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Abstract

Diaz Trigo et al. (2013) have recently claimed that they find evidence for baryons in the relativistic jets of the stellar-mass black-hole candidate X-ray binary 4U 1630-47. They claim they find three emission lines of which one is redshifted FeXXVI, one is blueshifted FeXXVI and the other blueshifted NiXXVII. In this paper we try to reproduce their findings and also explore a different, new model that they did not try. We find that this model, which differs from the others in the fact that it does not assume solar abundance for the interstellar matter along the line of sight to the source and includes an iron emission line, can fit the data equally well, but without the need for emission lines that are red- or blueshifted. Furthermore, we also analyze the data without applying the Science Analysis Software (SAS) task epfast to find other results. The model that they use can not be fitted in this case and instead of an iron emission line in our model there appears to be an absorption line around 7 keV. If our model is correct, it implies that there are no baryons in the jets of 4U 1630-47.

1. Introduction

1.1 X-ray binary star systems

X-ray binary systems are binary star systems that are very luminous in the X-ray part of the spectrum. They emit in the X-ray region because it is believed that one of the components is a compact object accreting matter from the other star. The compact object can either be a neutron star or a black hole. Often, there are also jets visible¹ (see subsection 1.6). The emission processes believed to be responsible for the emission in the X-ray part of the electromagnetic spectrum, for the system as a whole are thermal disk emission and inverse Compton scattering². Comptonization normally means that high-energetic photons scatter off electrons, thereby giving off some of their energy to the electrons, so the photons become less energetic and the electrons more energetic. Inverse Compton scattering is exactly the opposite. Here, the electrons are more energetic and give off some of their energy to the photons in scattering processes. So these photons get more energetic and eventually become X-ray photons. The emission processes believed to be responsible for the emission in the jets are either inverse Compton scattering or synchrotron radiation or a combination of these³. Synchrotron radiation occurs when a charged particle gets accelerated by a magnetic field. Accelerated charged particles emit radiation. It is believed that electrons spiral around magnetic field lines, produced by the accretion disk, and thereby get accelerated. They spiral outward in a jet-like outflow. During this process they emit radiation and this radiation is mostly in the radio regime. These radio photons then get upscattered due to inverse Compton scattering and end up in the X-ray part of the spectrum.

Because the source of interest, 4U 1630-47, is a black-hole candidate, we will only talk about a black hole in the remaining of this thesis and not about a neutron star. The picture of a black hole is that you have the central object, which is the black hole, and it has an accretion disk around it. In this accretion disk there is matter that is in orbital motion around the black hole and gradually spirals inward towards the black hole. There is also the corona, which is an aura of plasma that surrounds the black hole (see Figure 1 for a very schematic picture of a black hole). This plasma consists of ions and electrons. The disk accounts for the thermal disk emission and the corona for the inverse Compton scattering⁴.

1.2 X-ray emission components

There are some standard components for the X-ray emission for a black hole in a binary system. These are:

1. The disk part. This is the emission part of the accretion disk of the black hole. Most often the emission is regarded as a sum of many blackbody components⁵. So it is the spectrum from an accretion disk consisting of multiple blackbody components. The disk part of the emission spectrum depends strongly on the temperature at the inner disk radius. The inner disk radius is the distance from the centre of the black hole to the inner edge of the accretion disk. As can be seen from Figure 1, the inner disk radius is vastly different in the hard state and in the soft state. In the hard state this radius is larger

than in the soft state (more about the different states in subsection 1.3). Now, the temperature is of course not constant radially along the accretion disk, it will decrease with increasing radius. To account for that, one divides the accretion disk radially into several parts and defines a temperature for each part. Then for each part the emission is assumed to be a blackbody with a certain temperature, so that the whole can be regarded as the sum of many blackbody components.



Figure 1 - The hard/soft state. X-ray binaries are known to exist in two different states, the hard state and the soft state. The hard state is characterized by a large inner disk radius, so the accretion disk is far away from the central object. In addition, the corona is strong and the source emits hard photons especially. The soft state, on the other hand, is characterized by a small inner disk radius, so the accretion disk is near to the central object. In addition, the corona is weak and the source emits soft photons especially.

2. A power-law component. The power law represents the extent to which the corona around the black hole is present or not. In the hard state the corona is larger and stronger than in the soft state. So in the hard state the power-law component will be more dominant than in the soft state, whereas in the soft state the disk is more dominant. It is believed that this component results from inverse Compton scattering, of which will be said more in point 3. The power law has the form of AE^{- Γ}. Here A is the normalization parameter of the power law and Γ is the photon index. The photon index typically is ~ 1.5 – 2.0 for the hard state and ~ 2.5 – 3.0 for the soft state⁶, meaning that the power law is steeper in the soft state.

3. A comptonization component. This component is due to the corona around the black hole. The corona consists of a hot plasma. In this plasma a very important process is the inverse Compton scattering of photons. Actually, the power-law component is just a mathematical approximation to this process, using a simplified formula. In this case there are a lot of soft photons from the disk, with a lower energy than the electrons in the hot plasma. This means that the high-energetic electrons can give some of their energy to the soft photons. The processes are a bit different for the hard state and the soft state. In the hard state the thermal comptonization is dominant, while in the soft state it is the non-thermal comptonization that is dominant⁷. In the thermal case the distribution of electrons follows a Maxwellian distribution. That is to say, dNe/dE ~ Maxwellian. In the non-thermal case, it follows a different distribution, dNe/dE ~ E^{-p}. In the hard state a soft photon suffers multiple inverse Compton scatterings, whereby it gains so much energy that it ends up being at the hard part of the spectrum. Due to relativistic effects, it is also possible to have just one single inverse Compton scattering. In the first case there are many scatterings, but just a small shift in energy per scattering and in the second case there is one scattering with a large shift in the energy⁷. In the soft state a photon encounters non-thermal electrons, which are believed to be located in compact regions just above and below the accretion disk⁸.

4. Emission lines. There are a lot of emission lines that show up in X-ray spectra of black-hole binary systems. The one that is most important and broad is an iron emission line⁹. The rest energy of the iron emission lines lie in the range 6.4 - 6.97 keV. Here the 6.4 keV is the FeI emission line, which is just neutral iron. The 6.97 keV is the FeXXVI emission line, which means it is 25 times ionized, so it has only one electron left. We call this hydrogen-like iron. Mostafa et al. (2013) report a broad iron emission line at 6.5 keV in the spectrum of the X-ray transient J1753.5 0127, most likely due to iron in the accretion disk. Furthermore, they discovered broad emission lines of NVII and OVIII at around ~ 0.52 keV and ~ 0.65 keV respectively⁶. These are highly ionized nitrogen and oxygen. There are more lines possible, for instance of NiXXVII, which has a rest energy of 7.74 keV¹⁰.

5. Absorption lines. Apart from emission lines there are also some absorption lines possible in the spectrum of a black hole. Rozanska et al. (2013) report absorption lines in the spectrum of 4U 1630-47. They found absorption lines of highly-ionized iron, both hydrogen-like and helium-like, which originates in the hot accretion disk atmosphere. They can originate in upper parts of the disk atmosphere which is intrinsically hot due to high disk temperature¹¹.

1.3 States of X-ray binaries

The spectra of X-ray binaries can be divided into two states. One is the hard/low state and the other the soft/high state. The hard state is dominated by a power law rather than a disk thermal component. This power law contributes more than 80% of the flux in the 2 - 20 keV band. The photon index of this power law is ~ 1.5 - 2.0. The soft state, on the other hand, is dominated by a disk thermal component rather than a power law. The thermal component contributes more than 75% of the flux in the 2 - 20 keV band. The photon index of this power law. The thermal component contributes more than 75% of the flux in the 2 - 20 keV band. The photon index of this power law is ~ $2.5 - 3.0^6$.

The hard state can again be divided into three distinct states according to Abe et al. (2004). The first is the standard regime. This state is described by the standard model of Shakura and Sunyaev (1974). The

second is the anomalous regime. This is the state in which some of the disk emission is converted into hard X-rays by means of inverse Compton scattering. In this case the spectrum will be shifted towards a harder state. The last state is the apparently standard state. This is a bit of a mixing model between the first two. In this case the disk thermal component is dominant, but also a weak hard tail can be seen. When the inner temperature of the accretion disk is less than 1.2 keV, it appears to be in the standard regime. When the inner temperature of the accretion disk exceeds 1.2 keV, the source is in the anomalous regime or the apparently standard regime¹². Diaz Trigo et al. (2013) state that 4U 1630-47 was observed while it was in its anomalous accretion state¹⁰.

1.4 Roche lobe overflow

For 4U 1630-47 the donor star is most likely a relatively early-type (late B or F class) star. The accretion occurs by means of Roche lobe overflow¹⁰. The Roche lobe is that region of space around a star in a binary system within which orbiting material is gravitationally bound to that star. Material which lies within the Roche lobe of a star will not be able to escape the gravitational pull of the star. When the star, however, expands past its Roche lobe, then that material will be able to escape from the gravitational pull of the star. In a binary system one can define equipotential surfaces in a non-inertial frame. In this case the potential consists of the gravitational force and the centrifugal force. Surfaces where this potential, described by these two forces, is constant are called equipotential surfaces. Now, when close to each star, these equipotential surfaces are approximately spherical and concentric with the star. When moving farther away from the star, the surfaces become more and more ellipsoidal and elongated parallel to the line through the centres of the stars. However, there is one critical equipotential surface. This one intersects itself at the L1 Lagrangian point of the system. This forms a two-lobed figure that resembles an eight with one of the two stars at the centre of each lobe (Figure 2). These figures define the Roche lobes. A Lagrangian point is a point where the gravitational pull of both stars provides exactly the centrifugal force needed to orbit with them. So, consider for instance that a particle is at the L1 Lagrangian point of the system and that the origin of the coordinate system is at the centre of one of the two stars. The particle will have exactly the same angular velocity as the second star around the first star and hence it will maintain the same position as seen from the second star relative to the first star. Roche lobe overflow means there is mass transfer from one of the stars to the companion. This happens when a star exceeds its Roche lobe, which means that its surface extends farther out than its Roche lobe and all the material that is outside this lobe can fall off into the Roche lobe from the other star. This happens via the first Lagrangian point. So in 4U 1630-47 it is believed that the black hole accretes matter from its companion star via the first Lagrangian point, because the companion star's surface exceeds its Roche lobe¹³.



Figure 2 - Roche lobe overflow. The lines shown here are lines of equal potential. The potential here consists of the gravitational force and the centrifugal force. In reality, these should be equipotential surfaces instead of just lines. In the centre of the circles are the two objects, one is the black hole and the other the companion star. Close to the objects the equipotential surfaces are nearly spherical and concentric and farther out they become more ellipsoidal. The purple colored line is the critical surface. These define the Roche lobes. The point of intersection is the inner Lagrangian point. Mass flows from the companion star to the black hole via this point.

1.5 *X*-ray transients

4U 1630-47 is a recurrent X-ray transient system¹⁰. This means that it shows changing levels of X-ray emission, it is not constant in time. It has periods of enhanced X-ray emission, which last longer than a week, but are not representative of the normally observed emission from the source. It is known that 4U 1630-47 exhibit X-ray outbursts with a period of about 650 days¹². Diaz Trigo et al. (2013) observed the source during its 2012 outburst.

It is believed that the transient effect is due to sudden changes in the accretion rate onto the black hole. Until now it is not known why these sudden changes happen, but there are some theories about it¹⁴. In high-mass X-ray binaries the companion star is often a Be star. This means that this star is of spectral type B, but it shows some emission lines in its spectrum. Be stars are known to have a circumstellar envelope which is strongly concentrated in the equatorial plane. They can eject lots of material in a

sudden outburst from their equatorial region. Probably because they are rotating so quickly that they are near to their break-up point.

It could also be that accretion only occurs during a small part of the binary orbit. This is important for systems where accretion occurs by means of Roche lobe overflow, as is the case for 4U 1630-47. Then accretion only occurs when the companion star enters the Roche lobe of the black hole. If the orbital period is long, then the source will look like a transient, because the companion star is not always in the Roche lobe of the black hole, but just for some limited time.

The most popular model for lower-mass X-ray transients is the creation of an instability in the accretion disk. It is believed that material can accumulate 'quietly' in the disk until there is enough material accumulated. Then you have a thermal instability and this will enhance the accretion rate onto the black hole¹⁴.

1.6 Jets

Jets are often seen in astronomy, not only in black holes, but also in certain stars. A jet is a stream of matter that is emitted from the compact object along a narrow cone. It is not known how these jets are formed and powered, though it is believed that the accretion disk plays a major role¹⁵. One of the best ways to explore how jets are produced, is to determine the composition of the jets. Jets that contain baryons are more likely to be powered by the accretion disk than by the spin of the black hole, while jets that are purely leptonic are more likely to be powered by the black-hole spin¹⁰. The most popular theory for the powering of jets by black-hole spin is the Blandford-Znajek process¹⁶. In this process magnetic field lines around the accretion disk are dragged by the spin of the black hole and the material is possibly launched by the tightening of the magnetic field lines.

Most jets in black hole binary systems appear to be relativistic jets, which means that matter is ejected nearly at the speed of light. Thereby, there appear to be some apparently superluminal jets. Matter appears to be moving at a speed larger than the speed of light. This is due to the fact that matter is ejected at speeds very near the speed of light and are ejected at a very small angle towards the observer. The jet constantly emits light due to synchrotron radiation and therefore the light they emit does not approach the observer much more quickly than the jet itself. This gives the illusion of jets going faster than the speed of light, though in reality they of course do not go faster, so it does not violate special relativity¹⁵.

Jets emit not only X-rays, but also emit in the radio part of the electromagnetic spectrum. This is also possibly caused by synchrotron radiation³.

In the paper by Diaz Trigo et al. (2013), they claim that in the X-ray spectrum from 4U 1630-47 three clear emission lines can be seen, of which they say they come from blueshifted FeXXVI and NiXXVII and from redshifted FeXXVI. They then claim that these emission lines arise from relativistic jets moving towards and away from the observer⁶. This is a strong claim and in this paper we look at other possibilities than this one. First, we try to reproduce all their results by fitting the models they took and see if we get the same fits and the same values for the parameters. Secondly, we introduce a new model to see whether it could also fit the data well. This model has a slightly different form than the ones Diaz

Trigo et al. (2013) use in their paper. Finally, we look at the uncorrected spectrum where the epfast task is not applied and see whether there are some large deviations from the corrected spectrum where epfast is applied (epfast is to correct for calibration uncertainties, which show up in the spectrum of the source).

2. Observations and data analysis

Diaz Trigo et al. (2013) used the European Space Agency's XMM-Newton spacecraft to make two observations of the stellar-mass black hole candidate X-ray binary 4U 1630-47 during its outburst in 2012¹⁰. The first X-ray observation was done on 2012 September 11-12 and its observation ID is 0670673101. The second X-ray observation was done on 2012 September 28 and its observation ID is 0670673201. The exact times can be found in Table 1.

Observation	Observation ID	Observation time (UTC)			
XMM1	0670673101	11-09-2012 20:14 – 12-09-2012 05:39			
XMM2	0670673201	28-09-2012 06:33 – 28-09-2012 21:50			

Table 1 - Observation names, observation ID's and times of the observations

The observations were both made with XMM-Newton, whereby they used the EPIC pn chargecoupled-device (CCD) camera in burst mode.

2.1 Burst mode

In this so-called burst mode just one of the CCD chips is read out. In this case this is chip number 4. Imaging is only made in one direction, along the column axis. Along the other direction, the row axis, the data are collapsed into a one-dimensional row. This row can be read out at very high speed. The second positional dimension is replaced by timing information. So actually, you gain very much timing resolution (7 μ s), but this goes at the expense of spatial information and the efficiency. In fact, the burst mode has an efficiency of just 3%, whereas the so-called timing mode has an efficiency of 99%. The difference with the timing mode is that the timing mode has much lower time resolution than the burst mode¹⁷.

2.2 Photon pile-up

The other advantage of using the burst mode is that it prevents the process of photon pile-up. Photon pile-up actually means that more than one X-ray photon arrives in one camera pixel or in an adjacent pixel before it is read out. This leads to a decrease of the photon flux, but to an increase in individual photon energy¹⁸. Suppose, for instance, that 2 photons with an energy of 4 keV each arrive in one pixel before this pixel is read out. Then the flux reduces, because it looks like there is just one photon in that pixel instead of two. The energy read out for this pixel will be higher than 4 keV, because the charge read out is also higher. So, all in all, the flux of soft photons (photons with a low energy) reduces, because the charges of these photons combine and they are seen at higher energies. This can dramatically change the measured spectrum and also the parameter values used to fit a model to this spectrum¹⁸. Since in burst mode the CCD chip is read out at very high speed, the probability of pile-up is very low.

The arrival of more than 1 photon at the same time within one readout cycle creates certain multi-pixel photon patterns. Here Pattern 0 means there is one or more photons that arrive in a pixel without adjacent pixels being hit by a photon. Pattern 1 means a certain pixel is being hit by a photon, but there is also some charge in an adjacent pixel. Pattern 2 means a different adjacent pixel is also being hit, and so on. Note that in the absence of pile-up there will always be Pattern 0, while the other way around it is not always true. When Pattern 0 occurs, it is very unlikely that the photon is piled up.

2.3 Epfast

Diaz Trigo et al. (2013) applied the Science Analysis Software (SAS) task epfast to all event files. This is to correct for calibration uncertainties due to charge transfer inefficiency (CTI) effects. This effect occurs during the readout of the CCD detector. The CCD detector will be read out in a certain readout direction by transferring charge from one pixel to another. This will not always be a 100% efficient process. Sometimes, some of the electrons may be lost into charge traps. These are just randomly distributed throughout the silicon lattice. Because of the loss of electrons, the apparent energy of the incoming photons will become smaller. This leads to residuals in the data at lower energies. These

residuals are also observed in our data, especially between ~ 2 - 2.5 keV. The SAS task epfast tries to account for these CTI effects. Diaz Trigo et al. (2013) applied epfast and only worked with the epfast-corrected spectra of XMM-Newton. We expand this and not only work with the corrected spectra, but also with the uncorrected spectra, which are not yet corrected for CTI effects by performing the epfast task. In a paper by Walton et al. (2012)¹⁹ the use of the task epfast is discussed. They found that epfast corrects for these effects well in the lower energy range, especially at 1.5 - 2.5 keV, but at higher energies it overcorrects the spectrum. This is because epfast applies a correction which is independent of energy. So in this case $\Delta E/E = \text{constant}$. However, studies show that CTI depends on energy in a different fashion, as ($\Delta E/E$)_{CTI} $\propto E^{-\alpha}$, with $\alpha \simeq 0.5$. This means that at lower energies CTI has a larger impact than at higher energies. For instance, the relative impact of CTI at 2 keV is two times as large than at 6-7 keV. Also when the calibration uncertainties are due to some other effect, for instance X-ray loading or optical loading²⁰, the correction made by epfast is not a good one. In fact, it will even be a

worse approximation. So this is the reason why we also explored the uncorrected spectrum.

Before fitting the data with the program XSPEC, we make the data ready to be processed by SAS. First, we initialize the calibration files and the observation data files. We build a ccf.cif file which contains references to all calibration files and tells SAS which calibration files have to be used for each instrument and observation. We do exactly the same data analysis as Diaz Trigo et al. (2013) did¹⁰. We also created an RMF (Response Matrix File) and an ARF (Ancillary Response File). However, there is one thing that we do different. Diaz Trigo et al. (2013) did not subtract the background spectrum when making the final fits. We do subtract the background spectrum.

2.4 XSPEC models

We fit the X-ray spectra using the spectral analysis package XSPEC²¹. We use the following XSPEC models for our fits:

1. Single-disk emission. This model is called *diskbb* in XSPEC. This model represents the emission spectrum from an accretion disk consisting of multiple blackbody components. There are two free parameters in this model. The first is the temperature at the inner disk radius. As said earlier, the inner disk radius is the distance from the centre of the black hole to the inner edge of the accretion disk. The second is a normalization parameter. It is given as follows: $(R_{in}/D)^2 \cos\theta$. R_{in} in this case is the apparent inner disk radius in km, D is the distance to the source given in units of 10 kpc and θ is the angle of the disk, where $\theta = 0$ means face-on and $\theta = 90$ means edge-on.

2. Power-law emission. This model is called *powerlaw* in XSPEC. It is believed that this component results from inverse Compton scattering in the corona around the black hole (see subsection 1.2). It is just a simple photon power law. There are two free parameters in this model. The power law is given by $A(E) = KE^{-\alpha}$. Here E is the energy of a photon, α is the photon index and K is the normalization of the power law. The normalization is given in units of the number of photons keV⁻¹ cm⁻² s⁻¹ at 1 keV. The photon index is the slope of the straight line in a log-log plot of the flux of photons versus their energy.

3. Thermal Comptonization. This model is called *comptt* in XSPEC. It describes the Comptonization spectrum of soft photons off electrons in the corona and also includes relativistic effects. The Comptonization process is described in the Introduction. This model was developed by L.Titarchuk (see ApJ, 434, 313)²². There are 6 free parameters in total. The first one is the redshift. The second is the input soft photon temperature, where the soft photon input spectrum follows a Wien law. The third parameter is the temperature of the hot plasma. The fourth is the optical depth of the plasma. In principle, the plasma temperature ranges from 2 - 500 keV, but the model is not valid when the plasma temperature and the optical depth are both low or when they are both high. Parameter 5 determines which approximation technique is used for a so-called parameter *b*. This is an important parameter since the Comptonized spectrum is completely determined by the temperature of the plasma and this *b* parameter. The sign of the fifth parameter determines the approximation technique that is used and the magnitude determines the geometry. If parameter $5 \ge 0$ then parameter *b* is obtained from the optical

depth using an analytical approximation. If parameter 5 < 0 then parameter b is obtained using an interpolation technique. Furthermore, if parameter $5 \le 1$ then the geometry is a disk and if parameter 5 > 1 then the geometry is a sphere. We choose this parameter to be the default value, which is 1. The last parameter of *comptt* is the normalization.

4. Bremsstrahlung. This model is called *bremss* in XSPEC. Bremsstrahlung is the process of decelerating a charged particle. Typically, when an electron encounters a positively charged atomic nucleus or another electron, the electron will be deflected and gets decelerated. During this process, it loses energy and this is converted into a photon of this energy. The model has two free parameters. The first is the temperature of the plasma in keV. The second is the normalization. It is defined as $(3.02 \times 10^{-15}) / (4\pi D^2) n_e n_I dV$. Here, D is the distance to the source in cm, n_e is the electron density in cm⁻³ and n_I is the ion density in cm⁻³.

5. Collisionally-ionized spectrum. This model is called *bvapec* in XSPEC. This is a velocity- and thermally-broadened emission spectrum from a collisionally-ionized diffuse gas. There are 17 free parameters in this model. The first is the temperature of the plasma. Parameters 2 -14 set the abundances for He, C, N, O, Ne, Mg, Al, Si, S, Ar, Ca, Fe, Ni with respect to Solar abundance. Parameter 15 is the redshift. Parameter 16 is the Gaussian sigma for velocity-broadening given in km/s. The last parameter is the normalization.

6. Emission lines due to the presence of certain elements. For these emission lines we use the model called *gaussian* in XSPEC. This fits a gaussian model to the data.

7. Absorption due to the ISM. One can use the models called *tbabs* and *vphabs* (and more, but we only use these two models) in XSPEC to include absorption by interstellar matter. These models take into account that some of the emission is absorbed along the way to the observer. The two models are basically the same and only differ in how the process is modelled. In the first model, *tbabs*, it calculates the absorption cross-section by the ISM taking into account absorption due to the gas-phase ISM, the grain-phase ISM and the molecules in the ISM. There is just one free parameter here. This is the hydrogen column density given in units of 10^{22} cm⁻². The second model, *vphabs*, has the form of exp[- $n_H \sigma(E)$]. Here n_H is the hydrogen column density and σ is the photo-electric cross-section. This model has 18 free parameters in total. The first is the hydrogen column density, again given in units of 10^{22} cm⁻². The other 17 parameters are the abundances of He, C, N, O, Ne, Na, Mg, Al, Si, S, Cl, Ar, Ca, Cr, Fe, Co, Ni with respect to Solar.

We first fit the same models as Diaz Trigo et al. (2013) did. These are the following: 1) *tbabs*diskbb*, 2) *tbabs*(comptt+gauss+gauss+gauss)*, 3) *tbabs*(diskbb+powerlaw+gauss+gauss+gauss)*, 4) *tbabs*(diskbb+bremss+gauss+gauss+gauss)*, 5) *tbabs*(diskbb+comptt+gauss+gauss+gauss)*, and 6) *tbabs*(diskbb+bvapec+bvapec)*. The model with the disk blackbody and the powerlaw is the one most frequently used and the most important one, so we will mainly focus on this model in the remaining of this paper. In the *Results* section, we only analyze the results from this model and the fits of the other models can be found in the *Appendix*. After fitting these models, we will introduce a new model, which is *vphabs*(diskbb+powerlaw+gauss)*. This one differs from the one Diaz Trigo et al. (2013) use in the use of *vphabs* instead of *tbabs* and we only have one emission line instead of three. We use *vphabs*

because in this model we are able to vary the abundances in the ISM and we will vary the abundance of iron and sulfur as it turns out that these two have the most effect on the model. The gaussian represents an iron emission line and we do not use the three emission lines Diaz Trigo et al. (2013) did.

2.5 Abundances and cross-sections

For the absorption models it is important to make clear which values one chooses as the solar abundances. One can set this by using the *abun* command in XSPEC and then typing the name of the paper in which the abundances are stated. In the paper by Diaz Trigo et al. (2013) they chose this to be *abun angr*, where *angr* stands for the Solar abundances as stated in Anders E. & Grevesse N. Geochimica et Cosmochimica Acta 53, 197 (1989)²³. We choose it to be *abun wilm*, since the ISM abundances were updated since then. The abundances are then as stated in Wilms, Allen and McCray (2000, ApJ 542, 914)²⁴. This gives a better fit to the data, as χ_v^2 is getting closer to 1. Another variable is the cross-section. One can set these values equal to values stated in a paper by using the command *xsec* in XSPEC. In the paper by Diaz Trigo et al. (2013) they chose this to be *xsec bcmc*, where *bcmc* means the cross-section values come from Balucinska-Church and McCammon, 1998²⁵. We choose this to be *xsec vern*, because they have a much finer energy resolution than *bcmc*. These values for the cross-section come from Verner, Ferland, Korista, and Yakovlev 1996²⁶.

We do not fit the whole spectrum of the data, because the satellite is only sensitive to certain energy ranges. The satellite is not very efficient for energies much above 10 keV. Below energies of 2 keV there are some calibration issues as mentioned in subsection 2.3. Furthermore, the ISM absorbs most of the photons below 2 keV, since the hydrogen column density, N_{H} , is very high in this case. Diaz Trigo et al. (2013) just fitted the energy range from exactly 2 – 10 keV. We fit a slightly larger energy range, since we also want to include the 2 keV and the 10 keV. We choose to fit the data in the energy range 1.95 – 12 keV, since the satellite is efficient enough in this region.

We do not add a systematic error to the model, unlike Diaz Trigo et al. (2013), who did add a systematic error of 0.8% to the model.

3. Results

Observ	vation Model	χ_{v}^{2} (d.o.f.)							
	tbabs*diskbb_								
XMM1	$N_{\rm H}$ $kT_{\rm dbb}$ $k_{\rm dbb}$ 8 67+0 07 1 82+0 01 77+2								
	thahe*(comptt+gause+gause)	1 14 (276)							
<u>ιυαυς (computzgausszgaussz</u> N _H kT _{bb} kT _e τ k _{comput} Egan σ k _{ran}									
XMM1	8.2±0.4 0.72±0.06 1.75±0.08 7.7±0.6 2.1±0.2								
XMM2	8.2±0.4 0.71±0.05 2.05±0.09 6.7±0.4 2.2±0.2 4.08±0.06 tied 0.002±0.002	1							
	7.25 ± 0.03 0.11±0.04 0.003±0.000 7.02±0.22 tipd 0.0008±0.00)// DOE							
	7.92±0.22 tied 0.0008±0.00								
	tbabs*(diskbb+powerlaw+gauss+gauss+gauss)	1.34 (278)							
XMM1	$N_{\rm H}$ $K_{\rm I}_{\rm dbb}$ $K_{\rm dbb}$ I $K_{\rm po}$ $E_{\rm gau}$ σ $K_{\rm gau}$ 9.25+0.10 1.70+0.02 $9.4+4$ 2.(f) 0.67+0.11								
XMM2	9.25 ± 0.10 1.70 ± 0.03 99 ± 6 2 (f) 1.80 ± 0.13 4.06 ± 0.08 tied 0.005 ± 0.002								
	7.28±0.03 0.19±0.05 0.005±0.0009								
	8.05±0.12 tied 0.002±0.0007								
	tbabs*(diskbb+bremss+gauss+gauss+gauss)	1.28 (276)							
	N_{H} kT_{dbb} k_{dbb} kT_{bremss} k_{bremss} E_{gau} σ k_{gau}								
XMM1	9.7 \pm 0.2 1.71 \pm 0.08 63.12 ⁺¹⁸ 4.46.0.56 ^{+0.85} 2.47.0.80 ^{+0.47}								
XMM2	9.7 \pm 0.2 1.61 \pm 0.07 58-5 ¹²³ 5.3+0.7p 4.4-1.1 ^{10.3} 4.09 \pm 0.07 tied 0.004 \pm 0.	.001							
	7.20 ± 0.03 0.10 ± 0.04 0.004 ± 0.07 7 98+0.13 tied 0.002+0	0008							
	the het (diskich - compatt - gauge - gauge)	1.26 (274)							
	<u>IDads (UISKOD+Compli+gauss+gauss+gauss)</u> Nu kTar kar kTr T kume Fan G kan	1.30 (2/4)							
XMM1	8.9 1.29 211 1.30 62 0.01 0.01								
XMM2	8.9 1.39 221 1.39 393 0.0003 0.002 4.05 tied 0.004								
	7.27 0.20 0.005								
	8.05 tied 0.002								
	tbabs*(diskbb+bvapec+bvapec)	1.00 (134)							
	$N_{\rm H}$ $kT_{\rm dbb}$ $k_{\rm dbb}$ $kT_{\rm bvapec}$ Ni $z_{\rm red}$ v								
XMM2	9.0 ± 0.3 1.69 ± 0.07 107_{-9}^{-10} 18 ± 2 $5.4-1.6p$ 1.02 ± 0.05 15054_{-2555}^{-15550}								
	$1.9_{-0.3}^{+0.6} -0.059_{-0.015}^{+0.004} 1.6\pm0.5$								
vphabs*(diskbb+powerlaw+gauss) 1 29 (280)									
	$N_{\rm H}$ S Fe $kT_{\rm dbb}$ $k_{\rm dbb}$ Γ $k_{\rm po}$ $E_{\rm gau}$	(
XMM1	16.9±0.5 0.74±0.20 0.34±0.09 1.63±0.02 113±7 2 (f) 0.67±0.11 6.73±0.10								
	$\sigma = k_{gau}$								
VNAND	0.32 ± 0.10 0.003 ± 0.001 16 0±0 5 0 74 ±0 20 0 24±0 00 1 62±0 02 120±0 2 (f) 1 94±0 12 6 72±0 10								
	10.5 ± 0.5 0.74 ±0.20 0.54 ±0.05 1.05 ±0.05 120 ±0.2 (1) 1.04 ±0.12 0.73 ±0.10								
	0.32±0.10 0.003±0.001								

Table 2 - Parameters for each of the models, in the case where epfast is applied, to the spectra from 4U 1630-47. XMM1 and XMM2 refer to the two different observations. All the uncertainties listed here are quoted at the 90% confidence level.

The parameters are as follows. N_H is the hydrogen column density in units of 10^{22} cm⁻², for which we force it to be the same in both observations. kT_{dbb} , kT_{bb} , kT_{bremss} , kT_e and kT_{bvapec} are the temperature at the inner disk radius of the disk blackbody, the input soft photon temperature, the plasma temperature of the bremss model, the plasma temperature of the comptt model and the plasma temperature of the bvapec model respectively, in units of keV. k_{dbb} , k_{comptt} , k_{gau} , k_{po} , k_{bremss} , k_{red} and k_{blue} are the normalizations of the disk blackbody, the Comptonization model, the gaussian lines, the power law, the bremsstrahlung, the redshifted bvapec component and the blueshifted bvapec component respectively, in XSPEC units. In the diskbb+comptt model we couple the temperature of the seed photons to the temperature of the disk blackbody. We fix the photon index of the power law to 2, because it is poorly constrained. 'p' means that the parameter is pegged at an upper or lower limit. τ is the optical depth. E_{gau} is the energy of the gaussian emission line and σ is the width of this line. We tie (link) the width for all the emission lines during the fit. Ni represents the nickel abundance in terms of the solar abundance. z_{red} and z_{blue} are the redshifts for both bvapec components. v is the velocity broadening for the bvapec model, for which we impose the same value for both components. S and Fe represents the abundance of sulfur and iron respectively, in terms of the solar values.





Figure 3 – Models and residuals from the fits to the data from 4U 1630-47 in the case where epfast is applied. The black line is for the first observation and the red line for the second observation. (a) The model used by Diaz Trigo et al. (2013). The dotted lines show the different components. The upper two dotted lines represent the diskbb model and the lower two represent the powerlaw. The first gaussian accounts for a calibration issue, the last three are the emission lines. (b) Residuals of the fit of the model by Diaz-Trigo et al. (2013). The upper panel shows the ratio of the data to the model and the lower panel shows the residuals in terms of sigmas with error bars of size one. (c) Our new model. All the different components are shown with dotted lines. Again, the upper two dotted lines represent the diskbb model and the lower two represent the powerlaw. The first gaussian accounts for a calibration issue. The second gaussian represents the iron emission line. (d) Residuals of the fit of our model. There are no clear structures or features visible anymore.

As can be seen from Table 2, we find reasonably the same values for the parameters as Diaz Trigo et al. (2013) when we use the same models they used, although some of the parameters are different from theirs. For our analysis the parameter N_H in all cases has a somewhat larger value than what they get, although the relative effect is the same. By this we mean that the parameter has the smallest value for the *comptt* model in both cases and the highest values for the *diskbb+powerlaw* and the *diskbb+bremss* in both cases. A difference is that we fix the value to be the same for both observations and they let it free in both observations.

There are a few parameters for which we get different values, but these parameters are not the most important ones, so we do not pay much attention to these. For instance, we get a smaller value for the

normalization of the *diskbb* model. Again, the relative effect is the same, as we get a smaller value for this parameter in the first observation and a larger value in the second observation, the same as what Diaz Trigo et al. (2013) got.

The most important thing to mention is that we find the same energy for the first two emission lines (at around 4.04 keV and 7.28 keV) as they do, although for the last emission line we find a lower energy at around 8.05 keV. In the *comptt* model the energy is even lower, 7.92 keV. The width that we find for these lines are in accordance with Diaz Trigo et al. (2013).

For our own model we use different values for the solar abundance and the cross-section as mentioned before in subsection 2.5. We use the solar abundances as stated in Wilms, Allen and McCray (2000, ApJ 542, 914)²⁴. We use the cross-sections as stated in Verner, Ferland, Korista, and Yakovlev 1996²⁶. This leads to higher values of the parameter $N_{\rm H}$, around 17.

Instead of using *tbabs* which assumes all abundances other than hydrogen to be solar, we use *vphabs*. We let the abundances of sulfur and iron free as it turned out that these two have the largest effect on the model. We find a sulfur abundance of 0.74 ± 0.20 and an iron abundance of 0.34 ± 0.09 , which means they are both less than solar. The parameters for the *diskbb* and the *powerlaw* model do not vary much from the *diskbb+powerlaw* model as Diaz Trigo et al. (2013) used. The temperature of the disk at the inner radius is slightly smaller and the normalization is slightly larger. Furthermore, we fit a gaussian to the model at around 6.73 keV. This gaussian accounts for a possible iron emission line at this energy. It is a broad emission line with a width of 0.32 keV.





Figure 4 – The effect of model components on our model. The black line is for the first observation and the red line for the second observation. (a) The effect of the iron emission line on our model. The upper panel shows the data and the fits and the lower panel shows the residuals. The plots show the fits and residuals of our model, but with the normalization of the gaussian, that represents the iron emission line, set to zero. The residuals show no clear structure except at energies below and around 7 keV, where the residuals are a lot larger. This is due to the iron emission line at that energy. (b) The effect of the iron abundance on our model. The plots show the fits and residuals of our model, but with the iron abundance set to 1, the solar value. The ratio of the data to the model is (much) larger than 1 in the range of 2 - 6 keV. The ratio is also larger than 1 in the range 7 - 10 keV. So the iron abundance has a large effect on the model. (c) The effect of the sulfur abundance on our model. The plots show the fits and residuals of our model, but with the solar value. The ratio is also larger than 2 larger than 1 in the range of 2 - 6 keV. The ratio is also larger than 1 in the range 7 - 10 keV. So the iron abundance has a large effect on the model. (c) The effect of the sulfur abundance on our model. The plots show the fits and residuals of our model, but with the solar value. The residuals show the fits and residuals of our model, but with the sulfur abundance set to 1, the solar value. The residuals show the fits and residuals of our model, but with the sulfur abundance set to 1, the solar value. The residuals show that at energies between $\sim 2.5 - 4.5$ keV the sulfur abundance has a large effect as the residuals are larger here.

Furthermore, we explore the effect of the iron abundance, the sulfur abundance and the iron emission line on the model. The effect of these parameters can be seen in Figure 4.

The iron emission line around 6.73 keV is needed, because there are a lot of residuals around $\sim 6.5 - 7.0$ keV. So a gaussian centered at 6.73 keV and a width of 0.32 keV can fit these residuals very well for both observations.

The sulfur abundance has a large effect at lower energies, especially in the range $\sim 2.5 - 4.5$ keV. The ratio of the data to the model becomes larger in this range. For energies higher than 4.5 keV the sulfur abundance does not have a large impact as the ratio of the data to the model does not change very much.

The iron abundance has a very large effect at almost all energies. In the range $\sim 2 - 6$ keV the residuals become really large. The ratio of the data to the model is as high as 1.4 at 2 keV and gradually declines to around 1 at 6 keV. In the range 6 - 7 keV the effect of the iron abundance is small. At energies in the range of $\sim 7 - 10$ keV the ratio of the data to the model is again larger than 1, but the effect is somewhat smaller than in the lower energy range.

Observ	ation	Model								
	tbabs*(diskbb+powerlaw)*gabs_									1.28 (282)
	\mathbf{N}_{H}	$\mathrm{kT}_{\mathrm{dbb}}$	$\mathbf{k}_{ ext{dbb}}$	Γ	\mathbf{k}_{po}		E_{gabs}	σ	\mathbf{k}_{gabs}	
XMM1	8.58 ± 0.06	1.59 ± 0.01	126±4 2	2 (f)	0.40±0.	.08 6	.96±0.04	0.09±0.05	0.015 ± 0.00	4
XMM2	8.58 ± 0.06	1.62 ± 0.02	128±4 2	2 (f)	1.32±0.	.09 6	.96±0.04	0.09±0.05	0.015±0.00	4
vphabs*(diskbb+powerlaw)*gabs_										1.09 (280)
	\mathbf{N}_{H}	S	Fe	k	T_{dbb}	\mathbf{k}_{dbb}	Γ	\mathbf{k}_{po}	$\mathrm{E}_{\mathrm{gabs}}$	σ
XMM1	14.2±0.2	$0.94{\pm}0.07$	0.70 ± 0.10	1.58	3±0.02	132±5	5 2 (f)	0.37 ± 0.08	7.02 ± 0.06	0.09 ± 0.08
XMM2	14.2±0.2	$0.94{\pm}0.07$	0.70 ± 0.10	1.60	0±0.02	136±6	5 2 (f)	1.26 ± 0.09	7.02 ± 0.06	0.09 ± 0.08

Table 3 - Parameters for each of the models in the case where epfast is not applied. XMM1 and XMM2 refer to the two different observations. All the uncertainties here are quoted at the 90% confidence level. The parameters are as follows. N_H is the hydrogen column density in units of 10^{22} cm⁻², for which we force it to be the same in both observations. kT_{dbb} is the temperature at the inner disk radius of the disk blackbody in units of keV. k_{dbb} , k_{po} and k_{gabs} are the normalizations of the disk blackbody, the power law and the gaussian absorption line respectively, in XSPEC units. We fix the photon index of the power law to be 2, since it is poorly constrained. E_{gabs} is the energy of the gaussian absorption line and σ is the width of this line. We tie the parameters for the absorption line in both observations during the fit. S and Fe represents the abundance of sulfur and iron respectively, in terms of the solar abundance.



Figure 5a



Figure 5 - Models and residuals from the fits to the data from 4U 1630-47 in the case where epfast is not applied. The black line is for the first observation and the red line for the second observation. (a) The model used by Diaz Trigo et al. (2013), but without the three emission lines as they are not visible here. The upper panel shows the data and the fits and the lower panel shows the residuals after fitting. There are no clear residual features visible around 4.04 keV, 7.28 keV and 8.14 keV, the energies of the three emission lines reported by Diaz Trigo et al. (2013). In addition, a gaussian absorption feature is visible around 7 keV. (b) Our new model. All the different components are shown with dotted lines. The two upper dotted lines represent the diskbb model and the two lower dotted lines represent the powerlaw. The gaussian accounts for a calibration issue. Instead of adding a gaussian emission line to the model, we added a gaussian absorption line to the model, since in the residuals this was clearly visible. (c) Residuals of the fit of our model. There are no clear structures or features visible here.

For the case in which we try to fit a model to the data where the data is not corrected with the SAS task epfast, we can not fit the model that Diaz Trigo et al. (2013) used for the corrected case. We only try to fit the model *diskbb+powerlaw* since this is the best model. When we fit the model *tbabs*(diskbb+powerlaw)* the three emission lines as found earlier in the epfast-corrected case are not seen here. As can be seen in figure 5a, there are no clear residuals in the energy regions where we first fitted the three emission lines, they are not there now. There are residuals around 7 keV, where we can fit a gaussian aborption line to the data. This absorption line has an energy of 6.96 keV. So the model as used earlier, with the three emission lines, does not work here.

Our own model works well, but also without the iron emission line between 6.4 - 6.97 keV. As in the previous case, there are absorption features visible around 7 keV. So we fit the data with our model, but instead of the iron emission line, we use a gaussian absorption line at 7.02 keV. Now we get for the abundance of sulfur 0.94 ± 0.07 , which means it does not deviate significantly from the solar abundance, and for the abundance of iron we get 0.70 ± 0.10 . These abundances are both higher than in the case where we do apply the epfast correction.





The effect of the iron abundance on the model

Figure 6 - The effect of model components on our model. The black line is for the first observation and the red line for the second observation. (a) The effect of the gaussian absorption line on our model. The upper panel shows the data and the fits and the lower panel shows the ratio of the data to the model. The plots show the fits and residuals of our model, but with the normalization of the gaussian absorption line set to zero. The residuals show no clear structure except at energies around 7 keV, where the residuals show an absorption feature. (b) The effect of the sulfur abundance on our model. The plots show the fits and residuals of our model, but with the sulfur abundance set to 1, the solar value. The ratio of the data to the model actually does not change very much here. In the range $\sim 2.5 - 3.0$ the ratio becomes little larger, but this effect is small. So the sulfur abundance does not have much of an effect on the model. (c) The effect of the iron abundance on our model. The plots show that at energies in the range $\sim 2 - 5$ keV the ratio of the data to the model becomes large. So the iron abundance has a large effect at this energy range.

Again, we investigate the effect of the iron abundance, the sulfur abundance and, in this case, the absorption line on the model. The effect of these parameters can be seen in Figure 6. The absorption line is needed at around 7 keV, because there are residuals there. The ratio of the data to the model is smaller than 0.95 there and so a gaussian absorption feature can fit these residuals well. The gaussian absorption line has an energy of 7.02 keV and a width of ~ 0.1 keV. It could be that this absorption line is due to FeXXVI that is slightly blueshifted. Normally, FeXXVI has a rest energy of 6.97 keV, so the fact that the energy is slightly larger here, could mean that it is blueshifted FeXXVI²⁷. The sulfur abundance actually has very little effect on the model here. It has a very small effect at the

energies in the range $\sim 2.5 - 3.0$, where changing the sulfur abundance to solar has the effect of shifting the ratio of the data to the model above 1. But this effect is really small. On all other energies, it does not have an effect at all.

The iron abundance affects the model much more than the sulfur abundance. Especially in the range of energies of $\sim 2-5$ keV, the ratio of the data to the model becomes large and can be as high as 1.15 at around 2 keV and after this it gradually decreases. At energies above 5 keV the iron abundance does not have much impact on the model as the ratio does not change by much.

4. Discussion

We are able to reproduce the results of Diaz Trigo et al. (2013), though not all values of the parameters that we get, are in accordance with theirs. The most important thing is that we also find three emission lines of which the first two, at 4.04 keV and 7.28 keV, are at the same energy and the last one has a slightly lower energy in our fits compared to theirs. We try a new model, not tested by Diaz Trigo et al. (2013), in which we let the abundance of some elements in the ISM to vary. Our own model fits the data actually equally well, and it has even less parameters than the other model. But the difference with their model is that we do not need the three emission lines. Furthermore, the model Diaz Trigo et al. (2013) used, is not applicable in the uncorrected case where epfast is not applied. There are no three emission lines visible when using their model. Our own model works well in this case, but instead of fitting an iron emission line, we fit a gaussian absorption line to the data, since there is an absorption feature visible in the residuals.

The most important model and the one most frequently used for black holes is the *diskbb+powerlaw* model, so we will focus the discussion on this model. We find for the temperature at the inner disk radius in both cases a value of 1.70 keV. This is a slightly lower value than Diaz Trigo et al. (2013) got, but it is very reasonable, since, as stated in subsection 1.3, for a temperature higher than 1.2 keV the black hole appears to be in the anomalous regime or the apparently standard regime. Diaz Trigo et al. (2013) also found that the black hole should be in the anomalous accretion state¹⁰. This is also implied by the large hard tail, which is characteristic of this accretion state, as described in the Introduction. For the normalization values of the *diskbb* component we find values slightly lower than 100, which is also lower than what Diaz Trigo et al. (2013) found. As mentioned in subsection 2.4 the normalization is defined as $(R_{in}/D)^2 \cos\theta$. Diaz Trigo et al. (2013) state a value of 65° as the angle of the disk, and previous observations²⁸ also suggest a value in the range 60° - 75°. Hjellming et al. (1999) state a distance estimate of ~ 10 kpc²⁸, so D in this case is 1. This means that, using these numbers, we find for the apparent inner disk radius a value of ~ 15 km. For the correction factor between the apparent inner disk radius and the true inner disk radius, we have $R_{in} = \kappa^2 \xi r_{in}$. Here, R_{in} is the true inner disk radius, κ is the spectral hardening factor (~ 1.7 - 2.0), ξ is a correction factor for a boundary condition (found to be 0.41) and r_{in} is the apparent inner disk radius²⁹. Using these numbers we find for the true inner disk radius a value of ~ 18 - 24 km. Kubota et al. (2001) found for black hole candidate GRO J1655-40 a value of the true inner disk radius varying from 6 to 27 km²⁹, so our value is consistent with this.

Furthermore, the parameters found for the *powerlaw* component are also in accordance with the values found by Diaz Trigo et al. (2013)¹⁰. Also, the energies and the width of the emission lines are in accordance, although the energy of the last emission line we find is somewhat lower, but it is still within the error bars.

For our own model, *vphabs*(diskbb+powerlaw+gauss)*, we find a slightly lower value for the temperature at the inner disk radius. Both observations share a temperature of 1.63 keV. This still implies that the source is in the anomalous state, so it is still consistent with previous results²⁹. The normalization values for the *diskbb* component are somewhat higher, but converting the largest value, which is 120, gives a true inner disk radius of ~ 20 - 27 km, which is still a reasonable value.

We find an iron emission line at an energy of 6.73 keV. As mentioned in subsection 1.2, iron emission lines are frequently observed in spectra of black hole X-ray binaries. Mostafa et al. (2013) report a broad iron emission line at 6.5 keV in the spectrum of black hole candidate Swift J1753.5-0127⁶. Wei Cui et al. (2000) also report a broad iron emission line at ~ 6.7 keV in the spectrum of 4U 1630-47³⁰. Terashima et al. (2000) found an iron emission line at exactly the same energy of 6.73 keV in the spectrum of of the AGN NGC 4579³¹.

The width of the iron emission line we find at 6.73 keV is large, 0.32 keV. This means it is a very broad emission line. This is larger than the width of the iron emission line at 6.73 keV Terashima et al. (2000) found. They found a width of 0.17 keV^{31} . Wei Cui et al. (2000) detected some other iron emission lines of which some have an even larger width than 0.32^{30} , so it seems a reasonable value.

In our model we do not assume the abundances of iron and sulfur to be solar, unlike Diaz Trigo et al. (2013) did¹⁰. We find lower values for these two abundances, of $[Fe/H]/[Fe/H]_{solar} = 0.34\pm0.09$ and $[S/H]/[S/H]_{solar} = 0.74\pm0.20$. Pinto et al. (2013) found for the iron abundance in several galactic lowmass X-ray binaries values that range from $[Fe/H]/[Fe/H]_{solar} < 0.1$ to $[Fe/H]/[Fe/H]_{solar} \sim 0.5^{32}$. So the value we find is consistent with this. It is of course dependent on where in the Galactic plane you are, the abundance of iron is not necessarily homogeneously distributed in the plane. For the sulfur abundance there is no good estimate. We find a lower than solar sulfur abundance and this is justified by Gondhalekar (1985). In his paper he says that the sulfur abundance in the gas phase of the ISM is depleted from solar³³, so the abundance of sulfur should be less, at least in this phase of the ISM.

For the uncorrected case, where the data is not been corrected by the SAS task epfast, we find an even slightly lower value for the temperature at the inner disk radius, but still consistent with the fact that the source should be in the anomalous accretion state. The normalization values for the *diskbb* model are also a bit larger, and the largest value gives a true inner disk radius of $\sim 21 - 29$ km, still consistent with previous results²⁹. The abundances of iron and sulfur that we find are again lower than solar. For [Fe/H]/[Fe/H]_{solar} we find a value of 0.70±0.10 and for [S/H]/[S/H]_{solar} we find a value of 0.94±0.07. The sulfur abundance is marginally lower than solar. The iron abundance is twice the value compared to the case where epfast is applied. As said earlier, Pinto et al. (2013) found values for the iron abundance in several low-mass X-ray binaries that range from [Fe/H]/[Fe/H]_{solar} < 0.1 to [Fe/H]/[Fe/H]_{solar} ~ 0.5²⁹. So 0.70 is larger than the largest value they found. But, since the iron abundance could vary from place to place, it could still be that the value we find is correct. At least, all the values Pinto et al. (2013) found are less than solar, so that justifies the fact that our abundance is also less than solar.

In the uncorrected case, we fitted a gaussian absorption line to the data. This line has an energy of 7.02 keV and a width of 0.09 keV. King et al. (2014) make notion of an absorption line found at an energy of 7.03 keV and with the same width of 0.09 keV in the spectrum of 4U 1630-47. They associate the line either with a blueshifted FeXXVI absorption line or with a blueshifted FeXXVI absorption line²⁷. Also, Rozanska et al. (2013) report iron absorption lines in the spectrum of 4U 1630-47¹¹.

5. Conclusion

In this paper we analyze the results from a paper by Diaz Trigo et al. (2013) in which they claim that they found evidence for baryons in the relativistic jets of the stellar-mass black-hole candidate 4U 1630-47. They claim they found three emission lines of which one is redshifted FeXXVI, one is blueshifted FeXXVI and the other blueshifted NiXXVII. They did this, because they saw 3 emission features in the spectrum of 4U 1630-47. This spectrum was first corrected by the SAS task epfast. In this paper we reproduce their results and we are able to fit the data with the same models as they did and we get nearly the same values for most of the parameters. The most important of these models is the *diskbb+powerlaw* model and the values we find are consistent with the fact that the source is in the anomalous accretion state and with the value for the inner accretion disk radius. We also introduce a new model in which we do not assume solar abundances in the ISM and fit an iron emission line to the data. The difference is that this model does not include the three emission lines as found by Diaz Trigo et al. (2013). It turns out that this model works equally well and the fact that there is an iron emission line visible, is justified by previous work where these emission lines were also visible. The fact that the abundances of iron and sulfur are less than solar is also consistent with previous work done by Pinto et al. (2013)²⁹. So if this model is correct, it does not require the presence of the three emission lines and the existence of baryons in the relativistic jets is not established. Finally, we also analyze the data in the case where it was not corrected by the SAS task epfast. The fact that we do this is justified by Walton et al. (2012), who found that the epfast task applies a correction which is independent of the energy and that it overcorrects the spectrum at higher energies¹⁹. We find that the model used by Diaz Trigo et al. (2013) is not applicable here, since the three emission lines are not visible in this case. Our own model works well here, but instead of adding an iron emission line, we add a gaussian absorption line to the model, since there are absorption features seen in the spectrum around 7 keV. The appearance of this absorption line is justified by King et al. (2014) who also found this absorption line in the spectrum of 4U 1630-47²⁷. They associate this line either with a blueshifted FeXXVI absorption line or with a blueshifted FeXXV absorption line. Also, Rozanska et al. (2013) report iron absorption lines in the spectrum of 4U 1630-47¹¹. So, all in all, the model we introduce works equally well as the model used by Diaz Trigo et al. (2013). In the uncorrected case, this model works even better, since the three emission lines are not visible there. More research is needed to explore which model is correct.

Appendix







Figure 7 - Models and residuals from the fits to the data from 4U 1630-47 in the case where epfast is applied. The black line is for the first observation and the red line for the second observation. In all models the first gaussian accounts for a calibration issue. (a) The plot shows the different components of the model, which is just one in this case. (b) The residuals of the fit of the model after fitting. The upper panel shows the ratio of the data to the model and the lower panel the residuals in terms of sigmas with error bars of size one. The fit is clearly not good. (c) The Comptonization model with the three emission lines included. (d) The residuals of the Comptonization model after fitting. (e) The bremsstrahlung model with the three emission lines. The upper two dotted lines represent the diskbb model and the lower two represent the bremsstrahlung model. (f) The residuals of the bremsstrahlung model after fitting. (g) The two-component model with the disk blackbody and the Comptonization component with the three emission lines. The upper two dotted lines represent the diskbb model and the lower two represent the Comptonization model. (h) The residuals of the two-component model. (i) The byapec model, with the two byapec model components. The upper dotted line represents the diskk model. This model is only fitted here to the second observation, as it is not a good model for the first observation. (j) The residuals of the byapec model after fitting.

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