A propelling neutron star in the enigmatic Be-star γ Cassiopeia

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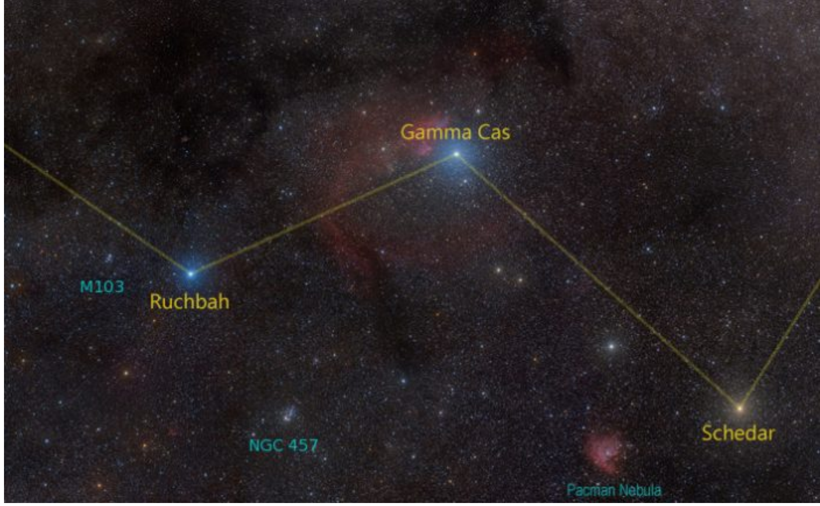
Physics of Neutron Stars - 2017
St. Petersbourg, July 14, 2017

PK, Oskinova, Torrejon 2017 MNRAS 465 L11; 1610.07799

Plan

- Introduction: gamma Cas
- Quasi-spherical shells around NS
- Propeller in quasi-spherical shells
- XMM/NuSTAR observations
- Evolution of gamma Cas
- Conclusions

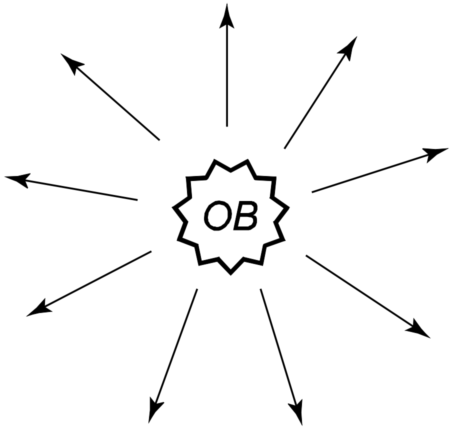
Gamma Cas: Factsheet

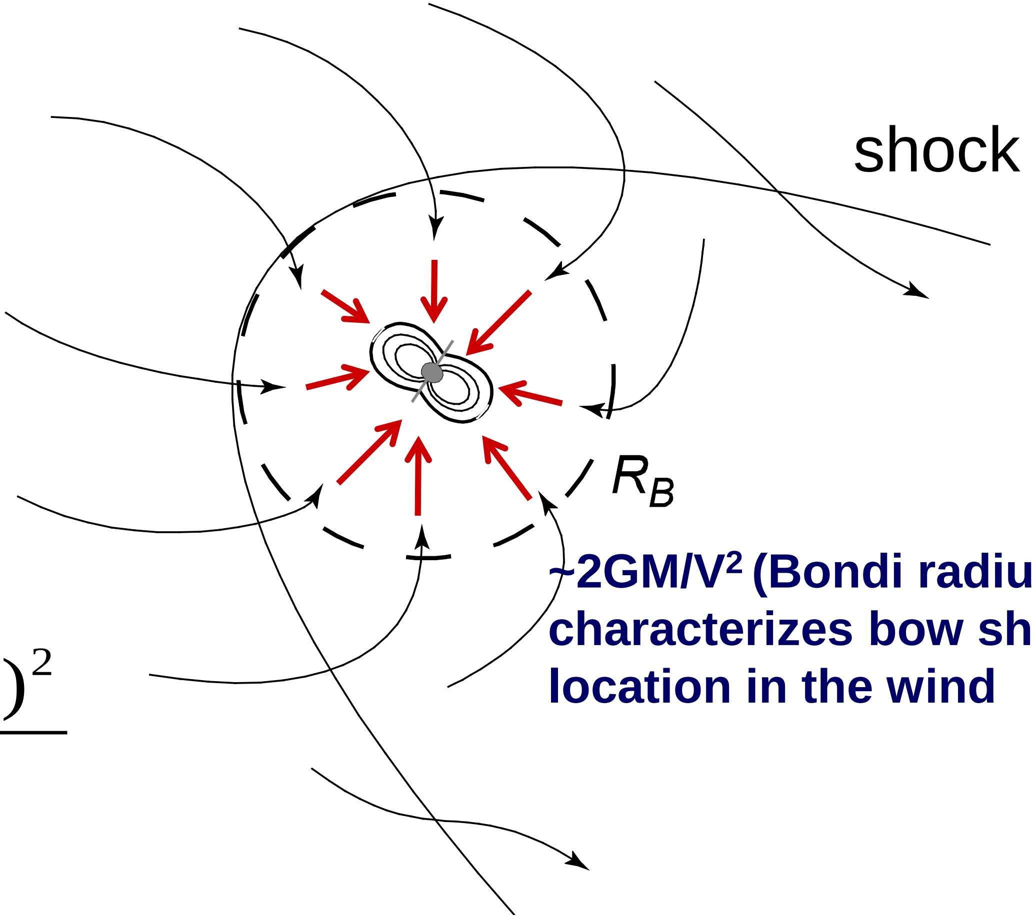


- **Brightest Be-star**
- B0.5IVpe ~16 $M_\odot$
- Binary system $P=204^d$, $e<0.03$
- $M_x \sim 1\ M_\odot$
- Prototype of X-ray Be-stars 10^{32}-10^{33} erg/s with (multitemperature) hot optically thin thermal spectrum
- $kT_{\rm hot} \sim 20$ keV $\quad n_e \sim 10^{13}$ cm^{-3} $\quad v_{turb} \sim 1000$ km s^{-1} (Lopes de Oliveira+2010)
- no pulsations
- Accretion onto NS or WD? X-rays from the Be-disk?

A model: quasi-spherical accretion onto a rapidly rotating NS

Accretion Bondi-Hoyle-Littleton





~2GM/V^2 (Bondi radius) characterizes bow shock location in the wind

$$t_{cool} << t_{freefall}$$

$$\dot{M} \approx \rho v R_B^2 \sim \rho \frac{(2GM)^2}{v^3}$$

$$R_B = \frac{2GM}{v^2}$$

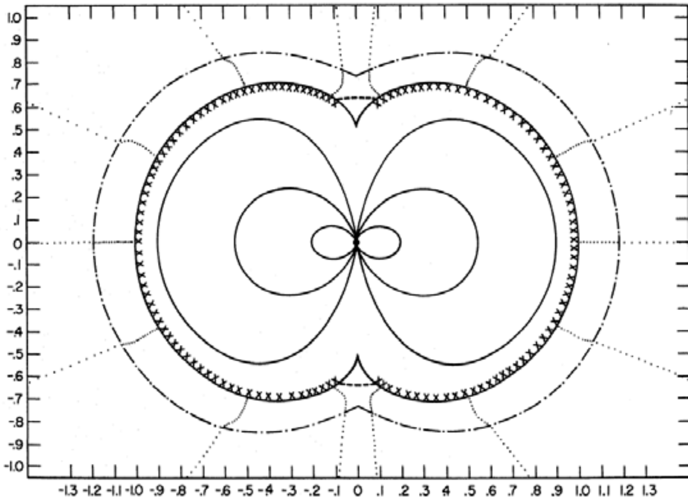
Bondi (supersonic) accretion regime

- If plasma cooling time << free fall time
- Free fall with velocity $u_r=u_{ff}$
- Shock close to magnetosphere ($h_s \ll R_A$)
- R_A is Alfven radius determined from ram and magnetic pressure balance
- Plasma rapidly cools and enters magnetospher due to Rayleigh-Taylor instability (Arons, Lea'
- Plasma carries angular momentum

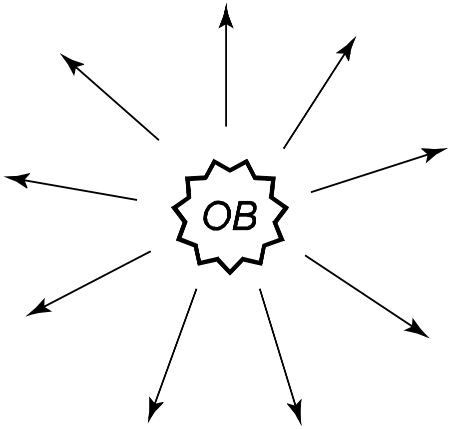
(Illarionov, Sunyaev'75)

$$j \sim \dot{M}\Omega_{binary}R_B^2$$

- Happens at high X-ray luminosities **L_x> 4 x 10^{36} erg/s**

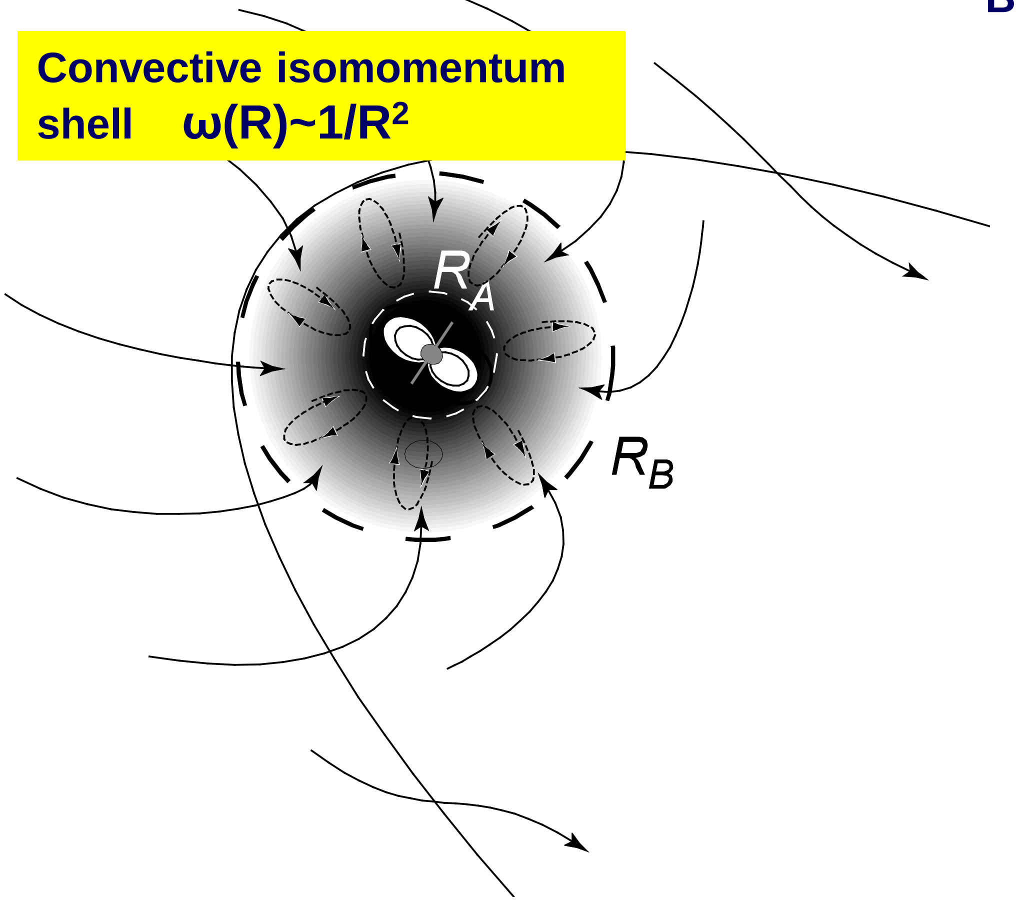


Subsonic settling accretion without shock near magnetosphere



Matter subsonically settles down inside the the shell with radius ~R_B

Convective isomomentum shell $\omega(R) \sim 1/R^2$



$$t_{cool} >> t_{freefall}$$

$$\dot{M} \sim \dot{M}_{Bondi} \left(\frac{t_{ff}}{t_{cool}} \right)^{1/3}$$

Shakura et al. 2012

Settling subsonic accretion regime

- If plasma cooling time >> free fall time
- Settling with velocity $u_r = f(u) u_{ff}$, $f(u) < 1$, determined by plasma cooling rate (Compton cooling, radiative cooling)

$$\dot{M} = 4\pi R_A^2 \rho(R_A) f(u) \sqrt{\frac{2GM}{R_A}}$$

R_A is Alfven radius from gas and magnetic pressure balance

- $f(u) \approx (t_{ff}/t_{cool})^{1/3}$
- Happens for moderate X-ray luminosities

$L_x < 4 \times 10^{36}$ erg/s (Shakura, PK+ 2012)

Vertical structure

- **Hydrostatic equilibrium**

$$-\frac{1}{\rho}\frac{dP}{dR}-\frac{GM}{R^2}=0$$

Adiabatic solution: $\frac{\Re T}{\mu_m}=\frac{\gamma-1}{\gamma}\frac{GM}{R}$

$$\gamma = 5/3 \qquad \rho(R) = \rho(R_A)\left(\frac{R_A}{R}\right)^{3/2}$$

Properties of magnetospheric shell

- **Density**

$$\rho_A \approx 4.4 \times 10^{-11}[\mathrm{g\,cm^{-3}}](L_{32}/\mu_{30})^{2/3}(M_X/M_\odot)^{1/3}$$

- **Temperature**

$$T_A = \frac{2}{5}\frac{GM_X}{\mathcal{R}R_A} \approx 27[\mathrm{keV}](R/10^9[\mathrm{cm}])^{-1}$$

$$\approx 36[\mathrm{keV}]\mu_{30}^{-8/15}L_{32}^{2/15}(M_X/M_\odot)^{19/15} .$$

- **Emission measure**

$$\mathrm{EM} = \int_{R_A}^{R_B} n_e^2(r)4\pi r^2 dr = 4\pi n_{e,A}^2 R_A^3 \ln\left(\frac{R_B}{R_A}\right)$$

$$\approx 3.7 \times 10^{54}[\mathrm{cm^{-3}}]\mu_{30}^{4/15}L_{32}^{14/15}(M_X/M_\odot)^{-2/15} \ln\left(\frac{R_B}{R_A}\right)$$

Propeller regime in quasi-spherical hot shell

The ϕ-component of the momentum equation:

$$\rho\left(u_R\frac{\partial u_\phi}{\partial R}+\frac{u_R u_\phi}{R}\right)=\frac{1}{R^3}\frac{\partial}{\partial R}\left(R^3 W_{\phi R}\right)+\frac{1}{\sin\theta\, R}\frac{\partial}{\partial\theta}\left(W_{\phi\theta}\sin\theta\right)$$

- **Separate variables (L&L IV)** $u_\phi(R,\theta) = U_\phi(R)\sin\theta$
- → $W_{\theta\phi}=\rho\nu_t\left(\frac{1}{R}\frac{\partial u_\phi}{\partial\theta}-\frac{u_\phi\cot\theta}{R}\right)$ $W_{\theta\phi} = 0.$ $W_{R\phi}=\rho\nu_t R\frac{\partial\omega}{\partial R}$
- $\frac{\dot M}{R}\frac{\partial}{\partial R}\omega R^2=\frac{4\pi}{R}\frac{\partial}{\partial R}R^3 W_{R\phi}$ **Integrate:** $\dot M\omega R^2 = 4\pi R^3 W_{R\phi}+D$
- **No accretion:** $0=4\pi\rho\nu_t R^4\frac{\partial\omega}{\partial R}+D$ $D = I\dot\omega^* < 0$
- **Viscosity:** $\nu_t=\langle u_t l_t\rangle = C_2 C_1 R^3\left|\frac{\partial\omega}{\partial R}\right|$

Rotation law in the shell at propeller stage

$$\omega(R) = \omega_m \left(\frac{R_A}{R}\right)^{7/4} ,$$

where

$$\omega_m = \frac{I|\dot{\omega}^*|}{7\pi\rho(R_A)v_t(R_A)R_A^3} .$$

- NS spin-down law:

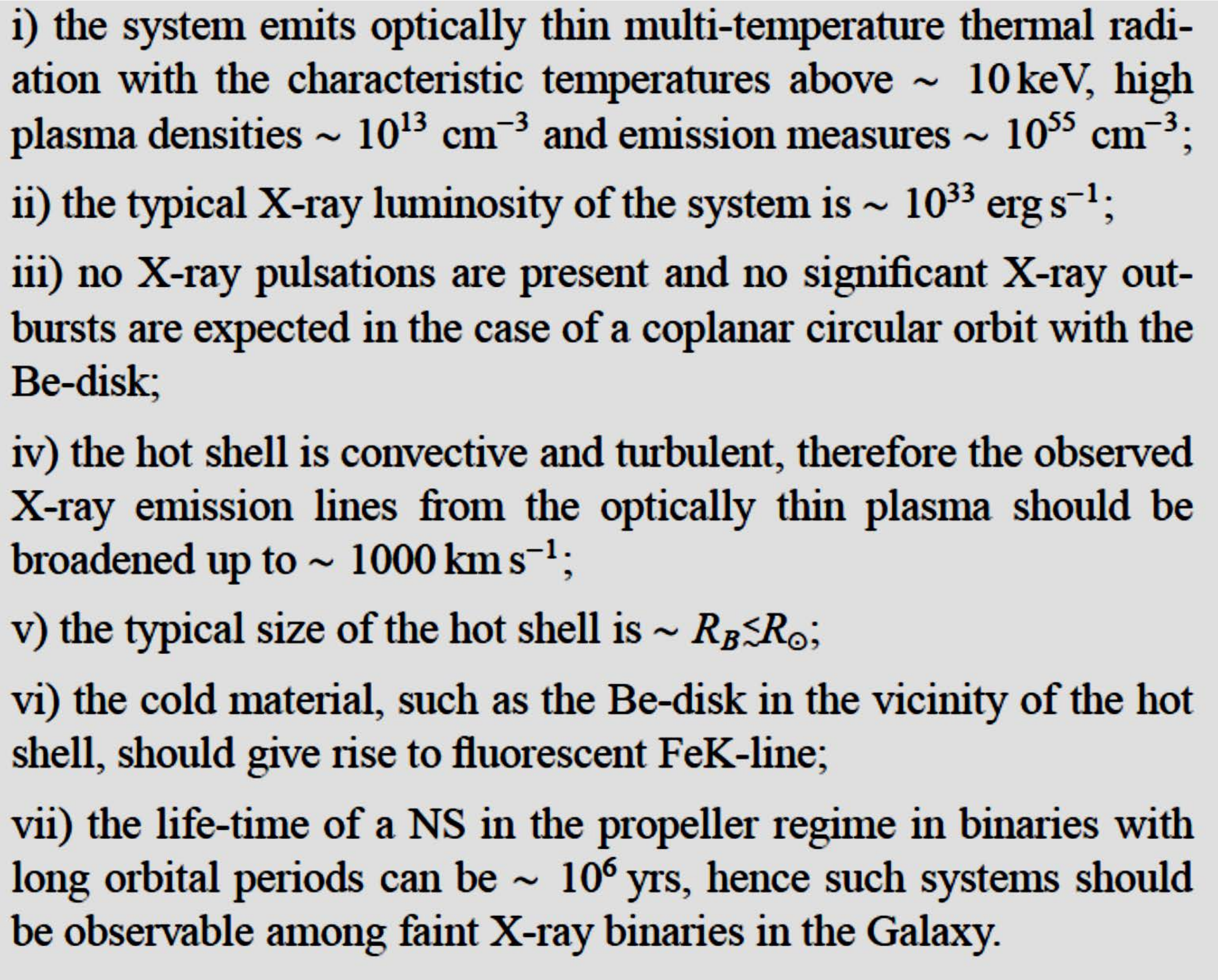
$$I\dot{\omega}_* = -49\omega_{\mathrm{B}}^2 R_{\mathrm{B}}^3 C \left(\frac{R_{\mathrm{A}} L_{\mathrm{X}}}{G M_{\mathrm{X}} v_0}\right)$$

- Spin-down time:

$$t_{\mathrm{sd}} \equiv \frac{I\omega_*}{I\dot{\omega}_*} = \frac{I\omega_*}{49\omega_{\mathrm{B}}^2 R_{\mathrm{B}}^3 C}\left(\frac{G M_{\mathrm{X}} v_0}{R_{\mathrm{A}} L_{\mathrm{X}}}\right)$$

$$\approx 2\times 10^5[\mathrm{yr}]\left(\frac{P_*}{1\,\mathrm{s}}\right)^{-1}\left(\frac{P_{\mathrm{orb}}}{100\,\mathrm{d}}\right)^2\left(\frac{v_0}{100\,\mathrm{km\,s^{-1}}}\right)^7\left(\frac{R_{\mathrm{A}}}{10^9\,\mathrm{cm}}\right)^{-1} L_{32}^{-1}$$

Summary of expected hot shell properties



i) the system emits optically thin multi-temperature thermal radiation with the characteristic temperatures above $\sim$ 10 keV, high plasma densities $\sim 10^{13}$ cm^{-3} and emission measures $\sim 10^{55}$ cm^{-3};

ii) the typical X-ray luminosity of the system is $\sim 10^{33}$ erg s^{-1};

iii) no X-ray pulsations are present and no significant X-ray outbursts are expected in the case of a coplanar circular orbit with the Be-disk;

iv) the hot shell is convective and turbulent, therefore the observed X-ray emission lines from the optically thin plasma should be broadened up to $\sim$ 1000 km s^{-1};

v) the typical size of the hot shell is $\sim R_B \lesssim R_\odot$;

vi) the cold material, such as the Be-disk in the vicinity of the hot shell, should give rise to fluorescent FeK-line;

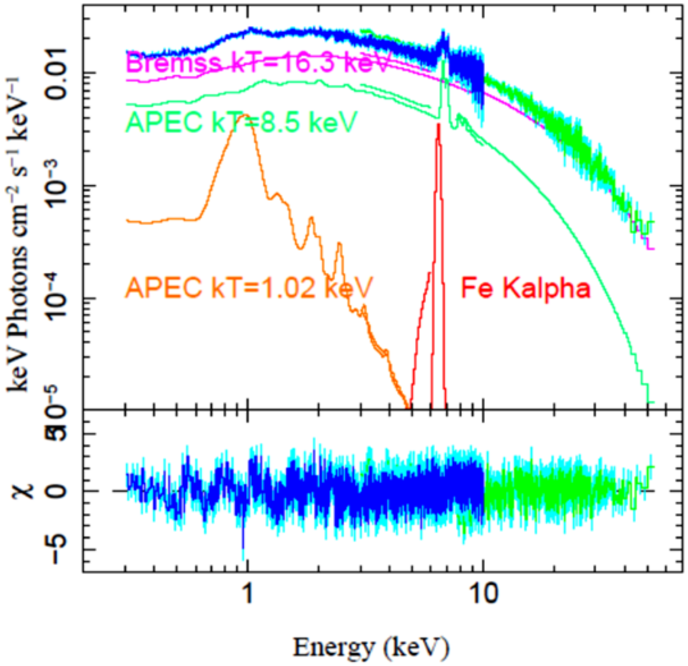
vii) the life-time of a NS in the propeller regime in binaries with long orbital periods can be $\sim 10^6$ yrs, hence such systems should be observable among faint X-ray binaries in the Galaxy.

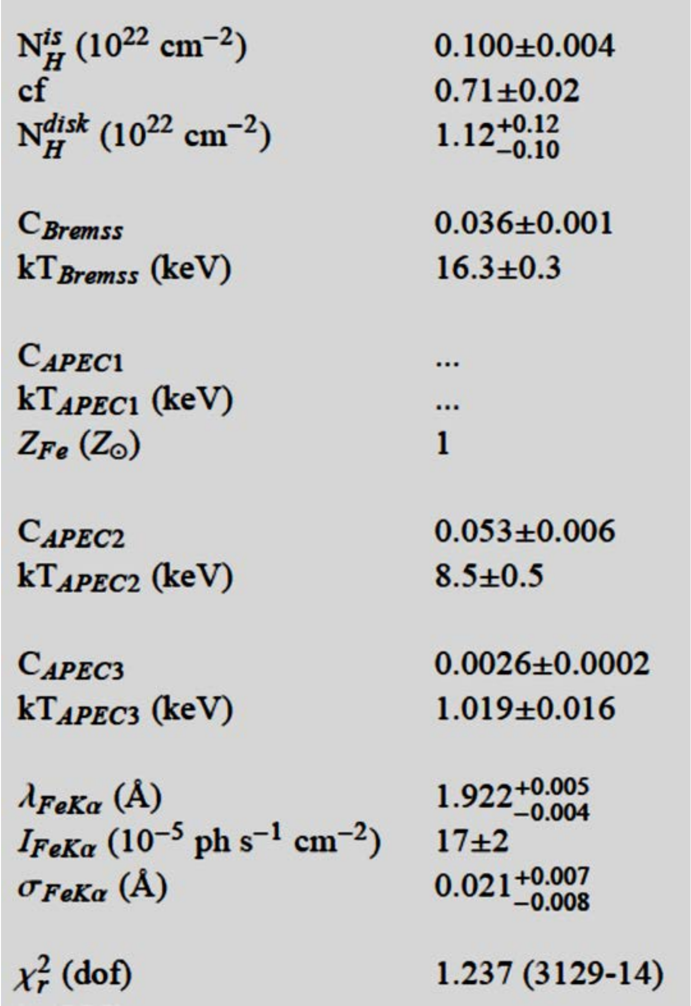
XMM+NuSTAR simultaneous observations

XMM-Newton (ObsID 0743600101) 34 ks
NuSTAR (ObsID 30001147002) 30.8 ks

Fe XXV He like at 6.68 keV.

Fe XXVI H-like Ly α at 6.97 keV.





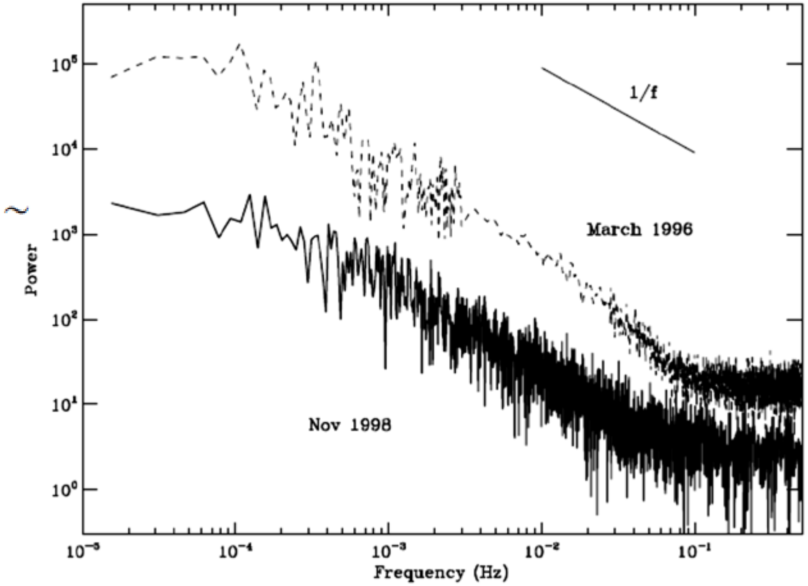
N_H^{is} (10^{22} cm^{-2})	0.100 ± 0.004
cf	0.71 ± 0.02
N_H^{disk} (10^{22} cm^{-2})	$1.12^{+0.12}_{-0.10}$
C_{Bremss}	0.036 ± 0.001
kT_{Bremss} (keV)	16.3 ± 0.3
C_{APEC1}	...
kT_{APEC1} (keV)	...
Z_{Fe} ($Z_\odot$)	1
C_{APEC2}	0.053 ± 0.006
kT_{APEC2} (keV)	8.5 ± 0.5
C_{APEC3}	0.0026 ± 0.0002
kT_{APEC3} (keV)	1.019 ± 0.016
$\lambda_{FeK\alpha}$ (Å)	$1.922^{+0.005}_{-0.004}$
$I_{FeK\alpha}$ (10^{-5} ph s^{-1} cm^{-2})	17 ± 2
$\sigma_{FeK\alpha}$ (Å)	$0.021^{+0.007}_{-0.008}$
χ^2_r (dof)	1.237 (3129-14)

Torrejon et al, in prep.

$$L_x = 1.5\times10^{33}\ \mathrm{erg\ s^{-1}} \quad EM \sim 4.7\times10^{55}\ \mathrm{cm^{-3}}$$

X-ray time variability

- RXTE power spectra (from Robinson & Smith 2000)



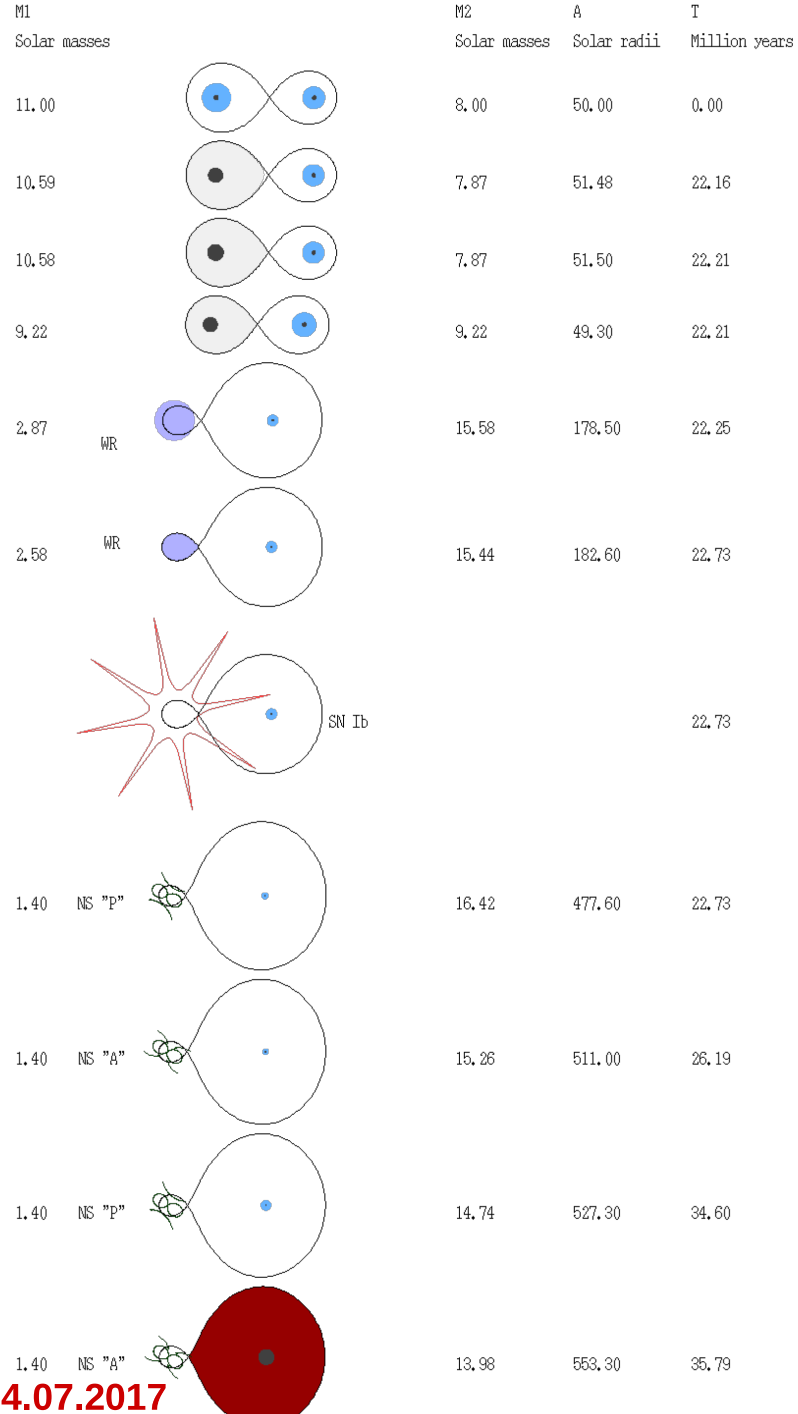
- Hot shell:

$t_{\rm min} \sim R_{\rm A}/c_{\rm s} \sim$

$R_{\rm m}/t_{\rm ff}(R_{\rm m}) \sim R_{\rm m}^{3/2}/\sqrt{2GM} \sim$ a few s

$$t_{\rm max} \sim R_{\rm B}/t_{\rm ff}(R_{\rm B}) \sim 10^6[{\rm s}](v_0/100{\rm km\,s}^{-1})^{-3}$$

Evolution of γ Cas binaries



M1 Solar masses		M2 Solar masses	A Solar radii	T Million years
11.00		8.00	50.00	0.00
10.59		7.87	51.48	22.16
10.58		7.87	51.50	22.21
9.22		9.22	49.30	22.21
2.87	WR	15.58	178.50	22.25
2.58	WR	15.44	182.60	22.73
	SN Ib			22.73
1.40	NS "P"	16.42	477.60	22.73
1.40	NS "A"	15.26	511.00	26.19
1.40	NS "P"	14.74	527.30	34.60
1.40	NS "A"	13.98	553.30	35.79

Formation of a Be-star

ECSN, low kick

Propeller from stellar wind

γ Cas stage

Accretion from stellar wind

X Per stage

Conclusions

- At $L_x < 4\times10^{36}$ erg/s direct (Bondi) accretion on magnetized NS magnetospheres from stellar winds in HMXB is hampered by the need for plasma to cool ➔ settling (subsonic) accretion
- X-ray evidence for hot plasma shells in non-accreting (propelling) gamma Cas stars
- Evolution: low-kick ECSN ➔ gamma Cas (NS @ propeller) ➔ X Per long-period pulsars in BeXRB (NS @ accretion)

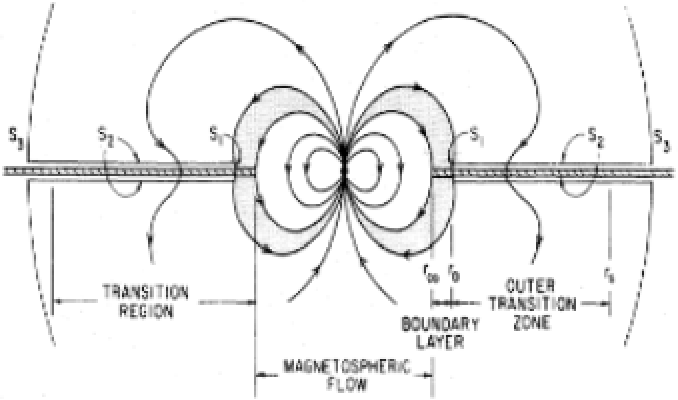
Back-up slides

Disk accretion

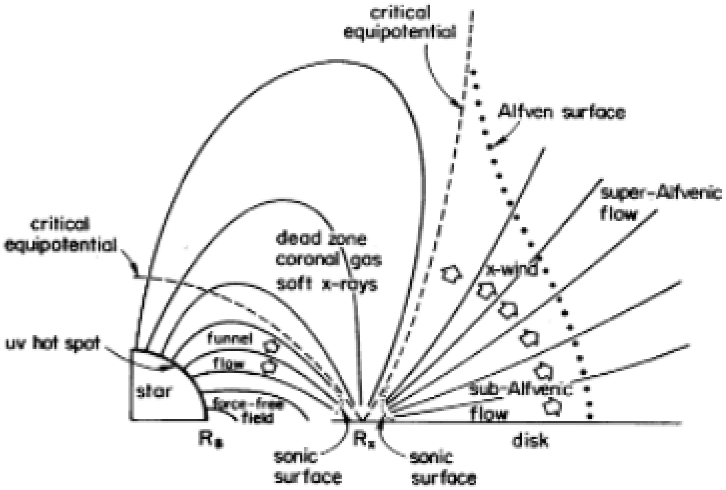
- Always occurs in Roche-lobe filling systems
- In wind-fed systems, condition for disk to form: specific angular momentum of captured matter > Keplerian value at the magnetosphere boundary

$$j \sim \Omega_{binary} R_B^2 > \sqrt{GMR_m}$$

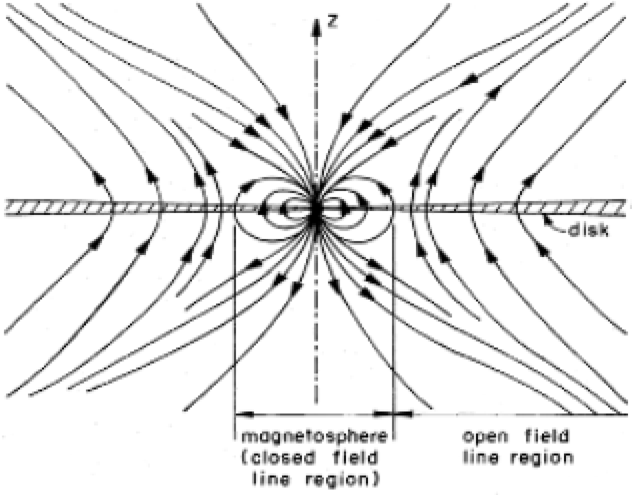
Disk-magnetospheric interaction



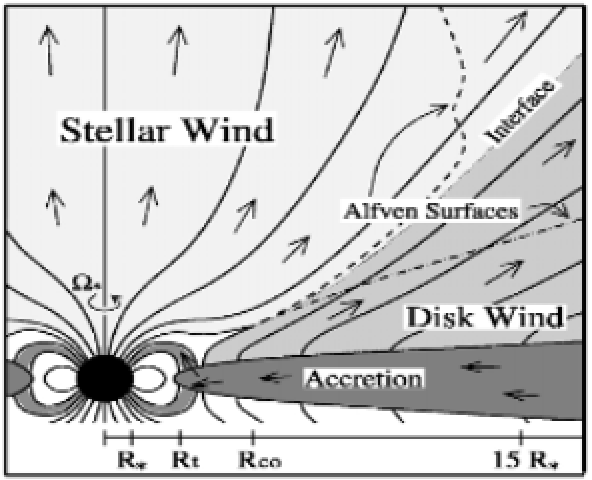
Ghosh & Lamb 1979



Shu et al. 1994



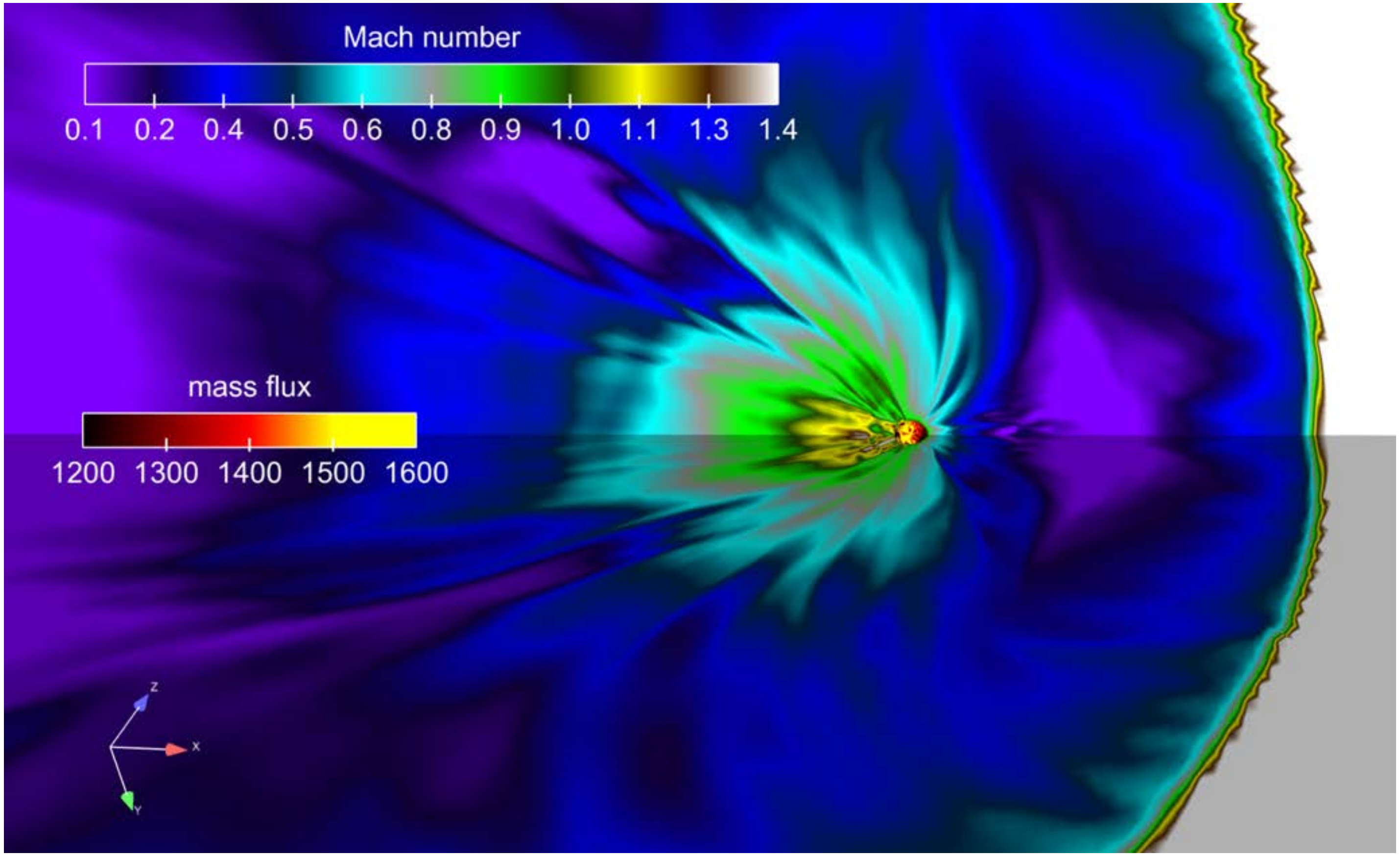
Lovelace et al. 1995



Matt & Pudritz 2005

Wind-fed accretors

- Matter is captured from (generally inhomogeneous) stellar wind.



3D, Γ=5/3, Blondin & Raymer 2012

Angular momentum transfer. I. Strong coupling

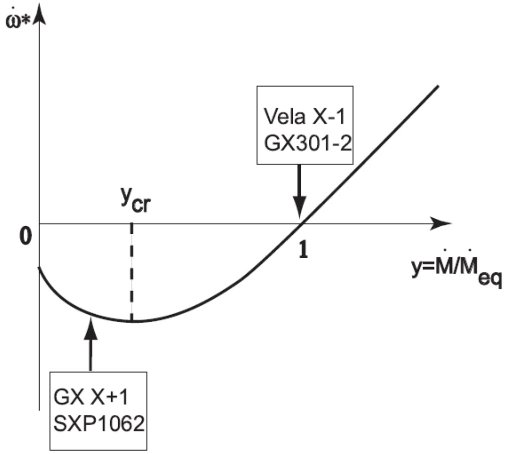
- Magnetic torque $$I\dot{\omega}^* = \int \frac{B_t B_p}{4\pi} \varpi dS$$
- Turbulent m.f. diffusion: $$B_t = \frac{R^2}{\eta_t}(\omega_m - \omega^*) B_p$$

$$\eta_t \simeq \nu_t \quad \nu_t = < u_t l_t > \quad u_t \simeq l_t |\omega_m - \omega^*| \quad l_t \simeq R_A$$

- ➔ $B_t \simeq B_p$

K_2~7.6 , (Arons & Lea, 1976)

$$\boxed{I\dot{\omega}^* = \int \frac{B_t B_p}{4\pi} \varpi dS = \pm \tilde{K}(\theta) K_2 \frac{\mu^2}{R_A^3}}$$



Non-equilibrium pulsars

1) Maximum possible spin-down rate

$$\boxed{\dot{\omega}^*_{sd,max} \approx -1.13\times 10^{-12}[\text{рад}/\text{с}](1-z/Z)^{7/4}\left(\frac{K_1}{\zeta}\right)\mu_{30}^2\left(\frac{v_8}{\sqrt{\delta}}\right)^3\left(\frac{P^*}{100\text{с}}\right)^{-7/4}\left(\frac{P_b}{10\text{д}}\right)^{3/4}}$$

2) From the condition $|\dot{\omega}^*_{sd}| \leq |\dot{\omega}^*_{sd,max}|$

➔ lower limit of NS magnetic field :

$$\mu_{30} > \mu'_{30,min} \approx 0.94\left|\frac{\dot{\omega}^*_{sd}}{10^{-12}\text{рад}/\text{с}}\right|\left(\frac{K_1}{\zeta}\right)^{-1/2}\left(\frac{v_8}{\sqrt{\delta}}\right)^{-3/2}\left(\frac{P^*}{100\text{с}}\right)^{7/8}\left(\frac{P_b}{10\text{д}}\right)^{-3/8}$$

References

1. Theory of quasi-spherical accretion in X-ray pulsars. Shakura, PK, Kochetkova, Hjalmarsdotter (MNRAS, 2012, 420, 216; arXiv:1110.3701)

2. On the nature of “Off” states in slowly rotating low-luminosity X-ray pulsars, Shakura,PK, Hjalmarsdotter, 2013, MNRAS, 428, 670 (arXiv:1209.4962)

3. Bright flares in Supergiant Fast X-ray Transients, Shakura, PK, Sidoli, Paizis, 2014, MNRAS 442, 2325

Thank you for your attention

ms QPOs from convective shells

- The characteristic time of X-ray variability is fully determined by the variability of physical conditions at the magnetospheric boundary, ~ free-fall time from R_m.
- In corotating X-ray pulsar magnetospheres, $t_{ff}(R_m)$~$1/\omega^*$ ➔ f_{QPO}~$2\pi/P^*$
- Examples of observed QPOs: HMXB IGR J19140+0951 at low state (Sidoli et al 2016)+ JMT talk yesterday

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MNRAS **460,** 3637–3646 (2016) doi:10.1093/mnras/stw1246
Advance Access publication 2016 May 24

XMM–Newton discovery of mHz quasi-periodic oscillations in the high-mass X-ray binary IGR J19140+0951

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Accepted 2016 May 20. Received 2016 May 20; in original form 2016 April 22

ABSTRACT

We report on the discovery of mHz quasi-periodic oscillations (QPOs) from the high-mass X-ray binary (HMXB) IGR J19140+0951, during a 40 ks *XMM–Newton* observation performed in 2015, which caught the source in its faintest state ever observed. At the start of the observation, IGR J19140+0951 was at a low flux of 2×10^{-12} erg cm^{-2} s^{-1} (2–10 keV; $L_X = 3 \times 10^{33}$ erg s^{-1} at 3.6 kpc), then its emission rose reaching a flux ~10 times higher, in a flare-like activity. The investigation of the power spectrum reveals the presence of QPOs, detected only in the second part of the observation, with a strong peak at a frequency of 1.46 ± 0.07 mHz, together with higher harmonics. The X-ray spectrum is highly absorbed ($N_H = 10^{23}$ cm^{-2}), well fitted by a power law with a photon index in the range 1.2–1.8. The re-analysis of a *Chandra* archival observation shows a modulation at ~0.17 ± 0.05 mHz, very likely the neutron-star spin period (although a QPO cannot be excluded). We discuss the origin of the 1.46 mHz QPO in the framework of both disc-fed and wind-fed HMXBs, favouring the quasi-spherical accretion scenario. The low flux observed by *XMM–Newton* leads to about three orders of magnitude the source dynamic range, overlapping with the one observed from Supergiant Fast X-ray Transients (SFXTs). However, since its duty cycle is not as low as in SFXTs, IGR J19140+0951 is an intermediate system between persistent supergiant HMXBs and SFXTs, suggesting a smooth transition between these two sub-classes.

Key words: stars: neutron – X-rays: binaries – X-rays: individual: (IGR J19140+0951).