Identifying Two Newly Discovered Black Hole X-ray Transients in the Galactic Center

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Abstract We analyze the two unclassified newly outbursting X-ray binary transients in the galactic center, Swift J174540.7-290015 and Swift J174540.2-290037, in an attempt to identify the nature of these sources. We engage in a thorough spectral analysis for the two systems, by examining the fits of various astrophysical models, in addition to assessing their light curves and power spectra. Our results showed that Swift 15 has a low temperature blackbody spectrum with a hard power-law tail, and Swift 37 has a broad iron line and a small equivalent width; both transients exhibit classic spectral signatures of black hole systems. Additionally, our observations for both sources yielded the absence of type 1 X-ray bursting and the possible presence of low-frequency quasi-periodic oscillations. Our finding that these two sources appear to be black hole X-ray systems is a groundbreaking discovery, as it adds on to an extremely small population of well-established black hole candidates in the entire galaxy, in addition to giving the first strong indication for a clustering of black holes within the central few parsecs of the galactic center.

1 Introduction

One of the most intriguing challenges in high-energy galactic center astrophysics, has always been to identify more black hole systems, in order to account for their curiously small population, contrary to popular theoretical implications. It is widely believed that as our galaxy began to progress many billions of years ago, the black holes should gradually fall closer into the center of the galaxy throughout time due to their loss of energy as they collide with astrophysical matter in the interstellar medium (Miralda-Escudé & Gould 2000). Thus, theoretical evidence implies millions of black holes in the galaxy; however, the culmination of all historical observations only yields less than 70 strong black hole candidates in the entirety of the Milky Way, with only 21 dynamically confirmed black holes (Tetarenko, 2016). Of these, only one has ever been identified in the central two to three parsecs of the center of the galaxy (Tetarenko, 2016). The ongoing studies of galactic center sources is extremely exciting to this date, as they add insight to the everlasting uncertainty regarding the scarcity of identified black hole systems in the galactic center.

X-ray telescope Swift, since 2006, has been monitoring the galactic center on a daily basis, and within these past seven months, they found very exciting observations of three completely new X-ray binary transient sources ("The Swift X-ray Monitoring Campaign," n.d). In early February of 2016, they reported the transient source, Swift J174540.7-290015 (Swift 15), located just under 17 arcseconds north of supermassive black hole Sagittarius A* (positioned at the center of the galaxy). In late May, another X-ray binary transient system was detected, Swift J174540.2-290037 (Swift 37), approximately 10 arcseconds south of the galactic center ("The Swift X-ray Monitoring Campaign," n.d). A third X-ray source detected in early May, thought to have started experiencing accretion bursts since late March, GRS 1741-2853, has already been identified unambiguously as a neutron-star binary (Rutledge, 2016). Our research will therefore focus on the identification of Swift 15 and Swift 37, two fresh and unclassified X-ray transients that are incredibly close to the galactic center.

Based on the preliminary observations from Swift, NuSTAR also became motivated to monitor the region of the galactic center in which the transients popped up and recorded their respective data. The NuSTAR telescope is internationally renowned as one of the premier X-ray telescopes due to its large effective energy...
Swift objects, and telescopes such as Swift, NuSTAR, Chandra, XMM, and others are able to detect many of these sources due to the X-ray emission from the source’s binary system (“Astronomer’s Toolbox,” n.d). X-ray binaries are two-star systems with a compact object and a main sequence companion star. In particular, X-ray transient binaries have a compact object, typically either neutron stars or, less commonly, black holes. In these binary systems, the compact object, with significantly larger gravitational force, will accrete matter from the companion, or donor star, forming an accretion disk as the matter gradually falls into the compact object (“Astronomer’s Toolbox,” n.d). In black hole and neutron star binary systems, X-rays are detected from the plasma generated from the differential rotational friction, which occurs due to the difference in rotation speeds within the accretion disk, alongside the impact of the accreted matter on the compact object’s surface if it is a neutron star; black holes do not have definitive surfaces (“Astronomer’s Toolbox,” n.d). In this study, we analyze a pair of X-ray binary transients, Swift 15 and Swift 37, that have been dominantly illuminating the field of view for all X-ray telescopes monitoring the galactic center since their outbursting six to seven months ago (Rutledge, 2016).

Through a thorough analysis of their spectroscopy, we establish two new solid black hole transient candidates, both less than one parsec away from the center of the galaxy. These highly suggestive black-hole transient systems are the closest black holes to the galactic center ever recorded. Our results present detailed characteristics of two new black hole candidates, and we hope our findings on Swift J174540.7-290015 and Swift J174540.2-290037 provide fascinating insight to the galaxy’s black hole population.

2 Methods

2.1 Swift and NuSTAR X-ray Telescope Details

From the various X-ray telescopes monitoring the galactic center, the focus of our research will include the initial Swift; however, the main dataset will be provided by the NuSTAR images. Although Swift has a relatively lower energy range, from 0.2 keV to 10 keV, it is one of the leading telescopes primarily designed to analyze the spectroscopy of the most luminous sources in our galaxy, such as Gamma-ray bursters and X-ray transients as well as time variable sources (Degenaar, Miller, 2015). Swift is able to cover the fluctuating variability and incoming count-rate range from these extremely bright sources due to its unique X-ray telescope (XRT). This XRT receives X-ray emission into a charge-coupled device using 12 multilayer mirrors of a fairly low-density material, silicon carbide, to utilize the emission flux for detection of the afterglow (Degenaar, Miller, 2015). X-ray bursting afterglows have energy ranges precisely that of Swift’s capability. These mechanics enable Swift to position sources accurately with only up to 1 arcsecond radius of error.

NuSTAR, on the other hand, has the specialty of having alternating coatings of high-density materials such as tungsten and platinum within its numerous layers of mirror coating, used to reflect incoming X-rays, and low-density materials such as silicon and carbon (“NuSTAR Bringing the High,” n.d). These materials, which have high resistivity, are able to give NuSTAR good quantum efficiencies at high energies, allowing an unmatched maximum range of 79 keV. There are two detectors on the NuSTAR telescope, denoted module A and module B, that give two sets of data images for each observation (“NuSTAR Bringing the High,” n.d).

2.2 DS9 Extraction and Xspec Modeling

We first process the NuSTAR observations into DS9, a software used to manipulate the images, or photon count maps, generated by the telescope detectors (Forster, Grefenstette, Madsen, 2014). With the DS9 images, we create a region of the central 20 arcseconds of the source and define that as our source region. We put a 20 arcsecond limit, as it captures around 40% of the source’s photons; however, anything above this radius might include other contaminating photons. Taking this into consideration, we also create a background region; an isolated source spectrum that we will then subtract from the source region photons. The purpose of this background region is to avoid contamination from other sources, detected light that does not belong to the source’s spectrum (stray light), and any other diffuse atmospheric emission from the interstellar medium (Forster, Grefenstette, Madsen, 2014).

Swift 15 and 37, being detected in different locations and times, we must choose different background regions for them. For Swift 15, we use the source photons from nearby neutron star AX J1745-2901 source...
region as our background file because the transient is located within supernova remnant, Sagittarius A\textsuperscript{e} East, and we have to account for its contamination (Rutledge, 2016). For Swift 37, detected later on in late May, we must account for the source contamination from Swift 15, due to the closeness of the two transients (Rutledge, 2016). Therefore, we use the source photons from Swift 15 as our background file for Swift 37.

X-Ray Spectrum, or Xspec, is a widely used astrophysical modeling language that we will be using to analyze the spectroscopy of these two transients. Xspec is used so frequently because of its compatibility with modeling analysis in addition to its convenience on generating model datasets from NuSTAR source and background files (Arnaud, Keith, Dorman, 2015).

2.3 Initial Modeling

With the source and background regions properly defined for Swift 15 and 37, we produced fits with common astrophysical models. The models we used, given by NASA’s astrophysics software (HEASARC), are components such as diskbb, bbody, compbb, powerlaw, and gaussian. The diskbb model calculates the temperature of the accreting matter in a disk shape, falling into the compact object, with respect to the radial distance from the compact object, and fits it to a blackbody spectrum (Arnaud, Dorman, 2015). Bbody, a simple a standard blackbody spectrum model, is an idealized spectrum obtained from a hot radiator that absorbs all electromagnetic radiation (Arnaud, Dorman, 2015). The compbb model is a blackbody spectrum, modified with Compton scattering. As jets of X-ray energy are emitted from the compact object or when a halo of electrons disperses the emitted photons the inner edge of the accretion disk, this energy collides with the extremely hot particles within the compact object’s corona and scatter away, forming a compbb spectrum (Arnaud, Dorman, 2015). The powerlaw model fits with many X-ray binary systems because as hard photons are scattered through the compact object’s corona and are reflected into our line of sight from our telescopes, we tend to see a power law fit (“NuSTAR Bringing the High,” n.d). Gaussian lines are used to fit iron-emission lines and possibly other interesting features within the spectra.

Each spectrum must be modified with the staple multiplicative models of tbabs and constant. Tbabs accounts for the X-ray absorption from hydrogen molecules in the interstellar medium between our telescopes on Earth and the sources we are observing (Arnaud, Dorman, 2015). The constant component is an energy independent factor that accounts for the difference between the effective areas of module A and module B (Arnaud, Dorman, 2015).

With these models, we will find the best fits for Swift 15 and 37 in order to determine their properties and to analyze their parameters. While fitting, we look for the reduced chi-square (rX\textsuperscript{2}) statistic to be as close as possible to 1, to determine whether the modeling is accurate. The rX\textsuperscript{2} is the summation of the residuals of observed and expected model calculations for the dataset.

Additionally, analyzing the visual spectra of the models is extremely important, as the residuals and spectral features are vital for our understanding of the model. We used the Xwindows device for the plots, because it is the premier software for model building on Xspec.

After finding the best fits for the two transients, we use the models to calculate the equivalent widths, which is the integrated areal photon flux of the iron emission lines that we expected to see. This result is extremely important, as different source populations tend to have accepted general ranges of equivalent widths (Parker, 2016). This can be done with Xspec using the “eqwidth” command.

2.4 Timing Analysis

When attempting to find the nature of new X-ray binary systems, examining the light curves is essential, as its features could be indicative of the nature of a source population. We created these plots with count rate as a function of time (s) and used the photons generated by extracting our source regions from their respective event files. We used 512 equal newbins, to obtain reasonable bin sizes and to include the entire timespan of the inputted data. As with the Xspec modeling, we also used the Xwindows device for plotting.

We did this analysis to see if the transient datasets yield interesting features in their light curves, namely Type 1 X-ray bursts. This outbursting occurs periodically when hydrogen and helium burn unstably on the surface of the compact object; during the duration of the bursts, the count rate of photons can be detected as extreme outlier peaks (Galloway, 2008). This will be imperative to analyze, as these bursts are a definitive characteristic of neutron star systems (Galloway, 2008).

2.5 Power Spectrum

Power spectra analysis is one of the most fundamental aspects of looking into a new source, being a plot of power (erg/s) as a function of source frequency (Hz). Spectral features of power spectra are studied intensively by a select group of world-renowned galactic center astrophysicists, who have produced strong evidence and theories pertaining to black hole and neutron star
classification. In our analysis of Swift 15 and 37, we looked for the classic black hole X-ray binary spectral signature of low frequency quasi-periodic oscillations (QPOs) (Wijnands, van der Klis, 1999). QPOs are an indication of X-ray emission from the inner edge of the accretion disk, and detection of this at low frequency, at between 0.01Hz and 1 Hz, is a widely believed confirmed characteristic of black holes (Wijnands, van der Klis, 1999).

2.6 More Sophisticated Reflection Models

Some xspec models, such as the power law, are used simply to fit the higher-energy photons, without any astrophysical meaning or relation to the source population. The more complicated reflection model, reflionx, will be used to take into account the reflection of high energy photons bouncing off the surface of the accretion disk, or reabsorbed and emitted energy from the disk (Arnaud, Dorman, 2015). This pure astrophysical model calculates for this radiation from a power-law spectrum (Arnaud, Dorman, 2015).

3 Results

3.0.1 Best Fits for Transient Swift J174540.7-290015

As displayed in Fig. 1, we have generated a best fit model, with counts as a function of energy (keV). The datasets, upper emission (source) and lower emission (background) are in the top region. The bottom box is the residuals between the model and the data.

![Fig. 1 Folded spectrum for Swift 15 with the best fit model, with counts as a function of energy (keV). The datasets, upper emission (source) and lower emission (background) are in the top region. The bottom box is the residuals between the model and the data.](image)

As displayed in Fig. 1, we have generated a best fit to model the data of Swift 15: \( \text{tbabs} \times \text{constant} \times (\text{diskbb} + \text{powerlaw} + \text{gaussian}) \). The reduced chi-square statistic of this model is 0.999; the closeness of this \( rX^2 \) value to 1 is stunning. Looking into its parameters, we see very interesting results. The power-law photon index gives a relatively hard value of 1.888, and the diskbb component yields a physically reasonable temperature of 0.967 keV. Many theoretical and observational astrophysical perspectives have deduced that between approximately 1.8 to 2.0 in photon index, a transient source is currently transitioning between a hard and soft state; thus, we see a presence of a diskbb component, here (Tetarenko, 2016).

Comparing with the results of known neutron star binaries, which typically have disk temperatures around 1.5 keV and higher, we find Swift 15 yields a significantly lower blackbody temperature. Having a low disk blackbody characteristic temperature in addition to a hard power-law tail is a strong indication of the X-ray spectral signature of a black hole (Tetarenko, 2016).

The gaussian fitting produced, as expected, a neutral iron line at 6.444 keV with a relatively broad line width (Sigma) of 1.904 keV. Equivalent width calculations yielded 1.461 keV. Looking into the spectrum, we see very reasonably oscillating residuals, with no sharp peaks or dips. With the smooth residuals between 6 and 7 keV, we notice the gaussian almost perfectly accounting for the iron emission. At around 8 - 10 keV and above 20 keV, we do not see any spectral signatures of cyclotron lines; these features are classic indication of neutron stars (Tetarenko, 2016).

With the tremendous fit with a disk blackbody and power-law characteristics, we are motivated to fit with a reflionx model, for a better astrophysical understanding of the the source with its high-energy power-law tail. The best fit with reflionx that we generated was \( \text{tbabs} \times \text{constant} \times (\text{reflionx} + \text{diskbb}) \), which yields a \( rX^2 \) of 1.083; a solid chi-square and a strong model. We froze the solar abundance ratio at 1.0, a reasonable ratio for X-ray binaries (Arnaud, Dorman, 2015).

The reflection model photon index of 1.605 confirms our previous power-law index: this source has a hard photon tail at high energies. Additionally, the optical depth generated from reflionx gives 1.05, indicating that the emission from the jets of energy coming from the compact object is scattering off the hot particles and electrons in the corona in high amounts, which is why we see a power law. This reflection model, helping us understand the high energy astrophysics, also contributes to the strong suggestion that our modeling of Swift 15 is that of a black-hole system.
3.0.2 Light Curves and Power Spectra for Transient Swift J174540.7-290015

Observing the light curve for Swift 15, we do not see exceptionally interesting features. There are no apparent peaks or significant outliers in count rate throughout the duration that was observed, indicating no type 1 X-ray bursts. The slight modulation of counts throughout time hints at similarities to previous black hole candidate observations, which have shown temporal variability in relatively high count rate, whereas neutron stars tend to have very consistent count rates in the lower count rates, with the exception of the few bursting outliers from the type 1 X-ray bursts (Tetarenko, 2016). Overall, this heavily leans towards the possibility of a black hole, as throughout the seven months of Swift 15’s outburst, no signs of type 1 X-ray bursts have ever been identified.

The power spectrum, given in Fig. 3, shows a definite red noise accumulating from the extreme low frequencies, up to approximately 0.01 Hz, which then level off to white noise. The red noise is simply reflective of the accretion falling from the disk onto the compact object, and as we get into the higher frequencies, everything looks relatively stable. Expanding the power spectrum to 500 Hz, we observe continuous white noise. This trend is very common for most X-ray binaries.

Some notable features in the power spectrum of Swift 15 are the slight residual differences and small increasing peak between 0.01 Hz and 0.04 Hz, which may be indicative of a QPO at a low frequency. However, due to the lack of professional statistics and fluctuation observations, we cannot confirm this phenomenon. This result is still very fascinating, as it hints and provides more suggestive evidence that Swift 15 is likely to be a black-hole candidate.

3.0.3 Best Fits for Transient Swift J174540.2-290037

As shown in Fig. 4, we produced the best fit model for Swift 37, which is $tbabs \times constant \times (powerlaw +...$
The rX^2 result is 1.091, a strong fit for the dataset. Unlike the modeling for Swift 15, modeling for Swift 37 does not have a diskbb component. This absence of a blackbody component is likely because the power law photon index is 1.475; the source is at its very hard state. At this initial hard state, we see no diskbb component in our model, currently; however, as time progresses, it will transition into a hard-soft state. This reasoning is logical, as Swift 37 was detected several months after the outbursting of Swift 15.

The gaussian creates an iron line at 6.501 keV, only a slight 0.1 keV deviation from the expected neutral-iron emission at 6.4 keV. A noticeable feature of this gaussian component is its linewidth (Sigma) at 0.707 keV. Similarly, to Swift 15, this source has a broad line energy.

Using our best fit models, we calculate an equivalent width of 0.288 keV for Swift 37; this is an incredibly small value (Parker, 2016). The 1.461 keV width we found for Swift 15 falls in the ambiguous range between black hole and neutron star systems as previously observed; however, Swift 37 has a very small value of 0.288 keV. This small equivalent width, coupled with its broad-line energy, is highly indicative of spectral signatures of black hole LMXB systems (Tetarenko, 2016).

In the spectrum, the residuals fluctuate fairly evenly throughout the energy scale. Again, there are no signs of cyclotron peaks at around 8-10 keV, nor at any higher energies.

Since we found such a solid result using equivalent widths and line energies, as well the reasonable spectral residuals, there is no need to delve deeper into the more sophisticated reflection model, reflionx, to analyze its photon-index parameters.

As with the light curve for Swift 15, within this observation, Swift 37 does not show any outlier peaks indicative of type 1 X-ray bursting. Thus, it cannot be shown to be a definitive neutron star, leading to the strong possibility that it is a black hole system, especially that three months worth of observations have not yielded any outbursts. Likewise with the observation from Swift 15, Swift 37 shows trends of variability in its light curve, indicating that this source is indeed a binary system (which we already know). The high count rate variability, fluctuating between 8 to 9 counts/sec, also suggests black hole signatures, as seen with Swift 15 as well.

The power spectrum for Swift 37, given in Fig. 6, shows a red noise descending from the low frequencies up to approximately $2 \times 10^{-3}$ Hz, which then levels off to white noise. The white noise carries on until roughly 0.04 Hz but then shows red noise again. Stretching this preliminary graph up to 500 Hz (not shown here), we see a continuous and steady white noise after 1 Hz.
Zooming in to see the power spectrum up to the maximum of 0.5 Hz, we see many interesting line features. Between 0.03 Hz and 0.05 Hz, we see a peak in the dataset, the only noticeably significant fluctuation within the entire power spectrum. This finding highly suggests the presence of a low-frequency QPO, a definitive characteristic of a black hole. Again, as with Swift 15, we need to apply astrophysical statistics, which is beyond our research, to solidly confirm this feature.

3.1 Conclusions and Future Work

We have completed a thorough spectral analysis of transients Swift J174540.7-290015 and Swift J174540.2-290037, with model fitting, timing analysis, and power-spectrum evaluations. Through our combined results, we present a huge discovery: highly suggestive evidence of two new black hole sources in the center of the galaxy.

Our modeling for transient Swift J174540.7-290015 yields a low temperature disk blackbody spectrum coupled with a hard power-law tail, a spectral signature that is very indicative of black-hole systems. In addition, the model spectrum shows stably fluctuating residuals with no presence of high-mass neutron-star cyclotron lines. The light curves did not show any sign of type 1 X-ray bursting, but they do show some definite count-rate variability. Also, the presence of black-hole low-frequency quasi-periodic oscillations within the power spectrum are definitely noticeable. The culmination of our spectral results yields strong evidence that Swift 15 is a black-hole transient—one that is located just 17 arcseconds from the galactic center.

From our results, transient Swift J174540.2-290037 also appears to be an extremely strong black-hole candidate. The combination of its broad gaussian iron line and its exceptionally small equivalent width is already a solid argument that it is a black-hole transient. Moreover, the absence of type 1 X-ray bursts, alongside the increasing fluctuational peak features observed in the power spectrum analysis, possibly of a low-frequency QPO, adds further evidence that Swift 37 is a black hole transient, only 10 arcseconds from the center of the galaxy.

Our extremely exciting results must be pursued further by professional astrophysicists who can solidify our identification of these two black hole systems. Many more NuSTAR observations need to be collected to monitor the light curves for X-ray bursts. Furthermore, for QPO confirmation, intense statistical analysis, that is beyond the scope of our project, should be performed on our power spectra. Outside our research, and to definitively categorize our transients into a source population, dynamical mass observations must be done; however, if a continuation of one year’s observations of light curves do not show outbursts, and the power spectra yields statistical QPO indications, our analysis of the spectroscopy is enough to make any astrophysicist believe that these two sources are black holes systems.

Black holes are one of the most exciting fields in X-ray astronomy due to their enigmatic nature, and we have identified two new transients, located extremely close to the center of the galaxy, as strong black hole candidates! Previously, only one highly believed, unambiguous black hole candidate has been located within two or three parsecs from the galactic center, and now, our analysis yields the addition of two more within this closeness to the galactic center. With less than 70 solid black hole candidates identified throughout the entire galaxy; we now present that three of these are within the central few parsecs of the galaxy. This is the first highly suggestive evidence for an excess of observed black holes clustered in the center of the galaxy!

We hope that our research will motivate other astrophysicists to further analyze our thrilling results and to give more insight into the longstanding challenge of deciphering the nature of black holes in our galaxy.
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