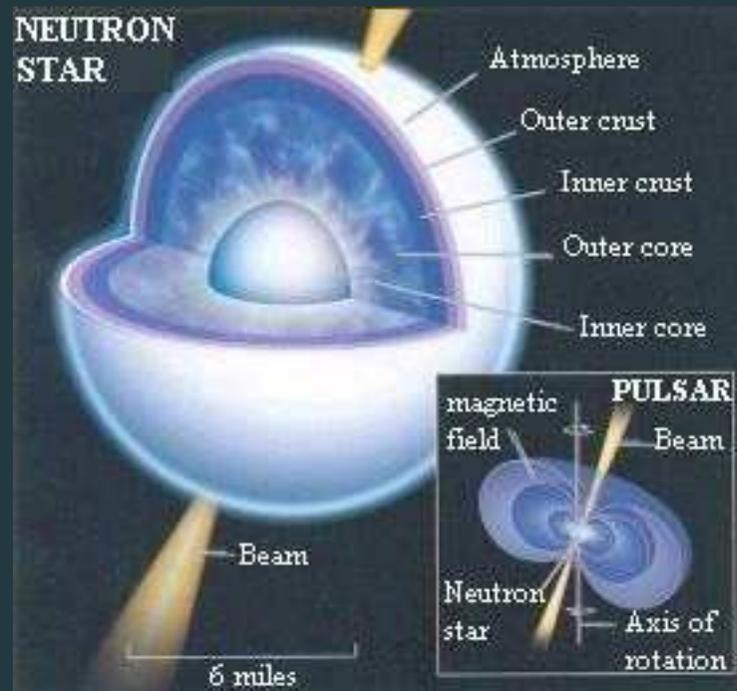


*Магнитные белые карлики,
пульсары
и магнитары:
теория и наблюдения*



Масштабы магнитных полей: теорема вириала

PROBLEMS OF GRAVITATIONAL STABILITY IN THE PRESENCE OF A MAGNETIC FIELD

S. CHANDRASEKHAR AND E. FERMI

Astrophys. J. **118**, 116 (1953)

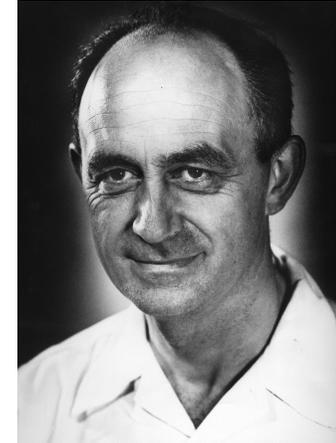


I. THE VIRIAL THEOREM AND THE CONDITION FOR DYNAMICAL STABILITY

2. *The virial theorem.*—In a subject such as this it is perhaps best that we start by establishing theorems of the widest possible generality. The extension of the virial theorem to include the forces derived from the prevailing magnetic field provides such a starting point. We shall see that under conditions of equilibrium this extension of the virial theorem leads to the relation

$$2T + 3(\gamma - 1)U + \mathfrak{M} + \Omega = 0 \quad (1)$$

between the kinetic energy (T) of mass motion, the heat energy (U) of molecular motion, the magnetic energy (\mathfrak{M}) of the prevailing field, and the gravitational potential energy (Ω), where γ denotes the ratio of the specific heats. That a relation of the form (1) should exist is readily understood: For the balance between the pressures p_{kin} , p_{gas} , and p_{mag} due



$$E_B < -E_G \sim -\frac{3}{5} \frac{GM^2}{R}$$

$$E_B \sim \frac{B^2}{8\pi} \times \frac{4\pi R^3}{3} = \frac{B^2 R^3}{6}$$

$$\Rightarrow B \lesssim \left(\frac{18}{5} \frac{GM^2}{R^4} \right)^{1/2} \sim 10^{18} \frac{M/M_\odot}{(R/10\text{km})^2} \text{G}$$

Магнитные белые карлики

1. Одиночные магнитные белые карлики
Grw+70°8247: Kuiper (1934); Kemp et al. (1970)
2. Поляры
3. Промежуточные поляры

Наблюдаемые эффекты

1. Круговая поляризация
2. Эффекты Зеемана и Пашена – Бака
3. Пульсации
4. Циклотронные линии

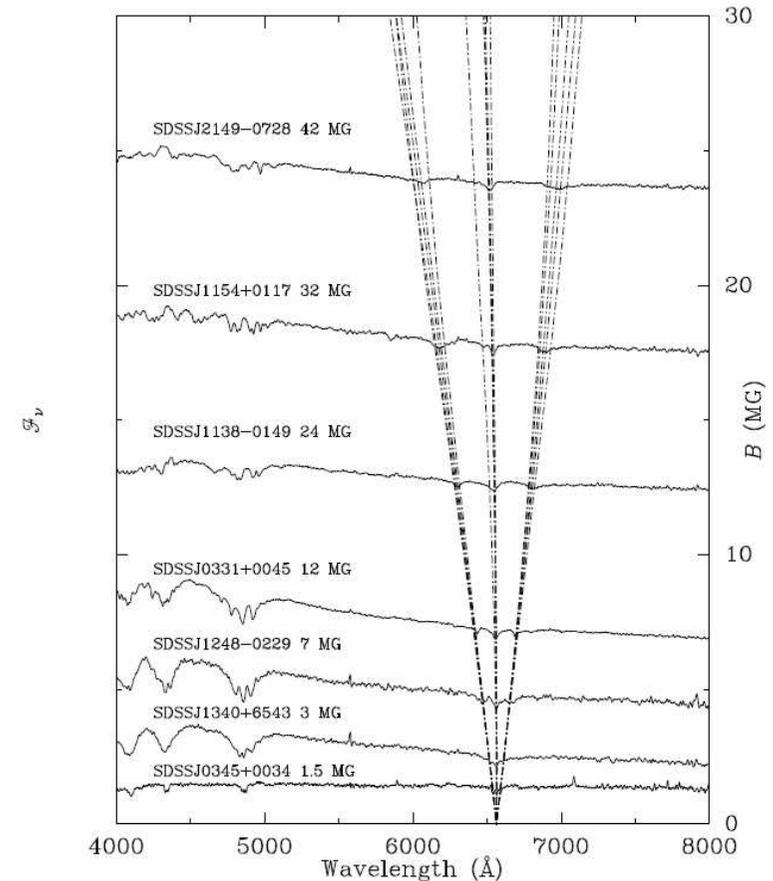
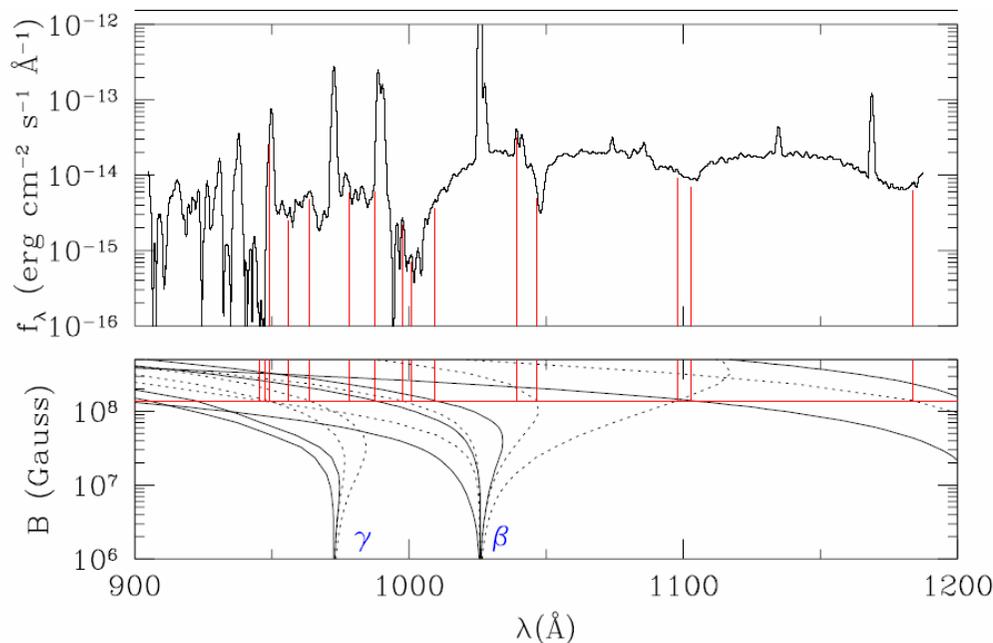
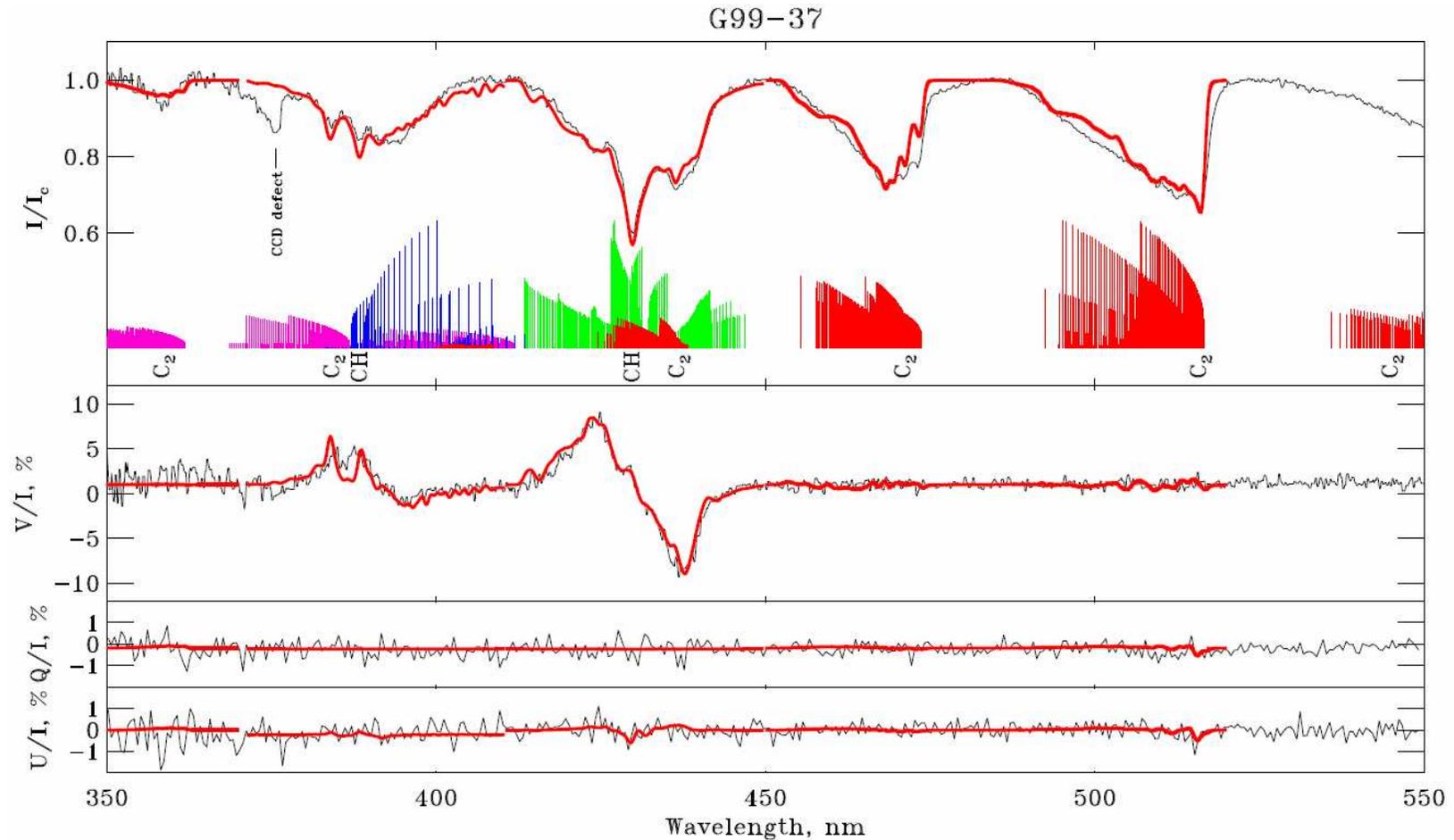


Fig. 1 The Zeeman effect on H α in the linear and quadratic regimes for fields of 1.5 – 42 MG). The quadratic effect becomes gradually more important in the higher members of the Balmer series and as the field strength increases (Schmidt et al. 2003)

Спектр катаклизмической переменной AR UMa в сравнении с длинами волн лаймановских линий в магнитном поле. Пунктирные линии – запрещённые в отсутствие электрического поля (Hoard et al. 2004)

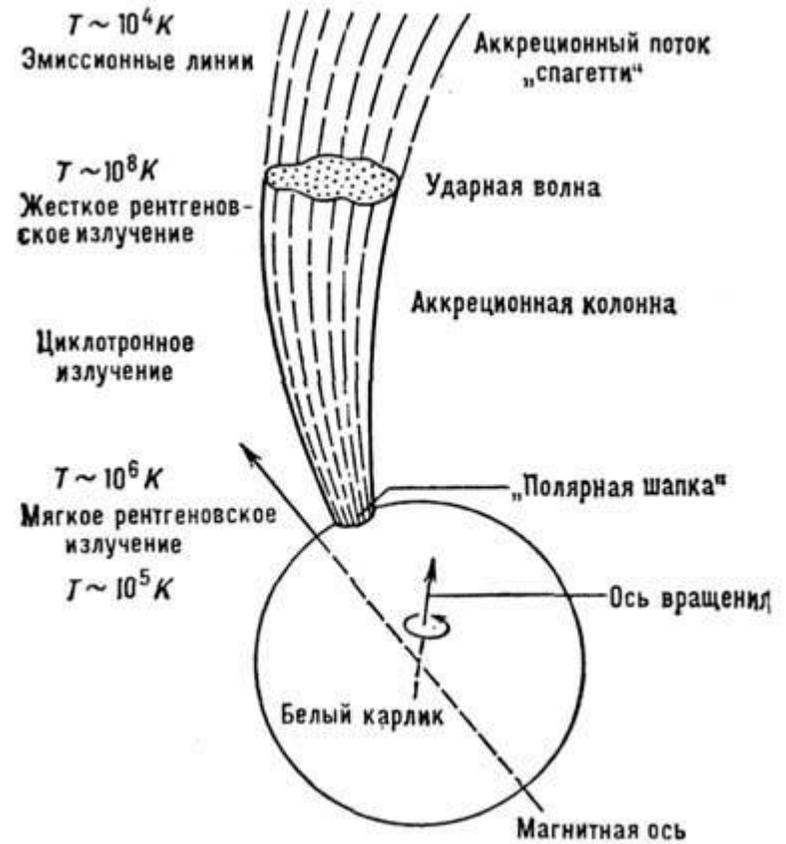
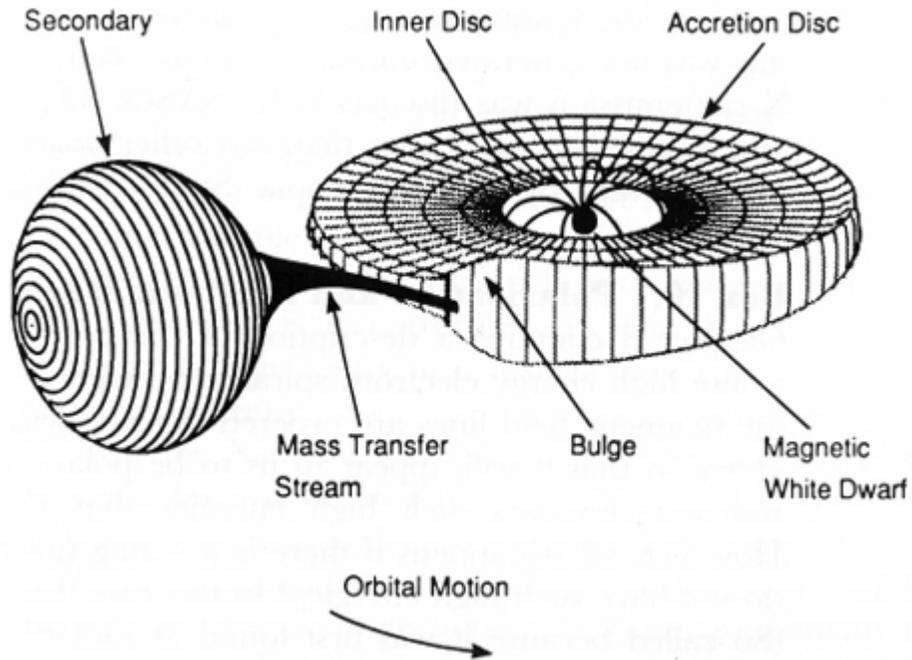
Магнитные белые карлики

Berdyugina et al., *Phys. Rev. Lett.* **99**, 091101 (2007)



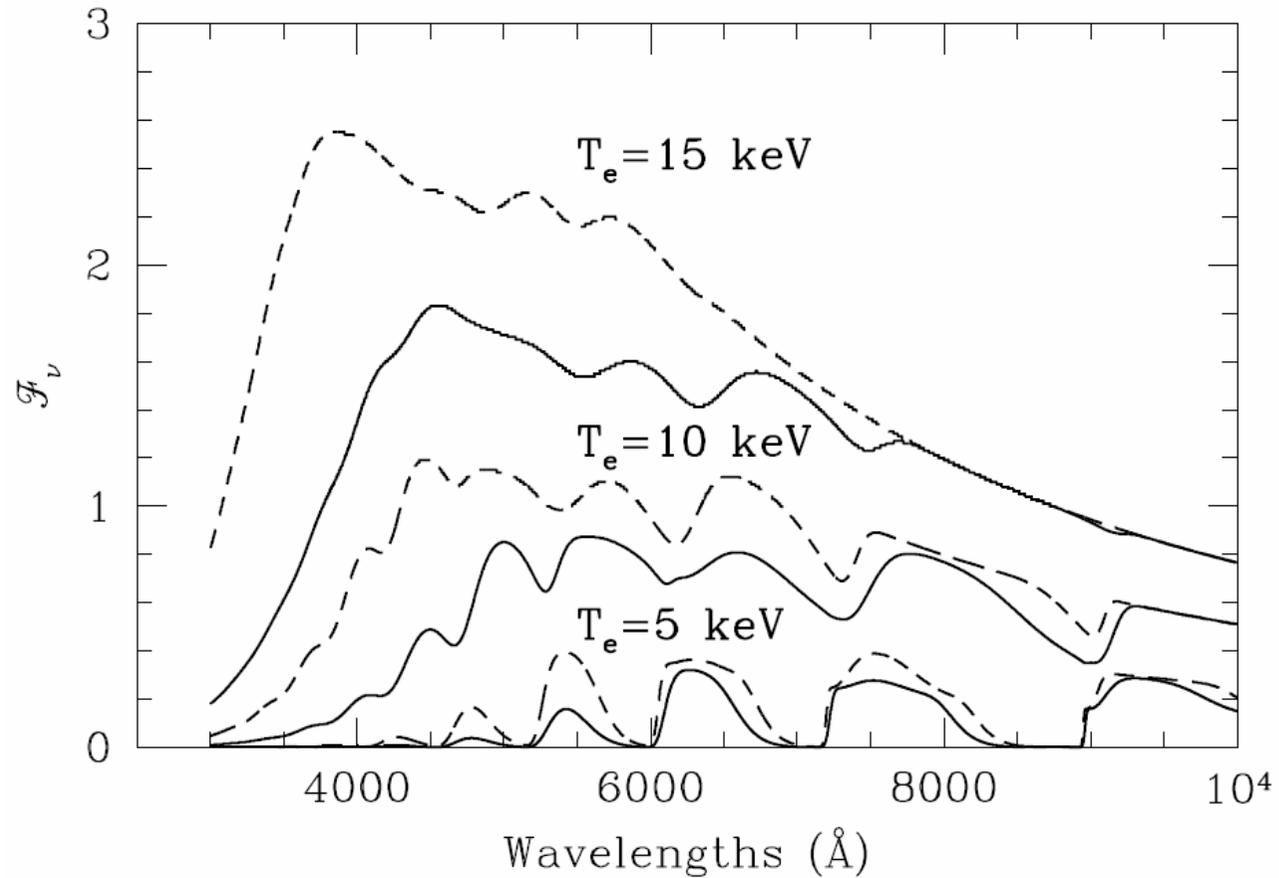
Пример сравнения наблюдаемого и теоретического спектров параметров Стокса для белого карлика с молекулярными полосами

Поляры



Поляры

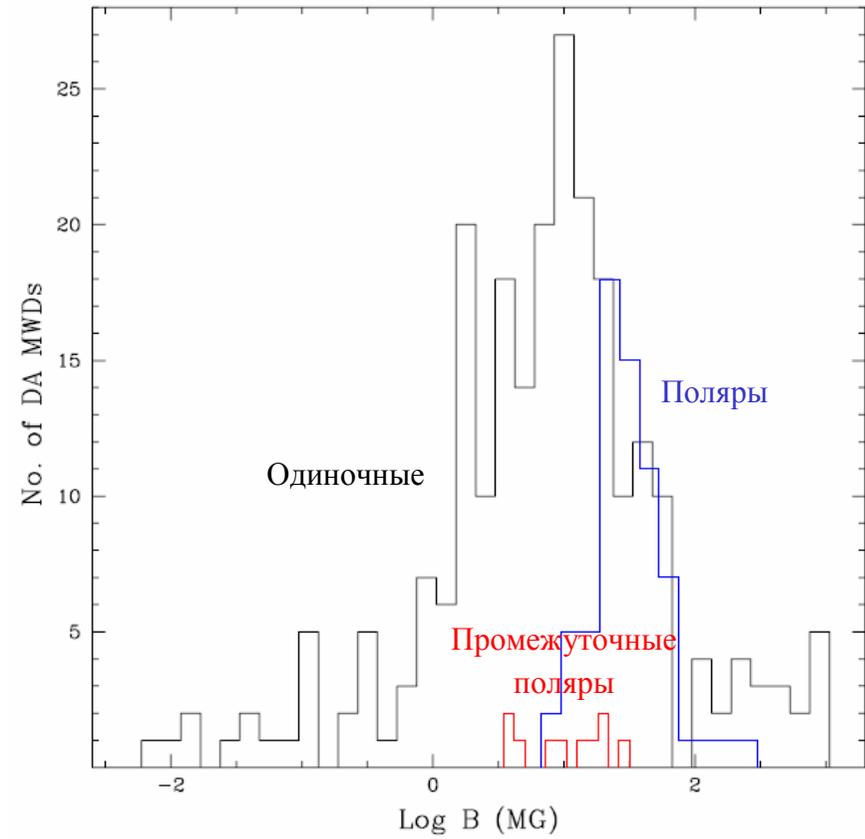
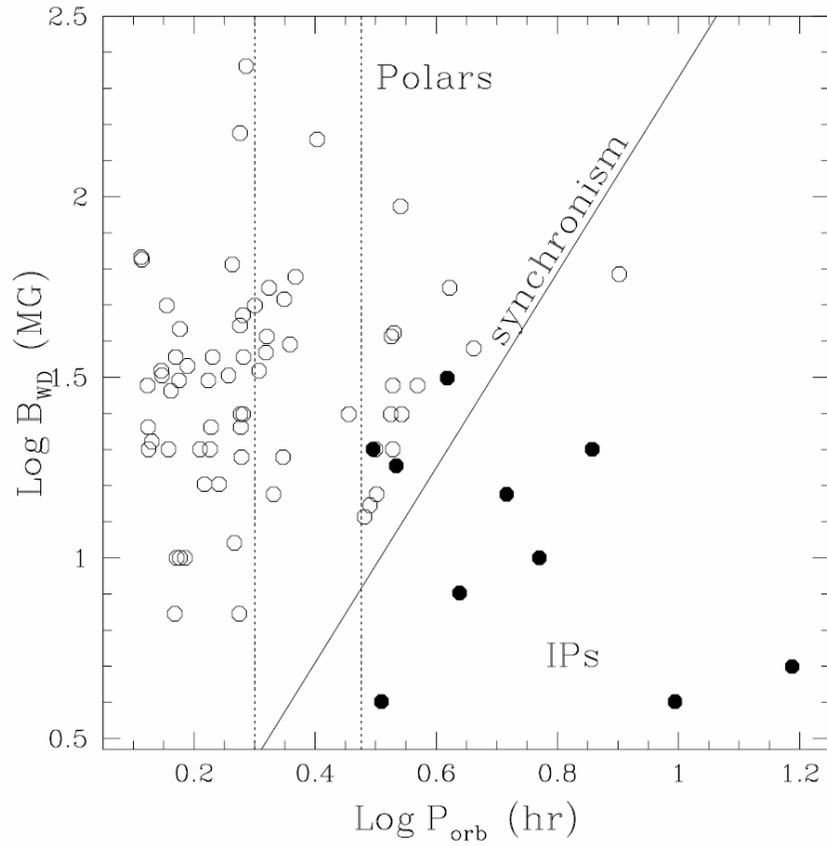
$$\lambda_n = \frac{10710}{n} \left(\frac{10^8 \text{G}}{B} \right) \text{ \AA}.$$



Циклотронные линии для поля $B = 30$ МГс при трёх разных эффективных температурах и двух разных оптических толщинах зоны ударной волны

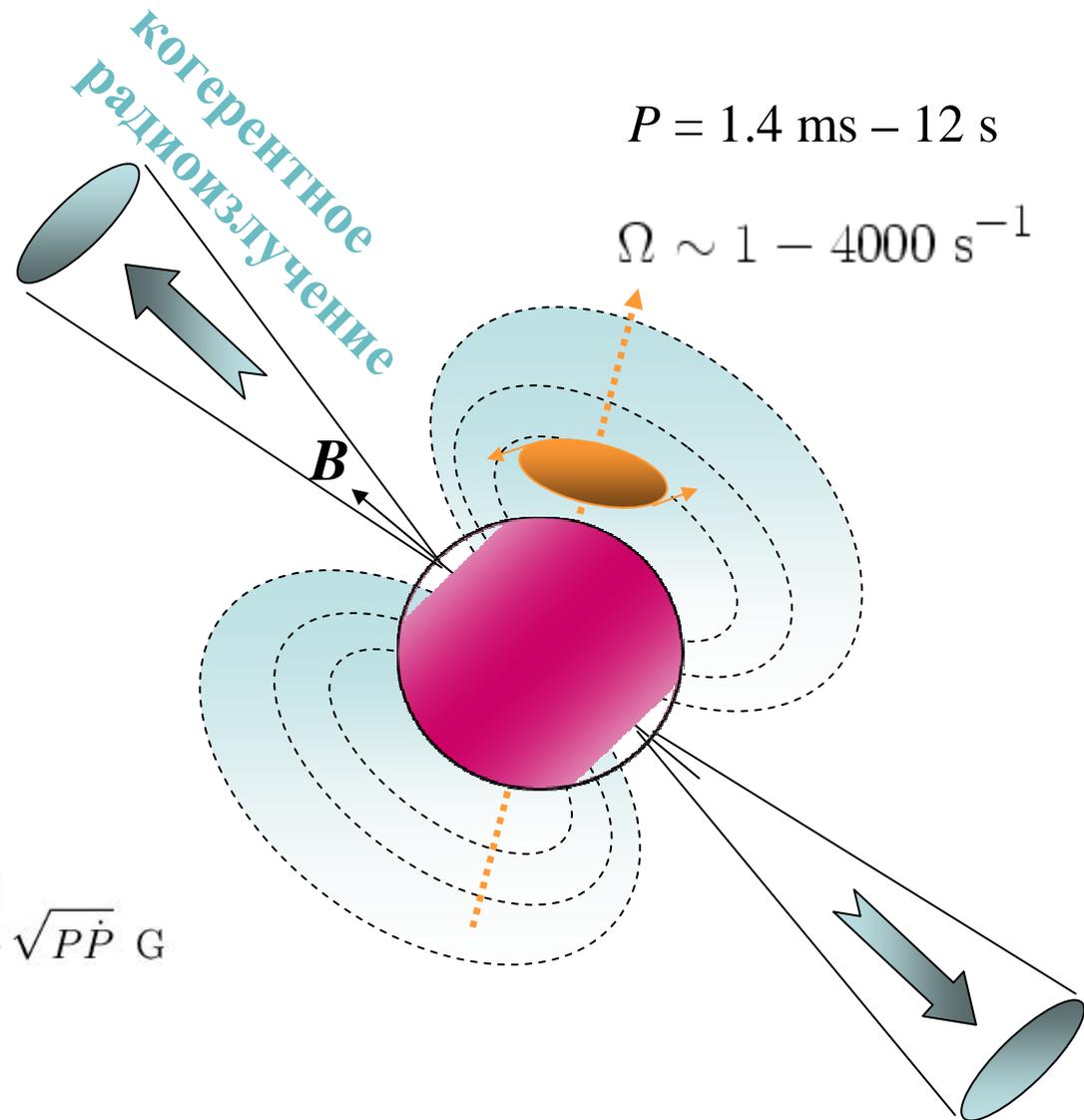
Магнитные белые карлики и полярны

Обзор: Ferrario et al., *Space Sci. Rev.* **191**, 115 (2015)



Радиопульсары

Обзор: Beskin et al., *Space Sci. Rev.* **191**, 213 (2015)



$$I\dot{\Omega} = -\frac{2\Omega^3 B_{\text{eff}}^2 R^6}{3c^3}$$

$$B_{\text{eff}} = \left(\frac{3Ic^3}{8\pi^2 R^6} P\dot{P} \right)^{1/2} \approx 3.2 \times 10^{19} \frac{I_{45}^{1/2}}{R_6^3} \sqrt{P\dot{P}} \text{ G}$$

$$t = P/(2\dot{P})$$

Радиопульсары

Обзор: Beskin et al., *Space Sci. Rev.* **191**, 213 (2015)

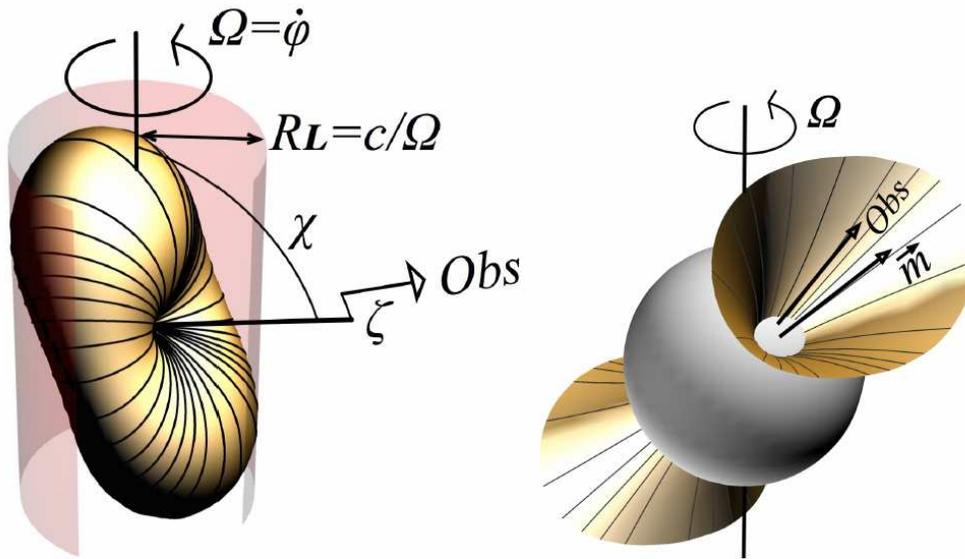
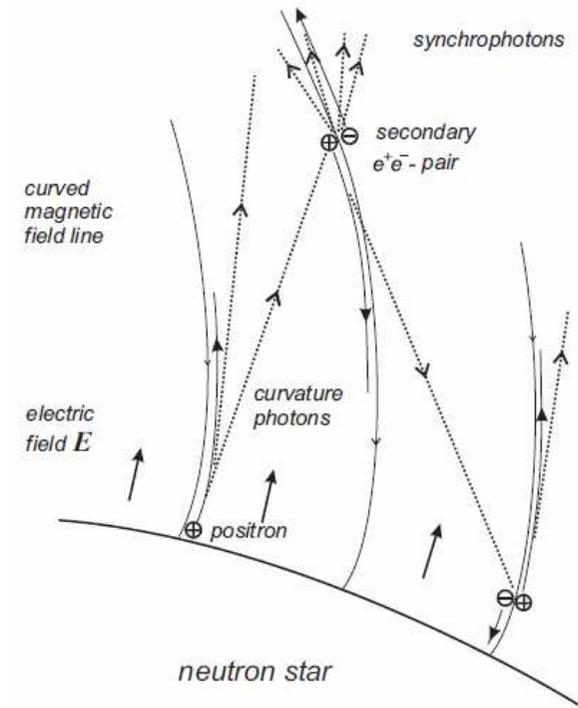


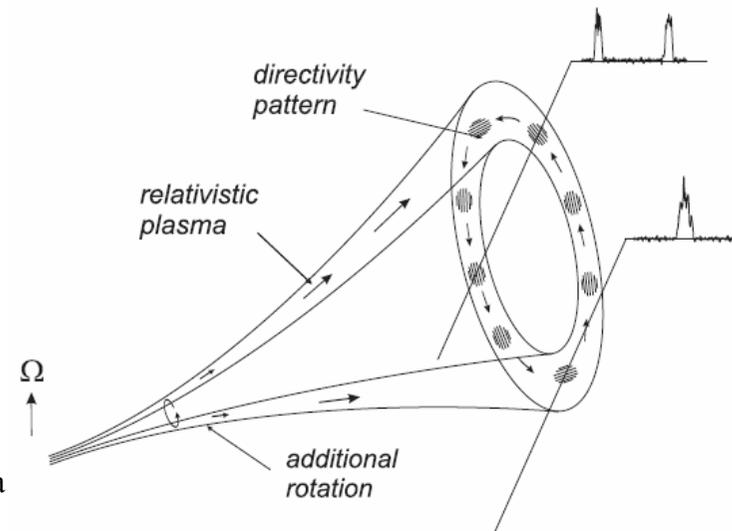
Fig. 1 Vacuum dipole model of a pulsar, showing the region of closed magnetic field lines and the light cylinder. The angle between the rotation and magnetic poles is χ , often called the "inclination angle"; and the minimum angle between the line of sight and the magnetic axis is ζ , sometimes called the "impact angle". Sometimes χ is denoted by α , and ζ by β . See [Lyne & Manchester \(1988\)](#).

Fig. 2 Intersection of the cone of the last open field lines with the surface of the neutron star, showing the polar cap. The vector \mathbf{m} is the axis of the magnetic dipole field, and Obs points toward the observer.

Модель полого конуса

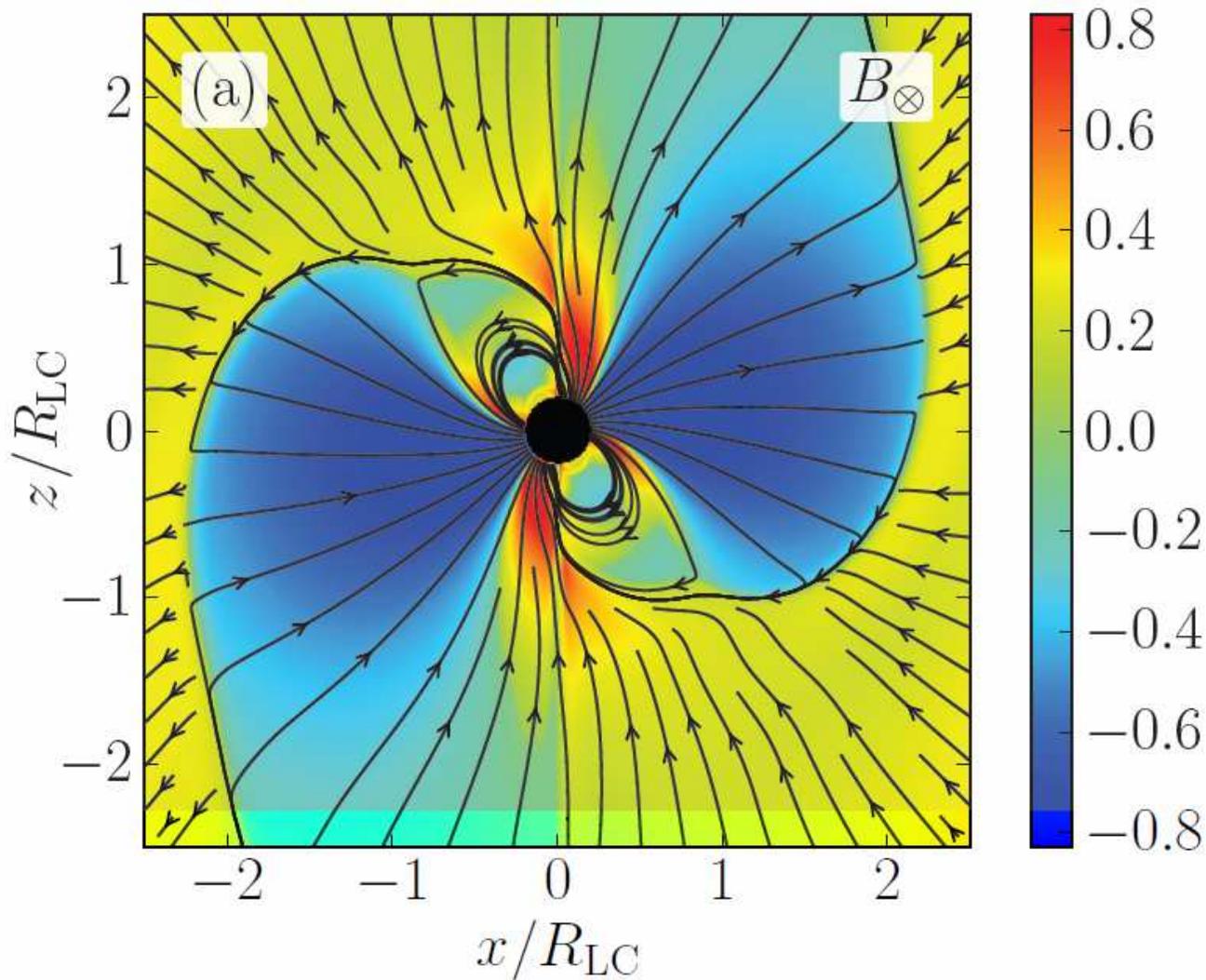


Структура области генерации пар

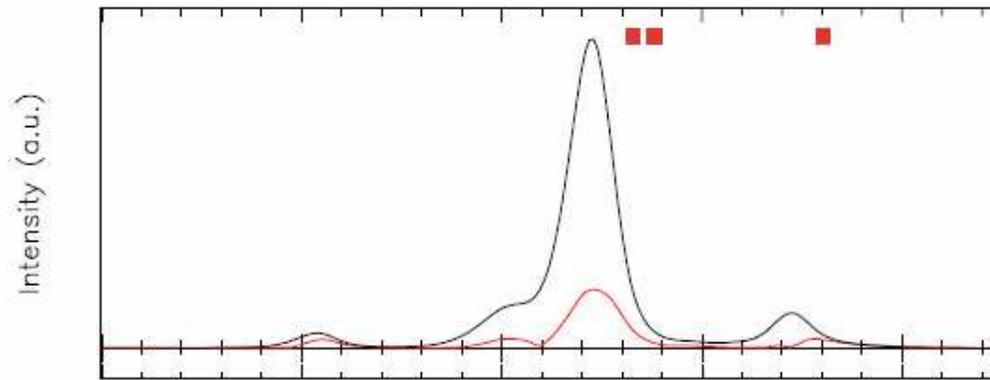


Структура магнитосферы: численное моделирование

Tchekhovskoy et al. (2013)



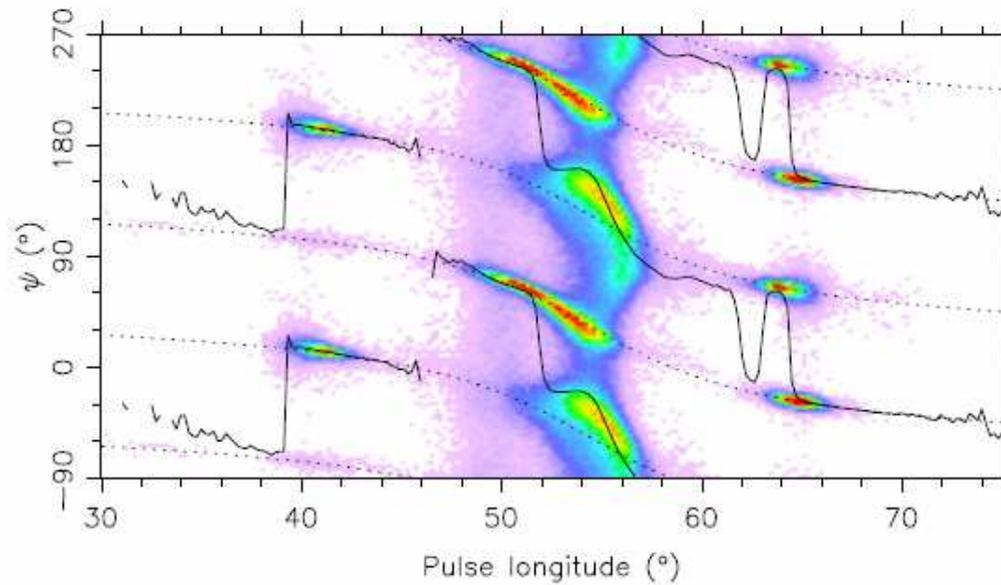
Поляризация радиоизлучения пульсаров



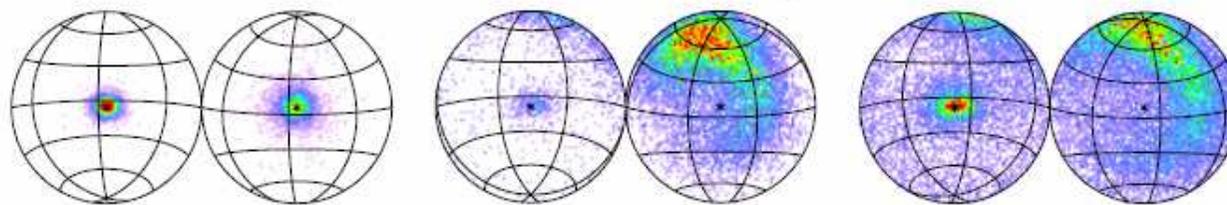
Edwards & Strappers (2004)

PSR B0329+54

Полная интенсивность
и поляризованная доля

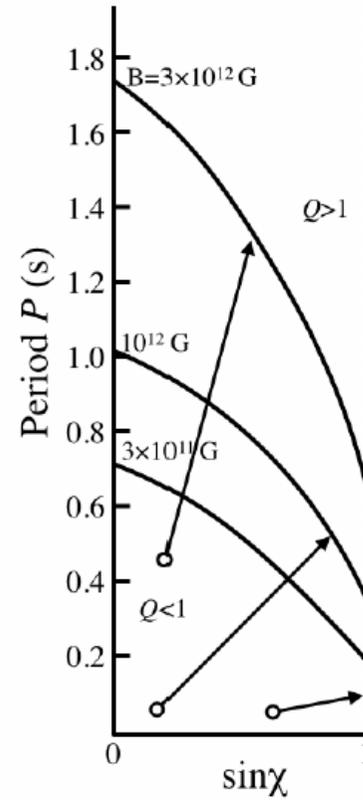
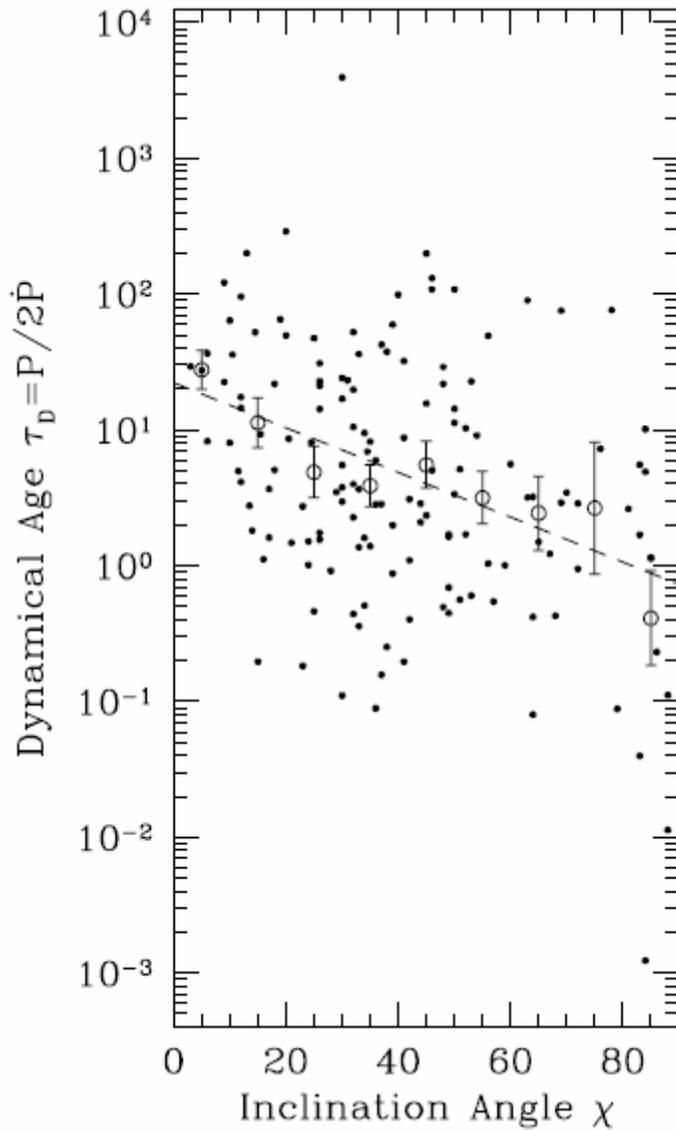


Гистограмма угла линейной поляризации в зависимости от фазы вращения. Кривые – теор. модель для двух нормальных мод. Точки разного цвета – наблюдаемая поляризация (красные – наибольшая доля наблюдений).



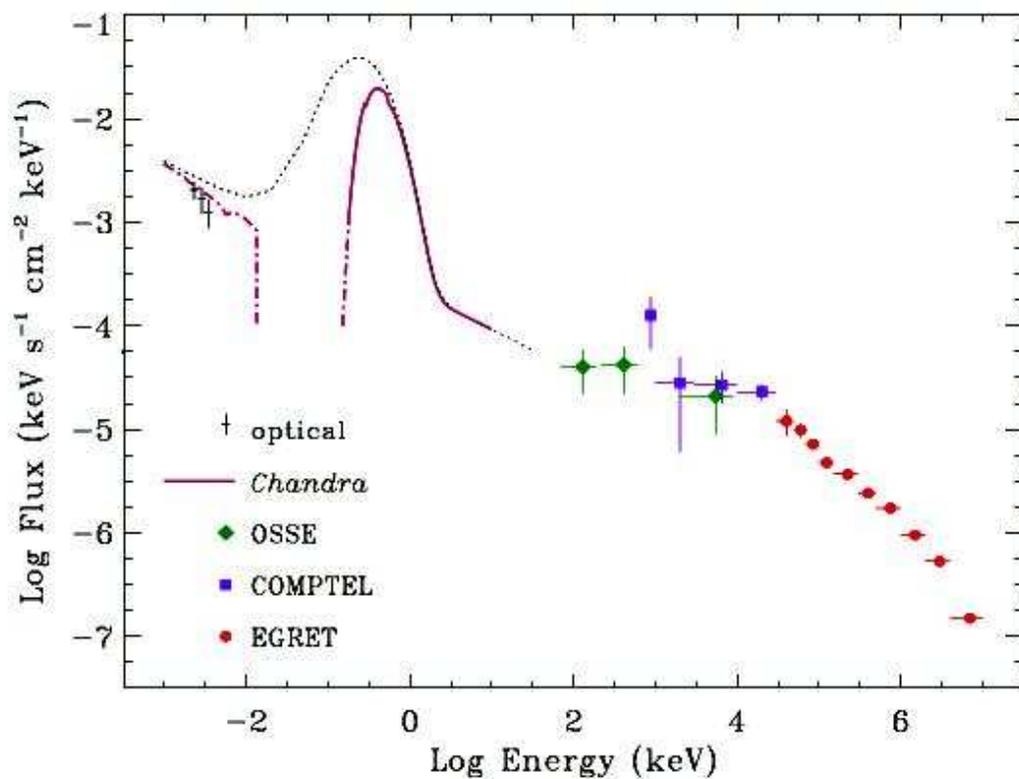
Наблюдаемая поляризация на сфере Панкаре для 3 фаз, указанных красными квадратами в верхнем окне (экватор – линейная поляризация)

Эволюция угла наклона магнитной оси

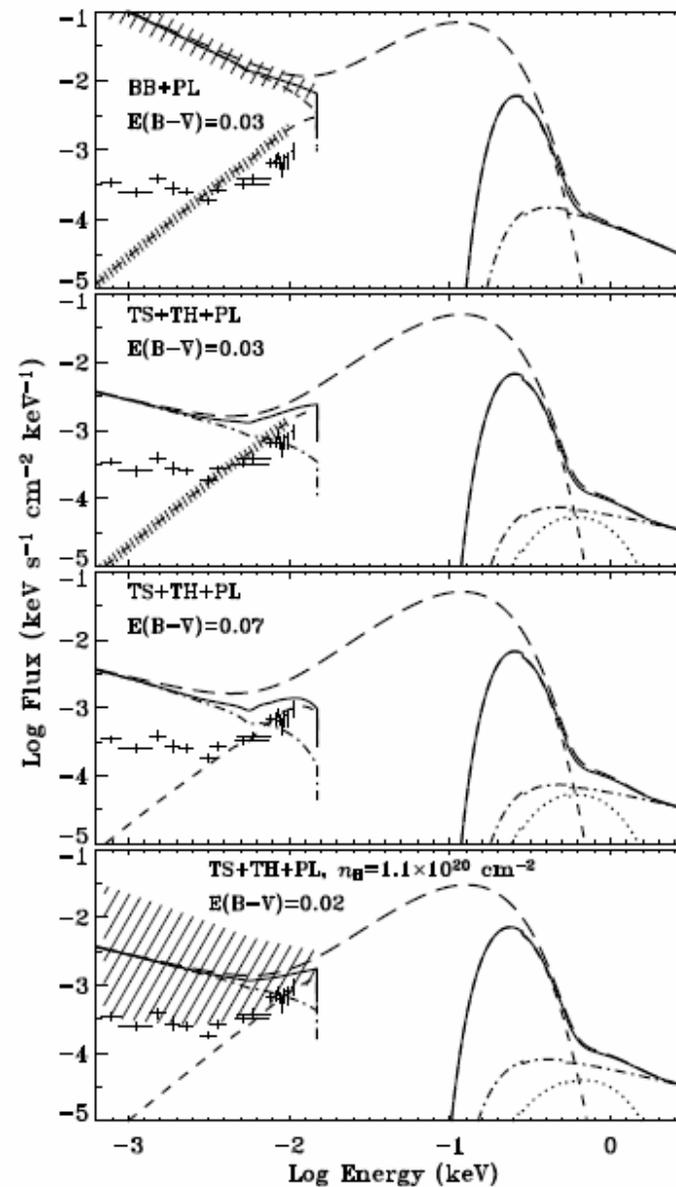


Слева – наблюдаемая зависимость характеристического возраста от среднего угла наклона, справа – «линия угасания пульсаров»: рождение частиц подавлено при больших углах. Стрелками показаны эволюционные треки отдельных пульсаров (Бескин и др. *Усп. физ. наук* 183, 179, 2013; Beskin et al., *Space Sci. Rev.* **191**, 213, 2015)

Излучение пульсаров в других волновых диапазонах



Pavlov *et al.* (2002): многоволновой спектр пульсара Вела



Kargaltsev *et al.* (2005): многоволновой спектр пульсара Геминга

Излучение пульсаров в других волновых диапазонах

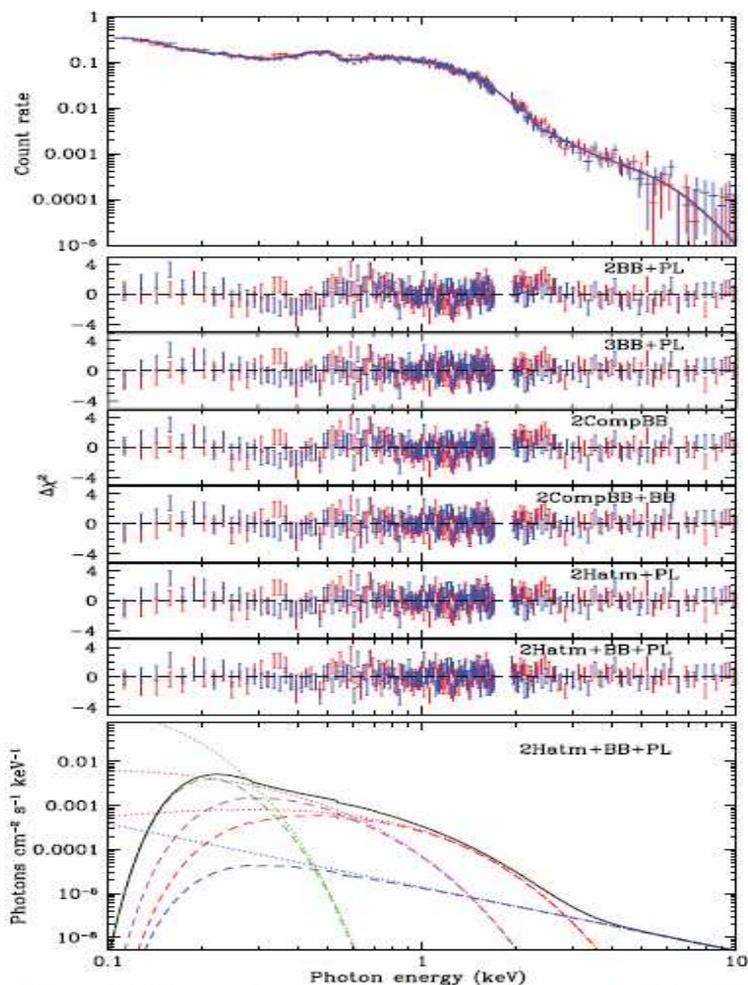


Figure 3. *XMM-Newton* X-ray EPIC MOS1/2 spectra of PSR J0437-4715 fitted with a two-temperature H atmosphere model plus a power law and a cool blackbody (solid line). The middle six panels show the fit residuals for the various models listed in Table 1. The bottom panel shows the best-fit two-temperature H atmosphere model plus a power law and a cool blackbody. The dashed and dotted lines show the individual absorbed and unabsorbed model components, respectively, while the solid line shows the total spectrum. See the text and Table 1 for best-fit parameters and acronym definitions.

Bogdanov (2013): $R > 11,3$ км
при $M = 1,76 M_{\text{Sun}}$
(жесткое УРС)

THE ASTROPHYSICAL JOURNAL, 762:96 (9pp), 2013 January 10

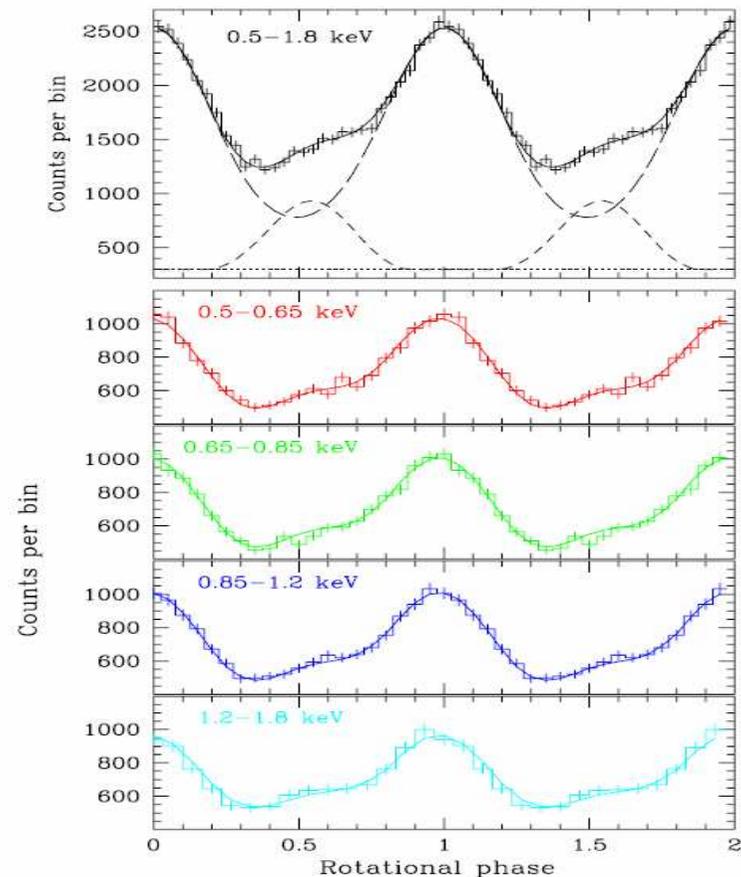
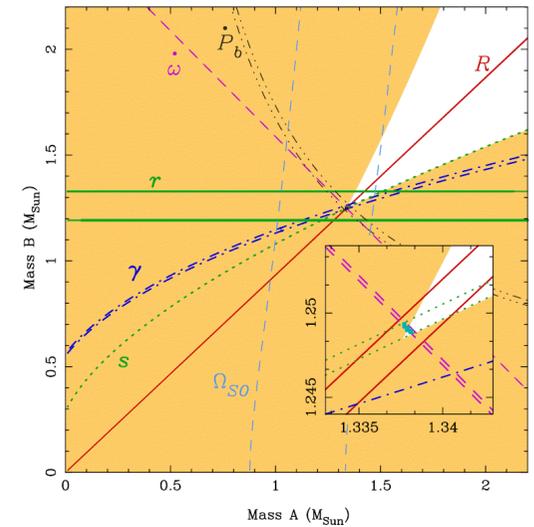
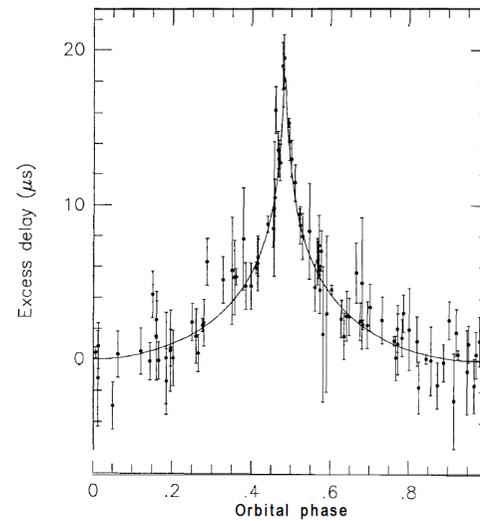
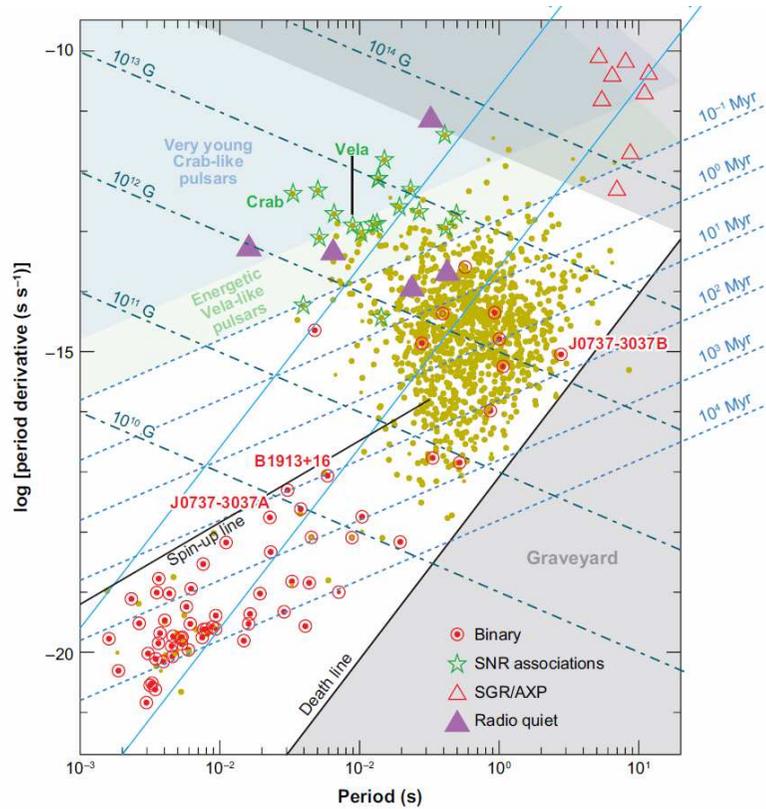
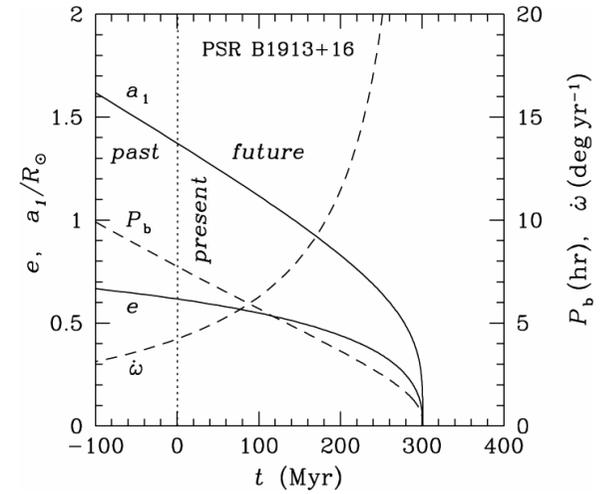
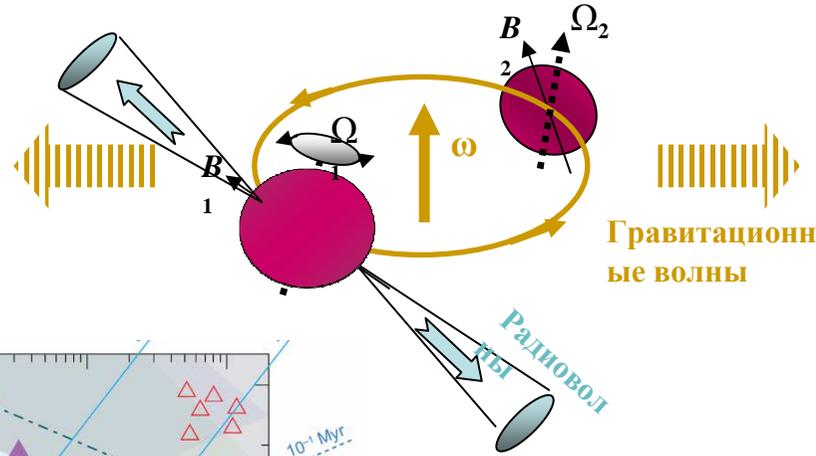


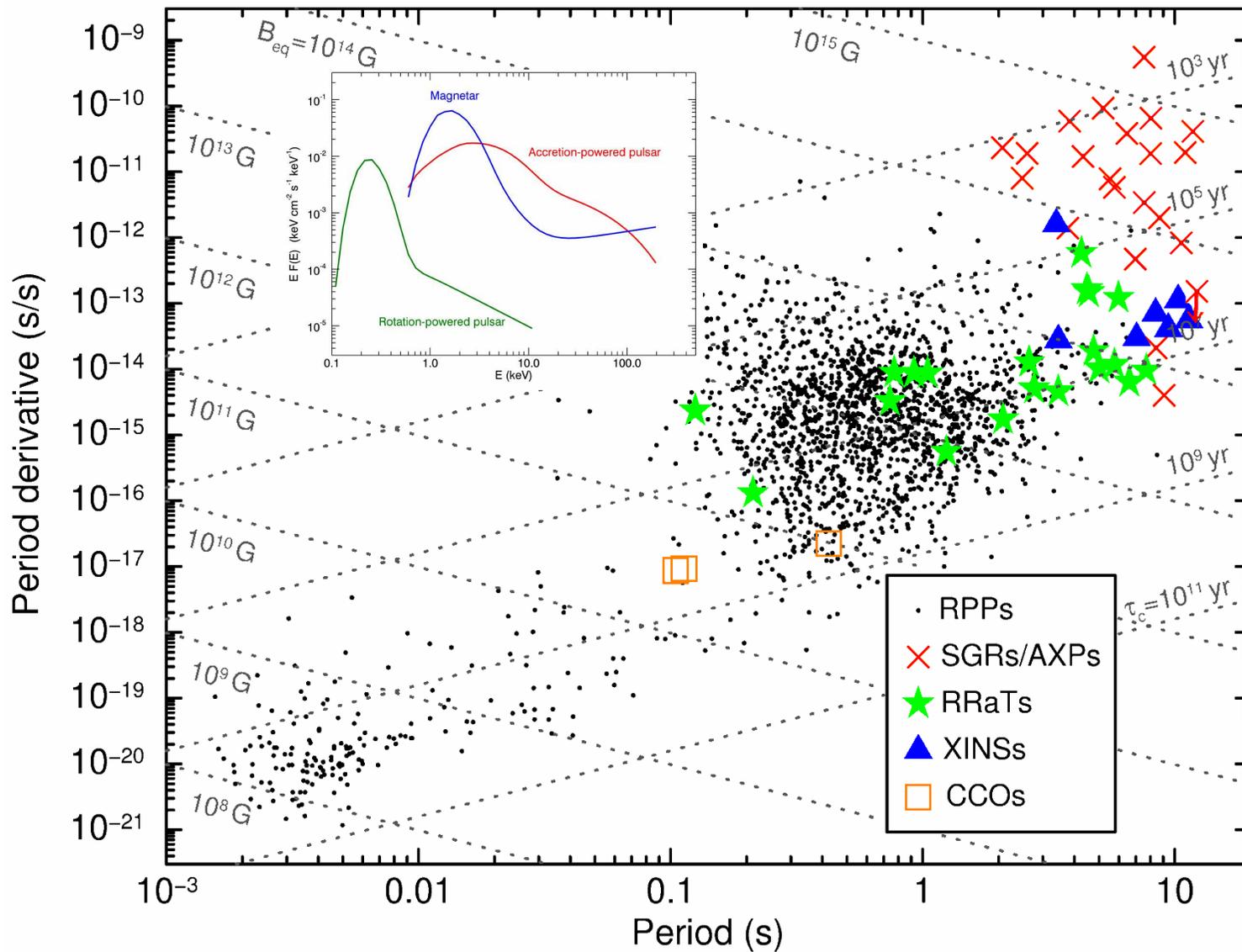
Figure 5. Top panel: the *XMM-Newton* EPIC pn pulse profile in the 0.5–1.8 keV range with the best-fit model (solid line). The individual contributions from each polar cap are shown with the dashed lines. The dotted line shows the background level. Bottom four panels: *XMM-Newton* EPIC pn pulse profiles of PSR J0437-4715 in the 0.5–0.65, 0.65–0.85, 0.85–1.2, and 1.2–1.8 keV bands (from top to bottom, respectively) fitted with a model of a rotating neutron star with two-temperature H atmosphere polar caps. See the text for best-fit parameters.

Двойные и подкрученные радиопульсары

Обзор: Бисноватый-Коган, *Усп. физ. наук*, **176**, 59 (2006)



Нейтронные звёзды разных типов на диаграмме $P - \dot{P}$



SGR-AXP и XINSs – вероятно, магнитары.

Магнитары

Обзор: Mereghetti et al., *Space Sci. Rev.* **191**, 321 (2015)

SGR + AXP

1. (Вероятно,) изолированные нейтронные звёзды
2. $P = 3 - 12$ секунд
3. (Вероятно,) сверхсильное магнитное поле
4. Светимость выше, чем потери вращательной энергии
5. (Почти) отсутствует радиоизлучение
6. Мощные рентгеновские вспышки в диапазоне 1 – 50 кэВ

Магнитары

Обзор: Mereghetti et al., *Space Sci. Rev.* **191**, 321 (2015)

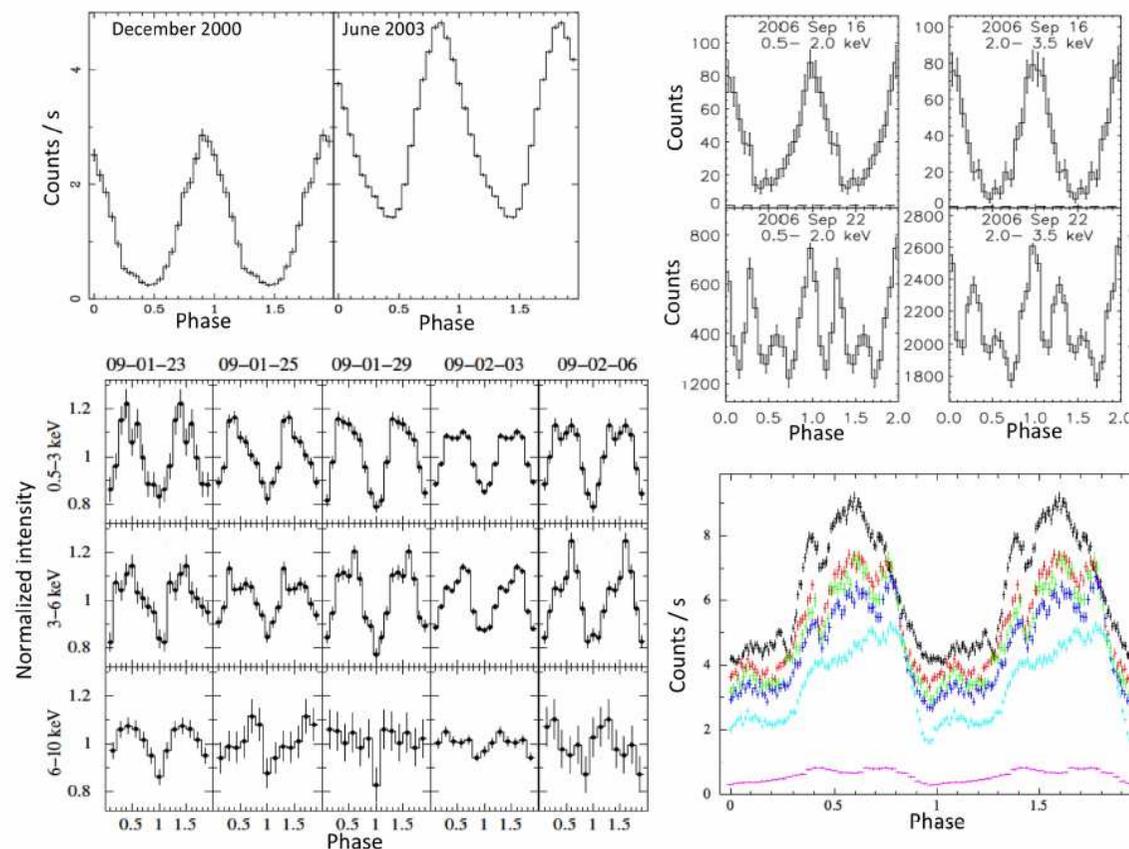
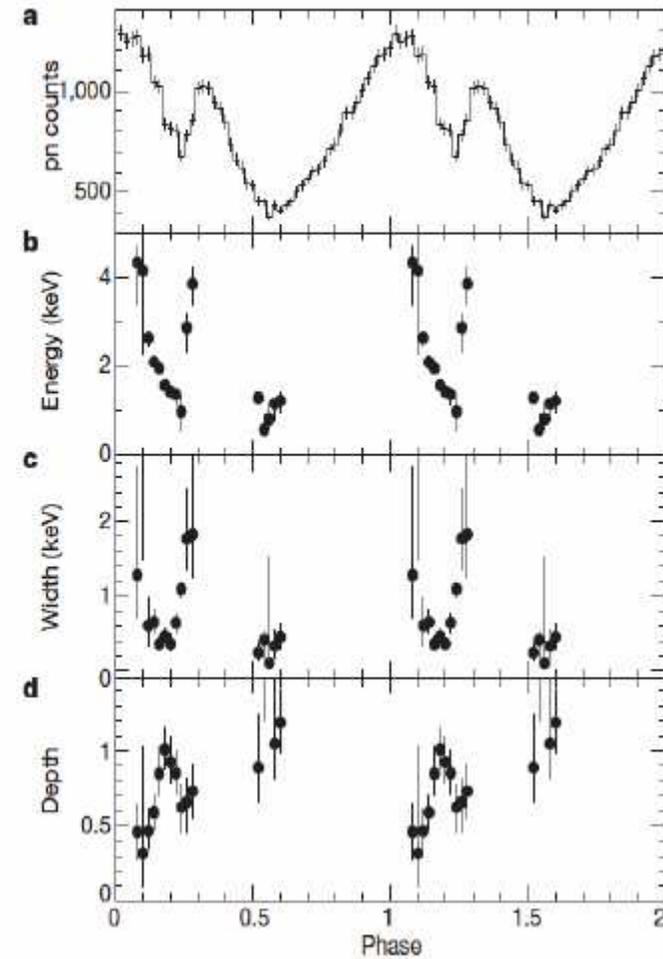
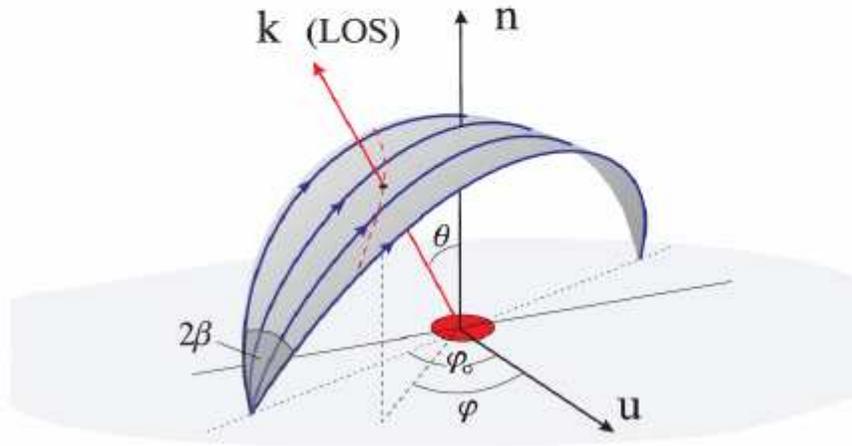
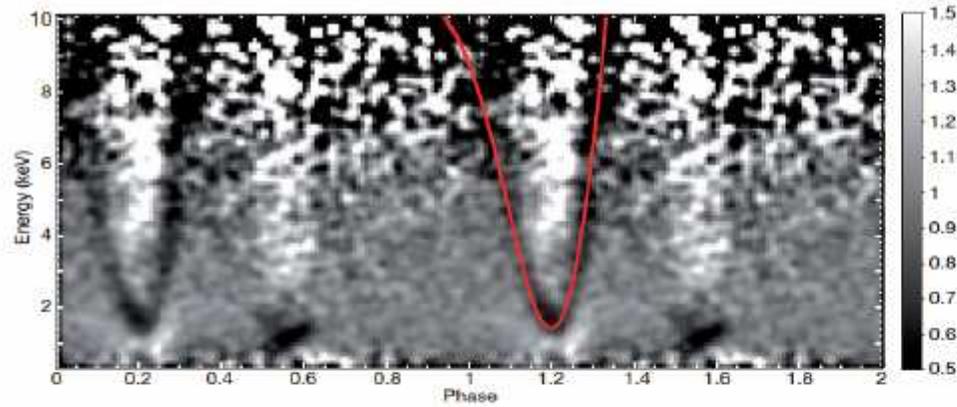


Fig. 1 Examples of X-ray pulse profiles of magnetars (for clarity, two neutron star rotations are shown in each plot). *Top left panel:* the pulsed fraction of the persistent magnetar 1E 1048.1–5937 anticorrelates with the luminosity (Mereghetti et al. 2004): when the flux was about twice that of the normal level, the pulsed fraction was smaller (53% wrt 89%); both curves refer to the 0.6–10 keV range and were obtained with the EPIC instrument on *XMM-Newton*. *Top right panel:* pulse profile variations in two energy ranges of the transient magnetar CXOU J1647–4552 (Muno et al. 2007) in quiescence (*upper panels*) and during the outburst (*lower panels*). *Bottom left panel:* evolution of the pulse profiles of 1E 1547.0–5408 during the decaying phase of the January 2009 outburst (Bernardini et al. 2011). *Bottom right panel:* pulse profiles of the transient magnetar SGR 0501+4516 at different luminosity levels (Camero et al. 2014).

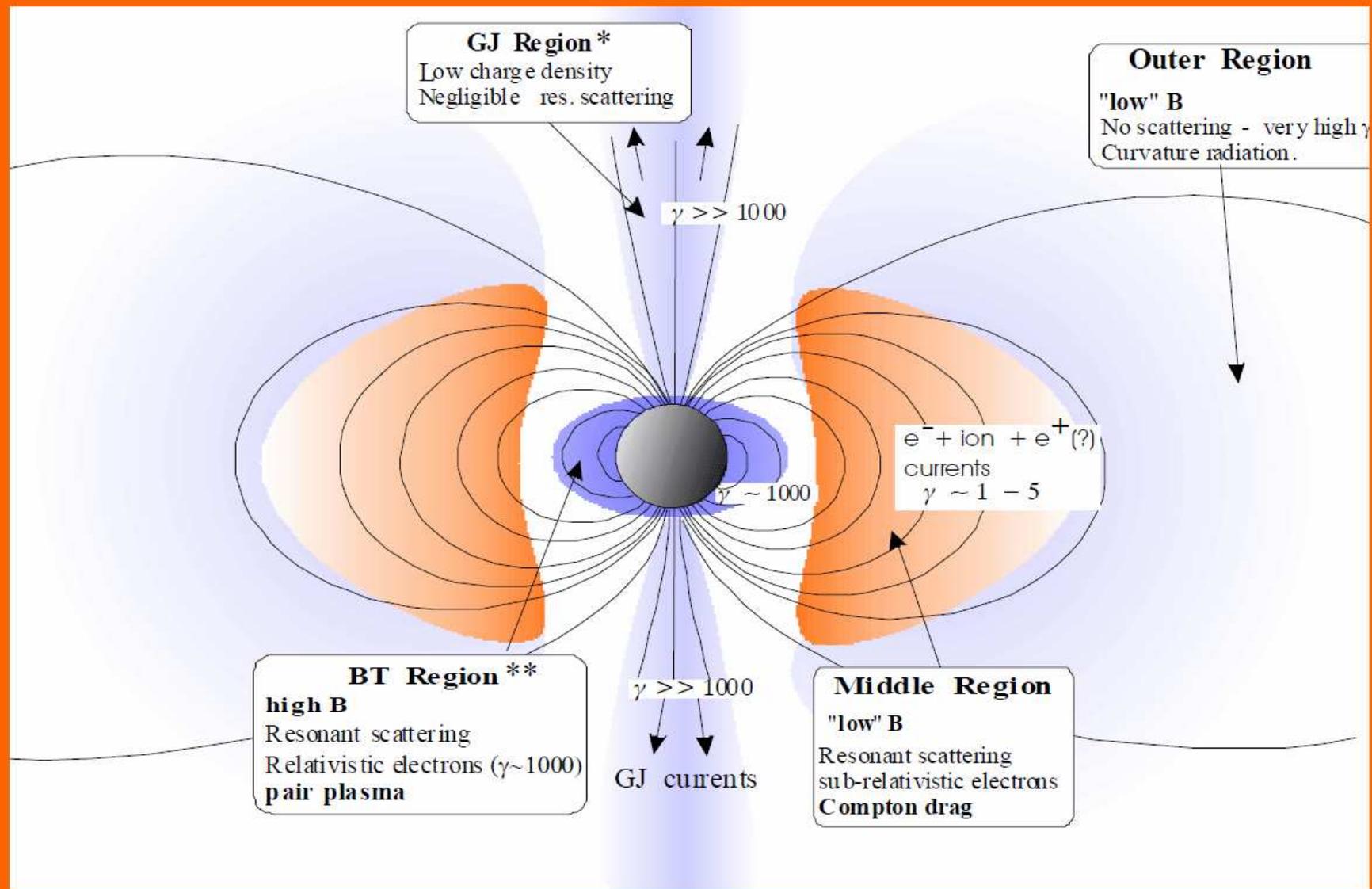
Магнитары

Обзор: Mereghetti et al., *Space Sci. Rev.* **191**, 321 (2015)



Возможно, протонная циклотронная линия в спектре SGR 0418+5729 (Tiengo et al. 2013)

Магнитары: закрученная магнитосфера



* Goldreich & Julian 1969

** Beloborodov & Thompson 2007

(not in scale)