Neutron star radius measurement from the ultraviolet and soft X–ray thermal emission of PSR J0437–4715

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ABSTRACT

We analyzed the thermal emission from the entire surface of the millisecond pulsar PSR J0437–4715 observed in the ultraviolet and soft X–ray bands. For this, we calculated non-magnetized, partially ionized atmosphere models of hydrogen, helium, and iron compositions and included plasma frequency effects that may affect the emergent spectrum. This is particularly true for the coldest atmospheres composed of iron (up to a few percent changes in the soft X–ray flux). Employing a Markov chain Monte Carlo method, we found that the spectral fits favour a hydrogen atmosphere, disfavour a helium composition and rule out iron atmosphere and blackbody models. By using a Gaussian prior on the dust extinction, based on the latest 3D map of Galactic dust, and accounting for the presence of hot polar caps found in previous work, we found that the hydrogen atmosphere model results in a well-constrained neutron star radius \( R_{\text{NS}} = 13.6^{+0.9}_{-0.8} \) km and bulk surface temperature \( T_{\infty} = (2.3 \pm 0.1) \times 10^5 \) K. This relatively large radius favours a stiff equation of state and disfavours a strange quark composition inside neutron stars.

Key words: stars: neutron — stars: atmospheres — plasmas — pulsars: individual (PSR J0437–4715)

1 INTRODUCTION

The study of the thermal emission from neutron stars (NSs) is particularly relevant to understand their cooling history, determine their radii, and constrain the equation of state (EOS) of ultra-dense matter. In general, the thermal emission from NSs is expected to be reprocessed by an atmosphere, whose spectrum depends on the temperature gradient, surface composition, and magnetic field strength of the source. There already exists substantial literature dedicated to the effects of these parameters on the emergent spectra of relatively hot NS atmospheres, with temperature \( T > 10^6 \) K (for reviews, see e.g., Zavlin 2007; Özel 2013; Potekhin 2014).

The spectra of cooler NS atmospheres, in which plasma effects start to become important, have been less studied. However, these atmosphere models are relevant for analyzing the thermal emission from old NSs (ages > 10^8 yr), such as millisecond pulsars (MSPs), which have lost most of their thermal energy. Up to now, Hubble Space Telescope (HST) observations have revealed ultraviolet (UV) emission from two MSPs, PSR J0437–4715 (hereafter “J0437”; Kargaltsev et al. 2004; Durant et al. 2012) and PSR J2124–3358 (“J2124”; Rangelov et al. 2017), and from the middle-aged classical pulsar PSR B0950+08 (“B0950”; Pavlov et al. 2017). In all three cases, the interpretation of the thermal spectrum as blackbody (BB) emission yields bulk surface temperatures around 10^5 K, whereas an upper limit of 4 \times 10^4 K was inferred from the non-detection of the old, very slow pulsar PSR J2144–3933 (Guillot et al. 2019).

More realistic estimates of the surface temperature of these objects, using atmosphere models, will help to distinguish between different possible heating mechanisms in old NSs (Gonzalez & Reisenegger 2010). This would in turn provide constraints on NS internal parameters, such as the superfluid energy gaps, which regulate the strength of these mechanisms (Petrovich & Reisenegger 2010, 2011; González-Jiménez et al. 2015).

Furthermore, J0437 and J2124, as well as PSR J0030+0451 (“J0030”), are among the targets of the Neutron Star Interior Composition Explorer (NICER) mission (Gendreau et al. 2016; Gendreau & Arzoumanian 2017). NICER aims at measuring the mass \( M_{\text{NS}} \) and radius

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$R_{\text{NS}}$ of these MSPs through the effect of gravitational light bending and other relativistic effects on their X-ray light curves produced by hot polar caps (Bogdanov 2013; Özel et al. 2016; Miller 2016). In fact, combined analysis of hydrogen (H) atmosphere models with XMM-Newton X-ray spectral/timing observations of the hot polar cap emission have permitted establishing some constraints on X-ray spectral/timing observations of the hot polar cap emission of hydrogen (H) atmosphere models with $R_{\text{NS}} > 7.8$ km (68% confidence, Bogdanov et al. 2008), $R_{\text{NS}} > 10.4$ km (99% confidence, Bogdanov & Grindlay 2009) and $R_{\text{NS}} > 10.9$ km (3σ, confidence, Bogdanov 2013), respectively. In light of upcoming NICER analyses, it is therefore important to characterize the atmospheric properties of MSPs (e.g., composition and temperature) as accurately as possible to establish further constraints on the properties of these sources.

We model non-magnetized, partially ionized NS atmospheres for temperatures down to $\sim 10^{4.5}$ K, and fit them to the UV and soft X-ray spectra of J0437. Besides being the main target for NICER, J0437 is the brightest and nearest MSP, with a precisely measured distance $d = 156.79 \pm 0.25$ pc (Reardon et al. 2016). In addition, it is in a 5.74 day binary orbit with a helium-core white dwarf companion (Bailyn 1993), allowing for a precise radio-timing measurement of the pulsar mass, $M_{\text{NS}} = 1.44 \pm 0.07 M_\odot$ (Reardon et al. 2016). The white dwarf has an effective temperature of 3950$\pm$150 K (Durant et al. 2012), making it very unlikely to contribute significantly to the UV emission of the system. The spin period of J0437, $P = 5.76$ ms, and its spin-down rate, $\dot{P} = 5.73 \times 10^{-20}$ s$^{-1}$, imply a large spin-down age (after kinematic corrections), $\tau = P/2 \dot{P} = 6.7$ Gyr, and a weak dipole magnetic field, $B = 2.8 \times 10^8$ G.

The X-ray spectrum of J0437 is composed of two thermal components from the pulsar’s hot polar caps (Zavlin & Pavlov 1998), generally fitted with a pair of NS atmosphere components (with $T \sim 10^9$ K), and a non-thermal component fitted with a power-law (Zavlin et al. 2002). Because of its proximity, J0437 is also the only MSP for which the $\sim 10^9$ K thermal emission from the entire pulsar surface is detectable in the soft X-ray range below $\sim 0.4$ keV. This third (cool) thermal component is clearly seen in the UV (Kargaltsev et al. 2004; Durant et al. 2012), but it was poorly constrained in studies that only considered the X-ray data, due to uncertain contributions of a non-thermal component (Bogdanov 2013). This is because the mild excess below $\sim 0.4$ keV in the XMM data could be compensated by a soft power-law. More recent work used NuSTAR observations to better constrain the high-energy tail (at $\gtrsim 4$ keV), which lifted ambiguities with the spectral modeling at lower energies ($\lesssim 0.4$ keV). Combined ROSAT, XMM-Newton and NuSTAR spectral analysis confirmed the presence of this third thermal component (with $T \sim 10^5$ K, fitted with a BB), which was interpreted as the thermal emission coming from the entire surface (Guillot et al. 2016).

However, only the Wien tail of this cool surface emission is detected in the soft X-ray regime. Therefore, its minimal contribution to the X-ray flux in the 0.1–0.5 keV range, affected by absorption due to the interstellar medium, and dominated by the hotter thermal components, prevented precisely determining the surface temperature and emitting area (i.e., the NS radius). In addition to the evidence for the cool thermal emission in the soft X-rays, J0437 is also the only pulsar for which one can precisely determine, thanks to the pulsar’s proximity, the slope of this emission in the UV band with spectroscopic observations (Kargaltsev et al. 2004; Durant et al. 2012).

This paper aims at obtaining better constraints on the cool thermal emission of J0437 by combining the UV and soft X-ray observations. We model and apply realistic NS atmosphere models, for various compositions, to the UV data from HST and soft X-ray data from ROSAT. The organization of the article is as follows. In Section 2, we describe the theoretical framework to compute the emergent spectrum from a NS atmosphere, and how we introduce the plasma effects. In Section 3, we verify the accuracy of our models and investigate their properties, particularly the plasma effects. In Section 4, we confront our atmosphere models for different compositions to the observed UV to soft X-ray spectral energy distribution of J0437. A summary of our main conclusions and the discussion are given in Section 5.

2 THEORETICAL FRAMEWORK

Substantial literature on both magnetic and non-magnetic NS atmosphere models already exists (for reviews see Zavlin 2007; Özel 2013; Potekhin 2014). In particular, spectra from non-magnetized, passively cooling NSs are usually obtained via the computation of the atmosphere structure coupled with either: a) the Milne integral (Romani 1987; Rajagopal & Romani 1996; Fons et al. 2002), b) the radiative transfer equation in the form of a second-order boundary problem (Zavlin et al. 1996; Heinke et al. 2006; Suleimanov & Werner 2007; Haakonsen et al. 2012), or c) the radiative transfer equation using the Rybicki method (Gänsicke et al. 2002).

2.1 Neglect of magnetic effects

The criteria to establish whether non-magnetized atmospheres are suitable for analyses of the thermal emission from different classes of NSs consider the temperature, spectral energy range, and magnetic field strength of the source. Basically, a magnetic field changes the properties of the atmosphere in two ways: by modifying the energy levels of the atoms, which changes the bound-bound and bound-free opacities, and by modifying the dynamics of free electrons with kinetic energy below the electron cyclotron energy, which changes the free-free opacities. Considering the electron cyclotron energy $E_c = hB/m_e c \approx 1 B_8$ eV, magnetic fields are negligible for the bound-bound and bound-free opacities if the ratio $E_c/Z^2 R_y \sim 0.1 B_8 Z^{-2} \ll 1$, where $Z$ is the atomic number, $R_y = 13.6$ eV is the Rydberg energy, and $B_8 = B/10^8$ G. Similarly, for the free-free opacities, magnetic fields are negligible if the ratio $E_c/k_B T \sim 0.1 B_8 T_5 \ll 1$, with $T_5 = T/10^5$ K, or the spectral energy range of interest is above the electron cyclotron energy, $E \gg E_c \approx 1 B_8$ eV.

Spectra for **fully ionized** atmosphere models of NSs with different field strengths have been reported, for example, in Figure 2.7 of Lloyd (2005). In particular, for the lowest temperature considered in that work, log$(T/K) = 5.6$, the spectrum for $B = 10^8$ G is indistinguishable from that of a non-magnetic NS. As also shown in the same figure, the magnetic field produces an absorption feature around the
electron cyclotron energy. In the case of J0437, the magnetic field is $B_{\text{J0437}} \approx 2.8$, the associated electron cyclotron frequency is $\log(E_{\text{e}}/\text{keV}) = -2.6$, and we will fit the spectrum to UV data well above this value, for $\log(E/\text{keV}) > -2.2$, finding typical temperatures $T_\text{\mu} \sim 3$.

Depending on the composition, partially ionized atmospheres show absorption features at different energies. In particular, the H atmosphere spectrum has a Lyman alpha absorption feature at $E = 12.13 \text{ eV}$, which, depending on the NS gravitational redshift, can be within the range of the ultraviolet HST observations. Magnetic fields such as those present in MSPs are strong enough to induce a large Zeeman effect, i.e., the splitting of the Lyman alpha absorption feature into three separate components (see e.g., Kargaltsev et al. 2004). These are expected to be washed out in the measured, phase-averaged spectrum, because the latter combines radiation from different parts of the NS surface, where the magnetic field strength and direction are expected to be very different, thus placing the absorption components at different wavelengths. Therefore, we will ignore the presence of the magnetic field in our atmosphere model calculations. For the spectral fitting of J0437 (Section 4.2), we eliminate the Lyman alpha absorption feature from the spectra of the H atmosphere models by linearly interpolating through the spectral range covered by this feature.

Another important effect of magnetic fields on NS atmospheres is that they can suppress convective instabilities. As shown by Rajagopal & Romani (1996), a pure iron (Fe) atmosphere with $T \sim 10^7 \text{ K}$ is unstable to convective motion in zones of the atmospheres with optical depths $\tau \sim 0.1-1.0$, which could modify the temperature gradient of the atmosphere and produce a dramatic effect in the emergent spectra. However, they also showed that a magnetic field $B \gtrsim 10^8 G$ can suppress this instability and, therefore, it should not be present in the atmospheres of MSPs. Consistently, our models do not include convection.

### 2.2 Atmosphere model calculations

We use our own new code based on the iterative scheme discussed in Romani (1987, see also Rajagopal & Romani 1996; Pons et al. 2002) to simultaneously calculate the atmosphere structure and the spectral energy distribution via the Milne integral, for the case of unmagnetized NSs with low temperatures. It imposes that the NS atmosphere is in hydrostatic and radiative equilibrium. The latter means that the radiative flux through the atmosphere is constant and there is no additional source of energy. Because the thickness of the atmosphere is much smaller than the radius of the star, the radiative transfer equation is solved in the plane-parallel approximation, assuming the atmosphere is in local thermodynamic equilibrium.

In order to determine the structure of the atmosphere, we solve the equation of hydrostatic equilibrium

$$\frac{dP}{d\tau_R} = \frac{\kappa_{\text{eff}}}{\kappa_R}$$

where $P$ is the pressure, $\kappa_R$ is the Rosseland mean opacity (defined later in equation 9) and $d\tau_R = \rho d\ell$, with $\rho$ and $\ell$ the density and physical depth of the atmosphere, respectively. Here, for a given mass $M_{\text{NS}}$ and coordinate radius $R_{\text{NS}}$, the gravitational acceleration $\ddot{\text{g}}_{\text{eff}} = (1+z)G M_{\text{NS}}/R_{\text{NS}}^2$ and the gravitational redshift $1+z = (1-2GM_{\text{NS}}/R_{\text{NS}}c^2)^{-1/2}$, where $G$ and $c$ correspond to the gravitational constant and the speed of light, respectively. For equation (1), we use the boundary condition $P(\tau_R = 0) = 0$ and an ideal gas equation of state, adding the pressure of degenerate electrons, which becomes relevant in the deepest zones of the atmosphere.

The problem is solved through successive iterations, starting from an initial temperature profile given by the solution for the gray atmosphere, $T_\text{eff} = (3/4) T_\text{eff}^4 (\Delta T + q)$, where $T_\text{eff}$ is the effective temperature and $q = 2/3$. Subsequently, we calculate the energy-dependent flux through the atmosphere. Since the absorptive opacity $\kappa_\text{sc} \sim 10^{-3} - 10^{-5} \text{ cm}^2 \text{ g}^{-1}$ is much larger than the electron scattering opacity $\kappa_{\text{sc}} \approx 0.1 - 0.2 \text{ cm}^2 \text{ g}^{-1}$, we neglect the electron scattering effects. In this way, the expression for the energy-dependent flux reduces to the Milne integral (Mihalas 1978),

$$F_E(\tau_E) = 2\pi \left[ \int_{T_E}^{\infty} S_E(\tau'_E) E_2(\tau'_E - \tau_E) d\tau'_E \right. $$

$$- \left. \int_{0}^{T_E} S_E(\tau'_E) E_2(\tau'_E - \tau_E) d\tau'_E \right] ,$$

where the source function $S_E(\tau)$ is just the Planck function,

$$E_2(\tau) = \int_{1}^{\infty} e^{-xt} t^2 dt$$

is the second exponential integral, and

$$\tau_E(\tau) = \int_{0}^{\tau_E} \frac{\kappa_E}{\kappa_R} d\tau'_R$$

gives the transformation from Rosseland mean to energy-dependent optical depths.

Finally, in order to obtain a specified, constant energy-integrated radiative flux through the atmosphere, $F = \sigma T_{\text{eff}}^4$, we apply the Lucy-Unsold correction to the temperature profile, which is given by

$$\Delta T(\tau) = \frac{1}{16 \sigma T(\tau)^4} \left[ \frac{\kappa_J}{\kappa_P} \left( 3 \int_{0}^{\tau} \frac{\kappa_E(\tau')}{\kappa_R(\tau')} \Delta F(\tau') d\tau' + 2 \Delta F(0) \right) - \frac{\kappa_R}{\kappa_P} d\Delta F(\tau) \right] ,$$

where $\Delta F$ is the departure from the specified, constant flux $F$. In the previous expression, the quantities

$$\kappa_J = \int_{0}^{\infty} \kappa_E J_E dE / J ,$$

$$\kappa_P = \int_{0}^{\infty} \kappa_E B_E dE / B ,$$

$$\kappa_F = \int_{0}^{\infty} (\kappa_E^2 + \kappa_{\text{sc}}^2) F_E dE / F ,$$

and

$$\frac{1}{\kappa_R} = \int_{0}^{\infty} \frac{1}{\kappa_E^2 + \kappa_{\text{sc}}^2} dE dE \left| \frac{dB}{dE} \right|$$

are the absorption mean, Planck mean, flux mean, and Rosseland mean opacities, respectively (Mihalas 1978). Here, $J$ and $B$ are the mean intensity and Planck function integrated in energy, respectively, and we approximate
$\omega_f = \omega p$. A relatively constant flux (error $\lesssim 1\%$) is reached in $\sim 15$ iterations. In this procedure, we take into account the corrections from General Relativity in the emergent spectrum. This means that the flux measured by an observer at distance $D$ is

$$F_E^\infty(E) = \frac{F_E([1 + z]E)}{1 + \frac{z}{\mu}} \left(\frac{R_{NS}}{D}\right)^2,$$

where $F_E([1 + z]E)$ is the flux at the NS surface.

In order to compute the emergent spectrum, we use 100 energy bins logarithmically spaced from $10^{-4}$ keV to 10 keV and a grid of 120 depth levels logarithmically spaced in Rosseland optical depth, $\tau_R$, from $10^{-3}$ to $10^3$. Once the proper atmosphere structure is iteratively obtained, the spectrum is calculated using a denser grid with 900 energy bins. We use the energy-dependent opacities and the Rosseland and Planck mean opacities for H, helium (He), and Fe from the Los AlamosOpacity Project\(^1\) (LANL; Magee et al. 1995), which include bound-bound, bound-free, and free-free transitions. The LANL opacity tables also provide the number of free electrons per nucleus for a given composition, temperature and density (for details about ionization calculations see Magee et al. 1995, and references therein). However, the tables do not cover completely the energy-dependent opacities for relatively low energies, $E \sim 10^{-4} - 10^{-2}$ keV. We complete this region using the free-free opacity, which is dominant\(^2\) in this range and is given, in CGS units, by Rybicki & Lightman (1979) as:

$$\kappa_{ff} = 3.7 \times 10^8 T^{-1/2} n_e^2 \sum_i n_i Z_i^2 e^{-1 - \frac{h\nu}{kT}} g_{ff}(\nu, T),$$

where $i$ labels the kind of ions, $Z_i$ is the charge of the ions, $n_i$ is the ion number density, and $g_{ff}$ is the Gaunt factor, also obtained from Rybicki & Lightman (1979).

\(^{1}\) http://phyapscics2.lanl.gov/cgi-bin/opacrun/tops txt.pl

\(^{2}\) This may not be strictly true for a heavy element composition, such as Fe atmospheres. However, we use the free-free opacity in an energy range with a relatively low radiative flux, where the atmosphere is optically thick, and the photosphere has a relatively small temperature gradient. This means that the emergent spectrum is largely unchanged by increasing the opacities, for example, due to additional bound-bound or bound-free transitions.

### 2.3 Plasma effects

In the UV range, the emergent spectrum can be affected by absorption features due to atomic transitions in this energy range, as well as by plasma effects. The latter can be seen through the standard expression for the plasma frequency

$$\omega_p = \left(\frac{4\pi^2 n_e}{m_e}\right)^{1/2},$$

where $-e$ is the electron charge, $n_e$ is the electron number density, and $m_e$ is the electron mass. This frequency can be estimated by combining the equation of hydrostatic equilibrium (Equation 1) with an ideal gas equation of state $P = nk_BT$, where $n$ is the particle density and $k_B$ is the Boltzmann constant, yielding $n \sim \rho_{eff}\gamma/(k_B T)$. Assuming $n_0 \sim n$, an optical depth $\tau \sim 1$, a H Rosseland mean opacity $\kappa_R \sim 10^4 \text{cm}^2\text{s}^{-1}$, and an effective surface gravity $g_{eff} \sim 10^{14} \text{cm}^2\text{s}^{-2}$, we obtain $h\omega_p \sim 4\pi^2\kappa_{eff}\gamma/(n_0 k_B T)$, which is close to the UV range and therefore may affect the analysis of HST observations of cool NSs.

In a plasma, the dispersion relation connecting the wave number, $k$, the frequency, $\omega$, and the plasma frequency, $\omega_p$, is given by:

$$\omega = \left(\omega_p^2 + \frac{c^2 k^2}{\omega_p^2}\right)^{1/2},$$

where $c$ is the speed of light. Since for $\omega < \omega_p$ the wave number becomes imaginary, $\omega_p$ defines a cutoff frequency below which there is no electromagnetic wave propagation in the plasma. Aharony & Opher (1979) showed that, for $\omega > \omega_p$, the frequency-dependent opacities $\kappa_\omega$ should be replaced by:

$$\kappa_\omega \rightarrow \frac{\kappa_\omega}{1 - (\omega_p/\omega)^2}.$$
3 MODEL COMPARISON AND RESULTS

In order to test our atmosphere calculation code, we generate spectra for different temperatures and compositions and compare them with the spectra of Pons et al. (2002) for H and He atmospheres with temperatures ranging from $T_{\text{eff}} = 10^{4.0}$ to $10^{6.2}$ K, and for Fe atmospheres with effective temperatures ranging from $10^{5.0}$ to $10^{6.0}$ K. Like the present work, Pons et al. (2002) follow a standard technique to model the NS atmosphere (Romani 1987; Rajagopal & Romani 1996) and compute the emergent spectrum using the LANL opacities. The main differences are that their calculations consider only 200 energy bins, compared to 900 in our case, and cover the range of Rosseland optical depths $10^{-2} < \tau_R < 10^{-2}$, whereas we used $10^{-3} < \tau_R < 10^{-2}$ for the comparison and $10^{-2} < \tau_R < 10^{-1}$ for all other calculations. The range $10^{-3} < \tau_R < 10^{-2}$, which we do not cover, does not make a significant difference because very few photons are emitted or absorbed in this region. Including the interval $10^{-2} < \tau_R < 10^{-1}$, on the other hand, slightly increases the flux in the high-energy tail (worsening the agreement with Pons et al. 2002, as expected), but does not noticeably affect most of the spectrum.

Figure 1 shows that the emergent spectra for H, He, and Fe composition calculated with both codes do not show substantial differences. In particular, for $T_{\text{eff}} = 10^{5.0}$ K, the fractional difference in the UV range, $-2.0 \lesssim \log(E/\text{keV}) \lesssim -1.3$, is always < 2%. The largest differences likely originate in the width of the energy bins (wider in the work of Pons et al. 2002), which do not fully resolve the absorption lines. The agreement is much better in regions away from these lines. We also compare our Fe spectra with those of Rajagopal & Romani (1996) finding no significant differences.

We compute spectra for pure H, He, and Fe atmospheres with and without plasma effects. The plasma frequency has the largest impact on the high energy (Wien) tail of the spectrum of the coldest Fe atmosphere model, but far from the flux peak.

which is tabulated in the LANL opacity tables for a given composition, temperature, and density. Figure 2 shows that the energy associated with the plasma frequency, $\hbar \omega_p$, is always substantially below the peak of the spectra $\sim k_B T$. Since most of the flux is produced at energies $E \sim (1-10) k_B T$, plasma effects block an insignificant part of the photon flux. This means that plasma frequency effects do not produce a
significant change in the temperature profile and the structure of the atmosphere.

In addition, Figure 3 shows that the plasma frequency effects change the spectra just slightly below $E \sim 10^{-2}$ keV and above $E \sim 10^{-1}$ keV for all effective surface temperatures considered. The flux below $E \sim 10^{-3}$ keV is reduced because low energy photons are blocked at relatively low Rosseland optical depths. Instead, the flux increases above $E \sim 10^{-1}$ keV because, at high Rosseland optical depths, the plasma frequency blocks photons with higher energies, which, in order to conserve the radiative flux, requires a slight increase of the temperature in the inner parts of the atmosphere. In fact, since the opacities decrease at high energies, and the energy-dependent optical depth $T_R = 1$ is located at deeper zones, the emergent spectrum for $E \gtrsim 10^{-1}$ keV is sensitive to the plasma effects and to the change of the temperature profile in the inner parts of the atmosphere. However, even with this change in the atmosphere spectra, the overall effect in the relevant energy range $E \sim 10^{-2} - 1$ keV of the thermal emission from J0437 (considering $T_{\text{eff}} \sim 10^5$ K), is $\lesssim 2\%$ for H/He composition and $\lesssim 4\%$ for Fe composition.

For the analysis presented in this section, we have considered only three representative effective surface temperatures, $T_{\text{eff}} = 10^{4.5}$, $10^{5.0}$, and $10^{5.5}$ K. Figure 3 shows the tendency of plasma effects to become relatively less important, for all compositions, as the effective temperature of the atmosphere increases. Therefore, for $T_{\text{eff}} > 10^{5.5}$ K, plasma effects should be negligible. On the other hand, for $T_{\text{eff}} < 10^{4.5}$ K, the amount of free electrons throughout the atmosphere decreases for all compositions, i.e., the plasma becomes less ionized. However, at low temperatures (as shown in Figure 3), plasma frequency effects may still produce a substantial change in the spectra of Fe atmospheres in the soft X-ray energy range, although relatively far from the flux peak (as a reference, see also Figure 1).

Thus, we conclude that plasma effects are not important in the thermal emission of MSPs (and any non-magnetic NSs) with light element atmosphere, but it may become important in very cold and heavy element atmospheres, producing an enhancement of the soft X-ray emission, but limited just to the high energy (Wien) tail of the spectrum.

Figure 4 shows the relation between the temperature inferred from a BB fit and that from an atmosphere model, considering the flux in the energy range $E^\infty = 6.2 - 9.4$ eV (as observed at infinity). In particular, for a fixed “red-shifted radius” or “apparent radius” $R_{\text{app}} = (1 + z) R_{NS}$ and temperature $T \sim 10^5$ K, a BB fit roughly reflects the effective temperature for He and Fe atmospheres. Instead, a BB fit underestimates by a factor $\approx 2.1$ the temperature with respect to a H atmospheres. In the range plotted, the temperature transformation between a BB and a H atmosphere can be fairly well described by the function

$$T_H/T_{BB} \approx f_T = -1.994 x^3 + 29.42 x^2 - 142.1 x + 226.4,$$

where $x = \log(T_{BB}/K)$. Similarly, the temperature transformations from BB to He and Fe atmospheres can be described by the functions $f_{\text{He}} = 1.674 x^3 - 23.5 x^2 + 110.4 x - 172.6$ and $f_{\text{Fe}} = -3.157 x^3 + 48.65 x^2 - 248.7 x + 423.2$, respectively.

4 APPLICATIONS TO PSR J0437–4715

4.1 Fitting procedure, MCMC and tests

We fit our spectral model of non-magnetic NS atmospheres to the UV and soft X-ray emission from J0437. For the UV band, we use spectroscopic and photometric data from HST observations by Kargaltsev et al. (2004) and Durant et al. (2012). For the soft X-ray band, we use ROSAT archive data (Becker & Trümper 1993) reanalyzed by Guillot et al. (2016). We compute a $\chi^2$ statistic between spectral models and UV/X-ray data considering four fitting parameters: interstellar extinction, $E(B-V)$, neutral hydrogen column density, $N_{\text{H}}$, effective temperature, $T_{\text{eff}}$, and radius, $R_{NS}$, of the NS.

X-ray spectral fits account for the effects of interstellar neutral H via the absorption model of Wilms et al. (2000). We fold the (absorbed) spectral model using the response matrix and effective area of the ROSAT-PSPC camera, taken from the HEASARC webpage. The folded X-ray spectra are binned in such a way that they match the energy binning of the ROSAT data presented in Guillot et al. (2016). CCD pile-up is not considered in our analysis as the X-ray data for J0437 show relatively low photon count-rates. To compute the $\chi^2$ statistic in the X-ray band, we considered only the $0.1 - 0.4$ keV range, which is consistent with the cool thermal emission from the whole NS surface. In most of our analysis, we neglect the small contribution from the hot polar caps (Bogdanov 2013; Guillot et al. 2016), whose effect we evaluate approximately in § 4.4.

We account for the dust effects in the UV fits using Milky Way extinction curves from Clayton et al. (2003), which are computed using the polynomial function from Fitzpatrick & Massa (1990), setting $R_V = 3.1$. Following Durant et al. (2012), we compute the $\chi^2$ statistic in the UV band considering the $7 - 11$ eV range of HST data, which is consistent with a Rayleigh-Jeans tail of the surface emission. As discussed in Durant et al. (2012), the spectrum of J0437 shows, just below $\sim 7$ eV, a peaked optical/UV excess whose origin is still unknown (where the instrument spectral response is also rapidly decreasing).

To obtain the confidence levels for the fitted parameters, we run a set of MCMC simulations using the package EMCEE (Foreman-Mackey et al. 2013), considering four cases of emission models: H, He, and Fe atmosphere spectra and BB emission. The atmosphere spectra are obtained with log-scale polynomial interpolation from a 10x10 grid of models computed (from radiative transfer calculations, see Section 2) in a suitable range of temperatures and radii. We checked that the relative difference between interpolated spectra and actual atmosphere spectra is negligible, and we also found that our results remain largely unchanged by using for example a 5 x 5 temperature-radius grid. The models account for gravitational redshift considering a NS

https://heasarc.gsfc.nasa.gov/docs/ROSAT/pspc_matrices.html

MNRAS 000, 1–13 (2015)
NS radius measurement for PSR J0437–4715

Figure 5. MCMC marginalized (one-dimensional and two-dimensional) posterior distributions for the fitting parameters used in the spectral analysis of J0437. The models are computed for non-magnetized, partially ionized NS atmospheres considering H, He and Fe composition, as well as BB emission (panels a–d). (For the H atmosphere model, the Lyman alpha absorption line was eliminated, as explained in Section 2.1.) The black, dark gray and gray regions show the 68%, 95% and 99.7% confidence levels. The orange and blue bands show the $E(B-V)$–$N_H$ relations (3σ enclosure around the central value as dashed lines) derived by Güver & Özel (2009) and Foight et al. (2016), respectively, for the Milky Way’s interstellar medium. The red, vertical lines with the arrows show the 99% confidence range of the constraints on the NS radius obtained from the gravitational wave event GW 170817 (Abbott et al. 2018). While all compositions and the BB model produce sensible measurements of the NS properties, the H atmosphere model produces the best agreement with the empirical interstellar $E(B-V)$–$N_H$ relations and $E(B-V)$ values from Galactic dust maps.
mass $M_{NS} = 1.44 M_\odot$, and setting the source distance to $d = 156.79$ pc (Reardon et al. 2016).

We first considered uniform prior distributions in all the fitting parameters ($R_{NS}$, $T_{eff}^\infty$, $E(B - V)$, and $N_H$), and then we refined our results with a Gaussian prior on $E(B - V)$, with boundaries for the MCMC equal or larger than the limits shown in the Figure 5a–5d. For each MCMC run, we used 100 walkers (chains) over 10,000 iterations. The first 25% iterations of each run were excluded when generating the MCMC posterior distributions. We also checked convergence of the MCMC by visual inspection of the traces of parameters, and of the likelihood ($\chi^2$), to ensure the proper mixing and sampling of the parameter space. The final minimum $\chi^2$ were statistically acceptable with values between 43.7 and 45.9 depending on the model, for 34 degrees of freedom.

**Table 1.** Spectral fit parameters with different models for J0437. The values of $R_{NS}$, $T_{eff}^\infty$, $N_H$ and $E(B - V)$ are obtained from the MCMC posterior distributions. The values quoted are the medians (i.e., 50% quantile), and the lower/upper uncertainties are obtained from the 16% and 84% quantiles, so that they provide the 68% credible intervals.

| Model | $R_{NS}$ ($\text{km}$) | $T_{eff}^\infty$ ($10^3 \text{ K}$) | $N_H$ ($10^{10} \text{ cm}^{-2}$) | $E(B - V)$ | $\chi^2$/dof |
|-------|------------------|-----------------|-----------------|----------|-------------|
| H     | $16.3^{+3.0}_{-2.5}$ | $2.4^{+0.2}_{-0.2}$ | $1.7 \pm 0.3$ | $0.08^{+0.05}_{-0.03}$ | 43.7/34 |
| He    | $15.1^{+3.0}_{-2.5}$ | $2.5^{+0.1}_{-0.1}$ | $1.7 \pm 0.3$ | $0.12^{+0.04}_{-0.02}$ | 45.3/34 |
| Fe    | $8.9^{+3.4}_{-2.4}$ | $3.6^{+0.2}_{-0.2}$ | $2.3 \pm 0.4$ | $0.15^{+0.06}_{-0.04}$ | 43.7/34 |
| BB    | $7.8^{+2.7}_{-1.9}$ | $3.9^{+0.2}_{-0.2}$ | $2.8 \pm 0.4$ | $0.15^{+0.05}_{-0.04}$ | 45.2/34 |

Gaussian prior on $E(B - V)$

| Model | $R_{NS}$ ($\text{km}$) | $T_{eff}^\infty$ ($10^3 \text{ K}$) | $N_H$ ($10^{10} \text{ cm}^{-2}$) | $E(B - V)$ |
|-------|------------------|-----------------|-----------------|----------|
| H     | $13.1^{+0.9}_{-0.7}$ | $2.5 \pm 0.1$ | $1.6 \pm 0.3$ | $0.01 \pm 0.01$ |

| Including hot polar caps and Gaussian prior on $E(B - V)$ |
|-------------|------------------|-----------------|-----------------|----------|
| H           | $13.6^{+0.9}_{-0.8}$ | $2.3 \pm 0.1$ | $1.4 \pm 0.3$ | $0.01 \pm 0.01$ |

$\chi^2$/dof
4.2 Results of spectral fits with uniform priors

The results for the H, He, Fe, and BB spectral fits are summarized in Table 1. The spectral fits for all emission models have equally good $\chi^2$ statistics. However, the results of our MCMC analyses, considering flat priors on all fitting parameters (Figure 5), suggest that the H atmosphere model is favoured, as its posterior distributions for $E(B-V)$ and $N_H$ show the best agreement with:

a) the measurements $E(B-V) < 0.012$ obtained with a 2D map of infrared dust emission (Schlegel & Finkbeiner 2011, see also Schlegel et al. 1998) and $E(B-V) = 0.002 \pm 0.014$ (for distances $d = 155 - 160$ pc to J0437) from a 3D map constructed from starlight absorption by dust (Lallement et al. 2018, see also Lallement et al. 2014; Capitanio et al. 2017), and

b) previous estimates of the interstellar dust extinction towards J0437 in the range $0.0 < E(B-V) < 0.07$ (Kargaltsev et al. 2004; Durant et al. 2012), and

c) the correlation between $N_H$ and $A_V$ discussed by Foight et al. (2016, see also Predehl & Schmitt 1995; Güver & Özel 2013): $N_H = (2.81 \pm 0.12) \times 10^{21} A_V$, where $A_V = E(B-V) \times R_V$, and $R_V$ is taken as 3.1.

Similar arguments suggest that the He atmosphere model is somewhat disfavoured, and the Fe atmosphere and BB models are ruled out.

The posterior distributions for the H atmosphere model produce a radius $R_{\text{NS}} = 16.3^{+3.0}_{-2.5}$ km and a bulk surface temperature $T_{\text{eff}} = (2.4 \pm 0.2) \times 10^5$ K, substantially cooler than the polar caps ($\gtrsim 10^6$ K). In particular, the radius measurement is consistent with the lower bound obtained from the analysis of the X-ray light curve (hot polar cap emission) of J0437 by Bogdanov (2013), or the analysis of the broad X-ray spectral shape (Guillot et al. 2016). Furthermore, the lower end of the posterior distribution for $R_{\text{NS}}$ is also compatible with the 99% confidence limits on the NS radius obtained from the gravitational wave signal detected from the NS–NS merger GW 170817 (Figure 5a, red lines), determined assuming a parameterized equation of state consistent with 1.97 $M_\odot$ (Abbott et al. 2018).

The posterior distributions obtained with all atmosphere models show a strong correlation between $R_{\text{NS}}$ and $E(B-V)$ and an anti-correlation between $T_{\text{eff}}$ and $E(B-V)$. Therefore, an independent measurement of the dust extinction would strongly reduce the error intervals for the radius and temperature. If the extinction is negligible, as suggested by the Galactic dust maps mentioned above, the H atmosphere model can produce a NS radius as small as $R_{\text{NS}} \sim 12$ km. A discussion of the MCMC analysis including a prior on $E(B-V)$ is given in Section 4.3.

Figure 6 shows the best fitting spectra obtained with the MCMC analysis for all emission models. The UV data are de-reddened according to the best-fit $E(B-V)$ and the soft X–ray data are unfolded and transformed to un-absorbed flux using the best fitted $N_H$. Since the posterior distributions

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5 https://irsa.ipac.caltech.edu/applications/DUST/

6 https:// stilism.obspm.fr

7 Note that the constraints on the temperature and radius derived in our spectral fits are more restrictive than those reported by Durant et al. (2012), which were obtained with combined UV (HST) and soft X–ray data (XMM-Newton; spectral flux at $E = 600\text{eV}$ taken as an upper limit on the surface thermal emission), but considering a BB model and a range of NS radii between $R_{\text{NS}} = 7$ km and $R_{\text{NS}} = 24$ km.

8 The soft X–ray data are unfolded as $F_{\text{fold}} = F_{\text{data}} - S F_{\text{unfold}}$, where $F_{\text{fold}}$ correspond to the folded data, $S$ is the model spectrum, and $F_{\text{unfold}}$ is the spectral model folded according to the telescope response.
for $T_{\text{eff}}$, $R_{\text{NS}}$, $E(B-V)$, and $N_H$ are non-Gaussian, the best-fit parameters shown in Figure 6 differ slightly from the posterior medians listed in Table 1.

4.3 NS radius estimation with a Gaussian prior on $E(B-V)$

J0437 is located in a region particularly devoid of dust\(^9\). As discussed in the previous subsection, 2D and 3D maps of dust extinction toward this source give $E(B-V) < 0.012$ and $E(B-V) = 0.002 \pm 0.014$, respectively. Furthermore, these values are compatible within $2\sigma$ with those derived with the MCMC analysis for the H atmosphere model (using flat priors in all the fitting parameters) and the empirical $N_H - E(B-V)$ relation (Foight et al. 2016).

We repeat the MCMC analysis for the H atmosphere model including a Gaussian prior on $E(B-V)$, with mean $\mu_{\text{dust}} = 0.002$ and standard deviation $\sigma_{\text{dust}} = 0.014$, according to the latest 3D map of Galactic dust (Lallement et al. 2018), while ensuring $E(B-V) > 0$. A summary with the resulting medians for the fitting parameters is reported in Table 1. As expected, the results are compatible with those reported in Section 4.2. Remarkably, the uncertainties on the radius measurement are substantially reduced, yielding $R_{\text{NS}} = 13.1^{+0.9}_{-0.7}$ km (see also the posterior distributions in Figure 7).

4.4 Correction for hot polar caps and final radius estimate

Up to this point, we have neglected the effects on our fits from the hot polar caps, which are clearly identified in the X-ray data above $\sim 0.5$ keV (Becker & Trümper 1993; Pavlov & Zavlin 1997; Bogdanov 2013; Guillot et al. 2016). In our low-energy spectral analysis, there could be two such effects:

- a) The low-energy tail of the hot components could directly contribute to the high end of the spectral range considered in our models, and
- b) the folded soft X-ray spectrum can be contaminated with high-energy photons due to the spectral response of the detector.

We tested the effect of the hot polar caps by adding two hot BB components to our H atmosphere fit (see Figure 8). We used the parameters for the polar caps obtained by Guillot et al. (2016) for their H atmosphere + 2BB fit, which includes NuSTAR, XMM-Neutron, and ROSAT data, covering the X-ray spectrum of J0437 up to 20 keV. Their best fitting temperatures for the polar caps are $T_{\text{cap},1} = 1.8 \times 10^6$ K and $T_{\text{cap},2} = 3.4 \times 10^6$ K, with associated radii $R_{\text{cap},1} = 0.15$ km and $R_{\text{cap},2} = 0.03$ km, respectively. By including these fixed components in our MCMC analysis, we obtain a final NS radius estimation $R_{\text{NS}} = 13.6^{+0.9}_{-0.8}$ km (a summary with all posterior medians is reported in Table 1). In comparison to the results reported in Section 4.3, the addition of the hot components makes the inferred bulk temperature decrease and the NS radius increase by amounts smaller than the estimated $1 \sigma$ error bars.

A full analysis, including atmosphere model fits of the emission from both the hot polar caps and the cooler sur-

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\(^9\) Rosine Lallement, private communication.
NS radius measurement for PSR J0437–4715

5 DISCUSSION AND CONCLUSIONS

We modelled the cool thermal component of the spectrum of MSP J0437, observed in the UV (HST) and soft X-ray (ROSAT) bands, considering non-magnetized, partially ionized H, He, and Fe atmospheres. For surface temperatures $\sim 10^5$ K, as previously determined for this source (Kargaltsev et al. 2004; Durant et al. 2012), we found that plasma effects are negligible in the UV band (less than 1% flux suppression), but may become important for cooler sources with heavy-element atmospheres, particularly for the emission in the soft X-ray band (in the Wien tail of the spectrum).

Using a MCMC analysis, we found that spectral fits to the UV/X-ray data of J0437 favour a H atmospheric composition, disfavour a He composition, and rule out Fe atmospheric composition as well as BB emission. This is consistent with the fact that BB emission cannot reproduce the observed pulsed amplitude of J0437 (Bogdanov 2013). For the H atmosphere composition, we found that:

- a) By considering uniform priors in all fitting parameters, we obtain a NS radius $R_{\text{NS}} = 16.3^{+2.0}_{-0.9}$ km, a bulk surface temperature $T_{\text{eff}} = (2.4 \pm 0.2) \times 10^5$ K, a dust extinction value $E(B-V) = 0.06 \pm 0.03$, and a neutral H column density $N_H = (1.7 \pm 0.3) \times 10^{20}$ cm$^{-2}$.
- b) By including a Gaussian prior on the dust extinction, based on current 3D maps of galactic dust, we refine our measurements: $R_{\text{NS}} = 13.1^{+0.2}_{-0.5}$ km, $T_{\text{eff}} = (2.5 \pm 0.2) \times 10^5$ K, and $N_H = (1.6 \pm 0.3) \times 10^{20}$ cm$^{-2}$.
- c) By accounting for the effect of the hot polar caps, we obtain our final results: $R_{\text{NS}} = 13.6^{+0.5}_{-0.3}$ km, $T_{\text{eff}} = (2.3 \pm 0.1) \times 10^5$ K, and $N_H = (1.4 \pm 0.3) \times 10^{20}$ cm$^{-2}$.

Our radius determination for J0437, combined with its well-measured mass, allows us to establish the tightest constraint on the equation of state for ultra-dense matter to date (for a review see Lattimer & Prakash 2016) from a MSP. As shown in Figure 9, the constraint on $M_{\text{NS}}$ (Reardon et al. 2016) and $R_{\text{NS}}$ (this work) for J0437 combined with one of the largest measured masses for a pulsar (PSR J1614–2230, Demorest et al. 2010; Arzoumanian et al. 2018) favours a stiff EOS and disfavours a strange matter EOS. Precise 3D maps of Galactic dust, presently under development, based on GAIA data (see e.g., Lallement et al. 2019), and high quality X-ray observation from the NICER mission, will further improve the radius estimation for J0437 and the constraints on the EOS.

Compared with other results, our measurement of $R_{\text{NS}}$ for J0437 is:

- a) consistent with the lower limits on the radius previously published for this source. Specifically, Bogdanov (2013) derived $R_{\text{NS}} > 10.9$ km from the X-ray light curve (due to the hot polar caps), assuming a H atmosphere, while Guillot et al. (2016) obtained $R_{\text{NS}} > 10$ km from the soft X-ray spectrum (using a BB spectral component for the cool surface).
- b) consistent with the constraints derived for two other MSPs: PSRs J2124 and J0030, with the associated lower limits $R_{\text{NS}} > 7.8$ km and $R_{\text{NS}} > 10.4$ km, respectively (assuming $M_{\text{NS}} = 1.4$ $M_\odot$, Bogdanov et al. 2008; Bogdanov & Grindlay 2009).
- c) consistent with the NS radius derived from the NS-NS merger gravitational wave signal GW 170817 (Abbott et al. 2018).
- d) consistent with the NS radius measurement from recent statistical analyses combining quiescent low-mass X-ray binaries (e.g., Steiner et al. 2018; Bailaud d’Etivaux et al. 2019), which find radii in the 11–14 km range, and
- e) slightly larger, but still marginally consistent with the NS radius obtained through the analysis of the cooling tails of X-ray bursts from the low-mass X-ray binary 4U 1702–429, $R_{\text{NS}} = 12.4 \pm 0.4$ km (Nättilä et al. 2017).

Our analysis also allowed us to test the surface composition of the MSP J0437. In particular, a H atmosphere is in agreement with the expectations for these sources, as such composition might result from a) past accretion from a binary companion, b) accretion from the interstellar medium or c) spallation of heavier elements (Bildsten et al. 1992). If other heavier elements coexist in the surface layers of NSs, they would stratify within $\sim 100$ s (Romani 1987; Bildsten et al. 1992), leaving the lightest element on top. Furthermore, a very small amount of H, $\sim 10^{-20} M_\odot$ (Bogdanov et al. 2013), is consistent with the surface H abundance inferred by Nättilä et al. 2017.

Figure 9. Mass-radius relation for different cold, superdense matter EOSs. The curves with different colors show a few EOSs, labeled as in Lattimer & Prakash (2001). The blue filled region labeled “CEFT” shows a range of EOSs based on chiral effective field theory (Hebeler et al. 2013). The grey, horizontal bands show the mass measurements for PSR J1614–2230 (Demorest et al. 2010; Arzoumanian et al. 2018) and J0437 (Reardon et al. 2016). The black region shows the radius measurement for J0437, at 1σ, obtained in this work.
The bulk surface temperature of J0437 derived in the present work with the H atmosphere model is more restrictive than that obtained with a BB model by Durant et al. (2012). The effect of rotation is included in our model, which does not take into account the minimal value of $R_{\infty} = 3 \sqrt{3} GM/c^2 = 11.0 \pm 0.5$ km imposed by General Relativity (considering the currently measured mass the pulsar $M_{\infty} = 1.44 \pm 0.07 M_{\odot}$, Reardon et al. 2016). Our temperature measurement is also relevant to understand the heating mechanisms that might be operating in NSs. Gonzalez & Reisenegger (2010) performed a comparative analysis of different heating mechanisms, finding that rotochemical heating (Reisenegger 1995, 1997; Fernández & Reisenegger 2005; Petrovich & Reisenegger 2010, 2011; González-Jiménez et al. 2015) and vortex creep (Alpar et al. 1984; Shibazaki & Lamb 1989; Larson & Link 1999) might explain the temperatures measured in old NSs. Rotation-induced crustal heating, which was proposed later (Gusakov et al. 2015), could also be important. A full analysis of this issue will be presented in another work (Rodríguez et al., in prep.).

We note that our results rely on the assumption that non-magnetized atmosphere models appropriately describe the thermal emission from the entire surface of relatively cold NSs, such as J0437. The spin-down-derived magnetic field of this object, $B = 2.4 \times 10^{10} G$, can affect the transport of radiation in the atmospheric plasma for electromagnetic waves with energies lower than the electron cyclotron energy $E_{ec}/(1 + z) \sim 2 eV$, which is still below the UV band considered in our fits. Potentially, small-scale multipolar components present on the NS surface (stronger than the dipolar field) could affect the radiative transfer. If that is the case, and assuming that the transport of radiation becomes polarized (propagating in the so-called X-mode and O-mode), this would produce an excess in the optical/UV spectrum compared with the non-magnetized atmosphere model (see e.g., Ho & Lai 2001; Zane et al. 2001; Lloyd 2003; Suleimanov et al. 2012). Such spectral fits will produce a smaller NS radius, and so our results with non-magnetized atmosphere models may be considered as upper limits. A further caveat to consider is the possibility that no atmosphere is present on the cold surfaces of NSs (but probably at much lower surface temperatures than that of J0437), where the emission would arise directly from a liquid surface. However, no models exist so far to describe such emission from sources like MSPs.

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MNRAS 000, 1–13 (2015)
