The reflection spectrum of the low-mass X-ray binary *4U 1636–53*

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Wide Band Spectral and Timing Studies of Cosmic X-ray Sources





Introduction









Introduction

- Pandel, Kaaret & Corbel (2008): no correct for pileup; at least two Fe-K lines from iron in different ionization states; $> 64^\circ$, most cases peg at 90°
- cases peg at 90°
- corona illuminating the disc; $\sim 48-89^\circ$, most cases peg at 90°



• Cackett et al. (2010) : no correct for pileup; the boundary layer illuminating a geometrically thin disc; all

• Ng et al. (2010) : considering pileup and background effects; symmetric line profiles; upper limit at 70° • Sanna et al. (2013) : considering pileup and background effects; both the NS surface/boundary layer and the









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Table 1. NuSTAR Observations of 4U 1636–53 used in this paper

Obervation	Identification Number	Observation Times (UTC)		
		(day.month.year hr:min)	Exposure (ks)	
Obs. 1	30102014002	25.08.2015 02:51 - 25.08.2015 18:36	$27.4^{A} (27.3^{*})/27.7^{B} (27.3^{*})/27.7$	
Obs. 2	30102014004	05.09.2015 17:41 - 06.09.2015 11:01	30.3 ^A (30.2*)/30.4 ^B (30	
Obs. 3	30102014006	18.09.2015 07:06 - 18.09.2015 23:26	$28.9^A (28.8^*)/29.0^B (28)$	

^ATotal exposure time of FPMA of NuSTAR; ^BTotal exposure time of FPMB of NuSTAR; *Final exposure time excluding X-ray bursts.

Simultaneously observing the broad emission line and the Compton hump without pileup effects!





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Figure 2. *NuSTAR* spectra and models for the fit with *const*phabs*(bbody+nthcomp)* for 4U 1636–53. The bottom panel shows the residuals in terms of sigmas. The spectra have been rebinned for plotting purposes.

- large positive residuals at around 5-10 keV
- no clear Compton hump at high energies (above 10 keV)

Note: In Obs.1, we only fit the spectra at the energy range of 3-30 keV.





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Models we used to fit the line in this work:

- a simple symmetric model, GAUSSIAN;
- relativistically broadened emission line model, **KYRLINE**;
- with different coronal heights, **RELXILL** and **RELXILLP**.

Hereafter, rel is short for RELXILL and relp is short for RELXILLP!!!

two models including relativistically smeared and ionized reflection off the accretion disc





Figure 3. *NuSTAR* unfolded spectra and models fitted with the model *const*phabs*(bbody+gaussian+nthcomp)* for 4U 1636–53.

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Results of M1:

• kT_{bb} goes down from Obs. 1 to Obs. 3;

• Γ_{nth} decreases while kT_e increases from Obs. 1 to Obs. 3,

indicating the soft, transitional and hard state;

E_{gau} decreases from Obs. 1 (~6.7 keV) to Obs. 2 and 3,
 suggesting the disc becomes less ionized.





Figure 4. *NuSTAR* unfolded spectra and models fitted with the model *const*phabs*(bbody+kyrline+nthcomp)* for 4U 1636–53.

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Results of M2:

the parameters more or less followed the same trend

with them in M1;

• inclination ~88°,

excluding the possible effect of calibration uncertainties of *XMM-Newton*.

Figure 6. NuSTAR unfolded spectra and models fitted with the model *const*phabs*(bbody+relxill)* for 4U 1636–53.

Figure 7. The unfolded best-fitting model const*phabs*(bbody+relxill) to three spectra of 4U 1636–53.

• most of the parameters follow the same trend as those in other models; inclination ~88°;

- R_{in} increases from ~6 R_g in Obs. 1 to ~17 R_g in Obs. 3;
 - the ionization parameter $\boldsymbol{\xi}$ decreases with time;
 - supporting the standard accretion disc model.

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$\frac{\text{Grp. 1}}{\text{Grp. 1}} \frac{\text{Grp. 2}}{\text{Grp. 3}} \frac{\text{Grp. 3}}{\text{Grp. 4}}$ $\frac{\text{Grp. 1}}{1.00^{f}/1.02\pm0.01} \frac{1.82\pm0.02}{1.82\pm0.02} 0.93\pm0.02$ $k_{bb} (10^{-3}) 9.2\pm0.02 0.6\pm0.01 0.5\pm0.01$ $F_{bb} (10^{-11}) \frac{71.3\pm0.07}{64.5\pm0.07} \frac{4.4\pm0.05}{4.4\pm0.05} 2.0\pm0.03$ $\frac{i_{relp} (^{\circ})}{55.7\pm0.2} \frac{55.7\pm0.2}{1.01} 2.8^{+0.1}_{-0.3}$ $\frac{h/R_g}{R_{in}/R_g} 5.7\pm0.07 10.3\pm0.04 11.4\pm0.08$ $\Gamma_{relp} 2.19\pm0.01 1.93\pm0.01 1.76\pm0.01$ $E_{2ut} (keV) 7.9\pm0.05 61.5\pm0.6 135.9\pm0.7$ $\tau 4.9\pm0.04 1.5\pm0.02 0.9\pm0.01$ $k_{relp} (10^{-3}) 289.9^{+332}_{-0.3} 46.7\pm0.05 21.3\pm0.03$ $F_{relp} (10^{-9}) \frac{1.4\pm0.01}{1.4\pm0.01} 1.1\pm0.01 1.2\pm0.01$ $\frac{1.09(\zeta)}{K_{relp} (10^{-9})} \frac{2.12\pm0.01}{2.11\pm0.01} 1.13\pm0.01 1.17\pm0.01$ $\frac{1.72\pm0.01}{1.12\pm0.01} 1.19\pm0.01 1.19\pm0.01$	Component		M4		
$\begin{array}{c c c c c c c c c } \mbox{const} & 1.00^{f}/1.02\pm0.01 \\ \hline kT_{bb} (keV)$ 2.13\pm0.01 1.82 ± 0.02 0.93\pm0.02$ \\ k_{bb} (10^{-3})$ 9.2\pm0.02$ 0.6\pm0.01 0.5 ± 0.01 \\ \hline k_{bb} (10^{-11})$ 71.3\pm0.07$ 4.4\pm0.05$ 2.0\pm0.03$ 2.5\pm0.03$ \\ \hline F_{bb} (10^{-11})$ 71.3\pm0.07$ 4.4\pm0.05$ 2.5\pm0.03$ \\ \hline F_{bb} (10^{-11})$ 71.3\pm0.07$ 4.4\pm0.05$ 2.5\pm0.03$ \\ \hline k_{bb} (10^{-11})$ 71.3\pm0.07$ 4.4\pm0.05$ 2.5\pm0.03$ \\ \hline k_{bb} (10^{-11})$ 71.3\pm0.07$ 4.4\pm0.05$ 2.5\pm0.03$ \\ \hline k_{bb} (10^{-3})$ 2.3\pm0.2$ 2.5\pm0.1$ 2.8_{-0.3}^{+0.1}$ \\ \hline k_{relp} (10^{-3})$ 7.9\pm0.05$ 61.5\pm0.6$ 135.9\pm0.7$ \\ \hline k_{relp} (10^{-3})$ 289.9_{-0.3}^{+332}$ 46.7\pm0.05$ 21.3\pm0.03$ \\ \hline k_{relp} (10^{-9})$ 1.4\pm0.01$ 1.1\pm0.01$ 1.2\pm0.01$ \\ \hline k_{relp} (10^{-9})$ 2.12\pm0.01$ 1.13\pm0.01$ 1.17\pm0.01$ \\ \hline k_{cl} (def)$ 1.04(4636)$ \\ \hline k_{cl			Grp. 1	Grp. 2	Grp. 3
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	const		1.00 ^f /1.02±0.01		
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$		$kT_{\rm bb}~({\rm keV})$	2.13±0.01	1.82±0.02	0.93±0.02
$\frac{F_{bb} (10^{-11})}{r_{relp} (^{\circ})} = \frac{71.3 \pm 0.07}{64.5 \pm 0.07} = \frac{4.4 \pm 0.05}{4.4 \pm 0.05} = \frac{2.0 \pm 0.03}{2.5 \pm 0.03}$ $\frac{i_{relp} (^{\circ})}{\frac{h/R_g}{R_{in}/R_g}} = \frac{2.3 \pm 0.2}{2.5 \pm 0.1} = \frac{2.8 \pm 0.1}{2.8 \pm 0.3}$ $\frac{R_{in}/R_g}{\Gamma_{relp}} = \frac{2.19 \pm 0.01}{1.93 \pm 0.01} = \frac{1.76 \pm 0.01}{1.76 \pm 0.01}$ $\frac{E_{cut} (keV)}{r} = \frac{7.9 \pm 0.05}{r} = \frac{61.5 \pm 0.6}{1.5 \pm 0.6} = \frac{135.9 \pm 0.7}{1.35.9 \pm 0.7}$ $\frac{I}{Iog(\zeta)} = \frac{4.4 \pm 0.03}{4.4 \pm 0.03} = \frac{3.4 \pm 0.03}{3.4 \pm 0.03} = \frac{3.1 \pm 0.06}{3.1 \pm 0.06}$ $\frac{K_{relp} (10^{-3})}{F_{relp} (10^{-9})} = \frac{1.4 \pm 0.01}{1.4 \pm 0.01} = \frac{1.13 \pm 0.01}{1.1 \pm 0.01} = \frac{1.17 \pm 0.01}{1.2 \pm 0.01}$ $\frac{\chi^2_{\nu} (cof)} = \frac{1.04(4636)}{1.04(4636)}$	BB	$k_{\rm bb}~(10^{-3})$	9.2±0.02	0.6 ± 0.01	0.5±0.01
$\begin{array}{c c c c c c c c c c c c c c c c c c c $		$F_{\rm bb}~(10^{-11})$	71.3±0.07 64.5±0.07	4.4±0.05 4.4±0.05	2.0±0.03 2.5±0.03
$\frac{h/R_{\rm g}}{R_{\rm in}/R_{\rm g}} = \frac{2.3 \pm 0.2}{2.5 \pm 0.1} = \frac{2.8 \pm 0.1}{2.8 \pm 0.3}$ $\frac{R_{\rm in}/R_{\rm g}}{R_{\rm relp}} = \frac{5.7 \pm 0.07}{10.3 \pm 0.04} = \frac{11.4 \pm 0.08}{11.4 \pm 0.08}$ $\frac{\Gamma_{\rm relp}}{E_{\rm cut} (\rm keV)} = \frac{7.9 \pm 0.05}{7.9 \pm 0.05} = \frac{61.5 \pm 0.6}{61.5 \pm 0.6} = \frac{135.9 \pm 0.7}{135.9 \pm 0.7}$ $\frac{\tau}{1.0 g(\zeta)} = \frac{4.4 \pm 0.03}{4.4 \pm 0.03} = \frac{3.4 \pm 0.03}{3.1 \pm 0.06} = \frac{3.4 \pm 0.03}{1.1 \pm 0.01} = \frac{1.2 \pm 0.01}{1.2 \pm 0.01}$ $\frac{F_{\rm relp} (10^{-3})}{1.4 \pm 0.01} = \frac{2.12 \pm 0.01}{1.1 \pm 0.01} = \frac{1.12 \pm 0.01}{1.2 \pm 0.01}$ $\frac{\Gamma_{\rm total} {\rm flux} F_{\rm tel} (10^{-9})}{2.11 \pm 0.01} = \frac{2.12 \pm 0.01}{1.12 \pm 0.01} = \frac{1.17 \pm 0.01}{1.19 \pm 0.01}$		i _{relp} (°)		55.7±0.2	
$\frac{R_{in}/R_{g}}{\Gamma_{relp}} = 5.7 \pm 0.07 = 10.3 \pm 0.04 = 11.4 \pm 0.08$ $\Gamma_{relp} = 2.19 \pm 0.01 = 1.93 \pm 0.01 = 1.76 \pm 0.01$ $E_{cut} (keV) = 7.9 \pm 0.05 = 61.5 \pm 0.6 = 135.9 \pm 0.7$ $\tau = 4.9 \pm 0.04 = 1.5 \pm 0.02 = 0.9 \pm 0.01$ $log(\zeta) = 4.4 \pm 0.03 = 3.4 \pm 0.03 = 3.1 \pm 0.06$ $k_{relp} (10^{-3}) = 289.9^{+332}_{-0.3} = 46.7 \pm 0.05 = 21.3 \pm 0.03$ $F_{relp} (10^{-9}) = \frac{1.4 \pm 0.01}{1.4 \pm 0.01} = \frac{1.1 \pm 0.01}{1.1 \pm 0.01} = \frac{1.2 \pm 0.01}{1.2 \pm 0.01}$ $\frac{1.04(4636)}{1.04(4636)} = 1.04(4636)$	RELXILLP	h/Rg	2.3±0.2	2.5±0.1	$2.8^{+0.1}_{-0.3}$
$\frac{\Gamma_{\text{relp}}}{K_{\text{relp}}} = \frac{2.19 \pm 0.01}{1.93 \pm 0.01} = \frac{1.76 \pm 0.01}{1.76 \pm 0.01}$ $\frac{E_{\text{cut}} (\text{keV})}{7.9 \pm 0.05} = \frac{61.5 \pm 0.6}{61.5 \pm 0.6} = \frac{135.9 \pm 0.7}{1.35.9 \pm 0.7}$ $\frac{\tau}{\log(\zeta)} = \frac{4.9 \pm 0.04}{4.4 \pm 0.03} = \frac{1.5 \pm 0.02}{3.4 \pm 0.03} = \frac{0.9 \pm 0.01}{3.1 \pm 0.06}$ $\frac{k_{\text{relp}} (10^{-3})}{k_{\text{relp}} (10^{-3})} = \frac{289.9_{-0.3}^{+332}}{246.7 \pm 0.05} = \frac{21.3 \pm 0.03}{1.1 \pm 0.01}$ $\frac{1.4 \pm 0.01}{1.1 \pm 0.01} = \frac{1.1 \pm 0.01}{1.2 \pm 0.01}$ $\frac{1.2 \pm 0.01}{1.2 \pm 0.01}$ $\frac{1.13 \pm 0.01}{1.12 \pm 0.01} = \frac{1.17 \pm 0.01}{1.19 \pm 0.01}$ $\frac{\chi^2_{\nu} (\text{dof})}{k_{\nu}} = \frac{1.04(4636)}{k_{\nu}}$		$R_{\rm in}/R_{\rm g}$	5.7 ± 0.07	10.3±0.04	11.4 ± 0.08
$\frac{E_{\text{cut}} (\text{keV})}{\tau} = \frac{7.9 \pm 0.05}{4.9 \pm 0.04} = \frac{61.5 \pm 0.6}{1.5 \pm 0.02} = \frac{135.9 \pm 0.7}{0.9 \pm 0.01}$ $\frac{\tau}{\log(\zeta)} = \frac{4.9 \pm 0.04}{4.4 \pm 0.03} = \frac{1.5 \pm 0.02}{3.4 \pm 0.03} = \frac{0.9 \pm 0.01}{3.1 \pm 0.06}$ $\frac{k_{\text{relp}} (10^{-3})}{k_{\text{relp}} (10^{-3})} = \frac{289.9^{+332}_{-0.3}}{46.7 \pm 0.05} = \frac{21.3 \pm 0.03}{1.2 \pm 0.01}$ $\frac{1.4 \pm 0.01}{1.4 \pm 0.01} = \frac{1.1 \pm 0.01}{1.1 \pm 0.01} = \frac{1.2 \pm 0.01}{1.2 \pm 0.01}$ $\frac{1.4 \pm 0.01}{1.2 \pm 0.01} = \frac{1.13 \pm 0.01}{1.12 \pm 0.01} = \frac{1.17 \pm 0.01}{1.19 \pm 0.01}$ $\frac{\chi^2_{\nu} (\text{coff})}{k_{\nu}} = \frac{1.04(4636)}{k_{\nu}}$		Γ _{relp}	2.19 ± 0.01	1.93±0.01	1.76 ± 0.01
$\frac{\tau}{\log(\xi)} = \frac{4.9\pm0.04}{4.4\pm0.03} = \frac{1.5\pm0.02}{3.4\pm0.03} = \frac{0.9\pm0.01}{3.1\pm0.06}$ $\frac{\log(\xi)}{k_{\text{relp}}(10^{-3})} = \frac{289.9^{+332}_{-0.3}}{46.7\pm0.05} = \frac{46.7\pm0.05}{21.3\pm0.03} = \frac{21.3\pm0.03}{1.2\pm0.01}$ $\frac{F_{\text{relp}}(10^{-9})}{1.4\pm0.01} = \frac{1.1\pm0.01}{1.1\pm0.01} = \frac{1.2\pm0.01}{1.2\pm0.01}$ $\frac{1.13\pm0.01}{1.12\pm0.01} = \frac{1.17\pm0.01}{1.19\pm0.01}$ $\frac{\chi^2_{\nu}(\text{dof})}{1.04(4636)} = \frac{1.04(4636)}{1.04(4636)}$		$E_{\rm cut}$ (keV)	7.9 ± 0.05	61.5±0.6	135.9 ± 0.7
$\frac{\log(\xi)}{k_{\text{relp}}(10^{-3})} = \frac{4.4\pm0.03}{289.9^{+332}_{-0.3}} = \frac{3.4\pm0.03}{46.7\pm0.05} = \frac{3.1\pm0.06}{21.3\pm0.03}$ $\frac{k_{\text{relp}}(10^{-9})}{1.4\pm0.01} = \frac{1.1\pm0.01}{1.1\pm0.01} = \frac{1.2\pm0.01}{1.2\pm0.01}$ $\frac{1.4\pm0.01}{1.4\pm0.01} = \frac{1.13\pm0.01}{1.12\pm0.01} = \frac{1.17\pm0.01}{1.19\pm0.01}$ $\frac{\chi^2_{\nu} (\text{dof})}{1.04(4636)} = \frac{1.04(4636)}{1.04(4636)}$		τ	4.9±0.04	1.5 ± 0.02	0.9±0.01
$\frac{k_{\text{relp}}(10^{-3})}{F_{\text{relp}}(10^{-9})} \frac{289.9_{-0.3}^{+332}}{1.4\pm0.01} \frac{46.7\pm0.05}{1.1\pm0.01} \frac{21.3\pm0.03}{1.2\pm0.01}$ $\frac{1.4\pm0.01}{1.4\pm0.01} \frac{1.1\pm0.01}{1.1\pm0.01} \frac{1.2\pm0.01}{1.2\pm0.01}$ $\frac{2.12\pm0.01}{1.12\pm0.01} \frac{1.13\pm0.01}{1.12\pm0.01} \frac{1.17\pm0.01}{1.19\pm0.01}$ $\frac{\chi^2_{\nu}(\text{dof})}{1.04(4636)}$		$log(\xi)$	4.4±0.03	3.4 ± 0.03	3.1±0.06
$\frac{F_{\text{relp}}(10^{-9})}{\text{Total flux }F_{\text{ttl}}(10^{-9})} \frac{\begin{array}{c} 1.4\pm0.01\\ 1.4\pm0.01\\ 2.12\pm0.01\end{array}}{\begin{array}{c} 1.1\pm0.01\\ 1.1\pm0.01\end{array}} \frac{\begin{array}{c} 1.2\pm0.01\\ 1.2\pm0.01\\ 1.13\pm0.01\\ 1.12\pm0.01\end{array}}{\begin{array}{c} 1.17\pm0.01\\ 1.19\pm0.01\end{array}}$		$k_{\rm relp} (10^{-3})$	$289.9^{+332}_{-0.3}$	46.7±0.05	21.3 ± 0.03
Total flux F_{ttl} (10 ⁻⁹) $\begin{array}{c} 2.12 \pm 0.01 \\ 2.11 \pm 0.01 \end{array}$ $\begin{array}{c} 1.13 \pm 0.01 \\ 1.12 \pm 0.01 \end{array}$ $\begin{array}{c} 1.17 \pm 0.01 \\ 1.19 \pm 0.01 \end{array}$ χ^2_{ν} (dof)1.04(4636)		$F_{\rm relp} (10^{-9})$	1.4±0.01 1.4±0.01	1.1 ± 0.01 1.1 ± 0.01	1.2±0.01 1.2±0.01
χ^2_{ν} (dof) 1.04(4636)		Total flux F_{ttl} (10 ⁻⁹)	2.12±0.01 2.11±0.01	1.13±0.01 1.12±0.01	1.17±0.01 1.19±0.01
	χ^2_{ν} (dof)			1.04(4636)	

Table 3. Best-fitting parameters of the NuSTAR spectra of 4U 1636–53 with reflection model RELXILLLP.

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lts of M4:

ost of the parameters follow the same trend as those in other odels;

height of corona, h, increases from 2.3 R_g in Obs. 1 to 2.8 R_g Obs. 1;

clination $\sim 56^{\circ}$.

No geometry assuming and no relativistic boosting effects considering in the RELXILL model.

- model Gaussian;

Conclusion

• Four models fit the data well with different line profiles, even the simple symmetric

• The inclination is ~88° in KYRLINE and RELXILL, but is ~56° in RELXILLP; • The variation of the direct and reflection continuum evolves with the source state.

