Polarized Spectra from Magnetized Hydrogen Neutron Star Atmospheres

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Abstract:

Here we present an integration of the state of the art in the modeling of the thermal emission from magnetized neutron stars with a detailed calculation of the propagation of the radiation through the neutron star magnetosphere including both relativistic and quantumelectrodynamic effects. We find, counter to previous predictions, that the thermal radiation of NSs should be highly polarized even in the optical. When detected, this polarization will be the first demonstration of vacuum birefringence. It could be used as a tool to prove the high magnetic field nature of AXPs and it could also be used to constrain physical NS parameters, such as R/M, to which the net polarization is sensitive.

Introduction

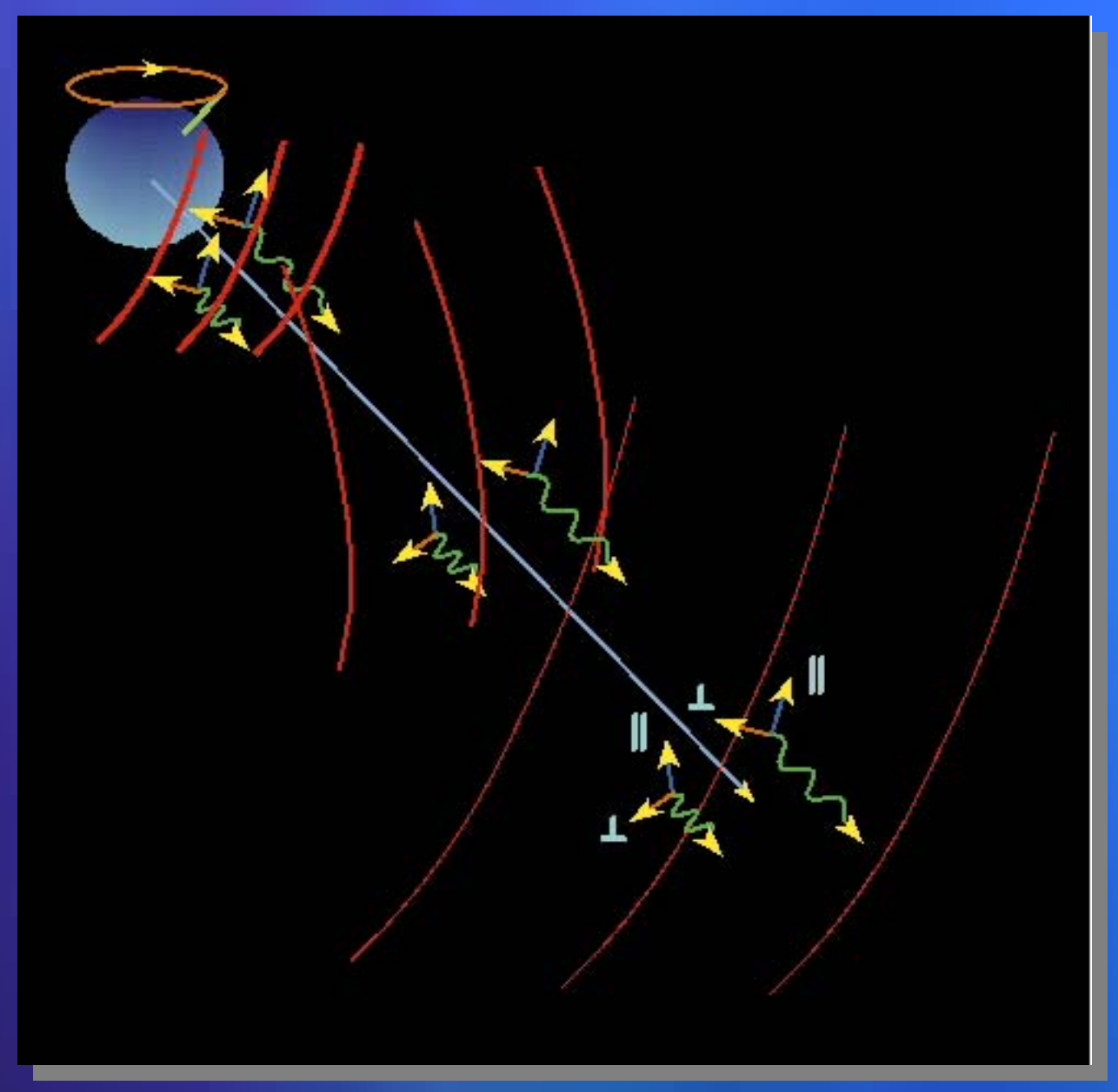
In the presence of strong magnetic fields, the vacuum becomes a birefringent medium. We show that this QED effect decouples the polarization modes of photons leaving the NS surface. Both the total intensity and the intensity in each of the two modes is preserved along a ray's path through the neutron-star magnetosphere. We analyze the consequences that this effect has on aligning the observed polarization vectors across the image of the stellar surface to generate large net polarization.

Why is the vacuum birefringent?

Here is the lowest order vacuum polarization diagram. The effects of the external magnetic field can be calculated exactly.

Photons travelling through a strong magnetic field are slowed by the presence of the virtual photons in the vacuum. Furthermore, photons whose electric vector has a component parallel to the magnetic field of the star are impeded more. Even for magnetars the difference in the index of refraction is small even for $B \sim 10^{15}$ G. However, not only is Δn important for the propagation of polarized radiation through a medium, but so is $\Delta n\, r/\lambda$ where r is the distance on which the strength or direction of the magnetic field changes substantially and λ is the wavelength of the radiation.

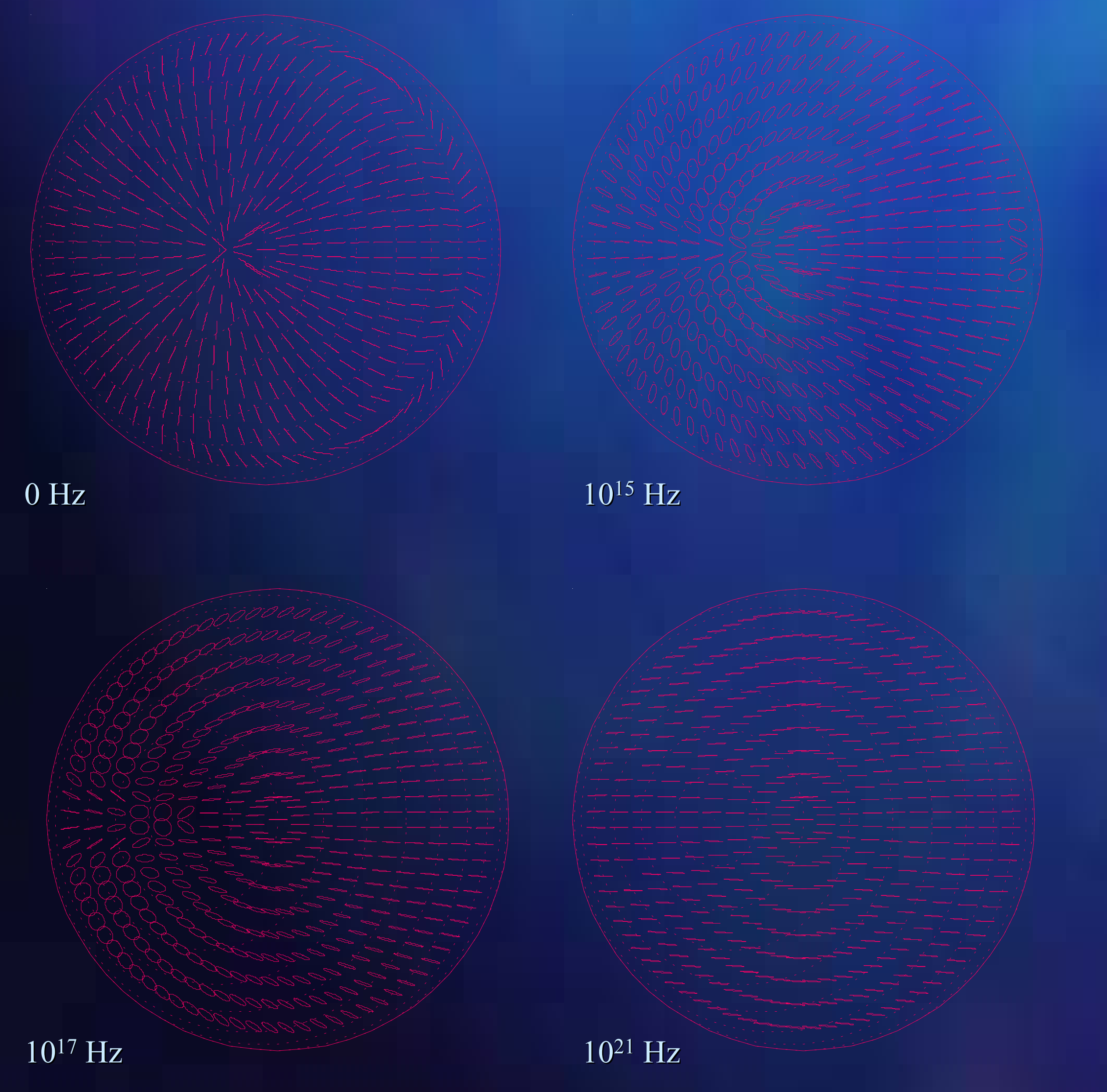
For neutron stars this number (the number of Faraday rotations over the scale length of the magnetic field) can be large within many stellar radii of the surface of the star. This has important consequences for the polarized radiation emerging from the atmosphere of the neutron star.



Polarized radiation follows the local direction of the magnetic field.

Dragging polarization through the magnetosphere

The atmosphere of a neutron star emits highly polarized radiation because the opacities for radiation propagating through it is vastly different for the two polarization states. Radiation with an electric field component along the magnetic field is more readily absorbed or scattered than the other polarization. Because the polarization states of the atmosphere are nearly the same as those of the vacuum, the Faraday depolarization of the magnetosphere does not depolarize the radiation but rather it causes the radiation to remain polarized preferentially perpendicular to large radii from the neutron star; therefore, the polarization that we observed from a portion of the surface reflects not the direction of magnetic field on the surface but its direction many radii from the star. At such a distance, all of the radiation that will ultimately reach our telescopes passes through only a small solid angle over which the direction of the magnetic field varies little.



The plots show the final polarization states of radiation leaving the surface of the neutron star polarized parallel to the local direction of the magnetic field. The upper left figure shows the result neglecting QED. The upper right figure gives the polarization pattern for $\mu_{30}\nu = 10^{15}$ Hz. The lower left panel has 10^{17} Hz, and the lower right panel is 10^{21} Hz. The dipole axis makes an angle of 60 degrees with respect to the line of sight, the radius of the star is 12 km, its mass is 1.4 solar masses

Magnetosphere above and atmosphere below

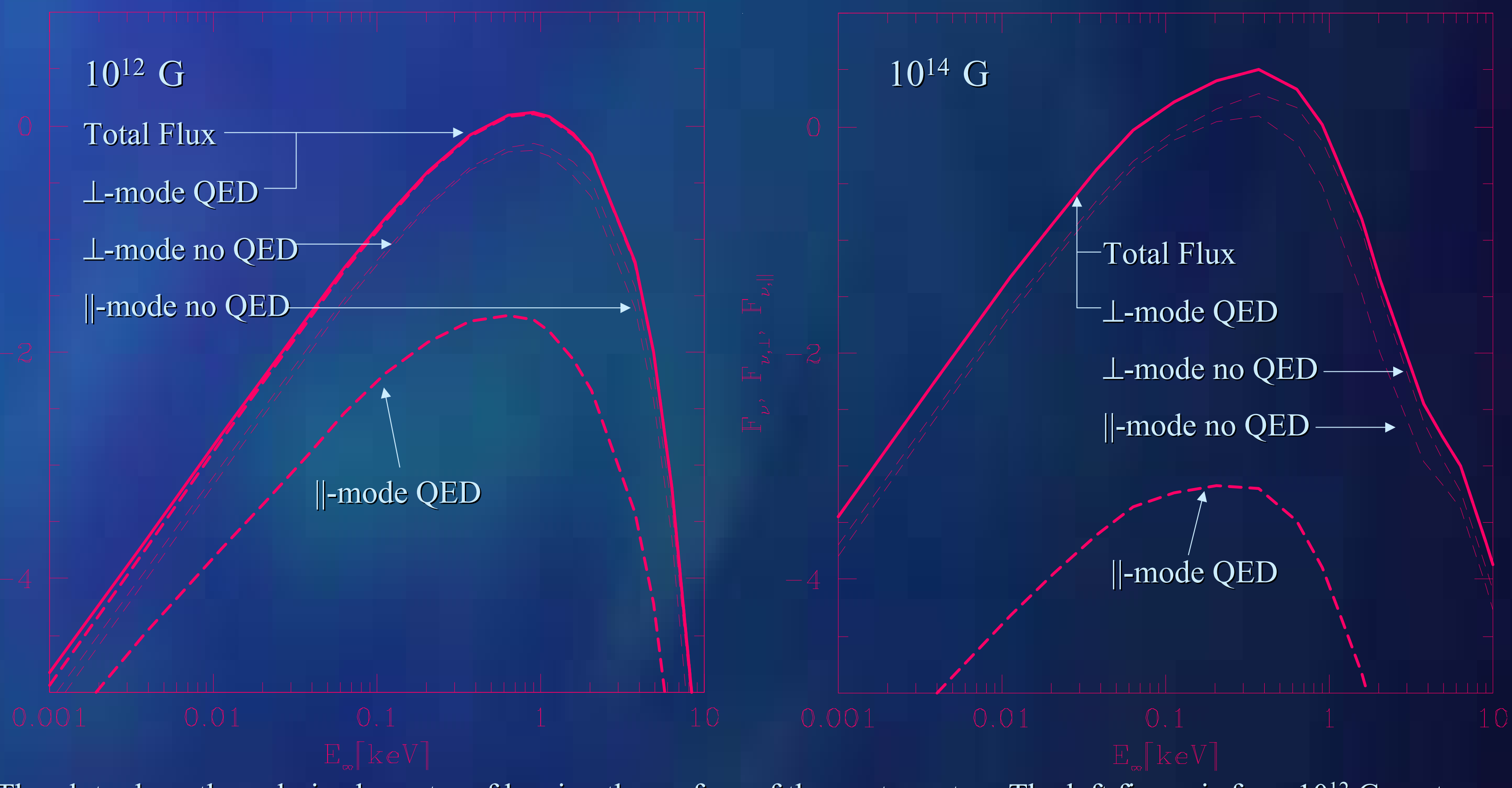
As described earlier the atmosphere of a neutron star typically emits radiation that is highly polarized. Here we will use the atmosphere models of Lloyd, Hernquist and Heyl (2003). Although some subtle details of the emergent spectra depend on the value of the surface gravity, we are only concerned with the gross polarization of the emergent radiation; therefore, we adopt a canonical value of $g = 2.4\ 10^{14}$ cm s^{-2}. This simplification reduces the number of atmosphere calculations by a factor of three.

The polarized spectrum is derived numerically from a self-consistent solution to the equations radiative transfer for a stationary, plane-parallel atmosphere in radiative equilibrium. We adopt the simplifying assumption that the atmospheric plasma is pure hydrogen in the limit of complete ionization, for which the opacity sources are inverse bremsstrahlung, Thomson scattering, and resonant scattering by protons. The magnetic field is assumed to be vertically uniform. The atmospheric model is obtained by the method of complete linearization, starting from a power-law prescription for the conductivity of the plasma as a trial solution. Convergence is achieved $\Delta T/T < 10^{-3}$ typically within 10-20 iterations; flux is conserved to about 10^{-4} at all depths.

Radiative transport proceeds in two coupled normal modes of polarization, uniquely defined for propagation angle θ_B with respect to the direction of **B**. The magnetic field induces a strong angular dependence in the plasma opacity, and suppresses the opacity by a factor E_γ/E_{cyc} in one mode of propagation. Consequently, the emergent flux is dominated by the "extraordinary mode" which sees a more transparent medium over a broad range of θ_B. To the best of our knowledge, these models are the first models to employ complete linearization and to consider neutron-star atmospheres where the magnetic field is slanted with respect to the normal.

Putting it all together

We divide the surface of the neutron star into patches of equal size and calculate the intensity of the emerging radiation for each patch in all directions. Furthermore, for each patch we calculate how the polarization states evolve between the surface of the neutron star and the telescope. We choose the observed polarization basis to be states with the electric field parallel to the projection of the magnetic dipole axis into the plane of the sky and the field perpendicular to this direction. We find in general that the observed radiation is preferentially polarized perpendicular to the direction of the projected dipole axis.



The plots show the polarized spectra of leaving the surface of the neutron star. The left figure is for a 10^{12} G neutron star, and the right figure is for a 10^{14} G neutron star. In each figure the top line is the total flux. The next line is the flux polarized perpendicular to the dipole axis (for the 10^{14} G star this line lies on top of the first line). The next pair of lines if the flux polarized perpendicular and parallel to the dipole axis with QED-induced birefringence neglected and the bottommost line is the flux in the state polarized parallel to the dipole axis including QED. The dipole axis makes an angle of 60 degrees with respect to the line of sight, the radius of the star is 12 km, its mass is 1.4 solar masses and the effective temperature at the pole is $10^{6.5}$ K.

Conclusions

We have found that without QED-induced birefringence the net polarization of the radiation from the surface of a neutron star is small. QED boosts the observed net polarization by an order of magnitude which makes it potentially observable both in the optical and the X-rays. Observations of the polarized radiation from the surface of a neutron star not only will verify the strong magnetic fields on the surface of neutron stars and predictions of QED but will also provide constraints on the neutron stars themselves.