Models of Extended Envelopes of Magnetars

Thijs van Putten, Anna Watts
Astronomical institute 'Anton Pannekoek', University of Amsterdam
tputten@science.uva.nl

Abstract

We are creating hydrostatic models of general relativistic envelopes of magnetars to test whether these envelopes could remain stable and in hydrostatic equilibrium during a phase of radius expansion and contraction. This is to see if it would be possible for magnetars to udergo Photospheric Radius Expansion (PRE) bursts. We present results for a simplified magnetic model, which is slightly unstable for large photospheric radius, and compare to nonmagnetic models which are stable. We discuss the complications and considerations for more advanced models.

Motivation

It was recently shown by Watts et al. (2010) that it might be possible to observe Photospheric Radius Expansion during magnetar bursts. If possible this would help to constrain the equation of state and the burst emission mechanism, as well as provide an independent measurement of magnetic field strength. We are following up on this work by creating hydrostatic envelope models to check the stability of the envelope during a phase of expansion and contraction.

Nonmagnetic models

We reproduced the models made by Paczynski & Anderson (1986), who solved the equations of stellar structure for the envelope of a nonmagnetic neutron star. The results show that the envelope consists of a compact inner envelope where physical parameters change rapidly and an extended outer envelope. Figure 1 shows that luminosity remains just below the critical luminosity (the luminosity at which the outward radiation force on a test particle overcomes gravity) throughout the envelope. These results show that the envelope of a neutron star can by in hydrostatic and radiative equilibrium at a large range of photospheric radii, and thus prove that PRE should be possible without the envelope becoming unstable.

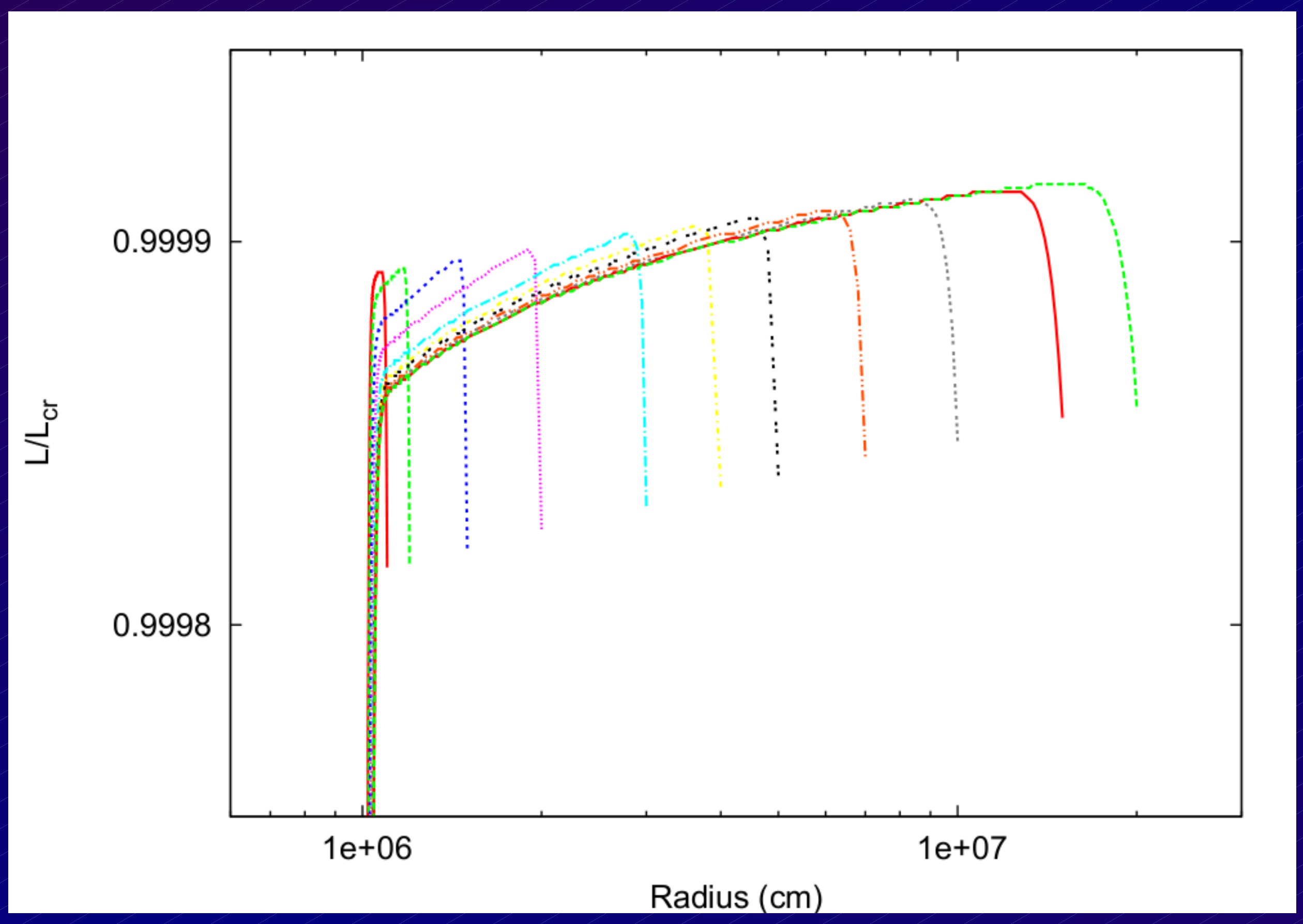

Figure 1. Luminosity structure for a series of models with neutron star radius 10 km and photospheric radii 11-200 km. It can be seen that the luminosity is very close to the critical luminosity throughout the envelope.

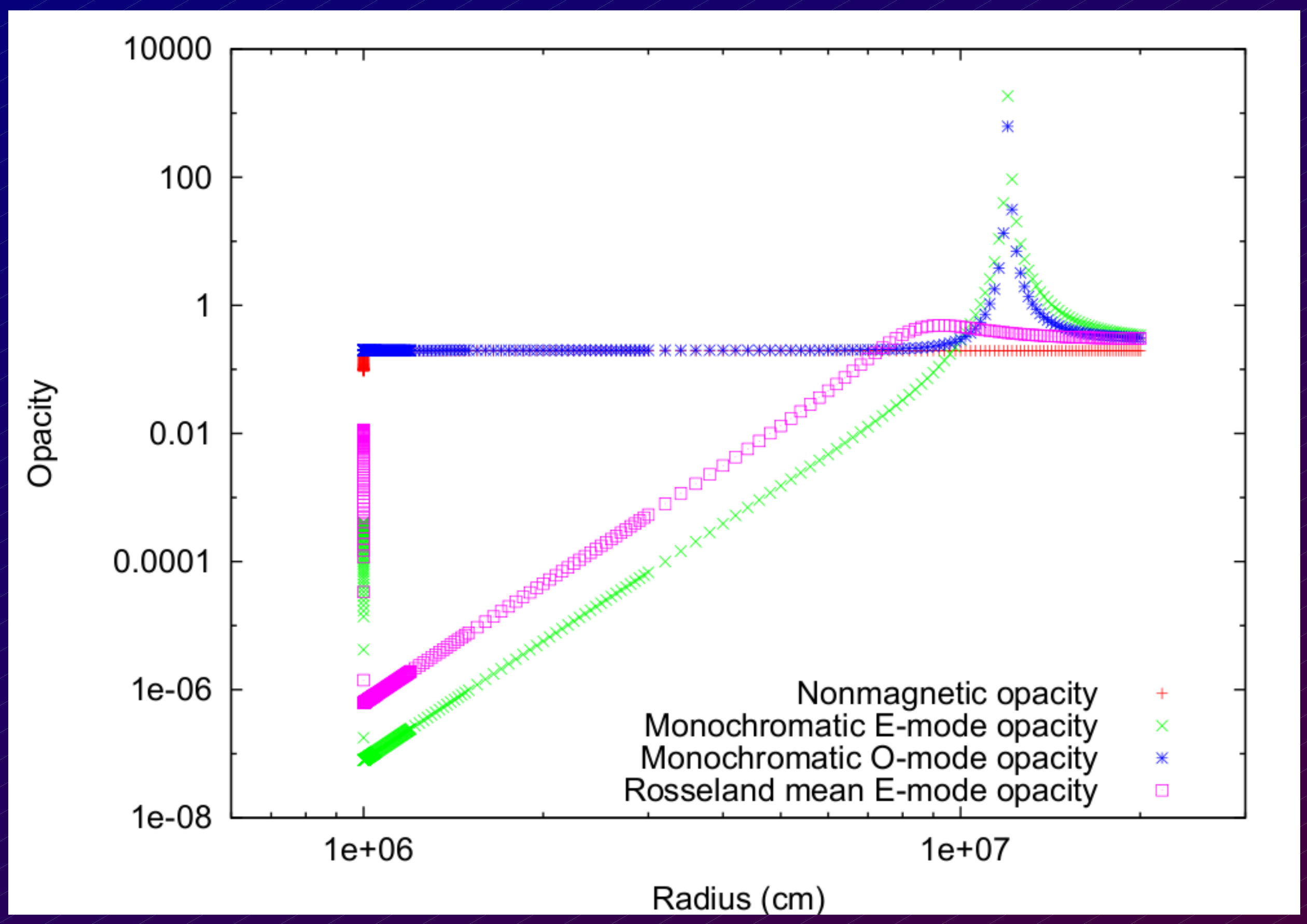

Figure 2. Plot of different opacities versus radius for a model with neutron star radius 10 km, photospheric radius 200 km and magnetic field at the surface of 10^{14} G. Shown are the nonmagnetic opacity, monochromatic opacities at the local temperature for E-mode and O-mode photons and the Rosseland mean opacity for E-mode photons. The peak in the monochromatic opacities is due to the cyclotron resonance. Magnetic opacities are based on Herold (1979).

References

Herold, H. 1979, Phys. Rev. D, 19, 2868
Paczynski, B. & Anderson, N. 1986, ApJ, 302, 1
Watts, A. L. et al. 2010, ApJ, 719, 190

Opacity in strong magnetic fields

The dominant source of opacity in neutron star envelopes is Compton scattering off free electrons. In the nonmagnetic case this opacity differs from the Thomson opacity by no more than a factor two, depending on temperature. However, in strong magnetic fields the opacity can be reduced by several orders of magnitude, depending on polarization. Figure 2 shows the nonmagnetic opacity as well as the opacities for E-mode (polarized perpendicular to the field) and O-mode (polarized parallel to the field) photons.

In addition to the mode dependency the scattering cross section, which gives rise to the opacity, is also strongly dependent on the angle between the direction of propagation and the magnetic field. Getting an accurate opacity at any point in the envelope thus requires knowing the distribution of photons over angles and modes, which requires photon by photon scattering simulations.

Simple magnetic models

We compute the same models as for the nonmagnetic case, changing just the opacity using the following assumptions.

- A purely radial magnetic field, falling off with radius as a dipole.
- All photons in the E-mode polarization state.
- Isotropic black body radiation at the local temperature.
- Rosseland mean opacity.

The resulting luminosity structure can be seen in Figure 3. This shows that for large photospheric radius the envelope is almost (but not entirely) stable. For smaller photospheric radius the luminosity is below critical everywhere, but will clearly become supercritical just outside the photosphere. For these radii the outer boundary has to be moved beyond the photosphere, as the point of maximum L/Lcr needs to be included, since for stability the luminosity has to be subcritical everywhere.

The actual luminosity propagated in these models is of the same order of magnitude as in the nonmagnetic models, where it is roughly 3.5x10^{38} erg/s.

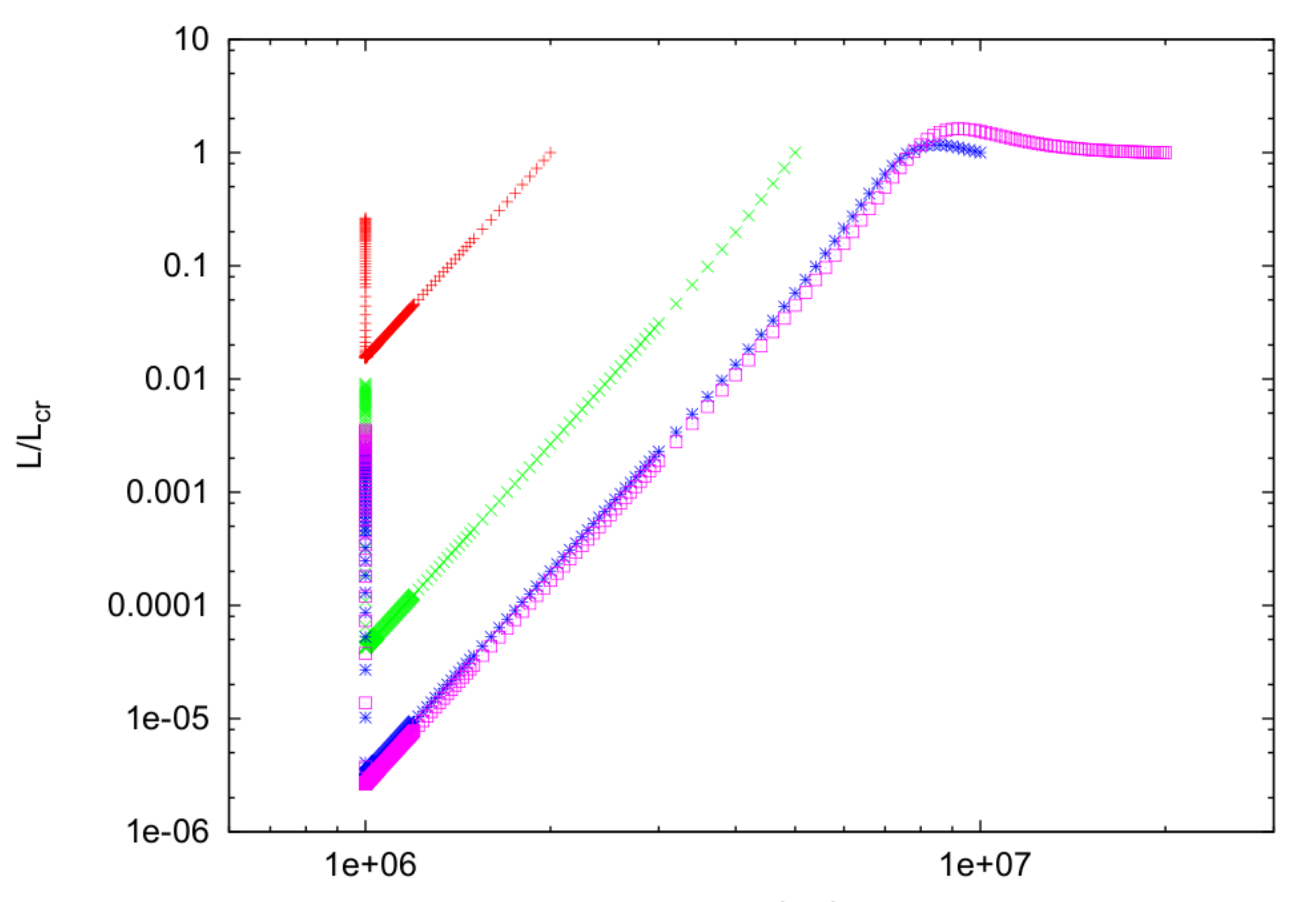

Figure 3. Luminosity structure for simple magnetic models with neutron star radius 10 km and photospheric radii 50, 100 & 200 km.

Advanced models

Iterating between solving the structure equations and Monte Carlo simulations would be ideal, but computationally expensive.

The simple models can be improved by moving the outer boundary conditions outwards to include the point of maximum L/Lcr and doing some Monte Carlo simulations to make better assumptions about the photon distributions.

The composition will make a large difference. The current model assumes ionized helium, but addition of an electron positron plasma will drastically decrease the critical luminosity.

For realistic magnetic fields closed field lines will prevent expansion, making these models only relevant in open field-line regions.

These factors need to be taken into account if we are to obtain a full understanding of PRE during magnetar bursts.