Image Analysis of Suzaku Observation of Transient Pulsar EXO 2030+375

Animesh Basak and Tamal Sarkar

Abstract--- “EXO 2030+375” is a well-known binary system showing periodic outburst. The spectral analysis on the system during the outburst helps us to know more about the origin as well as material present within the system. In this work, we have considered one such outburst data obtained using Suzaku X-Ray mission having very good imaging as well as energy resolution capabilities. Following the stepwise algorithm of the Suzaku analysis guide, we have applied the various computational modules for pre-processing as well as data reduction. After that, we have used the *ftools*, a specialized computational package for analysis of X-ray data obtained from various X-Ray missions. The data analysis helped us to understand the origin as well as given an insight of the material present within the system.

Keywords--- EXO 2030+375, Image Analysis, Pulsar, Suzaku, Spectral Analysis, X-Ray Binaries

I. INTRODUCTION

EXO 2030+375 is a transient X-Ray binary system which was first detected by EXOSAT [1]. The currently acceptable location of the system in equatorial coordinate system is 20h 32min 15.28 s (RA) and 37h 38min 14.9 s (Dec) with orbital period of 44.3-48.6 days. It was found that EXO 2030+375 has luminosity of 2×10^{38} erg/s and pulsation period of 41.41 sec. As we know that a pulsar is associated with strong magnetic field and in case of EXO 2030+375 the strength of the field is about 3.1×10^{12} Gauss. Here, the binary system consists of a neutron star and a normal B (or O) type star. Hence, EXO 2030+375 is believed to be powered by process of wind accretion. The neutron star in this system accretes matter from its binary companion through equatorial outflow which is believed to form a quasi-Keplerian disk [2],[3], [4]. The equatorial material forms a slow, dense outflow [5], which is generally believed to fuel the X-ray outbursts [6]. X-ray outbursts are produced when the pulsar interacts with the Be star's disk. It is also possible to find the mass of the X-ray pulsars in semi-empirical manner [7]. The radius of the X-ray emission surface is ~ 1 km, which agrees with the size of the neutron star polar caps [8].

Be/X-ray binaries typically show two types of outburst behavior:

- Type I is characterized by lower luminosities, low spin-up rates (if any), and repeated occurrence at the orbital period. It is also called normal outbursts,
- Type II is characterized by high luminosities and high spin-up rates. It is also called giant outbursts.

EXO 2030+375 is one of the best studied members of the described class of X-ray binary systems. The X-ray spectrum of EXO 2030+375 during the 1985 giant outburst observed by EXOSAT (2–25 keV) [1] was similar to that of other accreting pulsars. EXO 2030+375 was observed by INTEGRAL on 27 July and 19–21 August 2006 and by on 19–20 August and 23–25 September 2006. To study the X-Ray EXO 2030+375, the publicly available archival data of Suzaku space mission obtained with the instrument X-ray imaging Spectrometer (XIS) of Suzaku (1–10 keV) taken during outburst with Modified Julian Day (MJD) 5.423487785123480E+04 (2007-05-14 21:04:06.347 UTC) was used in the present work to investigate the properties of the pulsar during the outburst. Suzaku [9] is the fifth Japanese X-ray astronomy satellite and was launched on 2005, July 10. It has two sets of instruments onboard for X-rays. They are X-ray Imaging Spectrometer (XIS) which covers 0.2-12 keV energy range and Hard X-ray Detector (HXD) which covers 10-600 keV energy range. Suzaku also carries a third instrument, an X-ray micro-calorimeter (X-ray Spectrometer; XRS), but the XRS lost all its cryogen before routine scientific observations could begin. In full window mode, the field of view of the XIS is $18^\circ \times 18^\circ$ with an effective area of 340 cm² and 390 cm² at 1.5 keV for front-illuminated and back-illuminated CCDs, respectively. As XIS-2 was un-operational during the observation of EXO 2030+375, data from other 3 XISs are used in the present analysis.

II. PAYLOAD OF SUZAKU SPACE MISSION

The scientific payload of Suzaku initially consisted of three distinct co-aligned scientific instruments Figure 1. There are four X-ray sensitive imaging CCD cameras, X-ray Imaging Spectrometers (XISs) [10], three front-illuminated (FI; energy range 0.4-12 keV) and one back-illuminated (BI; energy range 0.2-12 keV), capable of moderate energy resolution. Each XIS is located in the focal plane of a dedicated X-ray telescope (XRT) [11]. The second instrument is the non-imaging, collimated Hard X-ray Detector (HXD) [12], which extends the bandpass of the observatory to much higher energies with its 10–600 keV bandpass [13]. The last instrument, XRS, is no longer operational.

Animesh Basak, Student, Department of Physics, University of North Bengal, Siliguri, India. E-mail: ani.science@yahoo.com

Tamal Sarkar, Technical Officer-I, University Science Instrumentation Centre, University of North Bengal, Siliguri, India. E-mail: ta.sa.nbu@hotmail.com

A. XIS

The XISs employ X-ray sensitive silicon charge-coupled devices (CCDs), which are operated in a photon-counting mode, similar to that used in the ASCA SIS; Chandra ACIS, and XMM-Newton EPIC. In general, an X-ray CCD converts an incident X-ray photon into a charge cloud, with the magnitude of charge proportional to the energy of the absorbed X-ray. This charge is then shifted out onto the gate of an output transistor via an application of time-varying electrical potential. This results in a voltage (often referred to as “pulse height”) proportional to the energy of the X-ray photon. The four Suzaku XISs are designated XIS0, XIS1, XIS2 and XIS3, each located in the focal plane of an X-ray Telescope; XRT-I0, XRT-I1, XRT-I2, and XRT-I3. Each CCD camera has a single CCD chip with an array of 1024×1024 picture elements (“pixels”), and covers a $17.8' \times 17.8'$ region on the sky. Each pixel is $24 \mu\text{m}$ square, and the size of the CCD is $25 \text{ mm} \times 25 \text{ mm}$. One of the XISs, XIS1, uses a back-illuminated CCD, while the other three use front-illuminated CCDs. The XIS has been partially developed (CCD sensors, analog electronics, thermo-electric coolers, and temperature control electronics) at Massachusetts Institute of Technology(MIT), while the digital electronics and a part of the sensor housing were developed in Japan, jointly by Kyoto University, Osaka University, Rikkyo University, Ehime University, and ISAS/JAXA.

Figure 1: Suzaku Space Mission

B. HXD

The Hard X-ray Detector (HXD) is a non-imaging instrument. It is a hard X-ray (energy $\sim 10\text{-}600 \text{ keV}$) collimated system of “well” detectors. The HXD is characterized by the low background of $\sim 10^{-5}$ counts/s/cm²/keV; its sensitivity is higher than any past

missions in the energy range from a few tens keV to several hundreds keV.

C. XRS

It is a non-dispersive imaging (30-element) spectrometer (about 6.5 eV FWHM). It is cryogenically cooled by an adiabatic diamagnetic refrigerator within a helium dewar. The detector array sits behind a conical foil mirror of XRT assembly, with spatial resolution of about 1.8' half power diameter (HPD). The effective area of this system at 6 keV is about 150 cm². Despite initial success of the XRS to obtain a cryogenic temperature of 60 mK with a cooling system consisting of a Stirling-cycle mechanical cooler (100K), solid neon (17K), liquid helium (1.3K), and an adiabatic demagnetization refrigerator (60mK), and an energy resolution of 7 eV [14]. On August 8, 2005 a thermal short between the helium and neon tanks resulted in the liquid helium coolant venting to space, leaving XRS inoperable.

Table 1: Scientific Payload of Suzaku Space Mission

Parameters	X-Ray scientific instruments of Suzaku		
	XRS	XIS	HXD
Energy Range	0.3-12 keV	0.2-12 keV	10 - 600 keV
Number of Sensors	1	4	1
Number of Pixels	30 pixels (6x6 geometry)	1024 x 1024 for each CCD	-
Pixel Size	625 $\mu\text{m} \times 625 \mu\text{m}$	24 $\mu\text{m} \times 24 \mu\text{m}$	-
Effective area per sensor	100cm ² @1 keV, 150 cm ² @6 keV	400 cm ² @1.5 keV, 250 cm ² @6 keV	160 cm ² @15 keV, 300 cm ² @120 keV
Energy Resolution (FWHM)	6.5 eV	120 eV @6keV, 50 eV @1 keV	3 keV (10-30 keV), 9% (at 662 keV)
Field of View	2.9'x2.9'	19'x19'	0.56 deg x 0.56 deg (E<100 keV), 4.6 deg x 4.6 deg (E>200 keV)

III. IMAGE ANALYSIS

For XIS data reduction, we reprocessed the unfiltered event data as in Figure 2 and Figure 4 using ‘aepipeline’ package of HEASoft version 6.12 and utilizing the calibration database (CALDB) released on 2012 February 10 (for XIS). In the spectral fitting, we selected data in the energy ranges of 1-10 keV for both front and back-illuminated CCDs (added spectra from XIS-0 and XIS-3, and left XIS-1 separate). Source light curves and spectra were extracted from the reprocessed cleaned event data of XIS. The XIS background spectra were accumulated from the same observation by selecting circular regions away from the source. We reprocessed the unfiltered event data as in Figure 2 and Figure 4; the corresponding light curves are given in Figure 3 and

Figure 5, respectively. The response files and effective area files for XIS were generated by using the “xissimarfgen” and “xisrmfgen” tasks of FTOOLS. After data reduction, we generally get four types of file: source information file, background information file, Response Matrix File and Auxillary Response File. In our case, the last two files are combined into one file with extension name .rsp as we opt to rebin the spectrum [9]. We have considered the option `resp=extent` as the source is a galactic source.

Figure 2: XIS-3 image

As per Suzaku Data Reduction Guide, we can have eight set of data, two set each XIS (XIS0 to XIS3) CCD sensor. But, literature review as well preliminary data analysis, we find only four set of useful data for XIS.

We analyze the Energy spectra of EXO 2030+375 using XIS event data. The spectra from both the front-illuminated CCDs (XIS-0 and XIS-3) were added together along with corresponding response matrices and background spectra. Data from XIS-1 was used separately in the spectral fitting. In the spectral fitting, we selected data in the energy ranges of 1-10 keV for both front and back-illuminated CCDs (added spectra from XIS-0 and XIS-3, and left XIS-1 separate).

Figure 3: Light Curve of XIS-3

In the beginning, we tried to fit the broad-band spectra of the pulsar with various continuum models such as “wabs*powerlaw” model modified with an exponential cut-off and high energy cut-off [15] model along with interstellar absorption and Iron $K\alpha$ emission line at 6.4 keV. The model component “wabs” stands for the photoelectric absorption model. It accounts for the galactic equivalent hydrogen

column density along the line of sight. The model component “powerlaw” is to account for the inverse Compton scattering.

After fitting the spectra, we got the spectrum residue as in Figure 6, in this residue, for example, there are two picks around 6.6 keV and 6.4 keV. To resolve these lines, we have introduced additive model-Gaussian line at 6.6keV and 6.4keV. Detection of several emission lines at soft X-rays and the pulsar being so bright during the Suzaku observation, we attempted to fit the broad-band spectra with the partial covering high energy cut-off power-law model with partially ionized absorber and Gaussian functions for detected emission lines.

Figure 4: XIS-1 image

Figure 5: Light curve of XIS-1

Table 2: Scientific Payload of Suzaku Space Mission

Model	Value of Reduced χ^2
wabs*powerlaw	1.78160
Model + adding component Gaussian line at 6.40keV	1.42929
Model + adding component Gaussian line at 6.60keV	1.37970
Model + adding component Gaussian line at 2.01keV	1.32581
Model + adding component Gaussian line at 2.50keV	1.29791
Model + adding component Gaussian line at 3.19keV	1.13929
Model + adding component pcfabs	1.09587

Proceeding in this manner and searching emission lines, we finally obtained the spectral model of EXO 2030+375 rotation powered pulsar. The corresponding reduced chi-square were given in Table 2 and fitted parameter obtained from our model “wabs*pcfabs *(powerlaw + gaussian + gaussian + gaussian + gaussian + Gaussian)” after introducing Gaussian line one by one. For purpose of testing, we have considered the model-I as proposed by Naik et al., [15] as given in Table 3. We found that the model proposed by Naik et al. satisfies all the extracted spectra if we vary NH1, NH2, covering fraction, Ec and Ef while keeping the Emission line freeze (i.e keeping the energy fixed during model fitting as in Table3). In Table 3, NH1 (parameter of wabs) indicates the Galactic equivalent hydrogen column density of material local to the neutron star. The parameter NH2 and covering fraction are for model component “pcfabs”. NH2 parameter is for additional hydrogen column density of material local to the neutron star. The covering fraction is a ratio having values in between ‘0’ to ‘1’ and accounts for the fraction of the absorbed power-law due to the presence of additional matter local to the neutron star. Ec and Ef are for parameter of model component “highcut”. These are used to define a fraction $I(E)$ called high energy cut(highcut), where $I(E)=\exp[-(E-E_c)/(E-E_f)]$ for $E>E_c$ and $I(E)=1$ for $E<E_c$. This is generally introduced to take account for high energies attenuation. Ef in expression of $I(E)$ is the e-folding energy for synchrotron cooling cut-off. Energy spectra of EXO 2030+375 obtained with the XIS detector of the Suzaku observation at the peak of the type I outburst, along with the best-fit model consisting of a partially absorbed power-law with high energy cutoff continuum model as in Figure 7. Five emission lines are detected in the broad-band spectrum of the pulsar as in Figure 8. High values of additional column density (pcfabs) at the dip phases in the pulse profile confirm the presence of stream of absorbers that are phase locked with the pulsar.

Figure 6: Spectral Residue with Absorption Lines at Different Energies

Figure 7: Added Folded Spectrum of XIS-0 + XIS-3

Figure 8: Energy Spectra of EXO 2030+375 Obtained with the XIS-0+XIS-3

IV. CONCLUSION AND FUTURE ENHANCEMENT

In this paper, we performed broad-band spectral analysis on the Suzaku observation of the Be/X-ray transient pulsar EXO 2030+375 during the peak of a type I outburst. The pulse profiles are found to be strongly energy dependent. High values of additional column density (pcfabs) at the dip phases in the pulse profile confirm the presence of stream of absorbers that are phase locked with the pulsar. Apart from the fluorescence iron emission line, several low energy lines from S and Si are also detected in the pulsar spectrum. Cyclotron resonance scattering features, though reported earlier in the spectrum of this pulsar, are not detected in the 1.0-200.0 keV spectrum of the pulsar. Also, the model is represented by a power law modified at lower energies by significant absorption and at higher energies by an exponential-cutoff Reynolds et al.[16]. Also, an iron emission line at ~6.6 keV was observed. So, in crude way we can say that EXO 2030+375 is formed due to supernova explosion. For other such, HMXBs we do not always see Silicon line but the composition of EXO 2030+375 is such that it allows us to observe Silicon lines.

Table 3: The best fit parameters obtained from the spectral fitting of EXO 200+375 (as proposed by Naik et. al., [15])

Parameter	N _{H1} 10 ²² atom/cm ²	N _{H2} 10 ²² atom/cm ²	Covering fraction	Power- law index	High Energy cutoff(E _c) (keV)	E-fold Energy (E _f) (keV)	Si XIII (keV)	Si XIV (keV)	S XV (keV)	Iron K α (keV)	Fe XXVI (keV)
Value	2.04	40.90	0.13	1.33	12.4	21.2	2.01	2.50	3.19	6.39	6.61

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Animesh Basak was born in Tufangunj, District. Coochbehar, West Bengal, India on April, 21, 1991. He received Bachelor Degree with Physics Honours in 2012 from A.B.N. Seal College under North Bengal University and is currently a final semester student of M.Sc. Physics course at University of North Bengal. His area of interest includes High Energy Astrophysics and X-Ray Astronomy. Due to his interest, he has taken a project/dissertation topic related to X-Ray Astronomy.

The project/dissertation involves study about observational features of pulsars in Binary systems using X-Ray space mission data. This work is partly motivated from his M.Sc. project done under the Guidance of Tamal Sarkar and Dr. B.C.Paul.(E-mail:ani.science@yahoo.com)

Tamal Sarkar was born in Balurghat, West Bengal, India on September, 18, 1977. He received Bachelor Degree with Physics Honours in 1998 from North Bengal University and Master Degree (Physics) in year 2000. In year 2012, he successfully completed the Ph. D Course work in Physics (Astronomy & Astrophysics) North Bengal University.

He is associated with University Science instrumentation centre, North Bengal University as Technical Officer since 2007. His area of interest includes High Energy Astrophysics, X-Ray Astronomy, Quantum Computing and Theoretical Opto-electronics. He has published few research articles in National and International Journals in above mentioned field. Apart from it, he is a guest faculty for the course of Post Graduate Diploma in Remote Sensing and GIS of Centre of Remote Sensing, North Bengal University. He has also worked as member of Expert Committees/ Tender Committees for University of North Bengal. He is also a member of FOSET, Kolkata.(E-mail:ta.sa.nbu@hotmail.com)