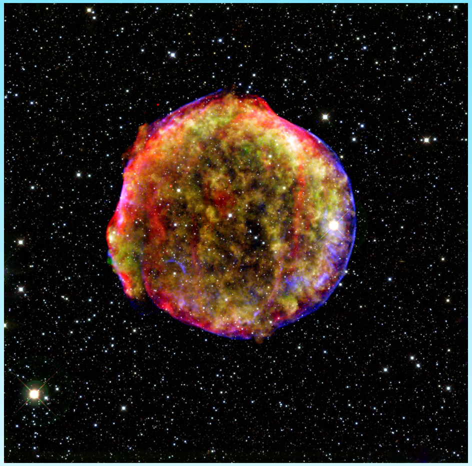
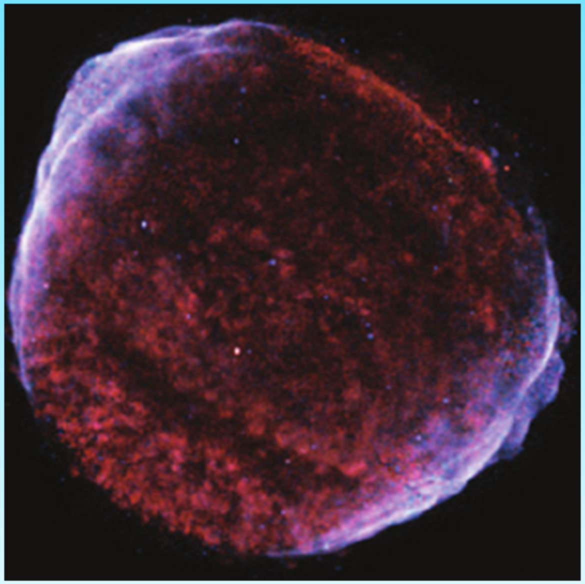
Termalno zračenje ostataka supernovih u radio-području

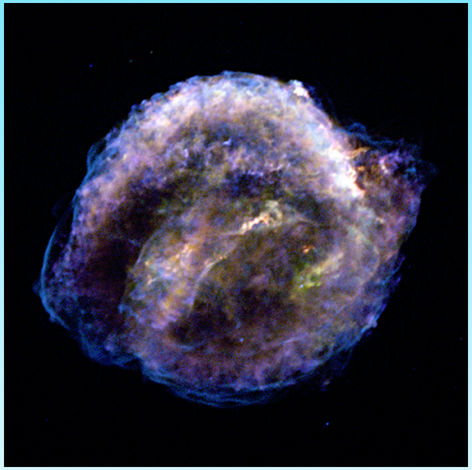
Dušan Onić

- Formiranje i evolucija bezsudarnog udarnog talasa: *rađanje* i *život* OSN

- Udarni talasi u MHD







$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \,,$$

$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla \cdot \left[\rho \mathbf{v}\mathbf{v} + (p + \tfrac{1}{2}B^2)\,\mathbf{I} - \mathbf{B}\mathbf{B} \right] = -\rho \nabla \Phi \,, \qquad p = (\gamma - 1)\rho e \,,$$

$$\frac{\partial}{\partial t}(\tfrac{1}{2}\rho v^2 + \rho e + \tfrac{1}{2}B^2) + \nabla \cdot \left[(\tfrac{1}{2}\rho v^2 + \rho e + p + B^2)\mathbf{v} - \mathbf{v} \cdot \mathbf{B}\mathbf{B} \right] = -\rho \mathbf{v} \cdot \nabla \Phi \,,$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}) = 0 \,, \qquad \nabla \cdot \mathbf{B} = 0 \,.$$

$$[\![\rho v'_n]\!] = 0 \,, \qquad \textit{(mass)}$$

$$[\![\rho {v'_n}^2 + p + \tfrac{1}{2}B_t^2]\!] = 0 \,, \qquad \textit{(normal momentum)}$$

$$\rho v'_n [\![\mathbf{v}'_t]\!] = B_n [\![\mathbf{B}_t]\!] \,, \qquad \textit{(tangential momentum)}$$

$$\rho v'_n \left[\!\!\left[\tfrac{1}{2}\left({v'_n}^2 + {v'_t}^2 \right) + \frac{1}{\rho}\left(\frac{\gamma}{\gamma - 1} p + B_t^2 \right) \right]\!\!\right] = B_n [\![\mathbf{v}'_t \cdot \mathbf{B}_t]\!] \,, \qquad \textit{(energy)}$$

$$[\![B_n]\!] = 0 \,, \qquad \textit{(normal flux)}$$

$$\rho v'_n \left[\!\!\left[\frac{\mathbf{B}_t}{\rho} \right]\!\!\right] = B_n [\![\mathbf{v}'_t]\!] \,, \qquad \textit{(tangential flux)}$$

- Kontaktni diskontinuiteti

$$[\![\rho]\!] \neq 0\,,$$

$$v'_n = 0\,, \qquad [\![\mathbf{v}'_t]\!] = 0\,, \qquad [\![p]\!] = 0\,, \qquad [\![B_n]\!] = 0\,, \qquad [\![\mathbf{B}_t]\!] = 0\,;$$

- Tangentni diskontinuiteti

$$[\![\rho]\!] \neq 0\,, \qquad [\![\mathbf{v}'_t]\!] \neq 0\,, \qquad [\![p]\!] \neq 0\,, \qquad [\![\mathbf{B}_t]\!] \neq 0\,,$$

$$v'_n = 0\,, \qquad B_n = 0\,, \qquad [\![p + \tfrac{1}{2}B_t^2]\!] = 0\,.$$

$$[\![\bar{\mathbf{v}}_t]\!] = [\![\bar{\mathbf{B}}_t]\!]$$

$$[\![(M^2 - 1)\bar{\mathbf{B}}_t]\!] = 0,$$

$$\left[\!\!\left[M^2 + \bar{p} + \frac{1}{2}\bar{B}_t^2 \right]\!\!\right] = 0,$$

$$\left[\!\!\left[\frac{\gamma}{\gamma - 1}\bar{p}M^2 + \frac{1}{2}(1 + \bar{B}_t^2)M^4 \right]\!\!\right] = 0,$$

$$[\![\bar{p}M^{2\gamma}]\!] \leqslant 0.$$

$$M_{\mathrm{A}n}^2 \equiv \frac{v_n^2}{v_{\mathrm{A}n}^2} \equiv \frac{\rho v_n^2}{B_n^2}\left(= \frac{\rho v_n}{B_n^2} \cdot v_n = \frac{\rho^2 v_n^2}{B_n^2} \cdot \frac{1}{\rho} \right),$$

$$\bar{v}_{ni} \equiv \frac{\rho |v_n|}{B_n^2} v_{ni} = -M_i^2, \quad \bar{B}_n \equiv \frac{B_n}{|B_n|} = -1,$$

$$\bar{\mathbf{v}}_{ti} \equiv \frac{\rho |v_n|}{B_n^2}\mathbf{v}_{ti}, \quad \bar{\mathbf{B}}_{ti} \equiv \frac{\mathbf{B}_{ti}}{|B_n|}, \quad \bar{p}_i \equiv \frac{p_i}{B_n^2} \quad (i = 1, 2),$$

$$\tan \vartheta_i \equiv B_{ti}/|B_n| \equiv \bar{B}_{ti}, \quad \beta_{ni} \equiv 2p_i/B_n^2 \equiv 2\bar{p}_i.$$

- Rotacioni (Alfvenovi) diskontinuiteti

$$M_1^2 = M_2^2 = 1, \quad [\![\bar{p}]\!] = 0, \quad [\![\bar{B}_t^2]\!] = 0,$$

$$[\![\bar{\mathbf{v}}_t]\!] = [\![\bar{\mathbf{B}}_t]\!] \neq 0.$$

- *Pravi* MHD udarni talasi

$$M_1^2 \neq M_2^2, \quad [\![\bar{p}]\!] \neq 0, \quad [\![\bar{B}_t^2]\!] \neq 0,$$

$$[\![\bar{\mathbf{v}}_t]\!] = [\![\bar{\mathbf{B}}_t]\!] \| \bar{\mathbf{B}}_{t1} \| \bar{\mathbf{B}}_{t2}, \quad (M_1^2 - 1)\bar{B}_{t1} = (M_2^2 - 1)\bar{B}_{t2}.$$

$$M_2^2 \leqslant M_1^2 \leqslant 1 \Rightarrow |\bar{B}_{t1}| \geqslant |\bar{B}_{t2}| \quad \text{(slow shocks)},$$

$$M_2^2 \leqslant 1 \leqslant M_1^2 \Rightarrow \bar{B}_{t1}/\bar{B}_{t2} < 0 \quad \text{(intermediate shocks)},$$

$$[\![S]\!] \equiv [\![\rho^{-\gamma} p]\!] \leqslant 0 \quad \text{(entropy)}.$$

$$1 \leqslant M_2^2 \leqslant M_1^2 \Rightarrow |\bar{B}_{t1}| \leqslant |\bar{B}_{t2}| \quad \text{(fast shocks)}.$$

- Paralelni, normalni, *kosi*, switch-on, switch-off

- *Pravi* MHD udarni talasi

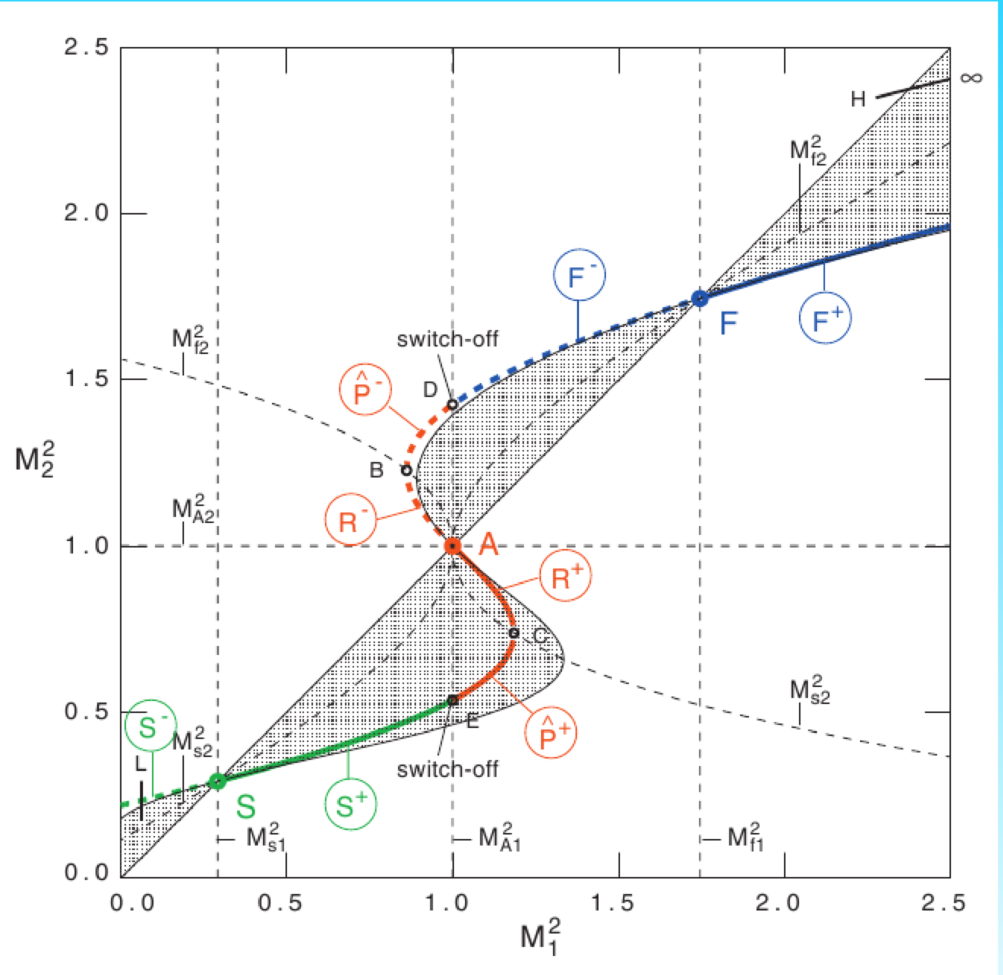
$$\left[\!\left[\frac{\gamma}{\gamma-1}\bar{p}M^2 + \frac{1}{2}(1+\bar{B}_t^2)M^4 \right]\!\right] = 0,$$

$$\begin{aligned} f &= f(M_2^2; M_1^2, \bar{B}_{t1}^2, \bar{p}_1) = 0 \\ &\equiv \tfrac{1}{2}(M_2^2-1)^2\{(\gamma+1)M_2^2 - (\gamma-1)M_1^2 - 2\gamma\bar{p}_1\} \\ &\quad + \tfrac{1}{2}\bar{B}_{t1}^2\{(\gamma-1)(M_2^2-1)(M_1^2-M_2^2) \\ &\quad - M_2^2(M_1^2+M_2^2-2)\}. \end{aligned}$$

$$[\![\bar{p}M^{2\gamma}]\!] \leqslant 0.$$

$$\begin{aligned} g &= g(M_2^2; M_1^2, \bar{B}_{t1}^2, \bar{p}_1) \geqslant 0 \\ &\equiv (M_2^2-1)^2\{M_1^2 - M_2^2 - \bar{p}_1[(M_1^2/M_2^2)^\gamma - 1]\} - \tfrac{1}{2}\bar{B}_{t1}^2(M_1^2 \\ &\quad - M_2^2)(M_1^2+M_2^2-2). \end{aligned}$$

$$(\vartheta_1 = 0.2\pi, \ \beta_1 = 0.4)$$



- Uopštenja: idealan gas + zračenje crnog tela, skok u γ (Onić 2012, Journal of Plasma Physics, prihvaćeno)

Korisna literatura:

- Goedbloed, J. P., Poedts, S. 2004, Principles of Magnetohydrodynamics, Cambridge University Press

- Goedbloed, J. P., Poedts, S., Keppens, R. 2010, Advanced Magnetohydrodynamics, Cambridge University Press

- OSN su zapravo bezsudarni udarni talasi

- Treumann, R. A. 2009 Fundamentals of collisionless shocks for astrophysical application, 1. Non-relativistic shocks, Astron. Astrophys. Rev., 17, 409

- Fizička kinetika

- Ubrazanje čestica – zračenje OSN

- Formiranje i evolucija bezsudarnog udarnog talasa: *rađanje* i *život* OSN

- Interakcija sa OZM i MZM: udarni talas jonizuje, zagreva i kompresuje sredinu kroz koju se prostire

- Retka i gusta sredina: različita evolucija!

Zračenje OSN u radio-području

- Neprekidni spektar oblika stepenog zakona:

$$S_\nu = S_{1\,\mathrm{GHz}} \cdot \nu^{-\alpha} \ [\mathrm{Jy}]$$

- Srednji spektralni indeks oko 0.5

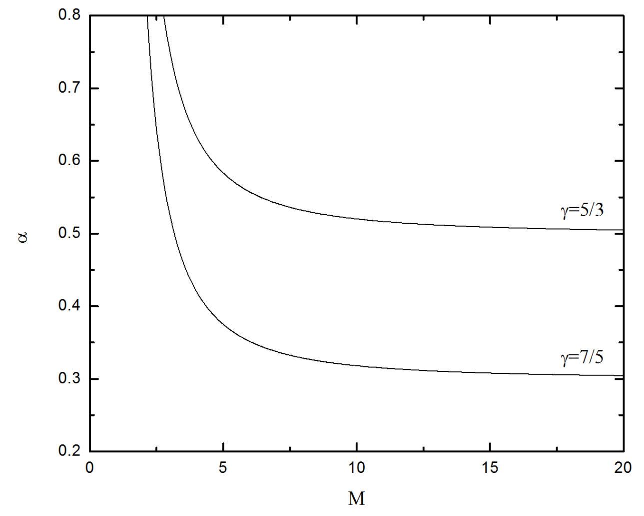
- Netermalno sinhrotronsko zračenje (Fermi I mehanizam - DSA)

Zračenje OSN u radio-području

- Značajan broj OSN sa α > 0.5

  - Mali Mahovi brojevi (za stare OSN, test-particle DSA)

$$\alpha = \frac{s-1}{2}, \quad s = \frac{\chi+2}{\chi-1}, \quad \chi = \frac{\gamma_g+1}{\gamma_g-1+\frac{2}{M^2}} \approx \frac{\gamma_g+1}{\gamma_g-1}$$



Zračenje OSN u radio-području

- Značajan broj OSN sa $\alpha > 0.5$ (UGLAVNOM MLADI OSN)

    - NDSA - pritisak relativističkih čestica, krivljenje spektra

    - *Kosi* udarni talasi (Bell, Schure & Reville 2011)

Zračenje OSN u radio-području

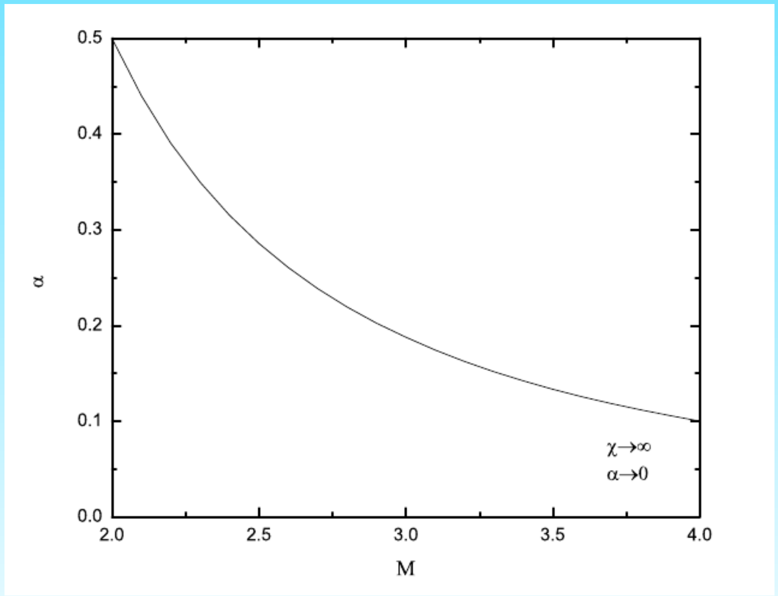
- Ne zanemarljiv broj OSN sa $\alpha < 0.5$

  - UGLAVNOM STARIJI OSN U GUSTOJ SREDINI (interakcija sa MO)

  - Kontamnacija !

- Veća kompresija - izotermalni udarni talasi:

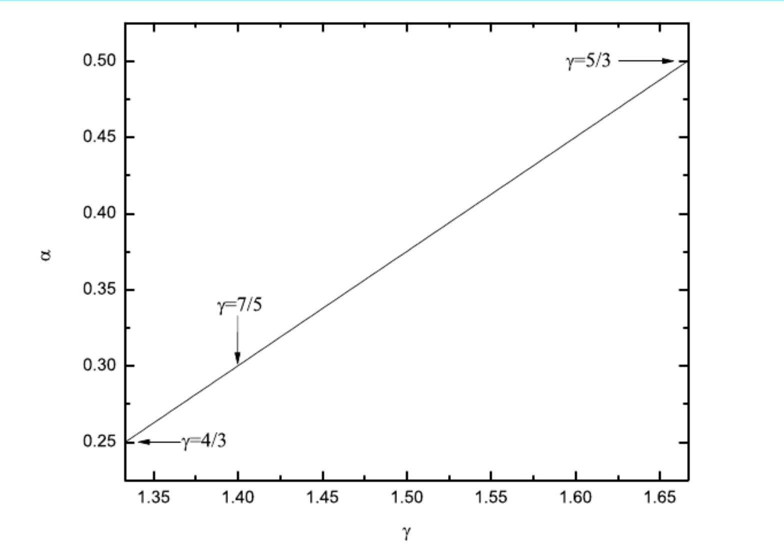
$$\alpha = \frac{3}{2(\chi - 1)}, \qquad \chi = M^2$$



Zračenje OSN u radio-području

- Ne zanemarljiv broj OSN sa $\alpha < 0.5$

  • Možda je γ manje od 5/3



Zračenje OSN u radio-području

- Ne zanemarljiv broj OSN sa $\alpha < 0.5$

  - Modeli koji uključuju Fermi II mehanizam:

    - Schlickeiser & Fürst (1989)
    - Ostrowski (1999)
    - Uchiyama et al. (2010)
    - ...

Zračenje OSN u radio-području

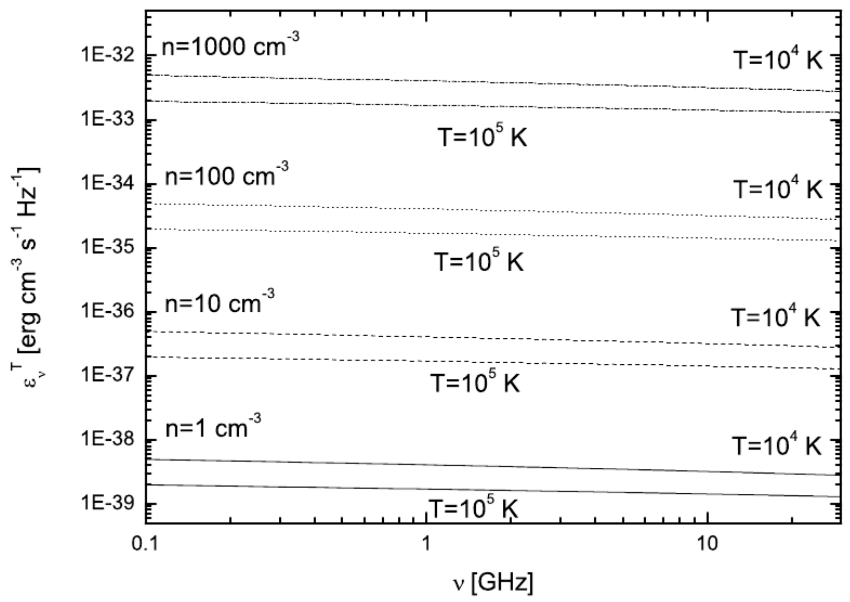
- Krivljenje spektra kod starijih OSN koji se prostiru kroz gustu sredinu i uglavnom interaguju sa MO (Urošević & Pannuti 2005, Tian & Leahy 2005, Leahy & Tian 2006, Urošević, Pannuti & Leahy 2007, Onić & Urošević 2008)

- Dosadašnji modeli ne objašnjavaju krivljenje!

Radio	X
- Netermalno sinhrotronsko zračenje	- Termalno zakočno zračenje
- Termalno zakočno zračenje ?	- Netermalno sinhrotronsko zračenje

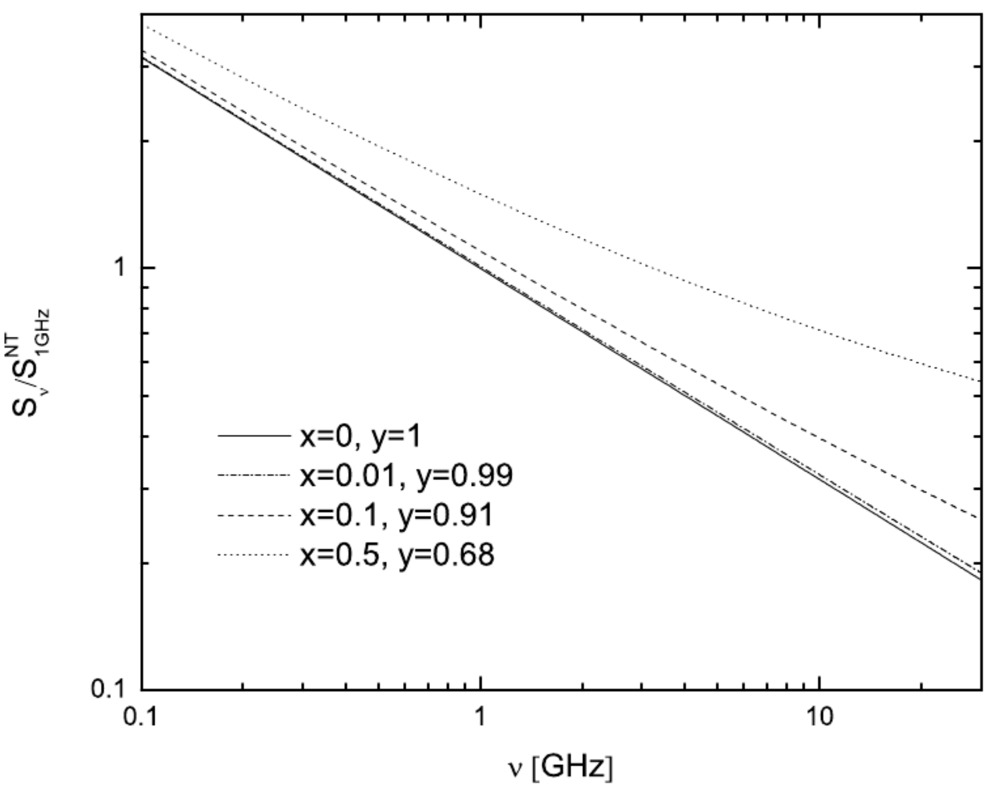
$$\varepsilon_\nu^T = 6.8 \times 10^{-38}\ g_{ff}(\nu, T)\ n^2\ T^{-0.5}\ [\mathrm{erg\ cm^{-3}\ s^{-1}\ Hz^{-1}}]$$

$$g_{ff}(\nu, T) \approx \begin{cases} 0.55 \ln(4.96 \times 10^{-2}\nu^{-1}) + 0.82 \ln T, & 10^2\ \mathrm{K} < T < 9 \times 10^5\ \mathrm{K} \\ 0.55 \ln(46.80\nu^{-1}) + 0.55 \ln T, & T \gtrsim 9 \times 10^5\ \mathrm{K} \end{cases}$$



$$S_\nu = S_\nu^{NT} + S_\nu^{T} = S^{\rm NT}_{1\,\rm GHz}\nu^{-\alpha}(1 + x\nu^{\alpha-0.1})$$

$$x = S^{\rm T}_{1\,\rm GHz}/S^{\rm NT}_{1\,\rm GHz}$$



- Termalni ansambl – deo čestica gasa koje ulaze u proces ubrzavanja je reda 10^{-3}

- Slabljenje udarnog talasa - ohlađeni termalni X elektroni

- Nehomogena sredina - različiti delovi OSN u različitim fazama

- Postojanje termalnog ansambla - detekcija u Hα, radio rekombinacione linije, …

- M-M OSN

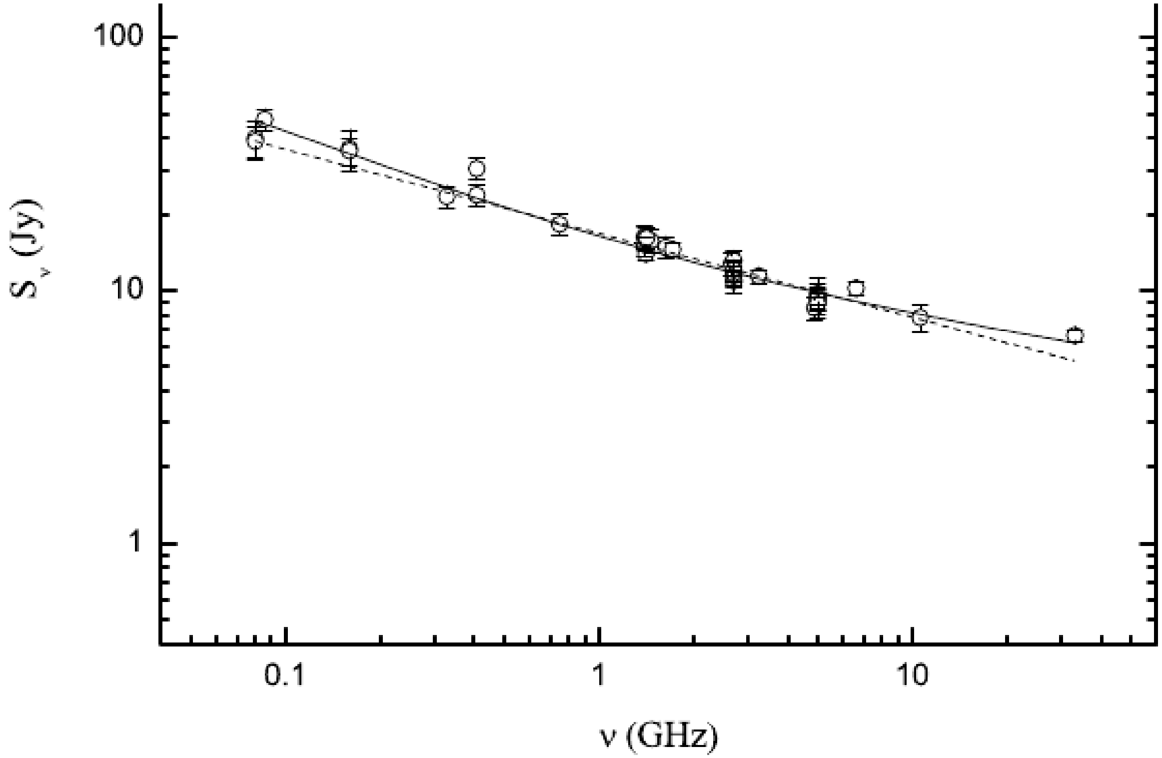
- Problem: *kvalitet* posmatranog radio-spektra !

  - Dovoljan broj tačaka sa *zadovoljavajućim* greškama

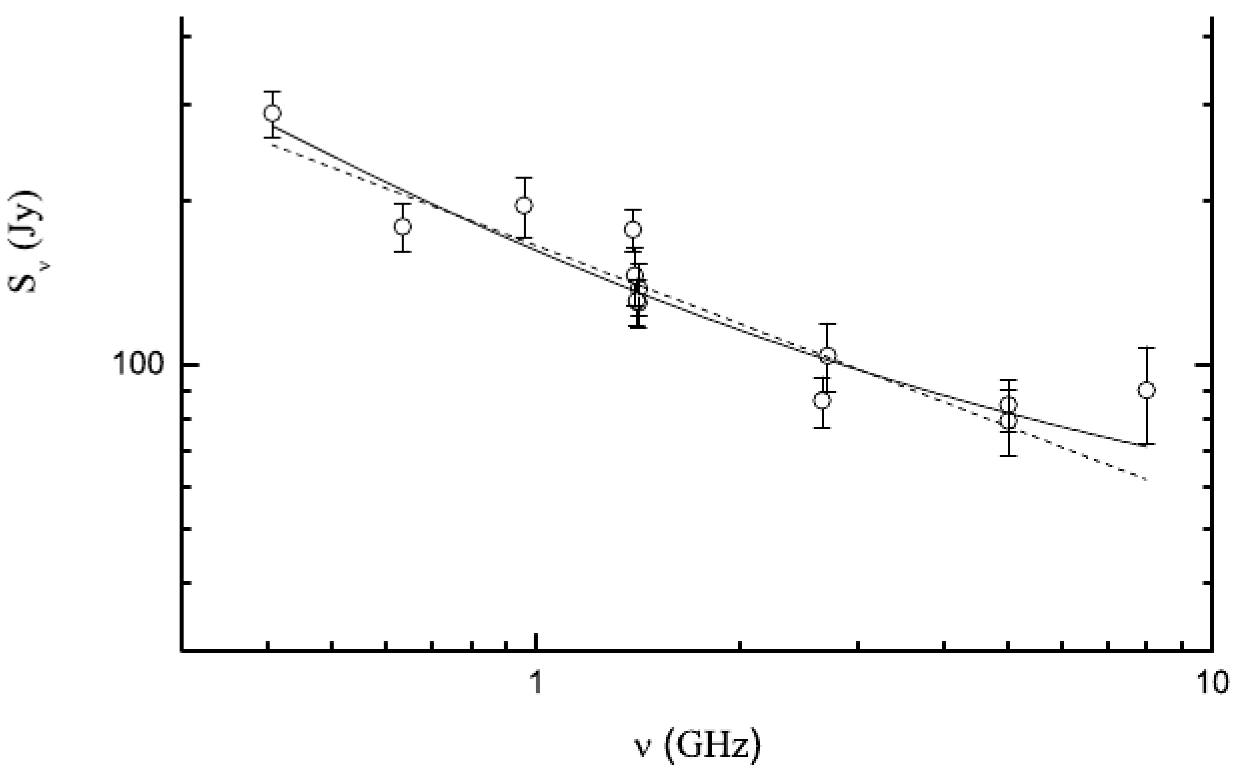
  - Precizno određivanje gustine fluksa (kontamnacija i sl.)

- Razmatrani samo oni OSN sa više od četiri tačke, gustine fluksa na skali Baars et al. (1977), gustine fluksa sa greškama manjim od 20%

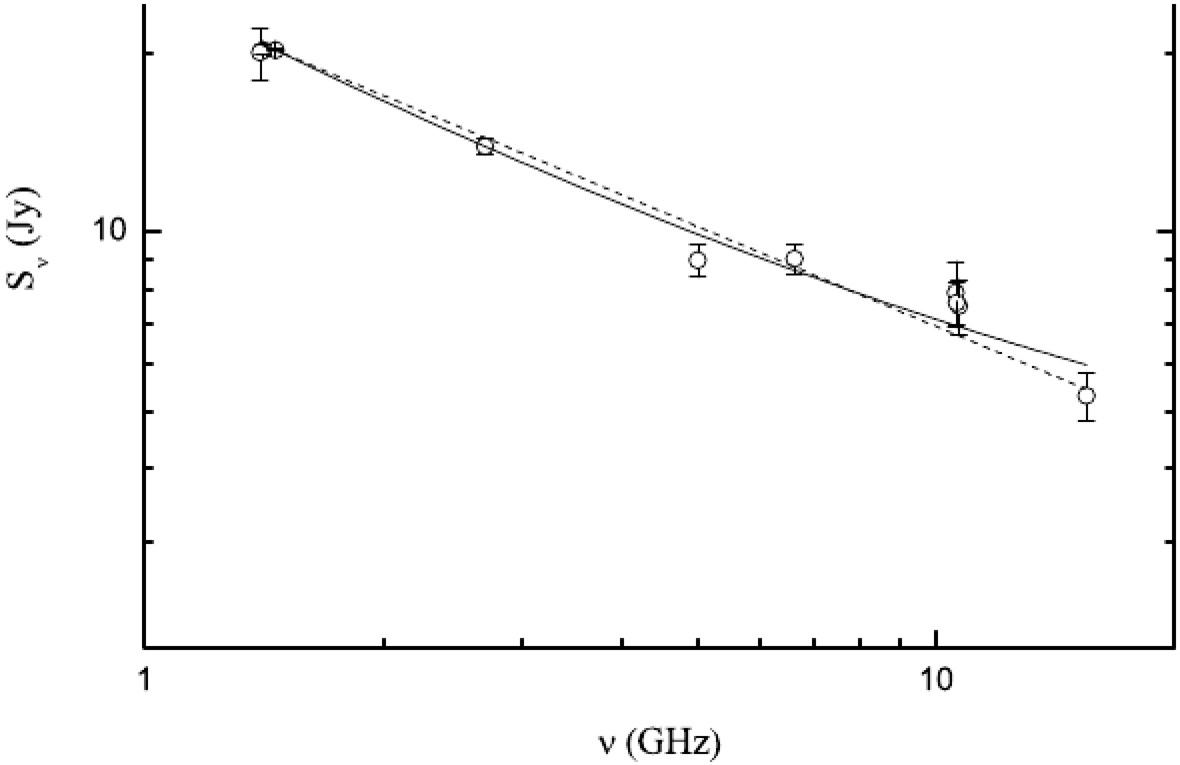
α	$S^{NT}_{1\,GHz}$ (Jy)	$\frac{S^{T}_{1\,GHz}}{S^{NT}_{1\,GHz}}$	χ^2/dof	Adj. R^2
0.55 ± 0.05	9.56 ± 1.14	0.71 ± 0.18	1.01	0.94
0.33 ± 0.02	16.78 ± 0.38	-	1.58	0.90



α	$S^{\mathrm{NT}}_{1\,\mathrm{GHz}}$ (Jy)	$\frac{S^{\mathrm{T}}_{1\,\mathrm{GHz}}}{S^{\mathrm{NT}}_{1\,\mathrm{GHz}}}$	χ^2/dof	Adj. R^2
0.82 ± 0.35	96.40 ± 40.50	0.68 ± 0.65	1.72	0.83
0.47 ± 0.06	165.40 ± 7.80	-	1.74	0.83



α	$S^{NT}_{1\,GHz}$ (Jy)	$\frac{S^{T}_{1\,GHz}}{S^{NT}_{1\,GHz}}$	χ^2/dof	Adj. R^2
0.80 ± 0.20	21.18 ± 1.41	0.22 ± 0.11	1.34	0.99
0.56 ± 0.02	24.92 ± 0.28	-	1.57	0.99



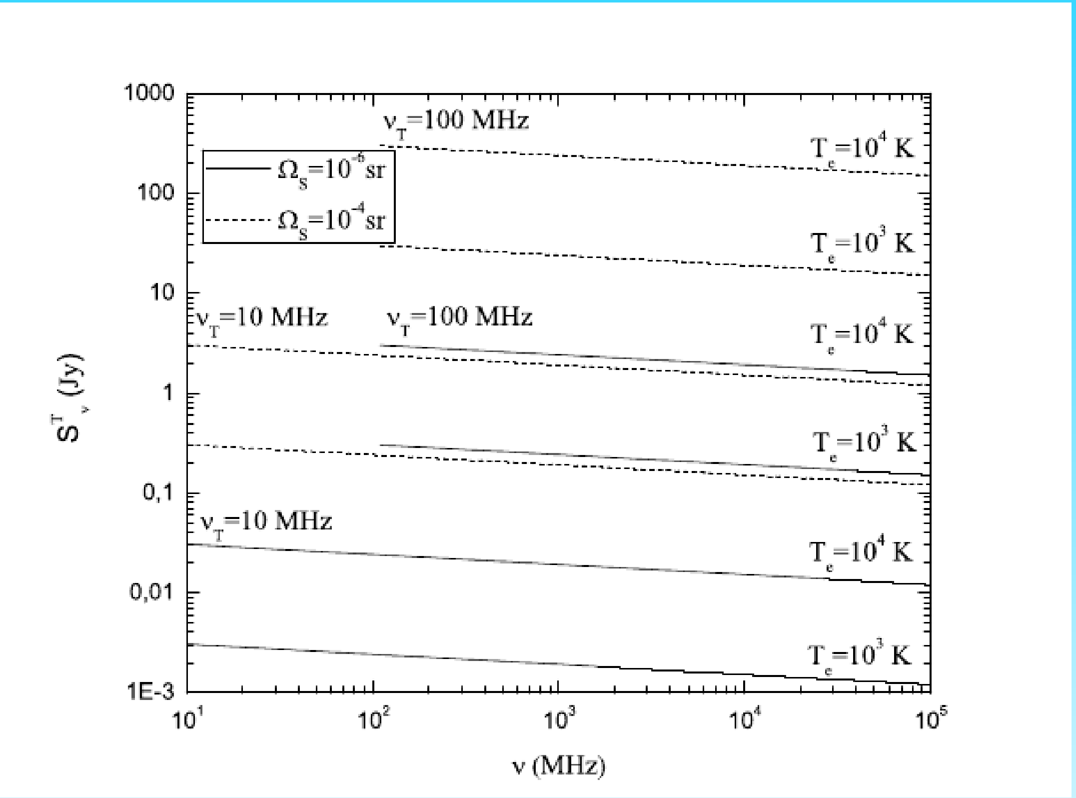
- Termlana apsorpcija povezana sa OSN (Brogan et al. 2005, Castelletti et al. 2011)

$$\nu_{\mathrm{T}} \approx 0.3045 T_e^{-0.643} EM^{0.476} \ [\mathrm{GHz}],$$

$$EM = \int_0^s n_e^2 ds.$$

$$S_{\nu_T} = \frac{2kT_e \Omega_S \nu_T^2}{c^2}$$

$$S_\nu = S_{\nu_T} \left(\frac{\nu}{\nu_T} \right)^{-0.1}$$


1000
100
10
1
0,1
0,01
1E-3
S^T_ν (Jy)
10^1
10^2
10^3
10^4
10^5
ν (MHz)
$\Omega_S=10^{-6}$sr
$\Omega_S=10^{-4}$sr
ν_T=100 MHz
ν_T=10 MHz
ν_T=100 MHz
ν_T=10 MHz
$T_e=10^4$ K
$T_e=10^3$ K
$T_e=10^4$ K
$T_e=10^3$ K
$T_e=10^4$ K
$T_e=10^3$ K

- Procene učešća termalne komponente na 1 GHz:

  - 3C396 iz fita <47% @ 1 GHz;

  - IC443: iz fita 3-57% @ 1 GHz;
    iz term. aps. 10-40% @ 1 GHz

  - 3C391 iz fita 10-25% @ 1 GHz;
    iz term. aps. 0.15-7% @ 1 GHz

- G7.7-3.7, HB3, Kes 67, W44, W49B, 3C397, HB21, 3C434.1, VRO 42.04.01, MSH11-61A

- Linearna polarizacija - donja granica za netermalnu komponentu

- Varijacije spektralnog indeksa

- Određivanje gustine/koncentracije na onovu posmatranja radio kontinuuma (kako za Galaktičke tako i za OSN u drugim galaksijama)

- Potrebna su nova merenja !

- Onić, D., Urošević, D., 2008, Serb. Astron. J., 177, 67
- Onić, D., Urošević, D., Arbutina, B., Leahy, D., 2012, ApJ, 756, 61
- Onić, D., u pripremi

Hvala na pažnji