Temperature, distance and cooling of the Vela pulsar

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Abstract. We use models of magnetized hydrogen atmospheres to fit the soft X-ray thermal spectrum of the Vela pulsar obtained by *ROSAT*. The distance and hydrogen column density required by our fits are in good agreement with other independents estimates and can be considered as an argument for the presence of hydrogen at the surface of this pulsar.

The low temperature obtained, $T_e^\infty = 7.85 \pm 0.25 \times 10^5$ K, is below the predictions of the 'standard' model of neutron star cooling and strengthens previous claims for the necessity of the occurrence of fast neutrino cooling in this neutron star.

1. INTRODUCTION

The Vela pulsar is the youngest pulsar for which there is strong evidence that thermal emission from the surface of the neutron star has been detected (Ögelman, Finley & Zimmermann 1993; Ögelman 1995). A reliable measurement of its surface temperature based on modeling of the surface thermal emission is of outmost importance for comparison with models of neutron star cooling and could give us evidence for the past occurrence of fast neutrino emission. Moreover, since the chemical composition of a pulsar's surface and its state (gaseous, liquid or solid) are still unknown, the 'succesfull' fit of the observations can also give us invaluable information about this question.

2. MAGNETIZED HYDROGEN ATMOSPHERE

There are many possibilities for the structure of a pulsar's surface and a magnetized hydrogen atmosphere is the most 'natural' and simplest choice although it has *a priori* no strict reason to be accepted (e.g., where does the hydrogen come from ?). Assuming the presence of an atmosphere, the magnetic field has three main effects: 1) the opacity depends strongly on the magnetic field direction and on the photon polarization, 2) for the polarization giving the main contribution to the emergent flux it is much smaller than in the nonmagnetic case and its dependence on the photon energy is weaker, 3) the ionization energy is strongly increased and at low T_e an absorption edge appears within the range of the *ROSAT* PSPC. The problem of ionization equilibrium in a magnetized hydrogen atmosphere is not yet completely solved but at $T_e \gtrsim 10^6$ K the whole atmosphere is fully ionized, its structure can be calculated accurately and the spectra we are using are reliable (Shibanov *et al*. 1992; Pavlov *et al*. 1994, 1995).

3. SPECTRAL FITS

We performed a χ^2 search of the whole parameter space using the *ROSAT* data as presented by Ögelman, Finley & Zimmermann (1993). Due to the high temperature several simplifications occur when considering emission within the *ROSAT*'s PSPC band: 1) the emitted flux is weakly dependent on the field strength at $B \gtrsim 10^{12}$ G, 2) the detectable flux practically depends only on the mean 'effective' surface temperature, not on the actual distribution of the temperature along the surface (Page 1995a, Page & Sarmiento 1995), 3) the red-shift is equivalent to a change (red-shift) of temperature and 4) the model depends only weakly on the surface gravity.

We are thus able to do spectral fits with only three parameters: effective temperature at infinity, T_e^∞, distance D and column density N_H. We assume a mass of 1.4 $M_\odot$ and a radius of $R = 10$ km, i.e., $R^\infty = 13.6$ km, but since the received flux scales like $(R^\infty/D)^2$ our results can be extrapolated to other radii with reasonable confidence. The final result of our χ^2 search is shown in Figure 1.

The pulsations of the soft X-ray emission from Vela show that the temperature of the polar cap region may be even larger than the mean effective surface tempeature found in our fit ($T_{surf} \sim 9 \times 10^5$ K) and the fully ionized atmosphere fit might be quite reliable for this object. However, at $T_{surf} \lesssim 10^6$ K an absorption edge (not taken into account in the spectra we used) should appear: as a result our fits give too low a T_e and our lower range would probably be pushed to higher values.

4. DISCUSSION

We obtain in our best fit a χ^2 per degree of freedom of 1.074; due to the low statistics any χ^2 p.d.f. of order one is acceptable. So the relevance of the model can only be assessed by discussion of the resulting values of the parameters.

Column density: $N_H = 2.35 \pm 0.8 \times 10^{20}$ cm^{-2}. Other components of the Vela PSR + SNR give independent estimates of N_H. Modeling of the pulsar 'hard tail' soft X-ray emission needs values of 4.3 ± 1.0

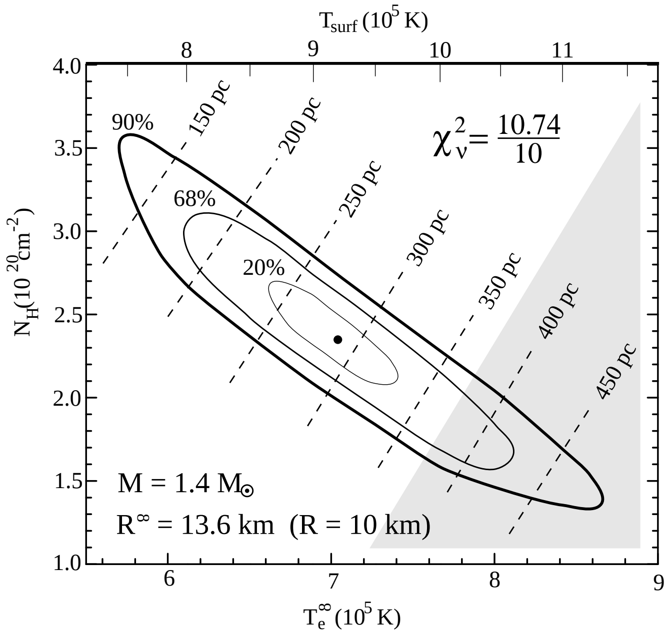

Fig. 1. Confidence contours for the three parameters (T_e, N_H and D), projected onto the $T_e - N_H$ plane. The grey area shows the '1σ' lower limit on the distance from the pulsar dispersion measure. The dot shows our best fit: $T_e^\infty = 7.04 \times 10^5$ K, ($T_e = 9.2 \times 10^5$ K), $N_H = 2.35 \times 10^{20}$ cm^{-2} and $D = 285$ pc.

or $4.4 \pm 1.5 \times 10^{20}$ cm^{-2} and modeling of the surrounding compact nebula gives values of 2.0 ± 0.5 or $3.0 \pm 0.5 \times 10^{20}$ cm^{-2} (Ögelman *et al.* 1993) while the six 'bullet' detected in the SNR give N_H's between 2.4 ± 1.9 and $5.4 \pm 2.1 \times 10^{20}$ cm^{-2} (Aschenbach *et al.* 1995). In addition, Table 1 list several reference objects in the line of sight of the Vela pulsar for comparison with our results which show that N_H reaches 10^{21} cm^{-2} well above 500 pc and probably needs at least 100 – 200 pc to reach 10^{20} cm^{-2}. In short, a N_H between 1.5 and 3×10^{20} cm^{-2} seems reasonable for a distance between 200 – 400 pc.

Distance: $D = 300 \pm 120$ pc. The pulsar's distance of 500 $\pm$ 125 pc (Taylor *et al.* 1993), confirmed by interstellar scintillation measurements (Gupta 1995), is compatible, in its lower range, with our deduced value, in its upper range. Moreover, increasing the star's radius R^∞ increases the fitted distance D in the same amount. Our results may possibly favor a larger radius: $R = 12$ km ($R^\infty = 15.5$ km) would increase D by 14%.

Our 68% confidence range ('1σ') combined with the puslar's distance (at '1σ', the grey area in Fig. 1) thus implies that $T_e^\infty = 7.85 \pm 0.25 \times 10^5$K (for a 10 km radius) and $N_H = 1.80 \pm 0.25 \times 10^{20}$ cm^{-2}. The corresponding surface temperature T_{surf} is above 10^6 K where our atmosphere models are most reliable.

Hydrogen atmosphere ? The consistency of our result for D and N_H with values obtained with other methods is an argument in favor of the presence of a hot ($\sim 10^6$ K) magnetized ($\gtrsim 10^{12}$ G) hydrogen plasma at the surface of

Table 1. Reference objects for interstellar absorption

Name (HD number)	l	b	LogN$_H$ [cm^{-2}]	D [pc]
IX Vel[a]	264.9	-7.9	19.30	140
(HD72350)[a]	262.7	-3.2	< 21.15	292
Vela PSR[b]	263.6	-2.8	20.35 ± 0.15	300 ± 120
Vela PSR[c]	263.6	-2.8	19 – 20.2	$\sim 1,500$
HX Vel (HD74455)[a]	266.6	-3.6	20.78 ± 0.10	422
(HD72179)[a]	262.1	-3.0	< 21.32	607
KX Vel (HD75821)[a]	266.3	-1.5	20.48 ± 0.10	972
(HD74531)[a]	266.7	-3.6	20.84 ± 0.10	996
(HD73658)[a]	264.7	-3.1	21.20 ± 0.05	1508

a: Fruscione, A. *et al.* 1994.
b: This work
c: Ögelman, Finley, Zimmermann 1993. $T_e^\infty \sim 1.6 \times 10^6$ K, blackbody fit.

the Vela pulsar in sufficient amount to provide an optical depth of unity, i.e., at least a few grams per cm^2.

5. COOLING

The Vela pulsar has already been claimed several times to be cooler than the predictions of the 'standard' model of neutron star cooling and our results reinforce such claims. If we accept our deduced T_e and believe neutron star cooling models then our results require fast neutrino emission by, e.g., direct Urca processes, kaon or pion condensates, which has been supressed by baryon pairing (e.g., Page & Applegate 1992). A critical temperature T_c of the order of $1 - 3 \times 10^9$ K for pairing in the inner core is then necessary, independently of the exact fast cooling agent (Page 1995b).

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