Neutron stars near the Galactic centre: their interaction modes and observable effects

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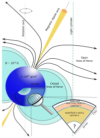


Topic: Galactic centre – low-luminosity (active) galactic nucleus

- Galactic centre – complex environment: **gas**, **dust**, **stars** (late- and early-type stars + compact remnants), **supermassive black hole** (Eckart et al. 2005; Genzel et al. 2010; Genzel & Karas 2007)
- closest galactic nucleus to us (highest resolution obtained)
- Multiwavelength figure (Credit: NASA/ESA):

Topic: Galactic centre – low-luminosity (active) galactic nucleus

- ionized gas of the Minispiral is located in the sphere of influence of the SMBH:

$$r_{\rm SI} \approx 1.7 \left(\frac{M_\bullet}{4.0 \times 10^6\,M_\odot} \right) \left(\frac{\sigma}{100\,{\rm km\,s^{-1}}} \right)^{-2}$$

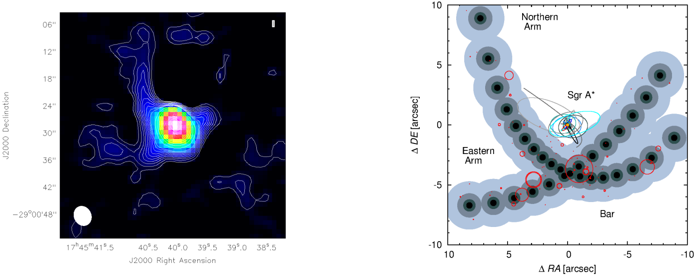


Figure : 3-mm continuum image by CARMA (left), synthetic image with the S-cluster (right).

Topic: Galactic centre – low-luminosity (active) galactic nucleus

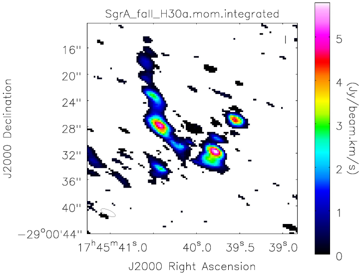


Figure : ALMA Band 6 (211 – 275 GHz) image – line H30α (231.9 GHz) integrated

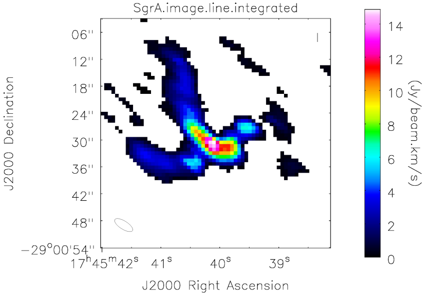
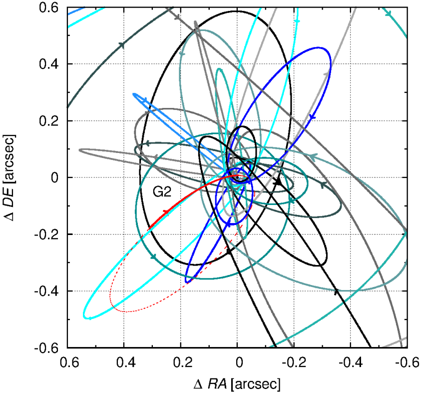


Figure : ALMA Band 3 (84 – 116 GHz) image – line H39α (106.74 GHz) integrated

Topic: Galactic centre – low-luminosity (active) galactic nucleus



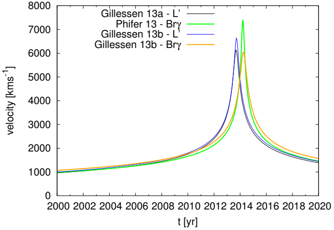


Figure : S-cluster (left), 3D velocity for G2/DSO (right).

Neutron stars near the Galactic centre

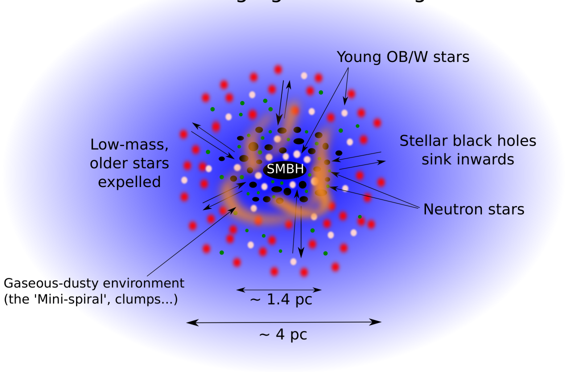
Importance

1. probes of the ISM: dispersion measure, rotation measure
2. precise tests of GTR
3. history of the Galactic centre: end-products of stellar evolution

Open questions:

- What is the estimated number of NS in the innermost parsec?
- How do they interact with the surrounding medium?
- What are the possibilities of their detection?

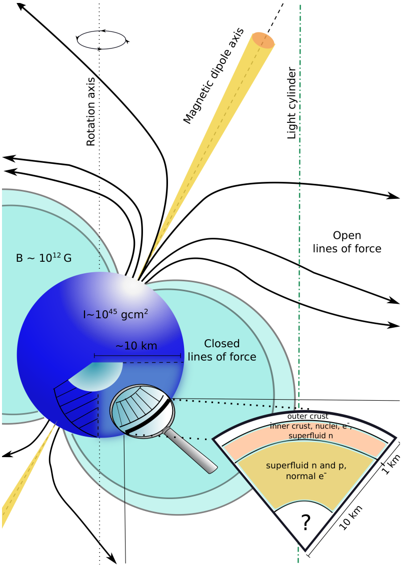
Mass segregation near Sgr A*



Aims

- constraining the number of NS
- studying the interaction with the environment: distribution of interaction modes
- possibility to reveal a part of the population indirectly: bow-shock structures

- NS characterized by: $M_{\rm NS}$, μ, and $P = 2\pi/\Omega$



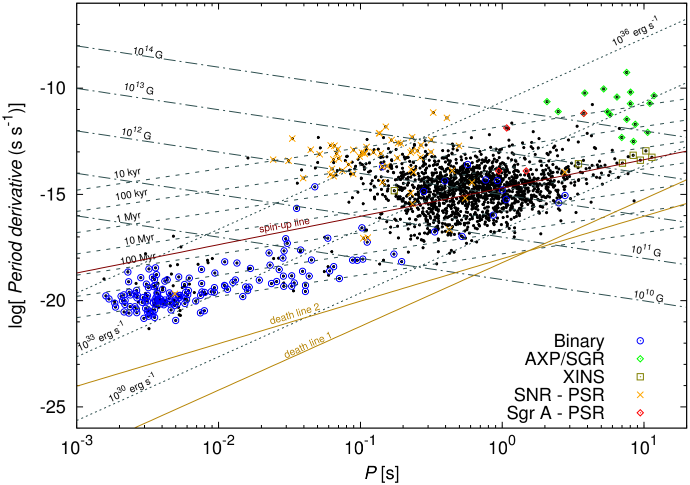


Figure : P–$\dot{P}$ diagram. The data are taken from ATNF Pulsar Catalogue (Manchester et al. 2005) and SNR catalogue (University of Manitoba).

Estimates of the number of NS near Sgr A*

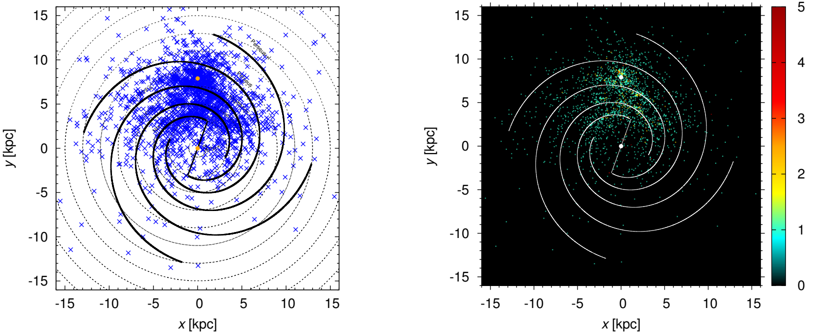


Figure : Spiral structure of the Galaxy and distribution of 2302 neutron stars in the *XY* Galactic plane. Data taken from the ATNF Pulsar Database (Manchester et al. 2005).

Estimates of the number of NS near Sgr A*

(i) estimates based on the enclosed dynamical mass and the IMF; $\alpha \in (0.4, 2.3)$ (Salpeter 1955; Morris 1993):

$$N_{\rm NS} = \frac{2-\alpha}{1-\alpha} \frac{m_{\rm NS2}^{1-\alpha} - m_{\rm NS1}^{1-\alpha}}{m_{\rm max}^{2-\alpha} - m_{\rm min}^{2-\alpha}} M_{\rm TOT}.$$

Estimated number for different parameters: $N_{\rm NS} = 11000 \pm 5000$

(ii) Considering density distribution (Lauer et al. 1995; Do et al. 2013):

$$\rho(r) = \rho_0 \left(\frac{r}{r_{\rm b}}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_{\rm b}}\right)^{\delta}\right]^{(\gamma-\gamma_0)/\delta}$$

$$N_{\rm CR} = 4\pi \int_{R_{\rm dis}}^{R_{\rm gc}} n_{\rm CR}(r) r^2 {\rm d}r\,.$$

- the order of 10^4–10^5 $\longleftrightarrow$ observed just one magnetar !?

- The HII region of Sgr A West ('Minispiral') is a promising target to search for the effects of interaction with propagating compact objects
- interactions with the three arms of the 'Minispiral': Keplerian model according to Zhao et al. (2009, 2010)
- $\sim$ 1%–10% of neutron stars should interact
- typical relative velocities: $\sim$ 100–500 $\mathrm{km\,s^{-1}}$

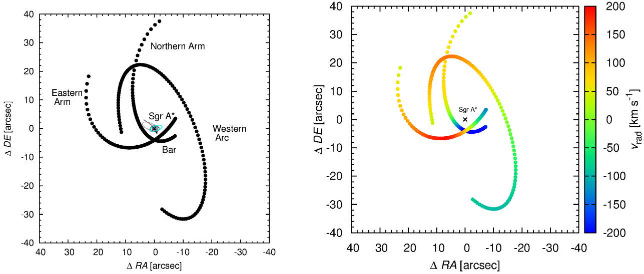


Figure : 'Minispiral' components (left) and model radial velocities (km/s).

- Keplerian velocity profile
- Observed radial velocities (hydrogen recombination lines):

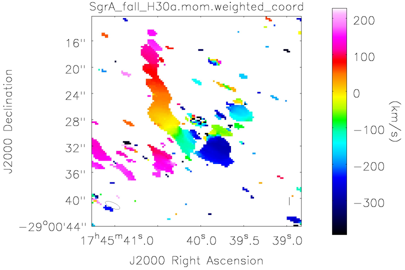


Figure : H30α observations by ALMA

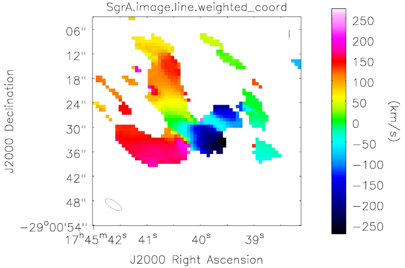
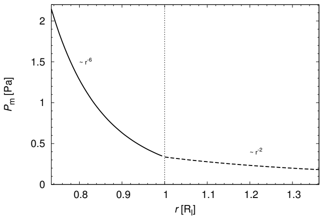
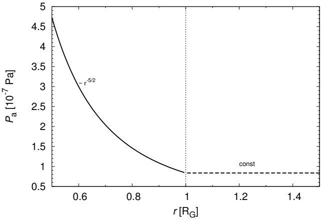


Figure : H39α observations by ALMA.

- interaction regime consists of *gravitational* and *electromagnetic* interaction
- *Gravitational interaction:* accretion rate $\dot{M}$
- *Electromagnetic interaction:* dipole moment μ, rotational period P
- another important parameter is the relative speed of the star with respect to the surrounding medium $v_\star$
- interplay of magnetic P_{m} and accretion pressure P_{a}, see Figure:





Neutron stars – interaction modes

Interaction with the 'Minispiral'

- the condition $P_\mathrm{m} = P_\mathrm{a}$ yields the stopping radius:

$$R_\mathrm{st} = \begin{cases} R_\mathrm{A} & \text{if } R_\mathrm{st} \leq R_\mathrm{l}\,, a \\ R_\mathrm{Sh} & \text{if } R_\mathrm{st} > R_\mathrm{l}\,. \end{cases} \tag{1}$$

$$R_\mathrm{A} = \begin{cases} \left(\dfrac{4\mu^2 G^2 M_\mathrm{NS}^2}{\dot{M}_\mathrm{c} v_\star^5}\right)^{1/6} & \text{if } R_\mathrm{A} > R_\mathrm{G}\,, \\ \left(\dfrac{\mu^2}{\dot{M}_\mathrm{c}(2GM_\mathrm{NS})^{1/2}}\right)^{2/7} & \text{if } R_\mathrm{A} \leq R_\mathrm{G}\,. \end{cases} \tag{2}$$

$$R_\mathrm{Sh} = \left(\frac{2L_\mathrm{ej}}{\dot{M}_\mathrm{c} v_\star v_\mathrm{ej}}\right)^{1/2} R_\mathrm{G}\,,$$

$$R_\mathrm{Sh} = \left(\frac{8\kappa_\mathrm{t}\mu^2(GM_\mathrm{NS})^2\Omega^4}{\dot{M}_\mathrm{c} v_\star^5 c^4}\right)^{1/2} \text{if} \quad v_\mathrm{ej} = c\,. \tag{3}$$

- Other important distance scales: $R_\mathrm{l} = c/\Omega$; $R_\mathrm{c} = (GM_\mathrm{NS}/\Omega^2)^{1/3}$; $R_\mathrm{G} = 2GM_\mathrm{NS}/(v_\star^2 + c_\mathrm{s}^2)$

- classification according to Lipunov (1992)
- interaction modes determined by the relation among four distance scales: $R_{\rm l}$, $R_{\rm c}$, $R_{\rm G}$, and $R_{\rm st}$

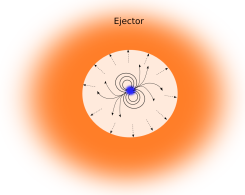


Figure : $R_{\rm st} > \max\{R_{\rm G}, R_{\rm l}\}$
radiopulsars

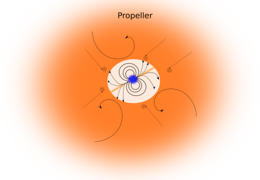


Figure : $R_{\rm c} < R_{\rm st} \leq \max\{R_{\rm G}, R_{\rm l}\}$
spinning-down more efficient, transient sources

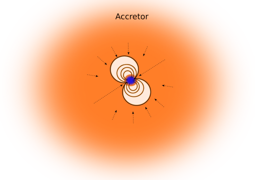
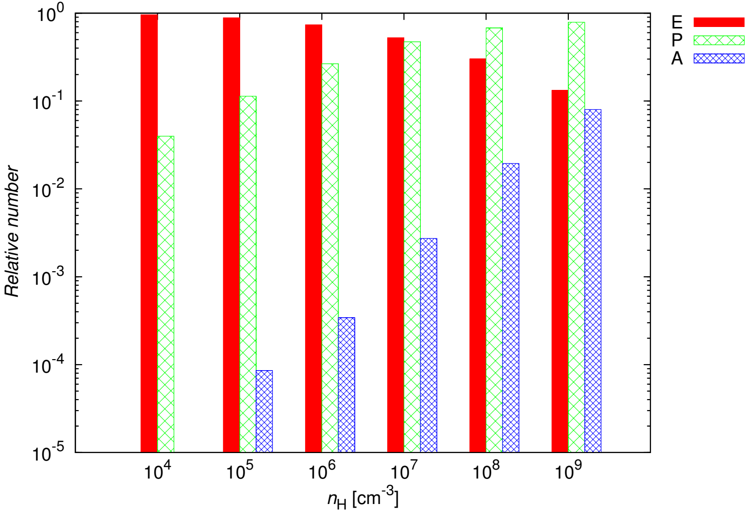


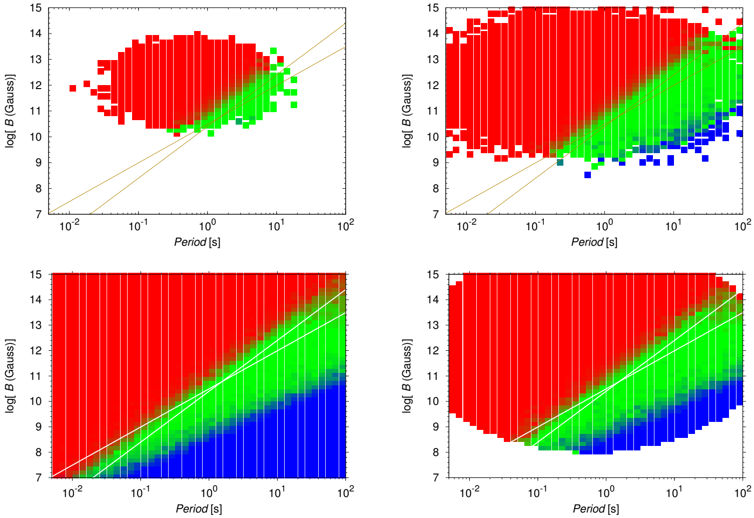
Figure : $R_{\rm st} \leq R_{\rm G}$ and $R_{\rm st} \leq R_{\rm c}$
X-ray pulsars, bursters

Neutron stars – interaction modes

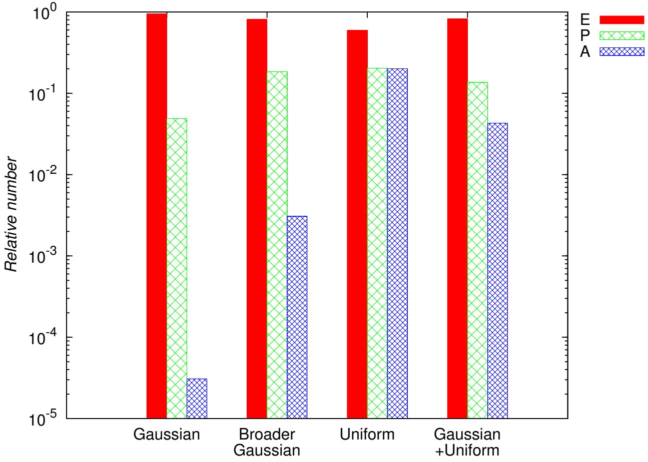
Interaction with the ‘Minispiral’ – effect of the density of the ambient medium



Magnetic field–period plane: effect of distribution



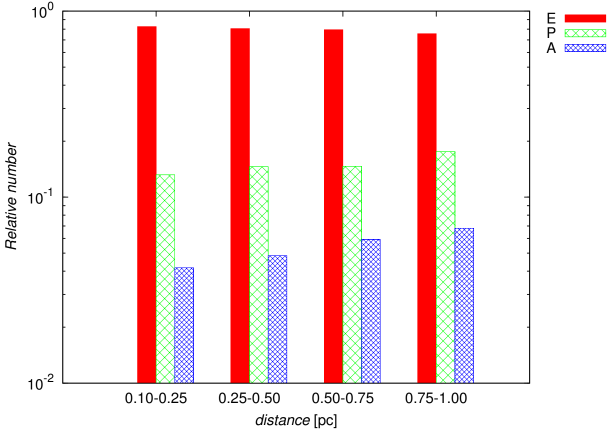
Distribution of interaction modes – effect of distribution:
(1) Gaussian, (2) broader Gaussian, (3) Uniform,
(4) Gaussian+uniform



Neutron stars – interaction modes

Interaction with the 'Minispiral' – effect of the distance from the SMBH

- distribution (4): Gaussian+Uniform
- uniform distribution in cos *i* and log *a*
- ejectors ↓, propeller+accretor ↑ with increasing distance from the SMBH



Neutron stars – interaction modes

Interaction with the 'Minispiral'

- effect of temperature small ($\uparrow T \leftrightarrow \downarrow$ propellers)
- evolution of neutron stars: prolongation of period, constant magnetic field $t < t_{\mathrm{d}} \approx 10^6\,\mathrm{yr}$

$$\dot{\Omega} = -\beta\Omega^3 - \gamma\Omega^5\,,$$

$$\beta = \frac{2}{3c^3}\frac{\mu^2}{I}\sin^2\alpha\,,$$

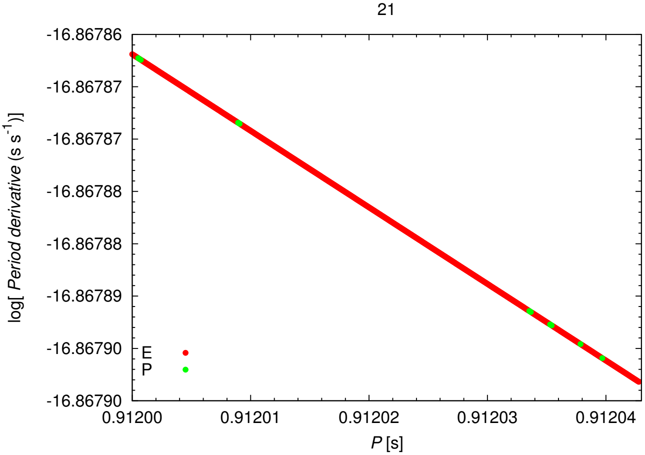
$$\gamma = \frac{32}{5}\frac{G}{c^5}I\epsilon^2\,.$$

- does not change the initial distribution on the time-scale of $10^4\,\mathrm{yr}$
- interaction mode changes temporarily due to density fluctuations

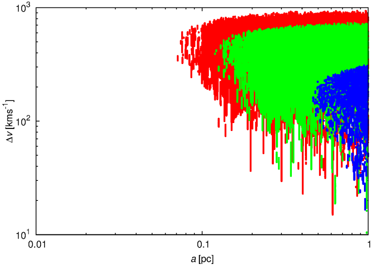
Neutron stars – interaction modes

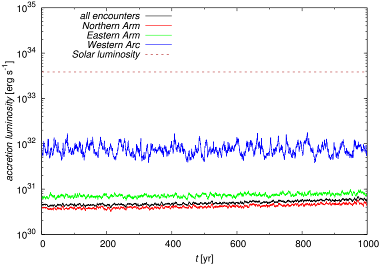
Interaction with the ‘Minispiral’

- Exemplary evolution of period (↑) and period derivative (↓) during $10^5\,\mathrm{yr}$ for a single neutron star
- Interaction mode changes (E $\leftrightarrow$ P) due to density fluctuations



- relative velocities (left) and bolometric accretion luminosities (right):





- Could be detected as faint X-ray sources?
- low flux and scattering by dust; halo $\approx 1.0(aE)^{-1}\,\mathrm{arcmin}$
- scattering cross section: $\sigma = 6.3 \times 10^{-7}(2Z/N)^2(\rho/3)^2 a^4 E^{-2}\,\mathrm{cm}^2$
- could contribute to diffuse X-ray emission

- characteristic PWN and bow-shock sizes:
  $r_{\rm bs} \approx [\dot{E}/(4\pi c \rho_{\rm a} v_\star^2)]^{1/2}$
  $\dot{E}(P, \dot{P}) = 4\pi^2 I \frac{\dot{P}}{P^3}$
- ejectors form naturally bigger bow-shock structures in the inter-arm region
- propeller bow shocks much smaller

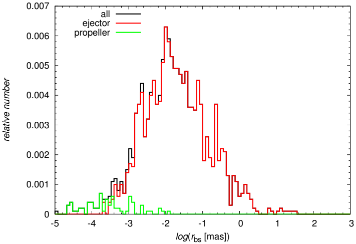


Figure : **Distribution of bow-shock sizes in the Minispiral arms**

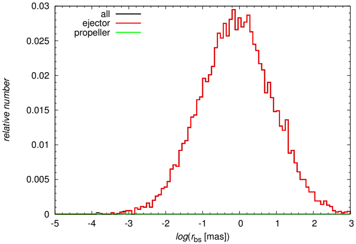
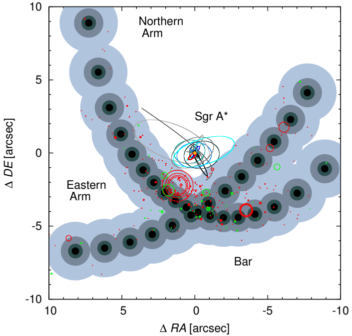


Figure : **Distribution of bow-shock sizes in the interarm region**

Neutron stars – observable effects

Bow-shock structures and Pulsar Wind Nebulae



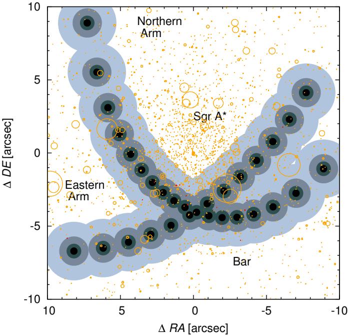


Figure : Comparison of bow-shock sizes of neutron stars passing through **the arms** in the simulated $20'' \times 20''$ image of the Minispiral (bow-shocks are artificially enlarged.)

Figure : All bow shocks (**the Arms** $+$ **the inter-arm region**) in the simulated $20'' \times 20''$ image of the Minispiral region. Ejector bow shocks are red, propeller ones are green.

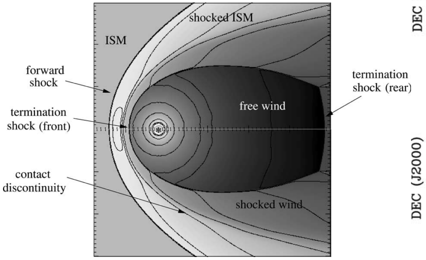


Figure : Bucciantini (2002)

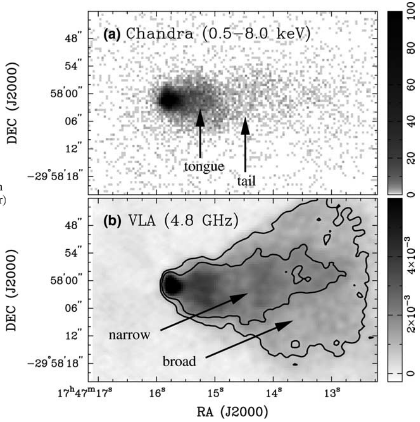


Figure : X-ray and radio image of the “Mouse” (Gaensler et al., 2004)

Conclusions

- the distribution of interaction modes (E,P,A) is strongly dependent on the density
- the distribution is weakly dependent on the temperature
- temporal evolution does not change the initial distribution on the timescale of $10^4\,\mathrm{yr}$
- a single neutron star changes interaction mode due to density fluctuations
- Minispiral densities ($\sim 10^4 \div 10^5\,\mathrm{cm}^{-3}$): $E > P \gtrsim A$ depending on the distribution of P and μ
- bow-shock structures and PWN as means of neutron star detection

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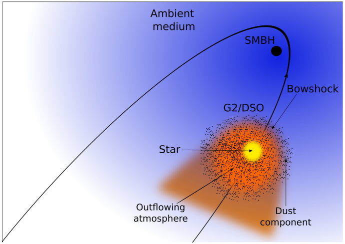
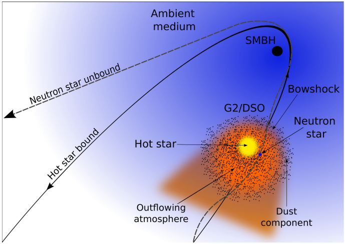
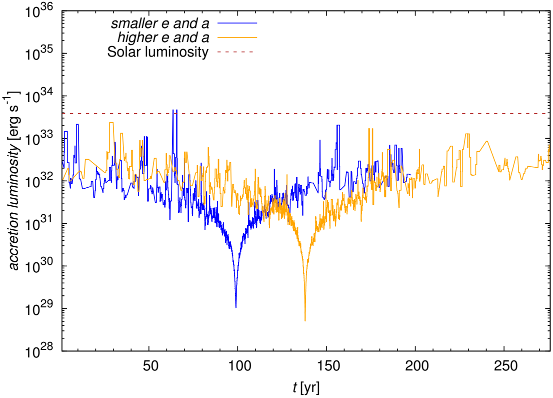
Three plausible scenarios: core-less cloud, dust-enshrouded star, binary with a common envelope (Zajaček et al. 2014)



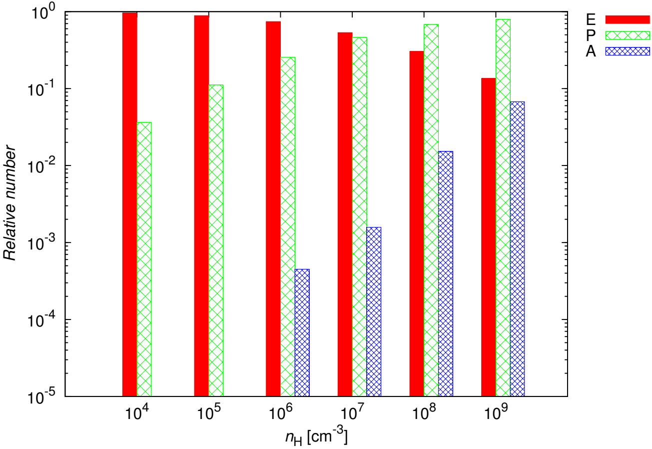


- High relative velocities at the pericentre $\rightarrow$ low accretion luminosity
- Non-magnetized neutron stars – accretors: $L_{\rm acc} = \eta \dot{M}_{\rm acc} c^2$; $\dot{M}_{\rm acc} \propto v_{\rm rel}^{-3}$

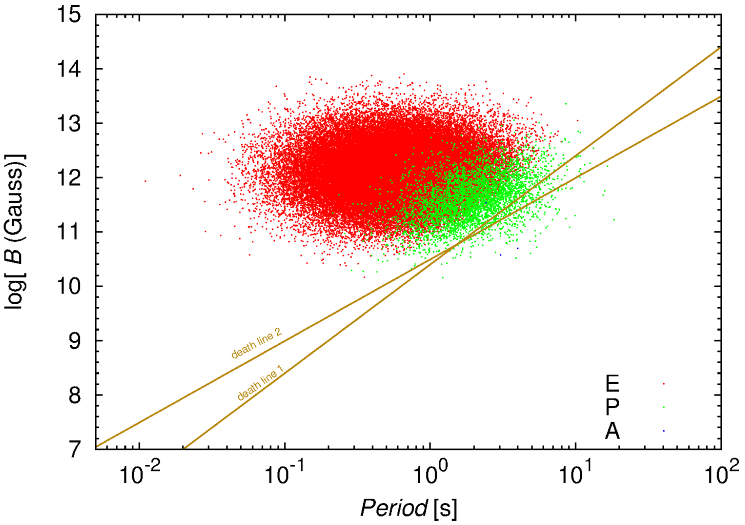


Answers to the referee

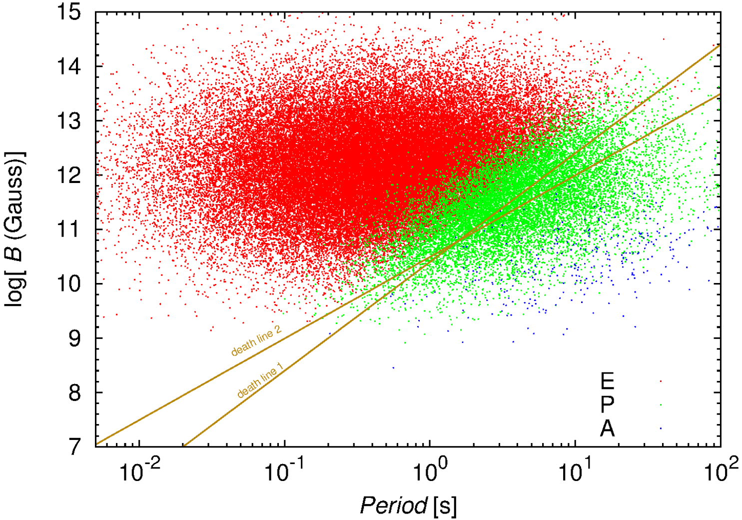
- uniform distribution in cos i and log a
- encounter rate increased from $\sim 1.2\%$ to $\sim 1.8\%$ (clump diameter $\approx 1''$)
- no qualitative difference in density dependence



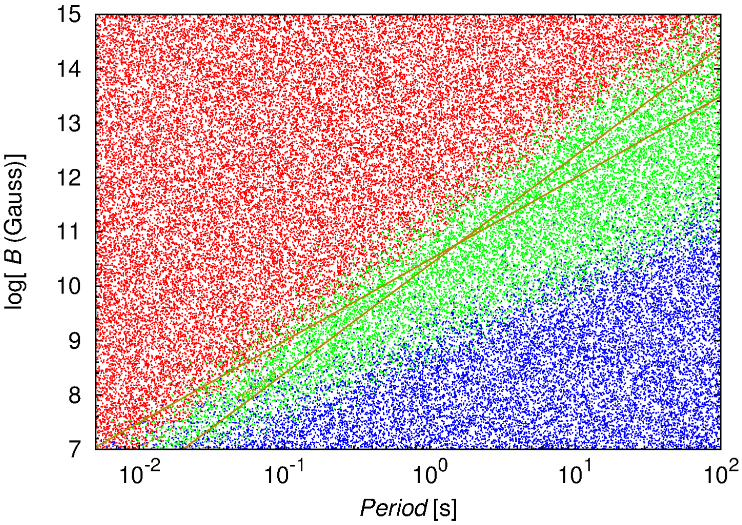
- Distribution: Gaussian



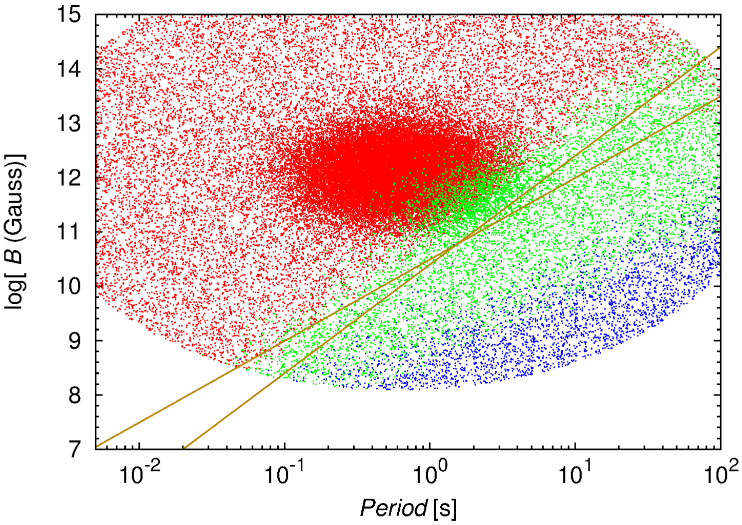
- Distribution: Broader Gaussian



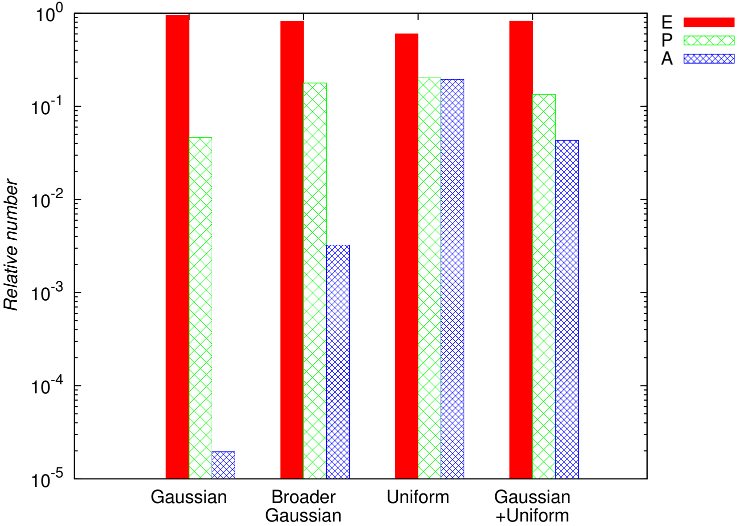
- Distribution: Uniform



- Distribution: Gaussian+Uniform



- distribution dependence: ratio differs



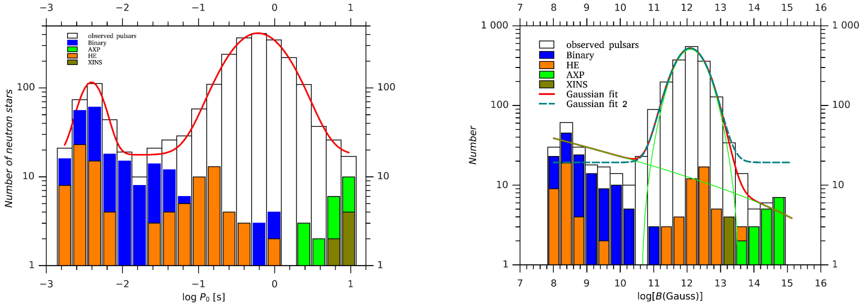
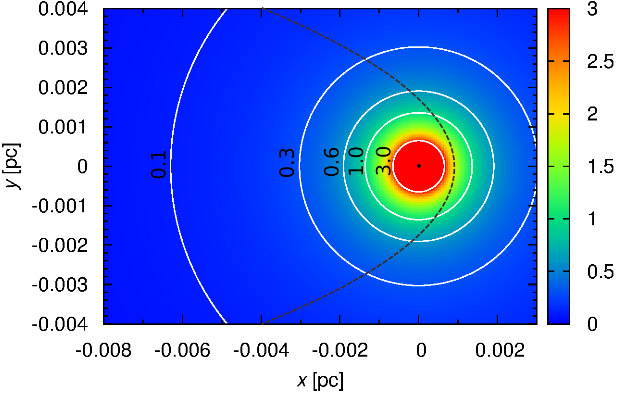
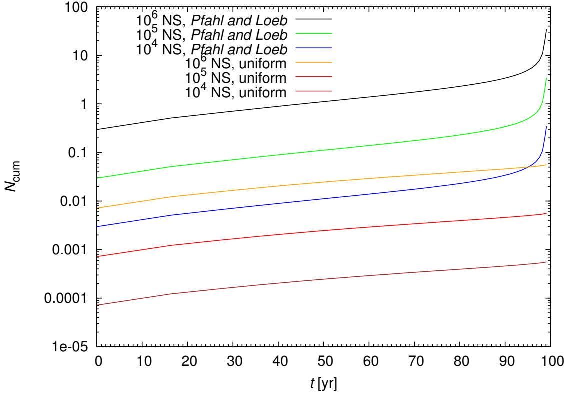


Figure : Period distribution (left) and magnetic dipole distribution (right). The data are taken from ATNF Pulsar Catalogue (Manchester et al. 2005).

- Is the distribution uniform in the central parsec or radial, e.g. $\propto r^{-3/2}$?
- Exemplary case: $N_{\rm NS} = 10^5$, radial distribution:



- cumulative number of encounters:
  $\langle N_{\mathrm{NS}} \rangle \approx \int_S n_{\mathrm{NS}}(r)\sigma_{\mathrm{cloud}} v_{NS}(r)\mathrm{d}t$



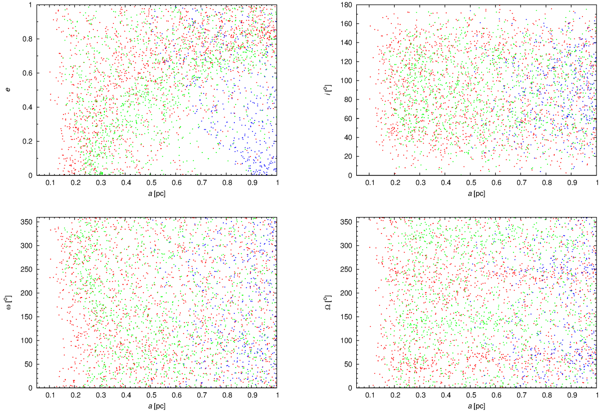
- Possibility to distinguish between uniform and radial distribution by observing G2?

- interaction modes determined by the relation among four distance scales: R_{l}, R_{c}, R_{G}, and R_{st}
- classification according to Lipunov (1992)

Name	Notation	Relation between distances	Observational effects
Ejector	E	$R_{\mathrm{st}} > \max\{R_{\mathrm{G}}, R_{\mathrm{l}}\}$	radiopulsars
Propeller	P	$R_{\mathrm{c}} < R_{\mathrm{st}} \leq \max\{R_{\mathrm{G}}, R_{\mathrm{l}}\}$	–
Accretor	A	$R_{\mathrm{st}} \leq R_{\mathrm{G}}$ and $R_{\mathrm{st}} \leq R_{\mathrm{c}}$	X-ray pulsars, X-ray bursters
Georotator	G	$R_{\mathrm{G}} < R_{\mathrm{st}} \leq R_{\mathrm{c}}$	–

Table : Summary of the interaction modes and thus types of neutron stars according to Lipunov (1992).

- encounters with individual arms: Northern Arm (red), Eastern Arm (green), Western Arc (blue)
- uniform distribution in cos *i*



- encounters with individual arms: Northern Arm (red), Eastern Arm (green), Western Arc (blue)
- distribution of orbital elements