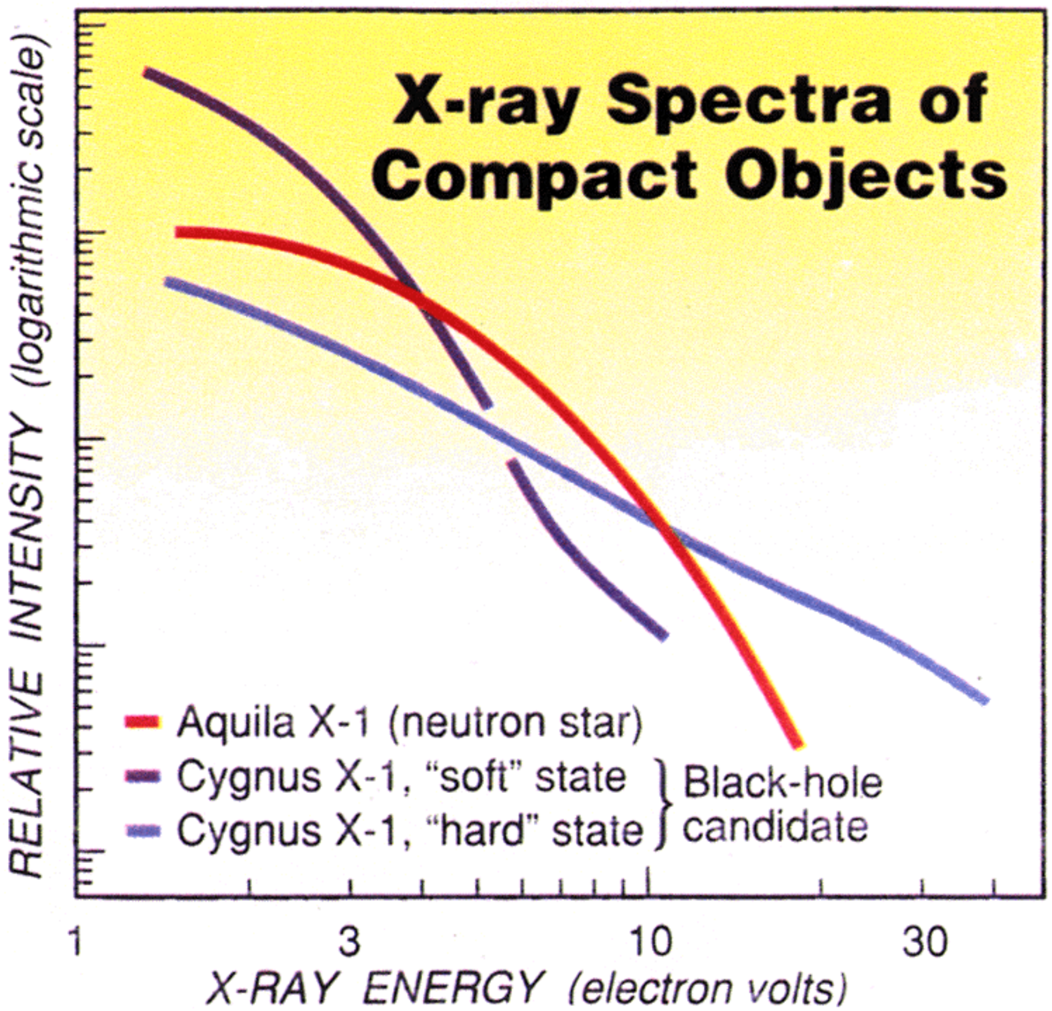


Figure 11 Intensity vs. Energy of Cygnus X-1 in its hard and soft states in comparison with the neutron star Aquila X-1

Analysis

The method of using symbolic streams was chosen for two reasons: one, this data analysis characterizes correlations in time and two, it detects periodicities and other patterns of behavior. Converting a continuous analog time series in to a symbolic stream has been found to sufficiently estimate correlations in the streams. Symbol statistics are also particularly robust to noise. Fourier transformations can be used for the analysis, however are badly aliased (Tracy 1998).

The symbol statistics approach to time-series analysis assigns a symbol to partitions of the data set. For the purpose of this analysis, pair-wise comparisons were made. Using the original time series, adjacent values are compared. This tends to de-trend the data and emphasize short timescale behavior. In a string of data values,

$$x_1, x_2, x_3, \ldots, x_{n-1}, x_n \tag{4}$$

$$0.966196, \quad 0.999941, \quad \ldots, \quad 0.99708, \quad 0.999463 \tag{5}$$

the difference between any given two adjacent data values, x_1 and x_2 are taken. For example, data value 1, or x_1, and data value 2, or x_2, as seen in equation 5, a sample of the original data stream yields a negative difference, $x_1 - x_2$ p 0. The number zero was assigned to this difference, as seen in the corresponding symbolic analogue in equation 6.

$$0, \quad 1, \quad \ldots, \quad 1, \quad 0 \tag{6}$$

Next, the data value x2 and x3 are compared. From the values shown in equation 5, this yields a positive difference and the number one is assigned in its place, shown in equation 6. Pair-wise comparisons are made in this way for all values of x. For comparisons between positions where there were gaps in the data[6] the number zero was assigned. Using this method, a symbolic stream of data was created.

Most signals appear to have a 'high entropy' (all except for data set 224), thus a method of bootstrapping must be used to estimate the significance. To compensate for this behavior, surrogate data sets were produced by shuffling the symbolic string 100 times. These iterations were done for all five of the original data sets. In addition, a new symbolic string was made by assigning the number one to data gaps and again shuffled. With successive iterations, this data filling method created 100 surrogate binary data sets for each of the ten data streams. The entropy of each of these 10 data sets is then calculated.

The Shannon entropy, H, is defined as

$$H(p(t,L)) = -\frac{1}{L\ln 2}\Sigma p_{s_1\, s_2 \ldots s_L} \ln(p_{s_1\, s_2 \ldots s_L}), \qquad (7)$$

[6] These data gaps can be the result of a number of occurrences, such as occultation or instrumentation and data collection.

where the tree entries, p, correspond to the number of data points for each particular data set, L is the tree level, which was given the value three for this research, and the time delay, τ, is given for each appropriate data set (Tracy 1998).

Entropy vs. τ for each of the shuffled binary data sets is then plotted. Plots of both comparisons are shown in Figures 12-21b. Data sets with suffix b correspond to the second method of comparison. The entropy of all 100 surrogate data sets, represented by the strings of circles, is compared to the original data set, represented by the solid line.

Comparing figures from the two data filling methods, the peaks and troughs that remained consistent through both methods of comparisons were noted. In addition, those peaks and troughs of the original data set which fell outside 5% of the bulk of the distribution (i.e. lies out of the 95% level) were flagged. They are labeled a-z and A-B in Figures 12-21b. These structures which appear to be significantly different from the shuffled states are of greatest interest. They possibly represent the deviants from the group which represent unusual dynamical behavior, which is more ordered than the shuffled data. For example, point ‘w’ and ‘y’ in Figures 20 and 21, respectively, at time, $\tau = 0.05$ s, show structures which are ‘significant’ with both methods of data filling. In this case, the periodicity comes out as being more significant.

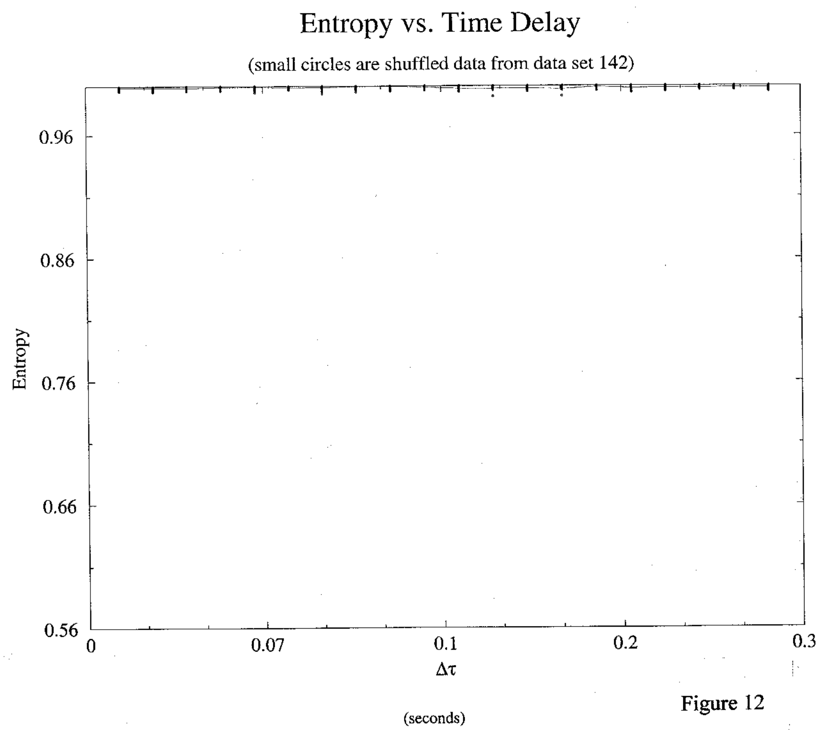


Figure 12

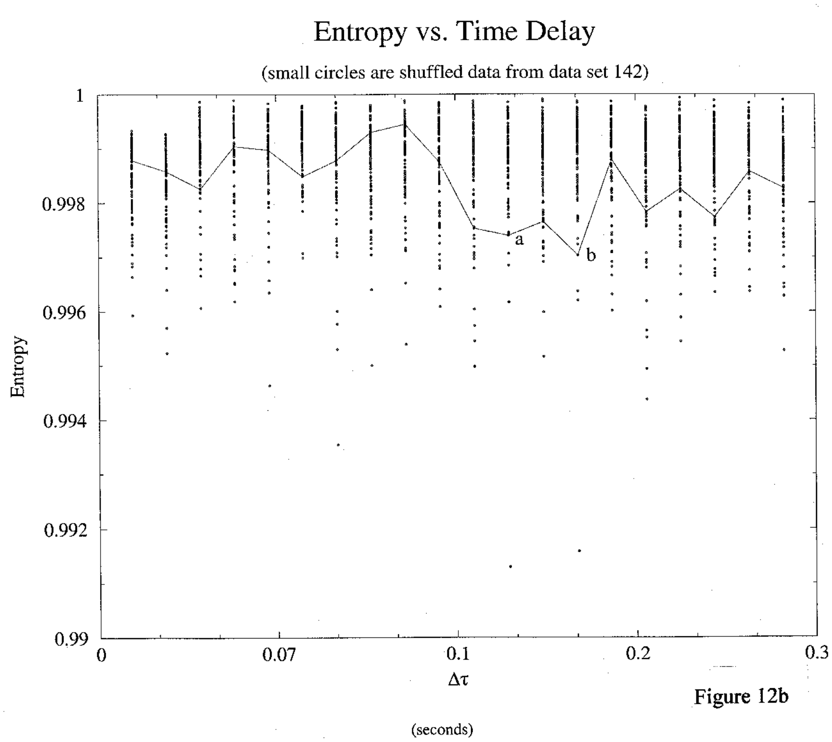


Figure 12b

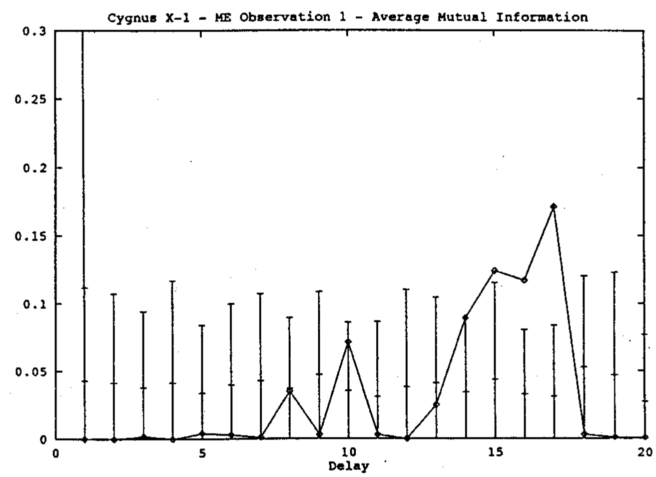

Cygnus X-1 - ME Observation 1 - Average Mutual Information
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
Delay

Figure 12c

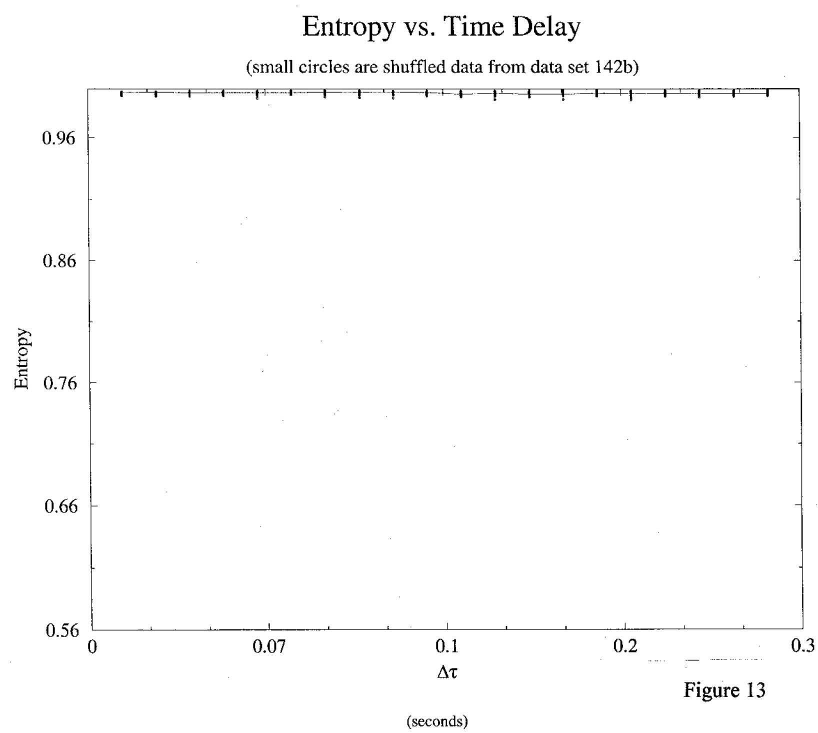


Figure 13

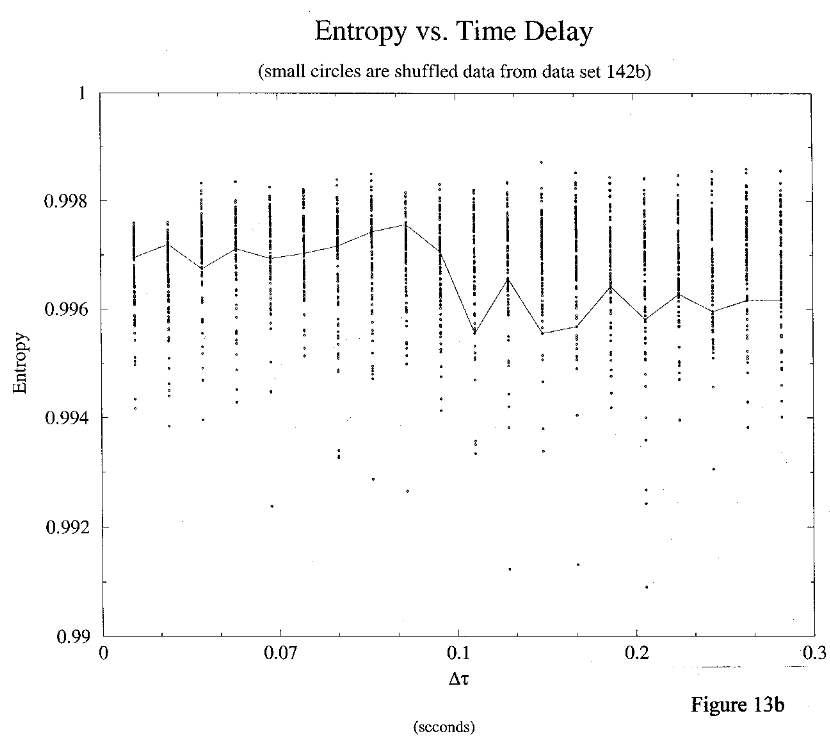


Figure 13b

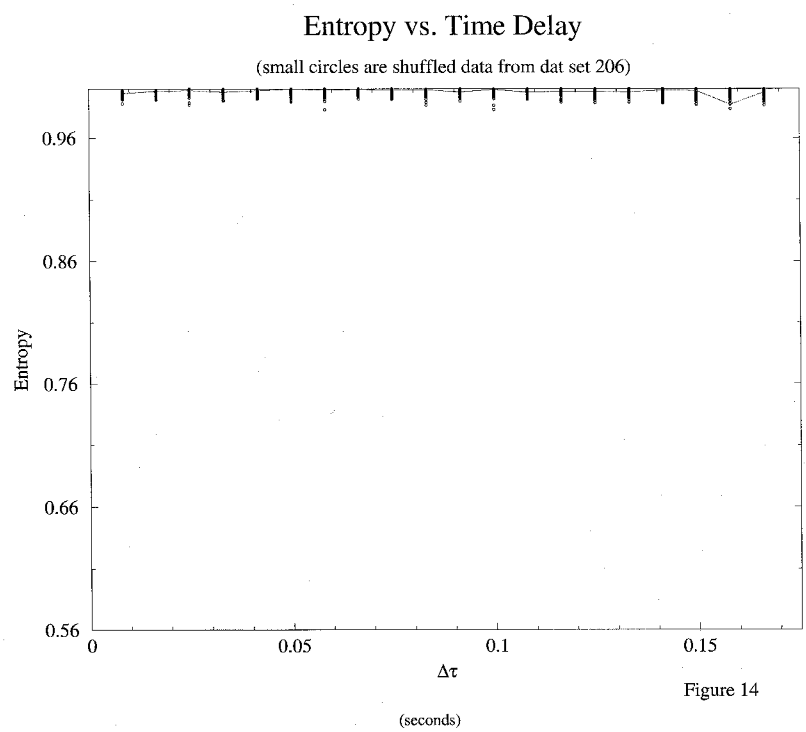


Figure 14

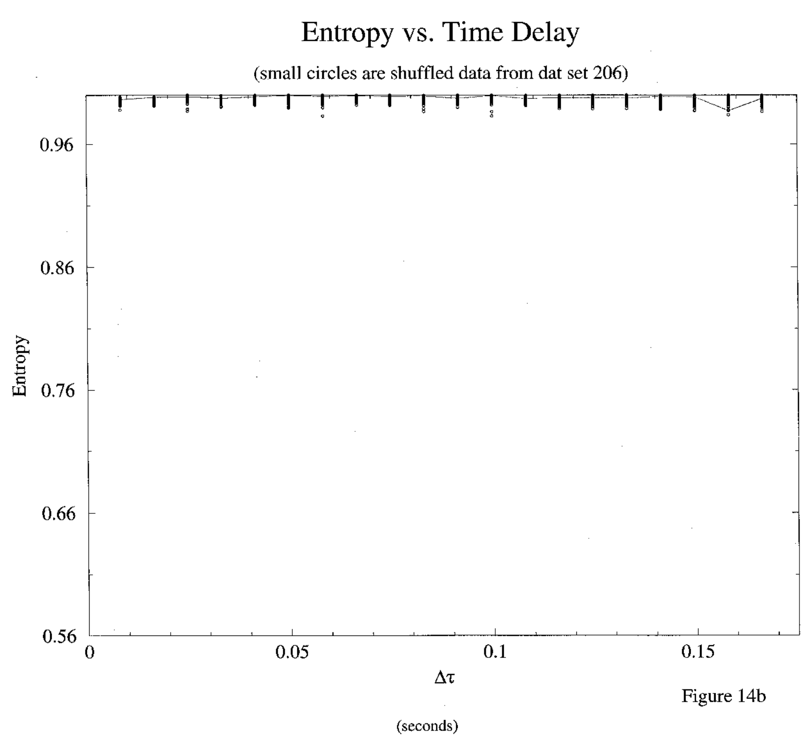


Figure 14b

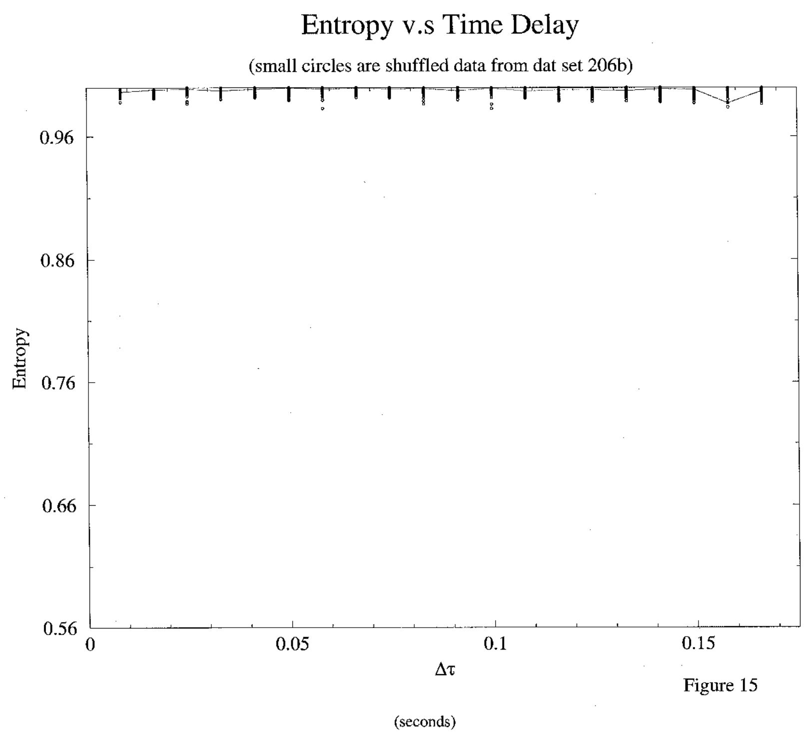


Figure 15

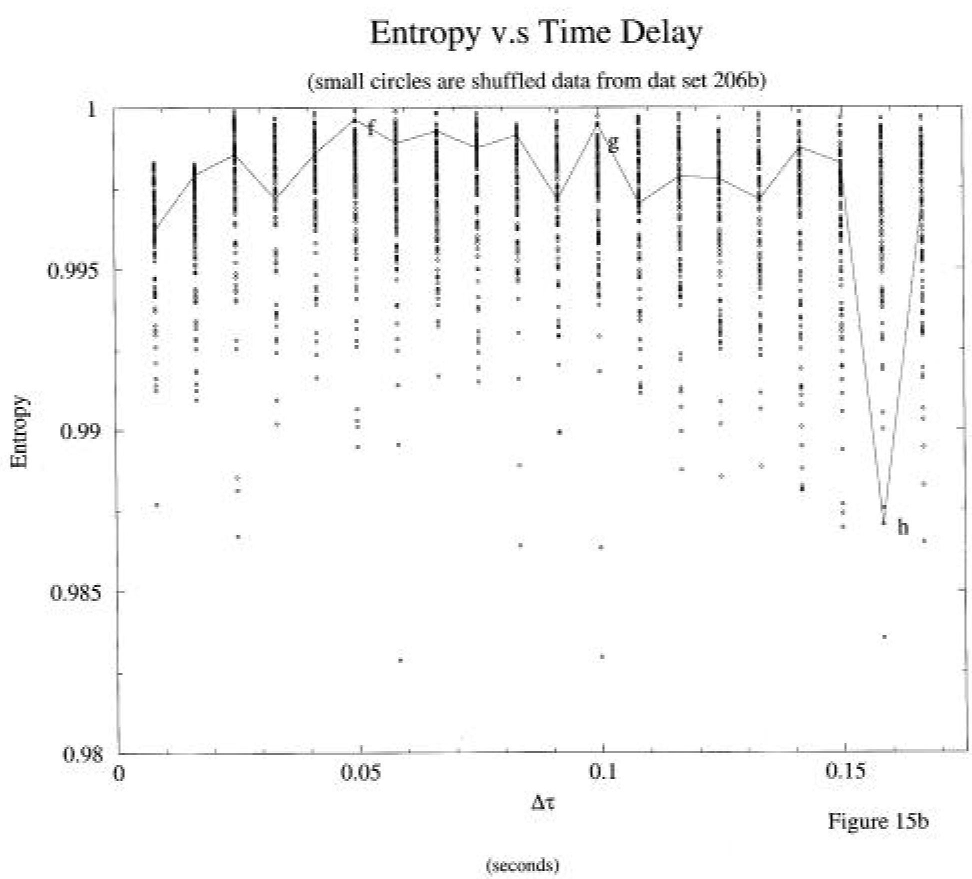


Figure 15b

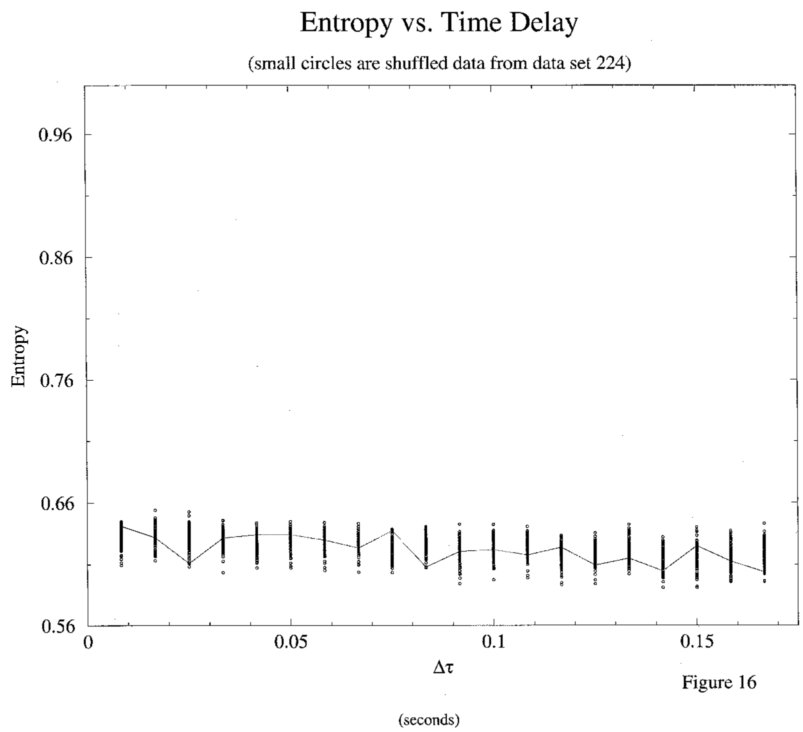


Figure 16

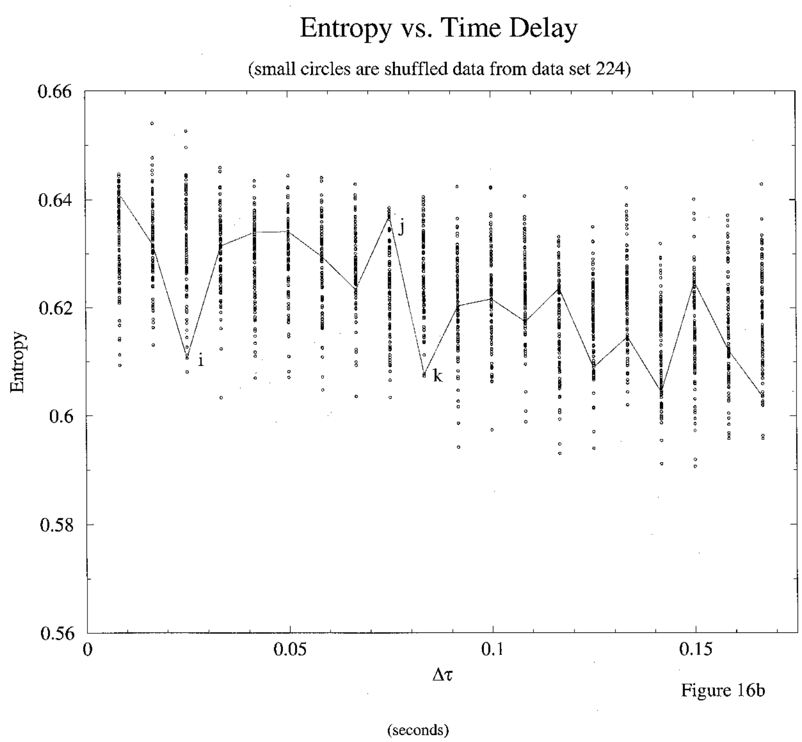


Figure 16b

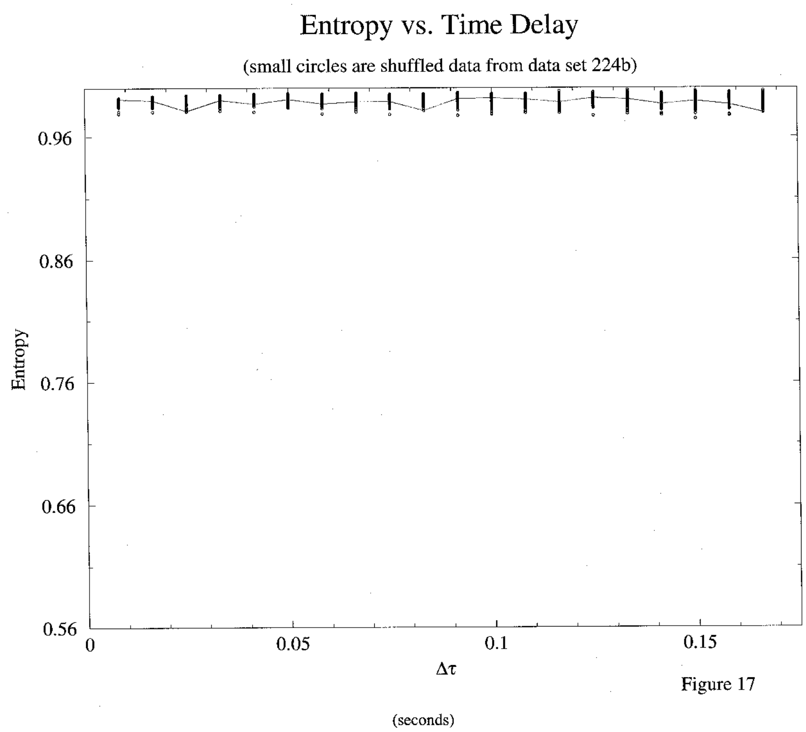


Figure 17

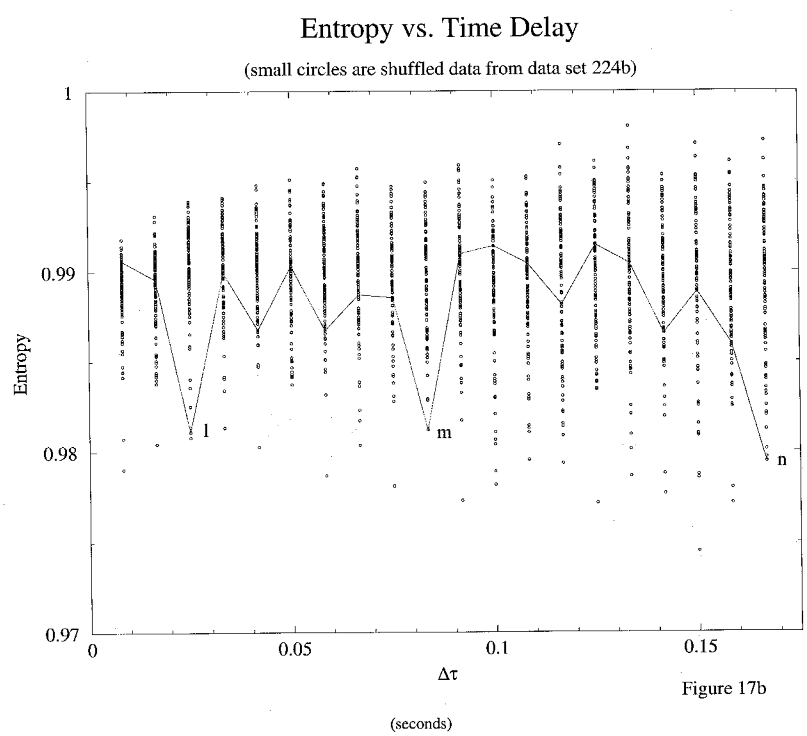


Figure 17b

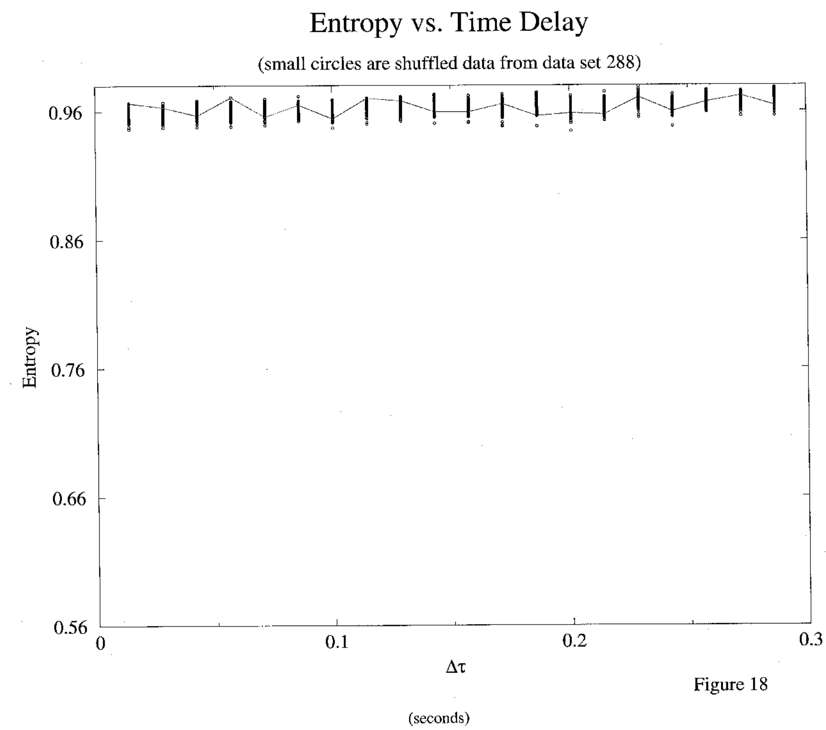


Figure 18

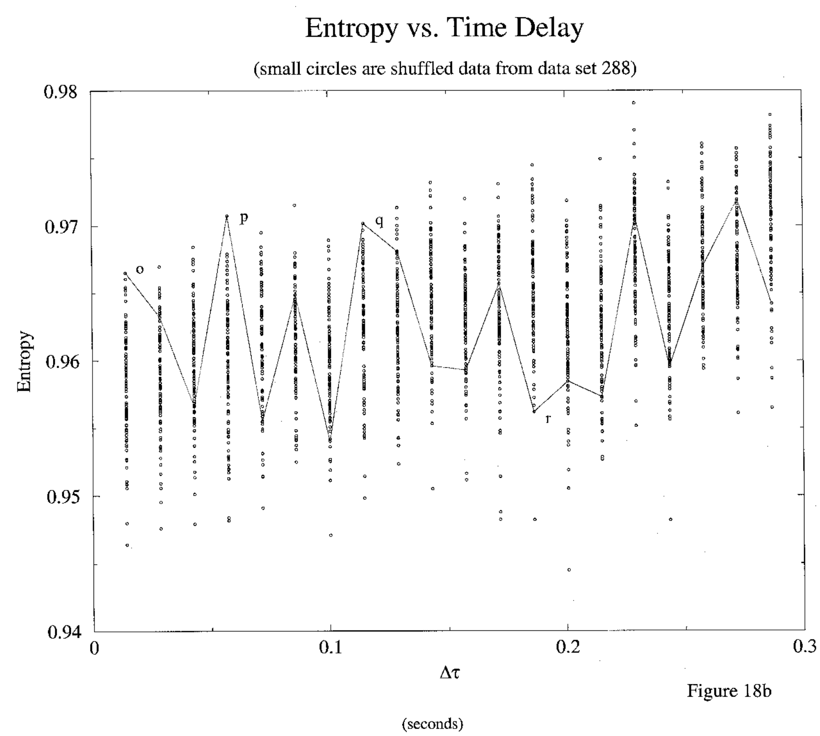


Figure 18b

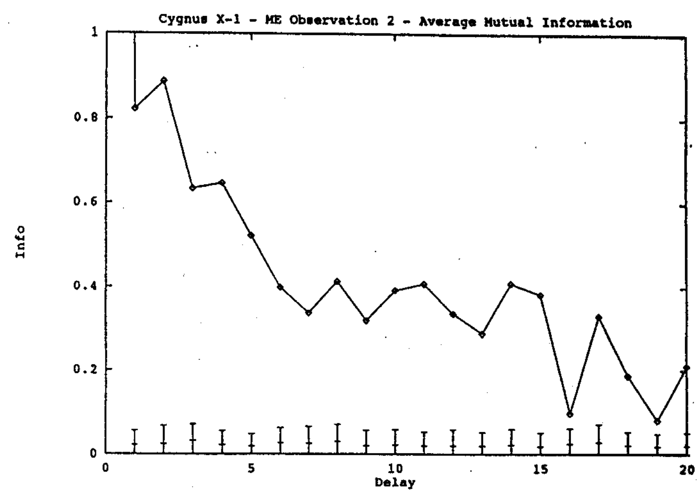

Cygnus X-1 - ME Observation 2 - Average Mutual Information
Info
Delay
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20

Figure 18c

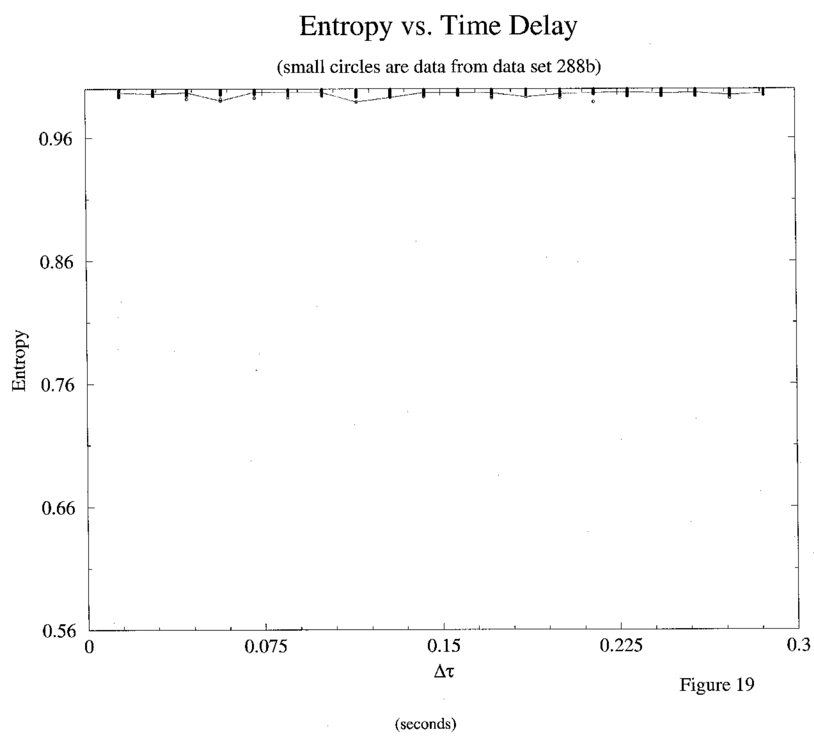


Figure 19

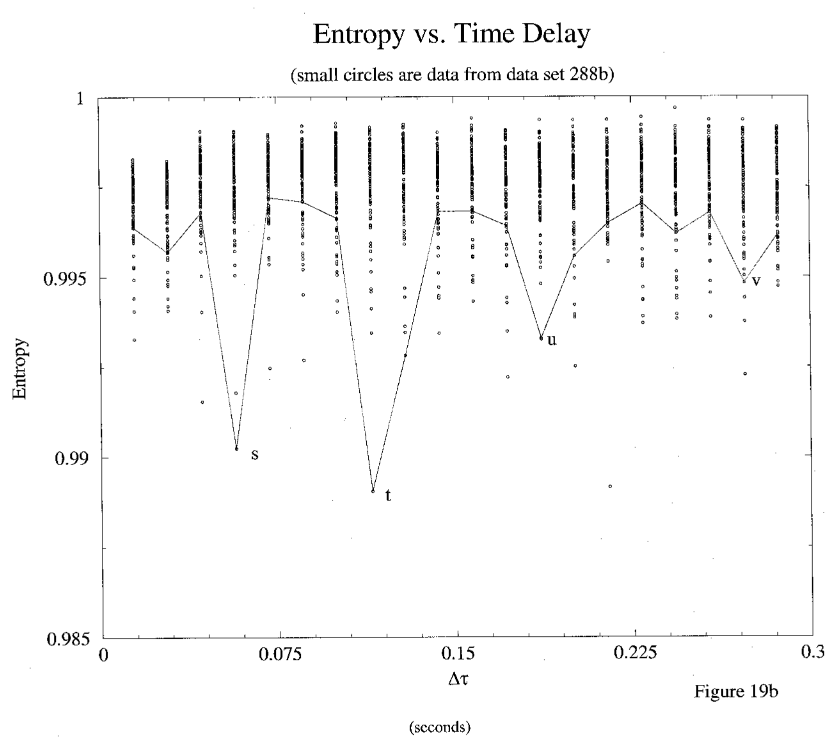


Figure 19b

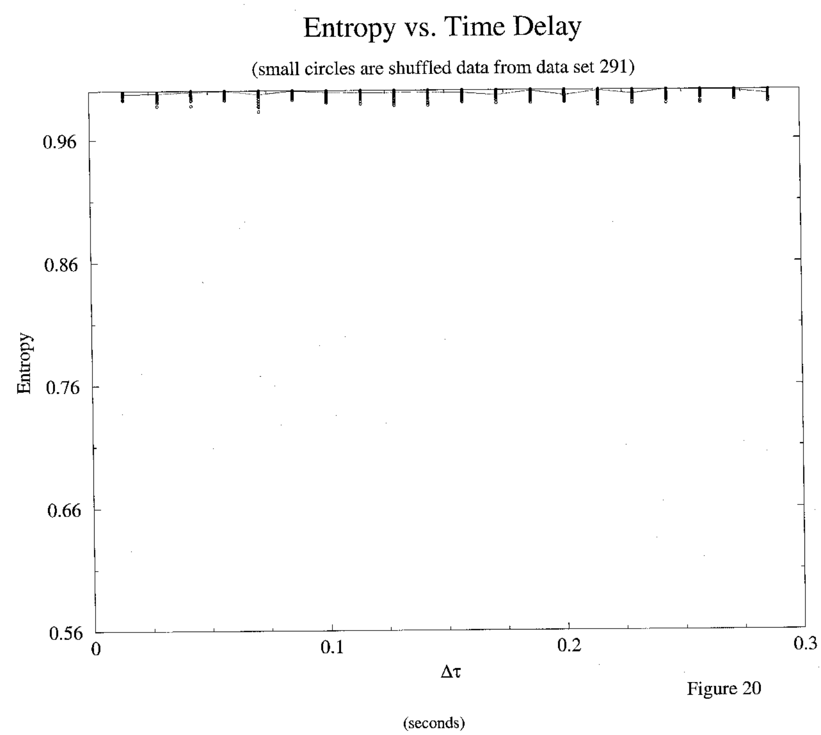


Figure 20

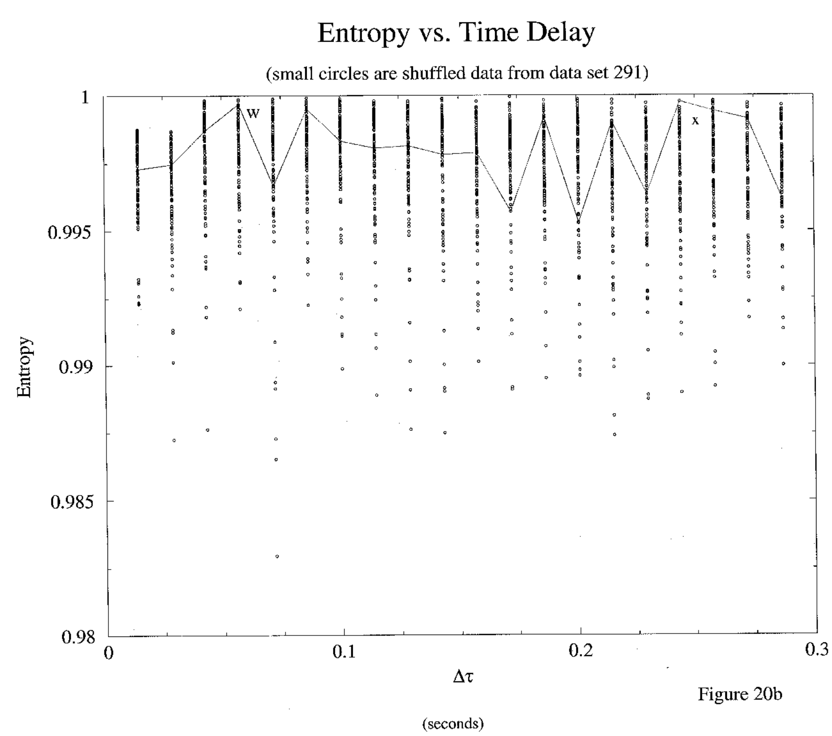


Figure 20b

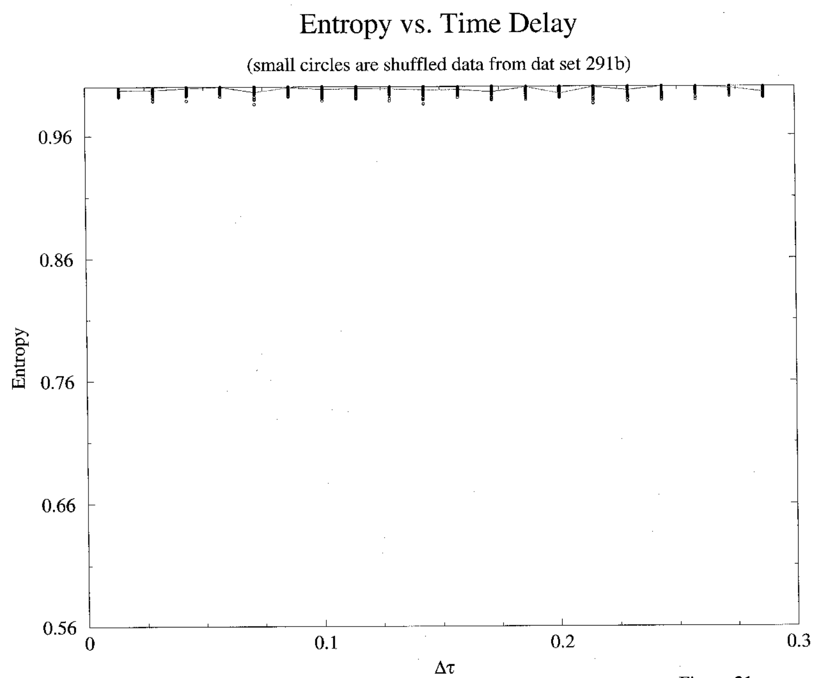


Figure 21

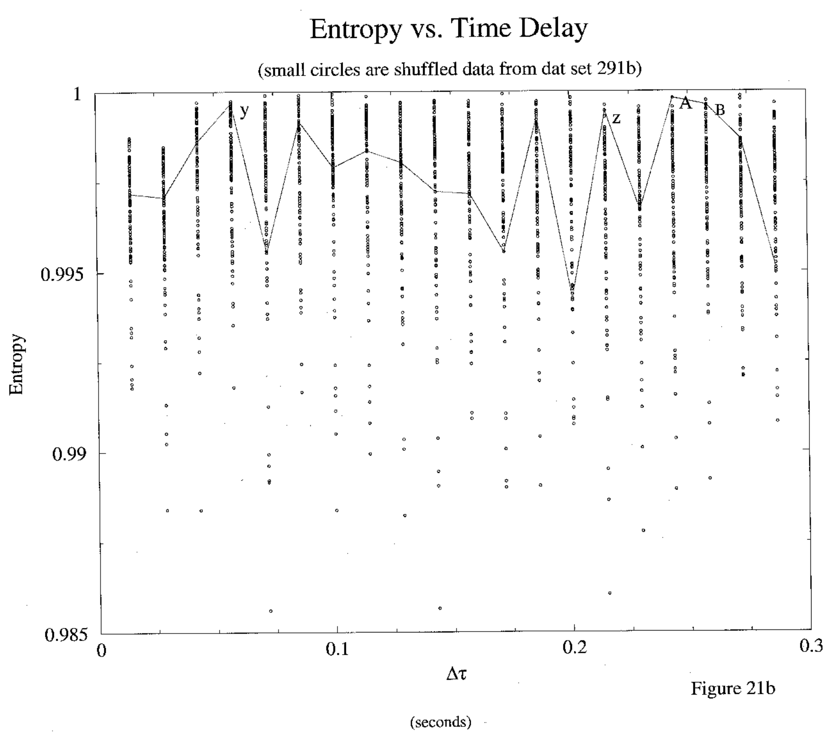


Figure 21b

Conclusion

In investigating the x-ray emissions from Cygnus X-1, the underlying question is whether or not these emissions have a pattern or are completely random. By generating surrogate data sets, any patterns or predictability in the emissions should be destroyed by revealing (by comparison) structures in the entropy. Figures 20 and 21, show a consistently high entropy, whereas Figure 16 shows a significantly lower entropy than its counterpart Figure 17, which remains at a high entropy. Figures of suffix b show the entropy on a scale fit to the window. The reason for this deviation is not obvious. Clearly, this great variance in entropy is a behavior worth studying further. However, this investigation is beyond the scope of my research.

Due to the gaps found in the data and the few data points, the confidence level of these results is low. The shuffling results show a sensitivity to the data filling, as seen in the inconsistent structures of data sets 288 and 288b of Figures 18 and 19, respectively. However, other data structures remained robust, as shown in data sets 291 and 291b of Figures 20 and 21, respectively. These two particular types of behavior possibly represent two dynamical states.

In comparison, results determined in previous research conducted by Rebull (1992 pp.123-125) were found using the method of mutual information - direct comparison of the original data streams - for analysis. The aim in using symbolic analysis instead of mutual information was to de-trend any periodicities found through mutual information. A seen in Figures 18c, the average mutual information from 288 (Rebull) and symbolic time series for data set 288b from this research seem to have similar structures at point 19 and point v, respectively. Comparing the two data filling methods, point r in Figure 18b shows a similar structure at point u in Figure 19b. This is a small representation of a "predictable" data set. Are these structures which survived data filling purely random or is there some preriodicity?

In comparison, data set 142 showed no similarities between the Rebull findings and the two data filling methods used here. In addition, irregularity in structures persists between both data filling methods used in this study, as seen in Figures 12b and 13b. This suggests a more chaotic state of the system during this observation because the structures did not survive the data filling methods. Between two separate observations – 142 and 288 - done nearly a year apart, Cygnus X-1 seemed to have exhibited two distinct structures in the signals, suggesting two dynamical states of the system. However, because of the large gaps in data and the few data points in each of the few data sets available, a firm conclusion could not be made. Further investigation of the system could yield a more conclusive answer, however present analysis of the data from EXOSAT is insufficient.

For greater confidence using the data from EXOSAT, a more robust method of data filling could be used in the future. For example, ten thousand iterations instead of merely 100 could be done to further study the behavior of the structures. Longer and more continuous data streams would yield more certainty by limiting the uncertainty of the analysis. The findings of this research greatly suggest the need for further investigation of the behavior of the x-ray emissions from Cygnus X-1 and its apparent relationship to the dynamical states of the accretion disk.

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