A Comment on "A note on polarized light from Magnetars: QED effects and axion-like particles" by L.M. Capparelli, L. Maiani and A.D. Polosa

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Abstract

The recent detection of a large polarization degree in the optical emission of an isolated neutron star led to the suggestion that this has been the first evidence of vacuum polarization in a strong magnetic field, an effect predicted by quantum electrodynamics but never observed before. This claim was challanged in a paper by Capparelli, Maiani & Polosa (2017), according to whom a much higher polarization degree would be necessary to positively identify vacuum polarization. Here we show that their conclusions are biased by several inadequate assumptions and have no impact on the original claim.

Subject headings: polarization — sources (individual): RX J1856.5-3754 —stars: magnetic fields — stars: neutron

1. Introduction

In a recent paper, Capparelli, Maiani & Polosa (2017) presented some considerations in connection with the discovery of a relatively high linear polarization degree ($\sim 16\%$) in the optical emission of the isolated neutron star (NS) RX J1856.5-3754 (hereafter RX J1856; Mignani et al. 2017). Specifically, they expressed some criticism on the interpretation of the measured polarization as the first evidence for vacuum birefringence, as stated by Mignani et al. (2017).

According to quantum electrodynamics (QED), photons propagate in a strongly magnetized vacuum in two normal polarization modes, the ordinary (O) and extraordinary (X) one, with different refractive indices and this strongly influences the polarization properties of the observed radiation (e.g. Heyl & Shaviv 2000, 2002; Harding & Lai 2006; Taverna et al. 2015; González Caniulef et al. 2016). This effect has been searched for but never observed in terrestrial laboratories (e.g the PVLAS experiment; della Valle et al. 2014). The main point raised by Capparelli, Maiani & Polosa (2017) is that the observed polarization degree in RX J1856 would be not high enough to provide an unambiguous signature of vacuum birefringence. According to their calculation, in fact, the maximum value of the polarization degree, neglecting vacuum birefringence, is $\sim 40\%$, while accounting for QED effects it should be close to 100%. Hence their conclusion that the measured value is too small to support the presence of vacuum birefringence in the magnetosphere of RX J1856.

Here we show that their conclusions are incorrect because of the oversimplified treatment of the magnetic field around the neutron star they use. Besides, their approach in computing the phase-averaged polarization observables appears flawed and the constraints set by the observed values of the star parameters, the surface magnetic field and the pulsed fraction, are not accounted for.

2. Magnetic field topology

Capparelli, Maiani & Polosa (2017) considered a simplified magnetic field configuration in which the magnetic field vectors are tangent to the meridians of the star surface. This assumption works well to illustrate how the photon electric field direction changes as the radiation propagates in the magnetized vacuum around the source (as shown in their figure 1). However, as also they themselves note, the external field of an NS is most likely a core-centered dipole, and this seems indeed the case for RX J1856, as recently discussed by Popov, Taverna & Turolla (2017). Actually, while meridional field lines well approximate the dipolar ones far from the star, the agreement becomes worse and worse closer to the star surface, where radiation is emitted. In assessing the maximum observed value of the polarization degree in the absence of vacuum birefringence (QED-off case), Capparelli, Maiani & Polosa (2017) keep to this unrealistic approximation (see their footnote 2) and get a value $\lesssim 40\%$ for photons initially 100% polarized in the X mode. We stress that the magnetic field topology is key in computing the observable polarization signal (in the QED-off limit). Since the magnetic configuration assumed by Capparelli, Maiani & Polosa (2017) is much more uniform than the dipolar one, this produces an overestimate of the polarization degree. This can be clearly seen in figure 1 which shows the magnetic field over the star surface (projected on the plane perpendicular to the line of sight, LOS) for both magnetic configurations. The meridional magnetic field configuration is indeed more organized/uniform than that of the dipolar field, so that the expected polarization degree in the absence of QED effects is higher for the meridional field.

This can be explained by the fact that the Stokes parameters associated to each photon have to be rotated around the LOS in order to be all referred to the same frame (the polarimeter frame) before they are summed together to obtain the overall polarization signal (see Taverna et al. 2015, for further details). Since the rotation angle

α is indeed the angle between the projection of the local B-field perpendicular to the LOS at the emission point and the polarimeter reference axis, it becomes clear that the configuration of the magnetic field on the star surface strongly influences the observed polarization degree when QED effects are neglected. In particular a narrow range of variation for the angle α over the star surface translates into a larger polarization degree at the observer.

To better assess this point, we recomputed the polarization observables with our ray-tracing code using a setup similar to that adopted by Capparelli, Maiani & Polosa (2017), i.e. meridional field and 100% polarized blackbody photons, obtaining a value of the polarization degree in the QED-off limit of $\sim 50\%$ for the most favourable viewing geometry, much higher than that for a dipolar field, $\sim 13\%$ for the same photon input. This is clearly illustrated in figure 2 which shows the observed phase-averaged polarization degree $\Pi_{\rm L}$ as a function of the two geometrical angles ξ and χ, the magnetic axis and the LOS, respectively, make with the rotation axis.

The value of $\sim 40\%$ reported by Capparelli, Maiani & Polosa (2017) as the upper limit for the observed polarization degree in the absence of QED effects is strongly affected by their oversimplified treatment of the star magnetic field, has no physical basis, and cannot be compared with the results discussed in Mignani et al. (2017). As a consequence, their statement that the measure of $\Pi_{\rm L} \sim 16\%$ in RX J1856 is insufficient to infer vacuum birefringence is devoid of any meaning.

3. Phase-average of the Stokes parameters

The definition adopted by Capparelli, Maiani & Polosa (2017) for the polarization degree is unclear. The polarization degree considered in Mignani et al. (2017) is defined in terms of the (normalized) Stokes parameters Q and U as $\Pi_{\rm L} = \sqrt{Q^2 + U^2}$. The

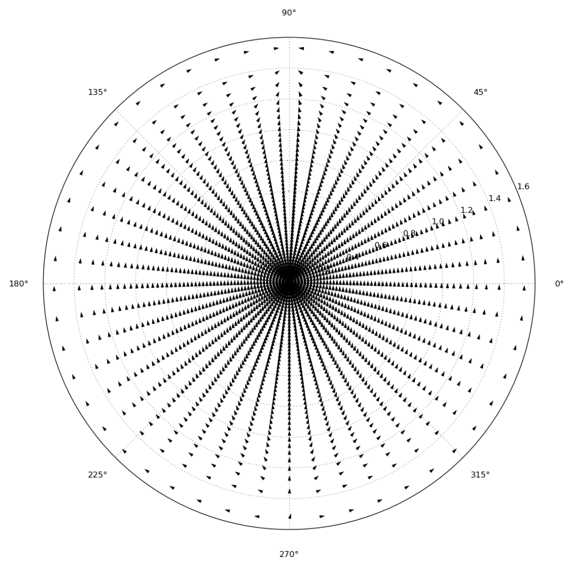

Fig. 1.— Magnetic field distribution over the star surface projected on the plane perpendicular to the LOS for both a meridional field (left-hand panel) and a dipolar field (right-hand panel).

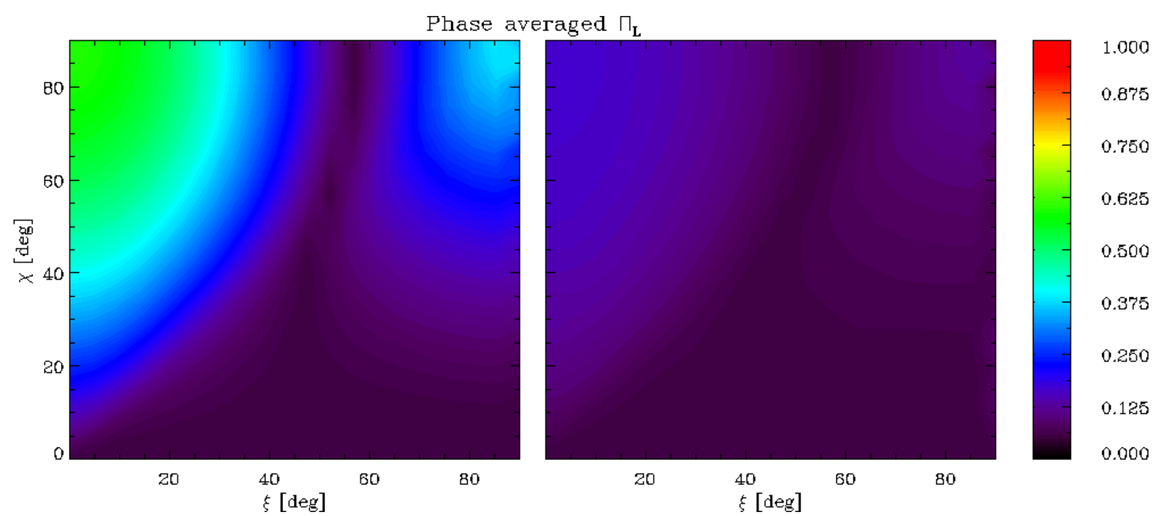

Fig. 2.— Contour plot of the phase-averaged polarization degree $\Pi_{\rm L}$ (see text) in the absence of QED effects for the meridional (left-hand panel) and dipolar (right-hand panel) magnetic field configurations, as a function of the geometrical angles χ (between the LOS and the rotation axis) and ξ (between the magnetic and the rotation axes).

FORS2 instrument used in the polarimetric observation measures the Stokes parameters of the collected radiation. Due to the limit on the time resolution imposed by the exposure duration, only an average of the polarized signal over the rotational phase can be obtained. Since the Stokes parameters are additive, the phase-averaged polarization degree can be obtained only by averaging the Stokes parameters before computing the polarization observables, a fact Capparelli, Maiani & Polosa (2017) completely neglect. Indeed, the effect of phase-averaging over the star rotation is that of an effective depolarization, and this holds also when QED effects are accounted for (as shown in Taverna et al. 2015; González Caniulef et al. 2016). As a key example, one may consider the configuration shown in figure 1 of Capparelli, Maiani & Polosa (2017), and set the star spin axis along the LOS. After a full rotation of the star, a polarimeter collects photons with electric field pointing in different directions. This reduces the polarization degree down to zero (even using the simplified meridional configuration for the magnetic field), despite the fact that a phase-resolved polarization measurement gives, instead, 100%. This means that the phase-averaged polarization degree as measured at infinity strongly depends on the viewing geometry and the observed signal in the presence of vacuum birefringence is not necessary 100% polarized. In particular, it attains a maximum when the phase-averaging effects are less important, i.e. in the case of an orthogonal rotator seen perpendicularly to the rotation axis.

4. Constraints on the star viewing geometry and magnetic field

In order to observe the maximum polarization degree Capparelli, Maiani & Polosa (2017) consider the case of the LOS perpendicular to the star magnetic axis. We point out that, actually, this is not entirely true. In fact, the angle between the LOS and the magnetic axis depend in general on the rotational phase (Taverna et al. 2015; González Caniulef et al. 2016). Hence, as illustrated in the previous section, the only geometrical configuration which allows to observe the maximum polarization degree turns out to be that in which both the LOS and the magnetic axis are orthogonal to the spin axis of the star. This is also shown in the contour plots of figure 2 above, as well as in those shown in Mignani et al. (2017), where the maximum polarization degree is attained at the top-left corner.

However, observations place several constraints on the geometrical angles χ and ξ for RX J1856. In particular the pair $(\chi\,,\xi)$ must be compatible with the observed pulsed fraction in the X-rays ($\sim 1.2\%$; Tiengo & Mereghetti 2007). This was accounted for in Mignani et al. (2017). In addition, also on the basis of spectral observations, a further constraint was placed by Ho (2007), forcing χ and ξ to vary in narrow ranges, i.e. $\chi \approx 20^\circ$– 45° and $\xi \lesssim 6^\circ$. Including these constraints, it becomes clear that the viewing configuration which gives the maximum polarization degree (i.e. $\chi = 90^\circ$, $\xi = 0^\circ$) is ruled out by observations.

Capparelli, Maiani & Polosa (2017) note that a 16% polarization degree may indeed be the maximum value attainable in the case the surface radiation is not 100% polarized. Since in this situation the estimate of the polarization degree at the emission may be uncertain, they claim that "only very high degrees of linear polarization ($\gtrsim 50\%$) would be the indisputable footprint of QED birefringence effects". However, Mignani et al. (2017) have clearly shown that, once all the available observational constraints are accounted for, a 16% polarization degree is indeed sufficient for a strong statement on the presence of QED effects even considering the worst case of surface blackbody radiation 100% polarized in the extraordinary mode.

Furthermore, Capparelli, Maiani & Polosa (2017) consider the source as a magnetar candidate, with a surface magnetic field $B \sim 10^{14}$ G. This is incorrect, since RX J1856 belong to the neutron star class known as the XDINSs (see e.g. Turolla 2009, for a review), and its spin-down magnetic field is $\sim 10^{13}$ G, one order of magnitude lower (van

Kerkwijk & Kaplan 2008). Besides the effects on the polarization observables, this may also impact on their analysis on axion-like particle effects on the polarization signal.

5. Conclusions

Capparelli, Maiani & Polosa (2017) state "Finally, even if we assume that every single point of the star emits polarized light, then a degree of polarization of 16% may be reached in the absence of QED effects just by a favourable orientation of the magnetic axis of the star with respect to the observation line, as is also evident from some models analyzed in Mignani et al. (2017)." However, by performing a careful analysis (i.e. taking a dipolar magnetic field on the star surface, computing the polarization observables from phase-averaged Stokes parameters and accounting for the geometrical constraints given by the observations), we showed that the minimum polarization degree sufficient for a conclusive claim about vacuum birefringence effects for RX J1856 is indeed much lower than the maximum polarization attainable, which is not 40% but rather $\lesssim 14\%$. Hence, the claim put forward by Capparelli, Maiani & Polosa (2017) is totally unjustified.

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