Constraining Gravitational Theories by Observing Magnetic White Dwarfs

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Abstract. Under the assumption of a specific nonminimal coupling of torsion to electromagnetism, spacetime is birefringent in the presence of a gravitational field leading to depolarization of light emitted from extended astrophysical sources. We use polarimetric data of the magnetic white dwarf RE J0317-853 to set for the very first time constraints on the essential coupling constant for this effect, giving \( k^2 \lesssim (22 \text{m})^2 \).

1. Introduction

Efforts to develop a quantum theory of gravity or a complete, consistent and unified theory of matter and all its interactions are rich and compelling sources of speculation about new physics beyond the scope of the standard model of particle physics or of general relativity. The effective field theories that emerge as low-energy limits of string theories are littered with new fields and interactions. Since cherished symmetries like CPT and Lorentz invariance can be broken in these contexts (Colladay et al. 1998), high-precision experimental and observational tests of these symmetries offer particularly effective ways of searching for evidence of new physics. This project was motivated by current speculations assuming a special nonminimal coupling of torsion to electromagnetism (Preuss et al. 2004, Solanki et al. 2004). Members of the class of metric-affine theories (Hehl et al. 1995) of gravity feature torsion and/or nonmetricity gravitational fields in addition to a symmetric second-rank tensor gravitational potential. We suggest, in addition to the conventional Maxwell Lagrangian, the additional nonminimal coupling

\[ L_{EM} = k^2 \ast (T_\alpha \wedge F) T^\alpha \wedge F, \] (1)

see (Itin & Hehl 2003) for other possibilities, where \( k \) is a coupling constant with the dimension of length, \( \ast \) denotes the Hodge dual, \( T \) denotes the torsion and \( F \) the electromagnetic field, which is related in the usual way to its potential \( A \). This addition is consistent with gauge invariance and, so, with charge conservation.

We use static, spherically symmetric torsion fields (Tresguerres, 1995) in which a nonminimal coupling to electromagnetism singles out linear polariza-
Metric-affine theory

Strong gravitational field

If $k > 0$

Different $\theta$ from all parts of an extended source

Depolarization of combined polarization from extended source

Observed polarization from extended source

Limits on $k$

Magnetic field modulus distribution

(concentrated between 140MG and 200MG at phase with strong polarization

Extreme assumption: All field vectors point towards observer

Maximum possible polarization: 26.5%

Observed: 17%

$\Delta \Phi = \sqrt{\frac{2\pi k^2 M (\mu + 2)(\mu - 1)}{\lambda R^2}} \frac{\mu}{\mu + 1}$, \hfill (2)

where $\mu$ denotes the cosine of the angle between the line of sight and the normal on the stellar surface ($\mu = 1$: stellar disk center, $\mu = 0$: limb), $\lambda$ is the light’s wavelength, $R$ is the stellar radius and $M$ the stellar mass in geometrized units.

2. Data, analysis and results

If an extended source covering a range of $\mu$ values is observed then light emitted from different points suffers different phase shifts and, so, adds up to an incoherent superposition. This yields a reduction of the observed polarization relative to the light emitted from the source: $(U_{\text{obs}}^2 + V_{\text{obs}}^2)^{1/2} < (U_{\text{src}}^2 + V_{\text{src}}^2)^{1/2}$. Since the rotationally modulated polarization from magnetic white dwarfs can only be produced by an extended source any observed (i.e. non-zero) degree of polarization provides a limit on the strength of birefringence induced by the star’s gravitational field.

The polarized radiation from white dwarfs is produced by the magnetic field. Since the disk of a white dwarf is unresolved, only the total polarization
from all surface elements is observable:

\[
V_{\lambda,\text{tot}}(k^2) = 2\pi \int \int V_{\lambda}(\mu, B, B_\parallel) \cos(\Delta \Phi) \mu \, d\mu \, d\phi ,
\]

where the Stokes parameter \( V_{\lambda} \) changes over the visible hemisphere and depends on the wavelength \( \lambda \), the location \( \mu \) (limb darkening), the total magnetic field strength \( B(\theta, \phi) \), the line-of-sight component \( B_\parallel(\theta, \phi) \), and on the parameters of the stellar atmosphere. Gravitational birefringence reduces the polarization by means of \( \cos(\Delta \Phi) \), see Fig. 1.

The Stokes parameters can be calculated by solving the radiative transfer equations through a magnetized stellar atmosphere on a large number of surface elements on the visible hemisphere. If the star is rotating, the spectrum and polarization pattern changes according to the respective magnetic field distribution visible at a particular moment. To obtain the degree of circular polarization, Eq. (3) has to be divided by the total stellar flux \( I_{\lambda,\text{tot}} \) emitted to the observer at wavelength \( \lambda \).

The rapidly rotating hot magnetic white dwarf RE J0317-853 (Barstow et al. 1995) is best suited for setting limits on gravitational birefringence, since it has a strong gravitational field (1.35 \( M_\odot \), 0.0035 \( R_\odot \)), and, with \( V_{\lambda,\text{obs}}/I_{\lambda,\text{tot}} \) of 17\% at 5760\,Å the highest known level of circular polarization in a white dwarf (Jordan & Burleigh 1999). We use a value of 17\% here instead of 20\% as in Preuss et al. (2004) since this more conservatively takes into account that higher value may only be reached by some noise peaks. The analysis of time resolved HST flux spectra in the UV has shown that the distribution of the field moduli is approximately that of an off-centered magnetic dipole oriented obliquely to the rotation axis with a polar field strength of \( B_d = 363 \text{ MG} \), leading to visible surface field strengths between 140 and 730 MG (Burleigh et al. 1999). This model can also approximately fit the optical spectra (Jordan et al. in prep.), which means that the distribution of the magnetic field moduli - but not necessarily of the longitudinal components - is correctly described. This result is completely independent of the magnitude of the gravitational birefringence. From radiative transfer calculations it follows that at the phase of rotation when the maximum value of 17\% polarization at 5760\,Å is measured, almost the entire visible stellar surface is covered by magnetic fields between 140 and 200 MG, with only a small tail extending to maximum field strengths of 530 MG. Using this special field geometry we calculated a histogram distribution of the visible surface magnetic field strengths in order to set sharp limits on gravitational birefringence. For each field strength bin of the histogram we calculated the maximum circular polarization from radiative transfer calculations by assuming that the field vector always points towards the observer. The total maximum polarization from the whole visible stellar disk without gravitational birefringence is then calculated by adding up the contributions from each field strength bin weighted with its relative frequency. This results in \( V_{\lambda,max}/I_{\lambda,\text{tot}} = 26.5\% \).

Assuming that the reduction to the observed \( V_{\lambda,\text{obs}}/I_{\lambda,\text{tot}} = 17\% \) is entirely due to gravity-induced depolarization – and not due to the fact that in reality not all field vectors point towards the observer – we can calculate an upper limit for this effect of \( k^2 \lesssim (22 \text{ m})^2 \), see Fig. 2. Since there is always a small uncertainty in determining the exact mass of a white dwarf, we also calculated an upper limit on \( k^2 \) assuming a lower mass of 1 \( M_\odot \). This leads to \( k^2 \lesssim (25.5 \text{ m})^2 \).
An even more extreme assumption would be to use the maximum circular polarization predicted by all field strengths in the interval $140 - 530$ MG (reached at $530$ MG) for the whole stellar disk. Then we obtain $V_{\lambda,\text{max}}/I_{\lambda,\text{tot}} = 48.3\%$ and an upper limit of $k^2 \lesssim (33 \text{ m})^2$. Independent from any dipole model and without any reference to radiative transfer calculations the assumption of $100\%$ emerging polarization leads to $k^2 \lesssim (47.5 \text{ m})^2$. In order to compare the quality of our method with previous similar results (Solanki et al. 1999) we also set new upper limits on the NGT parameter $\ell^2_\star$ which also causes gravitational birefringence in case of $\ell^2_\star \neq 0$. Assuming $V_{\lambda,\text{max}}/I_{\lambda,\text{tot}} = 26.5\%$ leads to $\ell^2_\star \lesssim (1.8 \text{ km})^2$ in contrast to $\ell^2_\star \lesssim (4.9 \text{ km})^2$, determined for the white dwarf GRW $+70^\circ 8247$.

3. Conclusions

The spectropolarimetric observations of the massive RE J0317-853 impose new strong constraints on the birefringence of space-time in the presence of a gravitational field with an upper limit for the relevant coupling constant $k^2$ of $(22 \text{ m})^2$ or $(47.5 \text{ m})^2$ for the most conservative assumptions. Since gravity-induced birefringence violates the Einstein equivalence principle, our analysis also provides a test of this foundation of general relativity and other metric theories of gravity. We consider as a specific case a metric-affine theory that couples the electromagnetic field nonminimally with torsion and for which a static spherically symmetric solutions has been found. Considerably tighter limits based on the same astronomical source could be provided by measurements of circular polarization in the FUV (in particular associated with Ly$\alpha$ absorption features) and also by a consistent model for the magnetic field geometry which reproduces the spectropolarimetry measurements in the optical.

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