Evidence of QED effects from the polarisation of the optical radiation from an Isolated Neutron Star

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RX J1856.5-3754 is a radio-quiet Isolated Neutron Star (INS) discovered in the soft X-rays through its purely thermal surface emission. Owing to its large inferred magnetic field of 10^{13} G, radiation from its surface is expected to be substantially polarised, independently on the mechanism actually responsible for the thermal emission. A large observed polarisation degree is, however, expected only if quantum electrodynamics (QED) vacuum birefringence effects are active in the magnetised vacuum around the star. Here, we report on the measurement of the optical linear polarisation for RX J1856.5-3754 ($V \sim 25.5$ mag) with the Very Large Telescope. We measured a polarisation degree P.D. = 16.43% ± 5.26%, large enough to support the effect of vacuum birefringence, as predicted by QED.

1 Introduction

Electromagnetic radiation in vacuum propagates along two modes, the ordinary mode (O mode), where the electric field oscillates parallel to the magnetic field plane, and the extraordinary mode (X-mode), where the electric field oscillates perpendicular to the magnetic field plane. The presence of a strong magnetic field, however, induces the formation of virtual electron/positron pairs, which changes the refraction indices along the X and O modes, and affects their propagation, changing the polarisation state of the electromagnetic radiation. This effect is known as vacuum birefringence and was predicted over 80 years ago by Heisenberg & Euler (1936) as one of the results of the quantum electrodynamics (QED). The change in the refraction index Δn between the two modes is proportional to the square of the magnetic field strength B as:

$$\Delta n = 4.031699 \pm 0.000005 \times 10^{-24} \left(\frac{B}{10^{14} G}\right)^2, \tag{1}$$

which means that the stronger the magnetic field, the larger the effect. The most recent laboratory measurement with the PVLAS experiment (Polarization of the Vacuum with LASer) yields $\Delta n = 4 \pm 20 \times 10^{-23}$ for $B = 10^{14}$ G, as shown by Della Valle et al. (2016), still a factor of ten above the value predicted for the same magnetic field intensity. In ground-based laboratories, magnetic fields up to $\sim 10^6$ G can be generated, paving the way to not too far in the future successful measurements. In any case, even when measured in laboratories, vacuum birefringence effects will be tested only in the weak field regime. With magnetic fields up to 10^{14} G at the surface, isolated neutron stars (INSs) are perfect cosmic laboratories to test vacuum birefringence effects in the strong field regime, unattainable on the Earth.

Of particular interest for this goal is a class of INSs that are radio quiet, in contrast to classical pulsars, and have been discovered only from the detection of thermal radiation from the hot ($T_\mathrm{s} \sim 10^5 - 10^6$ K) neutron star surface that is cooled by radiation. Seven of such cooling INSs are known, detected both in the soft X-rays ($0.05 - 0.1$ keV) and in the optical/ultraviolet. They have long spin periods ($P_\mathrm{s} = 3 - 11$ s) compared to most INSs and they have magnetic fields of the order of $10^{13} - 10^{14}$ G (Turolla, 2009).

What makes these cooling INSs interesting is that, in contrast to other INSs, such as the Crab pulsar where most of the electromagnetic radiation is produced by non-thermal processes in the neutron star magnetosphere and far from the star surface, the observed radiation is purely thermal and originates directly from the neutron star surface, possibly mediated by the presence of a thin atmosphere. Therefore, the study of the thermal radiation from these INSs is the only way to peek directly at (or close to) the star surface, i.e. where the magnetic field intensity is higher and vacuum birefringence effects are expected to be stronger. Since these INSs have exceptionally strong magnetic fields, the thermal radiation from the star surface is then expected to be significantly polarised (Potekhin, 2014). The effect of vacuum birefringence is to increase the linear polarisation degree dramatically, from a level of a few % up to 100 %, depending on the viewing geometry and the emission mechanisms (Heyl & Shaviv, 2000, 2002; Heyl et al., 2003).

The best target among the seven INSs with the purely thermal emission is RX J1856.5-3754. This source has a magnetic field of $\sim 10^{13}$ G, it is quite bright in the X-rays but rather faint in the optical ($V \sim 25.5$ mag), although it is still the brightest of the seven. Although polarisation measurements in the X-rays should be the obvious choice for this experiment, no dedicated X-ray polarimetry satellite is operating currently, with the first one, the NASA's *Imaging X-ray Polarimetry Explorer* (Weisskopf et al., 2016) to be launched early next decade with the Chinese *Enhanced X-ray Timing Polarimetry* satellite (Zhang et al., 2016), due to follow shortly. However, none of them will be sensitive in the soft X-ray regime, where this type of INSs are detected. Therefore, we decided to measure the linear polarisation of RX J1856.5−3754 in the optical domain, exploiting a well-consolidated technique in the optical astronomy.

2 Observations

We observed RX J1856.5-3754 with the Very Large Telescope (VLT) of the European Southern Observatory (ESO), an array of four telescopes of 8.2 m diameter, located at the Cerro Paranal Observatory (Chile). We used the second Focal Reducer and low dispersion Spectrograph (Appenzeller et al., 1998) mounted at the VLT/Antu telescope. The FORS2 camera is equipped with polarisation optics to measure linear polarisation through a Wollaston prism as a beam splitting analyser and two super-achromatic phase retarder 3×3 plate mosaics installed on rotatable mountings to be moved in and out of the light path. We used four half-wave retarder plate angles of $0°$, $22.5°$, $45°$, and $67.5°$, which correspond to the retarder plate orientations relative to the Wollaston prism. A filter with central wavelength $\lambda = 555.0$ nm and width $\Delta\lambda = 61.6$ nm, i.e. peaked in the V-band, was inserted along the light path. We acquired a total exposure time of 7920 s per retarder plate angle, with all exposures taken in dark time, with the target at the zenith and 0.8 arcsec seeing.

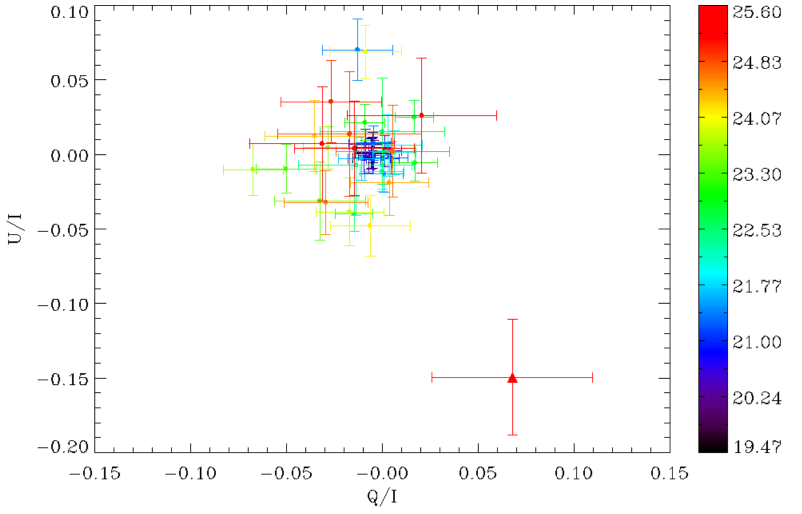

Fig. 1: Plot of the normalised Stokes parameters U/I and Q/I for a selected sample of 42 field stars (filled point; top left) and for RX J1856.5-3754 (filled triangle, bottom right). The colour scale on the right corresponds to the stars' V-band magnitude.

The degree of linear polarisation of a source is calculated from the normalised Stokes parameters: $P_{\rm U} \equiv U/I$ and $P_{\rm Q} \equiv Q/I$ computed as follows (Mignani et al., 2017):

$$P_{\rm Q} = \frac{1}{2}\left\{\left(\frac{f^{\rm o}-f^{\rm e}}{f^{\rm o}+f^{\rm e}}\right)_{\alpha=0^\circ} - \left(\frac{f^{\rm o}-f^{\rm e}}{f^{\rm o}+f^{\rm e}}\right)_{\alpha=45^\circ}\right\}, \quad (2)$$

$$P_{\rm U} = \frac{1}{2}\left\{\left(\frac{f^{\rm o}-f^{\rm e}}{f^{\rm o}+f^{\rm e}}\right)_{\alpha=22.5^\circ} - \left(\frac{f^{\rm o}-f^{\rm e}}{f^{\rm o}+f^{\rm e}}\right)_{\alpha=67.5^\circ}\right\}, \quad (3)$$

where $f^{\rm o}$ and $f^{\rm e}$ are the source fluxes in the ordinary and extraordinary beams, respectively, for each of the four retarder plate angles, and the polarisation degree P.D. $= ({P_{\rm Q}}^2 + {P_{\rm U}}^2)^{1/2}$.

3 Results

We measured a P.D. $= 16.43\% \pm 5.26\%$ for RX J1856.5-3754. Owing to the target faintness, it is important to verify that our measurement is not dominated by systematic errors and/or observational biases – see Mignani et al. (2017) for details. We tested the absolute accuracy of our polarisation measurement against polarised calibration stars and found that this is accurate to $0.13\% \pm 0.06\%$. Similarly, we estimated the spurious polarisation of the FORS2 optics to be $0.09\% \pm 0.06\%$ from the observations of un-polarised calibration stars. Both values are well below the statistical uncertainties. Since our observations were taken in dark time, the contamination of the sky background polarisation induced by the Moon reflection is also close to zero. Since our target is at a distance of 130 pc, we verified that our polarisation measurement was not affected by the dust grains along the line of sight by comparing the measured P.D. $= 16.43\% \pm 5.26\%$ with that of 42 stars in the field.

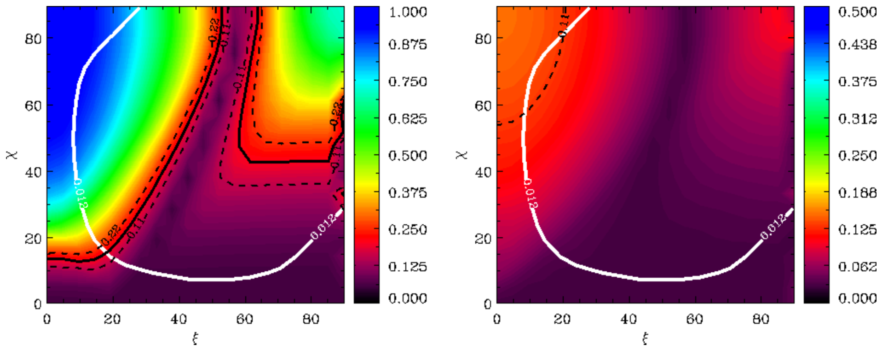

Fig. 2: Simulated P.D. of RX J1856.5-3754 as a function of the angles χ and ξ, i.e. between the LOS (line of sight) and the INS spin axis and between the INS magnetic and spin axis, respectively. A BB emission model is assumed. The white solid line represents the constraints on χ and ξ inferred from the pulsed X-ray lightcurve (Tiengo & Mereghetti, 2007), whereas the black solid line corresponds to our measurement, including 1σ errors (black dashed lines). The plots on the left and on the right represent the cases when we accounted or not for QED effects, respectively.

We found that the latter is consistent with zero as illustrated in Fig. 1. This implies that the foreground polarisation, which should affect all stars in the field of view in the same manner, is negligible. Thus, we are confident that our result is unaffected by calibration/observational biases.

We compared our measurement with the predictions for four different neutron star emission models: a plain back body (BB), a magnetised, completely ionised hydrogen atmosphere, and a condensed surface model (both in the fixed and free ion limit), based on numerical simulations (Taverna et al., 2015; González Caniulef et al., 2016). Fig. 2 shows the simulation corresponding to the BB case, where the P.D. is shown as a function of the angles χ and ξ between the LOS (line of sight) and the INS spin axis and between the INS magnetic and spin axis, respectively. The plot on the left accounts for QED effects. As it can be seen, the measured P.D. (black solid and dashed lines) is consistent with the model predictions and the constraints on χ and ξ imposed by the pulsed X-ray lightcurve profile (Tiengo & Mereghetti, 2007). This is also the case for the simulations performed for the different emission models (Mignani et al., 2017). Therefore, based on the current polarisation measurement, we cannot discriminate which of these models better describes the optical emission from RX J1856.5-3754. Decreasing the error on P.D. through deeper observations and deriving more constraining limits on χ and ξ will hopefully allow us to discriminate between different models. However interestingly, our simulations shows that when not accounting for QED effects all of the considered emission models predict values of P.D. that are only marginally consistent with our observations, see Fig. 2 (right) for the BB case. This is a clear indication that QED effects play a crucial role in explaining the observed value of the polarisation degree, as also discussed by Turolla et al. (2017). Therefore, this is the first, though indirect, observational evidence of the vacuum birefringence, as predicted by QED over 80 years ago by Heisenberg & Euler (1936) and the new example of synergy between astrophysics and nuclear/particle physics.

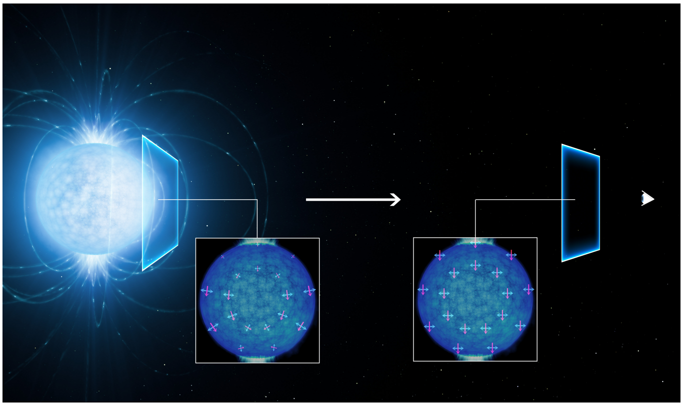

Fig. 3: Simulation of how the INS magnetic field affects the light polarisation as it propagates away from the neutron star up to a distance of 9 neutron star radii. The blue and red arrows indicate the electric and magnetic field vectors, respectively (image credit ESO).

Fig. 3 illustrates how the polarisation degree changes when moving away from the neutron star surface, with the electric and magnetic field vectors progressively aligning in a specific direction, as predicted by the vacuum birefringence effect[1]. The effect asymptotically reaches its maximum at the distance from the neutron star called adiabatic radius (r_a) (Taverna et al., 2015), defined as

$$r_\mathrm{a} \approx 4.8 \left(\frac{B}{10^{11}\mathrm{G}}\right)^{2/5} \left(\frac{E}{1\,\mathrm{keV}}\right)^{1/5} R_\mathrm{NS}, \quad (4)$$

where E is the photon energy, B is the magnetic field at the star surface, and R_NS is the neutron star radius. In the case of RX J1856.5-3754, $B \sim 10^{13}$ G and $E = 2.25$ eV is the photon energy at the peak of the V-band, which implies $r_\mathrm{a} \sim 9\,R_\mathrm{NS}$, i.e. very close to the neutron star surface.

4 Future perspectives

Follow-up polarimetry observations of RX J1856.5-3754 recently obtained at the VLT with the same instrument set-up but for a twice as long integration time will consolidate our result. Polarimetry measurements in other optical filters will also be important to test the dependence of the effect on the radiation wavelength. Measuring polarisation for other INSs like RX J1856.5-3754 would be important to verify the effect on sources with different magnetic field values. This is observationally challenging, however, since all these other sources are fainter than RX J1856.5-3754, which requires a more massive investment of the observing time. In the X-rays, polarimetry measurements with the upcoming X-ray polarimetry missions, sensitive between 2 and 8 keV, will make it possible to search vacuum birefringence effects in magnetars (Mereghetti, 2011), which have an X-ray spectrum harder than RX J1856.5-3754 and even higher magnetic field values, and for which polarisation measurements in the optical are complicated by their larger distances (a few kpc) and foreground

[1] The animated version of the figure is available at `https://www.eso.org/public/videos/eso1641a/`

polarisation contamination owing to their position in the Galactic disk. One of such missions is the NASA's *Imaging X-ray Polarimeter Explorer* (Weisskopf et al., 2016), which is due to be launched in the early 2020s. The other is the *enhanced X-ray Timing and Polarization* mission (Zhang et al., 2016), to be launched in the mid 2020s, which benefits of a strong participation from Polish astronomers and will be the most sensitive polarimetry mission ever flown.

Acknowledgements. RPM thanks the organisers of the 38th Polish Astronomical Society assembly and acknowledges financial support from an *Occhialini Fellowship* from the Italian national Institute of Astrophysics.

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