Estimating the mass of a black hole

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A black hole is a region of spacetime where the force of gravity makes it impossible for anything to escape it. Therefore, the only way to study its properties is by analyzing the X-rays it emits. The aim of this project is to analyse the data of GRS 1716-249 provided by the Swift explorer and use the concept of the limit of Eddington to find a lower limit for the mass of the alleged blackhole.

I. INTRODUCTION

In this section the most important aspects of the theory of this project will be explained to improve the understanding of the phenomena.

A. Black-holes

When a star with a mass of at least 10 to 15 times the one of the Sun undergoes a supernova explosion, it may leave behind a burned-out stellar remnant, and, if there are no external forces to oppose gravitational forces, this will collapse in on itself, creating a point with no volume and infinite density known as a "singularity". Around this region, because of the strength of the force of gravity, not even light can escape, being this what we know as black hole.

Since light can not escape it, a black hole floating alone in space would be nearly impossible to see in the visual spectrum. However, this black hole can accrete matter into itself when it's close to another star or passes through a cloud of interstellar matter. When this takes place, this matter gains kinetic energy, heats up and is squeezed by tidal forces, so that the heating ionizes the atoms until they reach a few million Kelvin and emit X-rays. [Joha]

Another place where we can find black hole candidates are binary X-ray sources. These are systems of two stars orbiting around the same center of mass, where one of them is a collapsed star and they are close enough so that the other one can transfer matter to it, producing X-rays in the process. It's in these cases where we can quite easily calculate the black hole candidate's mass and determine whether this candidate is a neutron star or a black hole, knowing that neutron stars always have masses of about 1.5 times the mass of the Sun.

While a few Black hole Binaries are persistent sources, most of them are of transient nature, making them hard to discover without a wide-field X-ray instrument. In them, the accretion rate onto the central objects increases by orders of magnitude and the sources go into outburst for some time. When this happens, their X-ray luminosity increases, peaks, and decreases after that, as it can be seen in the light curve, while the detailed properties of the energy spectra and fast variability change.[Tom16].

According to [NMa96], GRS 1716-249 is a soft X-ray Transient, subclass of Low Mass X-ray Binaries and candidate of having a blackhole. Therefore their data could only be detected thanks to a wide-field X-ray instrument, the Swift.

B. Swift

A gamma-ray burst (GRB) is a highly energetic and very directional extragalactic radiation from a determinate source. Some of these bursts last from milliseconds to hundred seconds and from any direction of the sky. Because of their nature, GRB are extremely complicated to observe. However, a slower and fading "afterglow" is usually emitted at longer wavelengths from the same source[Ved09].

In order to study this phenomena and its causes, NASA launched the Swift Gamma Ray Burst explorer [Johc], dedicated to identify gamma-ray bursts (GRB) and quickly send their location to stations so the burst's afterglow can be observed by specialized telescopes. This device relies on three different instruments [Pen] known as the BAT, the XRT and the UVOT.

The BAT (Burst Alert Telescope) is a highly sensitive instrument with a large field of view that allows the detection of GRB candidates and calculates an initial position within seconds. The XRT (X-ray telescope) refines the initial position of the GRB candidate and within ten seconds is capable of making measurements. The UVOT (UV/Optical Telescope) provides measurements fot the ultraviolet and optical wavelengths.

The measurements used in this particular study are the observations form the XRT of the Swift mission. This device measures fluxes, spectra, and lightcurves of GRBs and afterglows [Johb], which will be used to find the Eddington limit.

C. Eddington limit

Eddington limit is the luminosity of an object when there is an equilibrium between the gravitational forces and the radiation pressure. Beyond this luminosity, the radiation pressure will be stronger than the gravitational forces and outer material will be repelled rather than attracted. This limit is given by matching both competitive forces.

$$\boxed{\begin{aligned} F_{grav} &= \frac{GMm}{R^2} && \text{(1a)} \\ F_{rad} &= P_{rad}\kappa m = \frac{L}{c}\frac{1}{4\pi R^2}\kappa m && \text{(1b)} \end{aligned}}$$

$$\frac{GMm}{R^2} = \frac{L}{c}\frac{1}{4\pi R^2} \Rightarrow L = \frac{4\pi GMc}{\kappa}$$

Where a luminous object of mass M and luminosity L and a small cloud of mass m at a distance R are considered. Also, the opacity κ for radiation pressure against any surrounding material is needed.

Therefore, the Eddington luminosity depends only on the mass and so it can be used to determine an unknown mass by identifying this limit in the light curve of the studied source.

In order to specifying a needed value for κ, in certain cases it can be approximated by using Thompson scattering, being $\kappa = \sigma_T/m_p$. Therefore, the Eddington luminosity can be expressed as:

$$L_{Edd} = \frac{4\pi GMcm_p}{\sigma_T}$$

This approximation, however, is only valid in high-energy accretion scenarios.

In terms of the energy flux F, the previous relation yields:

$$L_{Edd} = 4\pi R^2 F = \frac{4\pi GMcm_p}{\sigma_T} \Rightarrow M = \frac{\sigma_T R^2 F}{Gcm_p}$$

Where R is the distance between the object of study and the receptor.

II. DATA ANALYSIS

The method for inferring an lower bound for the mass of GRS 1716-249 is based on the concept of Eddington limit. The parameters (apart from the known constants) needed for these calculations are:

- Distance from object to receptor
- Identification of Eddington limit
- Calculation of the mass

A. Distance

The distance to GRS 1716-249 is $\simeq 2.8kpc$ [NMa96]. According to the article, the data was obtained from Earth, but as the radius at which the Swift orbits is a much smaller distance(200-200km)[Johc] than $2.8kpc$ this number can be used for the following calculations.

B. Identification of Eddington limit

A candidate of the Eddington limit can be found by identifying the maximum luminosity of the XRT measures. Using the online tools of swift [Cen] a light curve of the object is obtained (figure 1):

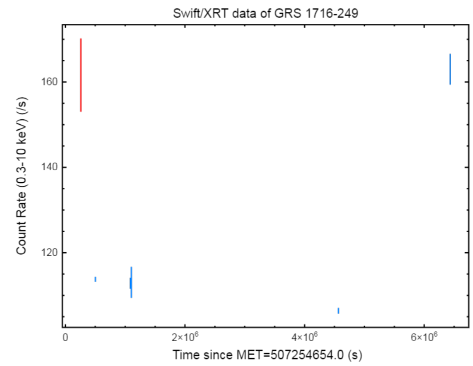

FIG. 1. Light curve

There are two maxima. Downloading the data file the following table has been generated, with the first column corresponding to the Swift time of every measure available.

TABLE I. Light curve data

READ TERR 1 2					
! WT					
500794.641	226.243	-226.243	113.7652	0.6009645	-0.5783704
1087968.647	2990.231	-2990.231	113.0086	1.098995	-1.447773
1102699.136	680.942	-680.942	113.1211	3.584345	-3.702865
4565682.677	124.894	-124.894	106.4033	0.6822264	-0.6803476
6435103.259	543.877	-543.877	160.4883	6.096469	-1.12853
NO	NO	NO	NO	NO	NO
! PC					
259184.386	37.610	-37.61	161.6036	8.600296	-8.600296

Using [Johd] the Swift times were translated to dates:

TABLE II. Conversions of time

Swift time (MET)	Calendar time (UTC)
500794.641	2017Feb02 at 19:10:30.086 UTC
1087968.647	2017Feb09 at 14:16:44.058 UTC
1102699.136	2017Feb09 at 18:22:14.547 UTC
4565682.677	2017Mar21 at 20:18:56.677 UTC
6435103.259	2017Apr12 at 11:35:57.259 UTC
259184.386	2017Jan31 at 00:03:39.845 UTC

Therefore, the Swift time and calendar times for the two maxima found are:

TABLE III. Times for the maxima

	Swift time(since MET)	Calendar time (UTC)
First maximum	259184.386	2017Jan31 at 00:03:39.845 UTC
Second maximum	6435103.259	2017Apr12 at 11:35:57.259 UTC

1. Data for first maximum

Using the software Heasoft the following light curve was obtained, with exposure time $701.16999s$.

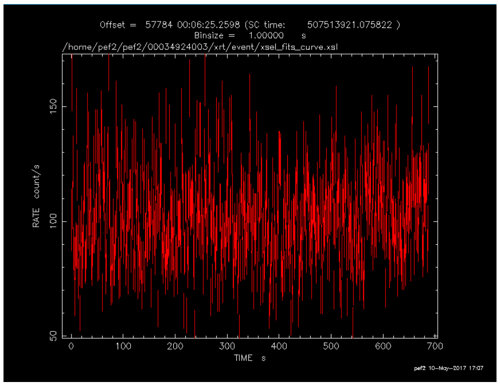

FIG. 2. Light curve for first maximum

And as can be seen in the light curve above, this maximum is the most intense one, and therefore, the useful one to find out information about the mass of the black hole. In addition, the available data for the second maximum was not enough to build the spectrum or get any reliable information from it, so it was not studied.

C. Calculation of the mass

Once identified the maximum in luminosity, the maximum flux is obtained using the online tools of swift [Cen].

Evaluating for the first 24 hours of observation, the following spectrum is found:

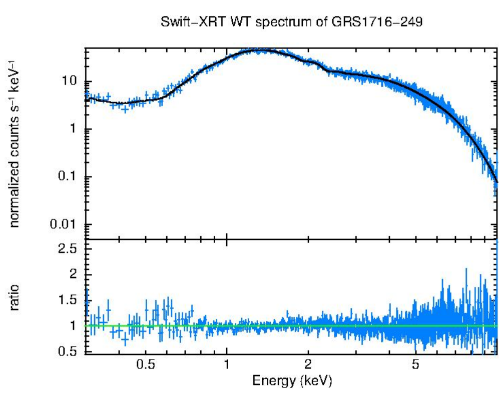

FIG. 3. Spectrum of first maximum

where the observed flux is $5.44 \pm 0.05 \cdot 10^{-9} ergcm^{-2}s^{-1}$ and the unabsorbed flux is $7.34 \pm 0.06 \cdot 10^{-9} ergcm^{-2}s^{-1}$, obtained by correcting the previous value for the interstellar absorption given by the presence of $6.45 \pm 0.15 \cdot 10^{21} cm^{-2}$ of N_H. Therefore, the intrinsic flux emitted by the object is the second one, and so the one needed to obtain the Eddington limit.

Using the following parameters, an upper limit for the mass is obtained (where M_S is solar mass):

- Thompson's cross-section $\sigma_T = 6.6524 \cdot 10^{-25} cm^2$
- Distance from GRS 1716-249 to the SWIFT telescope $R = 2.8kpc = 8.64 \cdot 10^{21} cm$
- Flux of energy $F = 7.34 \pm 0.06 \cdot 10^{-9} \dfrac{erg}{cm^2 s}$
- Gravitation constant $G = 6.674 \cdot 10^{-8} \dfrac{cm^3}{gs^2}$
- Mass of a proton $m_p = 1.67 \cdot 10^{-24} g$
- Light speed $c = 2.998 \cdot 10^{10} cm/s$

$$M = \frac{\sigma_T R^2 F}{Gcm_p} = \frac{6.6524 \cdot 10^{-25} \cdot (8.64 \cdot 10^{21})^2 10^{-9}}{6.674 \cdot 10^{-8} \cdot 2.998 \cdot 10^{10} \cdot 1.67 \cdot 10^{-24}}$$

$$M = 1.5 \cdot 10^{31} g = 0.011 M_S$$

This is a lower limit of the mass as there is no way to certify that the maximum in luminosity proposed is the absolute maximum. Also some other wavelengths have not been looked into so total flux has not been taken into account.

III. FURTHER ADJUST TO OBTAIN THE FLUX

Even though some techniques from Swift were used [Cen], a more in depth analysis of the spectrum was made using XSPEC [Dra]. XSPEC is an online tool to fit observational data taking into account theoretical models to have an estimation of the parameters of such models. In order to do so some documents were downloaded (the .arf and .rmf extensions were necessary to create the .pha extension to use on XSPEC) and the observations were fitted in XSPEC with the model tbabs*(diskbb + comptt). To understand this there is a need for some previous background on how the fitting is done, which can be found in the appendix.

A. Models used to fit the obtained data

The used models are: *tbabs*, *diskbb* and *paw*.

diskbb: The model of the spectrum corresponds to an accretion disk consisting of multiple blackbody components.

comptt: This model takes into account the comptonization of soft photons in a hot plasma.

tbabs: The Tuebingen-Boulder ISM (interstellar medium) absorption model calculates the cross section for X-ray absorption by the ISM as the sum of the cross sections for X-ray absorption. This cross-section depends on the quantity of present molecules in the column that goes from the source to the telescope and the radius of which is the radius of the telescopes aperture. The command tbabs allows the user to change the quantity of hydrogen per area (of aperture) in that column.

B. Results of the model

The data that should be modeled is shaped as follows:

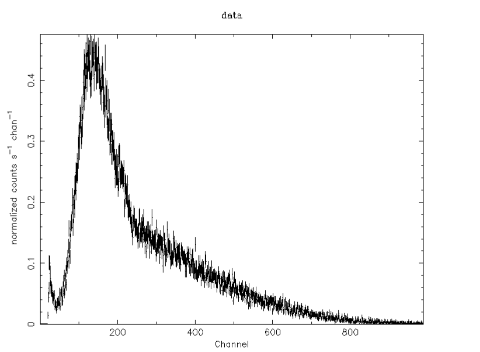

FIG. 4. Data to model

And the final model has the following shape:

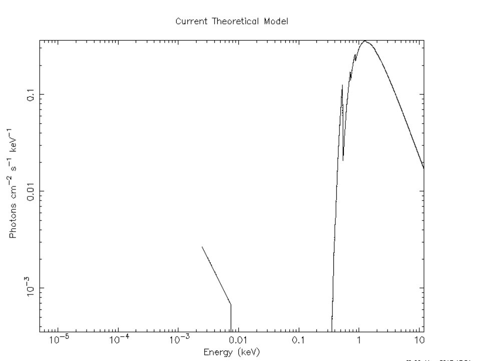

FIG. 5. Chosen model

where the first peak appears because the absorption is only present in certain frequencies. If it absorbed below $0.01 keV$, the peak would not be there.

The parameters estimated are:

TABLE IV. Parameters of the model tbabs*(diskbb + comptt)

Component	Parameter	Unit	Value
TBabs	nH	10^22	$0.491079 \pm 1.31294 \cdot 10^{-02}$
diskbb	Tin	keV	$6.29999 \cdot 10^{-03} \pm -1.00000$
diskbb	norm		$5.86486 \cdot 10^{-04} \pm -1.00000$
compTT	Redshift		0.0 frozen
compTT	T0	keV	$0.132669 \pm 1.67781 \cdot 10^{-02}$
compTT	kT	keV	42.7555 ± 1392.79
compTT	taup		1.23013 ± 39.0407
compTT	approx		1.00000 frozen
compTT	norm		$8.25525 \cdot 10^{-02} \pm 2.69163$

So, fitting the data to the model, the following adjust is obtained:

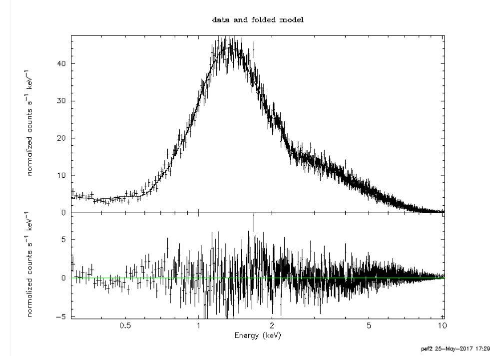

FIG. 6. Fitting of model to data

Where, in the bottom of the plot, it can be seen that the difference of the data and the model is constant and small enough. Also, with this model, the obtained flux is of $5.2436 \cdot 10^{-9} ergs/cm^2/s$, while the obtained flux with the online tools was of $5.44 \pm 0.05 \cdot 10^{-9} erg/cm^2/s$, proving that the chosen model has a really similar adjust.

IV. CONCLUSION

After modelling the data obtained from the first and brightest maximum of the light curve of the object GRS 1716-249, a very similar output to the one resulting from the online tools has been obtained. Therefore, it is reassured that its mass has a lower limit at $0.011 M_S$, which is a much lower value than the expected one. To obtain a more accurate approach, the study could be extended by considering the emission of the object at all wavelengths and not limiting the spectral range to the instrument's sensitivity.

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REFERENCES

[NMa96] N.Masetti, A.Bianchini, J.Bonibaker, M.Della Valle, R. Vio. "The superhump phenomenon in GRS 1716-249 (=X-Ray Nova Ophiuchi 1993)". In: *Astronomy and astrophysics* 314 (1996), p. 128.

[Ved09] J.-L. Vedrenne G; Atteia. *Gamma-Ray Bursts: The brightest explosions in the Universe*. Springer, 2009. ISBN: 978-3-540-39085-5.

[Tom16] Sara E. Motta Tomaso M. Belloni. "Transient Black Hole Binaries". In: *Astrophysics and Space Science Library* 440.1 (2016), p. 45. DOI: https://arxiv.org/pdf/1603.07872.pdf.

[Cen] UK Swift Science Data Centre. *Build Swift-XRT products*. URL: http://www.swift.ac.uk/user_objects/.

[Dra] Nikos Drakos. *XSPEC Manual*. URL: https://heasarc.nasa.gov/xanadu/xspec/xspec11/manual/manual.html.

[Joha] John.D.Myers. *Black Holes*. URL: https://imagine.gsfc.nasa.gov/science/objects/black_holes2.html.

[Johb] John.D.Myers. *Swift: About Swift - XRT Instrument Description*. URL: https://swift.gsfc.nasa.gov/index.html.

[Johc] John.D.Myers. *The Swift Gamma-Ray Burst Mission*. URL: https://swift.gsfc.nasa.gov/index.html.

[Johd] John.D.Myers. *xTime - A Date/Time Conversion Utility*. URL: https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/xTime/xTime.pl.

[Pen] PennState. *Welcome to the Swift Gamma Ray Burst Explorer Mission*. URL: http://www.swift.psu.edu.

I. APPENDIX

1. *Basics of spectral fitting*

A measurement of a magnitude usually depends on the instrument of measurement, but in measuring the spectrum of a certain source this dependence is crucial. What the spectometre obtains is a certain number of photons (C) within specific instrument channels, (I). Considering $f(E)$ the actual spectrum of a source,$R(I, E)$ as the instrumental response (it is proportional to the probability that an incoming photon of energy E will be detected in channel I) the previous magnitudes are related by:

$$C(I) = \int f(E)R(I, E)$$

As it is not easy to invert this equation, what XSPEC does is to, given a model $f_m(E, p_1, p_2, ...)$ ($p_1, p_2, ...$ are parameters to determine) chosen by the user, fit it to the observations with a "Chi statistic" test. The compared magnitudes are the real count $C(I)$ with the predicted one $C_m(I)$ given by the expression

$$C_m(I) = \int f_m(E)R(I, E)$$

This test will provide the user with a confidence interval that indicates whether the model fits well the observations taking into account the response of the instrument.