A white dwarf accretion model for the anomalous X-ray pulsar 4U 0142+61

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The persistent emission of the anomalous X-ray pulsar 4U 0142+61 extends over a broad range of energy, from mid-infrared up to hard X-rays. In particular, this object is unique among soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) in presenting simultaneously mid-infrared emission and also pulsed optical emission. In spite of having many propositions to explain this wide range of emission, it is still lacking one that reproduces simultaneously all the observations. Filling this gap, we present a model that is able, for the first time, to reproduce simultaneously the entire spectral energy distribution of 4U 0142+61 using plausible physical components and parameters. We propose that the persistent emission comes from an accreting white dwarf (WD) surrounded by a debris disk. This model is thoroughly discussed at Ref. 2 and assumes that: (i) the hard X-rays are due to the bremsstrahlung emission from the post-shock region of the accretion column; (ii) the soft X-rays are originated by hot spots on the WD surface; and (iii) the optical and infrared emissions are caused by an optically thick dusty disk, the WD photosphere, and the tail of the post-shock region emission. In this scenario, 4U 0142+61 harbors a fast-rotator near-Chandrasekhar WD, which is highly magnetized. Such a WD can be formed by a merger of two less massive WDs.

Keywords: Accretion, magnetic field, rotation, white dwarfs.

1. Introduction

4U 0142+61 is an Anomalous X-ray Pulsar (AXP) that presents quiescent emission in a broad range of energy, from mid-infrared up to hard X-rays. In particular, this object is unique among SGR/AXPs in presenting simultaneously mid-infrared emission and pulsed optical emission, which are rare features for the class. Its period is 8.68 s, the spin-down is around 2.0×10^{-12} s.s^{-1} and the soft X-rays luminosity is about 10^{35} erg.s^{-1} [23].

The emission nature of AXP/SGRs is still reason for debate and several scenarios have been proposed to explain their observed spectra and properties, such as the magnetars [8], accreting NSs [28], quark stars [24], or WD pulsars [5,20]. All the current models fail to explain the entire spectral range of 4U 0142+61. That problem is not exclusive of 4U 0142+61, since no scenario presents a complete model for the SGR/AXPs class. In this context, we propose that the persistent emission of 4U 0142+61 comes from an accreting isolated WD surrounded by a debris disk, having gas and dusty regions. This scenario is inspired by the periodic flux modulation and by the presence of mid-infrared emission, which is rare for NSs. In fact, apart from the SGR/AXP class in which only 1E 2259+586 and 4U 0142+61 have mid-infrared;[19,30], only three isolated NSs have detected mid-infrared: the radio pulsars Crab, Vela, and Geminga[6,27]. Thus, mid-infrared appears in about 0.3% of all isolated NSs. On the other hand, the presence of mid-infrared in WDs is quite common. Ref. 7 found that about 7% of all isolated WDs presents mid-infrared excess detected by *WISE*, which reinforces the WD origin for 4U 0142+61. This proceedings presents a study of 4U 0142+61 emission in the context of a WD nature. It is organized as follows. In section 2, we describe the WD accreting model we use to fit 4U 0142+61 data. In section 3, we show the spectral fit of 4U 0142+61. In section 4, we summarize our findings.

2. An accreting WD model for 4U 0142+61

We propose that the components of 4U 0142+61 persistent emission are the WD photosphere, a disk, and an accretion column. The disk is formed by a dusty external region and a gaseous internal region. The dusty disk is optically thick and emits such as a multi-temperature blackbody. The temperature of its inner radius is the grain sublimation temperature, which is about 1500 K for silicates. Conversely, the internal gaseous disk is optically thin and its emission can be neglected. The inner radius of the gaseous disk is equal to the magnetosphere radius. From that point on, the matter flows into the WD surface following the magnetic field lines and the debris disk ceases to exist.

Close to the WD photosphere, the in-falling flow of matter produces a shock, forming an extremely hot region, the so called post-shock region that emits bremsstrahlung. About half of that energy reaches the WD surface, where it is reprocessed, forming a hot spot. Once the high-energy emission for 4U 0142+61 is pulsed, with two peaks per phase, we assume that there are two accreting regions. Thus, we can express the total flux by:

$$F_{total} = F_{disk} + F_{wd} + F_{spot} + F_{brem}. \tag{1}$$

The WD photosphere (F_{wd}) and the hot spots (F_{spot}) emit as blackbodies, in which the intensity for a given wavelength λ and temperature T is the Planck function, $B(\lambda, T)$, whereas the post-shock region emits by thermal bremsstrahlung (F_{brem}). According to Ref. 21, the bremsstrahlung emitted power is:

$$P(\lambda, T_{brem}) = 2.051 \times 10^{-22} g_{ff} n_e^2 \lambda^{-1} T_{brem}^{-1/2} exp\left(\frac{-143.9}{\lambda T_{brem}}\right). \tag{2}$$

Assuming that the region is cylindrical, with a height H_{brem}, the optical depth of the bremsstrahlung emission, τ_{brem}, is:

$$\tau_{brem} = \frac{H_{brem} P(\lambda, T_{brem})}{4\pi B(\lambda, T_{brem})}. \tag{3}$$

Assuming that the radius is R_{brem}, and the electron number density is n_e, the flux of the bremsstrahlung emission can be written as

$$\begin{aligned} F_{brem}(n_e, R_{brem}, H_{brem}, T_{brem}, d) = \\ = (1 - e^{-\tau_{brem}}) B(\lambda, T_{brem}) \pi \left(\frac{R_{brem}}{d} \right)^2. \end{aligned} \tag{4}$$

At last, we have the multi-temperature disk component (F_{disk})[4]:

$$\begin{aligned} F_{disk}(\nu, T_{in}, T_{out}, T_{wd}, R_{wd}, d) = 12\pi^{1/3} \cos(i) \left(\frac{R_{wd}}{d} \right)^2 \\ \times \left(\frac{2kT_{wd}}{3h\nu} \right)^{8/3} \left(\frac{h\nu^3}{c^2} \right) \int_{x_{in}}^{x_{out}} \frac{x^{5/3}}{e^x - 1} dx. \end{aligned} \tag{5}$$

In this equation, $x = h\nu/kT$, where T is the debris disk temperature, which ranges from T_{out} to T_{in} and T_{wd} is the WD effective temperature. The model, as well as the parameters for each flux component, are described thoroughly in Ref. 2.

3. Fitting 4U 0142+61 SED

As the model parameters for each spectral region are not the same, we opted to fit spectral regions separately. To fit the SED of 4U 0142+61, we use the data presented in Figure 1. These data are dereddened and deabsorbed. We have used Markov Chain Monte Carlo MCMC -[14] to estimate the parameters and their uncertainties. The results are shown in Table 1 and Figure 1. We consider a distance of 3.78 kpc[2] and $N_H = 6.4 \times 10^{21}$ cm^{-2}.[9]

The fit quality of the hard X-rays increases for high bremsstrahlung temperatures, which can only be achieved for near-Chandrasekhar white dwarfs. We adopt a WD having mass of 1.41 $M_\odot$ and radius of 1021 km[3]. This corresponds to a bremsstrahlung temperature of 674.5 keV, which was considered as a fixed parameter.

After modelling the hard X-rays, we find the best fit for soft X-rays. The bremsstrahlung component is also included in the fit of the soft X-ray SED. To be consistent with the double peak in the soft X-rays light curve, we use two blackbodies components, which can have different temperatures and radii.

To fit the optical and infrared emission, we use the WD photosphere blackbody and the debris disk. The high-energy components are included in the fit and the tail of bremsstrahlung component from the post-shock region also contributes to the optical emission as shown in Figure 1. The flux of the disk is given by Eq. (5). We use the same values of R_{wd} derived from the bremsstrahlung fit.

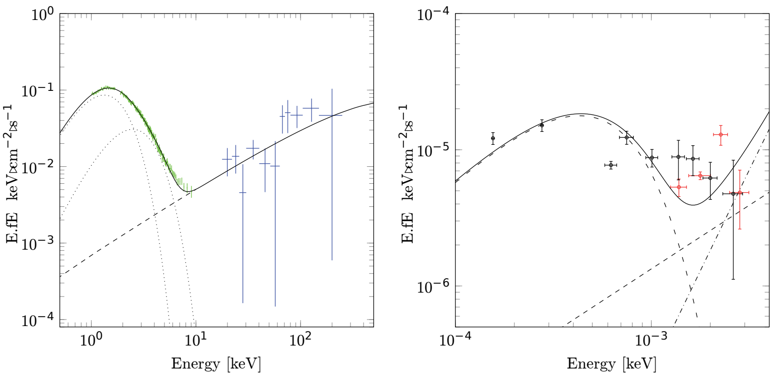

Fig. 1. Derreddened and deabsorbed SED of 4U 10142+61 along with the best fit. The continuous black curve is the complete fit, the long-dashed curve is the disk component, the dot-dashed curve is the WD photosphere, the two dotted curves are the hot spots components, and the short-dashed curve is the bremsstrahlung component. The black crosses are the data in low-energies used to fit the model and are from *Spitzer* (mid-infrared)[30], *Gemini* (near-infrared)[10] and *GTC* (optical)[22]; green crosses represent the soft X-ray data from *Suzaku*[11]; the blue crosses are the *INTEGRAL* data. *Left-bottom panel:* Zoom at the high-energy end. *Right-bottom panel:* Optical and infrared region. The red data[15,16] is displayed for comparison.

4. Conclusions

We obtained a good fit for the entire SED of 4U 0142+61. The optical/infrared emission of 4U 0142+61 comes from the WD itself and from the debris disk with a non-negligible contribution from the low-energy tail of the post-shock region. The hard X-rays is emitted by the accretion column and the soft X-rays by two hot spots in the WD photosphere.

The hard X-rays bremsstrahlung implies a near-Chandrasekhar WD, assumed to have a mass of 1.41 $M_\odot$ and a radius of 1021 km. Moreover, from the optical/infrared emission, we obtain an WD effective temperature of 9.4×10^4 K. Those radius and temperature point out to an young WD. The inner and outer disk temperatures are 1 991 K and 285 K.

In short, we were able to present a model that explains all the quiescent emission of 4U 0142+61, as well as the observed spin-down. Such a WD can be understood as the result of a recent merger of two less massive WDs.

Table 1. Parameters of the fitting of 4U 0142+61 in the accreting WD model.

Parameter	Description	Value
	X-rays	
	FIXED PARAMETERS	
d	distance of 4U 0142+61	3.78 kpc
N_H	columnar density of hydrogen	6.4 10^{21} cm^{-2}
T_{brem}	temperature of the emission for the accretion column	674.5 keV
M_{WD}	WD's mass	1.41 $M_\odot$
R_{WD}	WD's radius	1,021 10^5 cm
	FITTED PARAMETERS	
$\dot{M}$	accretion rate	3.43 10^{17}g s^{-1}
R_{brem}	radius of the hard X-ray emission	14.03 10^5 cm
H_{brem}	height of the accretion column	1.27 10^5 cm
n_e	electrons number density	2.05 10^{19} cm^{-3}
χ^2_{brem}/dof	reduced chi square for the hard X-rays	0.85
T_{spot1}	temperature of the spot 1	0.632 ± 0.033 keV
R_{spot1}	radius of the spot 1	2.35±0.45 10^5 cm
T_{spot2}	temperature of the spot 2	0.337±0.012 keV
R_{spot2}	radius of the spot 2	13.83±0.73 10^5 cm
χ^2/dof	reduced chi square for the soft X-rays	1.06
	Optical/Infrared	
	FITTED PARAMETERS	
T_{WD}	WD's effective temperature	9.4±7.3 10^4 K
T_{in}	inner temperature of the debris disk	1,991±16 K
T_{out}	outer temperature of the debris disk	285 ± 200 K
R_{in}	inner radius of the debris disk	2.35 ± 0.03 $R_\odot$
R_{out}	outer radius of the debris disk	31^{+127}_{-16} $R_\odot$

Note. The fixed parameters were derived before the fit by independent methods. For the infrared/optical fit all the X-rays parameters are considered fixed, therefore, R_{wd} is not a fitted parameter for this range of energy. The 1σ uncertainties for the last digit for the fitted parameters are in parenthesis.

Acknowledgments

We acknowledge T. Enoto for kindly provide us with Suzaku soft X-ray data of 4U 0142+61.

The authors thank the grant #2013/26258-4, São Paulo Research Foundation (FAPESP). CVR acknowledge CNPq (Proc. 303444/2018-5). JGC is likewise grateful to the grant #2013/15088-0, São Paulo Research Foundation (FAPESP), and CNPq (Proc. 421265/2018-3 and 305369/2018-0). MC acknowledges financial support under grant #2015/25972-0 from São Paulo Research Foundation (FAPESP).

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