Modeling of cyclotron lines in the spectra of isolated neutron stars

M. Garasyov, E. Derishev and Vl. Kocharovsky

Institute of Applied Physics, Nizhny Novgorod, Russia

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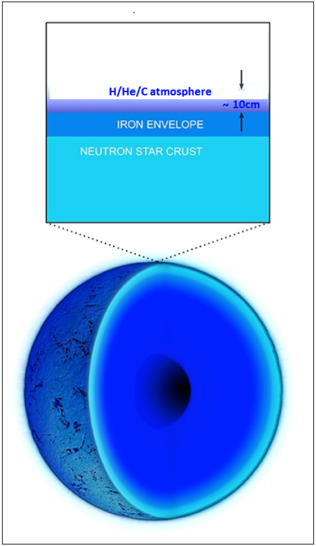
Transfer of radiation in atmospheres of compact stars



- Strong cyclotron lines, scattering is dominant over absorption
- Qualitatively different behavior of resonant photons in the cyclotron lines and in the atomic lines
- Vacuum polarization could be important
- Strong radiation pressure could create stellar wind

Radiation driven winds in the atmospheres of compact stars

- The opacity of magnetized plasma is very high near the frequencies $\omega = n\omega_B$, where $\omega_B = eB/(mc)$:

$$\frac{\sigma_{\rm cyc}}{\sigma_{\rm T}} \sim \frac{1}{\alpha\beta_T}\frac{mc^2}{\hbar\omega_B} \approx 4 \cdot 10^5 \frac{1}{\sqrt{T_{100\,eV}}B_{12}}$$

- Strong radiation force in the cyclotron line could accelerate plasma and form an outflow from the atmosphere, i.e., a cyclotron wind.

- Mitrofanov, Pavlov, 1981
- Sturner, Dermer, 1994
- Zheleznyakov, Koryagin, Serber, 2001

Approximations

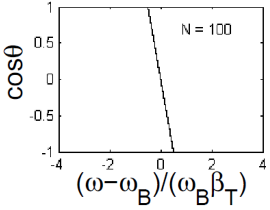
- Rarified plasma: $|n_{O,X} - 1| \ll 1$.
- All electrons on the ground Landau level.
- Isothermal atmosphere with constant temperature T, which corresponds to the Maxwellian distribution of electrons over longitudinal (with respect to the magnetic field) velocities

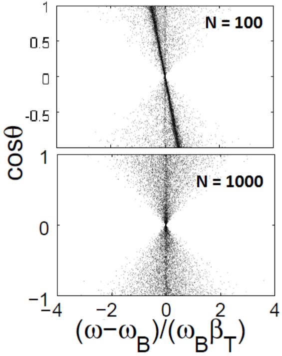
$$f(\beta) = \left(\frac{c^2}{2\pi m T}\right)^{1/2} \exp\left(-\frac{\beta^2}{2\beta_T^2}\right), \tag{1}$$

  where $\beta = v/c$ is the dimensionless longitudinal velocity, $\beta_T = (T/(mc^2))^{1/2}$ the thermal velocity.
- Plane-parallel atmosphere:

$$H = \frac{2kT}{m_p g} \ll R.$$

Trapping of resonant photons in the line core





Resonance condition. Nonrelativistic approximation. Quasicoherent scattering (Zheleznykov, Litvinchuk, 1987)

$$\omega(1-\beta\cos\theta)=\omega_B.$$

$$\beta_*=(\omega-\omega_B)/(\omega\cos\theta)$$

$$(\omega,\theta)\Longleftrightarrow(\frac{\omega-\omega_B}{\omega\cos\theta},\theta).$$

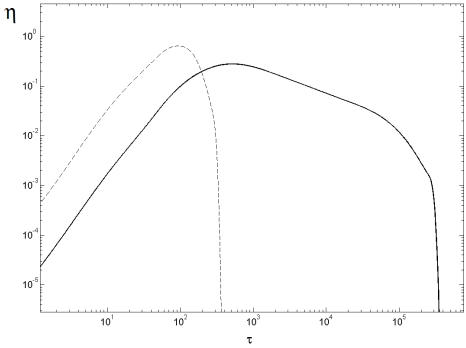
Mildly relativistic approximation

$$\omega(1-\beta\cos\theta+\frac{\beta^2}{2})=\omega_B.$$

Two resonance velocities:

$$\beta_{1,2}=\cos\theta\pm\sqrt{\cos^2\theta-2\left(1-\frac{\omega_B}{\omega}\right)}.$$

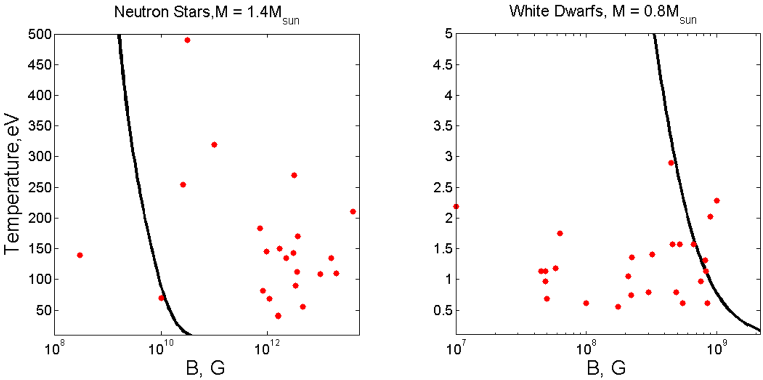
Semiinfinite atmosphere with absorption



Relative fraction η of photons emitted at optical depth τ in the emergent spectra. Solid line — with redistirbution effects; dashed — without (quasicoherent scattering).

Atmospheric parameters: $T = 50\,\text{eV}$, $\gamma/\omega_{\boldsymbol{B}} = 10^{-\mathbf{6}}$, $P_{\rm abs}/P_{\rm sc}(\tau = 1) = 10^{-\mathbf{6}}$.

Semiinfinite atmosphere with absorption



Quasicoherent approximation works well only to the left from the solid line. Redistribution effects become important in the right zone. Dots represent some known white dwarfs and neutron stars.

Conclusions related to the spectral redistribution

Statistically, the redistribution of photons out of the cyclotron line results in a boosted probability of their escape from a large optical depth. As our simulations show, the emerging radiation is gathered over a large interval of optical depths, spanning one or two orders of magnitude. Potentially, this causes all sorts of inhomogeneities to show up in the resulting spectrum in a more pronounced way, and the radiation transfer equation in these situations should be solved over a range of optical depths sufficiently large to capture the origin of the major part of outgoing photons.

Impact of different physical effects on radiation transfer

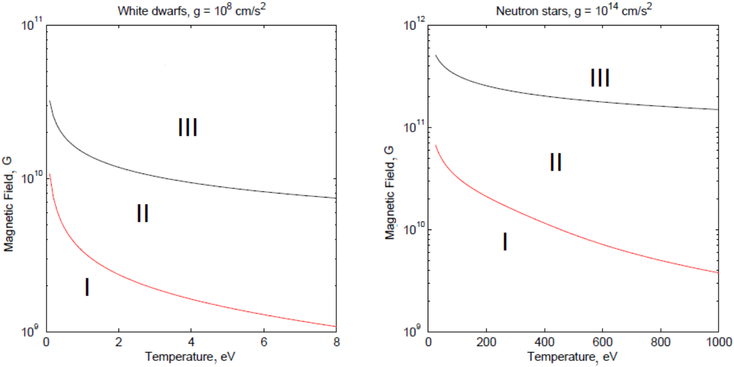


Figure 5. Zones where different physical effects influence the transfer of radiation. In zone I, photons leave the atmosphere without significant redistribution in the cyclotron line, in this situation it is sufficient to solve transfer equations in the quasicoherent approximation. In zone II, such redistribution plays an important role and can not be neglected in order to compute exact cyclotron line profile. Additionally, in zone III, vacuum polarization is strong enough to influence the dispersion properties of normal waves in the regions of atmosphere where scattering is still important (i.e., in regions with $\tau > 1$).

Transfer equations. General view

The intensity vector $\mathbf{J}$:

$$\mathbf{J} = \frac{1}{2} \begin{pmatrix} I + Q \\ I - Q \\ 2U \\ 2V \end{pmatrix} . \tag{2}$$

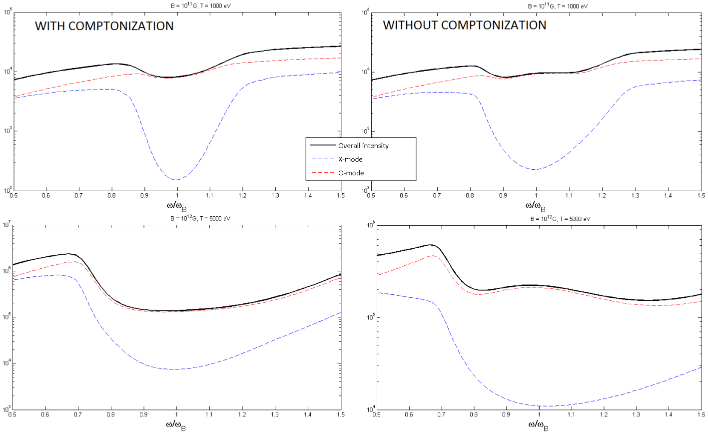
The evolution of intensity vector is described by transfer equations:

$$\frac{\mathrm{d}\mathbf{J}}{\mathrm{d}s} = -\mathbf{M} \cdot \mathbf{J} + \mathbf{S}_{\mathrm{em}} + \mathbf{S}_{\mathrm{sc}} , \tag{3}$$

where s is the coordinate along the ray. Source functions $\mathbf{S}_{\mathrm{em}}$ and $\mathbf{S}_{\mathrm{sc}}$ describe emission of plasma and rescattering respectively. $\mathbf{M}$ is the transfer matrix, which describes absorption, scattering and evolution of polarization.

Example spectra of emergent radiation

Neutron star, fully ionized hydrogen atmosphere, top - $B = 10^{11}\,G$, $T = 1000\,eV$
bottom - $B = 10^{12}\,\mathrm{G}$, $T = 5000\,\mathrm{eV}$



Radiation diskons

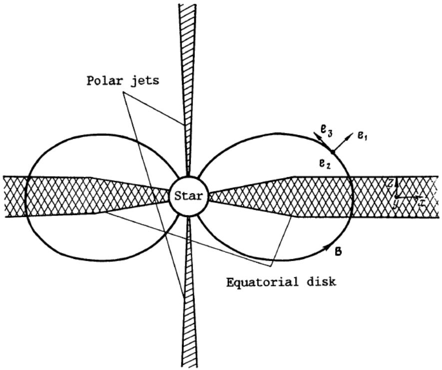


FIG. 1. Model of radiative discon.

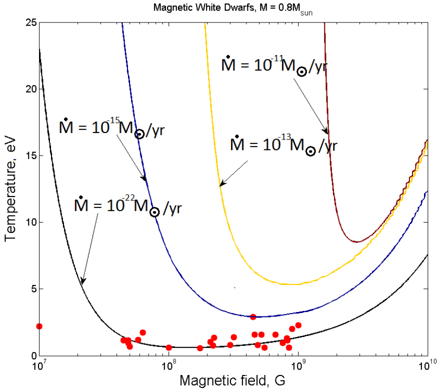
The model of radiation diskon [Zheleznyakov, Bespalov 1990]

- Hot magnetic white dwarf or neutron star
- Cyclotron wind from the photosphere due to cyclotron radiation pressure
- Extended plasma envelope
- Polar jets along the magnetic axis

Observational appearence:

- Wide and deep depression band in spectra
- Bipolar plasma outfow
- Quasiperiodic oscillations of radiation flux

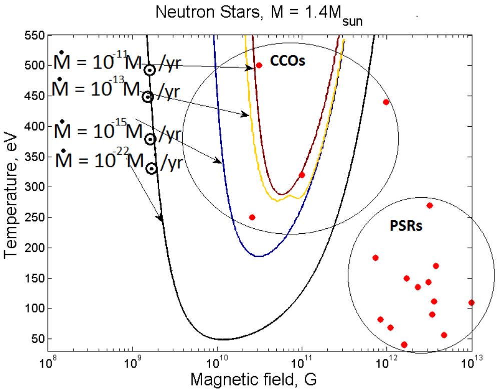
Cyclotron wind in the atmospheres of white dwarfs



- Pure hydrogen atmosphere.
- $M = 0.8 M_{\odot}$, $R \approx 10^9$ cm.
- Vacuum polarization and redistiribution of radiation
- $\dot{M} = 4\pi R^2 N_s c_s$

Points represent parameters of known white dwarfs (Kulebi et al., 2009; Kawka et al., 2004). Candidates: EUVE J0317-855, SDSS J100356.32+053825.6, HE 1043-0502, SDSS J234605.44+385337.7, GD 229

Cyclotron wind in the atmospheres of neutron stars



- Pure hydrogen atmosphere.
- $M = 1.4 M_{\odot}$, $R = 1.2 \cdot 10^6$см.
- Vacuum polarization and redistiribution of radiation
- $\dot{M} = 4\pi R^2 N_{\mathrm{s}} c_{\mathrm{s}}$

Points represent parameters of known neutron stars. Candidates: RX J0821-43, 1E 1207.4-5209, CXOU J185238.6+004020 and other CCOs