A Magnetic White Dwarf Accretion Model for the Anomalous X-Ray Pulsar 4U 0142+61

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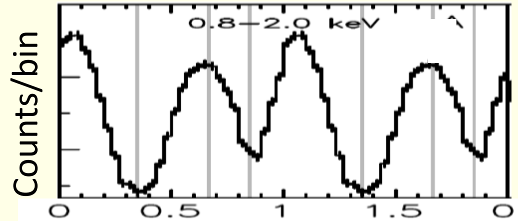
Abstract: The quiescent emission of the anomalous X-ray pulsar (AXP) 4U 0142+61 extends over a broad range of energy. Despite the many propositions to explain this wide range of emission, it still lacks one that reproduces all the observations. Filling this gap, we present a model to reproduce the quiescent spectral energy distribution of 4U 0142+61 from mid-infrared up to hard X-rays. In this model, the persistent emission comes from a magnetic accreting white dwarf (WD) surrounded by a debris disk. This model assumes that (i) the hard X-rays are due to the bremsstrahlung emission from the postshock 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 postshock region emission. In this scenario, the fitted model parameters indicate that 4U 0142+61 harbors a fast-rotator magnetic near-Chandrasekhar WD, which is very hot and hence young. Such a WD can be the recent outcome of a merger of two less massive WDs.

Introduction:

Anomalous X-ray pulsars (AXPs) and Soft Gamma-Ray Repeaters (SGRs) are currently considered the same class of objects, only differing in the way they are discovered. AXPs are primarily identified by a quiescent soft X-ray emission with a luminosity of about 10^{33} erg/s, whereas SGRs are identified due to the energetic outburst events. SGR/AXPs are observationally characterized by a quiescent soft X-ray (2–10 keV) luminosity in the range 10^{30}–10^{35} erg/s, a period of 2–12 s, and spin-down of 10^{-15} - 10^{-10} $s.s^{-1}$ (see Olausen & Kaspi 2014). In an outburst, the energy can reach 10^{43} erg. Some AXPs/SGRs also present quiescent emission in other ranges (radio, infrared, optical, and hard X-rays), as well as soft gamma-ray flare events. The most accepted scenario to explain SGR/AXPs is the magnetar model. In this model, the quiescent emission and the outbursts and flare events are described by the decay of a huge dipole magnetic field above the quantum limit. Nonetheless, the model presents some limitations, such as the existence of low magnetic field SGR/AXPs, which raised the interest for alternative models. Some examples are the neutron star (NS) accreting scenario and the white dwarf (WD) pulsar model. In this poster, we present a new scenario evoking an accreting WD to explain the AXP 4U 0142+61.

4U 0142+61:

The AXP 4U 0142+61 presents quiescent emission in a broad range of energy, from radio (Malofeev et al. 2010) to hard X-rays (den Hartog et al. 2008). This object is unique among SGR/AXPs in presenting simultaneously mid-infrared (mid-IR) and pulsed optical emissions. Its period is 8.68 s, and the spin-down is around 2.0×10^{-12} $s.s^{-1}$ (Olausen & Kaspi 2014). The outbursts and glitches in 4U 0142+61 are less energetic compared to the bulk of SGR/AXP bursts (Göğüş et al. 2017). No flare has been observed in 4U 0142+61 so far (Olausen & Kaspi 2014). In the picture below, we present the periodic pulsed profile in soft X-rays.



Pulsed profile of 4U 0142+61 in the 0.2 -8 keV range. Adapted from den Hartog et al. 2008

Issues within the magnetar model:

Existence of Low-B sorces

One of the most significant proofs of the magnetar model is the estimated dipole magnetic field from the timing parameters (see equation below). The results pointed out to magnetic fields for SGR/AXPs higher than the quantum limit (>4.4 × 10^{13} G). Nonetheless, in the last decade, the discovery of low-B sources—SGR 0418+5729, Swift J1822.3–1606, and 3XMM J185246.6+003317 (Rea et al., 2010; Livingstone et al., 2011; Zhou et al. 2014) - put a question into the model. Additionally, this magnetic field is estimated considering a dipole configuration, which is probably not true (de Lima et al., 2020; Bilous et al., 2019). Pétri, (2019) states that the magnetic field of all SGR/AXPs can be smaller than the quantum limit depending on the considered configuration. Thus, the estimate of the magnetic field using the dipole equation is an illusion, which also raises doubts on the magnetar model.

$$B_d = \left(\frac{3c^3 I}{8\pi^2 R^6} P\dot{P}\right)^{1/2} > 4.4 \times 10^{13} G$$

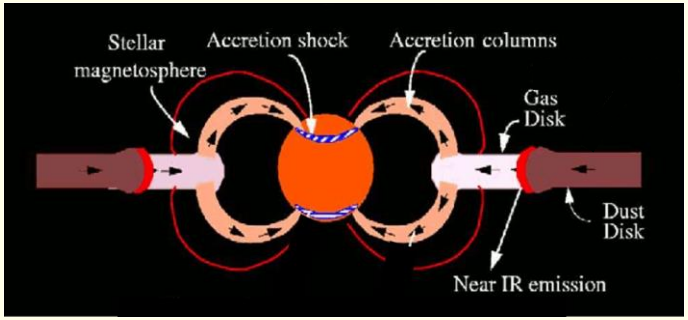
Presence of Infrared emission

Only three isolated NSs have detected mid-IR: the radio pulsars Crab, Vela, and Geminga (Sandberg & Sollerman 2009; Danilenko et al. 2011). Among AXPs/SGRs, only two have mid-IR emission, 1E 2259+586 (Kaplan et al. 2009), and 4U 0142+61 (Wang et al. 2006). Thus, mid-IR appears in about 0.3% of all isolated NSs. On the other hand, the presence of mid-IR in WDs is quite common. Debes et al. (2011) found that about 7% of WDs present an excess of mid-IR. Furthermore, the presence of a dusty disk to explain the mid-IR in 4U 0142+61 is widely accepted for the NSs proposed models (Wang et al., 2006; Ertan et al., 2007). Nonetheless, the presence of disks around isolated NSs is still question for debate. Protoplanetary disk is one possible origin of the planetary system around the PSR B1257+12 (Wolszczan & Frail 1992; Miller & Hamilton 2001). Also, fallback disks are raised as one possibility to explain the observed braking index smaller than 3 (Menou et al., 2001). However, no isolated NS has confirmed debris disk. On the other hand, at least 27% of WDs presents traces of high elements that only could be explained by the accretion of material from planetary discs (Koester et al. 2014). All these arguments reinforce a WD nature for 4U 0142+61

Features of the accreting WD model:

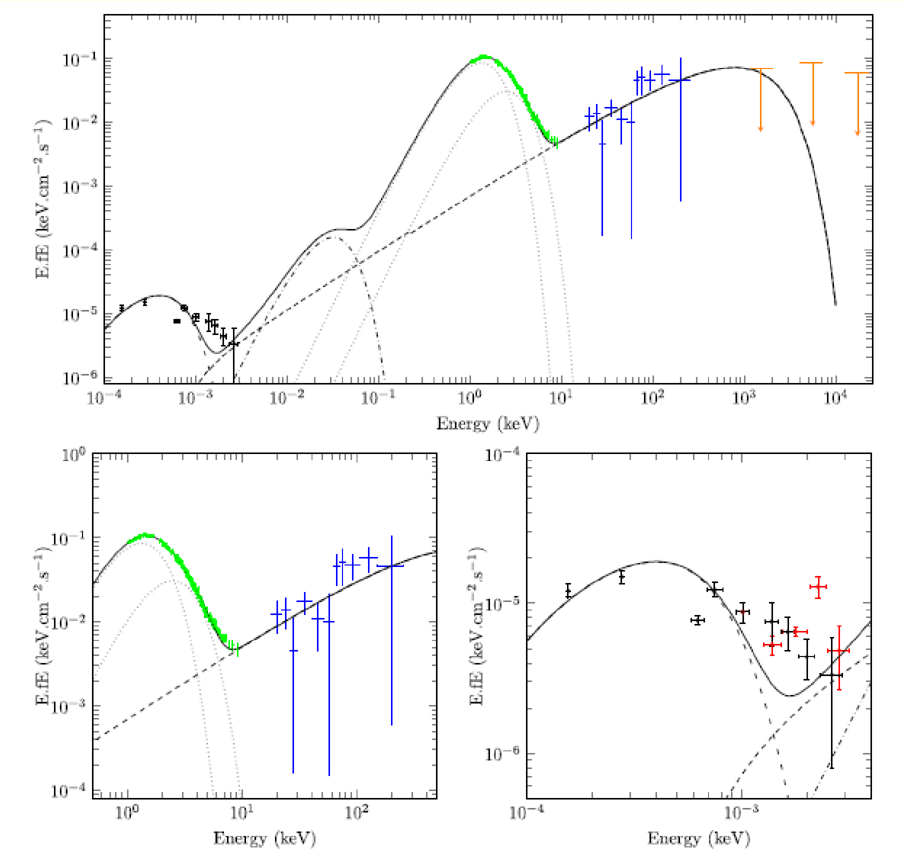
The persistent emission of 4U 0142+61 comes from the WD photosphere, a disk, and a magnetic accretion column. This scenario is inspired by (i) the periodic flux modulation, which could be explained by an accretion column, and (ii) the detected IR emission and silicate line emission, which indicate the presence of a disk. Below, we present the components of the model and a schematic figure.

- **White Dwarf photosphere**: blackbody ;
- **Debris Disk:**
  - **dusty region** - optically thick emitting as a multi-temperature blackbody
  - **Gaseous region** - optically thin. Inner radius equal to the magnetosphere radius. For that point on, the matter flows into the white dwarf's surface following the magnetic field lines and the debris disk ceases to exist;
- **Accretion Structure:**
  - **post-shock region:** the in-falling flow of matter suffers a shock, forming this extremely hot region emitting as bremsstrahlung;
  - **hot spot:** half of that post-shock emission is emitted inwards, reaches the white dwarf surface where it is absorbed and reflected as blackbody.



Schematic model of the scenario. Adapted from Hartmann, 2009

The Results:



Dereddened and deabsorbed spectral energy distribution (SED) of 4U 10142+61, along with the best fit. The solid black curve is the complete fit, the long-dashed curve is the disk component, the dotted–dashed curve is the WD photosphere, the two dotted curves are the hot-spot components, and the short-dashed curve is the bremsstrahlung component. The black crosses are from Spitzer (mid-IR; Wang et al. 2006), Gemini (near-IR; Durant & van Kerkwijk 2006a), and GTC (optical; Muñoz-Darias et al. 2016). Green crosses represent the soft X-ray data from Suzaku (Enoto et al. 2010), the blue crosses are the INTEGRAL data and the orange upper limits in gamma-rays are from COMPTEL (den Hartog et al. 2008). Top panel: entire spectral range, from mid-IR up to gamma-rays. Bottom left panel: zoom at the high-energy end. Bottom right panel: optical and IR region. The red points represent the measurements from Hulleman et al. (2000, 2004).

X-rays:

We used the Markov Chain Monte Carlo (MCMC) method to estimate the parameters and their uncertainties. The adopted figure of merit is the ratio between $\chi 2$ and the degrees of freedom (dof). The fit quality of the hard X-rays increases with the bremsstrahlung temperature. The highest temperature we can reach for the limiting mass of 1.41 Msun and radius of 1021 km (Carvalho et al. 2018) is 674.5 keV, which results in a $\chi 2/\mathrm{dof} = 0.84$ for the hard X-ray emission. In the soft X-rays, to increase the quality of the fit, we used two blackbody components, which can have different temperatures and radii. The results are 0.632 ± 0.033 keV 2.35 ± 0.45 km, for spot 1, and 0.337 ± 0.012 keV 13.83 ± 0.73 km, for spot 2.

WD photosphere:

The temperature of the WD photosphere for 4U 0142+61 in our model is $9.4 \pm 7.3\times10^4$ K, which is high for a WD. Nonetheless, Werner & Rauch (2015) presented two hotter WDs, H1504+65 (2.0×10^5 K) and RX J0439.8–6709 (2.5×10^5 K). Furthermore, considering this temperature, we can estimate a cooling age of 5.5 Myr.

Debris disk:

The debris disk's outer and inner temperatures are 285 ± 200 K and 1991 ± 16 K, respectively. The latter is larger than the silicate sublimation temperature (Ts) of about 1300–1500 K (Lodders, 2003). However, Ts is based on solar abundance and mainly used to model protoplanetary disks of young stars, which can present differences in respect to the disk of isolated WDs. In fact, other WDs have disks inner temperatures higher than 1500 K, such as HE 1349 −2305 (Girven et al. 2012), with an inner temperature of 1700 K.

Estimated Magnetic field:

From the timing parameters, we estimate a magnetic field of $2.82\times 10^7\mathrm{G} < B < 5.63\times10^7\mathrm{G}$, which is consistent with the magnetic field of cataclysmic variables. For instance, intermediate polars have magnetic fields of ~4–30 MG, with the highest value of ~32 MG for V405 Aur (Ferrario et al. 2015).

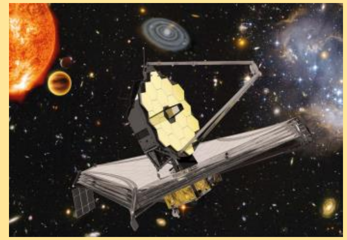
A thought about radio emission and bursts:

We can propose possible origins for the radio emission of 4U 0142+61 in our model based on the radio emission in other accreting WDs systems. According to Barrett et al., (2017), 21 out of 121 magnetic CVs have detected radio emission. The suggested emission models are gyrosynchrotron, for the weakly polarized radio emitters, and electron–cyclotron maser emission, for highly polarized sources. Since the polarization of the radio emission of 4U 0142+61 is not known, both interpretations are possible. Moreover, the bursts can be explained in terms of a Near-Chandrasekhar WD presenting sudden changes in the spin, thereby decreasing the core's centrifugal forces. Consequently, gravity would make the WD less oblate, which would lead to a change in the gravitational energy and consequent release of energy (Usov, 1994).

A WD-WD Merger origin for 4U 0142+61:

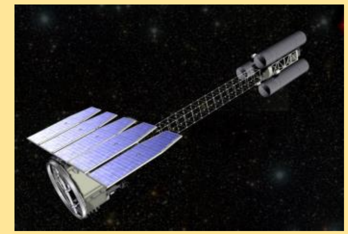
4U 0142+61 is a fast-spinning, isolated, magnetic, hot, and extremely massive white dwarf. Thus, based on those features, the most plausible origin is the merger of two less massive CO white dwarfs. In this case, the remnant consists of a cold-core formed by the former primary, a hot envelope made by a percentage of the secondary mass, and a Keplerian disk containing the rest of the secondary (Becerra et al. 2018). Once the newborn white dwarf is very fast (Yoon et al., 2007), we expect that it initially would pass trough a propeller phase. Once this propeller regime causes a high spin-down, the period and the co-rotational radius tend to increase, thus enabling the white dwarf to accrete matter from the disk.

What is next?



An IR spectroscopy with James Webb Space Telescope (left) will be a valuable tool to confirm the disk presence on 4U 0142+61 and its origin. For instance, in an NS scenario, the disk is thought to be formed by a supernova event's leftover. Thus, an spectroscopy would contain features of iron, silicon, oxygen, helium, and traces of hydrogen (Lin, Woosley & Bodenheimer, 1991).

The first generation of X-ray polarimeters, such as the Imaging X-ray Polarimetry Explorer (right), will also differentiate between different models. For instance, considering quantum electrodynamics effects, polarization will be nearly 100% in the magnetar model, whereas for accreting WDs, the highest expected linear polarization level is about 8% (McNamara et al., 2008).



Conclusion:

We obtain a good fit for the entire SED of 4U 0142+61, considering accreting isolated white dwarf surrounded by a debris disk, having a gaseous and a dusty region. The emission from the hard X-ray implies a near-Chandrasekhar WD, for which we assume a mass of 1.41 Msun and a radius of 1021 km. From the fit of the optical/IR emission, we obtain a WD effective temperature of 9.4 10^4 K, pointing to a young WD of a few Myr. The gaseous disk has inner and outer temperatures of 1991 and 285 K, consistent with disks seen around WDs. We can estimate a magnetic field of 10^7 G from the spin-down rate, compatible with the values in magnetic WDs. The most plausible origin is the merger of two less massive WDs.

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