FÍSICA DE ESTRELAS DE NÊUTRONS

Prof. Rodrigo Negreiros – UFF

XI Escola do CBPF

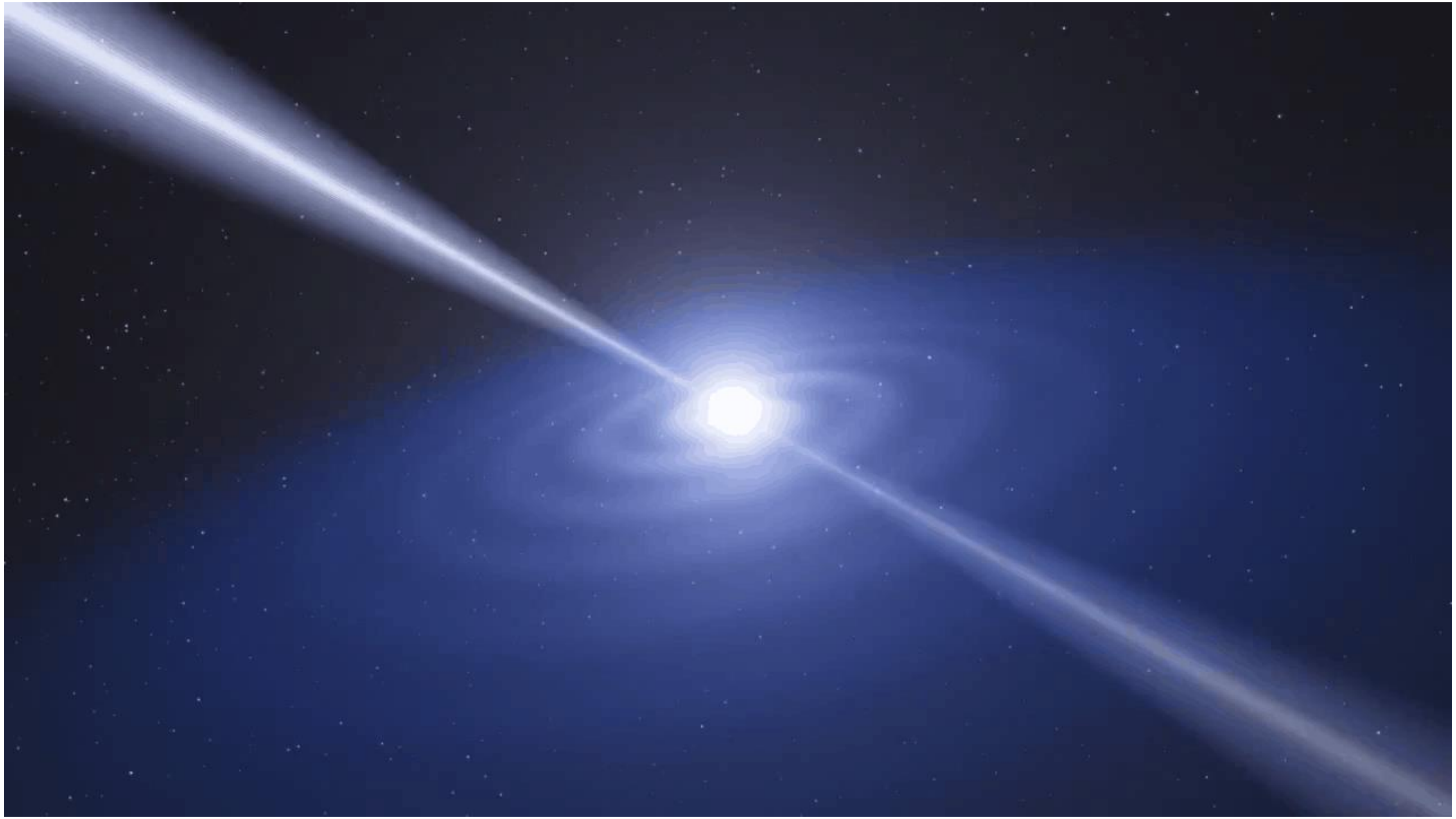
PROGRAMA

~~I. Introdução.~~	Aula I
~~II. Visão geral de estrelas compactas.~~	
~~III. Física nuclear relativística.~~	Aula II
~~IV. Estrelas de Nêutrons no contexto da física nuclear.~~	
~~Relatividade Geral – revisão~~	Aula III
~~Estrutura de estrelas de nêutrons dentro do contexto da relatividade geral.~~	
~~Estrelas de nêutrons com rotação não nula.~~	Aula IV
~~Estrelas de nêutrons com campos Magnéticos.~~	
~~Evolução de estrelas de nêutrons – aspectos gerais.~~	Aula V
Evolução rotacional de estrelas de nêutrons.	Aula VI
Evolução térmica de estrelas de nêutrons.	Aula VII
Evolução termo-rotacional de estrelas de nêutrons.	Aula VIII

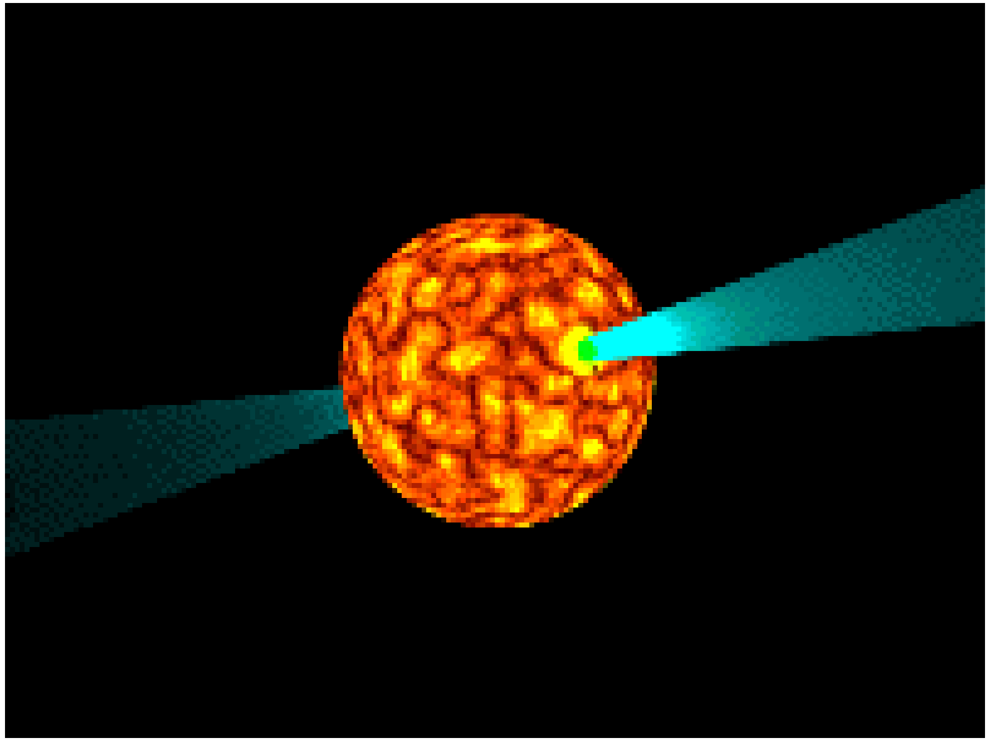
Para um melhor aproveitamento do conteúdo ministrado, recomendamos à audiência que mantenha os aparelhos eletrônicos (celulares, laptops) desligados durante as aulas.

Comissão Organizadora
XI Escola do CBPF

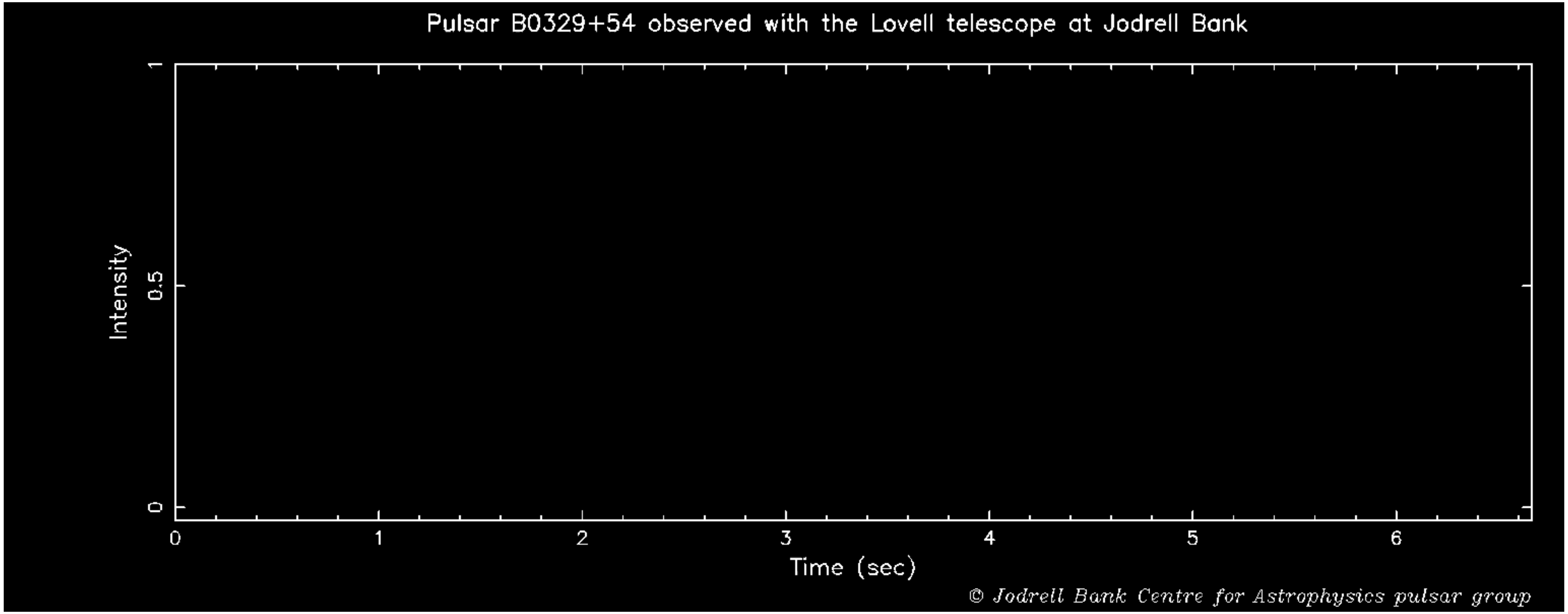
PULSARES



PULSARES

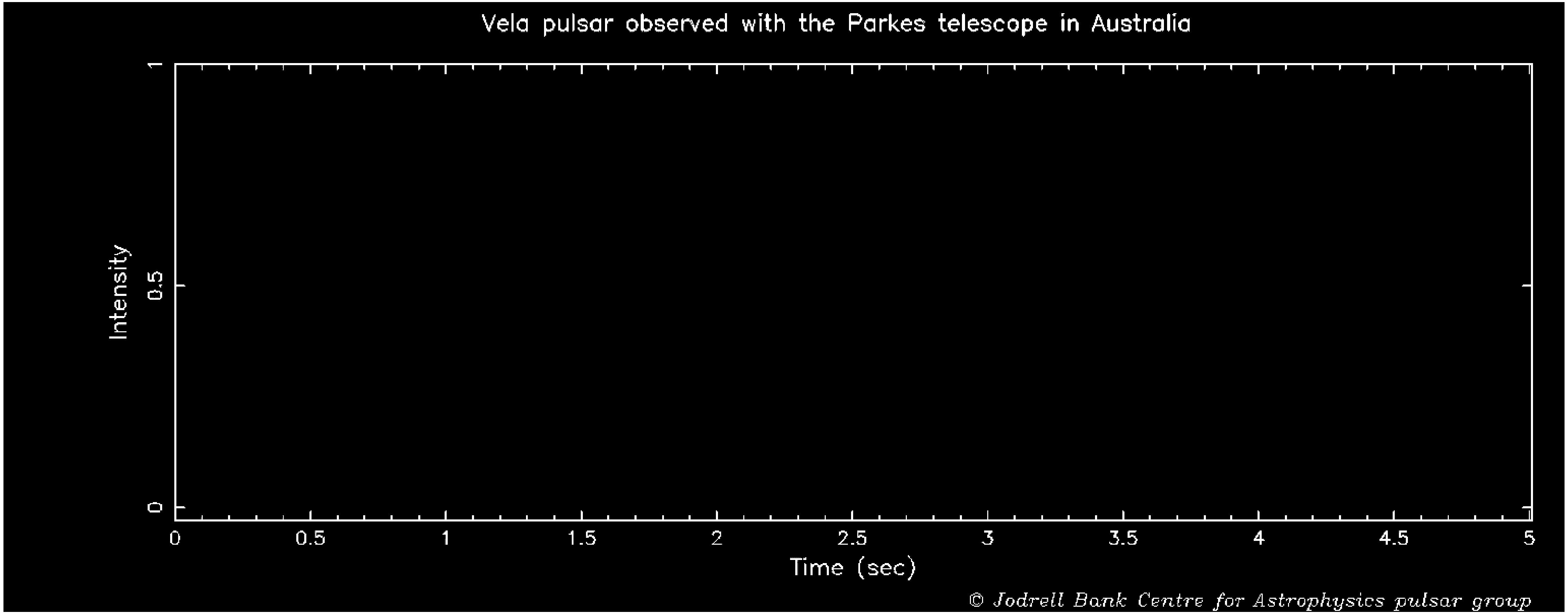


OUVINDO PULSARES!



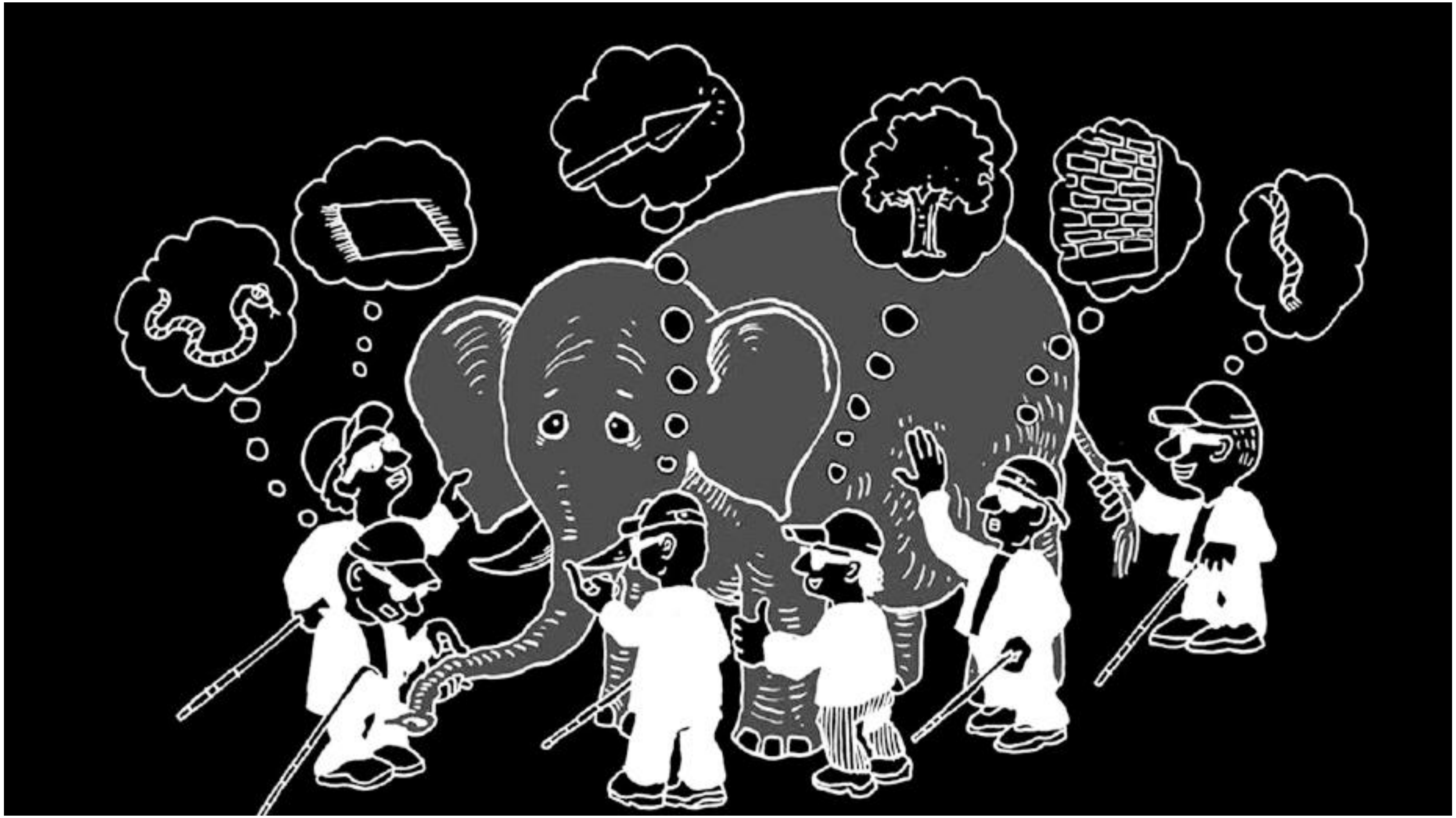
This is the brightest radio pulsar in the northern sky. Otherwise this pulsar is a typical, normal pulsar, rotating with a period of 0.714520 seconds, hence the star makes about one and a half turn in a second, giving it a locomotive kind of sound. You can hear and see that each pulse has a different structure, hence the beam of this cosmic lighthouse is constantly changing in shape

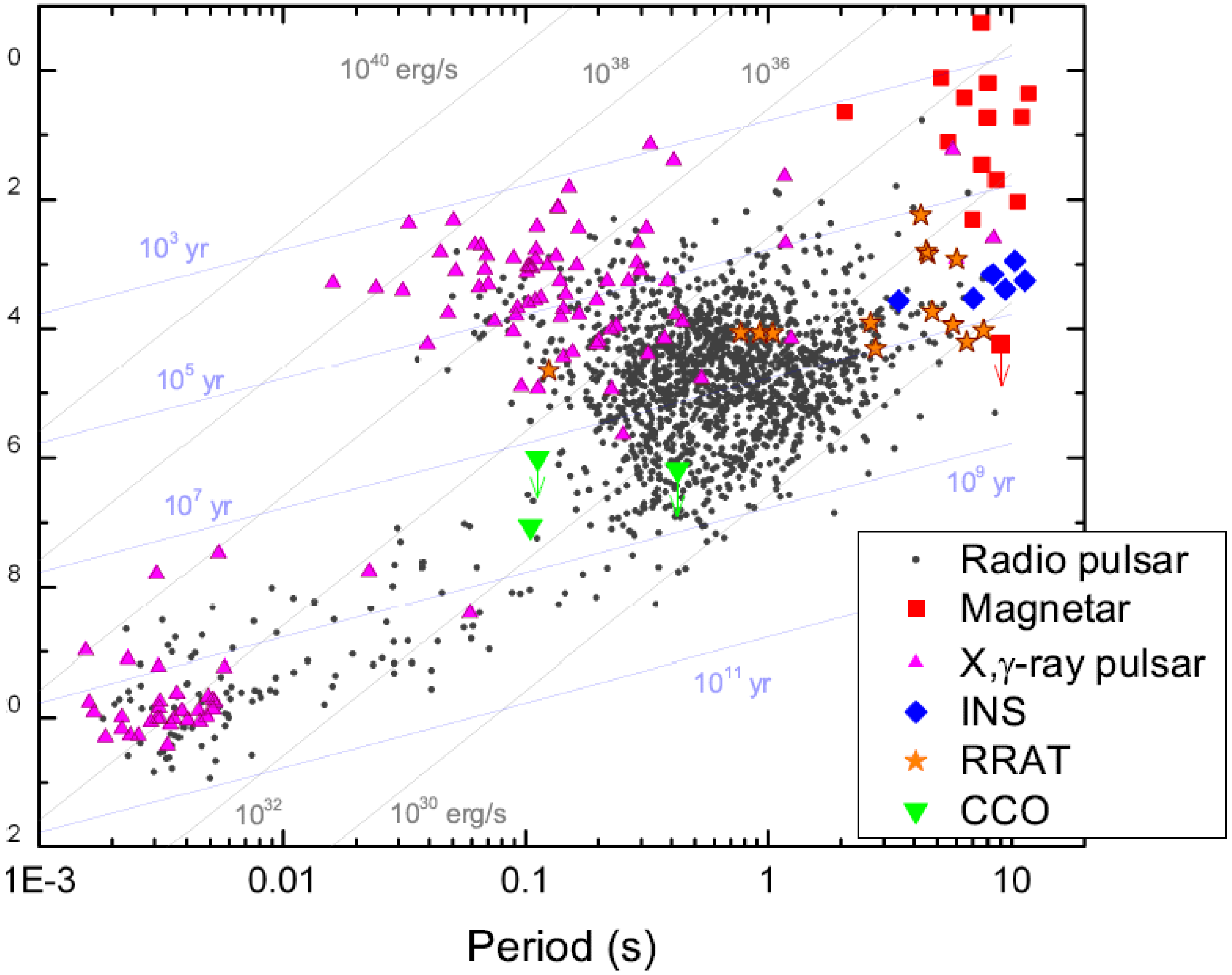
OUVINDO PULSARES!



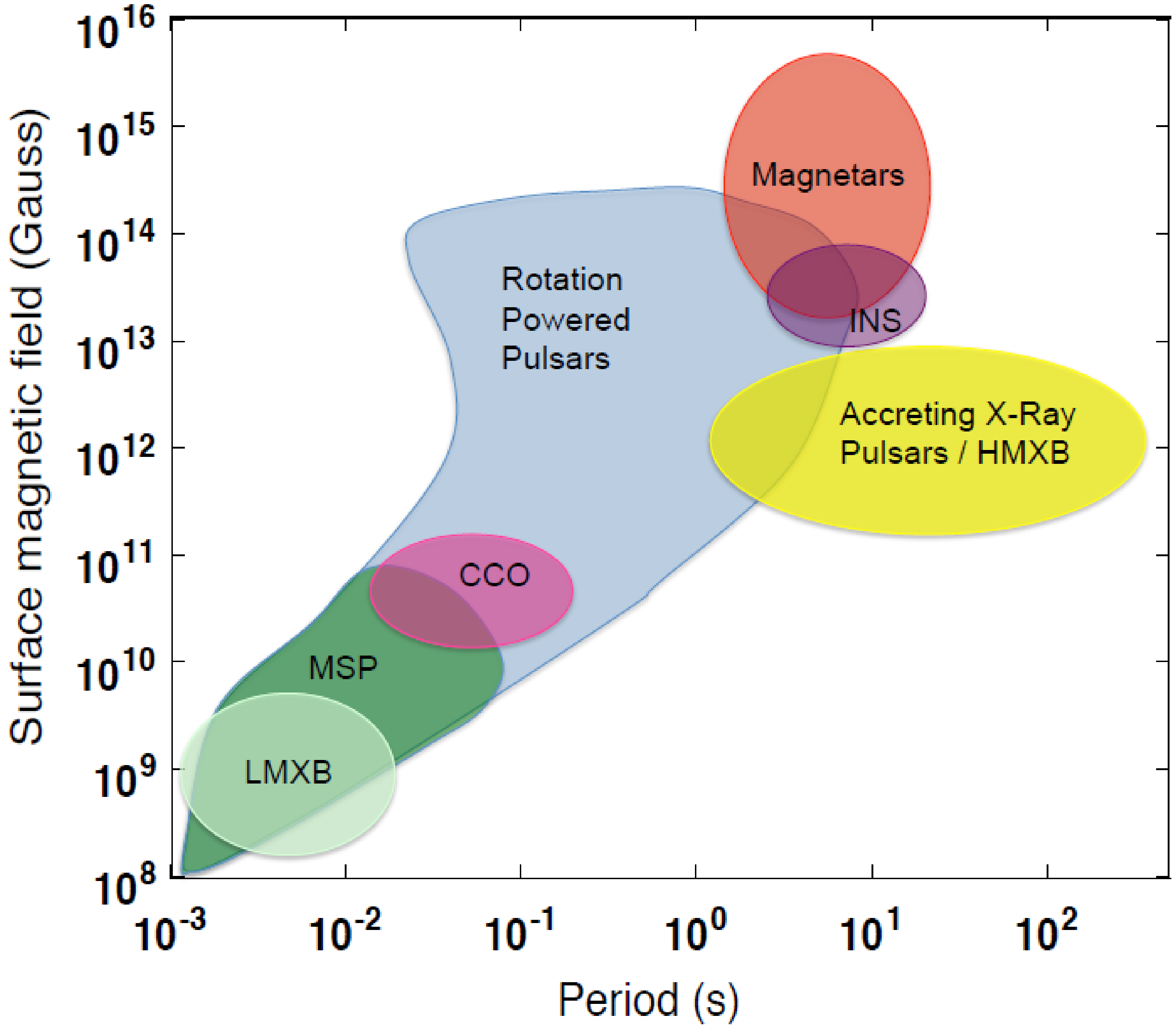
This pulsar lies near the centre of the Vela supernova remnant, which is the debris of the explosion of a massive star about 10,000 years ago. The pulsar (a so-called neutron star) is the collapsed core of this star, rotating with a period of 89 milliseconds or about 11 times a second.

DIVERSIDADE





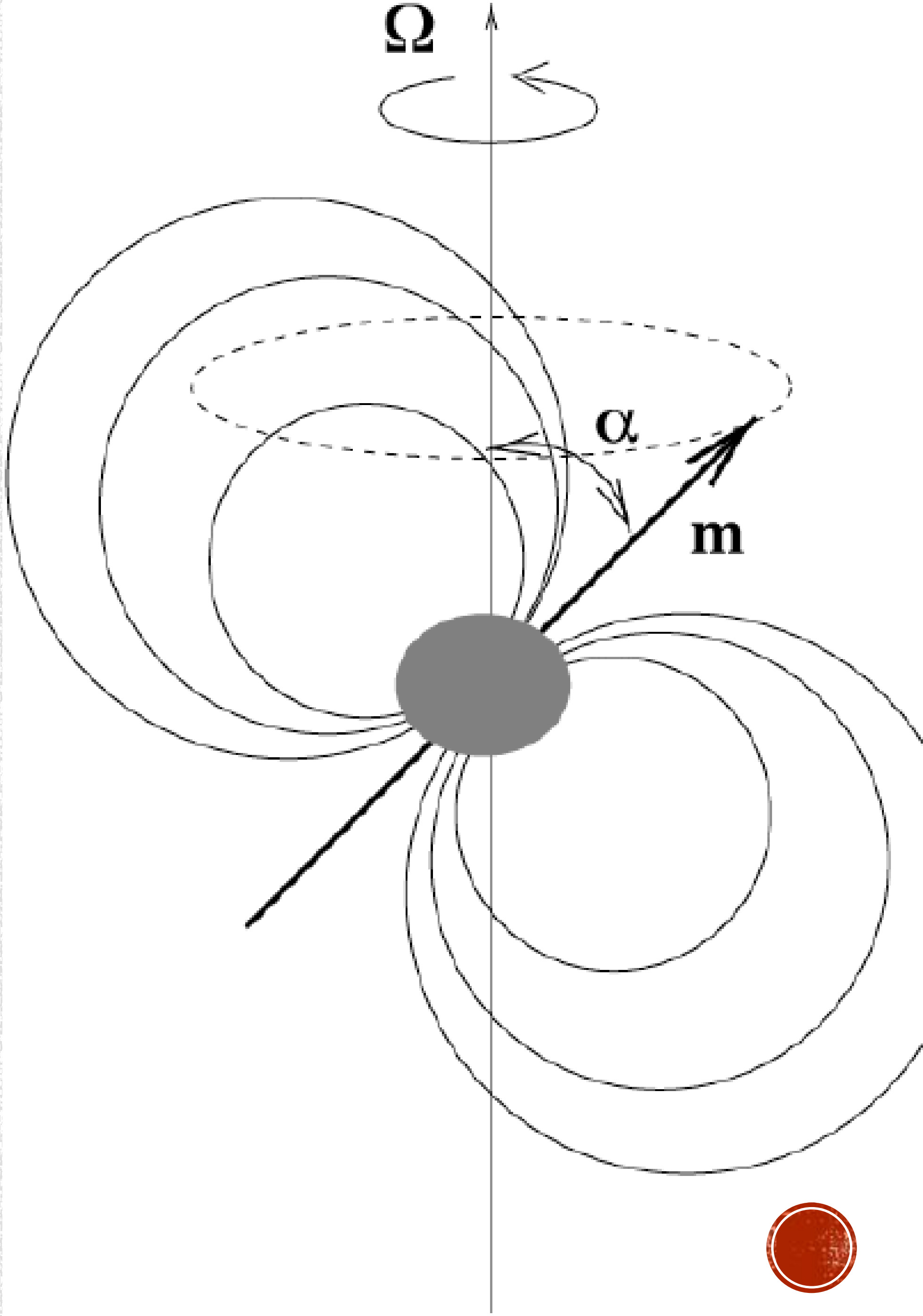
"ZOOLOGICO" DE ESTRELAS DE NÊUTRONS



"ZOOLOGICO" DE ESTRELAS DE NÊUTRONS

"ROTATION POWERED PULSARS"

- Estrelas de nêutrons que sofrem spin-down devido ao torque causado pelo campo magnético.
- A energia do spin-down se manifesta na forma de radiação dipolar magnética e no vento de partículas energéticas.
- Períodos que vão desde alguns *ms* até vários segundos.
- Mais de ~ 2000 radio pulsares são conhecidos.
- ~ 100 x-ray pulsares
- ~ 130 gamma-ray pulsares
- Pelo menos 1 – anã branca pulsar



MAGNETIC BRAKING MODEL

$$\dot{E} = \frac{d}{dt}\left(\frac{1}{2}I\Omega^2\right) = -C\Omega^{n+1}$$

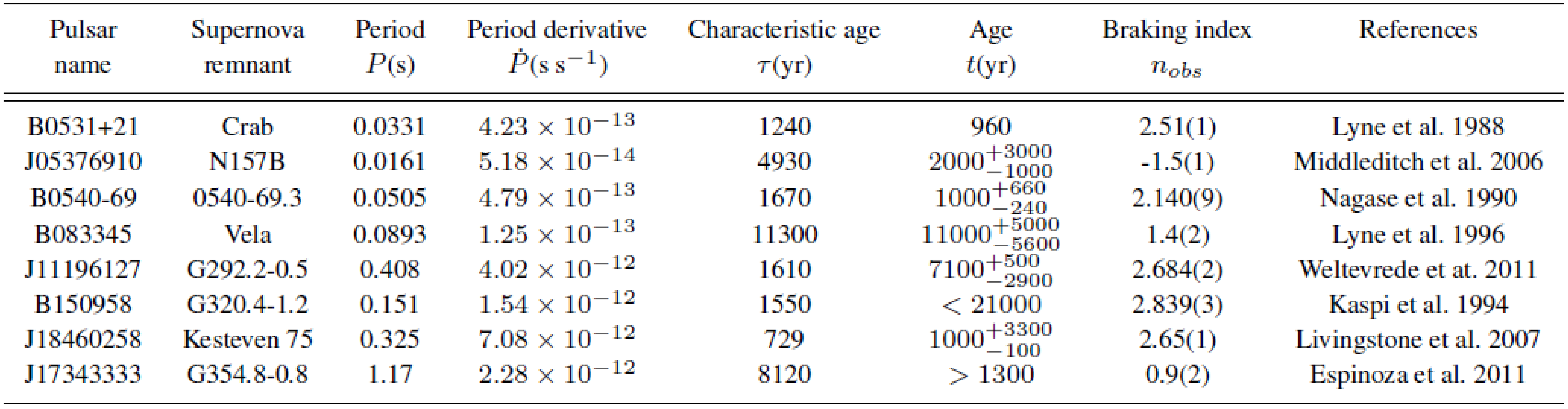
- For magnetic dipole radiation (n =3)

$$-\frac{dE}{dt} = -\frac{d}{dt}\left(\frac{1}{2}I\Omega^2\right) = \frac{2}{3}R^6B^2\Omega^4\sin^2\alpha$$

- Characteristic age

$$\tau = \frac{\Omega}{(n-1)\dot{\Omega}}\left[\left(\frac{\Omega}{\Omega_0}\right)^{n-1} - 1\right] = \frac{P}{(n-1)\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^{n-1}\right]$$

DADOS OBSERVACIONAIS - RPP



Pulsar name	Supernova remnant	Period P(s)	Period derivative $\dot{P}$(s s^{-1})	Characteristic age τ(yr)	Age t(yr)	Braking index n_{obs}	References
B0531+21	Crab	0.0331	4.23×10^{-13}	1240	960	2.51(1)	Lyne et al. 1988
J05376910	N157B	0.0161	5.18×10^{-14}	4930	2000^{+3000}_{-1000}	-1.5(1)	Middleditch et al. 2006
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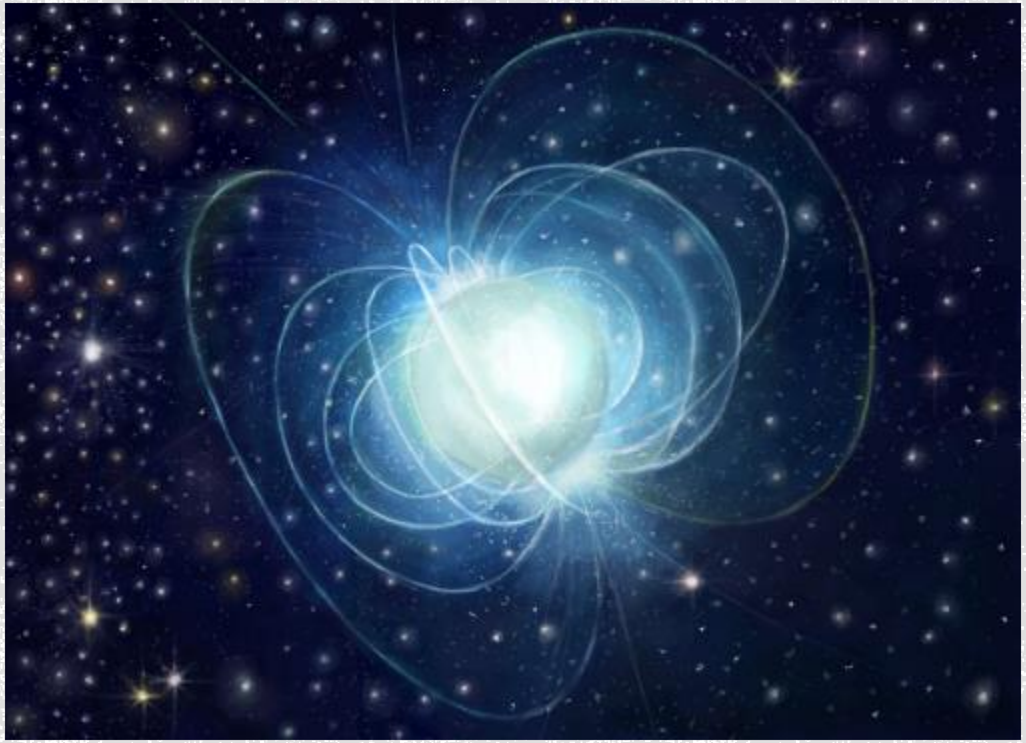
J17343333	G354.8-0.8	1.17	2.28×10^{-12}	8120	> 1300	0.9(2)	Espinoza et al. 2011

DESVIOS DO MODELO MAGNETIC BRAKING

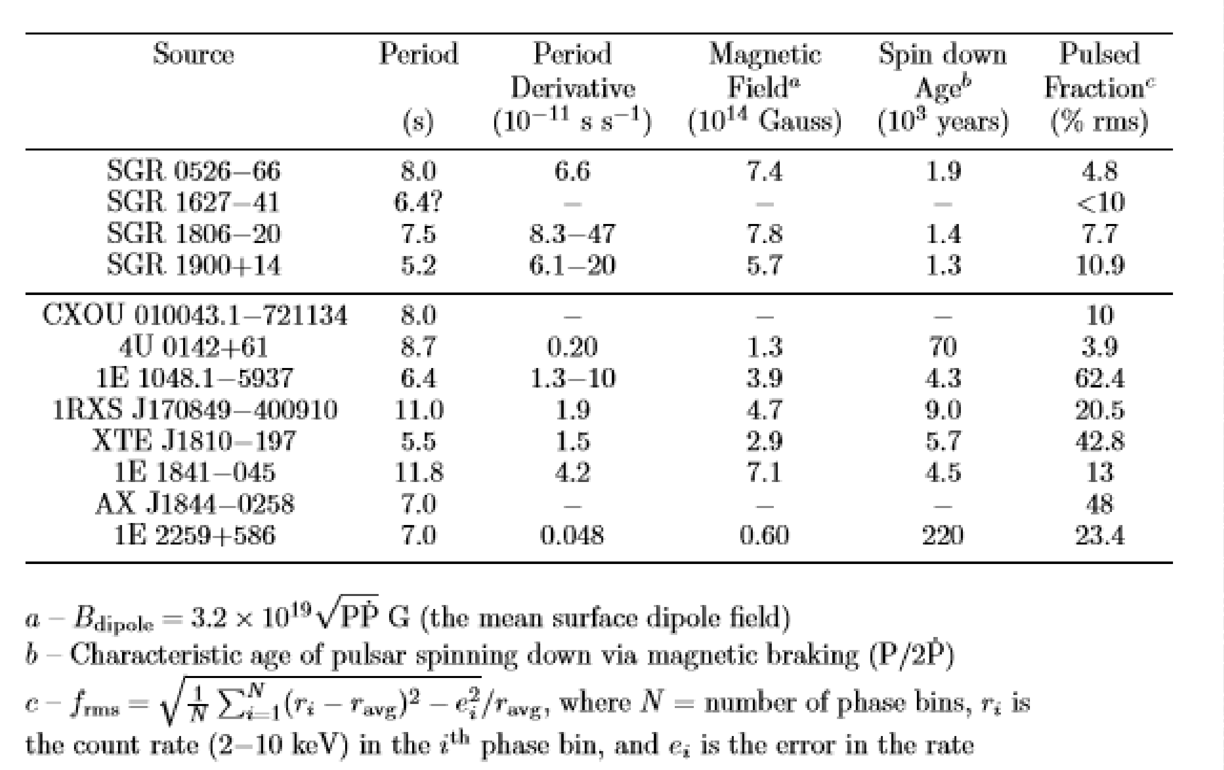
- Radiação multipolar eletromagnética ($n \geq 5$)
- Radiação quadrupolar gravitacional ($n = 5$)
- Decaimento do campo magnético ($n > 3$)
- Deformãção radial das linhas de campo magnético ($1 \leq n \geq 3$)
- Ventos relativísticos $n < 3$,
- Crescimento de um intenso campo magnético submergido na crosta estelar durante uma fase de acreção hipercritica, que posteriormente emerge devido a difusão ôhmica. ($n < 3$) (Muslimov & Page 1996, Bernal et al. 2010, 2013, Pons et al. 2012)
- Modificações no momento de inércia da estrela ($n < 3$) (Glendenning 2003, F. Weber 2010)

MAGNETARES



- Estrelas cuja luminosidade excede a energia perdida por spin-down.
- Em geral são subcategorizados em Anomalous X-ray pulsars (AXPs) e Soft-Gamma Ray Repeaters (SGRs)
- Emissão de bursts irregulares de alta energia.
- Altas temperaturas!
- Acredita-se que sua fonte de energia sejam altos campos magnéticos.

MAGNETARES – PROPRIEDADES OBSERVADAS

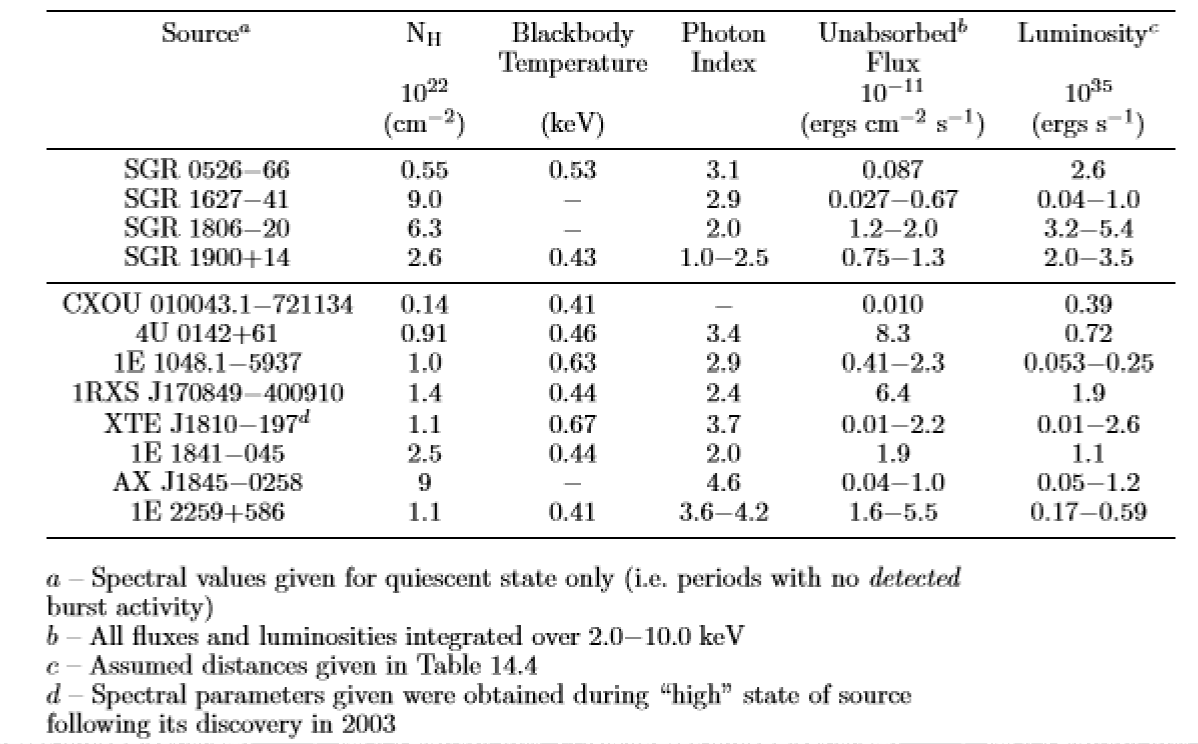


Source	Period (s)	Period Derivative (10^{-11} s s^{-1})	Magnetic Field[a] (10^{14} Gauss)	Spin down Age[b] (10^3 years)	Pulsed Fraction[c] (% rms)
SGR 0526–66	8.0	6.6	7.4	1.9	4.8
SGR 1627–41	6.4?	–	–	–	<10
SGR 1806–20	7.5	8.3–47	7.8	1.4	7.7
SGR 1900+14	5.2	6.1–20	5.7	1.3	10.9
CXOU 010043.1–721134	8.0	–	–	–	10
4U 0142+61	8.7	0.20	1.3	70	3.9
1E 1048.1–5937	6.4	1.3–10	3.9	4.3	62.4
1RXS J170849–400910	11.0	1.9	4.7	9.0	20.5
XTE J1810–197	5.5	1.5	2.9	5.7	42.8
1E 1841–045	11.8	4.2	7.1	4.5	13
AX J1844–0258	7.0	–	–	–	48
1E 2259+586	7.0	0.048	0.60	220	23.4

a – $B_{\text{dipole}} = 3.2 \times 10^{19}\sqrt{P\dot{P}}$ G (the mean surface dipole field)

b – Characteristic age of pulsar spinning down via magnetic braking ($P/2\dot{P}$)

c – $f_{\text{rms}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(r_i - r_{\text{avg}})^2 - e_i^2}/r_{\text{avg}}$, where N = number of phase bins, r_i is the count rate (2–10 keV) in the i^{th} phase bin, and e_i is the error in the rate



Source[a]	N_H 10^{22} (cm^{-2})	Blackbody Temperature (keV)	Photon Index	Unabsorbed[b] Flux 10^{-11} (ergs cm^{-2} s^{-1})	Luminosity[c] 10^{35} (ergs s^{-1})
SGR 0526–66	0.55	0.53	3.1	0.087	2.6
SGR 1627–41	9.0	–	2.9	0.027–0.67	0.04–1.0
SGR 1806–20	6.3	–	2.0	1.2–2.0	3.2–5.4
SGR 1900+14	2.6	0.43	1.0–2.5	0.75–1.3	2.0–3.5
CXOU 010043.1–721134	0.14	0.41	–	0.010	0.39
4U 0142+61	0.91	0.46	3.4	8.3	0.72
1E 1048.1–5937	1.0	0.63	2.9	0.41–2.3	0.053–0.25
1RXS J170849–400910	1.4	0.44	2.4	6.4	1.9
XTE J1810–197[d]	1.1	0.67	3.7	0.01–2.2	0.01–2.6
1E 1841–045	2.5	0.44	2.0	1.9	1.1
AX J1845–0258	9	–	4.6	0.04–1.0	0.05–1.2
1E 2259+586	1.1	0.41	3.6–4.2	1.6–5.5	0.17–0.59

a – Spectral values given for quiescent state only (i.e. periods with no *detected* burst activity)

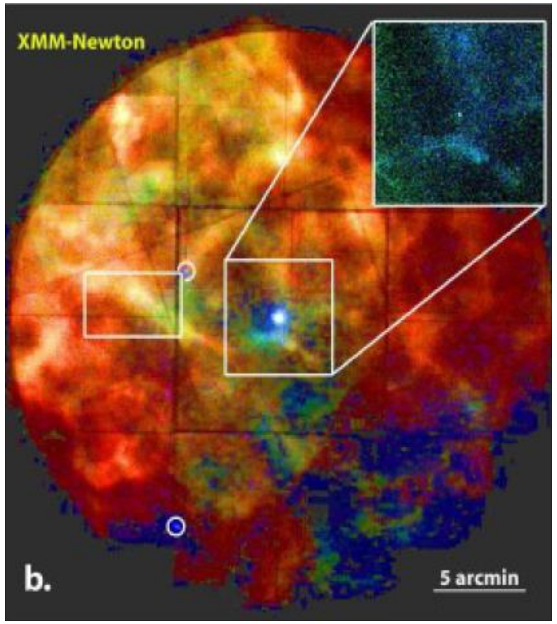
b – All fluxes and luminosities integrated over 2.0–10.0 keV

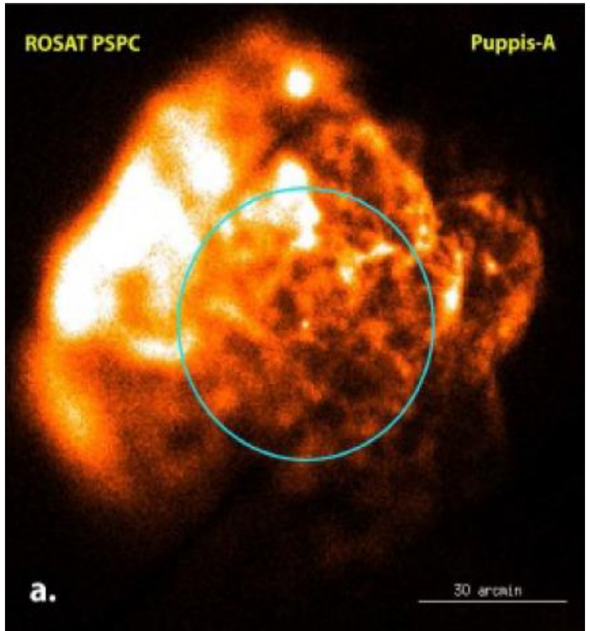
c – Assumed distances given in Table 14.4

d – Spectral parameters given were obtained during "high" state of source following its discovery in 2003

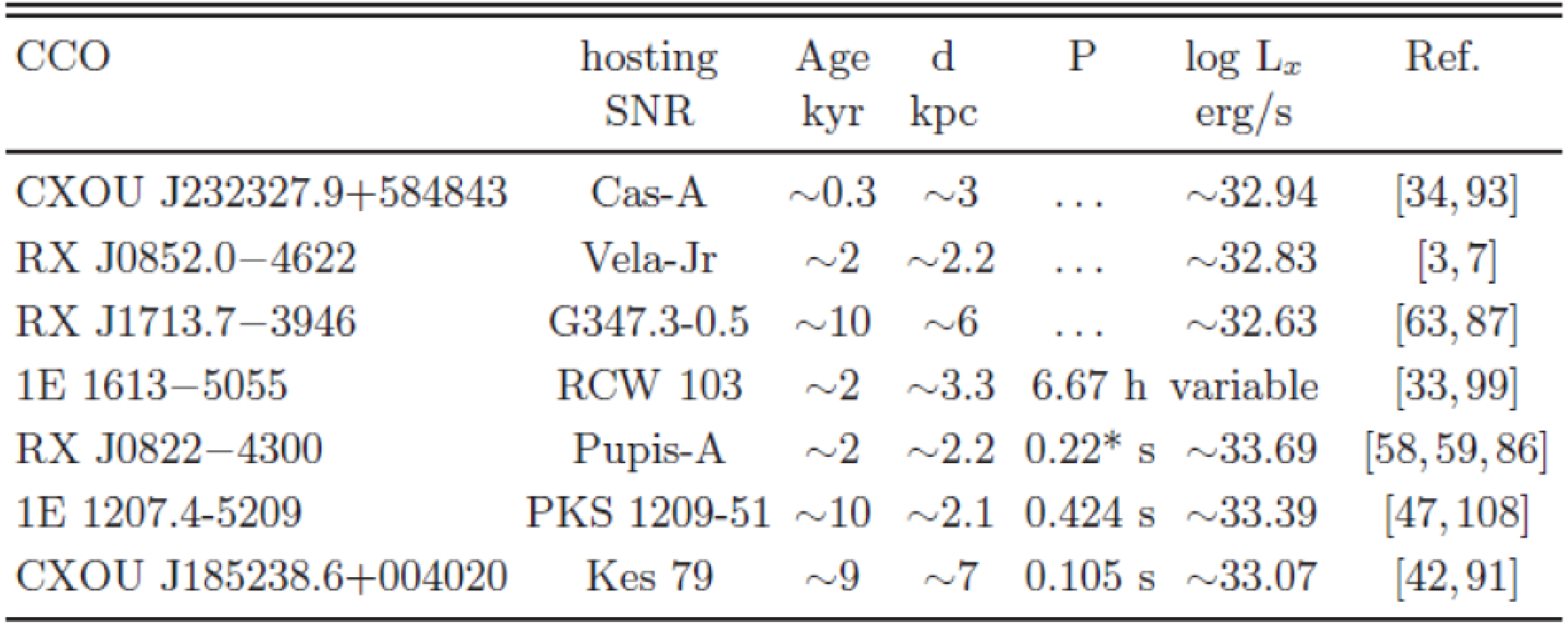
CENTRAL COMPACT OBJECTS (CCOS)

- Objetos centrais encontrados em remanescentes de supernovas.
- Silenciosos no rádio, mas brilhantes em raios X
- Fluxo continuo de raios-X, predominantemente térmico.
- Ausência de pulsar wind nebula.


XMM-Newton
b.
5 arcmin


ROSAT PSPC
Puppis-A
a.
30 arcmin

CENTRAL COMPACT OBJECTS – DADOS OBSERVADOS



CCO	hosting SNR	Age kyr	d kpc	P	log L_x erg/s	Ref.
CXOU J232327.9+584843	Cas-A	~0.3	~3	...	~32.94	[34, 93]
RX J0852.0−4622	Vela-Jr	~2	~2.2	...	~32.83	[3, 7]
RX J1713.7−3946	G347.3-0.5	~10	~6	...	~32.63	[63, 87]
1E 1613−5055	RCW 103	~2	~3.3	6.67 h	variable	[33, 99]
RX J0822−4300	Pupis-A	~2	~2.2	0.22* s	~33.69	[58, 59, 86]
1E 1207.4-5209	PKS 1209-51	~10	~2.1	0.424 s	~33.39	[47, 108]
CXOU J185238.6+004020	Kes 79	~9	~7	0.105 s	~33.07	[42, 91]

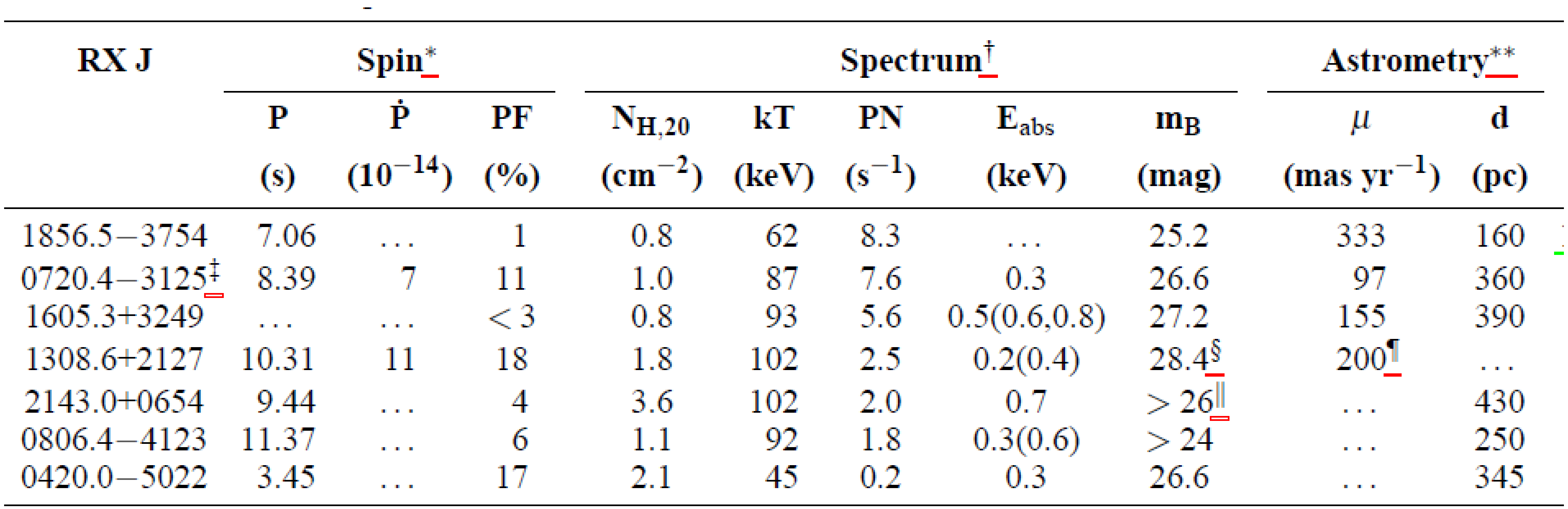
- Maioria dos CCO’s é bem modelada por um modelo de corpo negro com um ou dois picos com Tbb = (2 – 7) x 10^6 K.
- Isso nos dá uma área de emissão de Rbb ~ (0.3 – 5) km.

PULSARES ISOLADOS (INS)

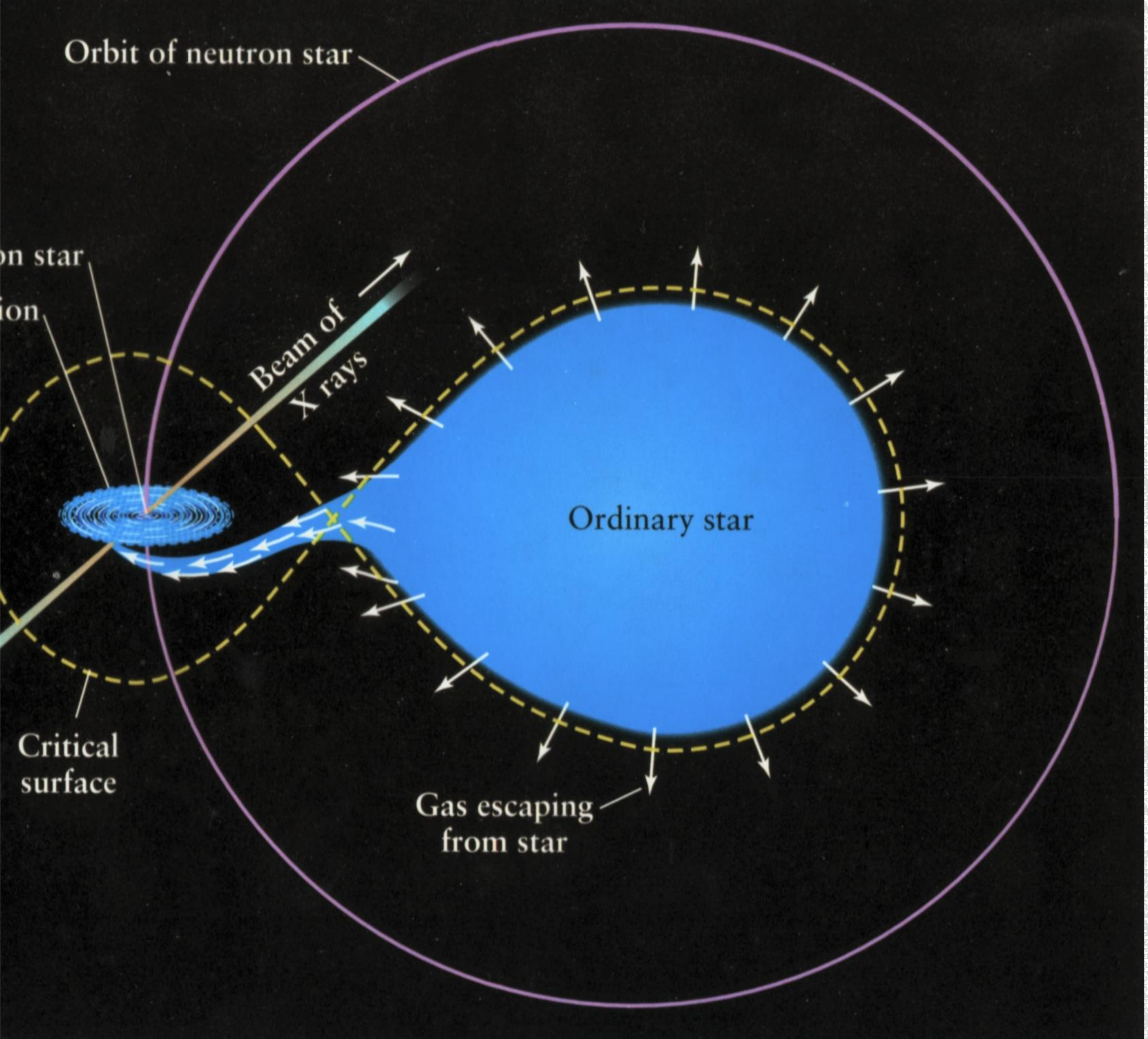
- Algumas vezes conhecidos como XDINS (X-ray dim Isolated Neutron Stars)
- Proprieades parecidas com as dos CCOs, com exceção do fato que não estão associados a nenhuma supernova.
- Emissão quase que exclusivamente térmica (faixa dos raios-X mole), com contra-parte óptica/UV muito fraca.
- 7 INS confirmados – Magníficos 7!

MOVIEWALLPAPERS.NET
THE
MAGNIFICENT
SEVEN
They fought like seven hundred
STEVE McQUEEN
JAMES COBURN
"BRITT"
HORST BUCHHOLZ
"CHICO"
YUL BRYNNER
"CHRIS ADAMS"
BRAD DEXTER
"HARRY LUCK"
ROBERT VAUGHN
"LEE"
CHARLES BRONSON
"BERNARDO O'REILLY"

INS – PROPRIEDADES OBSERVADAS



RX J	Spin[*]			Spectrum[†]					Astrometry[**]	
	P (s)	$\dot{P}$ (10^{-14})	PF (%)	$N_{H,20}$ (cm^{-2})	kT (keV)	PN (s^{-1})	E_{abs} (keV)	m_B (mag)	μ $(mas\ yr^{-1})$	d (pc)
1856.5−3754	7.06	…	1	0.8	62	8.3	…	25.2	333	160
0720.4−3125[‡]	8.39	7	11	1.0	87	7.6	0.3	26.6	97	360
1605.3+3249	…	…	< 3	0.8	93	5.6	0.5(0.6,0.8)	27.2	155	390
1308.6+2127	10.31	11	18	1.8	102	2.5	0.2(0.4)	28.4[§]	200[¶]	…
2143.0+0654	9.44	…	4	3.6	102	2.0	0.7	> 26[‖]	…	430
0806.4−4123	11.37	…	6	1.1	92	1.8	0.3(0.6)	> 24	…	250
0420.0−5022	3.45	…	17	2.1	45	0.2	0.3	26.6	…	345


Orbit of neutron star
on star
ion
Beam of X rays
Ordinary star
Critical surface
Gas escaping from star

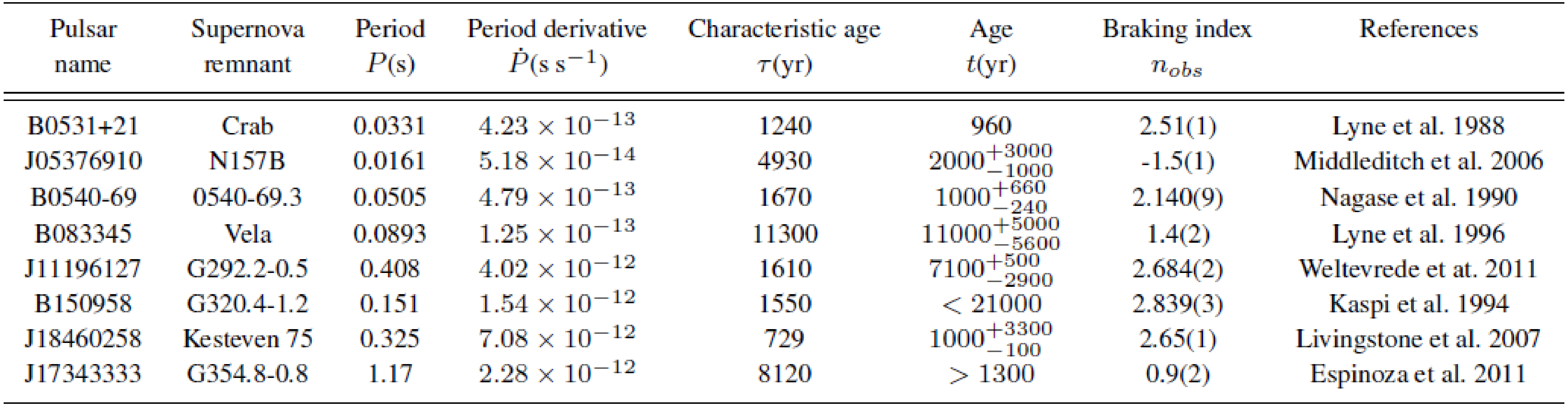
ESTRELAS DE NÊUTRONS COM ACREÇÃO

- Estrelas em sistemas binários, cuja energia gravitacional proveniente do processo de acreção alimenta (pelo menos parcialmente) o processo de emissão.

- Subdivididas em:
  - Low Mass X-ray Binaries
  - Intermediate X-ray Binaries
  - High Mass X-ray Binaries

- Acreditam que possam ser os precursores dos milisecond pulsars.

DADOS OBSERVACIONAIS – ROTATION POWERED PULSARS



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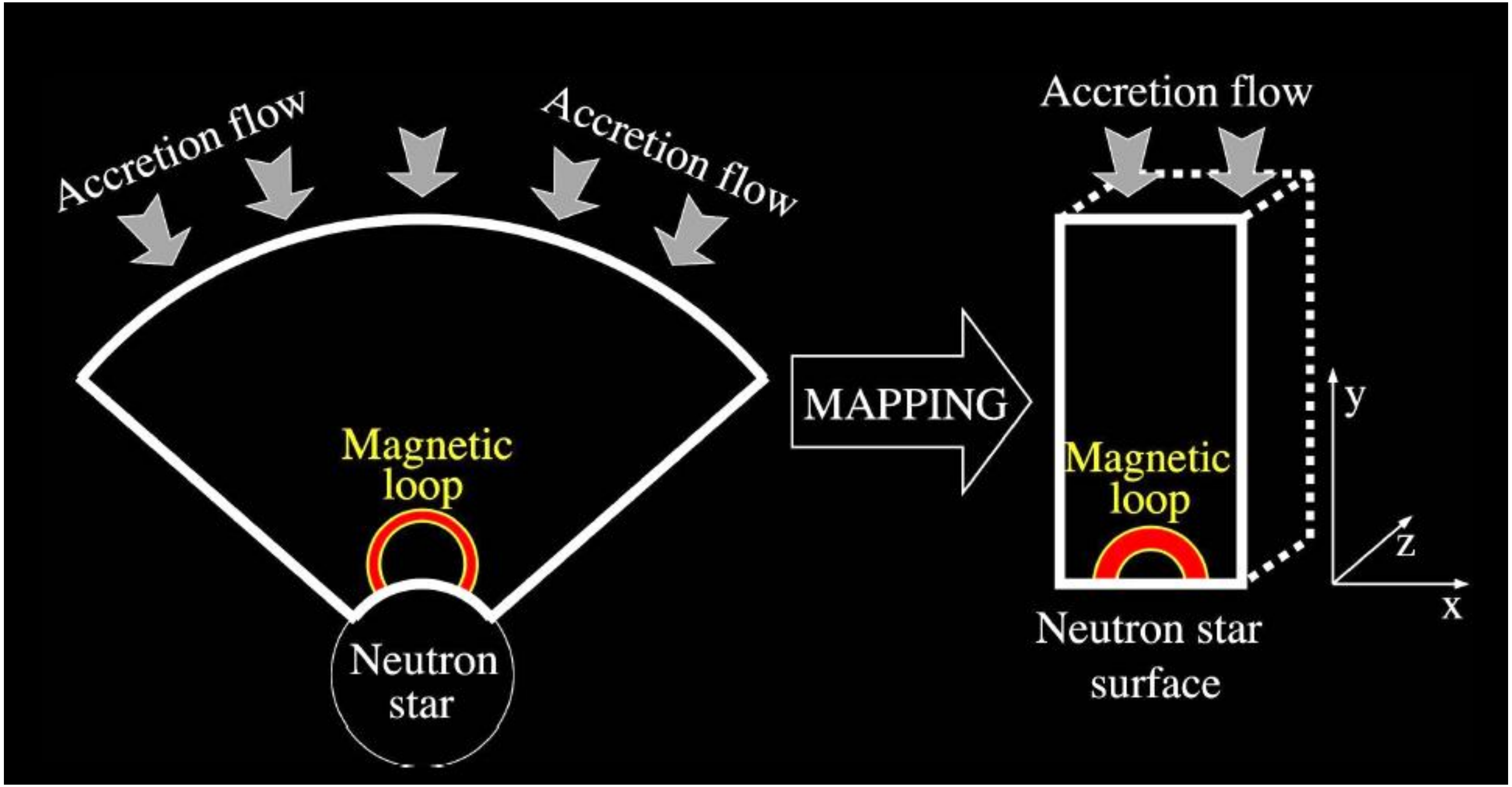
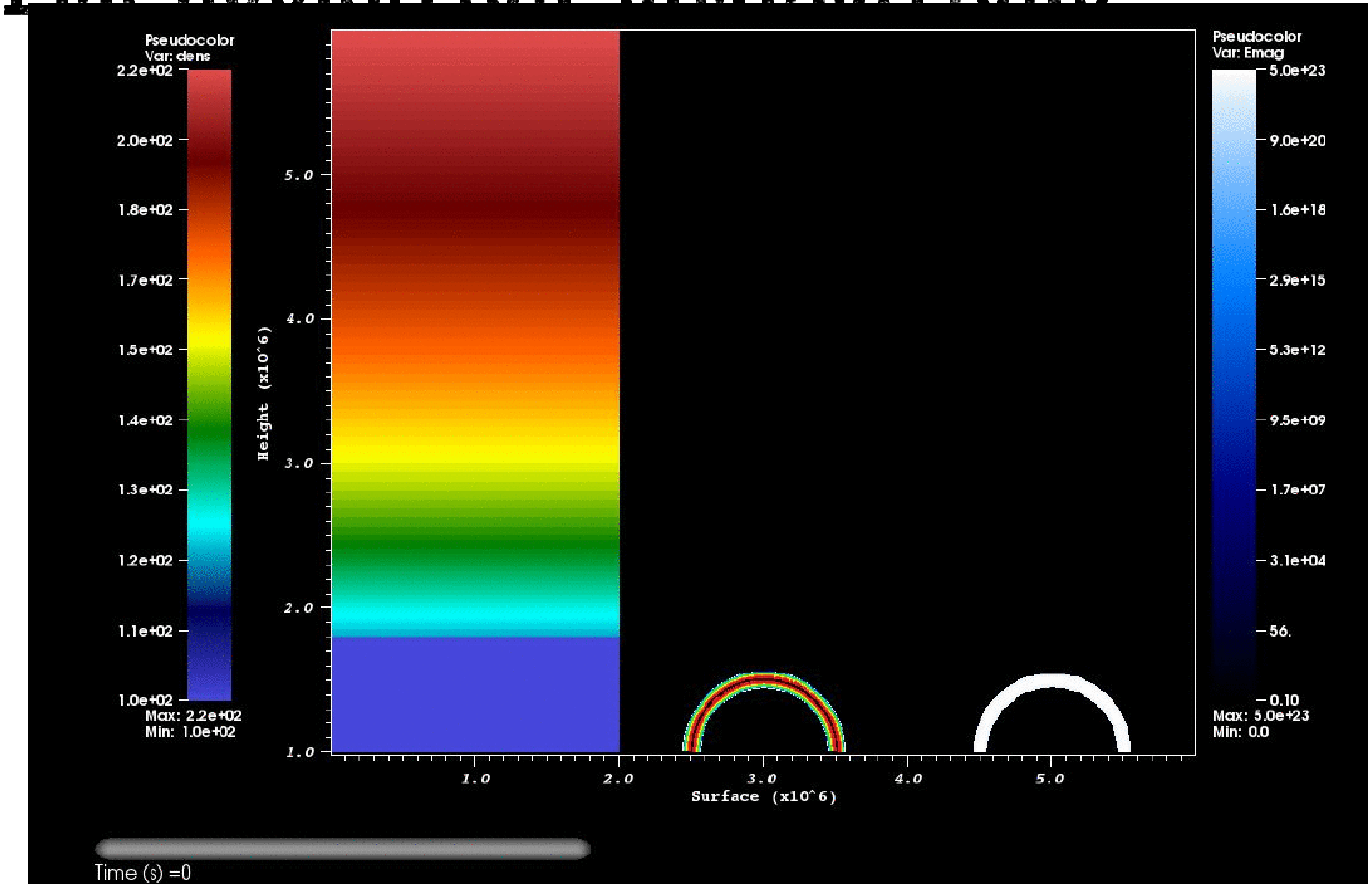
THE GROWTH OF THE MAGNETIC FIELD

- A newborn neutron star may be exposed to a hyper accretion phase few moments after the supernova explosion that originated it.
- In the core-collapse scenario, the shock wave sweeps the outer layers of the progenitor until it encounters a discontinuity in density. At this point, a reverse shock is generated leading to a fallback episode which allows to deposite large amounts of material on the stellar surface.
- The magnetic field can be submerged on the new crust of the neutron star during such phase.
- Following these ideas it is possible to study the growth of the magnetic field, when it re-emerge from the neutron star crust, and to follow its consequences on the pulsar spindown

HYPER-ACCRETION SIMULATIONS


Accretion flow
Accretion flow
Magnetic loop
Neutron star
MAPPING
Accretion flow
Magnetic loop
y
z
x
Neutron star surface

HYPER-ACCRETION SIMULATIONS



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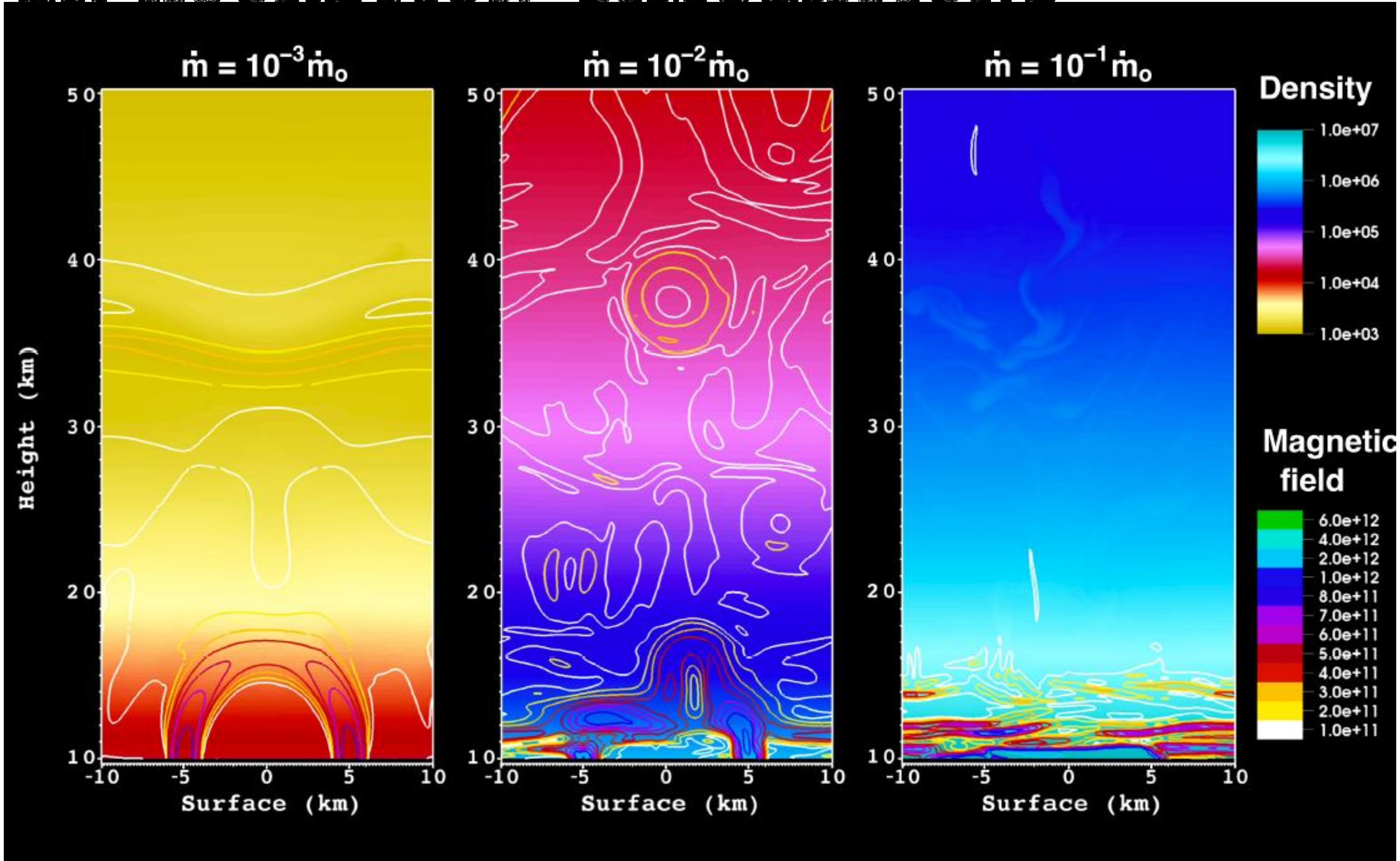


THE GROWTH OF THE MAGNETIC FIELD

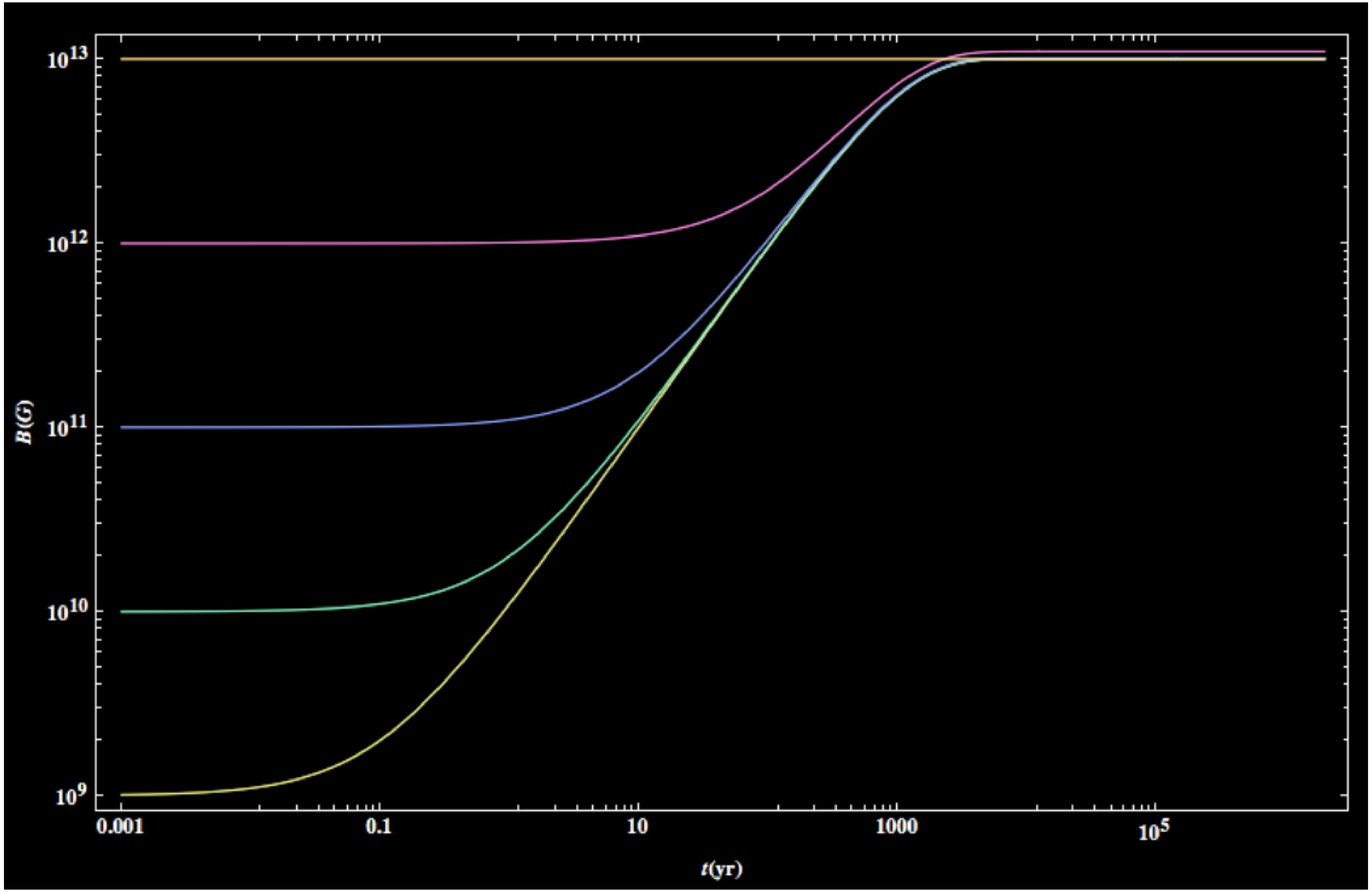
$$\dot{\Omega} = -k(t)\Omega^n, \quad k(t) = kf(t)$$

$$\tau = \frac{1}{f(t)}\left[\tau_0 + \int\limits_0^t f(t)dt\right]$$

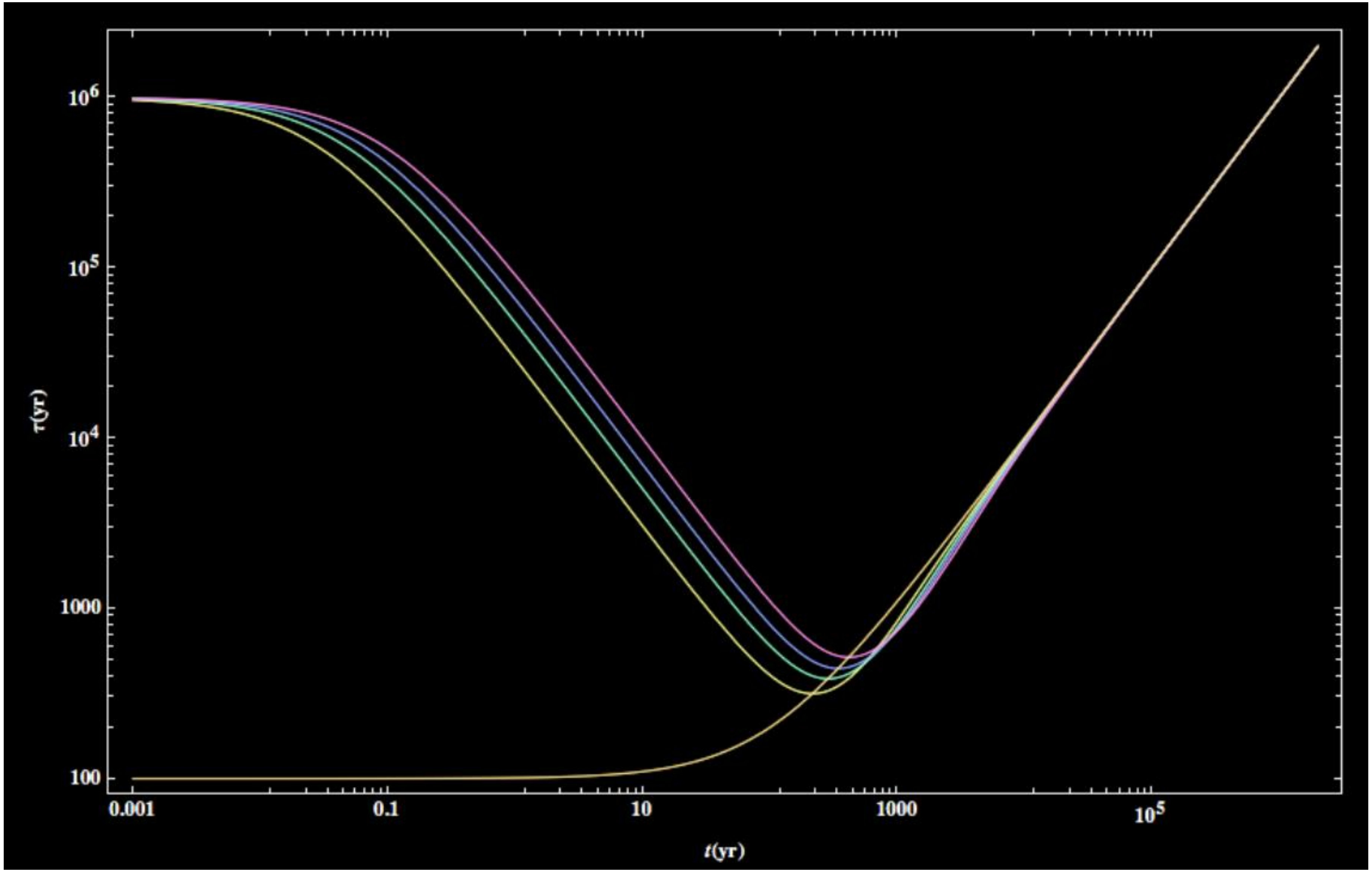
$$n = n_* + \frac{\dot{f}(t)}{f(t)}\frac{\Omega}{\dot{\Omega}} = n_* - \frac{\dot{f}(t)}{f(t)}\frac{P}{\dot{P}}$$

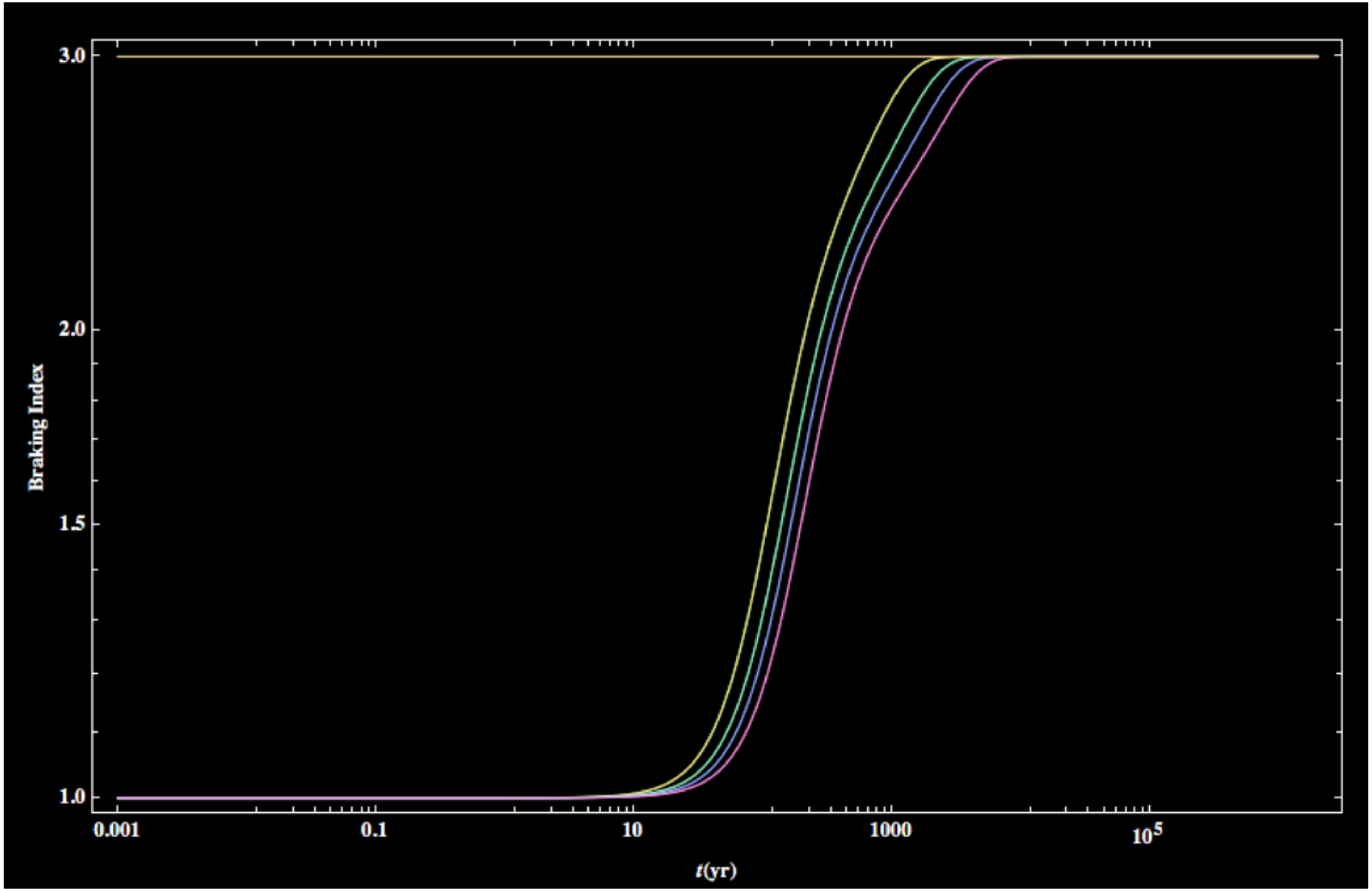
$$f(t) = \epsilon + \left[1 - \exp\left(-\frac{t}{\tau_B}\right)\right]$$

THE GROWTH OF THE MAGNETIC FIELD



THE GROWTH OF THE MAGNETIC FIELD



BRAKING INDEX