Title
Nustar and integral observations of a low/hard state of 1E1740.7-2942

Permalink
https://escholarship.org/uc/item/1vv121qb

Journal
Astrophysical Journal, 780(1)

ISSN
0004-637X

Authors
Natalucci, L
Tomsick, JA
Bazzano, A
et al.

Publication Date
2014

DOI
10.1088/0004-637X/780/1/63

Peer reviewed
NuSTAR AND INTEGRAL OBSERVATIONS OF A LOW/HARD STATE OF 1E1740.7-2942

LORENZO NATALUCCI1, JOHN A. TOSMICK2, ANGELA BAZZANO1, DAVID M. SMITH1, MATTEO BACCHETTI1,5, DIDIERR BARRET4,5, STEVEN E. BOGGS2, FINN E. CHRISTENSEN6, WILLIAM W. CRAIG7, MARIATERESA FIOCCIU1, FELIX FÜRST3, BRIAN W. GREFENSTETTE6, CHARLES J. HAILEY8, FIONA A. HARRISON8, ROMAN KRIVONOS2, ERIK KUULKERS10, JON M. MILLER11, KATJA POTTSCHMIDT12,13, DANIEL STERN14, PIETRO UBERTINI1, DOMINIC J. WALTON9, WILLIAM W. ZHANG15

Accepted by the Astrophysical Journal

ABSTRACT

The microquasar 1E1740.7-2942, also known as the “Great Annihilator”, was observed by NuSTAR in the Summer of 2012. We have analyzed in detail two observations taken ~ 2 weeks apart, for which we measure hard and smooth spectra typical of the low/hard state. A few weeks later the source flux declined significantly. Nearly simultaneous coverage by INTEGRAL is available from its Galactic Center monitoring campaign lasting ~ 2.5 months. These data probe the hard state spectrum from 1E1740.7-2942 before the flux decline. We find good agreement between the spectra taken with IBIS/ISGRI and NuSTAR, with the measurements being compatible with a change in flux with no spectral variability. We present a detailed analysis of the NuSTAR spectral and timing data and upper limits for reflection of the high energy emission. We show that the high energy spectrum of this X-ray binary is well described by thermal Comptonization.

Subject headings: accretion, accretion disks — black hole physics — X-rays: binaries — X-rays: spectrum — individual (1E 1740.7-2942)

1. INTRODUCTION

The astrophysical source 1E1740.7-2942 is a known microquasar located near the Galactic Center (GC), at an angular distance of 50′ from SgrA∗. First discovered by Einstein/IPC (Hertz & Grindlay 1984) in the soft X-rays, it is the most luminous persistent source above 20 keV in the region (Sunyaev et al. 1991), and has extended radio lobes reaching distances of up to a few parsecs (~ 1′) from its core (Mirabel et al. 1992).

1 Istituto Nazionale di Astrofisica, INAF-IAPS, via del Foso del Cavaliere, 00133 Roma, Italy; e-mail: lorenzonatalucci@iap.inaf.it
2 Space Sciences Laboratory, 7 Gauss Way, University of California, Berkeley, CA 94720-7450, USA
3 Physics Department and Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA
4 Université de Toulouse; UPS-OMP; IRAP; Toulouse, France
5 CNRS; Institut de Recherche en Astrophysique et Planétologie; 9 Av. colonel Roche, BP 44346, F-31028 Toulouse cedex 4, France
6 DTU Space, National Space Institute, Technical University of Denmark, Elektrovej 327, DK-2800 Lyngby, Denmark
7 Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
8 Caltech Center for Astronomy and Astrophysics, California Institute of Technology, Pasadena, CA 91125, USA
9 Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA
10 European Space Astronomy Centre (ESA/ESAC), Science Operations Department, 28691 Villanueva de la Cañada (Madrid), Spain
11 Department of Astronomy, University of Michigan, 500 Church Street, Ann Arbor, MI 48109, USA
12 CRESST and NASA Goddard Space Flight Center, Astrophysics Science Division, Code 661, Greenbelt, MD 20771, USA
13 Center for Space Science and Technology, University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA
14 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
15 NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

The core radio emission is found to be variable, with radio flux and spectral slope changes that are correlated with the X-ray flux, as observed by GRANAT/SIGMA in the early 1990’s (Paul et al. 1991). SIGMA reported a burst of emission in soft γ-rays characterized by a broad hump in the 300 – 600 keV band (Bouchet et al. 1991) and a further, more marginal episode of enhanced γ-ray emission (Churazov et al. 1993). It was then speculated that such transient events could be generated by the deceleration and interaction of positrons injected by the source into a molecular cloud (Bally & Leventhal 1991; Mirabel et al. 1993). However, nearly simultaneous observations by CGRO, namely by OSSE (Jung et al. 1995) and BATSE (Smith et al. 1996), did not detect any transient emission and also, the high energy observations by INTEGRAL (Bouchet et al. 2009) and other satellites could not confirm the high energy feature reported by SIGMA.

Many aspects about the nature of 1E1740.7-2942 remain a mystery. A clear optical/IR counterpart for the companion star has not been detected so far, probably due to the source environment characterized by a high concentration of dust and a large hydrogen column density (NH ~ 10^23 cm^-2). Therefore, its nature as a high mass or low mass object is not known, nor its distance and inclination. However, the high amount of absorption and its position near the GC favors a distance of ~ 8.5 kpc, and the presence of bipolar jets disfavors a face-on geometry for the accretion disk. Recently, Marti et al. (2010) reported a candidate companion consisting of a single near-infrared source with an apparent non-stellar morphology, localized at a position coincident with the source core. Despite its brightness, so far there is no evidence for strong reprocessing from 1E1740.7-2942. The Suzaku data established the absence (or evidence of...
SPI observations of 1E1740.7-2942 are contaminated a jet origin of the excess for Cyg X-1. The emission was also reported from the IBIS instrument (Winkler et al. 2003). They detected a high $\gamma$ level of polarization for energies $\gtrsim 200$ keV, which is reminiscent of a similar detection of disc reflection in the Suzaku data while a weak, broad iron line was marginally found at $E \sim 6.7$ keV. Simultaneous observations of 1E1740.7-2942 by RXTE and INTEGRAL/IBIS, obtained mostly when the source was in the hard state, were analyzed by Del Santo et al. (2010) who reported values of the reflection normalization in the range $\sim 0.3 - 0.9$. We note that their analysis is so far the only claimed detection of reflection in this source.

The recently launched NuSTAR observatory (Harrison et al. 2013) is the ideal instrument for the study of the reprocessed components in the spectrum of 1E1740.7-2942, due its unprecedented broadband coverage from soft to hard X-rays. In this work, we use nearly simultaneous observations by NuSTAR and the IBIS/ISGRI instrument on board INTEGRAL. IBIS, with its wide FOV and good sensitivity near 100 keV, can be used to complement the NuSTAR energy coverage and better constrain the parameters of the Comptonization. For INTEGRAL we limited our analysis to the IBIS data and did not attempt to use data from either Jem-X (Lund et al. 2003) or SPI, mainly because Jem-X had a relatively short exposure time and the SPI data are seriously contaminated by other sources. We also searched for nearly simultaneous observations of 1E1740.7-2942 in the Swift/XRT archive, but only very short, off-axis exposures were available. We verified that the statistics are too low to discriminate between spectral models from these data.

In Section 2 we describe the observations; Section 3.1 deals with the spectral and timing analysis of the NuSTAR data while in Section 3.2 we present the IBIS/ISGRI spectrum and lightcurves. Section 3.3 reports on the joint NuSTAR/INTEGRAL spectrum. In Section 4 our results are compared to previous observations of 1E1740.7-2942, and finally our conclusions are presented in Section 5.

2. OBSERVATIONS

All our observations were taken from July to September 2012. Data from NuSTAR are available from two epochs in July-August 2012, spaced by about two weeks (see details in Table 1). The total exposure times were 2172s and 6125s, respectively. NuSTAR is the first X-ray satellite with multilayer hard X-ray optics and is operational in the energy range 3–79 keV.
The mission carries two telescopes with grazing incidence optics, each one focusing on separate detector modules at a distance of 10m, i.e. two detectors named Focal Plane Modules A and B (FPMA, FPMB). These CdZnTe detectors have a spatial resolution of 0.6mm and sample a total Field-Of-View (FOV) of 13'. The telescope Point Spread Function (PSF) has an 18' Full-Width-At-Half-Maximum with extended tails resulting in a Half-Power-Diameter of 58'.

Shortly after the NuSTAR observations were completed, INTEGRAL began a GC monitoring campaign as part of its AO10 cycle. Furthermore, some of the Galactic Bulge Monitoring data were available. Due to the wide FOV (29' Full-Width-At-Zero Response) of IBIS/ISGRI, 1E1740.7–2942 was monitored over quite a long period. Figure 1 shows the Swift/BAT light curve of 1E1740.7–2942 taken around the time of our observations. The source experienced a significant flux decline near MJD 56175 followed by a decrease of the accretion rate that was further monitored by INTEGRAL. For the purpose of this work, we selected data in a time period comprised between the first NuSTAR observation and the latest date available before the flux decline. This results in a time coverage spanning nine INTEGRAL orbits from 2012 August 8 to September 1 (revolutions 1199–1207). These observations consist of a series of pointings, selected for the source being at an offset < 9’ from the IBIS instrument axis. Due to the high total flux of sources from the GC region, the sensitivity of IBIS is reduced particularly in the lowest energy channels. The NuSTAR observations are not simultaneous with INTEGRAL and on the basis of the light curve shown in Figure 1 we expect to have a ∼ 10% lower flux. However, rate fluctuations up to ∼ 20 − 30% or more are observed at daily time scale. We distinguish three epochs consisting of the two NuSTAR observations and of the further INTEGRAL monitoring. Since 1E1740.7–2942 does not usually exhibit substantial spectral variations within such a small flux range, we model the data from both satellites simultaneously, allowing the cross-normalization to vary.

Note that the total NuSTAR observation time is much shorter than the INTEGRAL one. IBIS/ISGRI, being particularly sensitive in the ∼ 50 − 100 keV spectral region, is expected to provide a good overlap of both data sets, allowing minimal possible bias in the spectral modeling.

### 3. Data Analysis

#### 3.1. NuSTAR

We analyzed the NuSTAR data using the NuSTAR Data Analysis Software (NuSTARDAS) version 1.1.1, CALDB version 20130509 and in-flight calibrated response matrices. The software applies offset correction factors to the energy response to account for the movement of the mast, causing a varying position of the focal spots on the detector planes. For the two FPMs the pipeline produces images, spectra and deadtime corrected lightcurves. For each NuSTAR observation, the source and background subtraction regions must be carefully evaluated due to the possible presence of contaminating sources outside the FOV. This straylight problem can be minimized prior to the observations by a tuning of the spacecraft position angle (PA) and if needed, of the optical axis position. In Figure 2 the images obtained for both FPMs are shown. The intensity is encoded in logarithmic scale, to emphasize underlying structures. The source net spectra were obtained by selecting counts in a circular region of 90" radius centered on the source position and subtracting count rates measured in a background dominated region, also circular, of radius 183". The different area normalizations were taken into account in the background subtraction. Both regions are shown in the figure.

The total source count rates in the energy range 3–75 keV, in the selected spatial region are: $8.66 \pm 0.06$ c/s (FPMA) and $8.05 \pm 0.06$ c/s (FPMB) for epoch 1, and $8.13 \pm 0.04$ c/s (FPMA) and $8.12 \pm 0.04$ c/s (FPMB) for epoch 2. The ratio of the source-to-background rates varies with energy and is as high as ∼ 25 and 35 for the energy bands 3–10 keV and 10–40 keV, respectively. We checked against possible systematic effects introduced by spatial variations of the background rates. For the epoch 2 observation, we extracted a set of source spectra in different annular regions of the detectors, far from the source, and having the same size as the source region shown in Figure 2. We found that the maximum variation of the 3–60 keV rates in these spectra is $\approx 10^{-2}$ counts s$^{-1}$, i.e. a fraction of only $\sim 10^{-3}$ of the total source intensity.

**Spectral analysis** — We first analyzed spectra of the two observations using XSPEC [Arnaud 1996] version 12.8.0 and models consisting of a PL and a PL with a high energy cutoff. To model the effect of X-ray absorption, we used the XSPEC TBabs model with abundances set as in [Wilms et al. 2000] and cross sections set as in
the soft band is found to be very good (Harrison et al. 2006). Note that the values of the absorption column derived from these abundances may be different to previously reported determinations of $N_H$. For each observation we fitted the two spectra obtained from FPMA and FPMB, rebinned to have at least 75 counts per spectral bin. This choice is appropriate for a good overlap with the IBIS spectra, i.e. it allows similar error sizes for the spectral bins in the range $\sim 30 - 70$ keV. Since the absorption is quite high, in all the fits we left the $T 수행한 실험에서, $C$는 a value, depending only on the data set and hence, is constant for all models. The model $M_k$ which yields the minimum $AIC$ is, regardless of the true (and unknown) underlying process, the one minimizing the information loss and the relative likelihood of a model $M_i$ can be estimated as $\exp(\Delta_{AIC}/2)$, where $\Delta_{AIC}$ is the difference in the $AIC$ values of $M_i$ and $M_k$. Applying the above method to the same model spectra used in the F-test and computing the relative probability, we found that the PL model without the soft component is $3.8\times10^{-3}$ less probable than the corresponding model with the added diskbb. This result provides evidence that the disk blackbody is indeed present in our data. Using the same data set, we computed the upper limits for the equivalent width (EW) of an iron line feature at 6.4 keV. Modeling with a narrow line yields a 90% confidence limit of 12 eV while a Gaussian line with a FWHM of 1 keV yields a corresponding value of 38 eV. These are statistical limits and do not include an analysis of the possible fluctuations of the line background.

We also used Comptonization models such as comppx (Titarchuk 1994; Hua & Titarchuk 1995) and compps (Poutanen & Svensson 1996) to fit the epoch 2 data. The latter includes modeling of reflection from the cold disk following the method of Magdziarz & Zdziarski (1995). In fitting with both models, we assume a Maxwellian distribution of electron temperature and a spherical geometry for the electron cloud. Moreover, for compps we used a disk viewing angle fixed at 60°. A good fit was obtained in both cases when adding the diskbb component, i.e. $\chi^2/\nu=753/740$ and $\chi^2/\nu=754/737$ for comppx and compps, respectively. The fit with comppx sets a lower limit to the electron temperature of the hot, optically thin cloud as $kT_e > 40$ keV, whereas compps puts some more constraints on this parameter, yielding $kT_e=115_{-61}^{+41}$ keV (90% confidence). For the latter model a reflection component cannot be detected and the 90% upper limit to the reflection
normalization is \( \approx 0.045 \) for \( \xi = 1000 \text{ erg cm s}^{-1} \), where \( \xi \) is the ionization parameter. We also computed upper limits using reflionx, a recently improved version of the constant density, ionized disc model of Ross, Fabian & Young (1999) and Ross & Fabian (2005). For the spectral fitting, we tied the spectral index parameter of the reflionx component to the one of the direct PL component. Figure 4 shows the best fit model with the diskbb and PL components along with the 90% upper limit spectra of the reflected components for a partially ionized and fully ionized disk \((\xi=1000 \text{ erg cm s}^{-1} \text{ and } \xi=10,000 \text{ erg cm s}^{-1}, \text{ respectively})\). The corresponding upper limits in the solid angle normalization, \( R = \Omega/2\pi \), for the above cases are \( R=0.007 \) \((\xi=1000 \text{ erg cm s}^{-1})\) and \( R=0.08 \) \((\xi=10,000 \text{ erg cm s}^{-1})\).

Timing analysis — We extracted light curves of 1E1740.7-2942 in the energy range 3–60 keV from epoch 2 with XSELECT V2.4b using a time resolution of 10ms, and corrected them using the tool nucorr. Prior to temporal binning, the filtered event files were corrected for arrival times at the Solar System Barycenter using the JPL 2000 ephemeris (for this purpose, we used the barycorr tool in the HEASOFT v13 distribution). We then calculated power spectra on different contiguous sections of the light curves and averaged them into a total spectrum. Each single power spectrum was built using intervals of 32768 bins and averaging up to 10 intervals in a frame. The total spectrum was finally rebinned in frequency channels for more statistics. An offset constant term was subtracted from the total spectrum to remove the Poisson noise level and compensate for residual effects of the deadtime correction. This term was evaluated as the average power in the frequency interval 10–49 Hz. The power spectrum is shown in Figure 5. Although the statistics are quite poor due to the short exposure time of the observations, we could model the power spectrum with a zero-centered Lorentzian function and obtained a good fit \((\chi^2/\nu=15.4/23)\). For our adopted normalization, the root-mean-square (RMS) variability is derived as the integral of the Lorentzian. This resulted in \(15.4 \pm 2.2\%\). The error also includes the uncertainty in the evaluation of the offset term.

### 3.2. INTEGRAL

We extracted images, spectra and lightcurves of 1E1740.7-2942 from the IBIS/ISGRI instrument using the INTEGRAL Off Line Analysis v.10 package which takes advantage of a recently updated calibration (Caballero et al. 2012). The lightcurves and spectra of 1E1740.7-2942 were extracted by simultaneous fitting of all the sources detected in the mosaic images above a detection level of \( \approx 7 \sigma \). This process reduces systematic noise in the reconstructed flux due to the cross-talk between sources to a level close to \(1\%\) or less. For 1E1740.7-2942 this effect is mostly limited to lower energies, because the source is the brightest one in the field at \( E > 50 \text{ keV} \). For this reason we excluded the energy channels below 26 keV from the analysis.

Figure 6 shows the IBIS/ISGRI light curves in the energy bands 26–60 keV and 60–150 keV for epoch 3. We performed an analysis of the IBIS spectrum to search for any evidence of spectral curvature at high energy, which is a typical signature of (thermal) Comptonization. The absorption value was fixed as \( N_H=2 \times 10^{23} \text{ cm}^{-2}\) in TBabs and a systematic error of 1% has been added to all spectral channels. For IBIS, the PL model fit is not
between the three different observations by including the energy intervals 26–60 keV (bottom) and 60–150 keV (top).

\[ \chi \]

to follow the Wien law and is typically of energies. The spectrum of the seed photons is assumed ining by an electron plasma with a Maxwellian distribution accretion disk are diffused via inverse Compton scatter-

ging the CPL model yields \( \chi^2/\nu \) \approx 68. Conversely, using the CPL model yields \( \chi^2/\nu = 24.2\) with a high energy cutoff at \( E_{\text{fold}} = 123 \pm 30 \) keV. The resulting count rate spectrum with the convolved best fit model is shown in Figure 7. This measurement yields definitive evidence for spectral curvature at high energies and is fully compatible with the \( \text{NuSTAR} \) measurements described in Sect. 3.1. See also the following Sect.3.3.

### 3.3. NuSTAR/INTEGRAL spectrum

We fitted the \( \text{NuSTAR} \) and IBIS/ISGRI data for the whole set of observations described in Table 3. For the spectral fits we considered, in addition to the empirical PL and CPL models, the thermal Comptonization model \( \text{comptt} \), which assumes that the soft seed photons in the accretion disk are diffused via inverse Compton scattering by an electron plasma with a Maxwellian distribution of energies. The spectrum of the seed photons is assumed to follow the Wien law and is typically \( kT < 0.5 \) keV. For our purposes, the shape of the seed photon spectrum is not relevant since our spectra are measured at energies \( > 3 \) keV. Conversely, the high energy part of the spectrum is dominated by the cutoff induced by the finite temperature of the plasma electrons.

The data set consists of four \( \text{NuSTAR} \) spectra and one IBIS/ISGRI spectrum. We allowed free normalization between the three different observations by includ-

![Figure 6: Light curves measured by IBIS/ISGRI for epoch 3, in the energy intervals 26–60 keV (bottom) and 60–150 keV (top).]

Satisfactory, resulting in \( \chi^2/\nu = 48.1/20 \). Conversely, using the CPL model yields \( \chi^2/\nu = 24.2/19 \) with a high energy cutoff at \( E_{\text{fold}} = 123^{+60}_{-30} \) keV. The resulting count rate spectrum with the convolved best fit model is shown in Figure 7. This measurement yields definitive evidence for spectral curvature at high energies and is fully compatible with the \( \text{NuSTAR} \) measurements described in Sect. 3.1. See also the following Sect.3.3.

### Table 2: Spectral analysis of individual \( \text{NuSTAR} \) observations

<table>
<thead>
<tr>
<th>Model</th>
<th>Epoch</th>
<th>( N_H ) (10(^{22}) cm(^{-2}))</th>
<th>( \Gamma )</th>
<th>( E_{\text{fold}} ) (keV)</th>
<th>( E_{\text{cut}} ) (keV)</th>
<th>( N_{\text{disk}} \times 10^{-3} )</th>
<th>( F_{\text{3–10}} )</th>
<th>( F_{\text{20–50}} )</th>
<th>( \chi^2/\nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL</td>
<td>1</td>
<td>19.4±1.1</td>
<td>1.65±0.03</td>
<td>144±88</td>
<td>343±9</td>
<td>478±12</td>
<td>408/377</td>
<td></td>
<td></td>
</tr>
<tr>
<td>diskbb+PL</td>
<td>1</td>
<td>24.3±2.4</td>
<td>1.71±0.35</td>
<td>371±16</td>
<td>467±13</td>
<td>387/376</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>2</td>
<td>19.4±0.7</td>
<td>1.67±0.02</td>
<td>477/711</td>
<td>449±7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>diskbb+PL</td>
<td>2</td>
<td>22.0±1.3</td>
<td>1.70±0.02</td>
<td>660±36</td>
<td>343±8</td>
<td>444±5</td>
<td>755/740</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPL</td>
<td>2</td>
<td>18.3±0.9</td>
<td>1.58±0.04</td>
<td>215±74</td>
<td>320±7</td>
<td>442±8</td>
<td>761/740</td>
<td></td>
<td></td>
</tr>
<tr>
<td>highcuto+PL</td>
<td>2</td>
<td>18.2±0.9</td>
<td>1.60±0.03</td>
<td>260±126</td>
<td>319±9</td>
<td>441±8</td>
<td>760/739</td>
<td></td>
<td></td>
</tr>
<tr>
<td>diskbb+CPL</td>
<td>2</td>
<td>20.9±1.5</td>
<td>1.65±0.06</td>
<td>&gt; 160</td>
<td>49±31</td>
<td>335±6</td>
<td>441±8</td>
<td>753/739</td>
<td></td>
</tr>
</tbody>
</table>

Note: \( N_H \) is the hydrogen absorption column estimated with the model \( TBabs \), \( \Gamma \) the PL photon index, \( E_{\text{fold}} \) the e-folding energy, \( E_{\text{cut}} \) the cutoff energy of the highcuto cut model, and \( N_{\text{disk}} \) is the normalization of the diskbb model. \( F_{\text{3–10}} \) and \( F_{\text{20–50}} \) are the flux values measured of the unabsorbed emission of the PL or CPL components, in the 3-10 keV and 20-50 keV bands, and are given in units of \( 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \). All errors are computed as 90% confidence.

![Figure 7: Total energy spectrum of IBIS/ISGRI modeled by a PL with high energy cutoff.]

In Table 3 also lists the values of the relative normalization factor in all the models. The \( \text{NuSTAR} \) spectra from FPMA and FPMB of the same observation are cross-calibrated between each other at the few % level. For this reason, we included another free normalization factor. The five spectra are the same discussed previously in this Section. We summarize the results of the overall fits in Table 3. In Figure 8, the resulting unfolded spectrum for the diskbb+comptt model is shown. The result of the fit, even if not formally acceptable, is adequate to describe the broadband shape and characterize it as dominated by a thermal Comptonized component in the energy band 3-250 keV. Adding the soft component improves the quality of all model fits; however, only for one model (diskbb+PL) it is possible to constrain both disk temperature and normalization.

Table 3 also lists the values of the relative normalization factor \( C_{3–2} \) between the IBIS/ISGRI and the \( \text{NuSTAR} \) epoch 2 observations. In the fit, we fixed to unity the normalization of the epoch 2 observation for the \( \text{NuSTAR} \) FPMA. The relative (variable) normalization of epochs 1 to 2 is actually found to be constant for all model fits, i.e. \( C_{1–2} = 1.04\pm0.01 \). Note that the value of \( C_{3–2} \) accounts not only for the different flux between the two observations but also for any difference in the cross-calibration of the two instruments.

Finally, to better describe the departure of the spectrum from a pure PL we plot in Figure 9 the data/model ratios in the energy band 3–250 keV. The positive residuals at low energies are likely due to the thermal disk.
NuSTAR and INTEGRAL observations of 1E1740.7-2942

TABLE 3

<table>
<thead>
<tr>
<th>Model</th>
<th>$N_{\text{H}}$ ($10^{22}$ cm$^{-2}$)</th>
<th>$\Gamma$</th>
<th>$E_{\text{fold}}$ (keV)</th>
<th>$kT_{\text{in}}$ (keV)</th>
<th>$\tau$</th>
<th>$N_{\text{disk}}$</th>
<th>$kT_{\text{in}}$ (keV)</th>
<th>$C_{\text{3-2}}$</th>
<th>$F(20-50)$</th>
<th>$F(50-200)$</th>
<th>$\chi^2/\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL</td>
<td>20.4±0.6</td>
<td>1.690±0.013</td>
<td></td>
<td></td>
<td>1.0±0.03</td>
<td>441±6</td>
<td>955±26</td>
<td>1337/1141</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>diskbb+PL</td>
<td>27.2±1.2</td>
<td>1.758±0.021</td>
<td></td>
<td></td>
<td>0.38±0.06</td>
<td>432±6</td>
<td>866±32</td>
<td>1262/1139</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPL</td>
<td>18.0±0.6</td>
<td>1.556±0.024</td>
<td>161±29</td>
<td></td>
<td>1.27±0.03</td>
<td>450±6</td>
<td>623±29</td>
<td>1188/1140</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>diskbb+CPL</td>
<td>20.3±1.3</td>
<td>1.597±0.029</td>
<td>190±22</td>
<td></td>
<td>0.3±0.03</td>
<td>438±6</td>
<td>625±28</td>
<td>1174/1139</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>diskbb+comptt</td>
<td>20.4±0.9</td>
<td></td>
<td>38±29</td>
<td>1.41±0.17</td>
<td>1.13±0.03</td>
<td>441±7</td>
<td>638±31</td>
<td>1168/1139</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. $kT_{\text{in}}$ is the inner disk temperature and $C_{\text{3-2}}$ is the multiplicative normalization constant of epoch 3 versus epoch 2 observations. See Table 2 for description of the other model parameters. All errors are computed as 90% confidence.

4. DISCUSSION

These observations show that 1E1740.7-2942 presents a featureless spectrum in its hard state and is consistent with being dominated by Comptonization with an electron temperature of $\sim$ 40 keV. Assuming a distance of 8.5 kpc, the luminosity of the source is $\approx 2.2 \times 10^{41}$ erg s$^{-1}$, i.e. a fraction less than a few % of the Eddington limit for a stellar black hole. The sensitivity of NuSTAR constrains the strength of the reflection component to be quite low, similar to the limits which have been measured previously by Reynolds & Miller (2010), who reported a disk reflection fraction $\lesssim 0.1$ at the 99% confidence level. However, in contrast to these observations, the Suzaku data are compatible with no high energy cutoff ($E_{\text{fold}} \gtrsim 350$ keV). This issue could be ascribed to either a genuine variation of the plasma temperature causing the cutoff energy to vary, to a different inherent mechanism for the hard X-ray emission, or to a difference in calibration with the HXD instrument. However, we note that the Suzaku and NuSTAR PL slopes are similar when data are fitted without a high energy cutoff. Also, a sensitivity bias is unlikely as Reynolds & Miller (2010) report a Suzaku detection up to 300 keV. Therefore, it is likely that the difference is related to a genuine variation of the physical conditions of the high energy corona in two different occurrences of the hard state. Both Suzaku and NuSTAR detect a soft component in the spectrum of the hard state and the NuSTAR data are compatible with a disk inner radius close to the ISCO. However, we cannot exclude a recessed disk as we cannot determine any reliable constraints of the parameters of the soft component. Using diskbb on the single NuSTAR observations and leaving $kT_{\text{in}}$ free, the fitting procedure converges to either values $\lesssim 0.15$ keV with a rather strong soft component (rather unlikely in a hard state), or to values $kT_{\text{in}} \sim 0.3 - 0.4$ keV, yielding normalizations similar to what was observed by Suzaku. Castro et al. (2012) also report the presence of a soft component in the hard state during an observation in 2005 by XMM/Newton, with an inner disk color temperature close to 0.25 keV. Our upper limits on the EW of a 6.4 keV Fe line are consistent with the ones reported by Nakashima et al. (2010), who found 8 eV with Suzaku/XIS, and by Sakano et al. (1999), who measured EW< 15 eV with ASCA. Heindl & Smith (1998) also report a line with EW=19$^{+15}_{-14}$ eV with observations by RXTE/PCA.

At the highest energies we can compare our observations with the available measurements from INTEGRAL/SPI. These observations, described in Bouchet et al. (2009), point to the presence of two different spectral components, of which the lower in energy is well described by thermal Comptonization with a cutoff energy of $\sim$140 keV. The higher energy component is above $\sim$200 keV. We did not detect this component: fitting our NuSTAR/INTEGRAL spectrum with a two
temperature model, in which the seed photon temperature of the high energy component is equal to 30 keV as in Bouchet et al. (2009), the 90% upper limit flux for the high energy excess is $4 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$ in the 20–250 keV band. This value, scaled by the intensity measured by SPI, is ~ 20% higher than the flux of this component reported by these authors. Our observations are then substantially in agreement with those of Bouchet et al. (2009) for the highest energies.

There are several possible reasons for the low level of reflection from 1E1740.7-2942. If the accretion disk is close to the ISCO and the upper layers of the disk are close to being fully ionized, the reflection would be non-negligible but the shape of the reflected spectrum could be quite similar to that of the directly radiated flux (see e.g. Figure 4). In this case, it would be quite difficult to detect it. Furthermore, Fe lines and edges can be significantly broadened by additional Doppler and relativistic effects. Conversely, if the disk is recessed, the geometry and positioning of the corona relative to the disk could play a role and likewise for the (unknown) disk inclination. A low level of reflection is also expected if a substantial part of the hard X-ray spectrum is generated in an outflow (Beloborodov 1999). However, the mechanism of acceleration in an outflow or jet and its connection to the hot disk corona are presently not understood and so, also the relative contribution of the jet component. The hard tail detected by Bouchet et al. (2009) could be non-thermal and associated with a jet, similar to the high energy polarized component in Cyg X-1. In this case we could have a scenario in which the bulk of hard X-rays are indeed produced by a hot corona up to ~ 200 keV, with a jet dominating emission at higher energies.

For 1E1740.7-2942 we report clear evidence for a high energy cutoff, which is a typical signature of a thermal electron plasma. However, this scenario is not the only one that is consistent with such a cutoff. The emergent spectra computed by jet models could also contain high energy exponential cutoffs in the region from ~100 to a few hundred keV, generated, e.g., by synchrotron cooling as described in Markoff et al. (2001). These features can also be produced by Comptonized emission from regions within the jet (Reig et al. 2003; Giannios 2003) or at the base of it (Markoff et al. 2005). For the jet model of Markoff et al. (2005), the interplay of the direct synchrotron and Comptonized components controls the hardening of the spectrum above 10 keV, which is commonly ascribed to reflection in a corona/disk model. If such hardening is not present, as in the case of 1E1740.7-2942, the synchrotron emission component could be dominant. However, we emphasize that in our case it is not possible to provide any direct evidence of synchrotron emission or non-thermal Comptonization, and our broadband spectrum in the range 3–250 keV is well described by inverse Compton radiation by a hot, optically thin thermal plasma plus a soft disk component.

5. CONCLUSIONS

We have analyzed spectra of the well known microquasar 1E1740.7-2942, located in the vicinity of the GC using the NuSTAR telescope and the hard X-ray instrument IBIS/ISGRI on board INTEGRAL. During the observations, the source was in a typical low/hard state. We have analyzed NuSTAR spectra from two different observations (taken about two weeks apart) and found that they are fully consistent. The NuSTAR and IBIS/ISGRI data, spanning a time range of ~ 1.5 months, are also well in agreement both for the spectral modeling and for the relative normalization. The broadband spectrum in the range 3–250 keV is essentially modeled by a component that is consistent with Comptonization with a thermal energy cutoff $kT_e \sim 40$ keV. The NuSTAR power spectrum is compatible with what was previously observed by RXTE (Smith et al. 1997; Lin et al. 2000) and also RMS variation is detected at the level of ~ 15%.

At the softest energies, near 3 keV, there is some evidence for a soft component. Although we cannot obtain a reliable measure of the disk temperature and inner radius, due to both the low threshold of 3 keV and the shortness of the NuSTAR observations, the disk component observed is quite compatible with previous observations by Suzaku. Conversely, the detection of a high energy cutoff points to a possible change in the physical conditions of the plasma in the Comptonizing corona (we also note that a state change occurred shortly after these observations).

The very high sensitivity of NuSTAR has allowed us to characterize in detail the spectrum of this source up to ~70 keV and combining NuSTAR and INTEGRAL provides a determination of the overall properties of the broadband emission. The complementarity of NuSTAR and INTEGRAL is excellent for the study of the properties of black holes in the low/hard state, for which the bulk of the emission is in the energy range ~ 50 – 120 keV. In the case of 1E1740.7-2942, we were able to rule out a single PL model for the broadband spectrum. NuSTAR could not detect any reflection feature; however, more interesting results/constraints will likely come from significantly longer observations of this source.

This work was supported under NASA Contract No. NNG08FD60C, and made use of data from the NuSTAR mission, a project led by the California Institute of Technology, managed by the Jet Propulsion Laboratory, and funded by the National Aeronautics and Space Administration. We thank the NuSTAR Operations, Software and Calibration teams for support with the execution and analysis of these observations. This research has made use of the NuSTAR Data Analysis Software (NuSTARDAS) jointly developed by the ASI Science Data Center (ASDC, Italy) and the California Institute of Technology (USA). LN wishes to acknowledge the Italian Space Agency (ASI) for financial support by ASI/INAF grants 1/037/12/0-011/13 and 1/033/10/0 and the engineering support of M. Federici for setup and maintenance of the INTEGRAL archive and Data Analysis Software at IAPS. MB wishes to acknowledge the support from the Centre National d’Etudes Spatiales (CNES).

REFERENCES

