SPECTRAL AND TIMING ANALYSIS OF RADIO QUIET X-RAY SOURCE 1E 161348-5055.1 USING XMM NEWTON MISSION

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Abstract

Neutron stars are remnants of supernovae explosion of massive stars upto 20-40 $M_\odot$ at the time of their formation, neutron stars gain recoil kicks due to asymmetries that develops during the core-collapse process. Neutron stars are classified as Radio Loud and Radio Quiet. 1E 161348-5055.1 is a radio quiet neutron star found in the Centre of RCW103 which is Supernova Remnant (SNR) and is a periodic X-Ray with a period of 6.67 hours. This source was discovered by the HEAO-2 (Einstein Observatory), which is the first fully imaging X-Ray telescope. This source attracted interest due to the two main reasons. Firstly, its periodicity of 6.67 hrs which is too long for star having age 2000 years, it is behaving like a multi-million-year-old star. Secondly, the star becomes 50 times brighter in between October 1999 and January 2000. Astrophysicist put forward many theories to explain this phenomenon. In present work, the author downloaded one archived data from XMM Newton Mission and analyzed it as well as reviewed the works related to this source to understand the nature of the neutron star 1E 161348-5055.1.

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Keywords: SNR, RCW103, Einstein Observatory, Radio loud and Radio quite source, XMM Newton Mission

1. Introduction

Neutron stars are remnants of supernovae explosions of massive stars ~ 10 $M_\odot$ up to the ~ 20-40 $M_\odot$; at the time of their formation, neutron stars acquire recoil kicks due to asymmetries that develop during the core-collapse process. We may find them as magnetically braking pulsars, accreting pulsars in binary systems, isolated cooling blackbodies, sources of astrophysical jets, and emitters of high-luminosity bursts of X-rays. Hence, due to rich variation, we may classify these stars into different species.

Classification of Neutron Star:

Radio Loud: The radio loud species includes rotation-powered radio Pulsars (PSRs), and Rotation Radio Transients (RRaTs)[1].

i. PSRs are the first neutron stars ever discovered due to regular radio emission from them
ii. RRaTs are a new class, discovered in 2006, that emits sparse bursts in radio wavelength.

Radio Quiet: The Radio Quiet species includes Anomalous X-Ray Pulsars (AXPs)[2], Soft Gamma Repeaters (SGRs)[3], Central Compact Objects (CCOs)[3] and X-ray Dim Isolated Neutron Stars (XDINS)[3].

i. AXPs are magnetars, that is neutron stars with ultra-high magnetic field (B ~ 10^{14}-10^{15} G), the ultimate source that powers their emission. It shows intense variability over a few years - time scale, and can emit bursts in X - rays, of diverse intensity. It rotates slowly, with spin periods P ~ 5-12 s.
ii. SGRs are also magnetars. Only difference is it can emit γ – rays. It has also ultra - high magnetic field.
iii. CCOs are a rather variegated class, whose objects are all pooled by being very close to the geometrical centre of supernova remnants (SNRs). It has magnetic fields ~ 10^{12} G.

iv. XDINS instead show thermal emission that is believed to emerge from the cooling neutron star surface.

A unified picture that includes birth properties and evolution paths connecting of all the isolated neutron stars, is still lacking, and in particular the Central Compact Objects are the least understood specie.

The soft X-ray source 1E 161348-5055 (Figure 1) is a neutron star discovered in 1980 when it was first detected by *Einstein* as a faint, unresolved source located near the center (from this is the classification of 1E 161348-5055 as a CCO) of the Supernova Remnant (SNR) RCW103 [4](**R**odgers, **C**ampbell & **W**hite-oak **Catalogue**) , at a distance ~ 3:3 kpc [5]. Already at the time of the detection it was clear that the object didn't have a point source radio counterpart, and on account of the close proximity to the geometrical center of RCW103 and its thermal-like spectrum 1E 161348-5055 was interpreted as a thermally cooling neutron star and thus classified as a **radio quiet**, (XDINS) isolated neutron star. After its discovery, many groups interpreted this source as an isolated neutron star as mentioned in references in Heyl and Hernquist 1998 [6]. Heyl and Hernquist put forwarded two scenarios that can account for the X-Ray emission from this source. They are either the presence of an accreted envelope or a sufficiently intense magnetic field.

This deceptively dull object came into attention in 1994 and more recently in 1999 when Gotthelf et al. detected a large variability[7], on a few years' time scale. In the more recent re-brightening, the X–ray luminosity increased by two orders of magnitude (from ~ 9×10^{-13} erg cm^{-2} s^{-1} to ~ 8×10^{-11} erg cm^{-2} s^{-1}) between September 1999 and March 2000[8]. The source has been continuously fading since the 1999-2000 brightening.

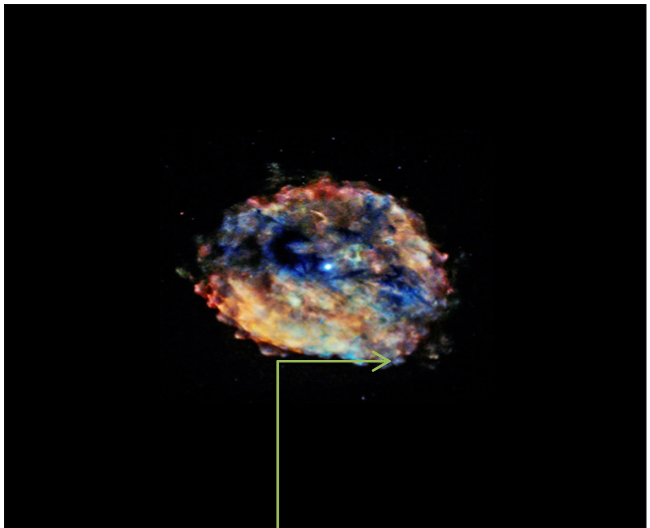


Figure 1: X-Ray image of RCW103 Young Magnetar *(Source: http://chandra.si.edu/photo/2016/rcw103/)*

In August 2005, 1E 161348-5055 was seen with a flux similar to the pre-outburst level. *XMM-Newton* data clearly show that the spectrum of the source is also evolving. While a double-blackbody model yields in any case the best description of the spectrum, the emission is harder when the source is brighter[7]. Moreover, a new piece to the puzzle was added: thanks to the *XMM Newton* data conclusive evidence for a periodicity of 6.67 h in the light curve, the highest ever detected in the hypothesis of an isolated neutron star, was reported. The combination of long-term variability, 6.67 h periodicity, young age, and under-luminous optical/IR counterpart singles 1E 161348-5055 out among the compact objects in SNRs. 1E 161348 5055 could be either a very young low-mass X-ray binary (LMXB) system, featuring a 2000 yrs. old compact object and a low-mass companion star in an eccentric orbit, or a very peculiar isolated neutron star [7]. Reynoso et al carried out a study on the influence of the neutron star 1E 161348-5055 in RCW 103 on the surrounding medium. According to them, the strong long-term variability in X-rays favours the hypothesis that 1E 161348–5055 is an accreting binary source rather than an isolated, cooling neutron star [9]. Recent deep optical/infrared observations [10] constrained the mass of a possible companion to be quite small, i.e. of class M4, or even later. These models were further investigated by Pizzolato et al. [11] [9] and Li [12]: according to Pizzolato et al., 1E 161348-5055 is a magnetar in a low mass binary system, that resembles the polars [13], whose spin rate has been braked and locked into synchronism with the orbital period by magnetic forces. Li instead boosted the hypothesis of an isolated magnetar thanks to his demonstration by means of simulations that debris disks play an active role in spinning down an INS to hours long periods. Using deep IR observations of the field with the NACO instrument at the VLT, searching for variability De Luca et al in 2008 suggest that the Central puzzling X-Ray source in RCW 103 could either be the first low-mass X-ray binary system discovered inside a SNR or a peculiar isolated magnetar with an extremely slow spin period [14]. Bhadkamkar et al model the light curve of 1E 161348-5055 in RCW 103 considering orbitally-modulated mass transfer through a viscous accretion disk and subsequent propeller emission and concluded that the pre-LMXB model for 1E 161348-5055 and similar sources agrees with observation and proposed that the distinguishing features between this model and the magnetar model should be explored [15].The importance of this is given by the fact that magnetars have to be born with very fast spin periods in order for the dynamo effect to increase their magnetic field to the observed values, but a simple propeller effect isn't able to spin a magnetar down to the observed period of 1E 161348-5055. In order to discriminate between the isolated vs. binary star model for 1E 161348-5055, it is therefore of great importance to analyze in great detail the spectral and timing evolution of 1E 161348-5055 from the outburst to the most recent observations. To shed more light on this source, a long time-span Swift monitoring of the central X-Ray source in RCW103 was carried out and Swift data allowed accurate measurement of the period of 1E161348–5055 [P = 24030.42(2) s] [16] and to derive the first upper limit on its period derivative ($\left|\frac{dP}{dt}\right|$ < 1.6 × 10−9 s s−1 at 3σ). 1E 161348-5055 was extensively studied during the last 20 years: from 1999 on a set of monitoring observations were taken by Chandra, together with some long ones (one of which was obtained in 2007), accompanied by two long XMM-Newton observations. Ikhsanov et al showed that the problems of the fall-back accretion scenarios encounter major difficulties explaining an extremely long spin period of the young neutron star, can be avoided if the accreting material is magnetized. The star in this case is surrounded by a fossil magnetic slab in which the material is confined by the magnetic field of the accretion flow itself and found that the surface magnetic field of the neutron star within this scenario is ~10^(12) G [17]. D'Aì et al reported on the detection of a bright, short, structured X-ray burst coming from the supernova remnant RCW 103 on 2016 June 22 caught by the Swift/BAT monitor, and on the follow-up campaign made with Swift/XRT, Swift/UVOT and the optical/NIR GROND detector. The UV/optical/NIR observations did not reveal any counterpart at the position of 1E161348-5055 [18]. Based on these findings, A D' A`i associate the BAT burst with 1E161348-5055 and classified it as a magnetar, and pinpoint the 6.67 hr periodicity as the magnetar spin period [18]. Rea et al give strong argument that the 6.67 hr periodicity and the variable X-ray flux of the central compact object (CCO) at the center of the SNR RCW 103 have been always difficult to interpret within the standard scenarios of an isolated neutron star or a binary system and give strong argument favoring the picture involving a period of fall-back accretion after the supernova explosion, similarly to what is invoked (although in a different regime) to explain the "anti-magnetar" scenario for other CCO [19]. The space for a binary system was already narrowed in view of the limit on the IR emission that was previously obtained by De Luca et al., but the picture changes after Tendulkar et al reported [20] the detection of the previous unseen infrared counterpart (m_{F110}=26.3 AB Mag and m_{F160W}=24.4 AM mag)using Hubble Space Telescope (HST)(WFC3/IR) They showed that there deep IR observation rule out the possibility that the source is an accreting binary with high degree of confidence but mimic IR emission properties of magnetar and isolated neutron star. Borghese et al observed this source using NuSTAR and through ongoing Swift X-Ray Telescope monitoring campaign of the peculiar source 1E 161348–5055, located at the centre of the supernova remnant RCW 103, which is recovering from its last outburst in 2016 June. Through the spectral decomposition and evolution along the outburst decay, they confirmed that these are consistent with 1E 161348–5055 being a magnetar, the slowest ever detected [21]. While Esposito et al also reported that at the position 1E1613, they found a near-infrared source with KS = 20:68 ± 0:12 mag that was not detected (KS > 21:2 mag) in data collected with the same instruments in 2006, during X-ray quiescence [22]. These observations created again a confusion regarding the source.Since we have full access to all of them, we performed a reanalysis of this big dataset, exploiting the capabilities of each instrument: the XMM-Newton observations are quite long and can provide good statistics, This dataset thus allows both a spectral and a temporal study of the evolution of 1E 161348-5055.

Table 1 (Information about 1E 161348-5055.1)

Name of Binary System*	**Location**	**Periodicity (hrs)**	**Mass (Solar Units)**	**Distance**
1E 161348-5055.1	Lies at the centre of the 2-kyr-old supernova remnant RCW103	*6.67 ± 0.03 hours*	*1.4*	*3.3 kpc*

*Reference: De Luca A., Caraveo P. A., Mereghetti S., Tiengo A., Bignami G. F., 2006, Science, 313, 814

XMM X-Ray Space mission: XMM-Newton is the second of ESA's four "cornerstone" missions defined in the Horizon 2000 Programme. It was launched on December 10th, 1999 and carries two distinct types of telescope: three Wolter type-1 X-ray telescopes, with different X-ray detectors in their foci and a 30-cm optical/UV telescope with a microchannel-plate pre-amplified CCD detector in its focal plane (see also below) as in figure 2. Thus, XMM-Newton offers simultaneous access to two windows of the electromagnetic spectrum: X-ray and optical/UV.

XMM-Newton provides the following three types of science instrument:

1. European Photon Imaging Camera (EPIC): CCD cameras for X-ray imaging, moderate resolution spectroscopy and X-ray photometry; the two different types of EPIC camera, MOS and PN.

2. *Reflection Grating Spectrometer (RGS):2 essentially identical spectrometers for high-resolution X-ray spectroscopy and spectro-photometry*

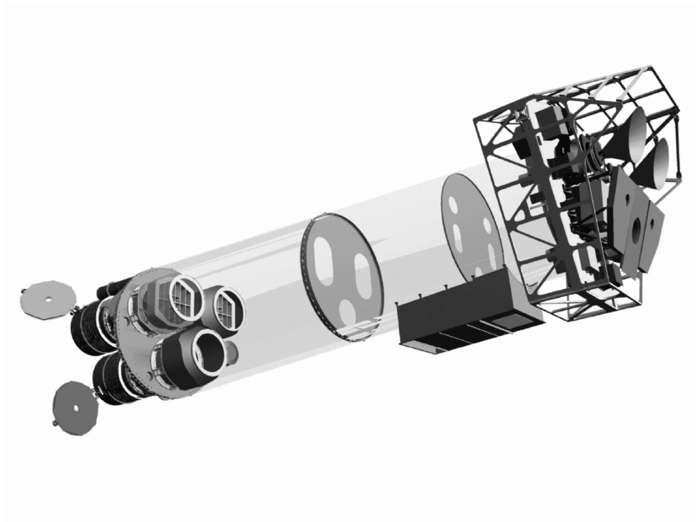


Figure *2*: Sketch of the XMM-Newton payload. The mirror modules, two of which are equipped with Reflection Grating Arrays, are visible at the lower left. At the right end of the assembly, the focal X-ray instruments are shown.

3. Optical Monitor (OM): For optical/UV imaging and grism (grating prism) spectroscopy. The three EPIC cameras and

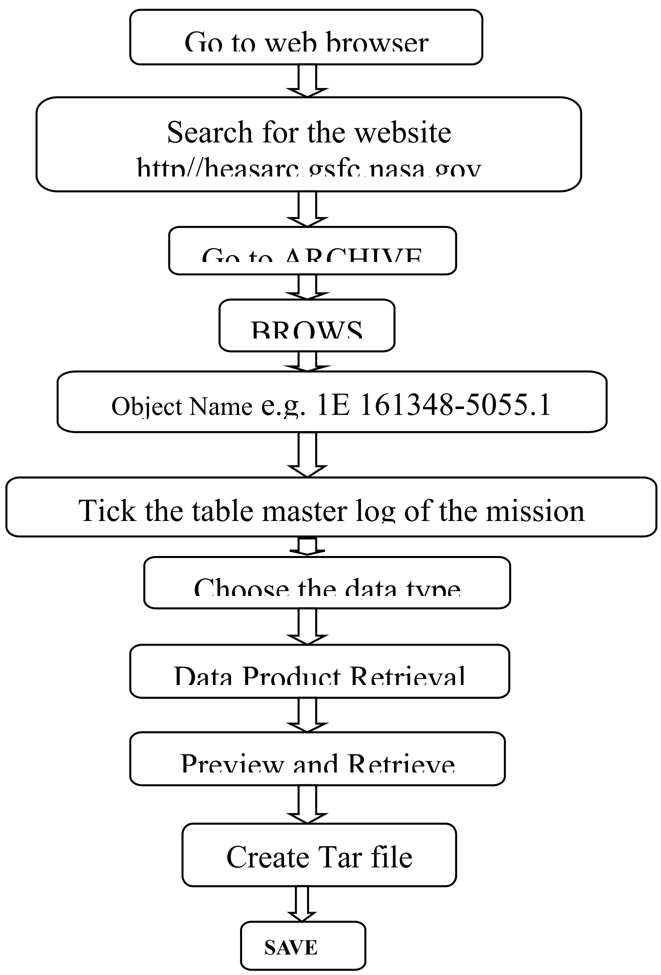
the two detectors of the RGS spectrometers reside in the focal planes of the X-ray telescopes, while the OM

has its own telescope. A sketch of the XMM-Newton

payload is displayed in the figure 2. There are in total six science instruments on board XMM-Newton, which are operated simultaneously (unless prohibited by constraints, for example, excessive target brightness). The instruments can be operated independently and each in different modes of data acquisition. Observers will receive data from all science instruments.

2. Data extraction process and XSPEC model used for study

The High Energy Astrophysics Science Archive Research Center (HEASARC) is the primary archive for NASA's (and other space agencies') missions dealing with electromagnetic radiation from extremely energetic phenomena ranging from black holes to the Big Bang. Since its merger with the Legacy Archive for Microwave Background Data Analysis (LAMBDA) in 2008, the HEASARC's holdings contain data obtained by NASA's high-energy astronomy missions observing in the extreme-ultraviolet (EUV), X-ray, and gamma ray bands, as well as data from missions, balloons, and ground-based facilities that have studied the relic cosmic microwave background (CMB). The procedure for downloading the data from NASA, HEASERC Centre is as follows:-



After downloading the data from HEASARC archive, we have to 'UNTAR' the tar data. On the UNTAR data from HEASARC archive, there are number of tasks that need to be done for each instrument on XMM-Newton. A number of SAS tasks, including those which rerun the pipeline, require an up-to-date list of calibration files (the CIF file) and extended

Observation Data File (ODF) summary file. These are obtained by running the tasks cifbuild and odfingest, respectively. Because of these dependencies, it is strongly recommended that users run these tasks, whether they plan to rerun the pipeline or not.

Table 2 (Observed data of XMM Newton)

Target	**Cygnus X1**
Scheduled Length (s)	**87914**
Mode & Detector	Timing (PN)
Observation ID	**0302390101**
PI	Dr Andrea De Luca

Sources (Table 2) were observed with XMM Newton EPIC pn camera was reduced using the XMM Newton Scientific Analysis Software (SAS) package. During data reduction, we have used the SAS's task "epchain datamode=ALL" for extraction of EPIC PN camera data. The data was filtered for good time intervals by setting a threshold count level.

Brief introduction of XSPEC model used for our study:

1. **wabs:**
   parameter1= N_{H1} [Galactic equivalent hydrogen column density along line of sight]
   parameter2= N_{H2} [Additional hydrogen column density of material local to neutron star]
   parameter3=z [redshift]
2. **powerlaw:** Powerlaw is a simple photon powerlaw.
   Parameter1 = α [photon index of powerlaw]
   Norm = k [photons $KeV^{-1}cm^{-2}s^{-1}$ @ 1KeV]
3. **bbodyrad:** A blackbody spectrum with normalization proportional to the surface area.

$$= A(E) = \frac{K \times 1.0344\times10^{-3} E^2\, dE}{\exp^{E/KT-1}}$$

Parameter = temperature KT, KeV

Norm k = R^2_{km}/D^2_{10} , where R_{km} is the source radius in km, and, D_{10} is the distance to the source in units of 10 kpc.

3. Spectral Analysis

The importance of a spectra re-analysis of the 10 years of observations of 1E 161348-5055 is easily grasped when one thinks that a systematic and simultaneous analysis could give insight in the flux decay process, in order to finally distinguish between the isolated magnetar model or the binary scenario. The XMM-Newton observations are particularly important because they provide an excellent statistic, and allow phase resolved spectral analysis. The spectral evolution was well modelled with a blackbody a power-law & photoelectric absorption Wisconsin cross-sections (wabs). They showed a smooth decay of the temperatures following the outburst, from $kT = 0.48$ keV approaching the 1999 level kT ~ 0:25 keV. This picture is consistent with a *hotspot* on the surface. In the binary scenario the heating of a portion of the neutron star surface would be due to an episode of accretion, while in the isolated magnetar, it would be provoked by a rearrangement of the magnetic field, which causes extra-currents in the magnetosphere and particles impacting on the surface. The peak observation instead is inconsistent with the decay: its spectrum is softer than the ones of the nearby observations, and the temperature is smaller than that detected by the monitoring observations (kT ~ 0:3 keV). This is somehow expected when one thinks that the phenomenon that caused the flux outburst is likely to be caused by a different mechanism than the following decay, and that it probably had shorter time decay constant. The different plot obtained from data fitting is given in figure 4- figure 11(see annexure 1 for details for steps).

Model wabs<1>(powerlaw<2> + bbodyrad<3>) Source No.: 1 Active/On

Model par	Model comp	Component	Parameter	Unit	Value
1	1	wabs	nH	10^22	3.02561 +/- 0.190569
2	2	powerlaw	PhoIndex		4.87863 +/- 0.212373
3	2	powerlaw	norm		1.70337E-02 +/- 5.10118E-03
4	3	bbodyrad	kT	keV	0.463438 +/- 2.57173E-02
5	3	bbodyrad	norm		3.59776 +/- 1.40202

Figure 3: Figure for fitted model

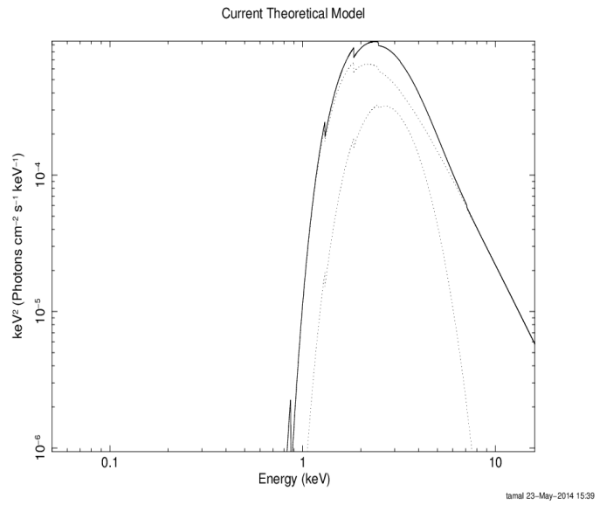


Figure 4: Figure for given model

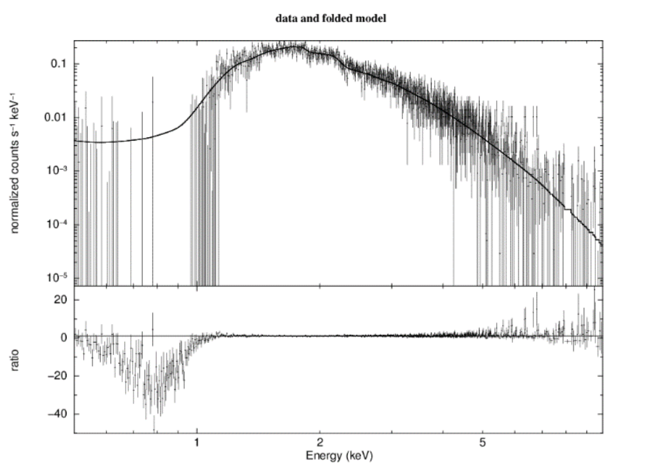


Figure 5: Folded Spectrum

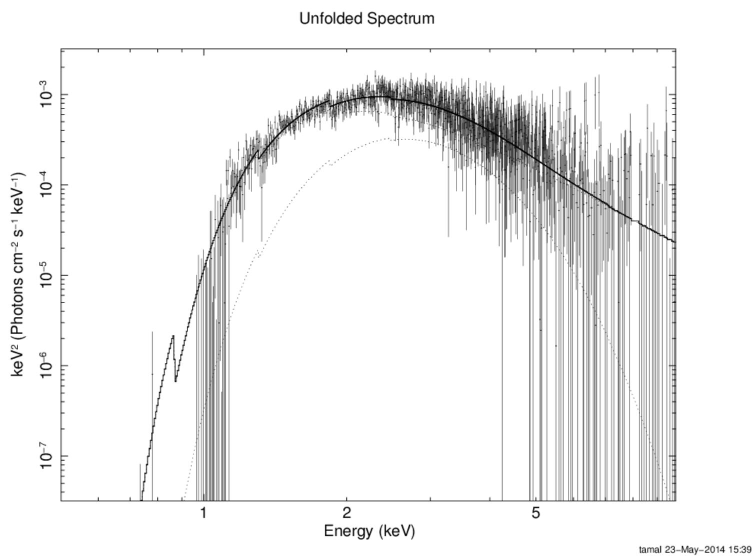


Figure 6: Unfolded Spectrum

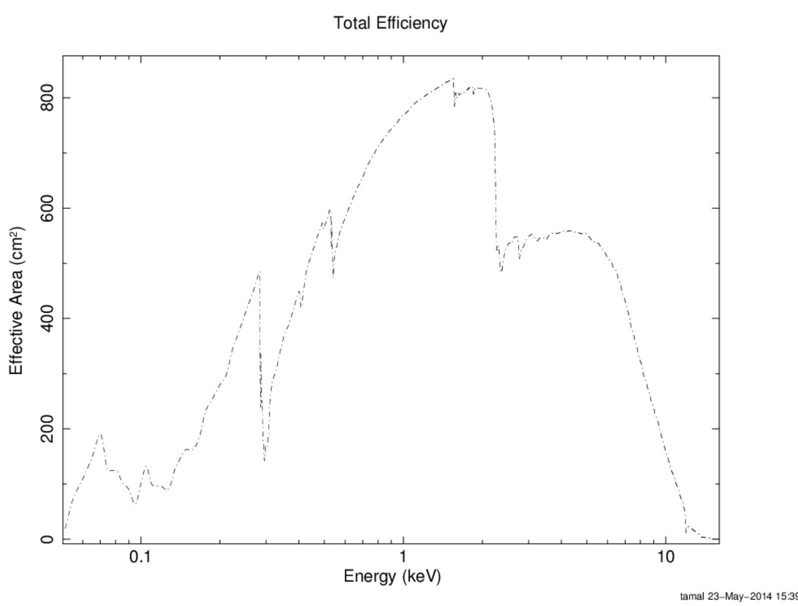


Figure 7: Figure for total efficiency

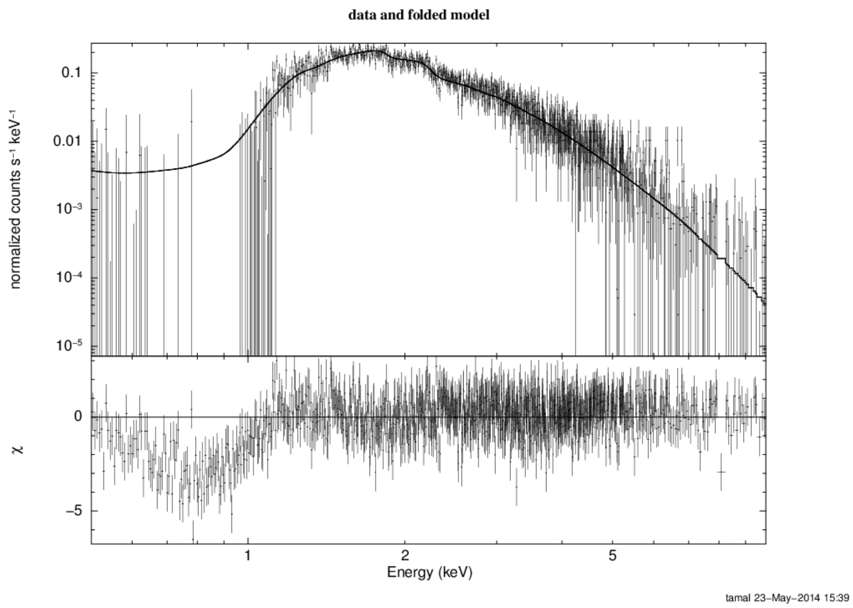


Figure 8: Ratio Curve

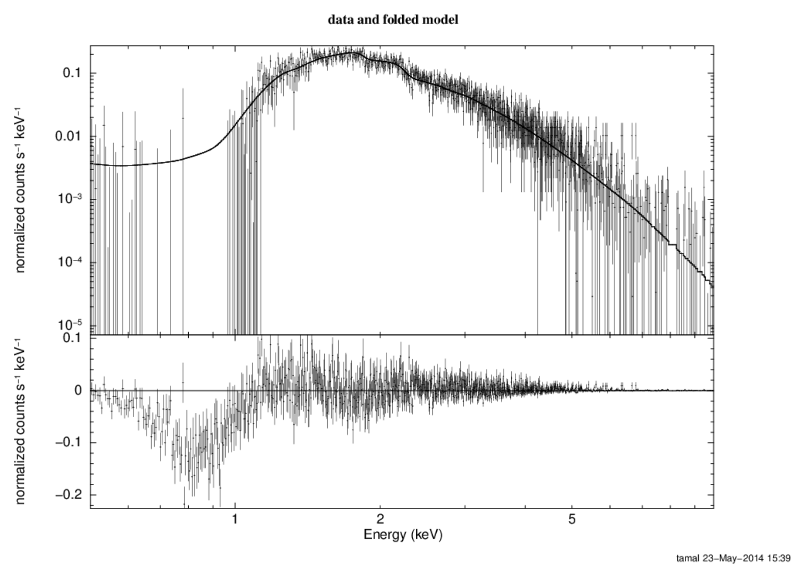


Figure 9: Response Curve

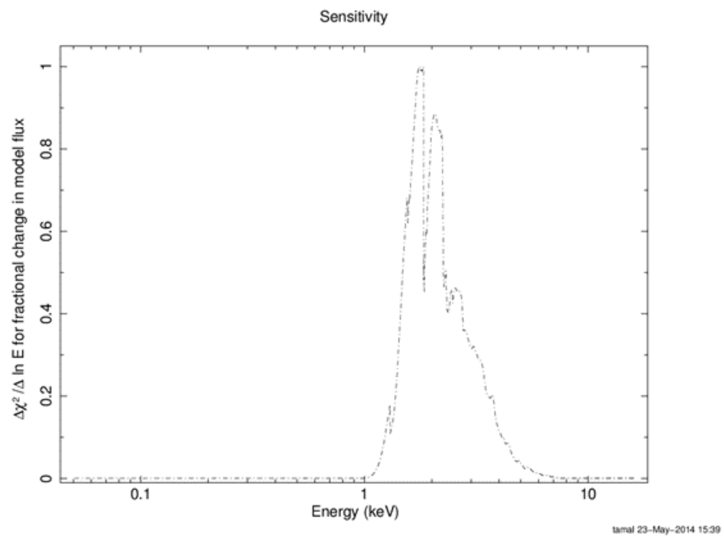


Figure 10: Sensitivity Curve

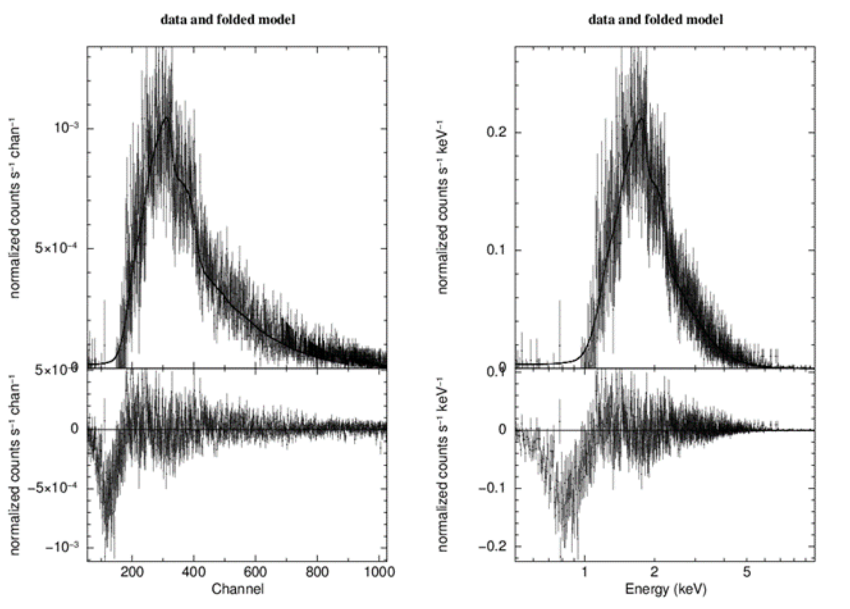


Figure 11: Folded Model Channel and Energy wise

4. Timing Analysis

The complete dataset from 1999 onwards is made of sparse and short observations, that taken alone don't allow a precise reconstruction of the period of 1E 161348-5055. In fact, the value of 24000±100 s derived from the 2005 XMM-Newton observation [14] doesn't allow its propagation for more than ~ 10 cycles: when this threshold is overcome, ambiguity arises when assigning a phase to older photons arrival time, and several values of the period that can fill in the gap between the observations with an integer number of cycles are indistinguishable. The error on the period, in fact, computed following is now small enough to propagate it backwards of several years without loss of accuracy.

lcurve:- In this case, we plot the light curve of a single time series from XMM-Newton of the pulsar,.1E 161348-5055. The light curve is obtained by executing 'lcurve' command (see annexure 2 for details) shown in figure 12.

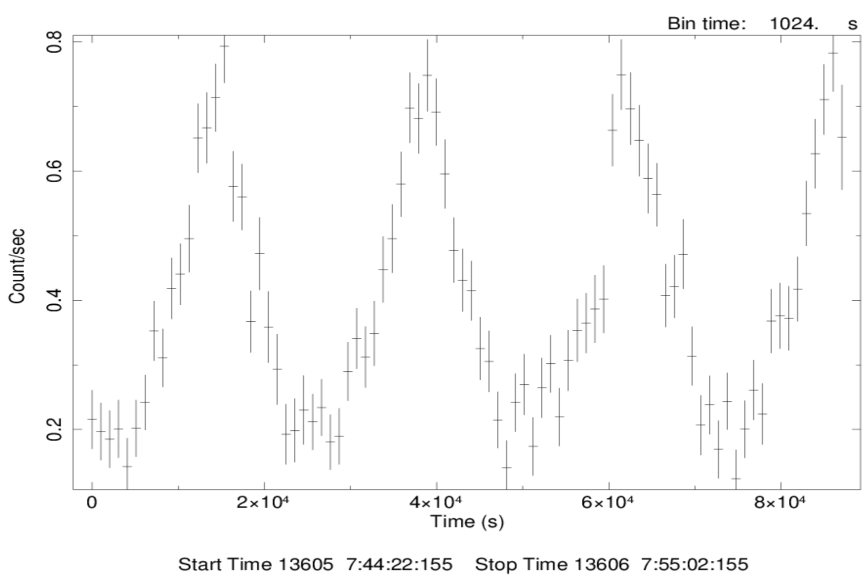


Figure 12: Light Curve

Power spectrum:-In this case, we plot the power spectrum of a time series from XMM-Newton of the pulsar, 1E 161348-5055 by executing the 'powspec' task (see annexure 2 for details) shown in figure 13:

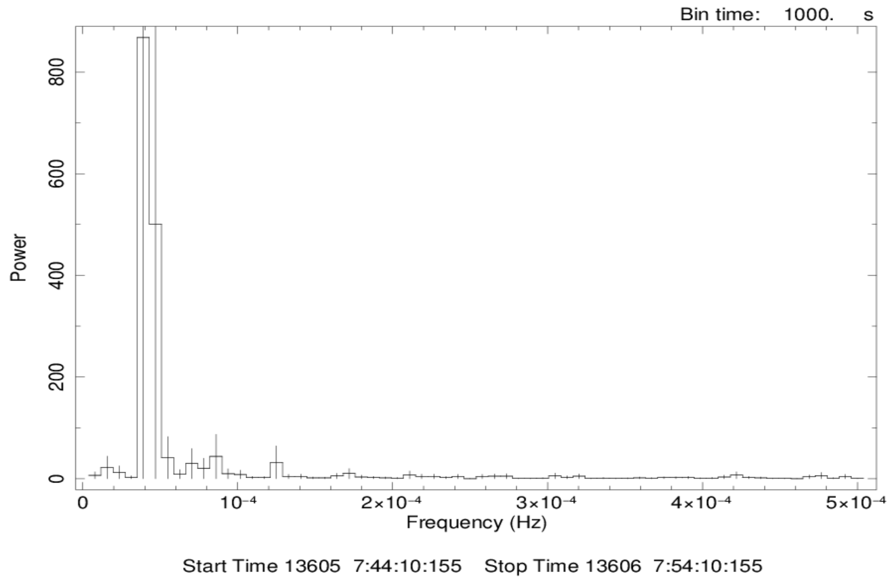


Figure 13: Power Spectrum

In this case, we search for the period of a light curve from XMM-Newton of the pulsar, 1E 161348-5055 by executing the "efsearch" task (see annexure 2 for details) , the period curve is shown in figure 14 :

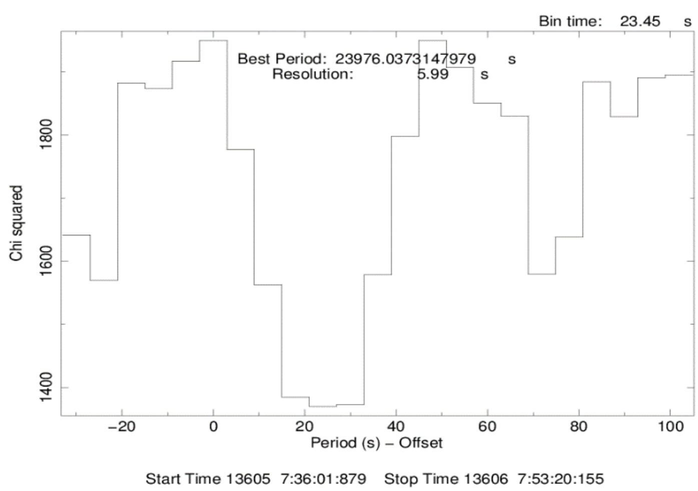


Figure 14: Period Curve

5. Result and Conclusion

(a) From Spectral Analysis: -

The XMM-Newton/EPIC (0.5−8 keV) X-ray spectra of 1E have been described by De Luca et al[10]. The time-averaged spectra from the 2005 low-state observations, when the source luminosity was $L \sim 10^{33}$ erg s−1, can be fitted by a two-component model consisting of a blackbody (BB) of temperature $kT_{bb} \sim 0.5$ keV and an equivalent blackbody radius $R_{bb} \sim$ 0.6 km, plus a power-law (PL) of index $\Gamma\sim3$, with ~ 70% of the total flux coming from the blackbody component. Alternatively, the second component can also be a blackbody with a higher temperature. A re-analysis of the earlier 2001 XMM-Newton data, when 1E had a higher luminosity (by a factor ~ 6), yielded a similar two-component (BB+PL) model with essentially the same blackbody temperature kT_{bb} and power-law index Γ, but a larger equivalent blackbody radius $R_{bb} \sim$ 1.3 km, and a higher contribution from the PL component (the blackbody contribution was ~50% of the total flux as opposed to the above ~ 70%), which made the overall spectrum harder . In our case, we consider only the first one and the figures 4-11 are obtained using this model. The figure 6 gives us the idea of the effective area vs energy which helps us to understand the instrument efficiency. Figure 9 gives us the sensitivity of the instrument. Figure 11shows the folded model both channel-wise and energy-wise, which help us to understand how the channels and energy are related.

Calculation of Red-shift:- Red-shift of our object is given by,

$$\mathbf{Z=H_0 \times D/c}$$

Where, H_0= Hubble Parameter =70 km/sec/Mpc.

D= Distance in MPc. = 3.3×10^{-3} MPc.

c= Light-speed = 3×10^{5} km/sec.

So, $\underline{Z= 7.7\times10^{-7}}$

Calculation of luminosity & flux & their dependence on energy:

Experimentally we get the value of luminosity as 1.8922×10^{33} ergs/s in the energy range 0.5 – 10.0 KeV, whose order is same as given above. Again, we further calculate the luminosity & corresponding flux in the various energy ranges. They are given in the table 3 and plotted in figure 15:

Table 3 (Calculation of luminosity, flux and energy)

Energy (KeV)	**Luminosity (ergs/sec) ($\times 10^{30}$)**	**Flux (ergs/cm^2/sec) (10^{-15})**
0.75	1.39	1.0778
1.5	560	432
2.5	745	574
3.5	345	266
4.5	132	101.6
5.5	54.1	41.65
6.5	25.9	19.98
7.5	14.0	10.787
8.5	8.56	6.59
9.5	5.585	4.302

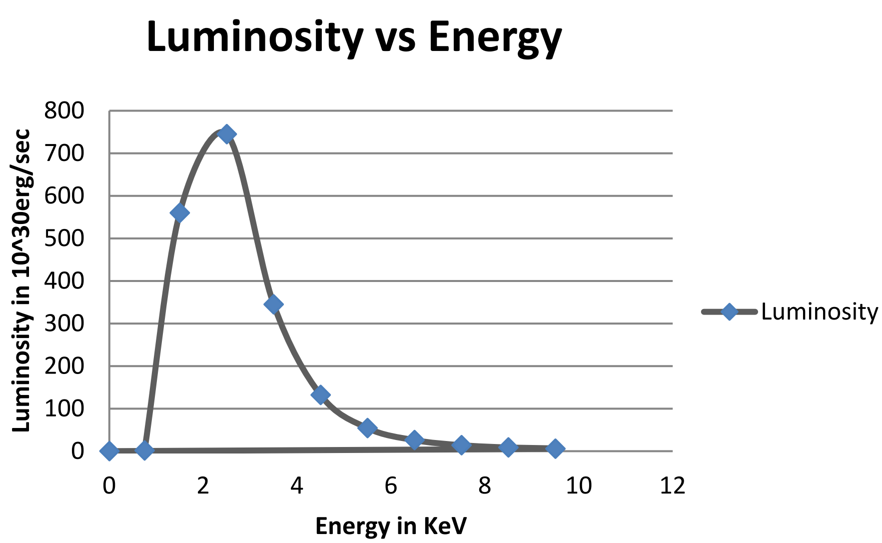


Figure 15: Luminosity Vs Energy

Calculation of blackbody radius (R_{bb}):-

From figure 2 we get for the 'blackbody' model kT~ 0.463438±2.57173E-02 KeV, which is slightly different as stated above. Now the 'norm' (k) is 3.59776±1.40202. For 'blackbody model',

$k=R^2_{bb}/ D^2_{10}$

where, D_{10} is measured in unit of 10kpc. So ,

$R_{bb}=\sqrt{k \times D^2_{10}}$ km

Therefore, $R_{bb} = \{3.59776\times(0.33)^2\}^{0.5}$ km = 0.6259 km. This is same as stated above. So we may conclude that our chosen model is well fitted.

(b) From Timing Analysis: -

From Figure12 we can easily determine the time period or periodicity of the given object. Its value lies in between 2.2-2.6 $\times 10^4$ sec. But for get more accurate result we have to plot power spectrum. From Figure13 we get the frequency ~ 10^{-5} Hz, so that the time period is ~ 10^4 sec. After plotting the data followed by 'efsearch' command we get the exact time period of the pulsar 1E 61348-5055 which is given by 23976.0373 sec. & it is shown on the Figure14. Now we already know the periodicity of the given pulsar is 6.67 hrs., i.e., 24012 sec. So our fitted model is nearly exact.

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