ACCRETION BY ISOLATED NEUTRON STARS

Nazar R. Ikhsanov

Institute of Astronomy, University of Cambridge, UK

Pulkovo Observatory, St. Petersburg, Russia

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- **The Missing Isolated Neutron Stars Problem**
- **Possible Solutions...**
- **Evolutionary Tracks of Isolated Neutron Stars**

The Evolutionary Track of a Neutron Star contains TWO states of *Propeller*

(Davies, Fabian, & Pringle 1979, MNRAS, 186, 779)

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I. EJECTOR (spin-powered pulsar) $\Longrightarrow$

II***.** SUPERSONIC PROPELLER $\Longrightarrow$

III****.** *SUBSONIC* **PROPELLER** $\Longrightarrow$

IV. ACCRETOR (direct accretion: $\dot{\mathfrak{M}}_{\rm c} \equiv \dot{\mathfrak{M}}_{\rm a}$)

The Problem

- Mass Capture Rate $\quad \dot{\mathfrak{M}}_{\rm c} \sim 10^{12}\,{\rm g/s} \quad N_{\rm ISM}\, V_6^{-3}\, M_{1.4}^2$
- Luminosity $\quad L_{\rm a} \sim 10^{32}\,{\rm erg/s} \quad N_{\rm ISM}\, V_6^{-3}\, M_{1.4}^3\, R_6^{-1}$
- Energy Range $\quad \epsilon_\gamma \sim 0.5\,{\rm keV} \quad L_{32}^{1/4}\, S_9^{-1/4}$

Predictions:

★ Treves & Colpi (1991, A&A, 241, 107)	$\sim 5 \times 10^3$	(ROSAT, All Sky Survey)
★ Blaes & Madau (1993, ApJ, 403, 690)	$\sim 10^3 - 10^4$	(ROSAT, All Sky Survey)
★ Popov et al. (2000, ApJ, 544, L53)	$\sim 3 \times 10^4$	Chandra & XMM-*Newton*

Observations:

ROSAT, All Sky Survey $\qquad$ a few candidates...

Possible Reasons

- **LOW MAGNETIZATION**
- **A DIFFERENT VELOCITY DISTRIBUTION**
- **LOW EFFICIENCY OF BONDY ACCRETION**
- **A DIFFERENT EVOLUTIONARY TRACK**

EJECTOR $\Longrightarrow$ SUPERSONIC PROPELLER $(r_{\rm m} > r_{\rm cor})$

★ Condition: $$p_{\rm wind}(r_G) = p_\infty(r_G) \qquad \left(r_G = \frac{2GM}{V_{\rm rel}^2}\right)$$

★ Transition period: $$P_{\rm md} \simeq 15\ {\rm s}\ \mu_{30}^{1/2}\, V_7^{1/2}\, N^{-1/4}\, M_{1.4}^{-1/2}$$

★ Spin-down timescale: $$\tau_{\rm md} \sim 5\times10^9\ {\rm yr}\ \mu_{30}^{-1}\, V_7\, N^{-1/2}\, I_{45}\, M_{1.4}^{-1}$$

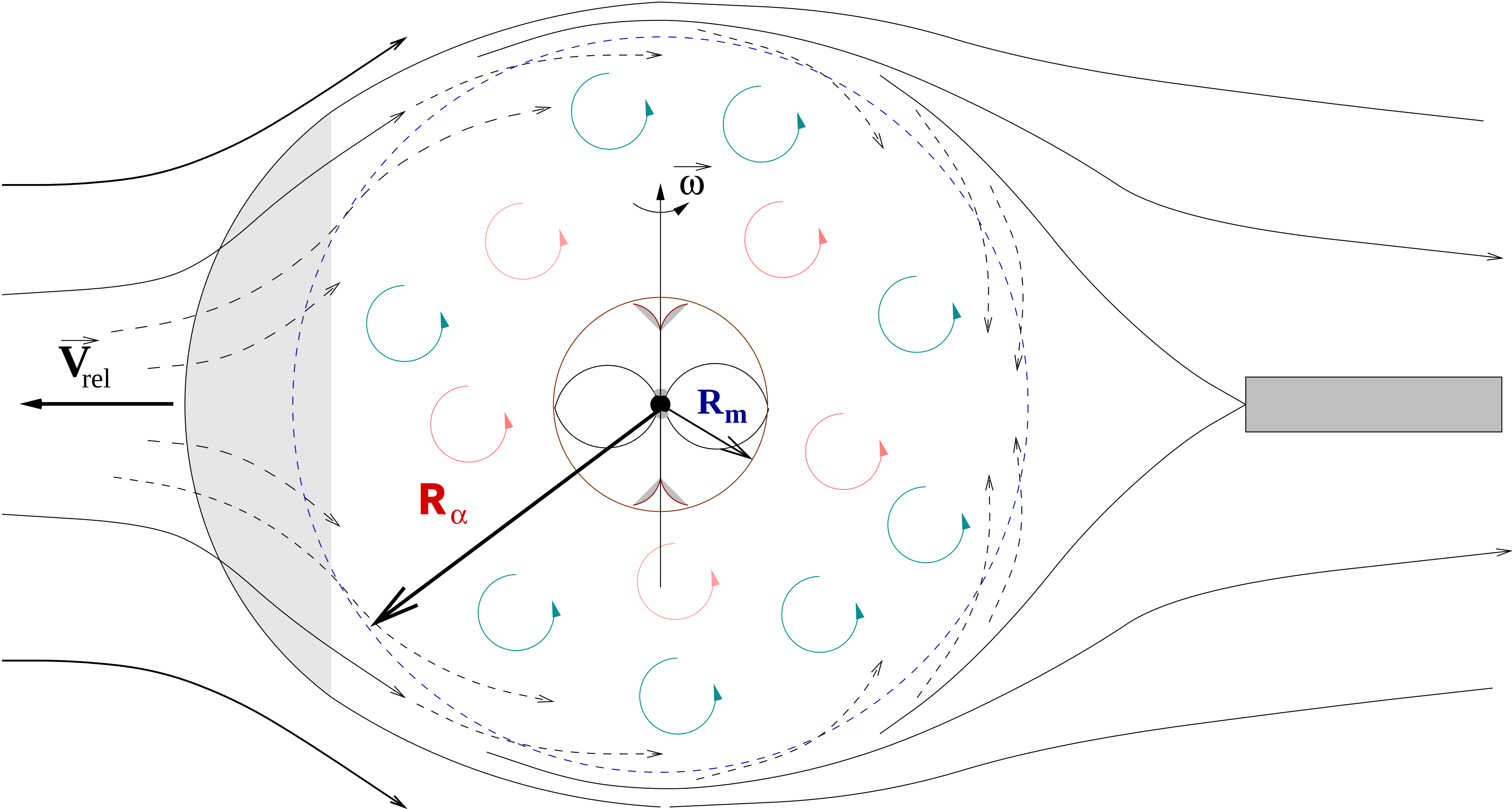
Why Propeller ?

For the direct *Ejector* $\longrightarrow$ *Accretor* transition to occur

$(\ r_{\rm m} \lesssim r_{\rm cor} = (GM/\Omega^2)^{1/3}\ )$:

$$\dot M_{\rm c} \gtrsim \dot M_{\rm ea} \simeq 0.1\ {\rm M_\odot\ yr^{-1}}\ \mu_{30}^2\, V_7^{7/5}\, M_{1.4}^4$$

!!! An intermediate spin-down state is required !!!



$\vec{\omega}$
$\vec{V}_{rel}$
R_m
R_α

Original: Davies, R.E. & Pringle, J.E., 1981, MNRAS 196, 209
Correction: Ikhsanov, N.R. 2002, A&A, 381, L61

Supersonic Propeller: Energy balance

$$\underline{\underline{\Gamma}} = \frac{\text{Excess heat content of convective blob}}{\text{Energy radiated in the lifetime of a blob}} = M_{\rm Mach}^2 \left[\frac{V_{\rm t}\ t_{\rm br}}{r}\right] \quad \underline{\underline{\geq \ 1}} \quad !$$

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$$\dot{\mathfrak{M}}_{\rm c} \lesssim \dot{\mathfrak{M}}_{\rm max} \simeq 10^{17}\ {\rm g\,s^{-1}} \left[\frac{M_{\rm ns}}{M_{\odot}}\right] \left[\frac{V_{\rm rel}}{10^7\,{\rm cm\,s^{-1}}}\right]$$

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$t_{\rm br} \simeq 2 \times 10^{11}\, T^{1/2}\, N_{\rm e}^{-1}\, {\rm s}$ is the bremsstrahlung cooling time;

$N_{\rm e}(r_\alpha) \simeq \dot{M}_{\rm c}/\pi r_\alpha^2 V_\infty m_{\rm p}$ is the number density of the envelope plasma;

$V_{\rm s} \sim V_{\rm t} \sim V_{\rm ff}(r) = \sqrt{2GM_{\rm ns}/r}$ is the velocity of turbulent motions;

$T(r) \sim T_{\rm ff}(r) = (GM_{\rm ns}m_{\rm p})/(kr)$ is the free-fall temperature;

$r_\alpha = (2GM_{\rm ns})/V_\infty^2$ is the capture radius;

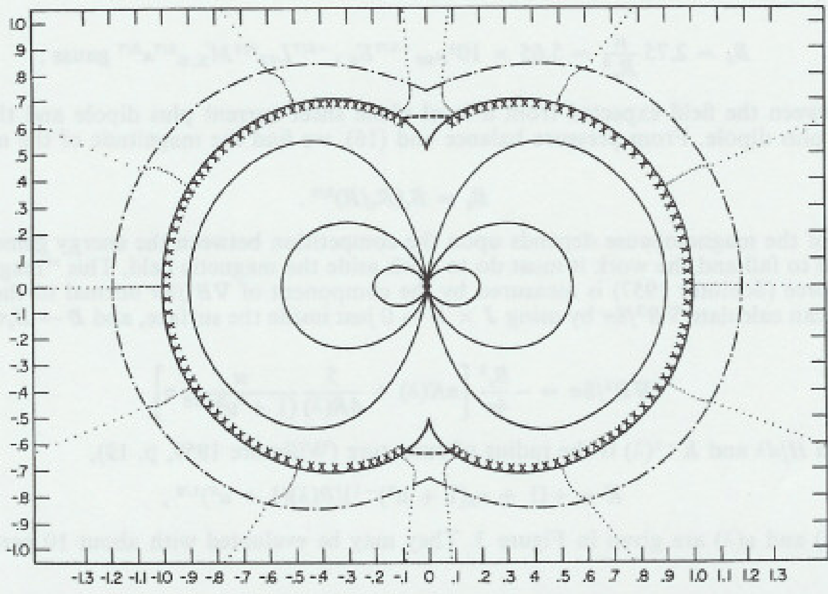
SUPERSONIC $\Longrightarrow$ *SUBSONIC* **PROPELLER**

★ Condition: $r_{\rm cor} = r_{\rm m}$ $\qquad r_{\rm m} = \left(\frac{\mu^2}{\dot{\mathfrak{M}}_{\rm c} \sqrt{2GM}} \right)^{2/7}$

★ Transition period: $P_{\rm pp} \sim$ 7000 s $\qquad \mu_{30}^{6/7}\, V_7^{9/7}\, N^{-3/7}\, M_{1.4}^{-11/7}$

★ Spin-down time: $\tau_{\rm pp} \sim 2.5 \times 10^7$ yr $\qquad \mu_{30}^{-8/7}\, V_7^{9/7}\, N^{-3/7}\, I_{45}\, M_{1.4}^{-4/7}$

$$(\tau_{\rm pp} \ll \tau_{\rm md})$$



1.0
.9
.8
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.6
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.2
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0
-.1
-.2
-.3
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-.6
-.7
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-1.0
-1.3 -1.2 -1.1 -1.0 -.9 -.8 -.7 -.6 -.5 -.4 -.3 -.2 -.1 0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0 1.1 1.2 1.3

Ikhsanov, N.R. 2001, A&A, 375, 944

PLASMA ENTRY INTO THE MAGNETOSPHERE $(r_{\rm m} < r_{\rm cor})$

I. Diffusion $\dot{M}_{\rm in} \simeq \dot{M}_{\rm B} = 2 \times 10^6\,{\rm g\,s^{-1}}\ \alpha_{0.1}^{1/2}\ \mu_{30}^{-1/14}\ M_{1.4}^{11/7}\ N^{11/14}\ V_7^{-33/14}$

II. Interchange instabilities of the magnetospheric boundary

ARE SUPPRESSED as long as $t_{\rm heat} < t_{\rm cool}$

(Arons & Lea 1976; Elsner & Lamb 1976)

$$g_{\rm eff} = \frac{GM_{\rm ns}}{r_{\rm m}^2(\lambda)} - \frac{V_{\rm T_i}^2(r_{\rm m})}{R_{\rm cur}(\lambda)} > 0, \qquad \longleftrightarrow \qquad T(r_{\rm m}) < 0.3 T_{\rm ff}(r_{\rm m})$$

Original: Davies, R.E. & Pringle, J.E., 1981, MNRAS 196, 209
Correction: Ikhsanov, N.R. 2001, A&A, 368, L5

SUBSONIC PROPELLER

SPIN-DOWN HEATING: Break period

★ Condition: $$\Gamma = M_{\rm Mach}^2 \left[\frac{V_{\rm t}\ t_{\rm br}}{r}\right] > 1$$

★ Break period: $$P_{\rm br} \simeq 10^5\ {\rm s} \quad \mu_{30}^{16/21}\ N^{-5/7} V_7^{15/7}\ M_{1.4}^{-34/21}$$

★ Spin-down time: $$\tau_{\rm br} \sim 2 \times 10^5\ {\rm yr} \quad \mu_{30}^{-2}\ I_{45}\ P_5\ M_{1.4}$$

$$\left(\tau_{\rm br} \ll \tau_{\rm pp} \ll \tau_{\rm md}\right)$$

Ikhsanov, N.R. 2001, A&A, 375, 944

Subsonic Propeller ≡ Diffusion-driven Accretor

$$L_{\rm a} \simeq 2 \times 10^{26}\ {\rm erg\,s^{-1}}\ \alpha_{0.1}^{1/2}\ \mu_{30}^{-1/14}\ N^{11/14}\ V_{7}^{-33/14}\ M_{1.4}^{19/7}\ r_{6}^{-1}$$

Quasi-stable envelope approximation

Drift velocity	$V_{\rm dr} \simeq (\dot{\mathfrak{M}}_{\rm a}/\dot{\mathfrak{M}}_{\rm c})\ V_{\rm ff}$
Drift time-scale	$t_{\rm dr} = r/V_{\rm dr}$
Time-scale of energy redistribution (due to turbulent motions)	$t_{\rm t} = r/V_{\rm t}$

The quasi-stable envelope approximation is applicable if $t_{\rm t} \ll t_{\rm dr}$, i.e.

$$P_{\rm s} \lesssim P_{\rm qs} = 10^{6}\ {\rm s}\ \ \alpha_{0.1}^{-1/2}\ \mu_{30}^{13/14}\ M_{1.4}^{-6/7}\ \dot{\mathfrak{M}}_{9}^{-3/14}$$

Ikhsanov, N.R. 2003, A&A, 399, 1147

SUBSONIC PROPELLER

HEATING by Radial Plasma Drift

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- $L_{\rm dr}$ dominates the Spin-Down Power if $\quad P_{\rm s} \gtrsim 5 \times 10^4\,{\rm s}\ \alpha_{0.1}^{1/6}\ \mu_{30}^{37/42}\ \dot{\mathfrak{M}}_9^{-5/14}\ M_{1.4}^{-16/21}$

- Heating time-scale: $\quad t_{\rm dr} \propto r^{3/2};$

- Cooling time-scale is $(T \propto 1/r, n \propto r^{-3/2})$ $\quad t_{\rm br} \propto r$

- Heating dominates cooling if

$$\dot{\mathfrak{M}}_{\rm c} \lesssim \dot{\mathfrak{M}}_0 \simeq 10^{14}\,{\rm g\,s^{-1}}\alpha_{0.1}^{7/17}\ \mu_{30}^{-1/17}\ V_7^{14/17}\ M_{1.4}^{16/17}$$

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A Neutron Star in a Weak Wind remains in the Subsonic Propeller state as long as $r_{\rm m} \gg r_{\rm ns}$

Ikhsanov, N.R. 2001, A&A, 368, L5

Why Subsonic Propellers ?..

Long spin-period ($P_s > 100\,\mathrm{s}$) Be/X-ray pulsars:

$$\dot{\mathfrak{M}}_c \sim 10^{15}\,\mathrm{g/s}; \quad \mu \sim 10^{30}\,\mathrm{G\,cm^3}; \quad V \sim 10^{8}\,\mathrm{cm/s}; \quad t_{\rm sd} \lesssim 10^{7}\,\mathrm{yr}$$

$$\dot{P} \gtrsim 10^{-13}\ P_{100}\ t_7^{-1}\,\mathrm{s\,s^{-1}}$$

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★ $\tau_{\rm sd} = (\tau_{\rm md} + \tau_{\rm pp} + \tau_{\rm br}) \sim 10^{6}\,\mathrm{yr}$

★ $P(r_{\rm cor} = r_{\rm m}) \simeq\ 23\ \mathrm{s}\ \ \mu_{30}^{6/7}\ M_{1.4}^{-5/7}\ \dot{\mathfrak{M}}_{15}^{-3/7}$

★ $P_{\rm br}\ \simeq\ \underline{450\ \mathrm{s}}\ \ \mu_{30}^{16/21}\ M_{1.4}^{-4/21}\ \dot{\mathfrak{M}}_{15}^{-5/7}$

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CONCLUSIONS

★ **The Evolutionary Track of a Magnetized INS ends by the state of SUBSONIC PROPELLER**

★★ **Luminosity of Old INSs accreting material from ISM is limited to**

$$L_{\rm a} \lesssim \underline{2 \times 10^{26}\ {\rm erg\,s^{-1}}}\ \ \alpha_{0.1}^{1/2}\ \mu_{30}^{-1/14}\ N^{11/14}\ V_7^{-33/14}\ M_{1.4}^{19/7}\ r_6^{-1}$$