



Seminar



Europska Unija
Ulaganje u budućnost
Projekt je sufinancirala Europska unija
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ERUPTIVNI PROCESI U SUNČEVOJ KORONI I NJIHOVO ŠIRENJE HELIOSFEROM

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Sadržaj

- Koronini izbačaji mase (CME)
 - Modeli erupcije
- Induktivitet magnetskog užeta
- Model magnetskog užeta
- Inicijacija izbačaja
- (Potpuno numerički MHD izračun (VAC kod) nastanka i propagacije udarnih valova
 - istraživanje Moretnonovih i EUV valova)
- Model MHD otpora (DBM)
 - s konstantnim Sunčevim vjetrom
 - testiranje modela
- Općeniti model i geometrija
 - primjena na međunarodnim prognostičkim stranicama
 - buduća integracija s naprednim numeričkim modelima, npr:
 - NASA – ENLIL
(<http://www.swpc.noaa.gov/products/wsa-enlil-solar-wind-prediction>)
 - automatska prognostika
- Rješavanje problema CME-CME međudjelovanja:
 - upotreba naprednih numeričkih modela – VAC (Versatile Advection Code)

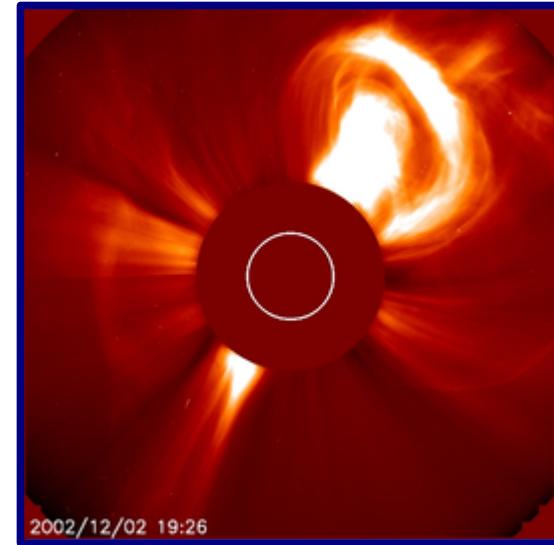
Koronini izbačaji mase (engl. CME)

- Procesima u koroni Sunce ($m_{\odot} \approx 2 \times 10^{30}$ kg) gubi masu na 2 načina (Aschwanden, 2006):
 - kontinuiranim Sunčevim vjetrom $\approx (0.4\text{--}2) \times 10^{-10}$ g cm $^{-2}$ s $^{-1}$ [ili $\approx (0.2\text{--}1.2) \times 10^{10}$ kg/s]
 - sporadičnim (nekoliko na dan) koroninim izbačajima mase $\approx (0.02\text{--}2) \times 10^{-12}$ g cm $^{-2}$ s $^{-1}$ [ili $\approx (0.01\text{--}1.2) \times 10^8$ kg/s]
- Magnetska aktivnost → eruptivni procesi → koronin izbačaj mase:
 - MHD „eksplozije“ u Sunčevoj koroni
 - magnetski „oblak“ ubrzano ekspandira u okolni prostor (100–2000 km/s)
 - unutar tjedan dana stižu do Zemlje
 - mnoštvo visokoenergetskih nabijenih elektrona stiže do Zemlje za otprilike 1/2–1 sat nakon početka erupcije
- Oko 70% izbačaja povezano je s **eruptivnim prominencijama** koje mogu prerasti u CME

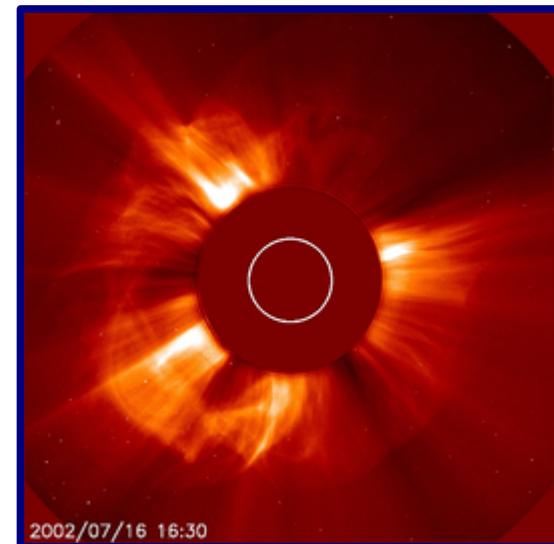
Trođijelna struktura CME

- Koronini izbačaji često imaju trodijelnu strukturu:
 - vodeći luk
 - praznina
 - svijetla jezgra - katkad eruptivna prominencija
- „halo“ CME → usmjereni prema ili od Zemlje
- Mogući oblici (nejasnoće zbog projekcijskih efekata):
 - magnetska vlakna (užadi, cijevi, engl. fluxropes)
 - polu-ovojnice
 - baloni/mjehuri

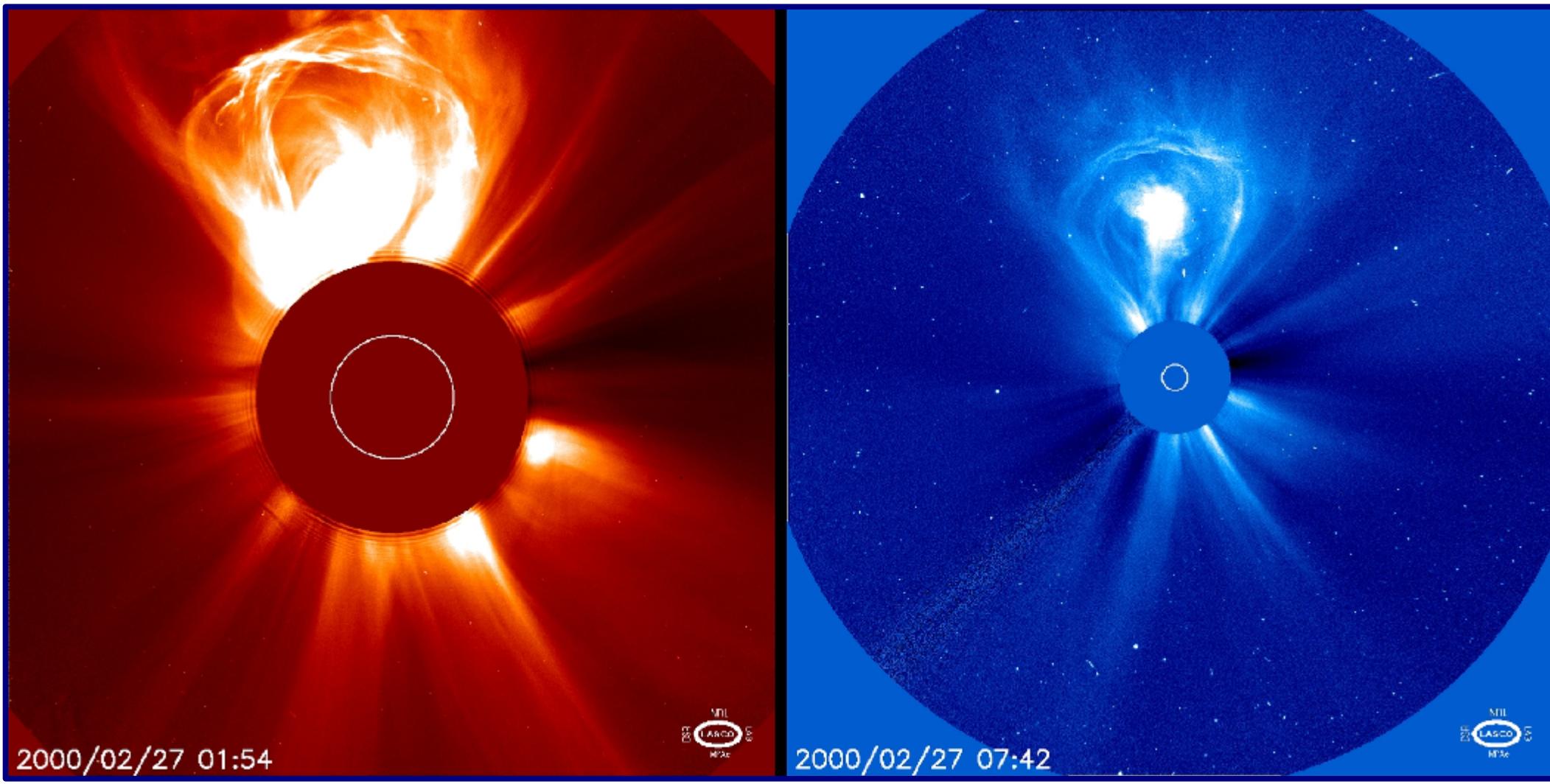
Karakteristični oblik



„Halo“ CME



Karakteristični oblik „žarulje“



SoHO LASCO C2/C3 koronograf. Erupcija CME-a 27.02.2000. Trodijelna struktura: vodeći luk, prazna šupljina sa svjetлом jezgrom (SoHO, 1995-)

Podjela modela izbačaja

Modeli
bez magnetskog prespajanja
(idealni MHD procesi)

model s magnetskim uzgonom

model s pritokom dodatnog
poloidalnog toka

model s „kink nestabilnosti“

model s pritokom/odljevom mase

Modeli
s magnetskim prespajanjem
(rezistivni MHD procesi)

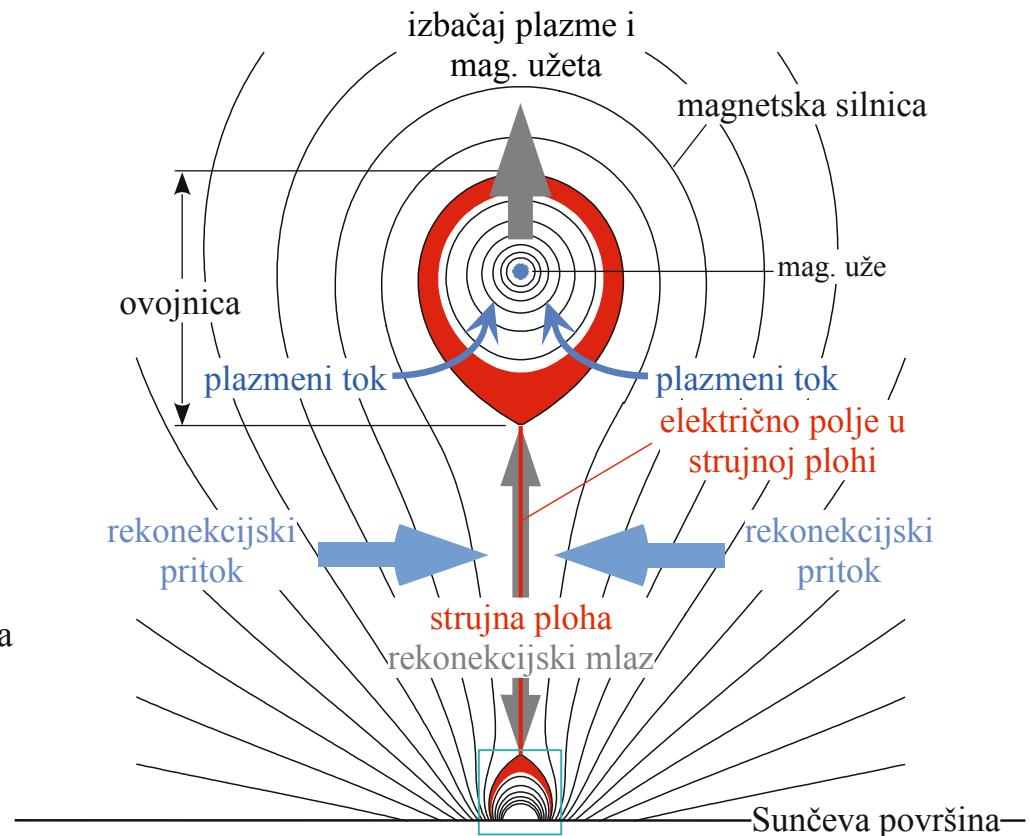
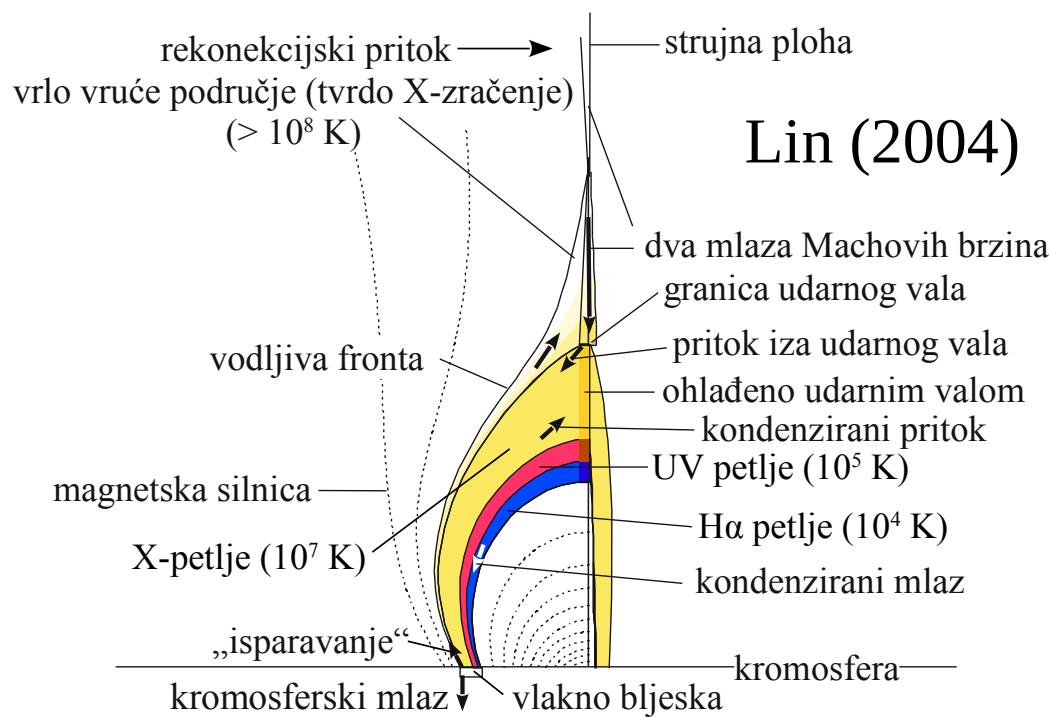
model „kidanja spona“
(engl. tether cutting)

model proboga (engl. breakout)

model poništavanja magnetskog toka
(engl. flux cancellation)

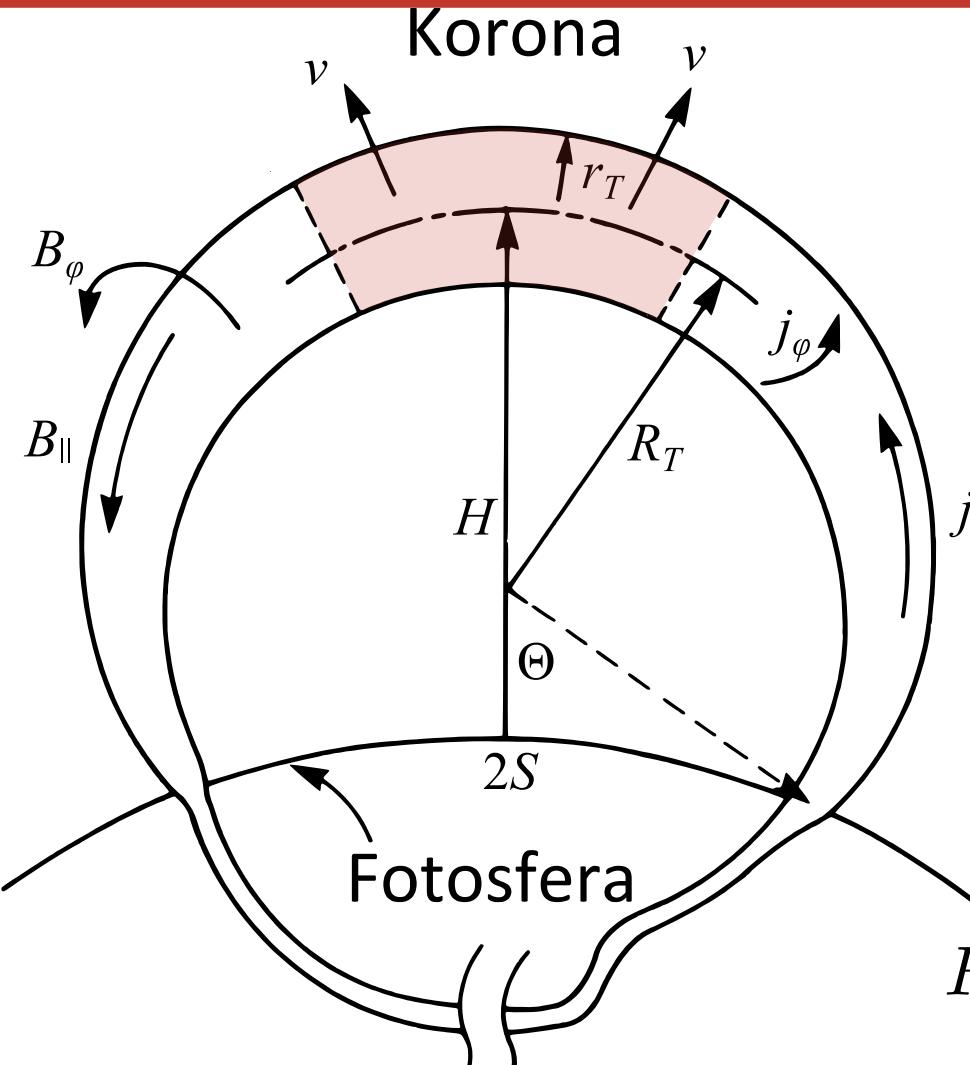
Model magnetske strukture CME/bljesak sistema

- Arkade magnetskih silnica obavijaju prominencijski materijal
- rekonekcijom se uvodi novi magnetski tok i plazmu
- novi rekonekcijski tok pospješuje uzdizanje magnetskog vlakna



- U podnožju → kromosferski mlaz → dvovlaknasti bljesak

Chen-ov (1989) model magnetskog užeta



$$F_R = \frac{V}{R} \left[\frac{B_\varphi^2}{\mu_0} \left(\ln \frac{8R_T}{r_T} - 1 + \frac{l_i}{2} \right) + \bar{p} + \frac{B_{||e}^2 - \bar{B}_{||}^2}{2\mu_0} + \frac{B_z B_\varphi R_T}{2\pi r_T} \right]$$

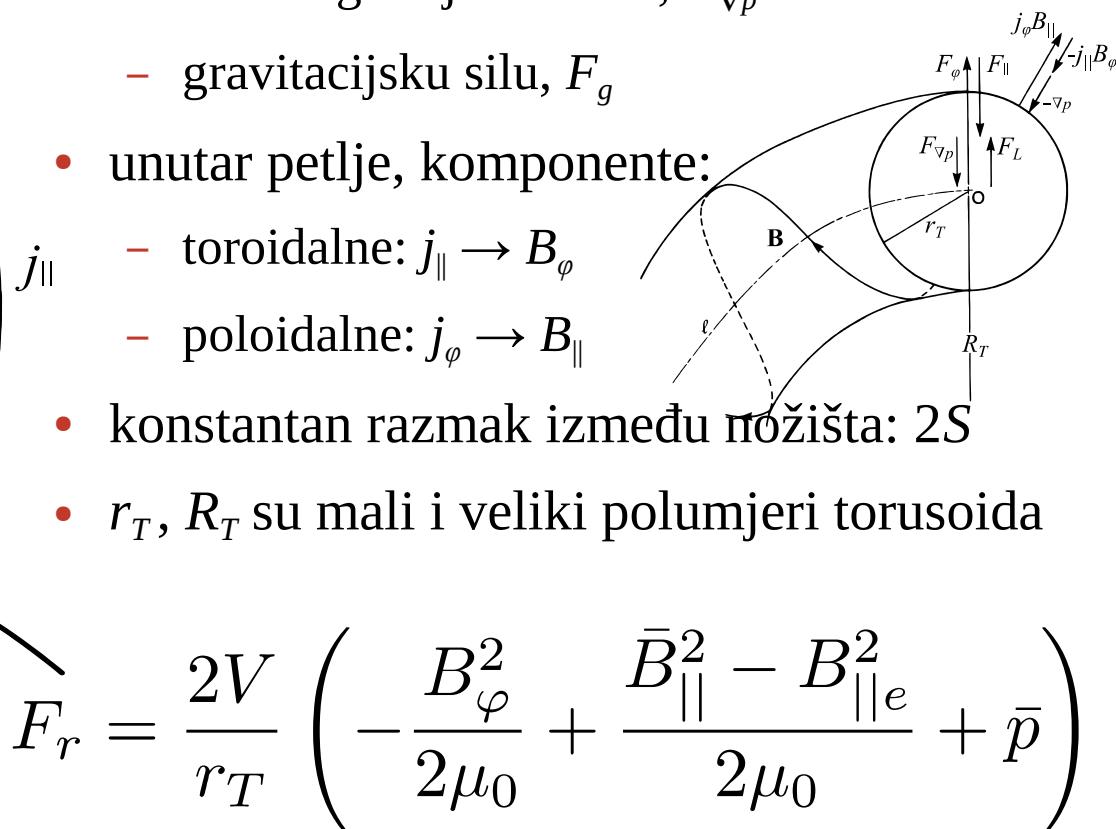
- uključuje:

- Lorentzovu silu, $\mathbf{j} \times \mathbf{B}$
- silu od gradijenta tlaka, $F_{\nabla p}$
- gravitacijsku silu, F_g

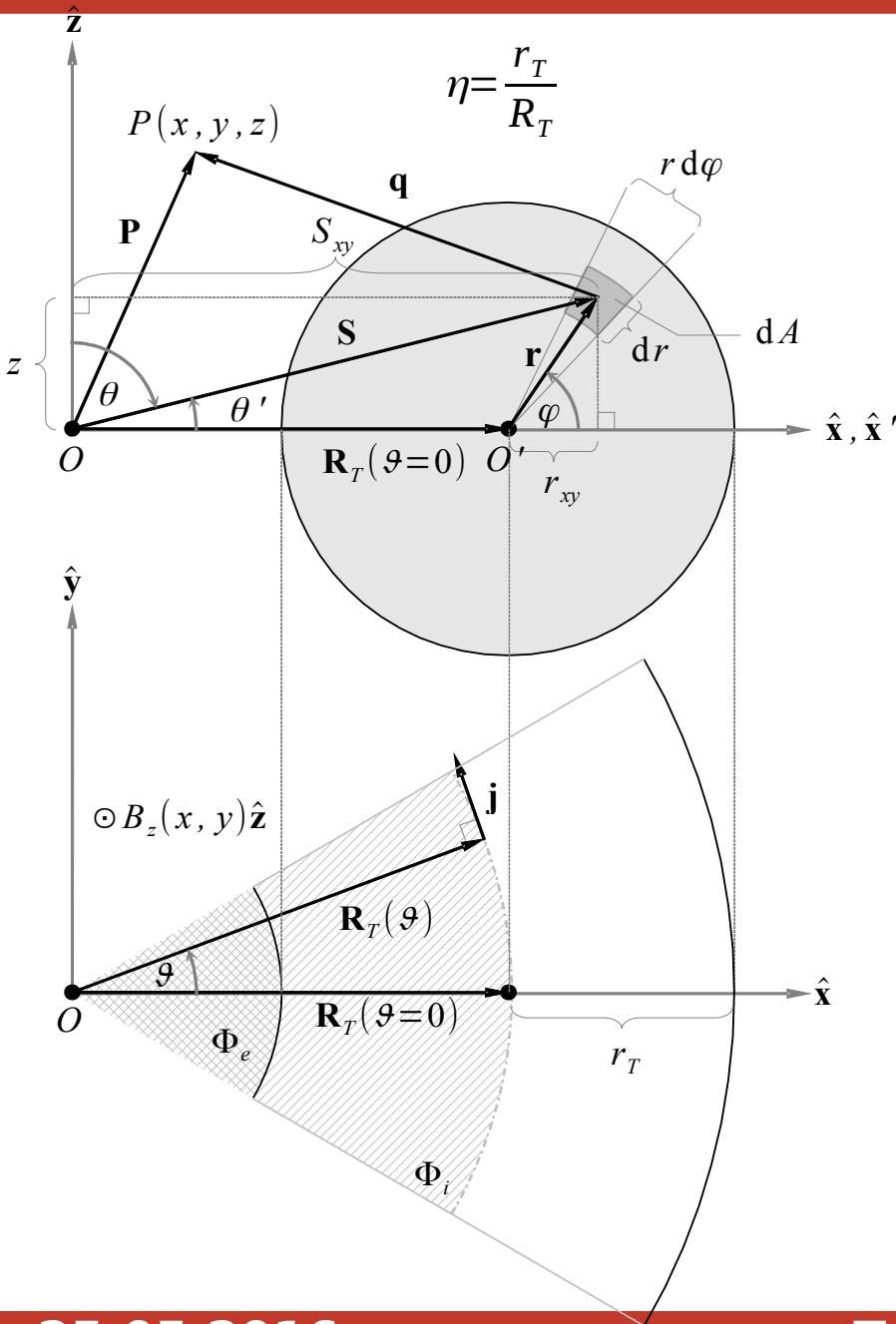
- unutar petlje, komponente:

- toroidalne: $j_{||} \rightarrow B_\varphi$
- poloidalne: $j_\varphi \rightarrow B_{||}$

- konstantan razmak između nožišta: $2S$
- r_T, R_T su mali i veliki polumjeri torusoida



Induktivitet debelog strujnog torusa



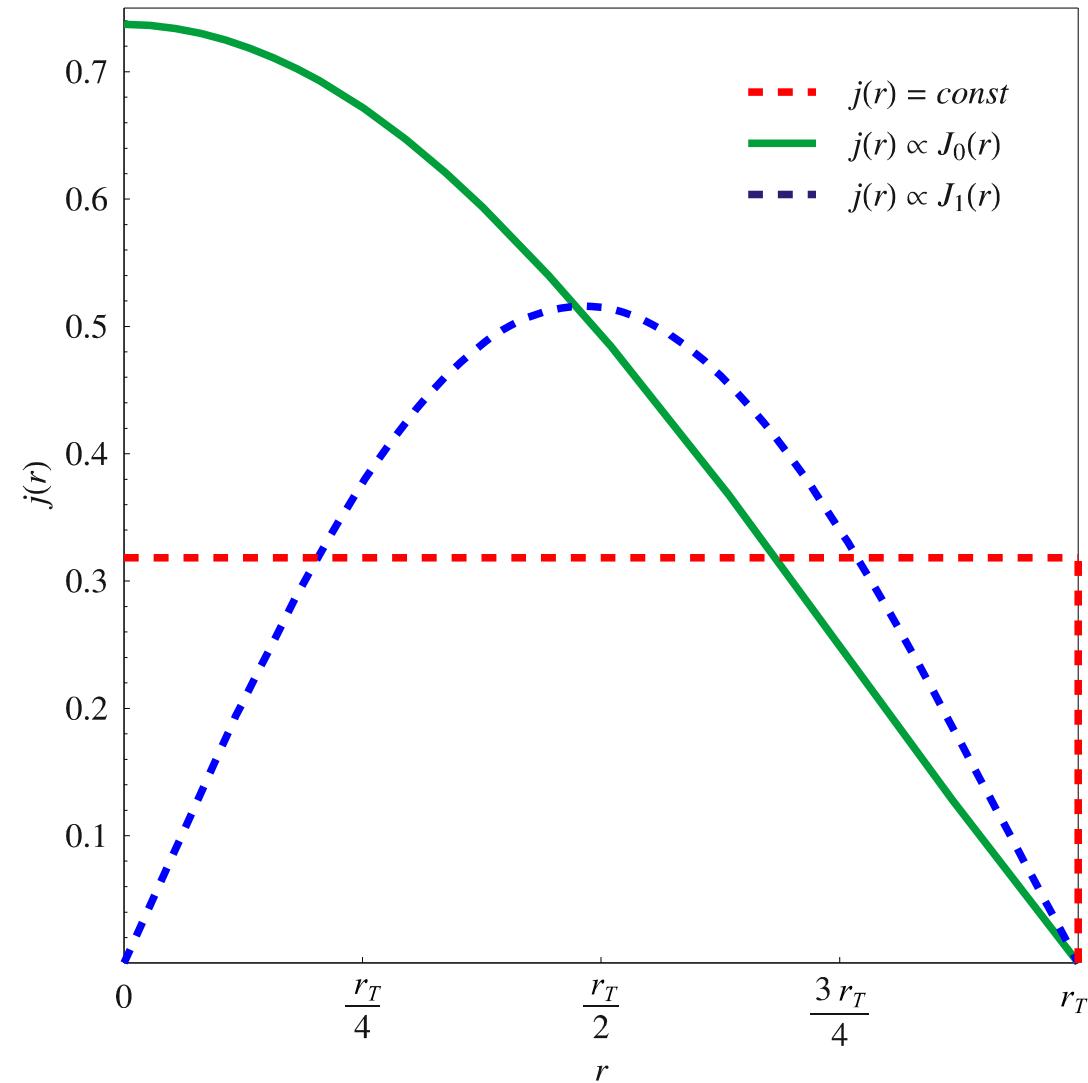
- u prijašnjim modelima se koristi induktivitet L tankih strujnih petlji
- u stvarnosti izbačaji su debeli
- numerički se odredio induktivitet za debelu toroidalnu struju - zbroj vanjskog i unutarnjeg,

$$L = L_e + L_i$$

- dobiva se iz ukupnog toka:
- $$\Phi = \Phi_i + \Phi_e = I(L_e + L_i)$$
- i Biot-Savart-ov zakona:

$$\vec{B}(\vec{P}) = \frac{\mu_0}{4\pi} \int_V \frac{\vec{j}(\vec{r}) \times \vec{q}(\vec{P}, \vec{r})}{|\vec{q}(\vec{P}, \vec{r})|^3} d^3 \vec{r}$$

Profilii gustoća struja unutar torusa



$$I = 2\pi \int_0^{r_T} j(r)r dr =: 1$$

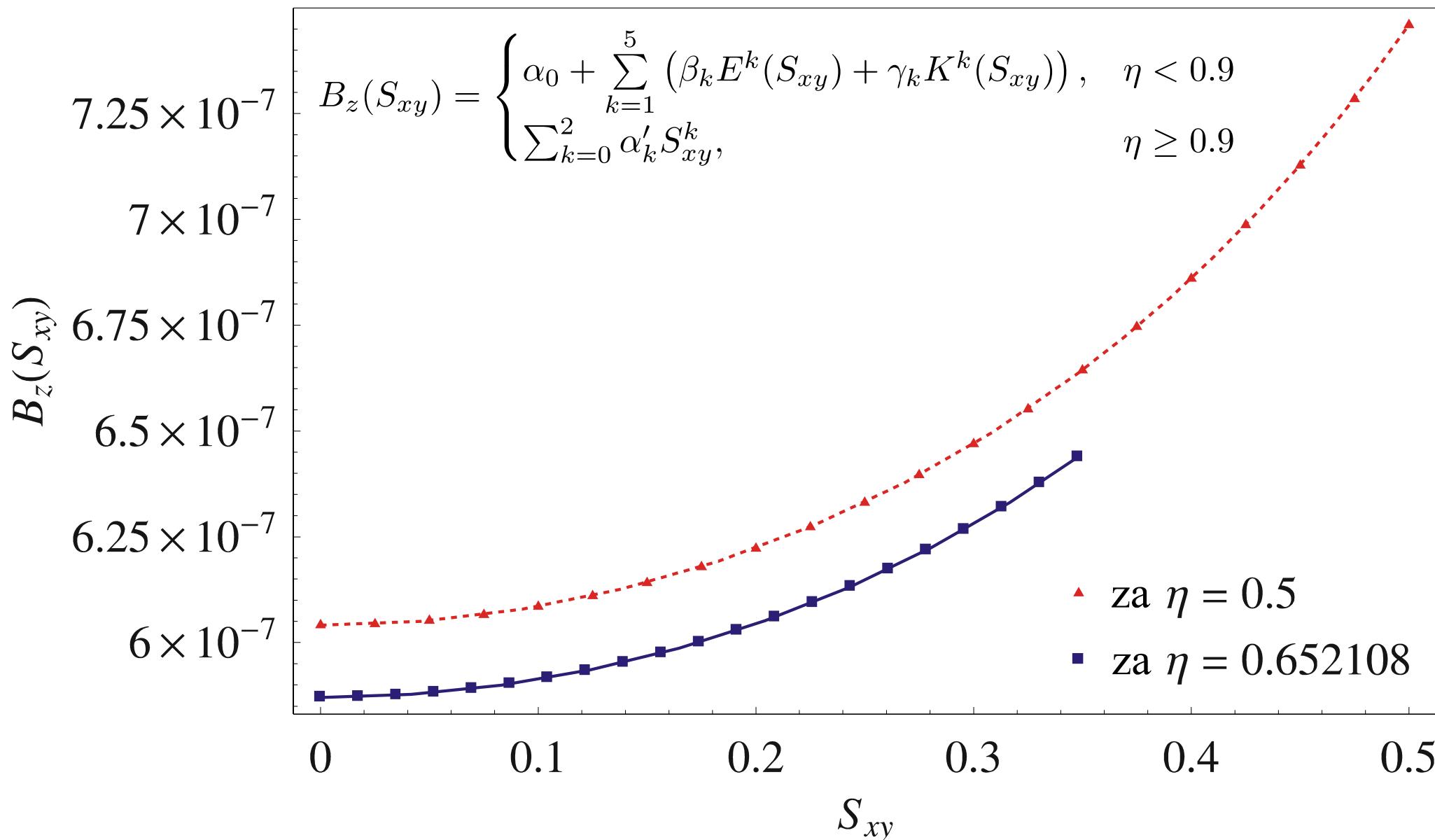
$$j_c(r) = \frac{I}{r_T^2 \pi}$$

$$j_0(r) = \frac{I}{2\pi r_T^2} r_0 \frac{J_0(\frac{r_0}{r_T} r)}{J_1(r_0)}$$

$$j_1(r) = \frac{I}{2\pi} \frac{J_1(\frac{r_1}{r_T} r)}{\int_0^{r_T} r J_1(\frac{r_1}{r_T} r) dr}$$

- r_0, r_1 - prve nul-točke Bessel-ovih funkcija J_0, J_1

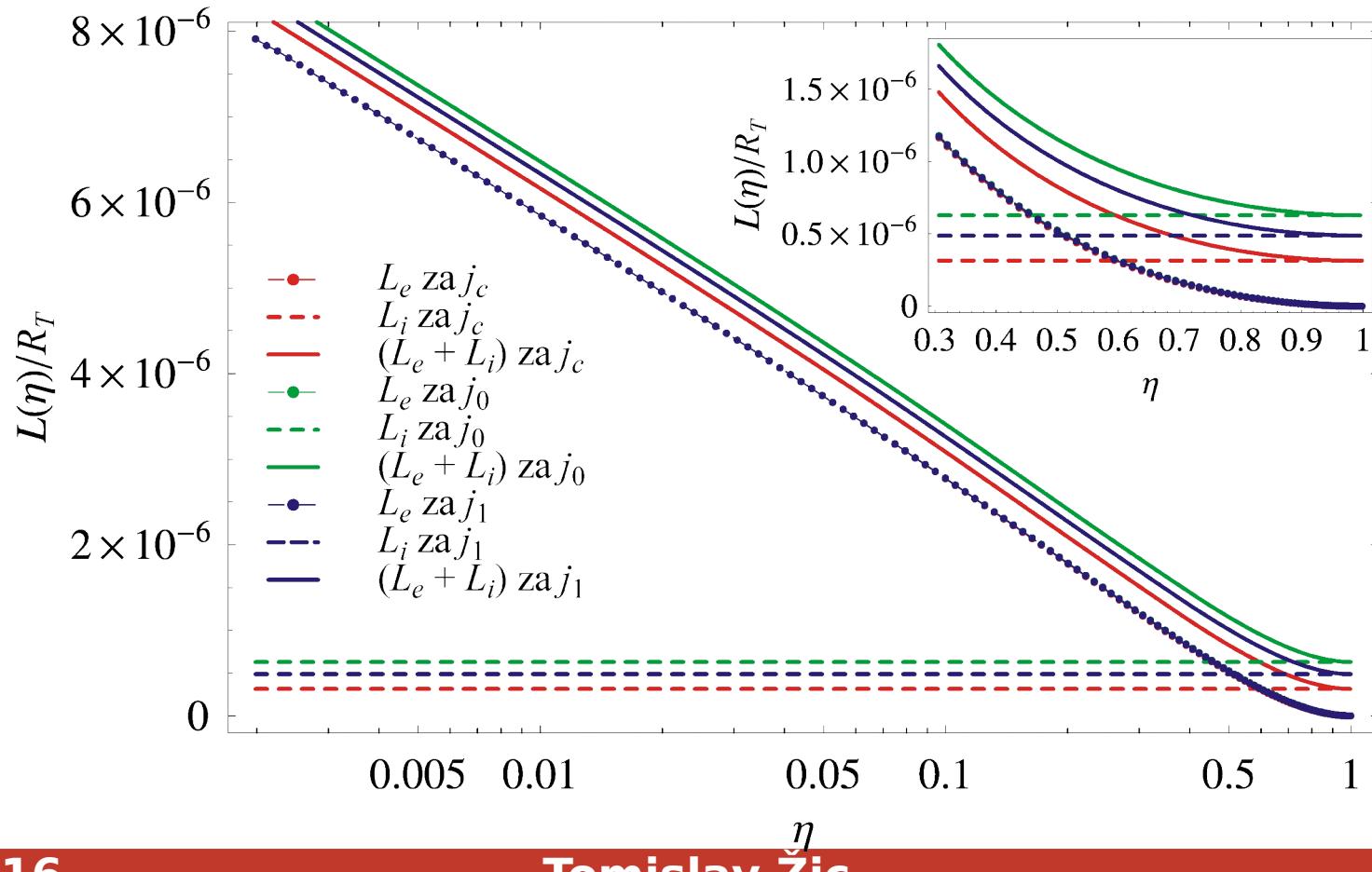
Prilagodba funkcije $B_z(S_{xy})$ izračunatom polju u xy-ravnini



Ukupni induktivitet ovisi o torusnom omjeru

$$L_i = \frac{2W}{I^2} \quad W = \int_V \frac{B_\varphi^2}{2\mu_0} dV \quad B_\varphi(r) = \frac{\mu_0}{r} \int_0^r r' j(r') dr' \quad L = L_i + L_e = L_i + \Phi_e/I$$

$$\frac{L_e(\eta)}{R_T} = \begin{cases} A' \left[\ln \left(\frac{8}{\eta} \right) - B' \right], & \eta \leq \eta^* \\ c_1(1-\eta)^{c_2}, & \eta > \eta^* \end{cases}$$



Koeficijenti prilagodbe funkcije induktiviteta

$$\frac{L_e(\eta)}{R_T} = \begin{cases} A' \left[\ln \left(\frac{8}{\eta} \right) - B' \right], & \eta \leq \eta^* \\ c_1(1-\eta)^{c_2}, & \eta > \eta^* \end{cases}$$

	j_c	j_0	j_1
$A' [10^{-7}\text{Hm}^{-1}]$	(13.98 ± 0.02)	(13.93 ± 0.02)	(13.95 ± 0.02)
B'	(2.416 ± 0.004)	(2.404 ± 0.004)	(2.409 ± 0.004)
A'/A°	(1.113 ± 0.002)	(1.109 ± 0.002)	(1.110 ± 0.002)
B'/B°	(1.208 ± 0.002)	(1.202 ± 0.002)	(1.204 ± 0.002)
$c_1 [10^{-7}\text{Hm}^{-1}]$	(23.7 ± 0.01)	(23.5 ± 0.01)	(23.6 ± 0.01)
c_2	(2.227 ± 0.005)	(2.178 ± 0.005)	(2.197 ± 0.005)
η^*	0.485624	0.487365	0.486743
$\Phi_i/IR_T [10^{-7}\text{WbA}^{-1}\text{m}^{-1}]$	6.339206	10.019046	7.833740
$\eta(\Phi_e \leq \Phi_i)$	0.453015	0.347892	0.406853
$L_i/R_T [10^{-7}\text{Hm}^{-1}]$	3.172148 $(=\mu_0/4)$	6.485828 $(=\mu_0/2)$	4.826240
$\eta(L_e \leq L_i)$	0.593147	0.453015	0.515703

- $A^\circ = \mu_0$ (magnetska permeabilnost) i $B^\circ = 2 \rightarrow$ koeficijenti za vrlo tanki torus (strujnu petlju)
- zadnja četiri retka prikazuju vrijednosti unutarnjeg toka i induktiviteta.
- $\eta(\Phi_e \leq \Phi_i)$ i $\eta(L_e \leq L_i) \rightarrow$ omjeri polumjera $\eta = r_T/R_T$ kada su unutarnji tok i induktivitet izjednačeni i postaju veći od vanjskog

Zaključak - induktivitet

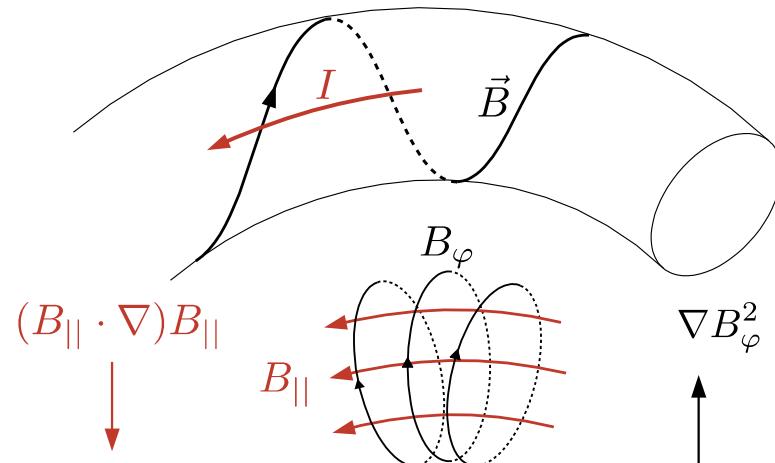
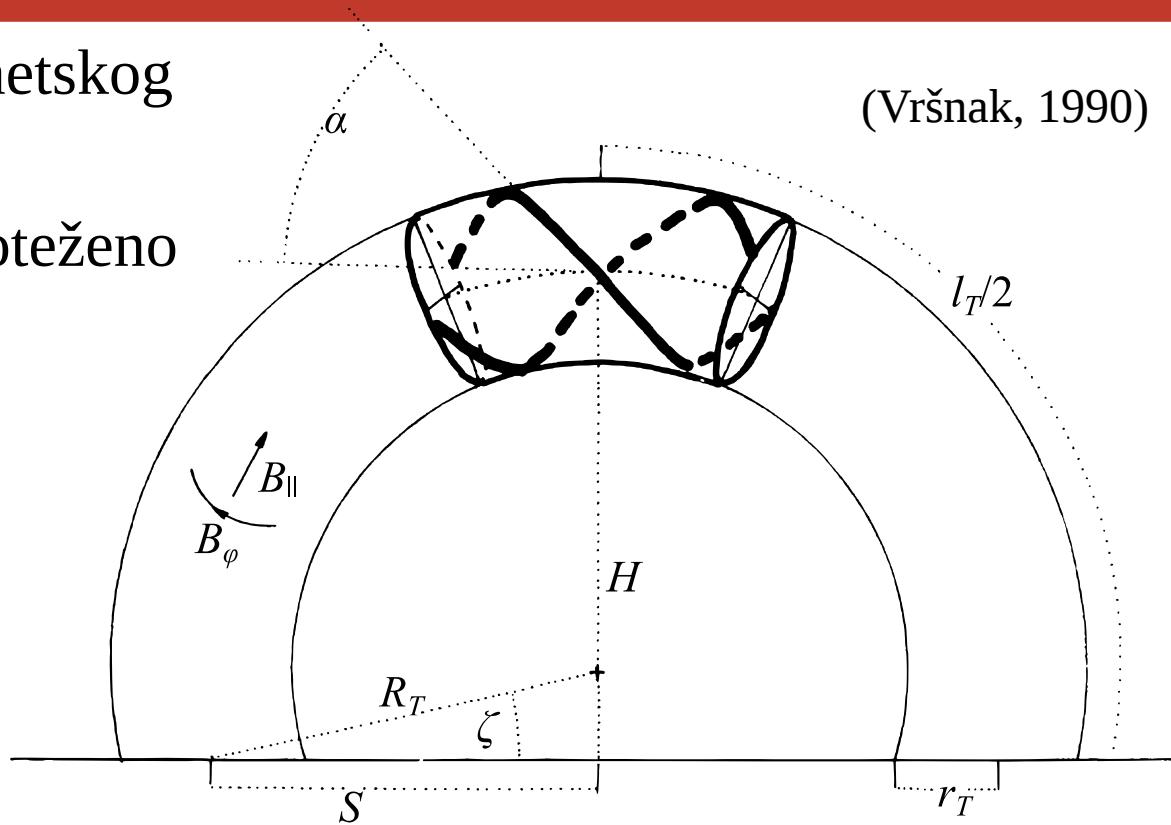
- izraz induktiviteta tankog torusa odstupa od numeričkog za $\eta \geq 0.1$
→ u proučavanju izbačaja bolje koristiti numerički dobiven izraz
- ostale vrijednosti: slabo ovise o profilu gustoće struje $j(r)$
- u visokoj koroni tlak plazme i vanjske sile su zanemarive, visoka vodljivost → polje je zamrznuto u plazmi:

$$\Phi_i = \text{konst.} \text{ i } \Phi_e = \text{konst.}$$

- pokazalo se: $\Phi_i \propto IR_T = \text{konst.} \rightarrow I \propto 1/R_T$
- iz $\Phi_e = L_e I = \text{konst.} \rightarrow L_e \propto 1/I \propto R_T$
- dobilo se: $L_e = R_T \ln(1/\eta)$ i kako vrijedi $L_e \propto R_T$ tada je:
 $\ln(1/\eta)$ konstanta proporcionalnosti → $\boxed{\eta = r_T/R_T = \text{konst.}}$
 - toroidalna stuktura se rasteže samosuglasno ili proporcionalno
 - opažačka činjenica za izbačaje (Bothmer and Schwenn, 1998)

Model magnetskog užeta

- debela zakrivljena cijev magnetskog toka (magnetsko uže)
- model polja $\mathbf{B} \rightarrow$ samouravnoteženo za cilindar $\rightarrow \mathbf{F}_L = \mathbf{j} \times \mathbf{B} = 0$
 - poloidalno, B_φ
 - toroidalno (uzdužno), $B_{||}$
- na uže utječe:
 - vanjsko koronino polje B_c
 - Sunčeva gravitacija
 - Sunčev vjetar stvara MHD „otpor“
- u sistem ulazi vanjski magnetski tok \rightarrow inducira dodatnu struju ΔI



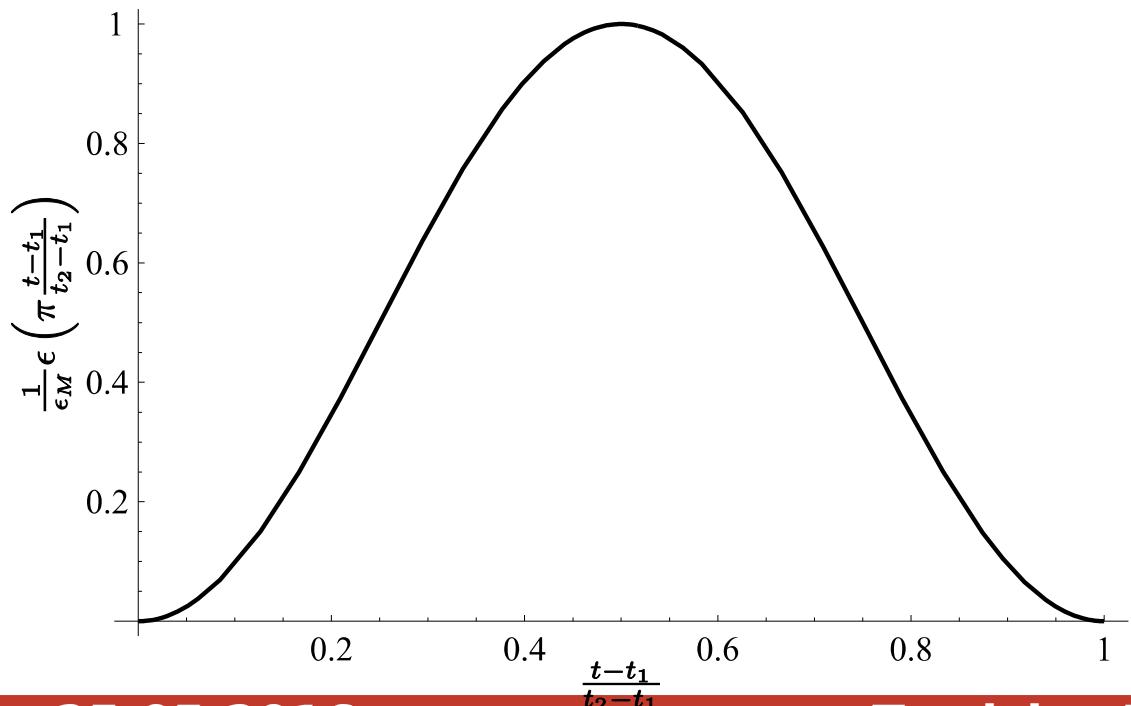
„Funkcija pojačanja“ $\varepsilon(t)$ i sile

- Magnetsko prespajanje povećava vanjski magnetski tok \rightarrow inducira $\Delta I(t)$
 \rightarrow opisano „funkcijom pojačanja“ $\varepsilon(t)$

$$\Delta\Phi_e = \Delta I L_e \quad I(\zeta, t) = I_0 \left[\frac{C_1}{l_T(\zeta)} + \varepsilon(t) \right]$$

$$\Delta I(t) = \varepsilon(t) I_0$$

$$\varepsilon(t) := \begin{cases} \epsilon_M \sin^2 \left(\pi \frac{t-t_1}{t_2-t_1} \right), & t_1 < t < t_2 \\ 0, & t \notin [t_1, t_2] \end{cases}$$



- Sačuvanje „namotaja“ silnica:

$$X(\zeta) = \frac{B_\varphi(r_T)}{B_{||}(r_T)} = X_0 \frac{C_2 R_T(\zeta)}{l_T(\zeta)}$$
- i omjera torusnih polumjera:

$$r_T(\zeta) = \eta R_T(\zeta)$$

\rightarrow opisuje magnetsku konfiguraciju i geometriju magnetskog užeta

- „Magnetske“ sile:
 - \downarrow sila tenzije:

$$f_t = -\frac{\mu_0 I^2}{2\pi R_T X^2}$$
 - \uparrow sila gradijenta mag. tlaka:

$$f_k = \frac{\mu_0 I^2}{4\pi R_T}$$
 - \uparrow „zrcalne struje“:

$$f_{zs} = \frac{\mu_0 I^2}{4\pi H}$$

Jednadžba gibanja magnetskog užeta

- ukupno ubrzanje vrha torusa je:

$$\frac{d^2 H(\zeta)}{dt^2} = \frac{\mu_0 I^2(\zeta, t)}{4\pi M} \left[\frac{l_T(\zeta)}{H(\zeta)} + \frac{l_T(\zeta)}{R_T(\zeta)} \left(1 - \frac{2}{X^2(\zeta)} \right) \right] + g(\zeta) + a_c(\zeta, t) + a_d(\dot{\zeta}, \zeta)$$

- gravitacijsko ubrzanje: $g(\zeta) = -\frac{g_0}{\left[1 + \frac{H(\zeta)}{r_\odot} \right]^2}$

- ubrzanje zbog vanjskog koroninog polja:

$$a_c(\zeta) = -C_3 \frac{I(\zeta, t)}{R_T(\zeta)}$$

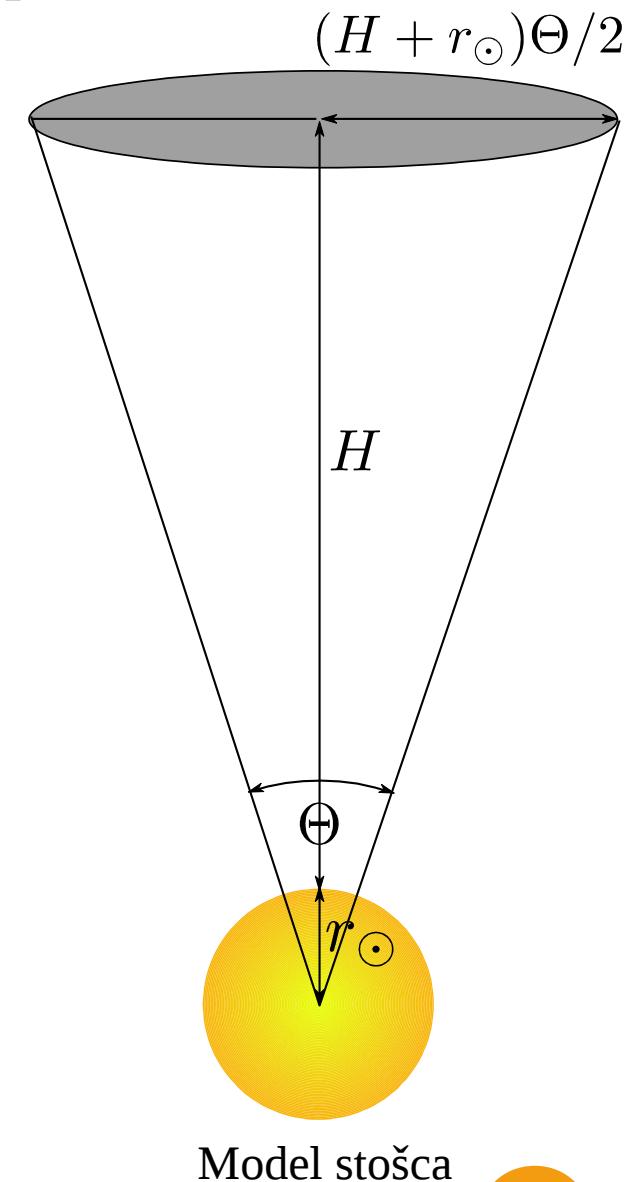
- doprinos ubrzanju zbog otpora Sunčevog vjetra

$$a_d(\dot{\zeta}, \zeta) = -\gamma(H(\zeta)) \left[\frac{dH(\zeta)}{d\zeta} \frac{d\zeta}{dt} - w(H(\zeta)) \right] \left| \frac{dH(\zeta)}{d\zeta} \frac{d\zeta}{dt} - w(H(\zeta)) \right|$$

- funkcija „otpora“: $\gamma \propto \frac{A\rho}{M}$

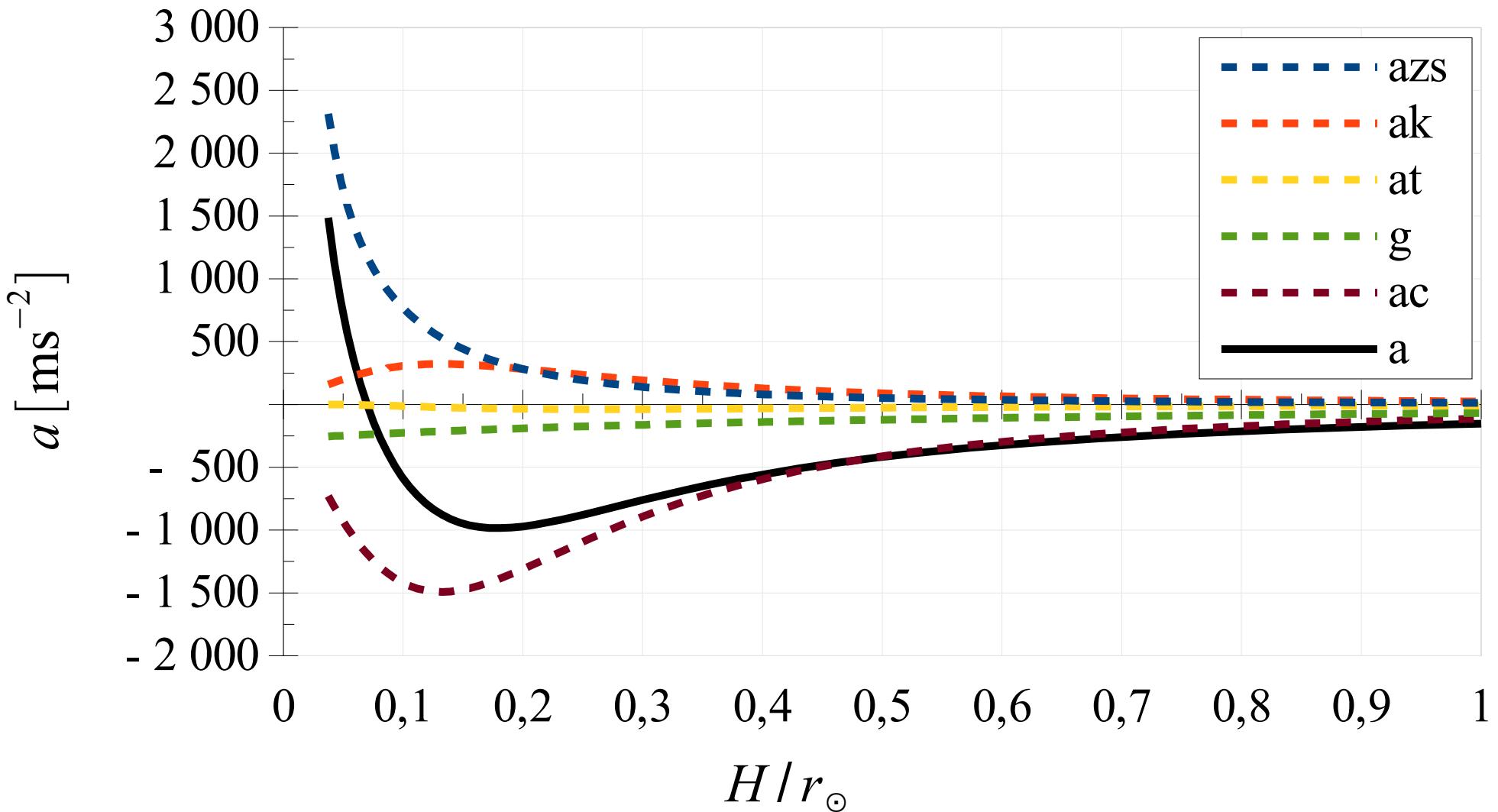
Primjena modela magnetskog užeta

- Različiti odabiri početne konfiguracije određuju četiri različite kinematike magnetskog užeta:
 - titranje oko ravnotežnog položaja
 - spora evolucija sistema kroz niz kvazi-stacionarnih stanja
 - gubitak ravnoteže
 - gubitak ravnoteže potaknut rekonekcijom
- modelom su opisani sljedeći izbačaji:
 - neuspjeli – sistem se relaksira i prigušeno titra
 - spori – preuzima ih Sunčev vjetar
 - postupni – $a < 100 \text{ m/s}^2$ tijekom vremena od 3-5 sati
 - tipični – $v \sim 1000 \text{ km/s}$; $a < 1000 \text{ m/s}^2$ tijekom 20-30 minuta
 - impulzivni – $v \sim 1000\text{-}10000 \text{ km/s}$; $a < 10000 \text{ m/s}^2$ tijekom 10 minuta



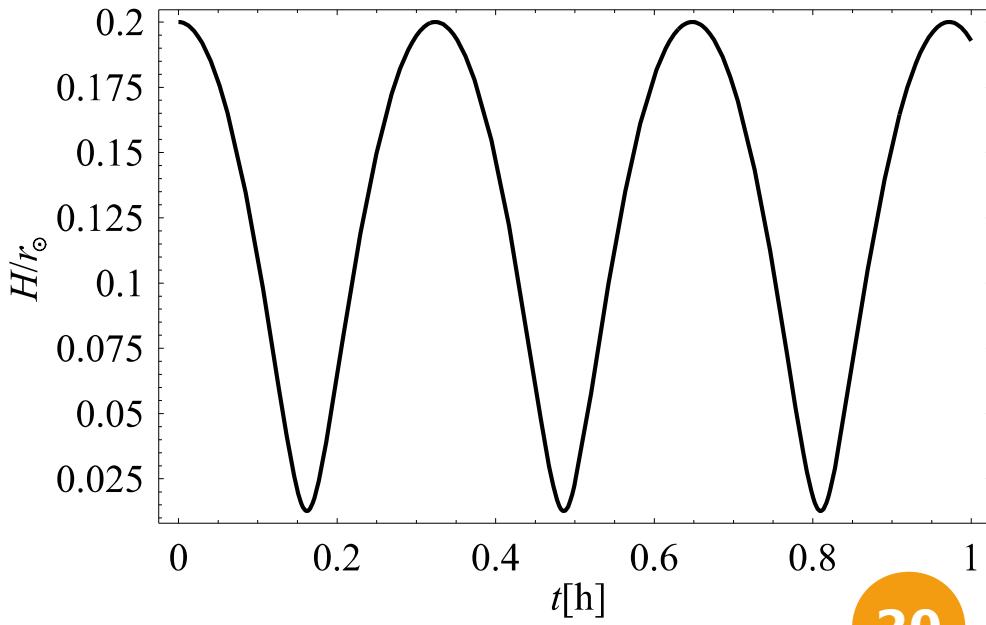
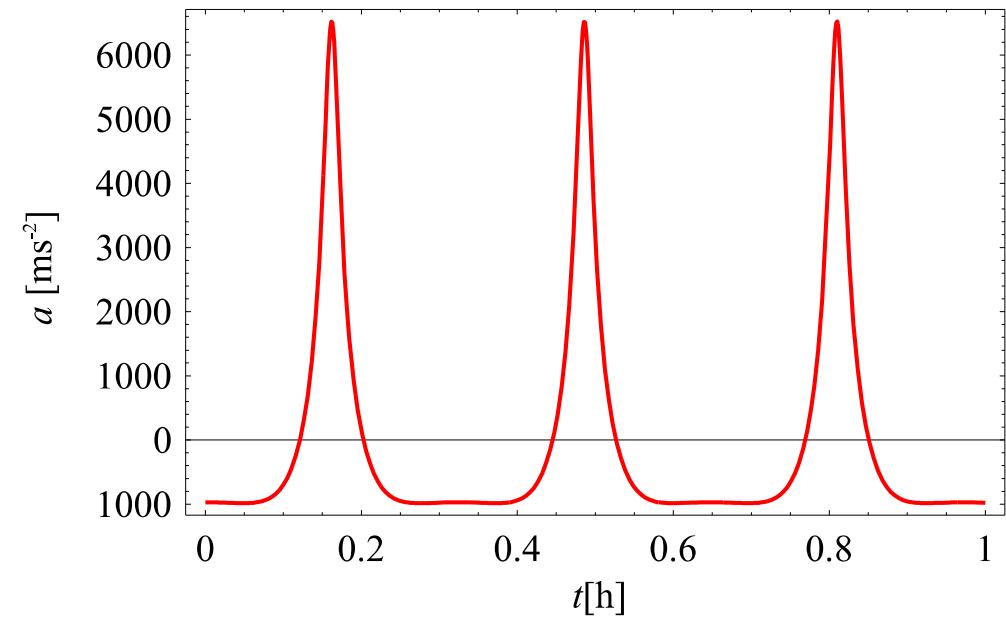
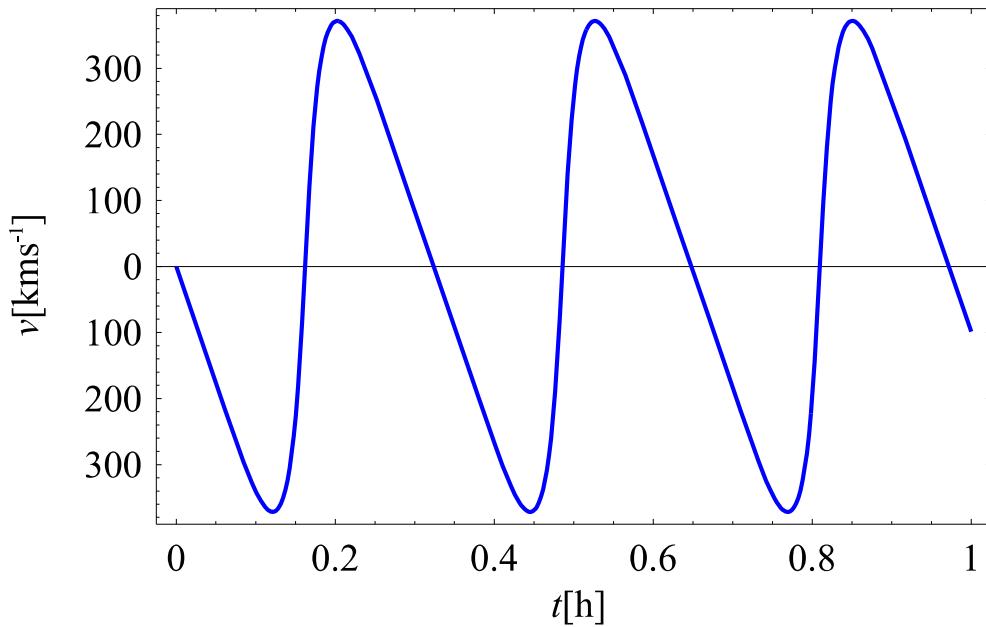
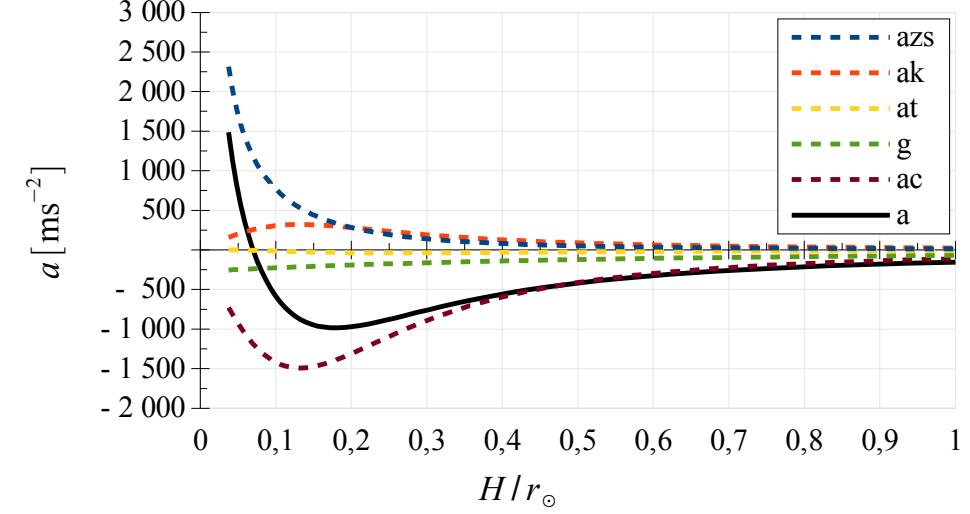
(a) Titranje oko ravnotežnog položaja

$$S=0.2 r_{\odot}; M=1 \times 10^{12} \text{ kg}; \zeta_0=0; \eta=0.1; I_0=3 \times 10^{10} \text{ A}; X_0=4; B_{c0}=1 \times 10^{-4} \text{ T}$$



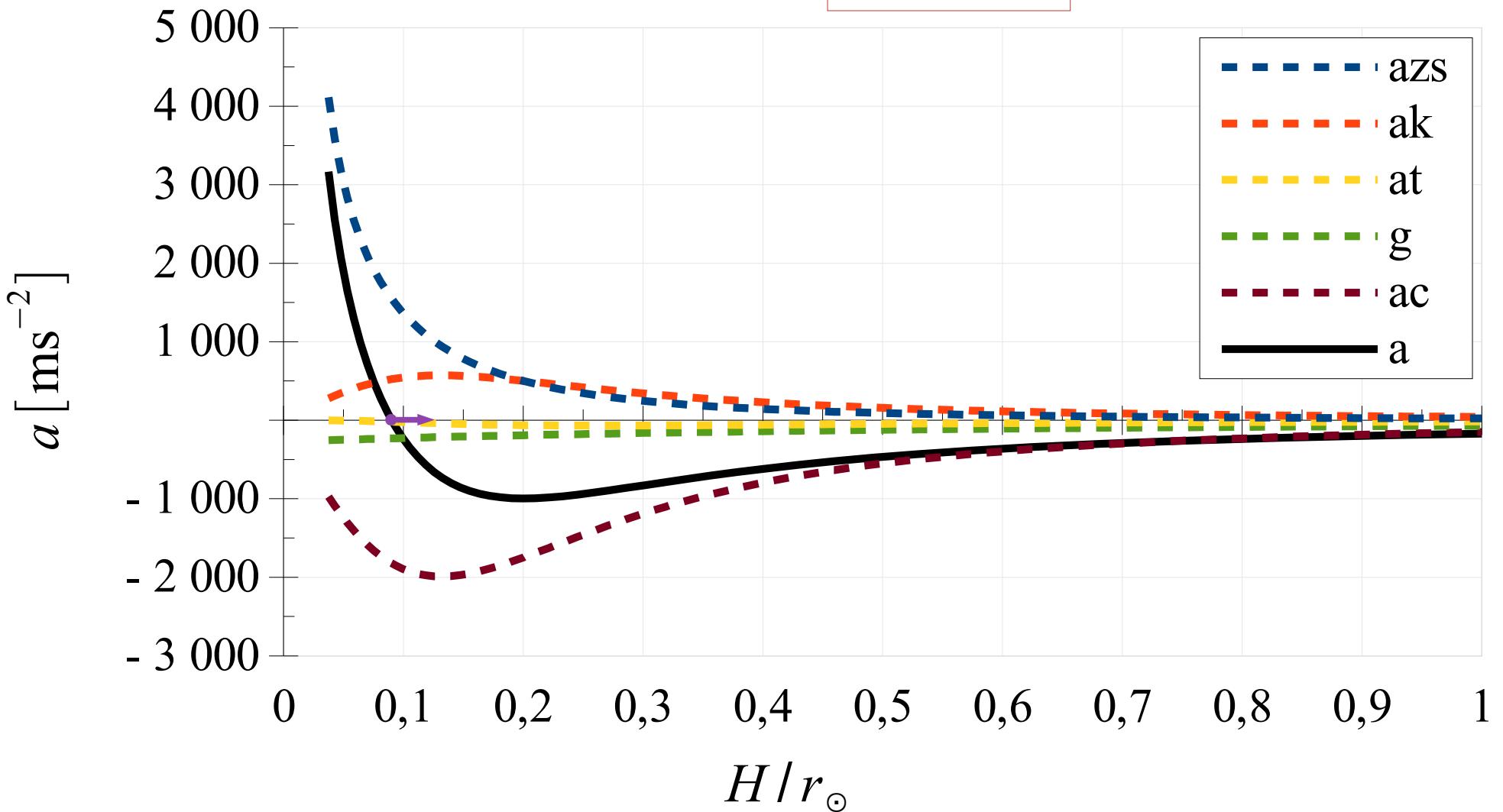
Kinematicke krivulje titranja (a)

$$S=0.2 r_{\odot}; M=1 \times 10^{12} \text{ kg}; \zeta_0=0; \eta=0.1; I_0=3 \times 10^{10} \text{ A}; X_0=4; B_{c0}=1 \times 10^{-4} \text{ T}$$



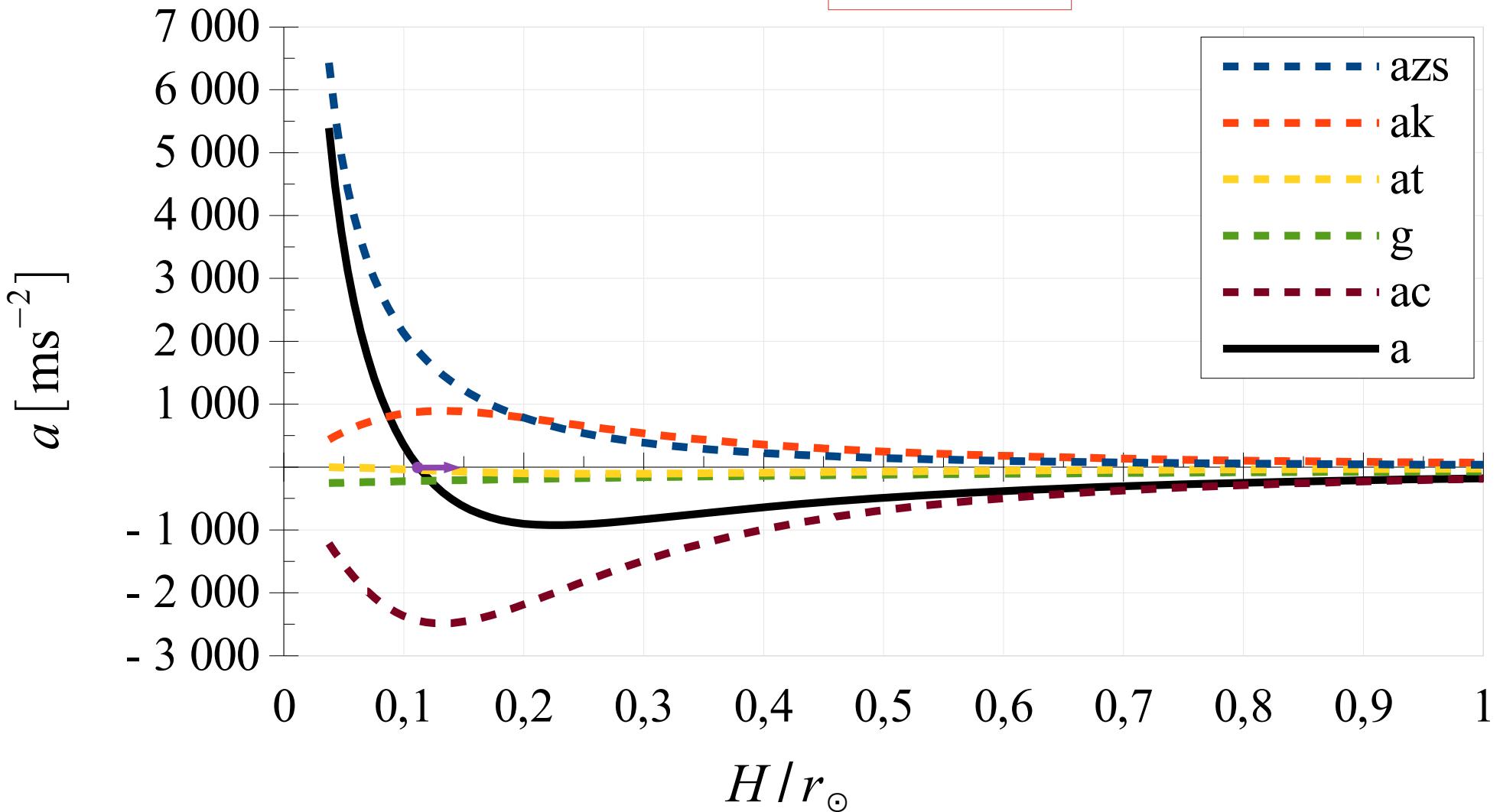
(b) Evolucija sistema kroz niz kvazi-stacionarnih stanja

$$S=0.2 r_{\odot}; M=1 \times 10^{12} \text{ kg}; \zeta_0=0; \eta=0.1; I_0=4 \times 10^{10} \text{ A}; X_0=4; B_{c0}=1 \times 10^{-4} \text{ T}$$



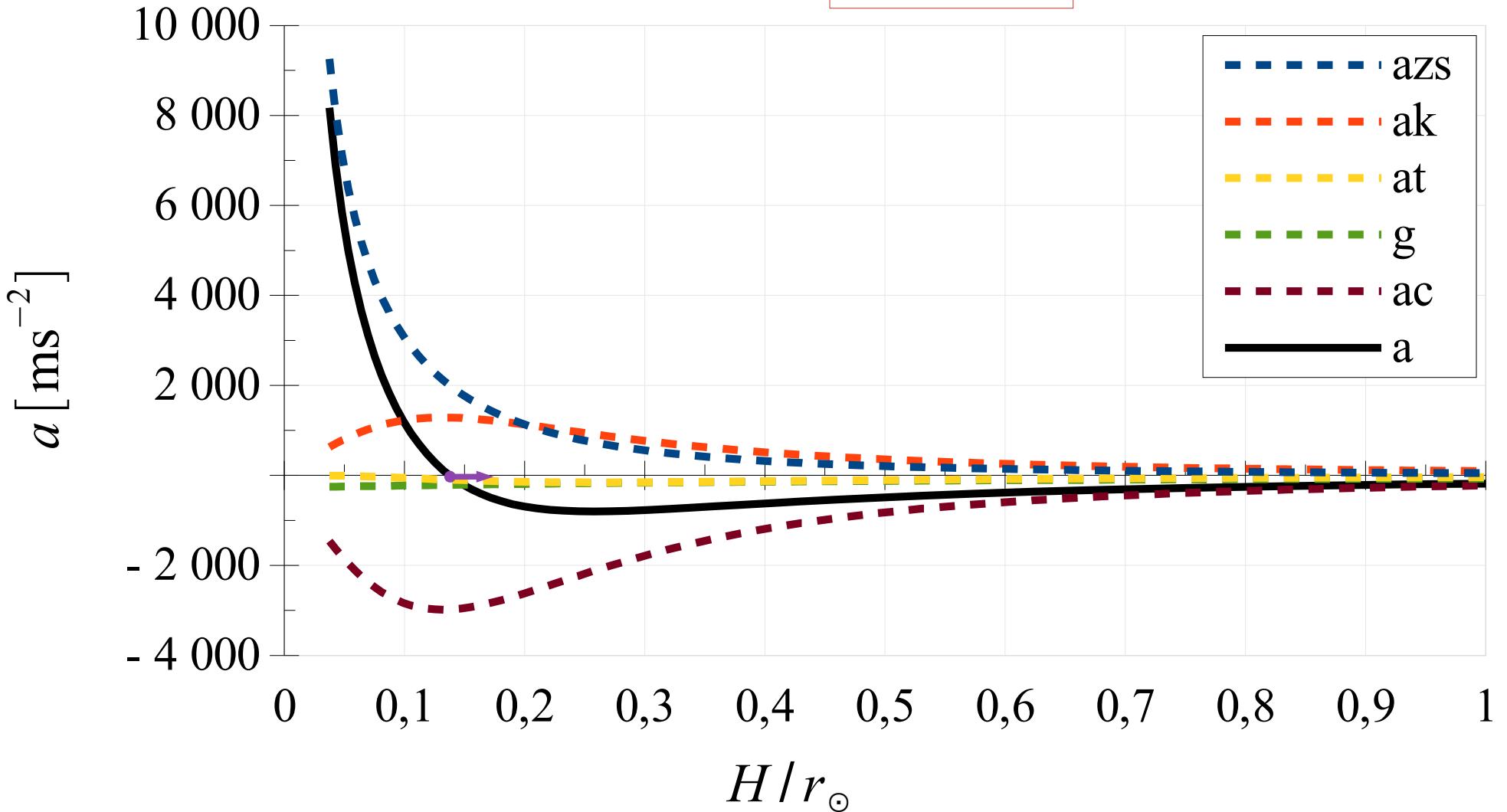
(c) Evolucija sistema kroz niz kvazi-stacionarnih stanja

$$S = 0.2 r_{\odot}; M = 1 \times 10^{12} \text{ kg}; \zeta_0 = 0; \eta = 0.1; I_0 = 5 \times 10^{10} \text{ A}; X_0 = 4; B_{c0} = 1 \times 10^{-4} \text{ T}$$



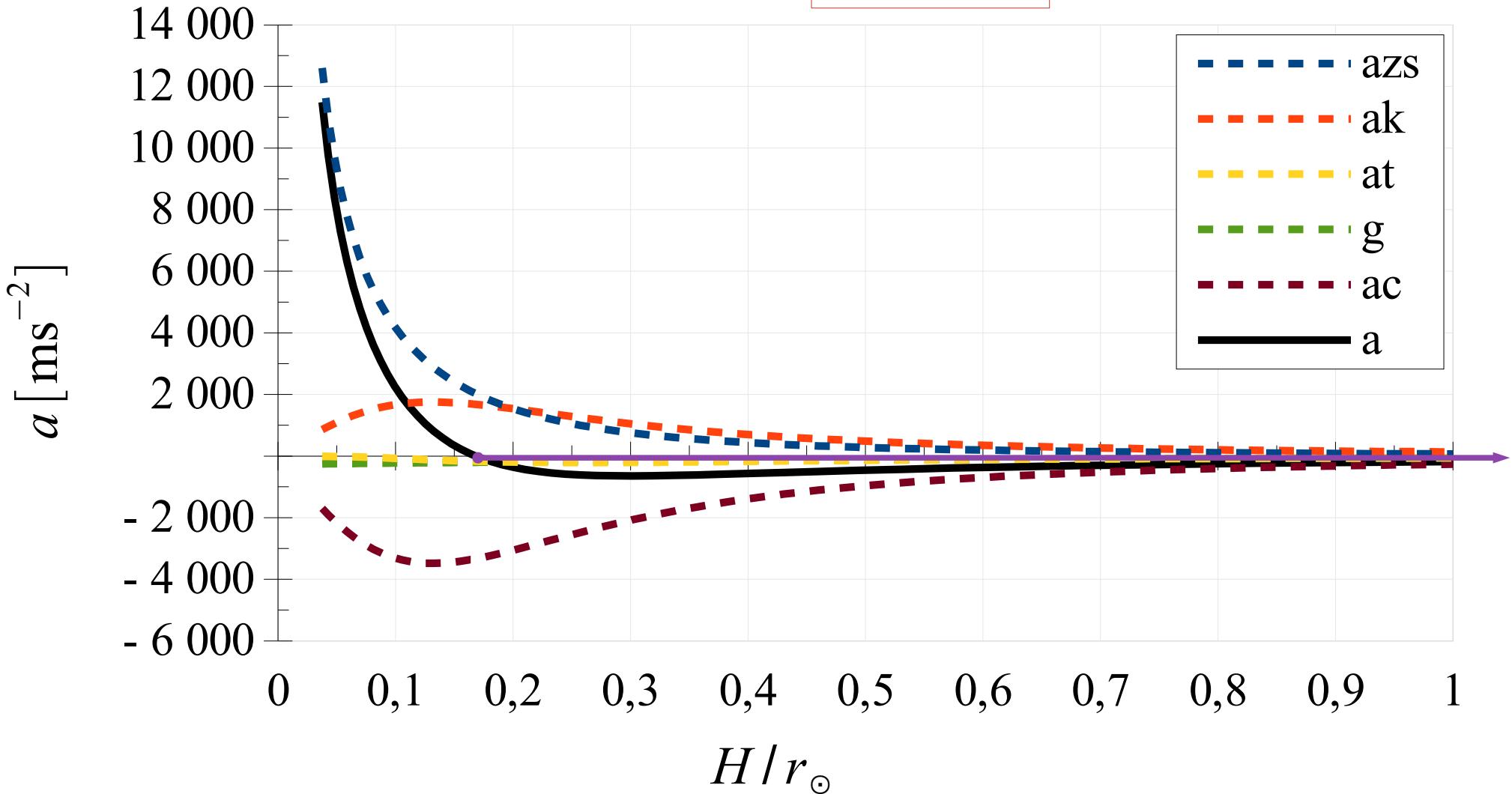
(d) Evolucija sistema kroz niz kvazi-stacionarnih stanja

$$S = 0.2 r_{\odot}; M = 1 \times 10^{12} \text{ kg}; \zeta_0 = 0; \eta = 0.1; I_0 = 6 \times 10^{10} \text{ A}; X_0 = 4; B_{c0} = 1 \times 10^{-4} \text{ T}$$



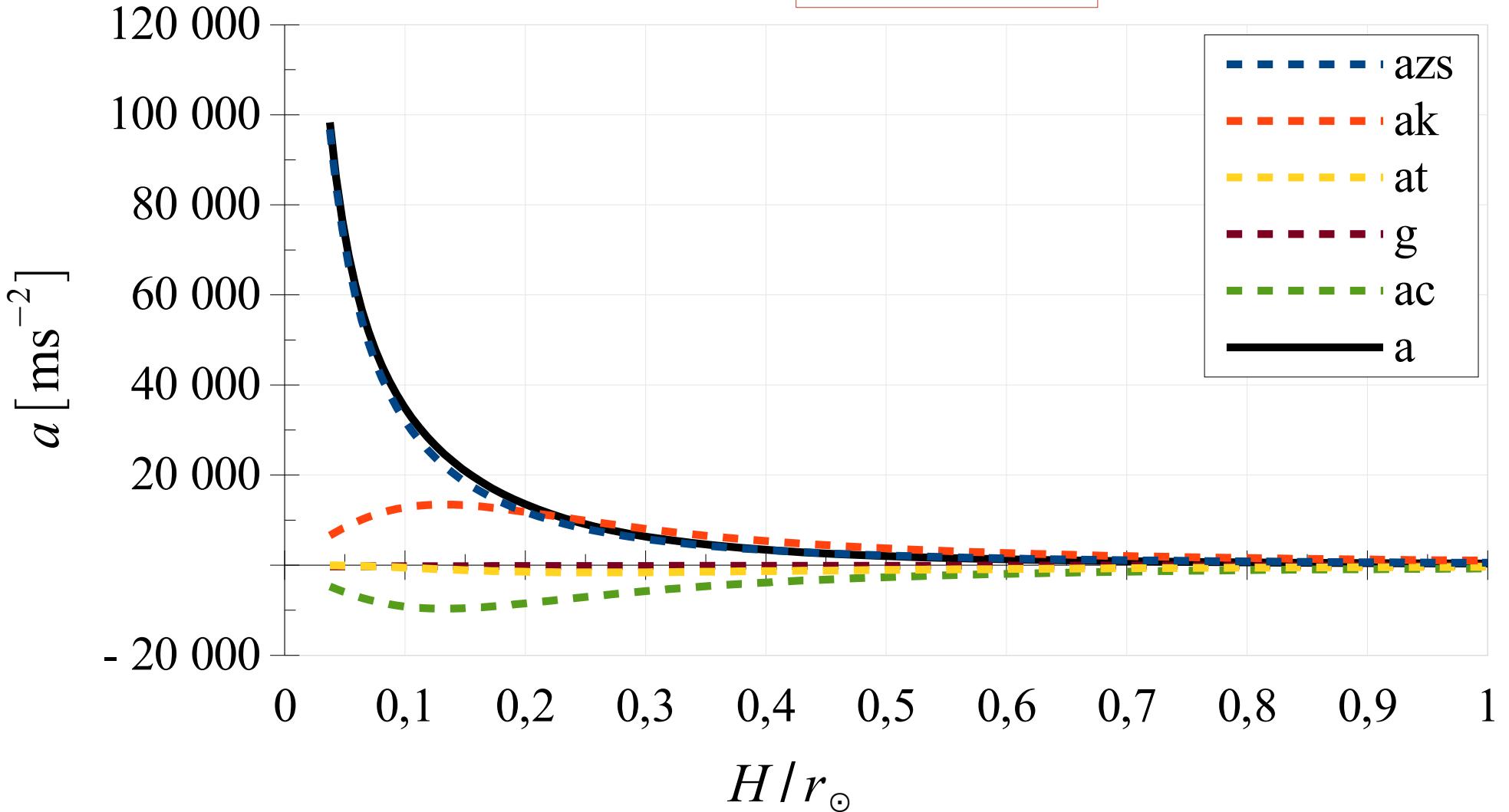
(e) Evolucija sistema kroz niz kvazi-stacionarnih stanja

$$S = 0.2 r_{\odot}; M = 1 \times 10^{12} \text{ kg}; \zeta_0 = 0; \eta = 0.1; I_0 = 7 \times 10^{10} \text{ A}; X_0 = 4; B_{c0} = 1 \times 10^{-4} \text{ T}$$

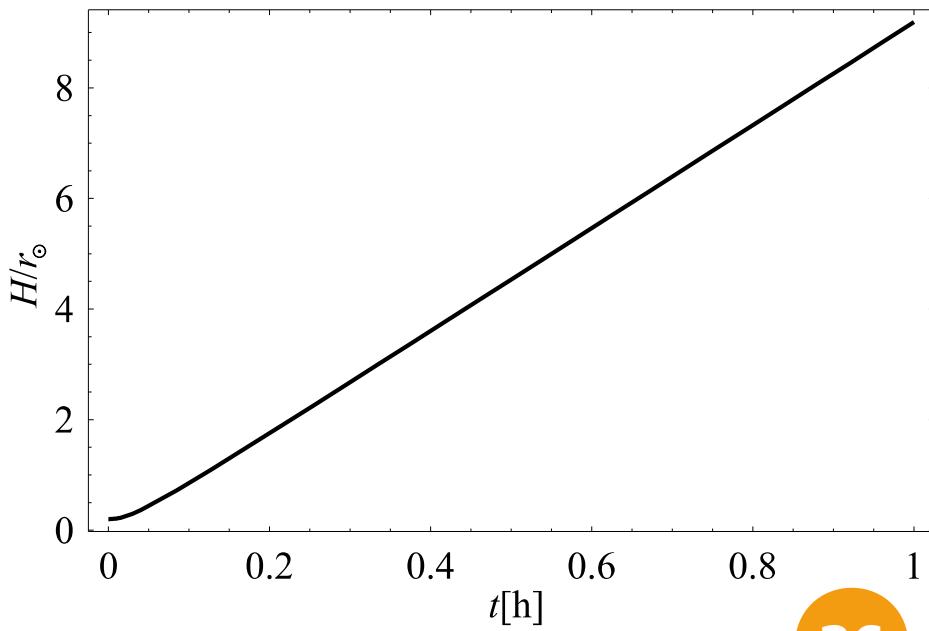
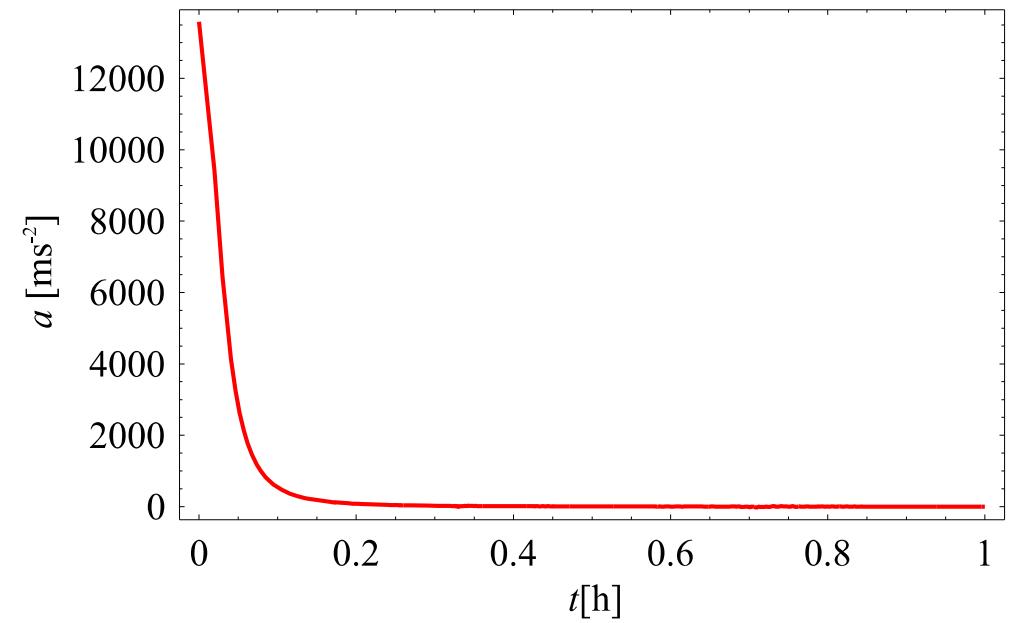
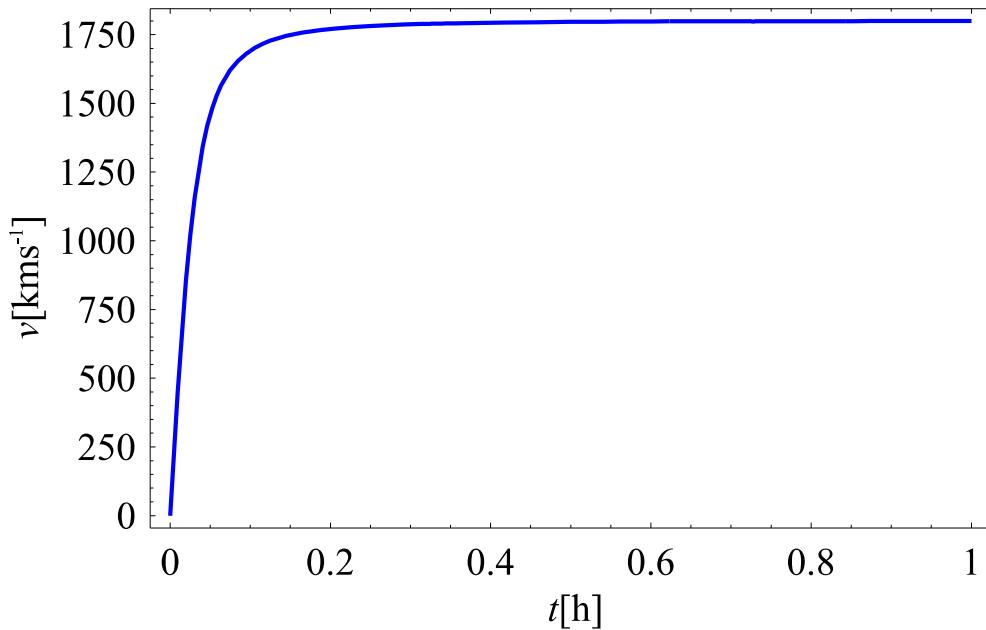
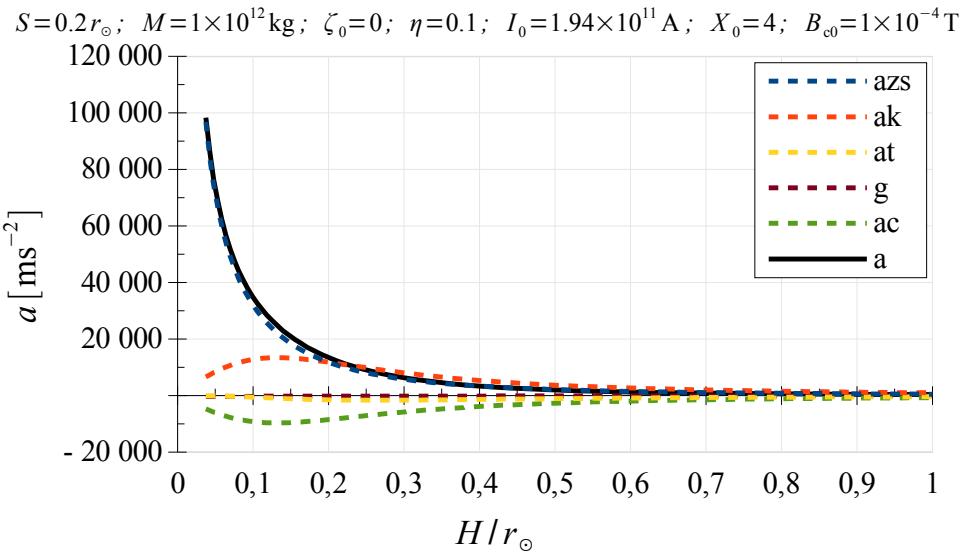


(f) Gubitak ravnoteže na kritičnoj vrijednosti I_0

$$S = 0.2 r_\odot; \quad M = 1 \times 10^{12} \text{ kg}; \quad \zeta_0 = 0; \quad \eta = 0.1; \quad I_0 = 1.94 \times 10^{11} \text{ A}; \quad X_0 = 4; \quad B_{c0} = 1 \times 10^{-4} \text{ T}$$

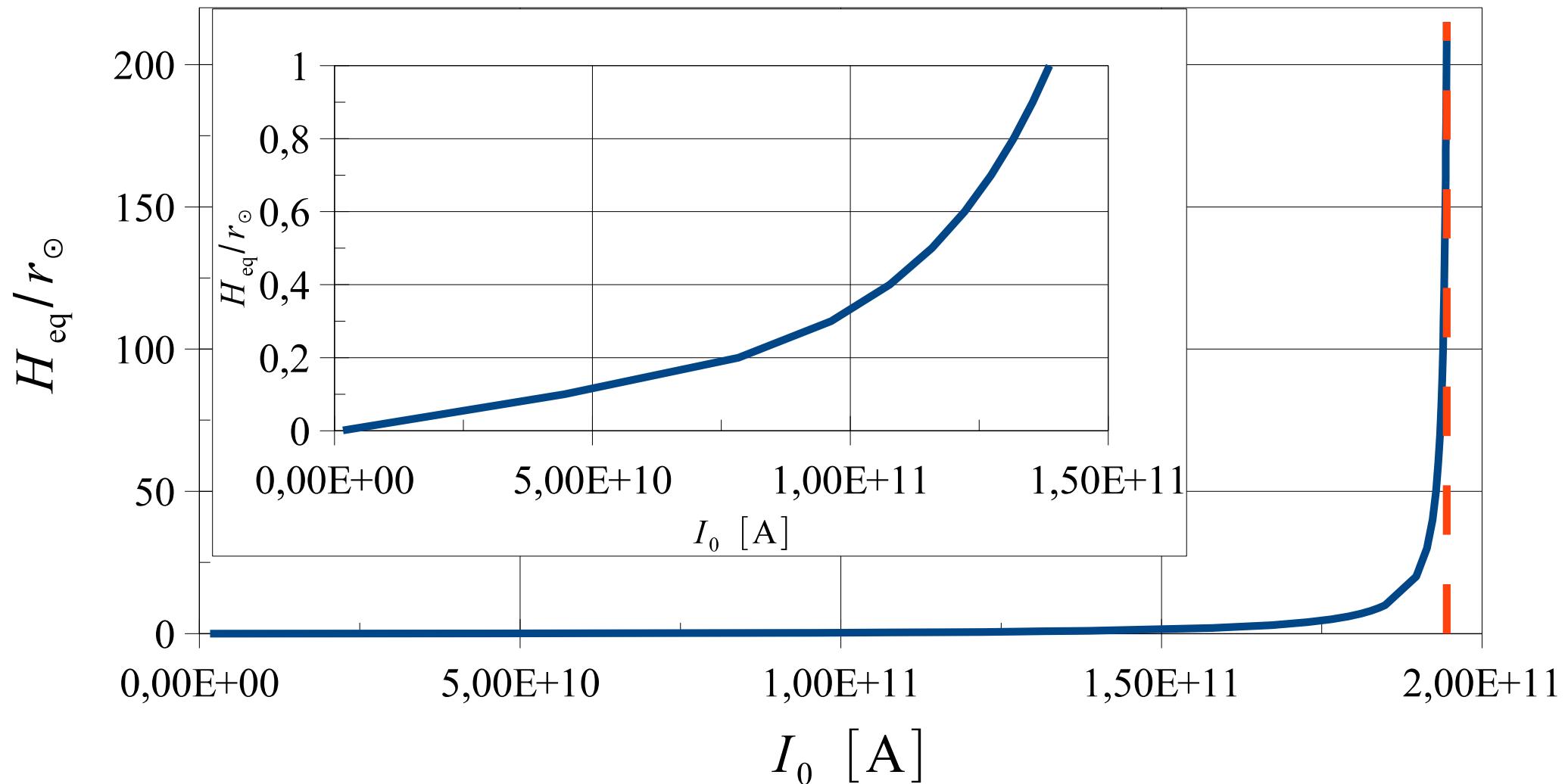


Kinematicke krivulje gubitka ravnoteze (f)

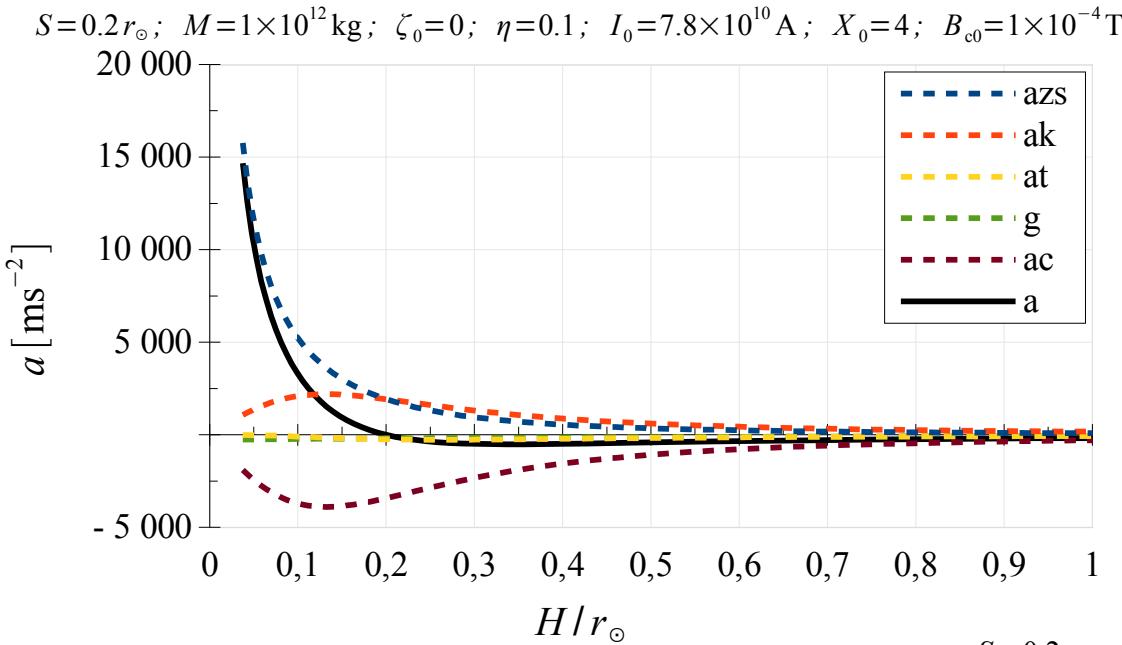


Pomak kvazi-stacionarnih stanja s povećanjem struje I_0

$$S = 0.2 r_\odot; \quad M = 1 \times 10^{12} \text{ kg}; \quad \zeta_0 = 0; \quad \eta = 0.1; \quad X_0 = 4; \quad B_{c0} = 1 \times 10^{-4} \text{ T}$$

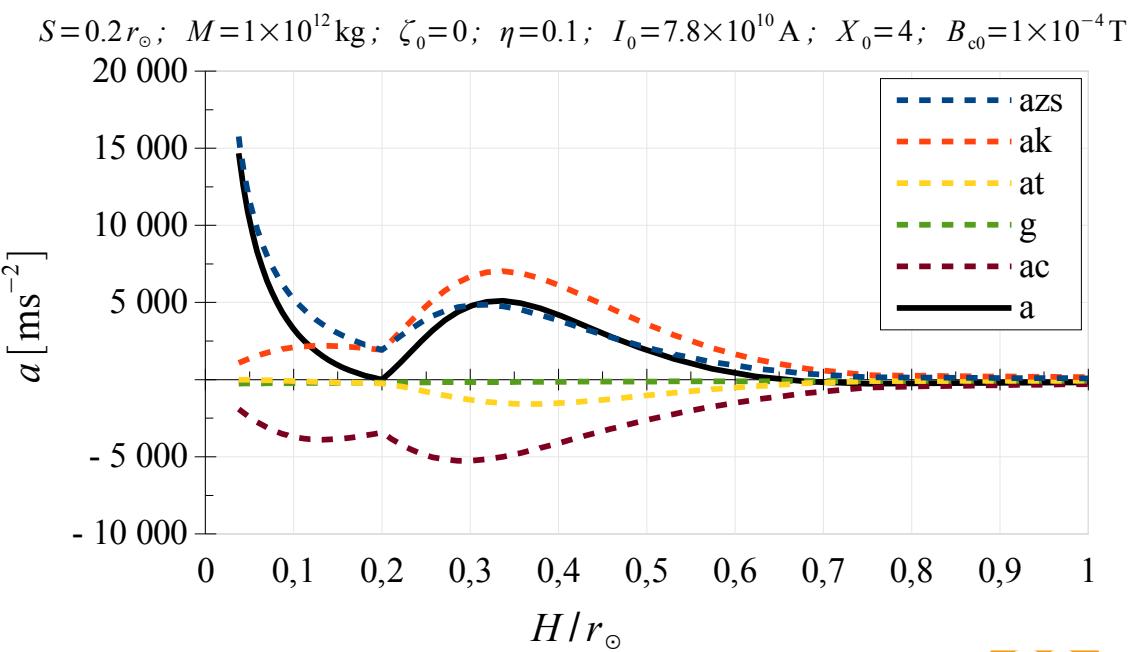


Ravnotežno stanje i početak rekonekcije

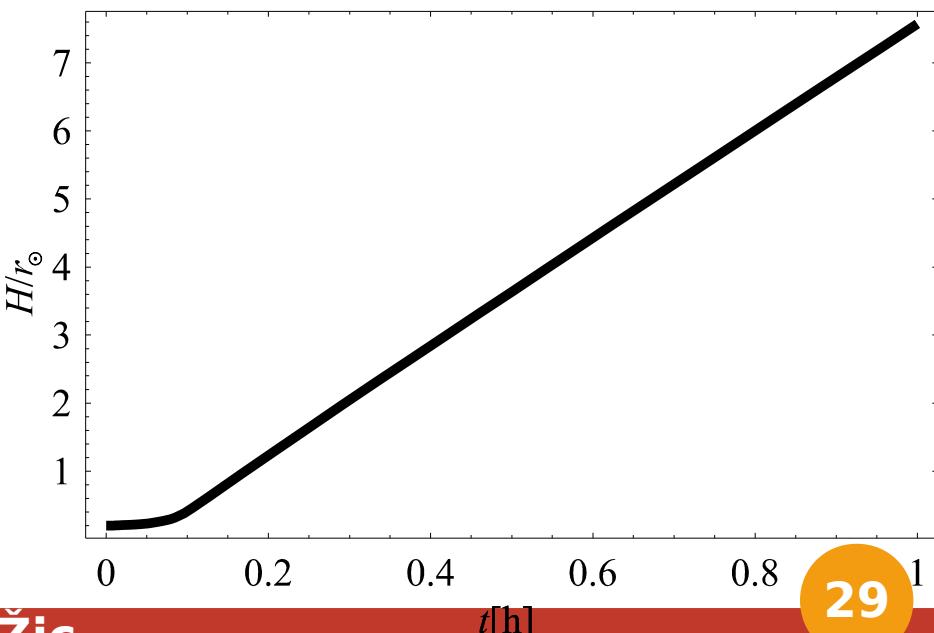
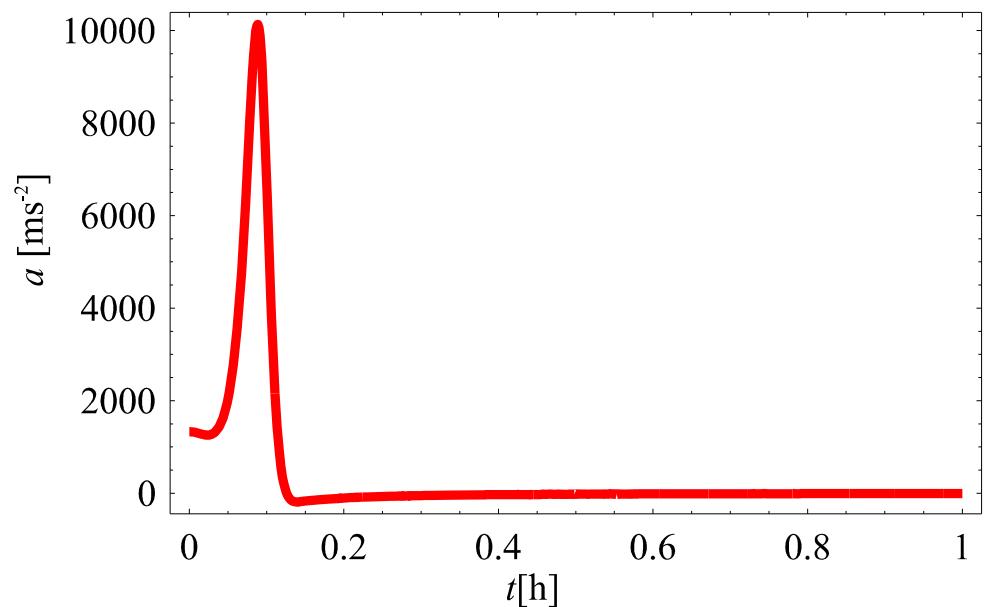
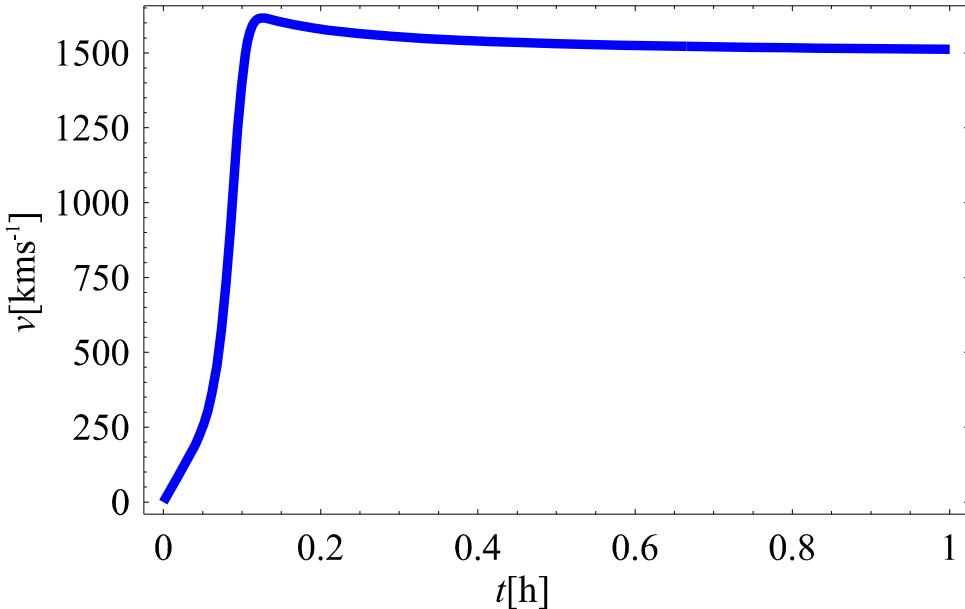
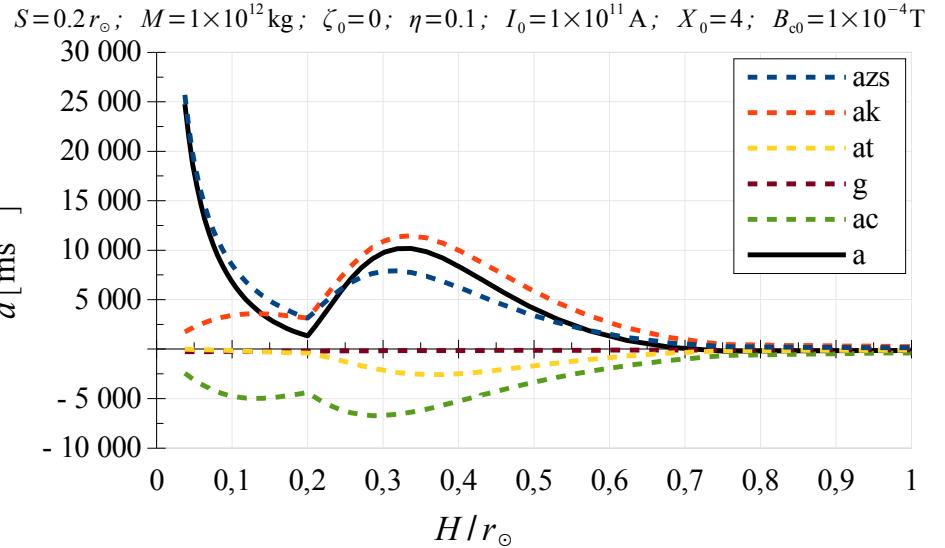


- struja I_0 kontinuirano raste
- sistem polagano prolazi kroz kvazi-stacionarna stanja
→ doseže kvazi-ravnotežno stanje na $H_{\text{eq}}/r_\odot = 0.2$

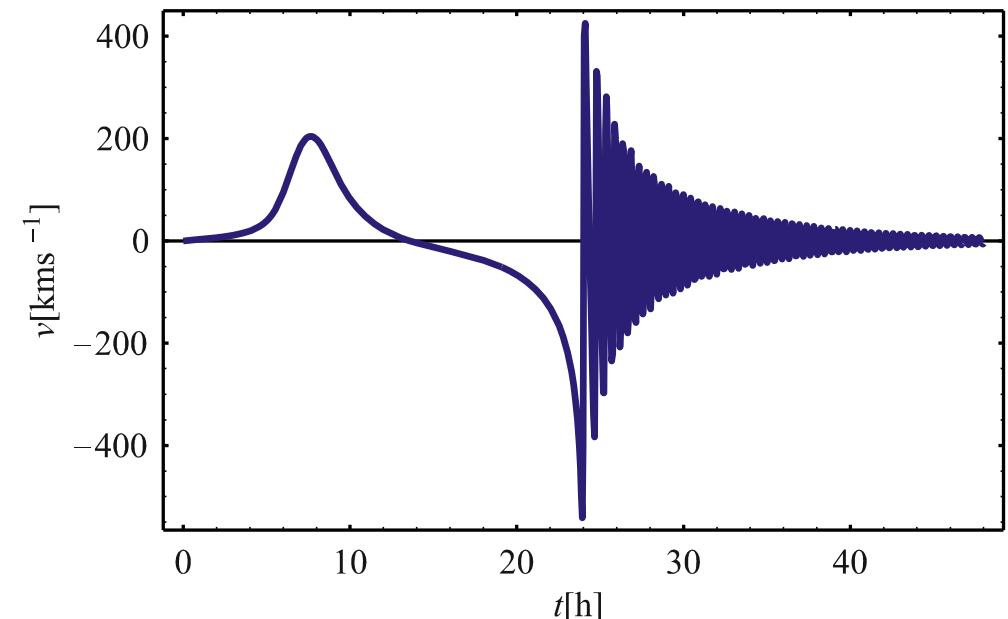
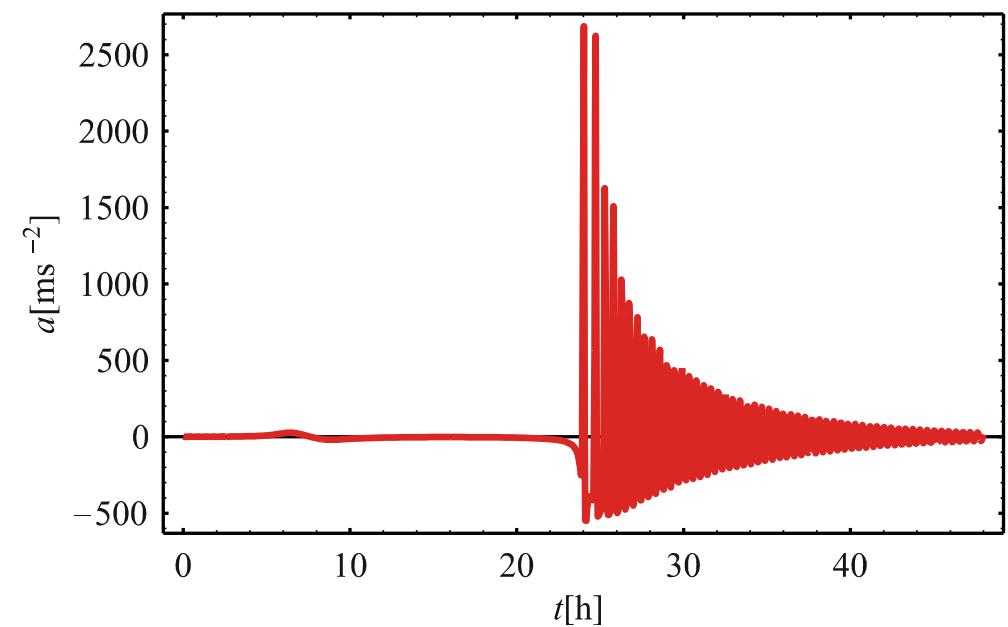
- u tom trenutku započinje rekonekcija: $0.2 < H_{\text{eq}}/r_\odot < 0.75$
- inducira se dodatna struja, ΔI
- daljnjim malim povećanjem I_0
→ potpun gubitak ravnoteže
- sistem eruptira



Potpun gubitak ravnoteže rekonekcijom

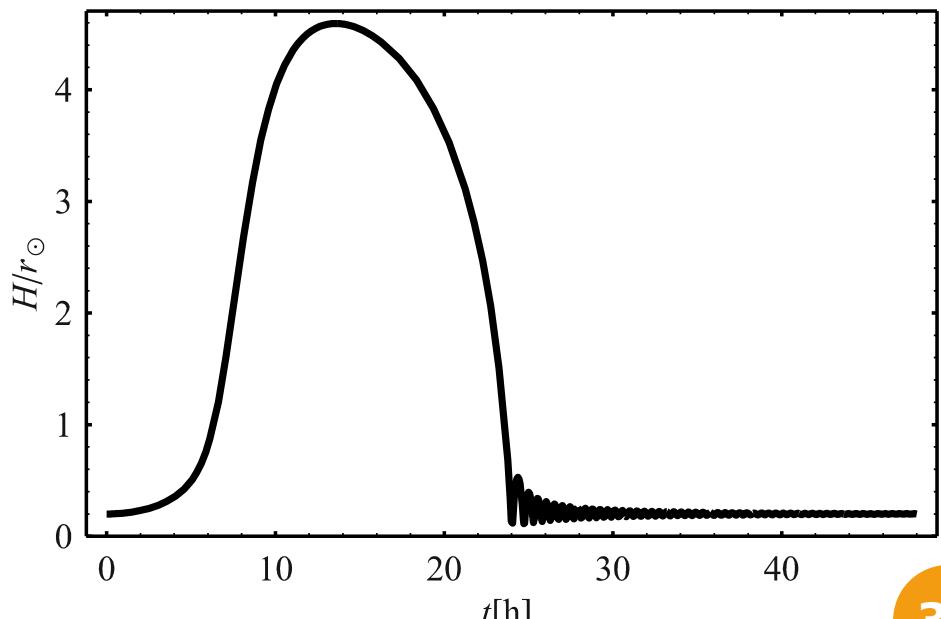


„Neuspjeli“ izbačaj

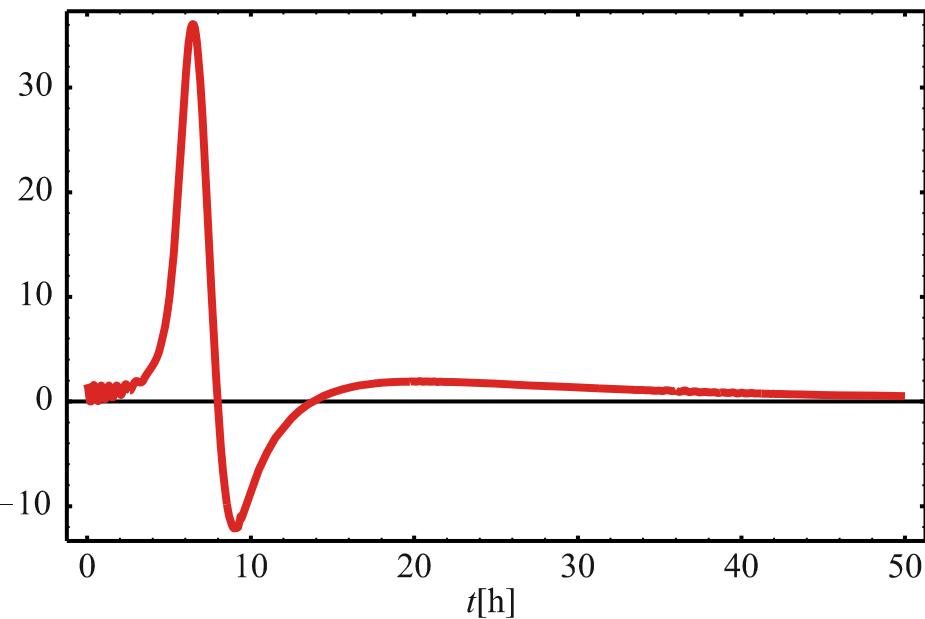


$S = 0.2 r_\odot$; $M = 1 \times 10^{12} \text{ kg}$; $\zeta_0 = 0$; $\eta = 0.1$;
 $I_0 = 7.8 \times 10^{10} \text{ A}$; $X_0 = 4$; $B_{c0} = 1 \times 10^{-4} \text{ T}$;
 $w_\infty = 400 \text{ km/s}$; $\Gamma = 1$

- rekonekcija nije dovoljno izdašna ili dugotrajna:
 ΔI : $0 < t < 10 \text{ h}$, $\varepsilon_M = 0.2212$
- otpor u niskoj koroni naglo zakoči izbačaj
- pada prema ravnotežnom položaju i zatitra

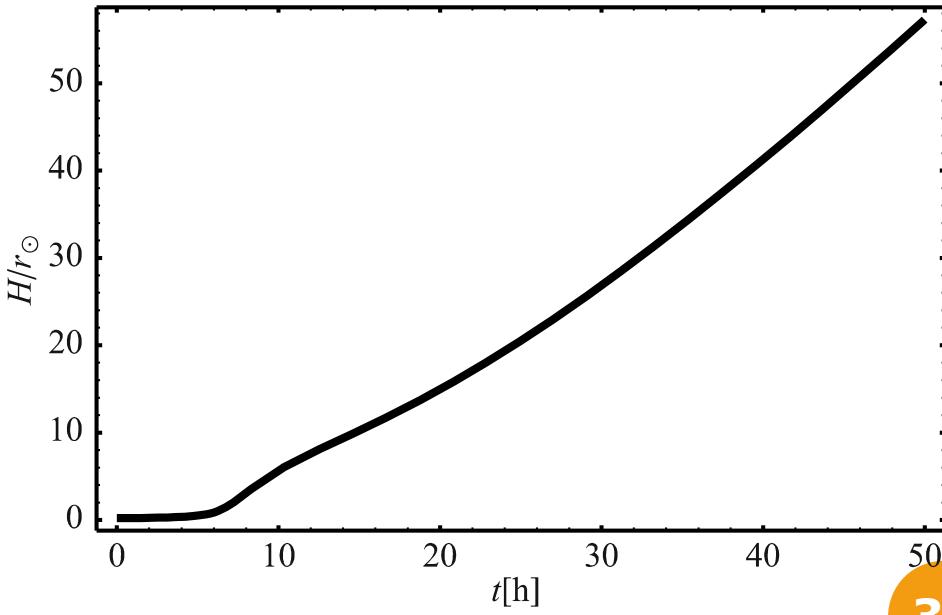
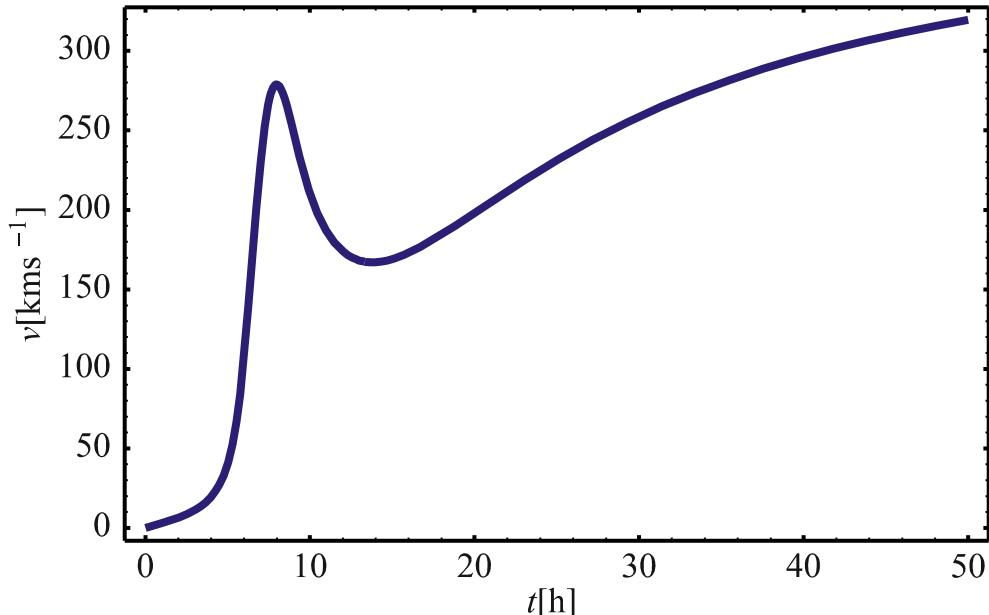


Spori izbačaj

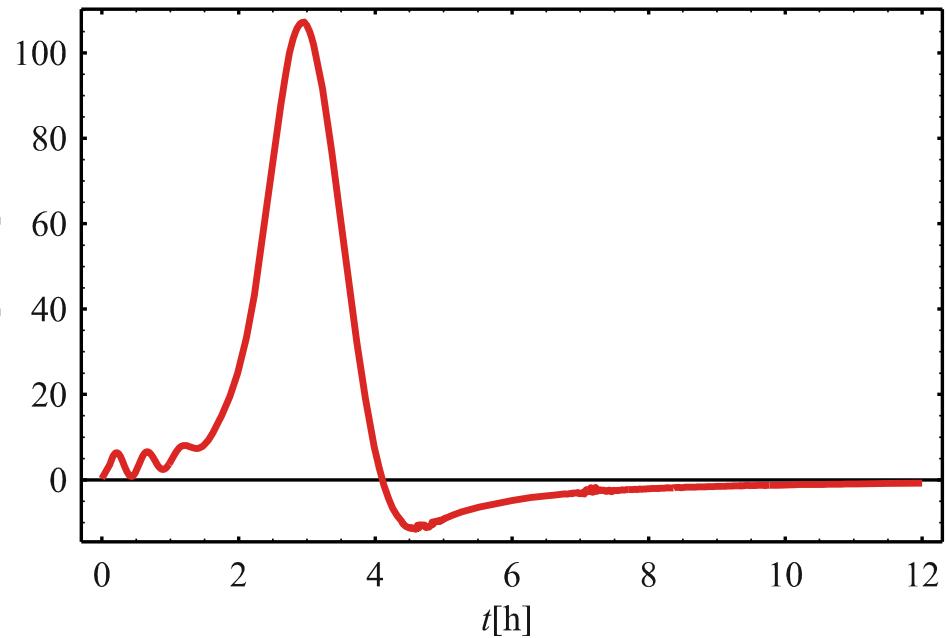


$$S = 0.2 r_{\odot}; M = 1 \times 10^{12} \text{ kg}; \zeta_0 = 0; \eta = 0.1; \\ I_0 = 7.8 \times 10^{10} \text{ A}; X_0 = 4; B_{c0} = 1 \times 10^{-4} \text{ T}; \\ w_{\infty} = 400 \text{ km/s}; \Gamma = 1$$

- rekonekcijski tok se neznatno poveća:
 $\Delta I: 0 < t < 10 \text{ h}, \varepsilon_M = \mathbf{0.23}$
- Sunčev vjetar odnosi izbačaj
- poprima brzinu Sunčevog vjetra

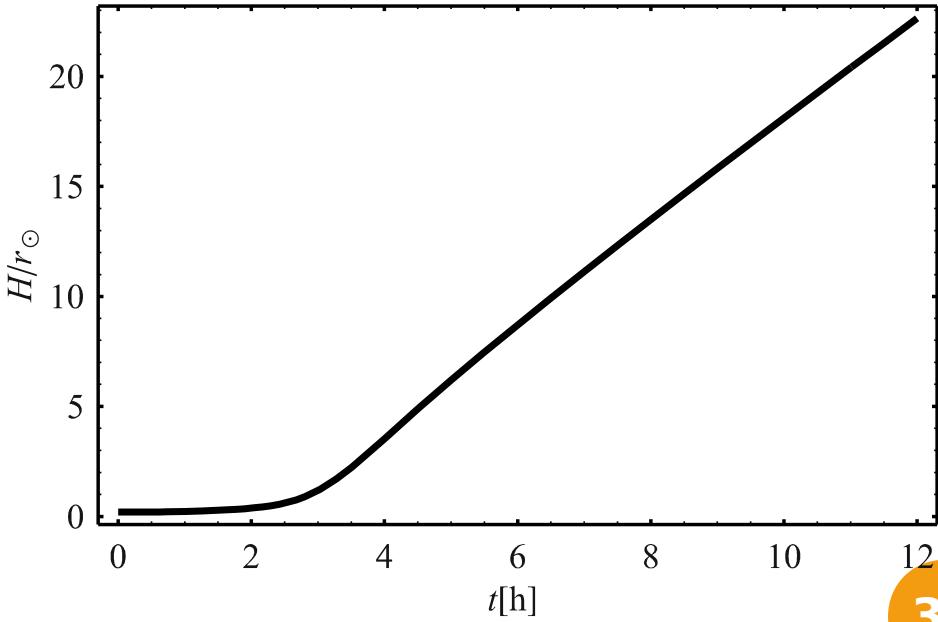
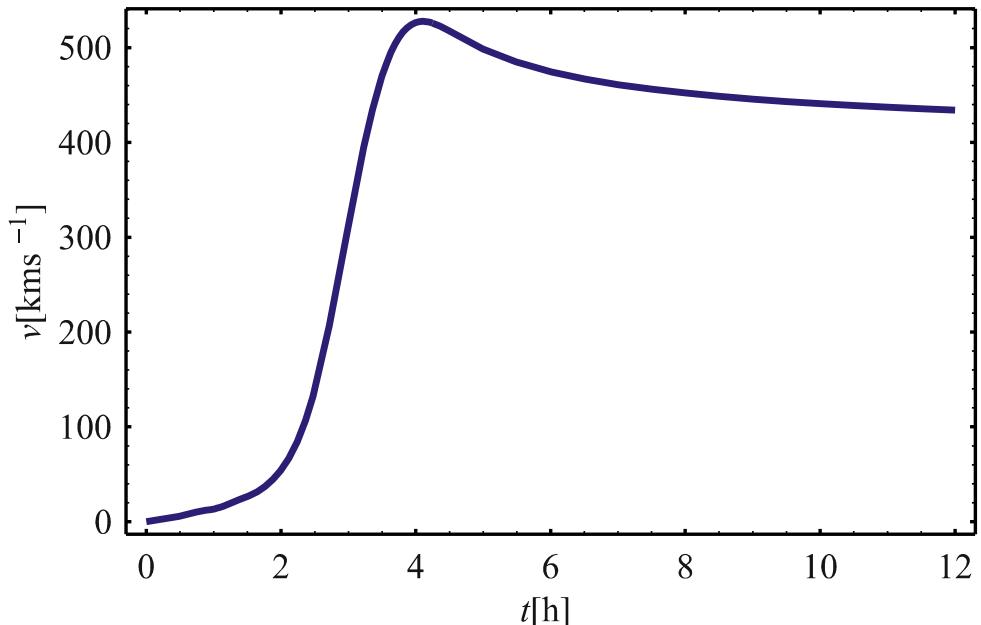


Postupan izbačaj

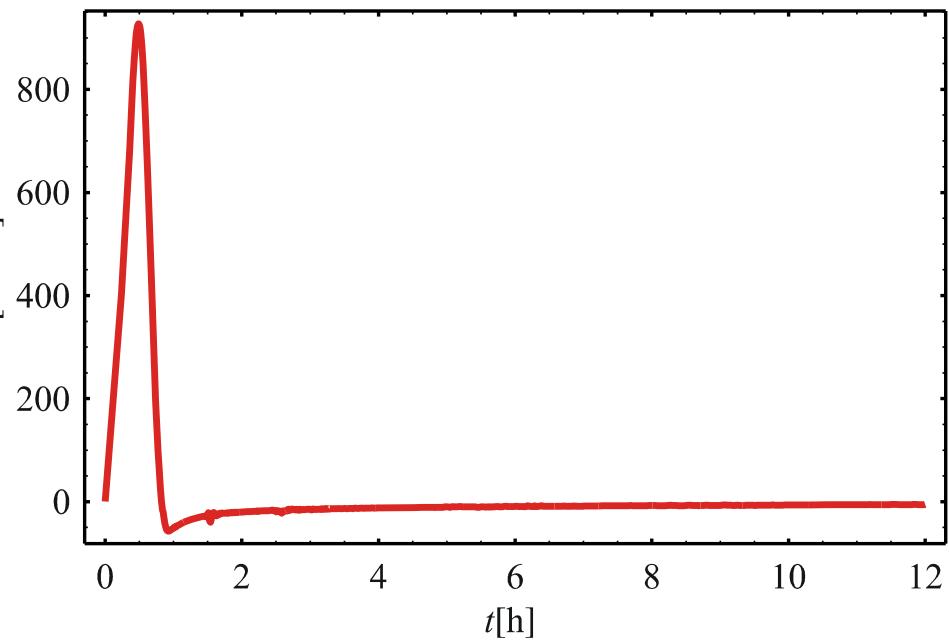


$$S = 0.2 r_{\odot}; M = 1 \times 10^{12} \text{ kg}; \zeta_0 = 0; \eta = 0.1; \\ I_0 = 7.8 \times 10^{10} \text{ A}; X_0 = 4; B_{c0} = 1 \times 10^{-4} \text{ T}; \\ w_{\infty} = 400 \text{ km/s}; \Gamma = 0.2$$

- $\Delta I: 0 < t < 5 \text{ h}, \varepsilon_M = 0.24$
- ubrzava se tijekom dužeg vremenskog perioda
- polagano se uzdiže → tok raste → eruptira → vjetar odnosi

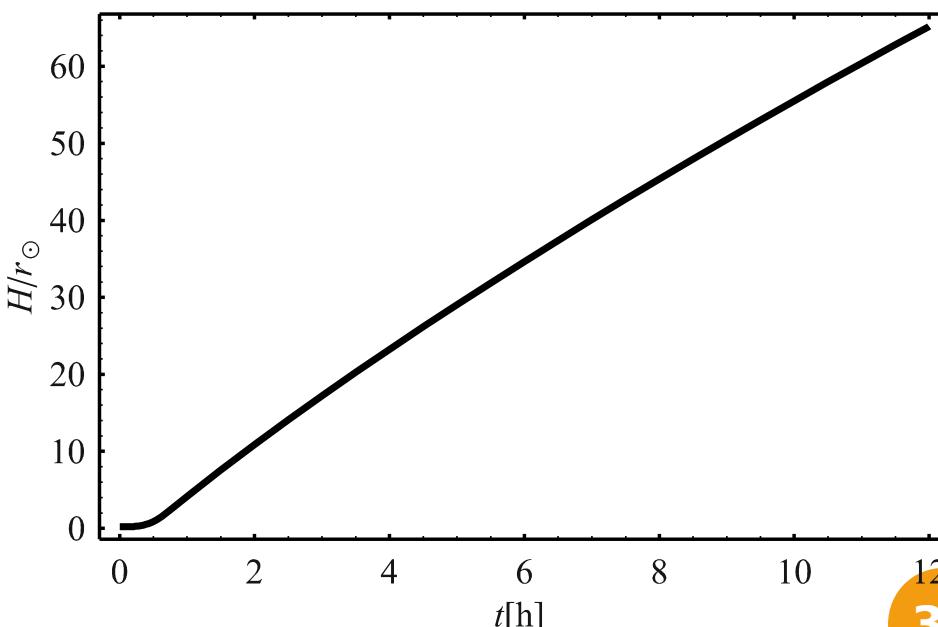
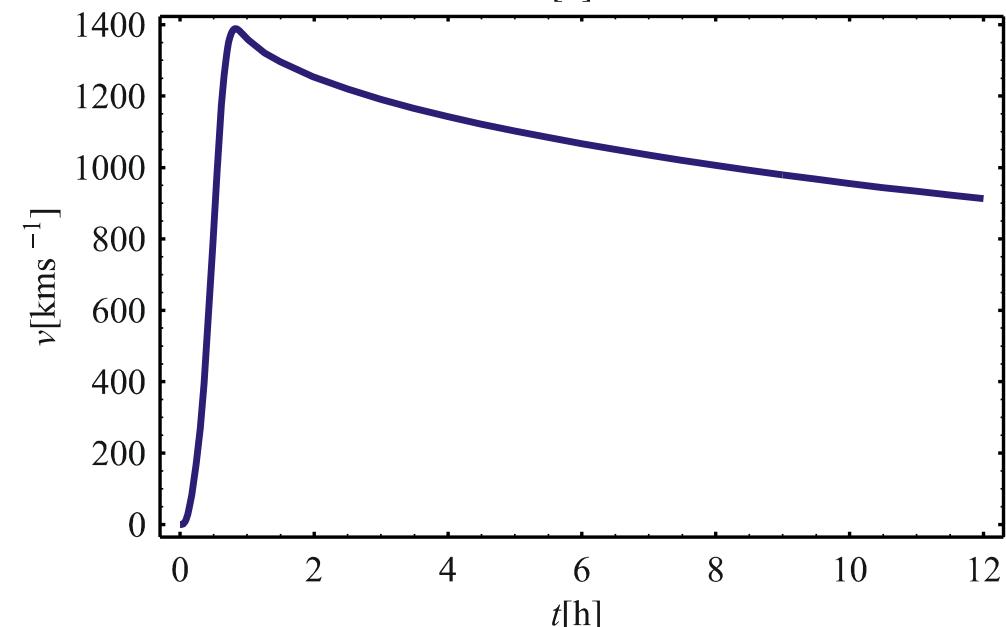


Tipičan izbačaj

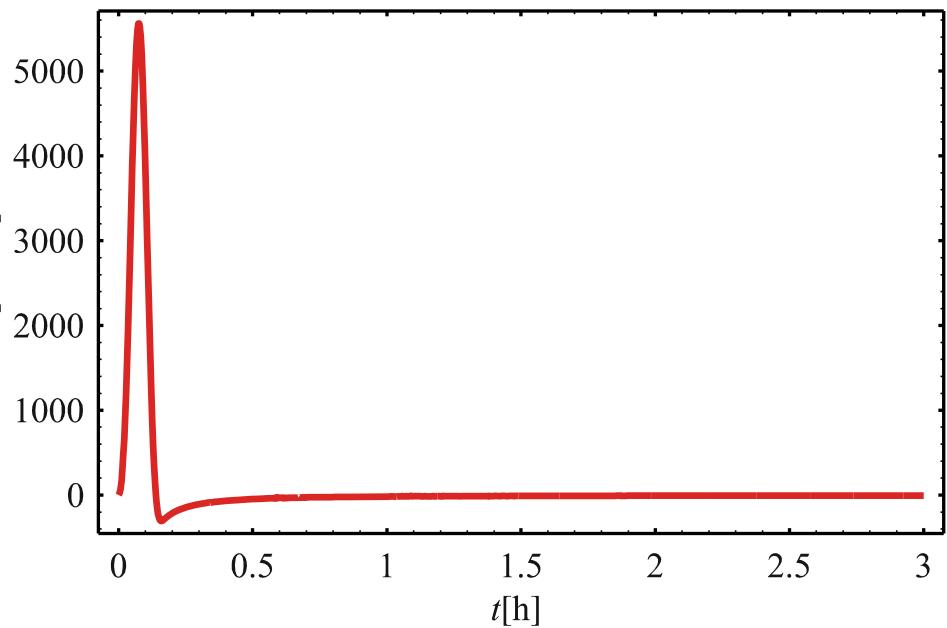


$$S = 0.2 r_{\odot}; M = 1 \times 10^{12} \text{ kg}; \zeta_0 = 0; \eta = 0.1; \\ I_0 = 7.8 \times 10^{10} \text{ A}; X_0 = 4; B_{c0} = 1 \times 10^{-4} \text{ T}; \\ w_{\infty} = 400 \text{ km/s}; \Gamma = 0.2$$

- $\Delta I: 0 < t < 1 \text{ h}, \varepsilon_M = 0.5$
- kraći i jači magnetski pritok \rightarrow intenzivnije ubrzavanje
- postiže brzinu $\sim 1300 \text{ km/s} \rightarrow$ kasnije: vjetar ga koči

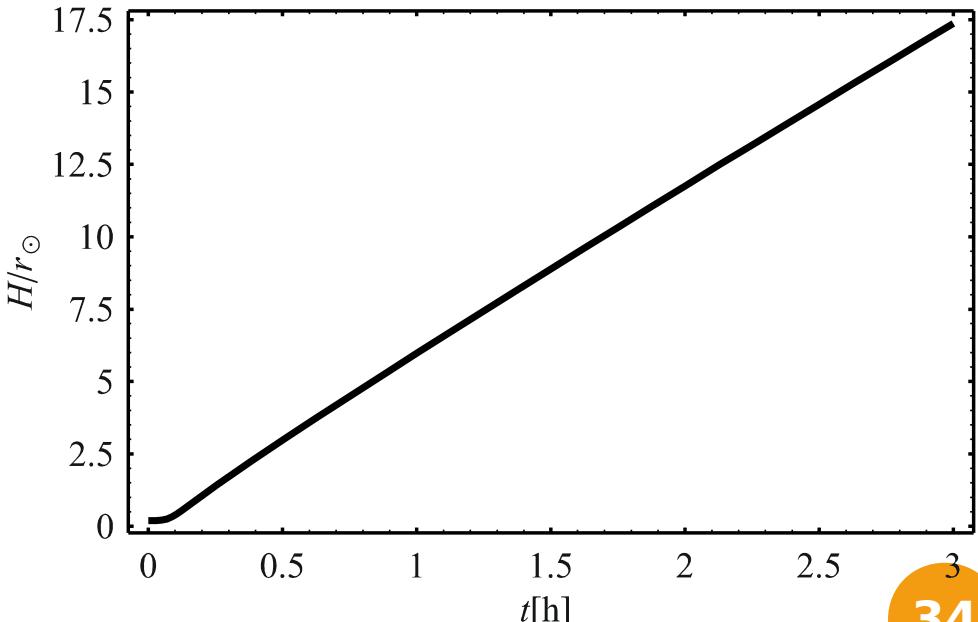
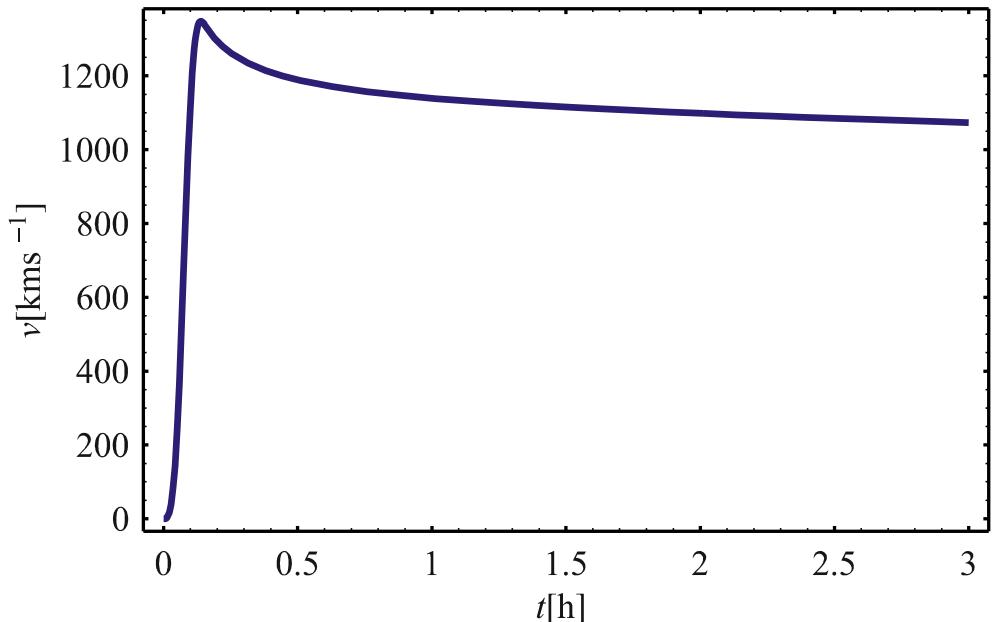


Impulzivan izbačaj



$$S = 0.2 r_{\odot}; M = 1 \times 10^{12} \text{ kg}; \zeta_0 = 0; \eta = 0.1; \\ I_0 = 7.8 \times 10^{10} \text{ A}; X_0 = 4; B_{c0} = 1 \times 10^{-4} \text{ T}; \\ w_{\infty} = 400 \text{ km/s}; \Gamma = 0.1$$

- $\Delta I: 0 < t < \mathbf{10 \text{ min}}, \varepsilon_M = \mathbf{1}$
- vrlo kratka akceleracijska faza: $\sim 10 \text{ min}$
- $v_{max} \approx 1400 \text{ km/s}, a_{max} \approx 5500 \text{ m/s}^2$
- neometano: za $3 \text{ h} \rightarrow \sim 20 r_{\odot}$



Zaključak - inicijacija izbačaja

- prolaskom kroz ograničeni parametarski prostor modela
→ model pogodan za opis i objašnjenje opažačkih rezultata u ranoj akceleracijskoj fazi koroninih izbačaja mase
- model je **najosjetljiviji** na:
 - početnu struju koja teče magnetskim užem I_0
 - dodatno inducirana struju $\Delta I(t) = I_0 \varepsilon(t)$
- nakon određene vrijednosti model je neosjetljiv na promjene početne „usukanosti“ magnetskog polja X_0
- model je ovisan i o „globalnim“ parametrima: npr. jačini pozadinskog polja korone B_{c0} , brzini Sunčevog vjetra i sl.
 - „globalne“ veličine slabo ili sporo se mijenjaju oko srednjih prosječnih opažačkih vrijednosti → drže se stalnim
- pogodnije **mijenjati „lokalne“ parametre**, vezanih za svaki pojedini izbačaj: npr. geometrijske parametre ζ_0 , η , struju I_0 , „usukanost“ X_0 , masu M , dodatni magnetski pritok ili ekvivalentno ΔI

Model MHD otpora (engl. *The Drag-Based Model, DBM*)

- Model MHD otpora: služi za predviđanje gibanja ICME u heliosferi → što je osnovni zadatak prognostike u svemirskom okolišu
- prognostički modeli se mogu podijeliti na:
 - a) potpuno emiričke/statističke modele
 - b) kinematičko-empiričke modele
 - b/c) analitičke (M)HD modele (DBM)
 - c) potpuno numeričke MHD-modele
- Model MHD otpora se oslanja na činjenice da na velikim heliocentričnim udaljenostima:
 - Lorentzova sila trne (u visokoj koroni)
 - dinamika ICME samo počiva na međudjelovanju sa Sunčevim vjetrom (okolinom) ← opažačke činjenice:
 - brz CME → usporava
 - spor CME → ubrzava
 - u nesudarnom okruženju:
 - niska je viskoznost
 - niska rezistivnost → dissipativni procesi su zanemarivi
 - impuls i energija se prenose magnetoakustičnim valovima

Međuplanetarno gibanje - MHD „otpor“

- na udaljenosti većoj $R \geq 15 r_{\odot}$, ukupno ubrzanje ovisi samo o sili MHD „otpora“:

$$a = (a_L - g - a_c) + a_d$$

- otpor nastaje zbog prijenosa impulsa i energije između izbačaja i Sunčevog vjetra:

$$\ddot{R}(t) = -\gamma(R)[\dot{R}(t) - w(R)]|\dot{R}(t) - w(R)|$$

$$n_0(R) = \frac{k_2}{R^2} + \frac{k_4}{R^4} + \frac{k_6}{R^6} \text{ za } R > 1.8$$

Empirički model
(Leblanc et al., 1998)

$$\gamma \propto c_d \frac{A \rho_{SW}}{M}$$

za $R \gg 1r_{\odot} \Rightarrow$
 $M = M_i + M_v = \text{konst.}$

v – brzina CMEa
 M – masa CMEa
 A – površina presjeka CMEa
 w – brzina Sun. vjetra
 ρ – gustoća ambijenta
 $c_d \approx 1$ – koeficijent otpora
(Cargill, 2004)

Perturbacije u Sunčevom vjetru

- neperturbirani Sunčev vjetar: stacionaran i izotropan
 - slijedi iz očuvanja toka gustoće (jednadžbe kontinuiteta)
- neperturbirani Sunčev vjetar:

POTREBNO:
 $w(R)$, w_∞ , γ_∞

$$w_0(R) = w_\infty \left(1 + \frac{k_4/k_2}{R^2} + \frac{k_6/k_2}{R^4} \right)^{-1}$$

$[w_\infty = \lim_{R \rightarrow \infty} w_0(R)]$

- ukupni Sunčev vjetar (neperturbirani, w_0 + perturbirani član, w_p):

$$w(R) = \begin{cases} w_0(R) + w_p(R), & R_1 < R < R_2 \\ w_0(R), & \text{inače} \end{cases}$$

+ „Konusna geometrija“:
 $A \propto R^2$

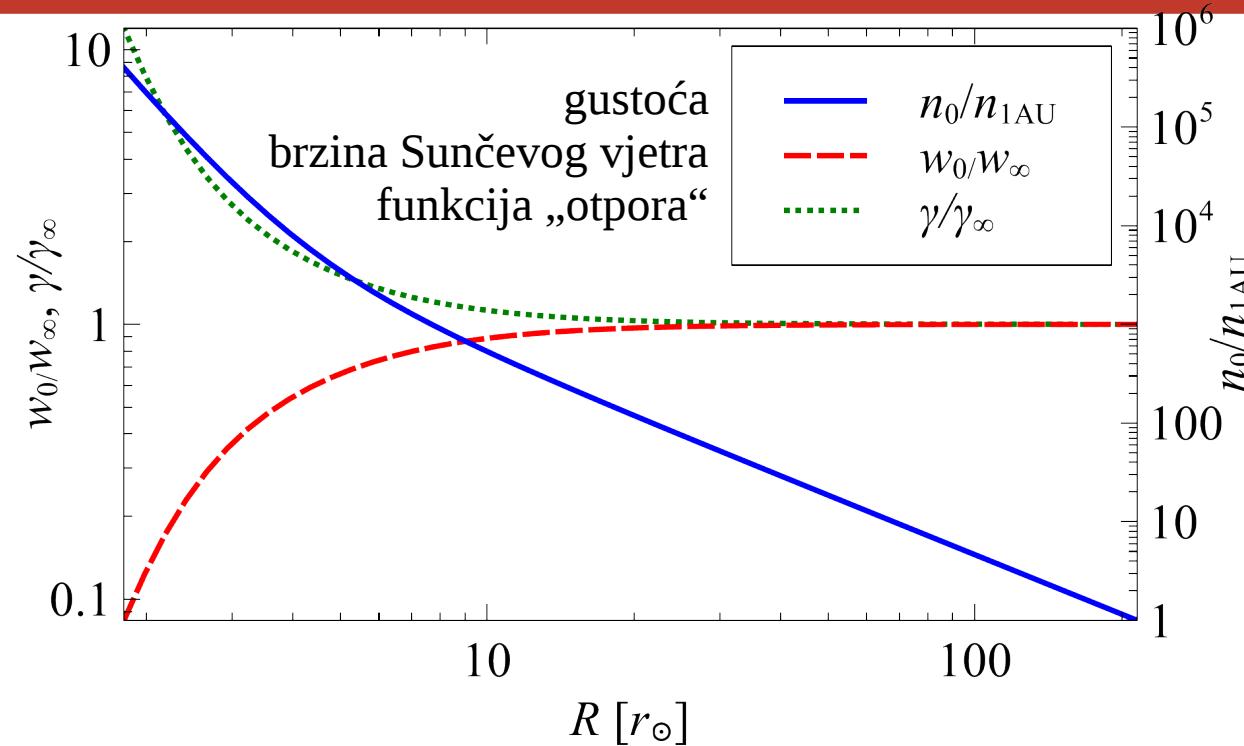
- vodi do:

$$\gamma(R) = \gamma_\infty \frac{w_\infty}{w(R)}; \quad n(R) = \frac{k_2}{R^2} \frac{w_\infty}{w(R)}$$

$[\gamma_\infty = \Gamma \times 10^{-7} \text{ km}^{-1}]$

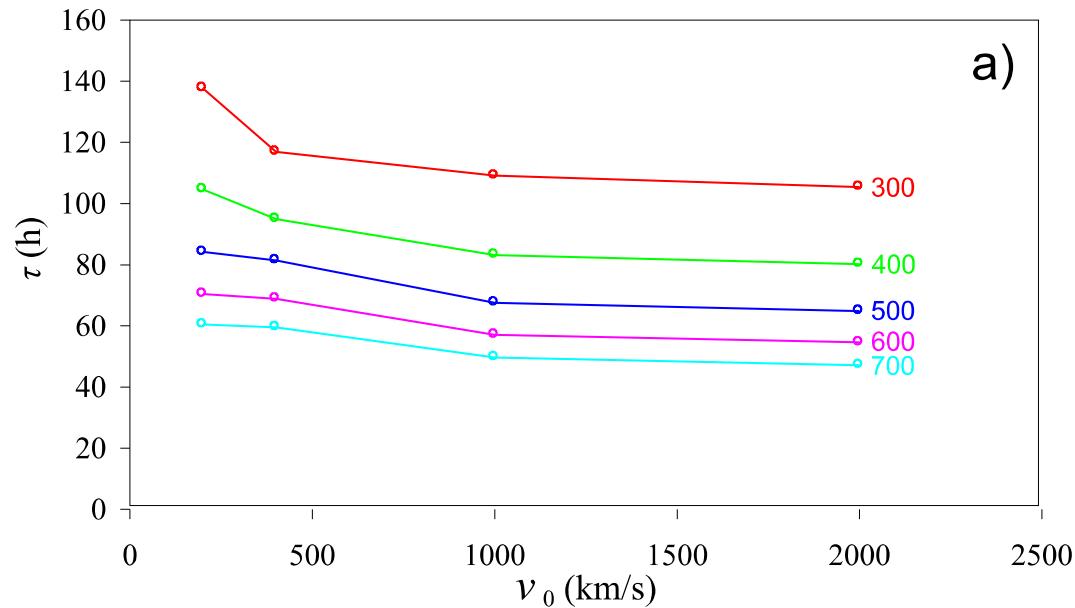
$[\gamma_\infty = \lim_{R \rightarrow \infty} \gamma(R)]$

Model „otpora“ s konstantnim γ_∞ i w_∞

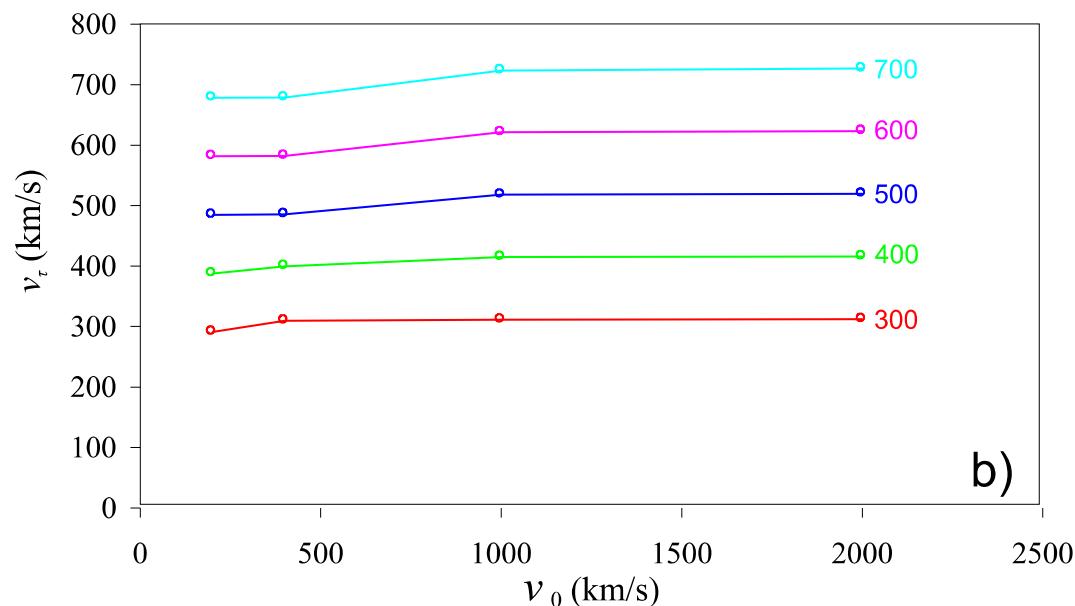


- nakon $R > 20$: $w(R) \approx w_\infty$, $\gamma(R) \approx \gamma_\infty$
$$\dot{v}(t) = -\gamma_\infty [v(t) - w_\infty] |v(t) - w_\infty|$$
- Dva slučaja riješivosti jednadžbe:
 - izbačaj brz: $v(t) > w_\infty \rightarrow$ opada i asimptotski se približava w_∞
 - izbačaj spor: $v(t) < w_\infty \rightarrow$ brzina raste i doseže brzinu w_∞

Tranzitne vrijednosti $\tau(v_0)$, $v_\tau(v_0)$ za zadani w_∞

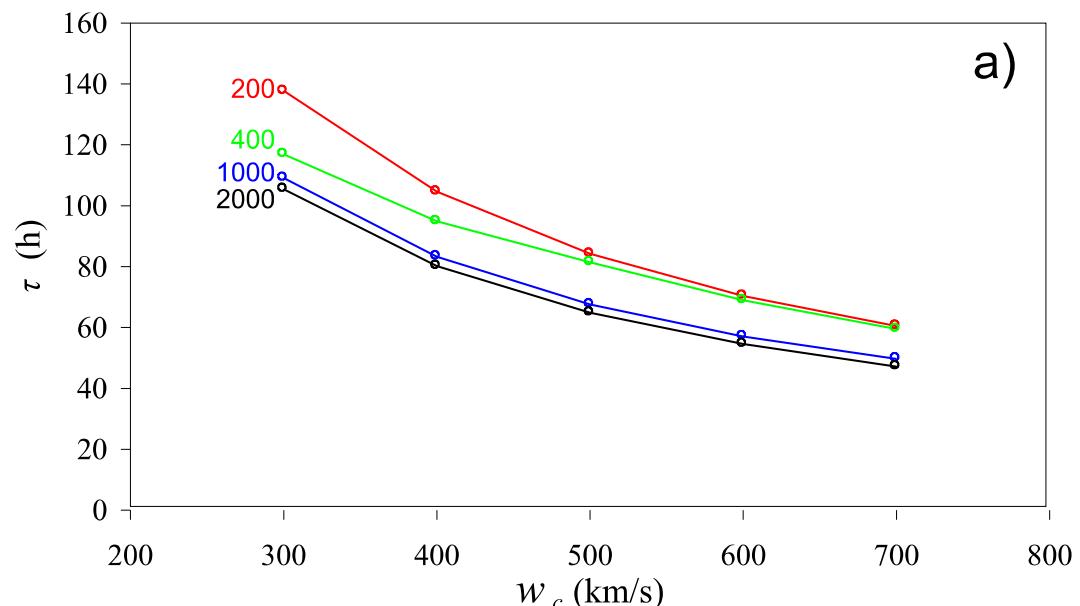


- izračunate krivulje ovisnosti tranzitnog vremena $\tau(v_0)$ i brzine $v_\tau(v_0)$ o početnoj v_0 brzini izbačaja
- različite asymptotske brzine Sunčevog vjetra w_∞ (pokraj linija)
- iste kutne širine $\Theta = 1$ rad i mase $M = 10^{12}$ kg
- krivulja tranzitnog vremena $\tau(v_0)$ gotovo da se ne mijenja povećanjem brzine v_0

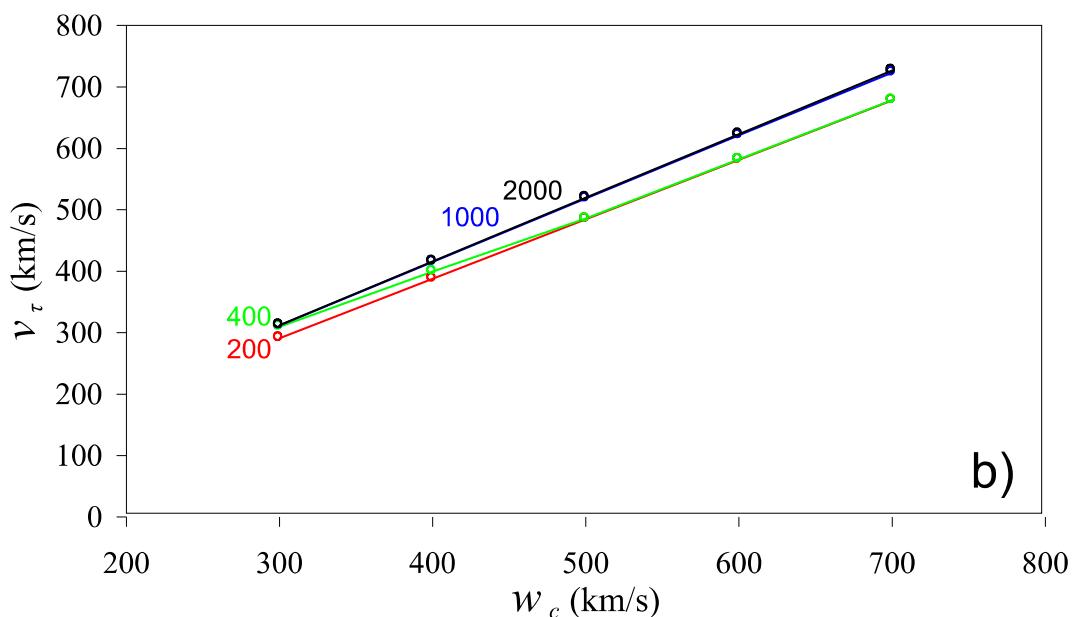


- tranzitna vremena su veća za male $w_\infty \rightarrow$ vjetar odnosi izbačaj sa sobom
- brzina Sunčevog vjetra manja \rightarrow izbačaj duže putuje do Zemlje
- Zaključak:** za navedeni skup parametara tranzitno vrijeme τ više ovisi o brzini Sunčevog vjetra, w_∞ , nego o početnoj brzini izbačaja, v_0

Tranzitne vrijednosti $\tau(w_\infty)$, $v_\tau(w_\infty)$ za zadani v_0



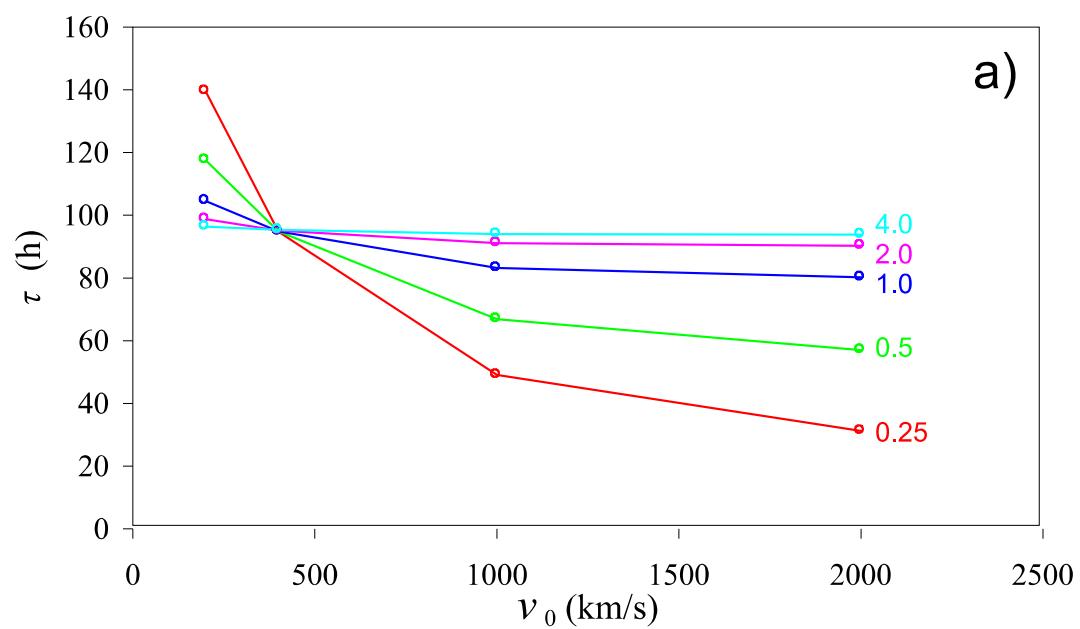
a)



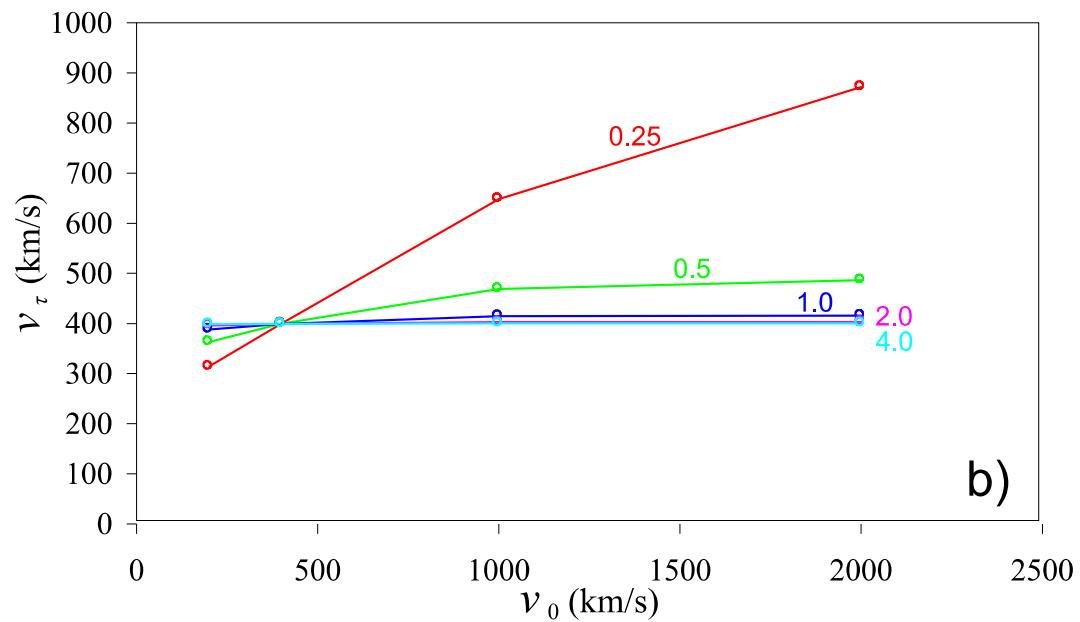
b)

- ovisnost tranzitnog vremena $\tau(w_\infty)$ i brzine $v_\tau(w_\infty)$ o promjeni asimptotske vrijednosti brzine Sunčevog vjetra w_∞
- krivulje se razlikuju prema početnoj brzini izbačaja v_0 (vrijednost uz krivulju)
- nagib krivulja i velik $\Gamma \rightarrow \tau(w_\infty)$ i $v_\tau(w_\infty)$ su osjetljiviji na promjenu brzine Sunčevog vjetra w_∞
- grupiranje krivulja $\rightarrow \tau(w_\infty)$ i $v_\tau(w_\infty)$ su neosjetljivi na promjenu brzine v_0
- **Zaključak:** brzina v_0 je bitna tek kod vrlo masivnih izbačaja (ili kod uskih koji se gibaju u plazmi niske gustoće)

Tranzitne vrijednosti $\tau(v_0)$, $v_\tau(v_0)$ za zadani Γ



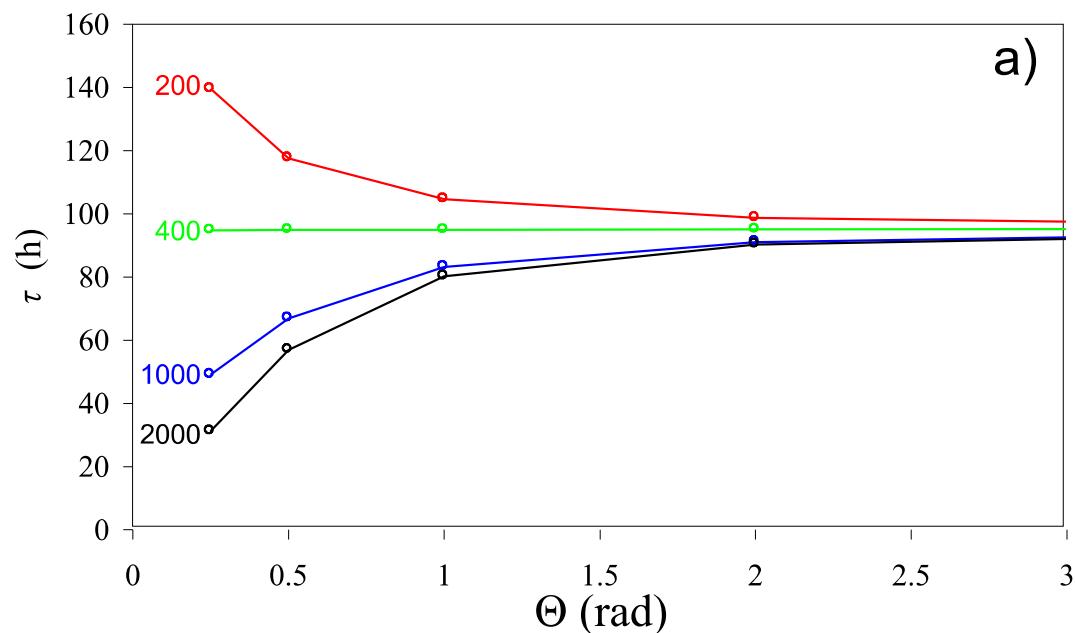
a)



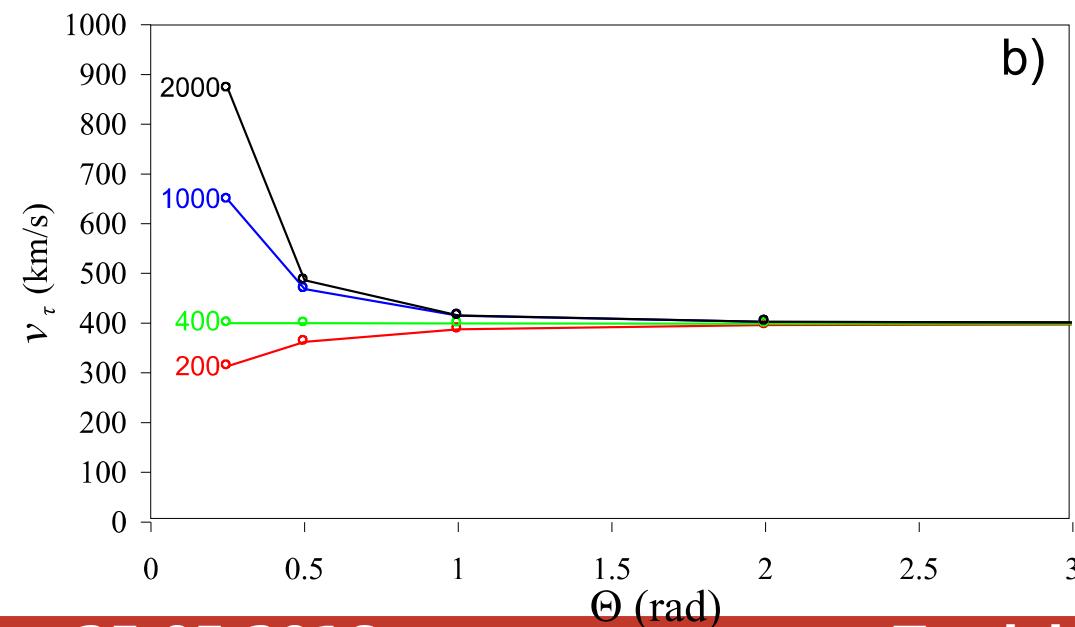
b)

- ovisnost tranzitnih veličina $\tau(v_0)$ i $v_\tau(v_0)$ o početnoj v_0 i kutnoj širini Θ (zapisanoj uz krivulje)
- asimptotska brzina Sunčevog vjetra je konstantna: $w_\infty = 400$ km/s
- sve krivulje se približno sijeku u $\tau(v_0 = w_\infty) \approx 100$ h:
 - nema razlike između brzine izbačaja i Sunčevog vjetra
 - sila MHD otpora je vrlo mala ili iščezava
 - izbačaji se gibaju brzinama koje približno slijede brzinu Sunčevog vjetra $w(R)$
- za $|v - w| > 0 \rightarrow$ gibanje izbačaja postaje osjetljivo na kutnu širinu Θ
- **Zaključak:** $\tau(v_0)$ i $v_\tau(v_0)$ uskih izbačaja osjetljivija na v_0 , nego što su kod širokih

Tranzitne vrijednosti $\tau(\Theta)$, $v_\tau(\Theta)$ za zadani v_0



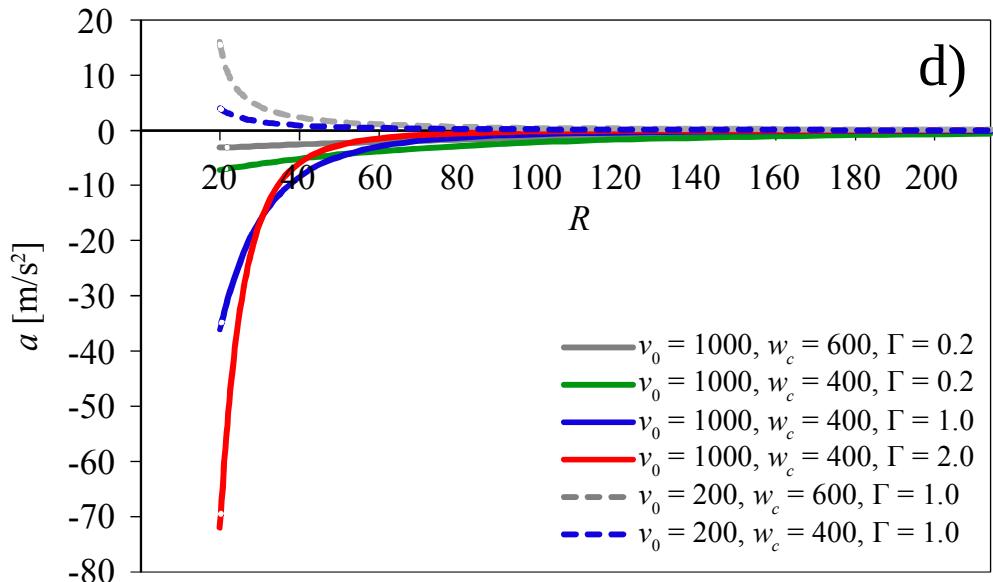
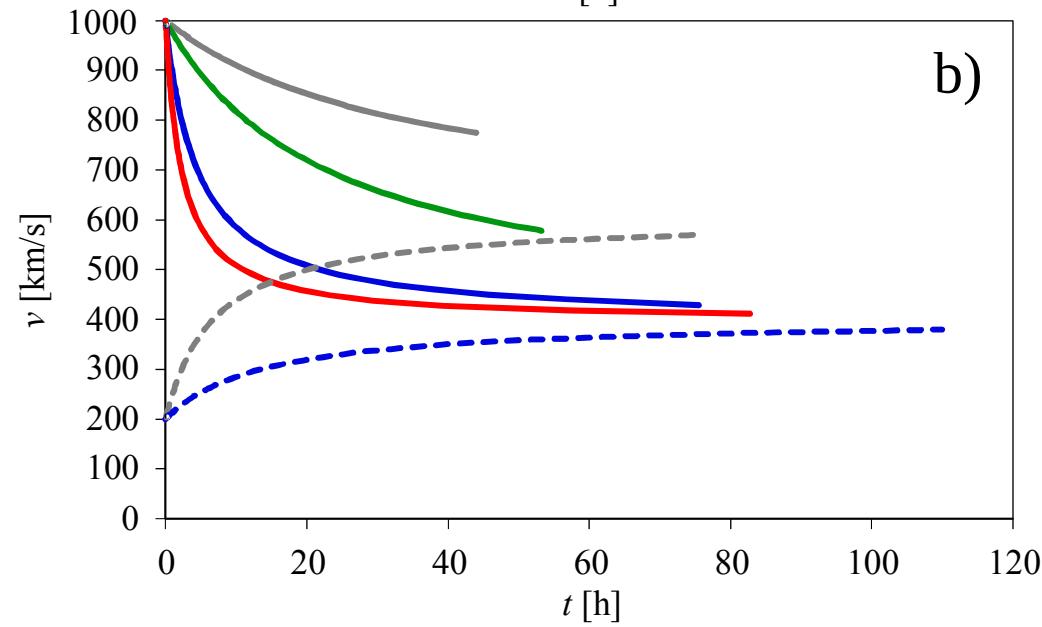
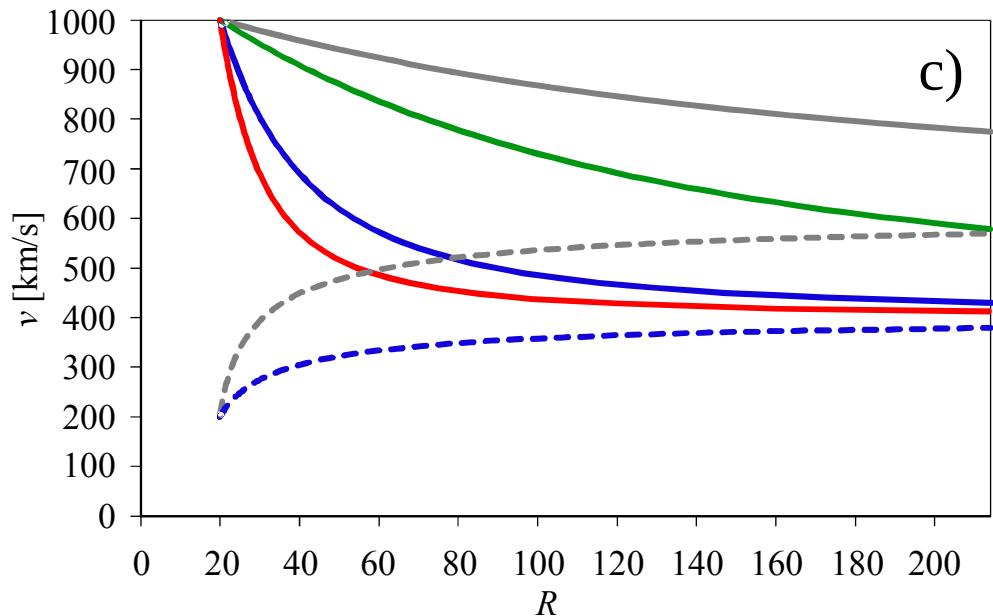
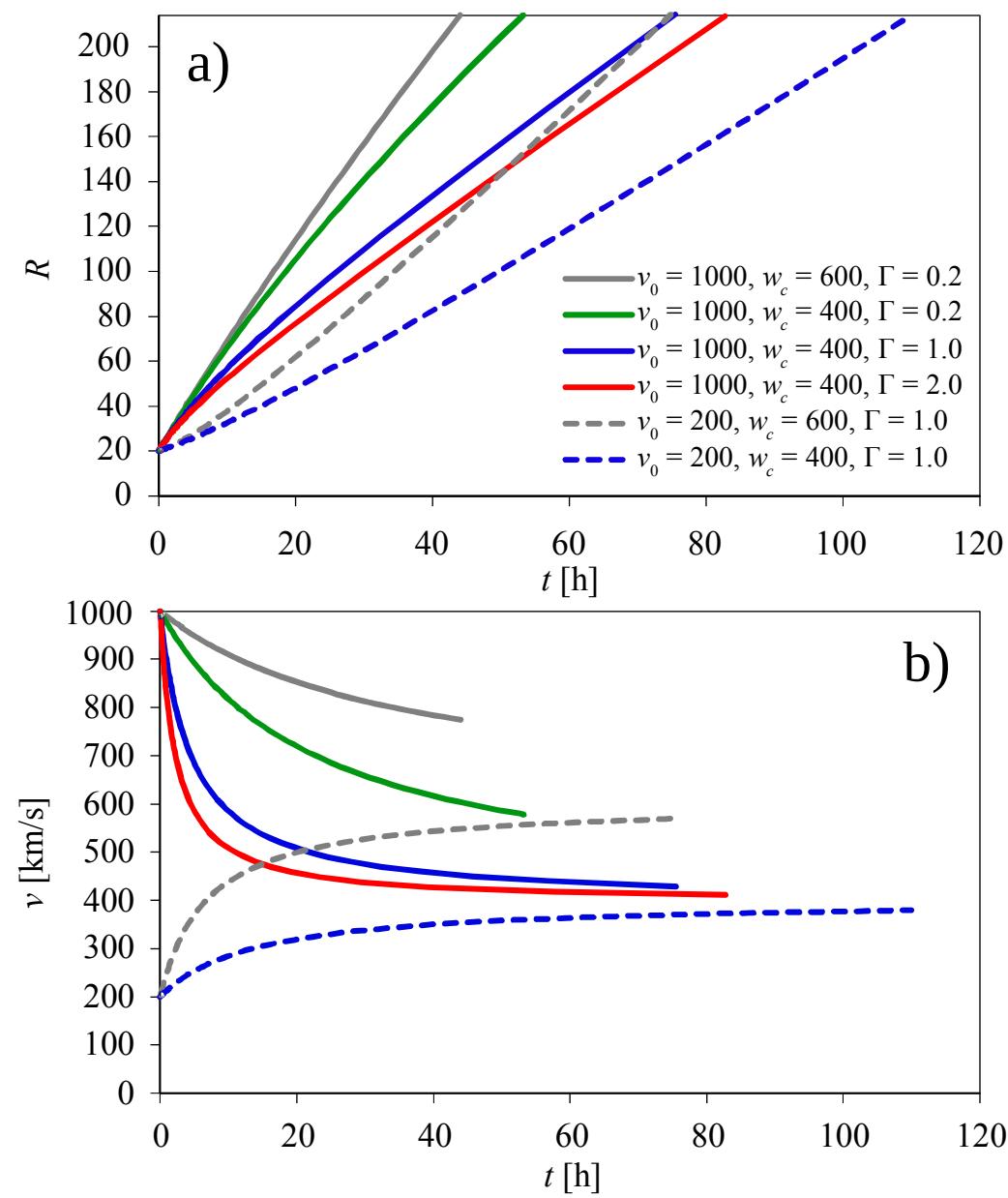
a)



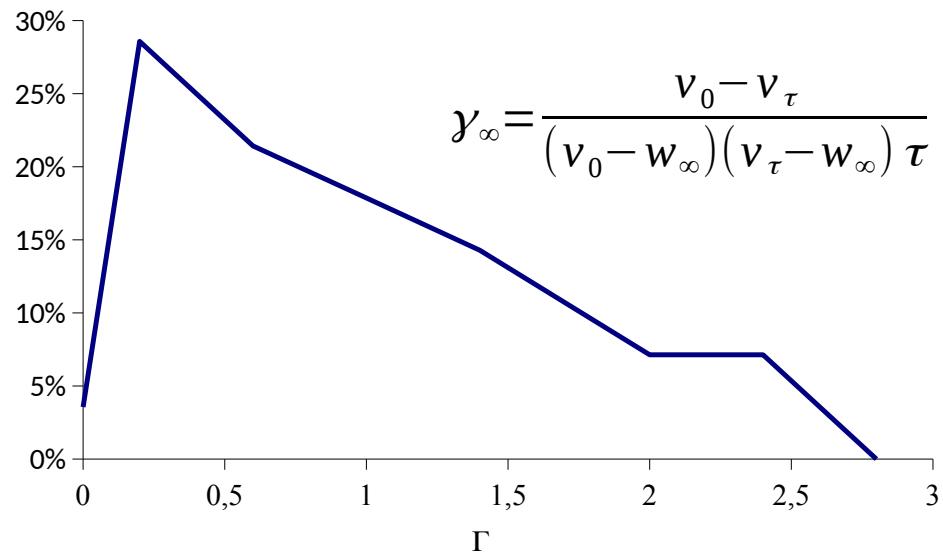
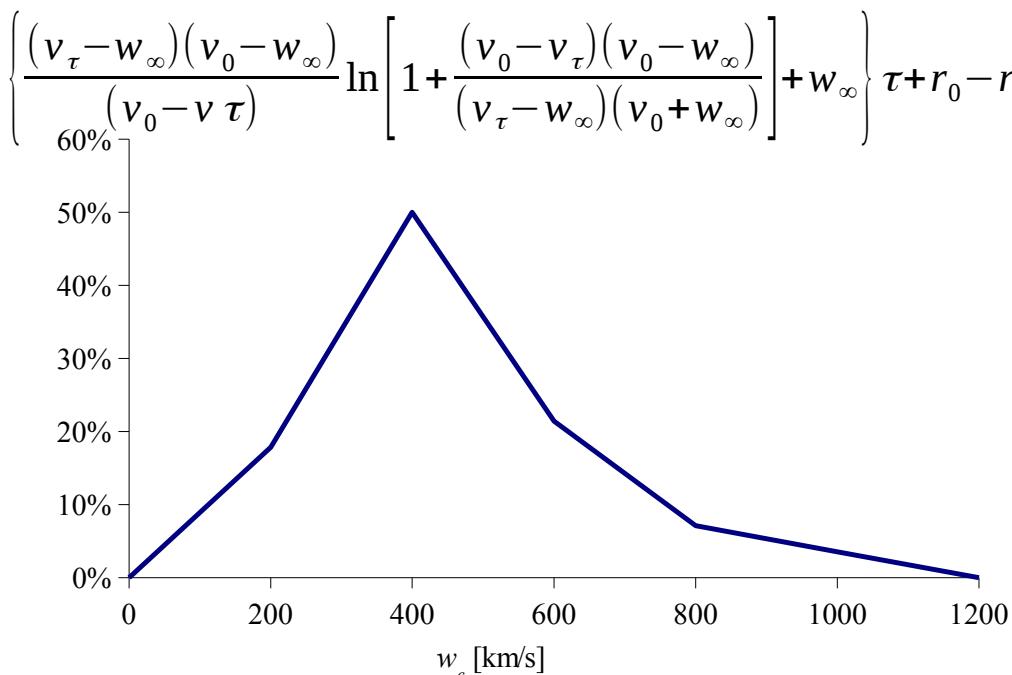
b)

- Sažeto: ovisnost tranzitnih vremena i brzina o kutnoj širini izbačaja Θ
- krivulje se razlikuju prema početnim brzinama izbačaja v_0
- brzina Sunčevog vjetra iznosi $w_\infty = 400 \text{ km/s}$
- krivulje se stapaju za $\Theta \gg 1$ ($M \ll 1$) $\rightarrow \tau(\Theta), v_\tau(\Theta)$ ne ovise o početnoj v_0
- **Zaključak:** brzina v_0 bitna samo kod $\Theta \ll 1$ (uskih) i $M \gg 1$ (masivnih) izbačaja (ili općenito onih s $\Gamma \ll 1$)

Model s konstantnim γ_c , w_c - primjeri

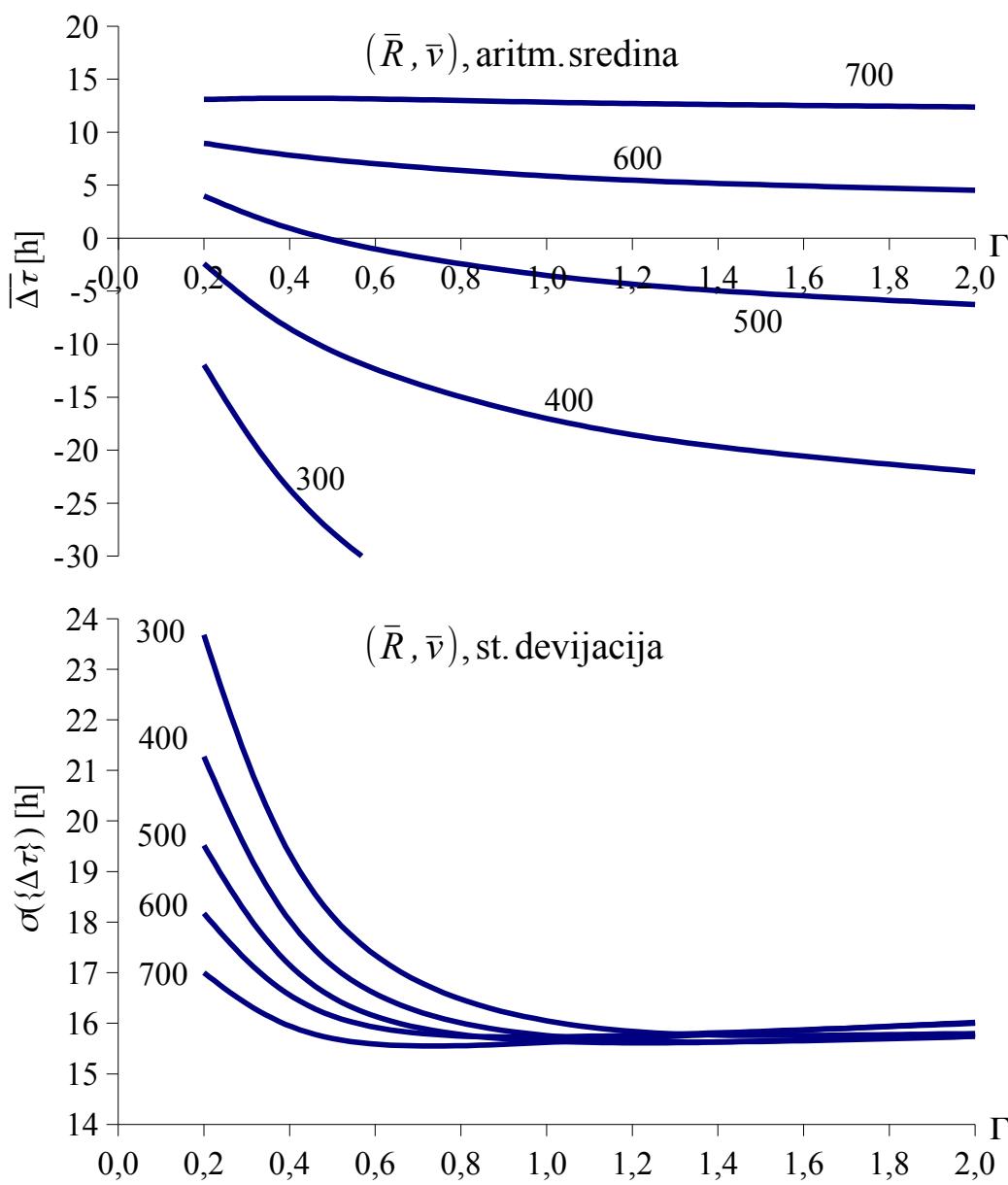


Raspodjele w_∞ i Γ iz opažačkih podataka



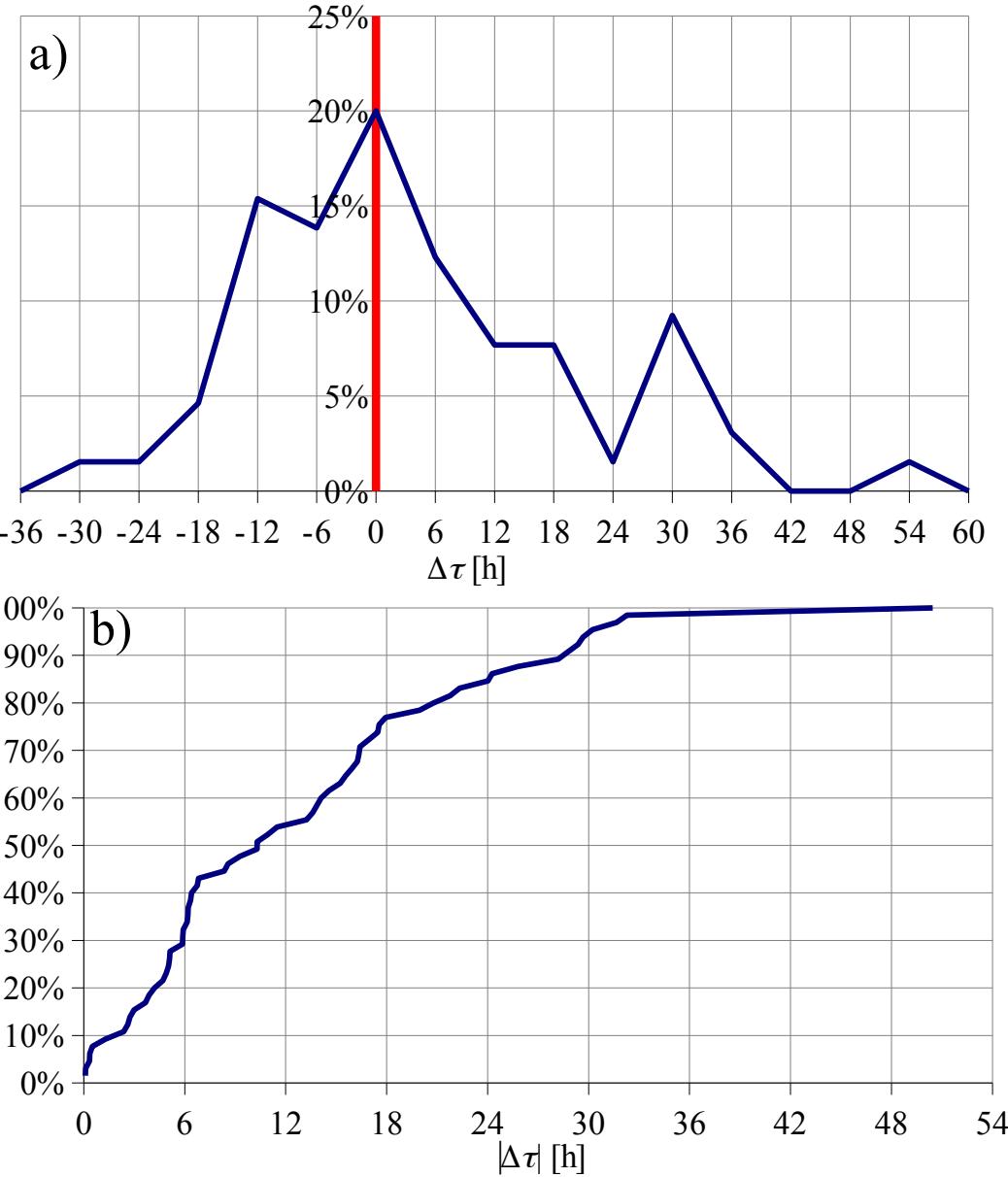
- iz skupa $\{r_0, v_0, \tau, v_\tau\} \rightarrow \{\Gamma, w_\infty\}$
- izračunate raspodjele w_∞ i Γ iz opažačkih $\{r_0, v_0, \tau, v_\tau\}$ podataka Schwenn et al. (2005) i Manoharan (2006)
- aritmetičke sredine distribucija:
 - $\bar{\Gamma} = (1 \pm 0.6)$
 - $\bar{w}_\infty = (470 \pm 190) \text{ km/s}$
- medijani:
 - $\text{Me}(\{\Gamma\}) = 0.8$
 - $\text{Me}(\{w_\infty\}) = 410 \text{ km/s}$
- raspodjela parametra Γ je nagnuta prema manjim vrijednostima
- nije nađena nikakva korelacija između Γ i w_∞

Aritmetička sredina i nepozdanost skupa $\{\Delta\tau\}$



- **Cilj:** pronaći kombinaciju Γ i w_∞ za fiksne $R_0 = \bar{R}$, $v_0 = \bar{v}$ iz Schwenn et al. (2005) uzorka, kada $\Delta\tau = (\tau_o - \tau) = 0$ h
→ sjecište krivulje s apscisom
- **Rezultat:** za bilo koju brzinu Sunčevog vjetra w_∞ → standardna devijacija opada porastom Γ i minimalna je za $\Gamma \geq 1$
- optimalne vrijednosti su:
 - $w_\infty = 500 - 550$ km/s
 - $\Gamma \approx 1$

Raspodjela uzorka za $\Gamma = 1$ i $w_\infty = 500$ km/s



- iz prijašnje raspodjele prosječne vrijednosti se kreću oko:

$$\Gamma = 1 \text{ i } w_\infty = 500 \text{ km/s}$$

→ primjenjene s $R_0 = R_N$ i $v_0 = v_N$ iz uzorka Schwenn et al. (2005) i Manoharan (2006)

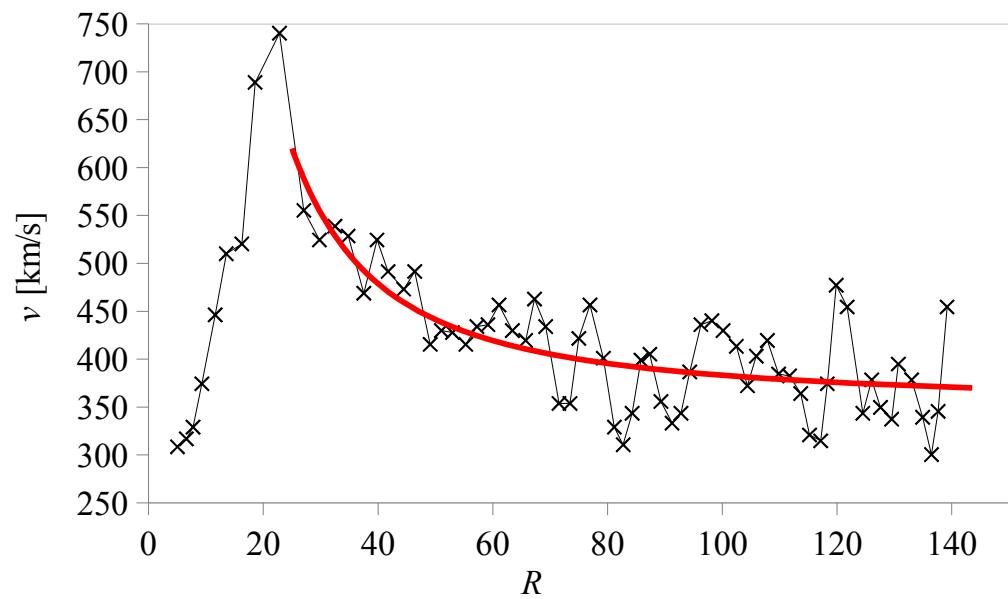
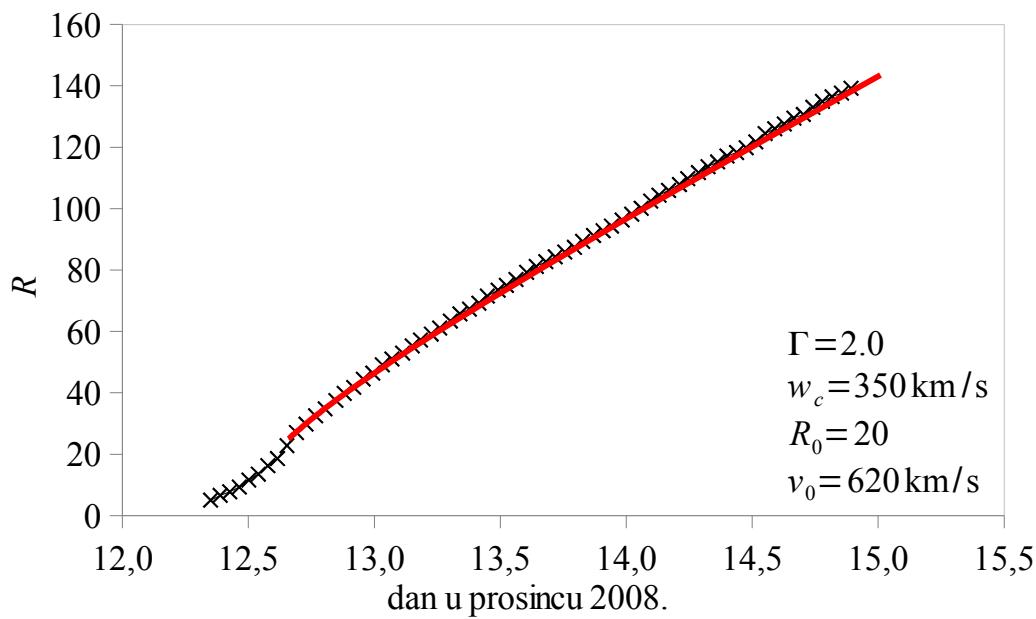
→ raspodjela razlika opaženog i tranzitnog vremena $\Delta\tau$

- za 55% izbačaja je $|\Delta\tau| < 12$ h
- više od 85% izbačaja je $|\Delta\tau| < 1$ d

Zaključak:

- najbolja prognostika za $w_\infty = 500$ km/s
- tijekom minimuma: $w_\infty = 300 - 400$ km/s
- za ekvatorijalnu koronu šupljinu: $w_\infty = 500 - 600$ km/s i smanjiti Γ

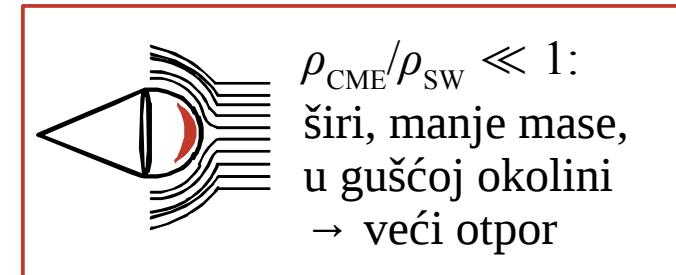
Primjena na pojedinačni izbačaj 12.12.2008.



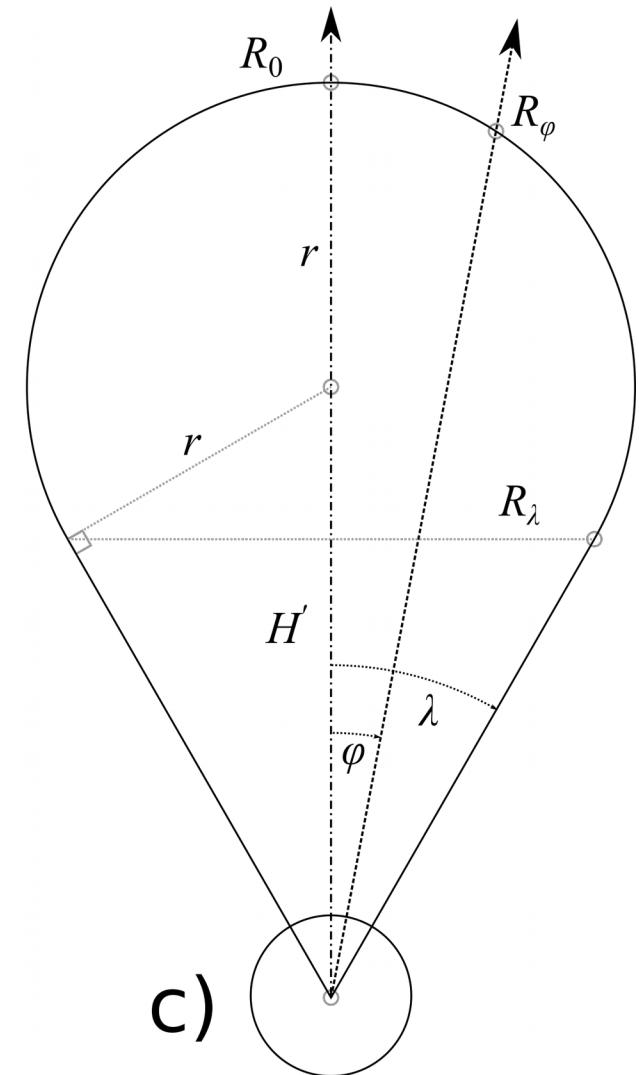
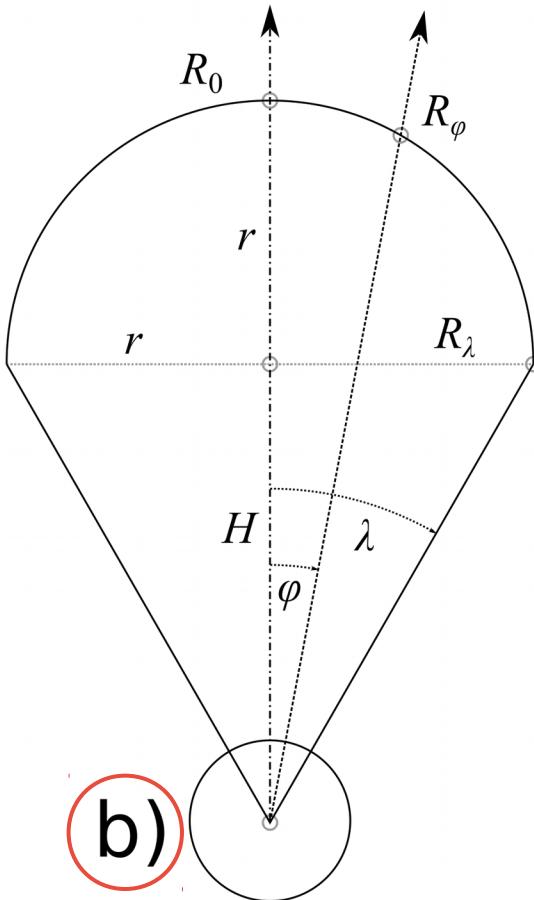
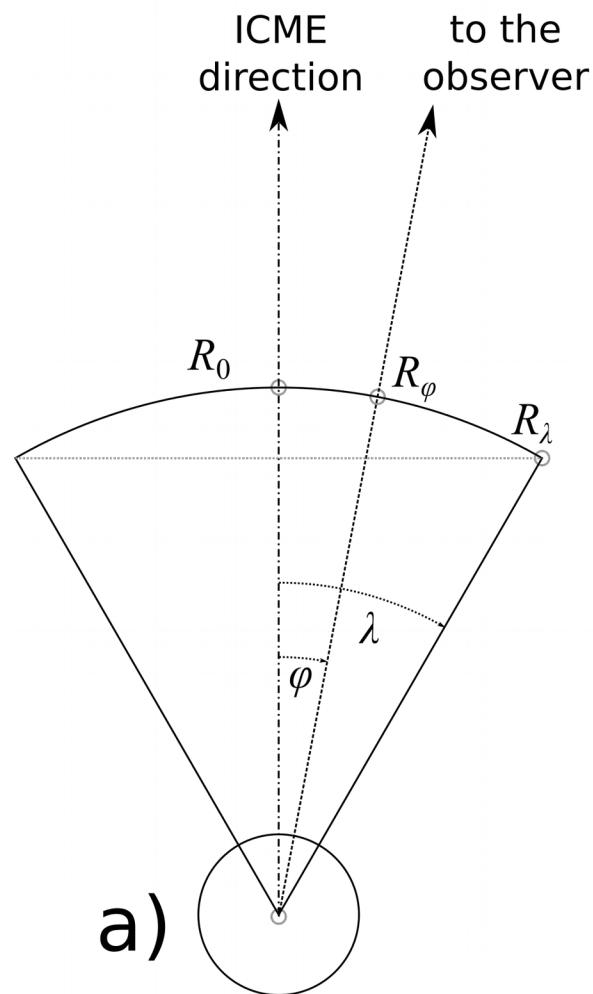
- upotreba modela s konstantnim:
 $w(R) = w_\infty = \text{konst.}$
 $\gamma(R) = \gamma_\infty = \text{konst.}$
- izbačaj vrlo naglo ubrzava do udaljenosti $R \approx 23$
- postiže visoku brzinu od 740 km/s
- kasnije počinje usporavati
- Model dobro opisuje deceleraciju pomoću:
 - $\Gamma = 2, w_\infty = 350 \text{ km/s},$
 - $R_0 = 20, v_0 = 620 \text{ km/s}$
- LASCO/SoHO katalog: „slab“ izbačaj → visoka vrijednost Γ

Zaključak - propagacija izbačaja s $w = \text{konst.}$

- Tranzitno vrijeme τ međuplanetarnog koroninog izbačaja mase ponajviše ovisi o:
 - početnoj brzini, v_0
 - masi, M
 - širini, Θ
 - brzini i gustoći Sunčevog vjetra, $w(R)$ i $n(R)$
- dva bitna granična slučaja:
 - izbačaj male gustoće $\rightarrow \tau$ prvenstveno je određeno $w(R)$
 - izbačaj velike gustoće $\rightarrow \tau$ ovisi o v_0
- $\tau < 1$ d \rightarrow izbačaji s $v_0 > 2000$ km/s u vjetru s $n(R) \ll 1$
- statistička analiza opažačkih podataka i model s $\gamma(R) = \gamma_\infty = \text{konst.}$ i $w(R) = w_\infty = \text{konst.}$
 - \rightarrow optimalne vrijednosti:
 - $\Gamma \in [0.2, 2]$, ($\gamma_\infty = \Gamma \times 10^{-7}$ km $^{-1}$)
 - $w_\infty = 500$ km/s
 - $\sigma(\tau) \approx 1/2$ d

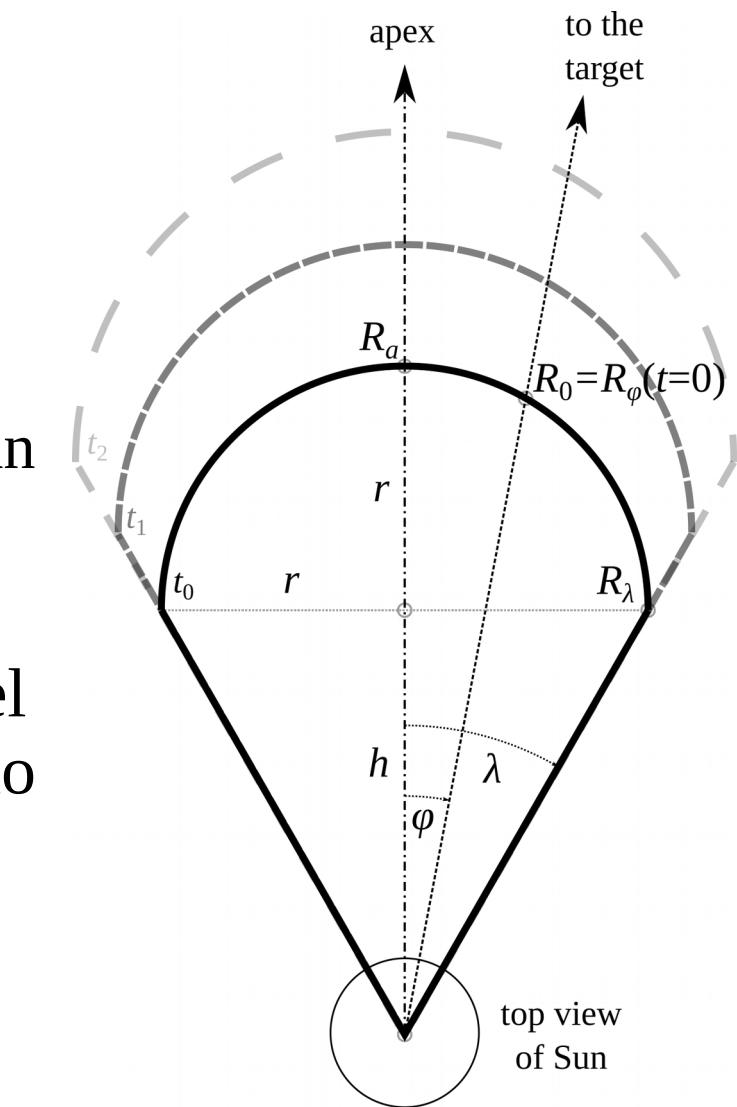


Konusne geometrije ICME



DBM s $w = \text{konst.}$ i samousuglašenom CME ekspanzijom

- Sunčev vjetar, w :
 - izotropan i konstantan
 - parametar γ je također konstantan
- „samousuglašeno“ (SS) CME širenje:
 - početni konusni oblik CME-a je sačuvan tijekom njegovog širenja u međuplanetarnom prostoru
- za zadan skup ulaznih parametara model računa propagaciju ICME-a od Sunca do odabrane „mete“:
 - tranzitno vrijeme
 - dolatni datum
 - udarnu brzinu



Osnovni izračun ($w=konst.$ & SS-širenje) (<http://oh.geof.unizg.hr/~tomislav/CDBM-SS/>)

Forecasting the Arrival of ICMEs: The Drag-Based Model with constant solar wind speed and self-similar CME expansion

Basic DBM Advanced DBM Documentation

CME take-off **date**:

CME take-off **time (UTC)**:

y - constant drag parameter: $\times 10^{-7} \text{ km}^{-1}$

w - constant solar wind speed: km/s

R₀ - starting radial distance of CME: r_{Sun}

v₀ - speed of CME at R_0 : km/s

Select target from the list:

© Tomislav Žic, Hvar Observatory, 2013

Zadnja obnova stranice: 8.4.2016.

Napredniji uzračun ($w=konst.$ & SS-širenje) (<http://oh.geof.unizg.hr/~tomislav/CDBM-SS/>)

Forecasting the Arrival of ICMEs: The Drag-Based Model with constant solar wind speed and self-similar CME expansion

Basic DBM Advanced DBM Documentation

CME take-off **date**:

CME take-off **time (UTC)**:

y - constant drag parameter: $\times 10^{-7} \text{ km}^{-1}$

w - constant solar wind speed: km/s

R₀ - starting radial distance of CME: r_{Sun}

v₀ - speed of CME at R_0 : km/s

λ - CME's angular half-width: deg

φ_{CME} - central meridian distance of source region: deg

Select target from the list:

© Tomislav Žic, Hvar Observatory, 2013

Zadnja obnova stranice: 8.4.2016.

Rezultat izračuna ($w=konst.$ & SS-širenje) (<http://oh.geof.unizg.hr/~tomislav/CDBM-SS/>)

Forecasting the Arrival of ICMEs: The Drag-Based Model with constant solar wind speed and self-similar CME expansion

Results | Kinematic plot | CME geometry plot | Documentation

Output:

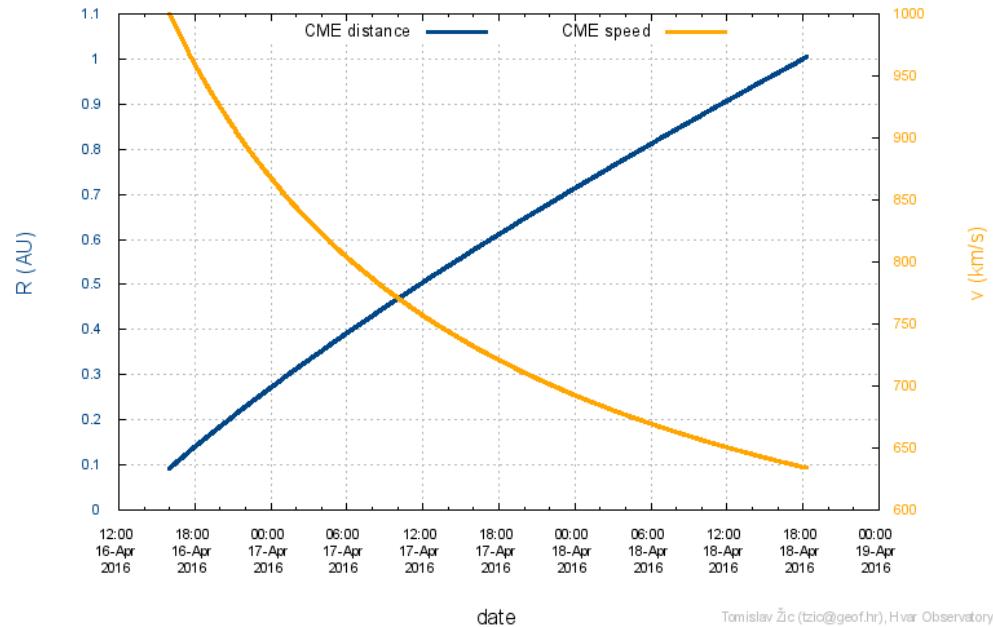
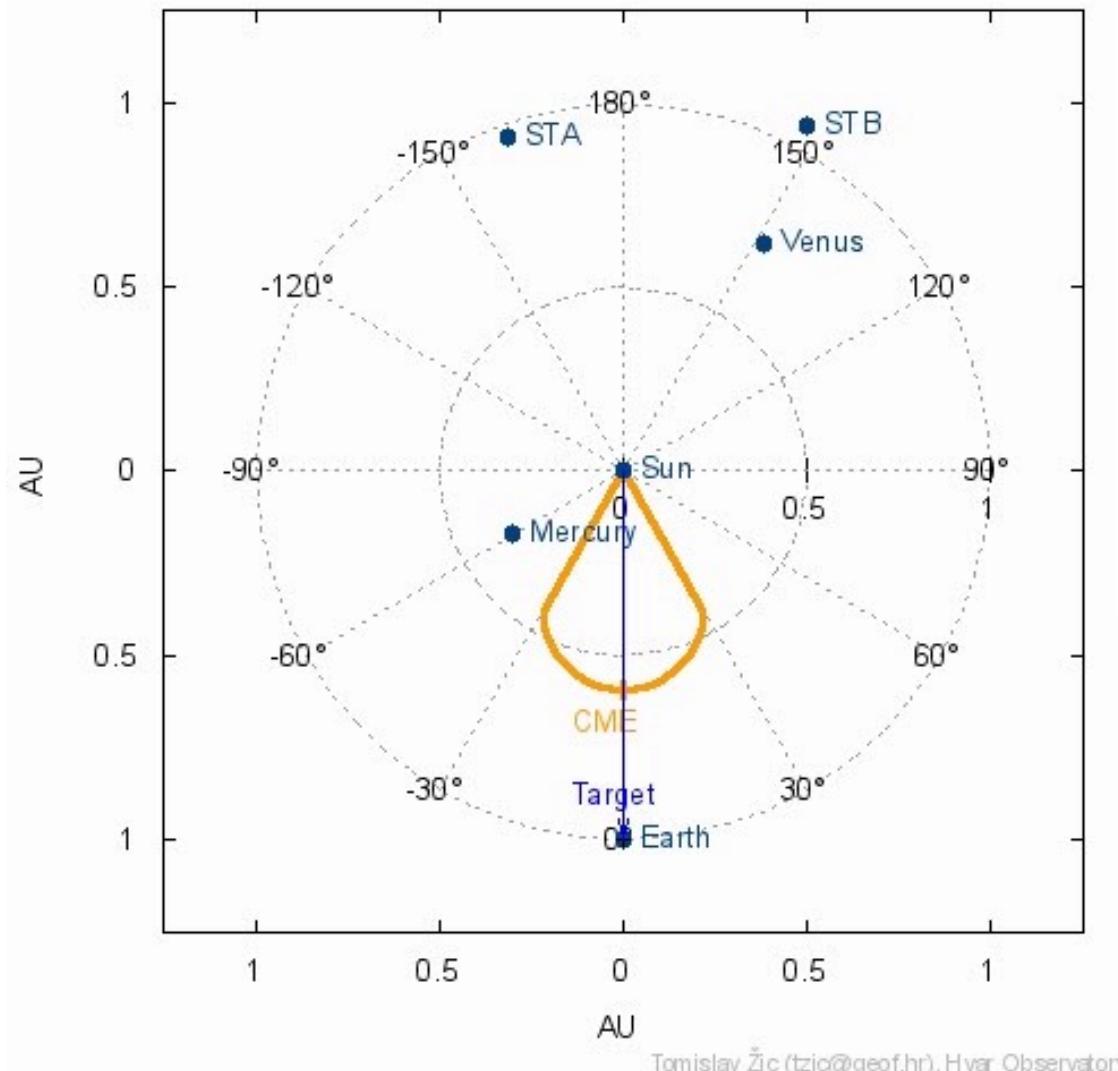
CME arrival at target (date & time): **14.04.2016 at 18h:12min**
Transit time: **50.20 h**
Impact speed at target (at 1 AU): **634 km/s**

Input parameters:

CME take-off date & time: **12.04.2016 at 16h:00min**
 $y = 0.2 \times 10^{-7} \text{ km}^{-1}$, $w = 450 \text{ km/s}$,
 $R_0 = 20 r_{\text{Sun}}$, $v_0 = 1000 \text{ km/s}$, $\lambda = 30^\circ$, $\varphi_{\text{CME}} = 0^\circ$
 $R_{\text{target}} = 1 \text{ AU}$, $\varphi_{\text{target}} = 0^\circ$

Calculated in 3.15 seconds.

Prikazi izračuna ($w=konst.$ & SS-širenje) (<http://oh.geof.unizg.hr/~tomislav/CDBM-SS/>)



↑ GORE:

Kinematika '+ CME' segmenta u ekliptici

← LIJEVO:

Širenje presjeka CME-a u ekliptici

Primjena DBM s $w=konst.$ i SS-širenjem na međunarodnim stranicama za prognostiku

Opservatorij Hvar - Forecasting the Arrival of ICMEs:
<http://oh.geof.unizg.hr/DBM/dbm.php>

Forecasting the Arrival of ICMEs: The Drag-Based Model

Basic DBM

Advanced DBM

Documentation

CME take-off **date**:

Apr 8 2016

CME take-off **time** (UTC):

16 h 47 min

R₀ - starting radial distance of CME (R_S)

20

v₀ - speed of CME at R₀ (km/s)

1000

Γ - drag parameter (10⁻⁷ km⁻¹)

0.4

w - asymptotic solar wind speed (km/s)

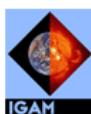
450

R_{target} - target heliocentric distance (AU)

1

Calculate Reset!

Drag-Based Model has performed 3254 successful calculations (since 26.12.2012).



© Hvar Observatory, 2014

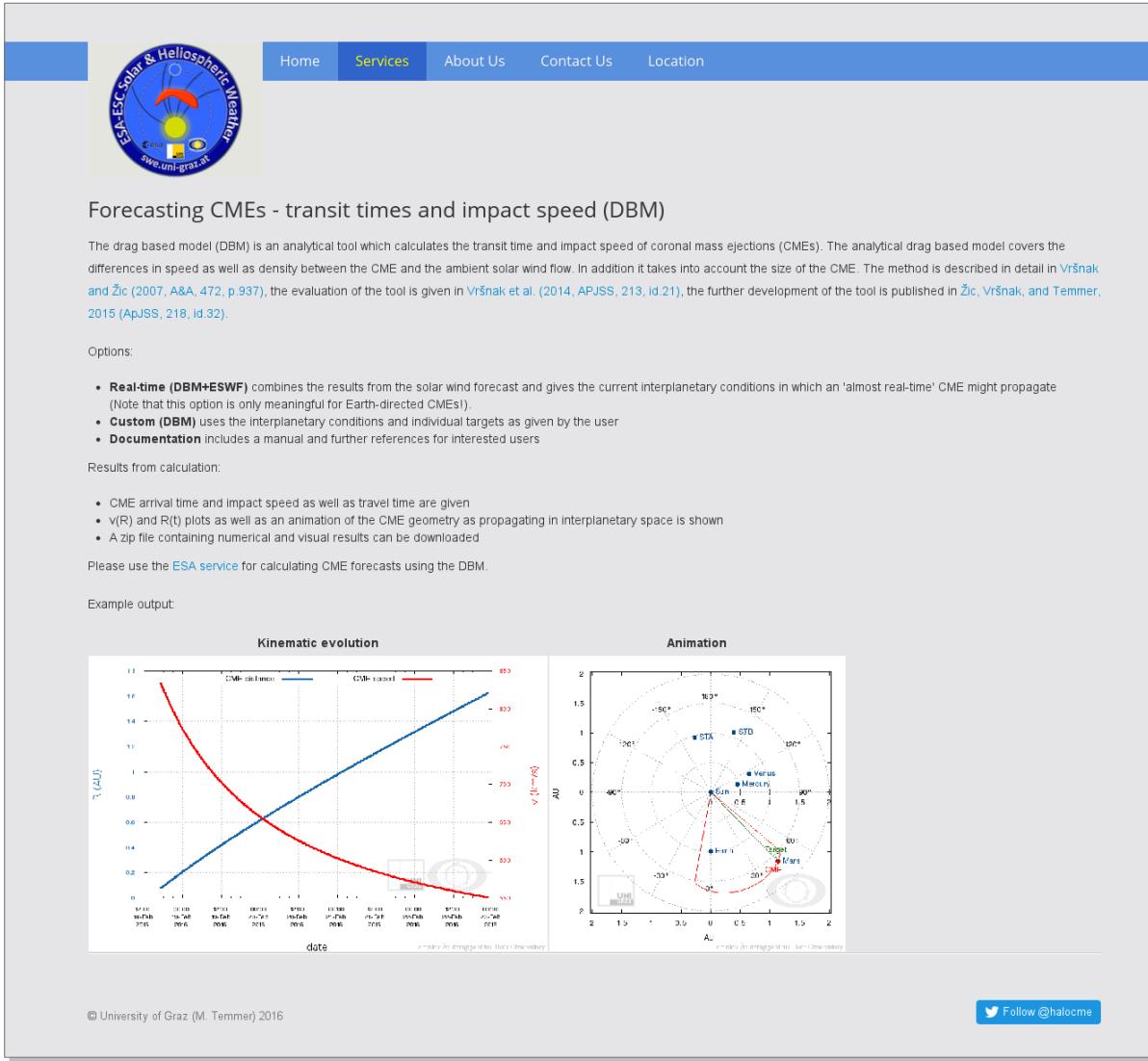
Primjena DBM s $w=konst.$ i SS-širenjem na međunarodnim stranicama za prognoziku

The COMESEP alert system:
<http://www.comesep.eu/alert/>

The screenshot shows the COMESEP alert system's user interface. At the top, there is a banner featuring a solar flare image and the text "COMESEP". Below the banner, the page title "System overview" is displayed. On the left, a "Main Menu" sidebar lists various links such as Home, Project Description, Consortium, Alert System, Alert System Help (which is currently selected), News, Publications, Meetings, Jobs, Links, Frequently Asked Questions, and Consortium Members Only. The main content area contains a brief description of the alert system's architecture, mentioning a network of alert tools connected to a central node, and a flow diagram illustrating the interaction between different tools. The flow diagram is organized into three horizontal levels: "FIRST LEVEL PRODUCERS" (CACTUS (ROB), Solar DEMON (ROB), Flaremail (ROB), GLE alert (BIRA-IASB)), "CONSUMERS/PRODUCERS" (DBM (HVAR), Geomag24 (DTU), CGFT (RCB), SEP forecast (BIRA-IASB)), and "ALERTS" (Gmag #2, Gmag #1, SEP Alert). Arrows indicate the flow of information between these tools. At the bottom of the main content area, there is a link "Back to main help page". The footer of the website features logos of various partner institutions, including University of Graz, University of Central Lancashire, European Union flag, HO (Heliophysics Observatory), DTU, BIRA-IASB, George Mason University, Community Coordinated Modeling Center, NASA, and the European Union flag again.

Primjena DBM s $w=konst.$ i SS-širenjem na međunarodnim stranicama za prognoziku

ESA Expert Service Center for Solar & Heliospheric Weather:
<http://swe.uni-graz.at/index.php/services/cme-forecast>



The screenshot shows the homepage of the ESA Expert Service Center for Solar & Heliospheric Weather. The top navigation bar includes links for Home, Services, About Us, Contact Us, and Location. The main content area features a logo for "ESA-ESC solar & heliospheric weather" and the URL "swe.uni-graz.at". Below the logo, a section titled "Forecasting CMEs - transit times and impact speed (DBM)" is displayed. This section contains a detailed description of the DBM model, options for real-time, custom, or documentation forecasts, results from calculations (travel time, impact speed, and R(t) plots), and a note about using the ESA service. Two figures are shown: "Kinematic evolution" (a plot of travel time vs. date) and "Animation" (a heliocentric coordinate system showing the Sun, Earth, Mars, and other planets). The bottom of the page includes copyright information and a Twitter link.

Forecasting CMEs - transit times and impact speed (DBM)

The drag based model (DBM) is an analytical tool which calculates the transit time and impact speed of coronal mass ejections (CMEs). The analytical drag based model covers the differences in speed as well as density between the CME and the ambient solar wind flow. In addition it takes into account the size of the CME. The method is described in detail in Vršnak and Žic (2007, A&A, 472, p.937), the evaluation of the tool is given in Vršnak et al. (2014, APJSS, 213, id.21), the further development of the tool is published in Žic, Vršnak, and Temmer, 2015 (ApJSS, 218, id.32).

Options:

- **Real-time (DBM+ESWF)** combines the results from the solar wind forecast and gives the current interplanetary conditions in which an 'almost real-time' CME might propagate (Note that this option is only meaningful for Earth-directed CMEs).
- **Custom (DBM)** uses the interplanetary conditions and individual targets as given by the user
- **Documentation** includes a manual and further references for interested users

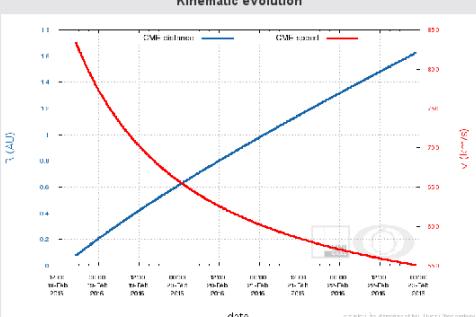
Results from calculation:

- CME arrival time and impact speed as well as travel time are given
- $v(R)$ and $R(t)$ plots as well as an animation of the CME geometry as propagating in interplanetary space is shown
- A zip file containing numerical and visual results can be downloaded

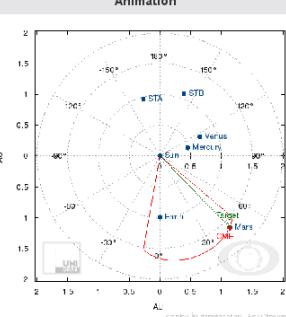
Please use the [ESA service](#) for calculating CME forecasts using the DBM.

Example output:

Kinematic evolution



Animation

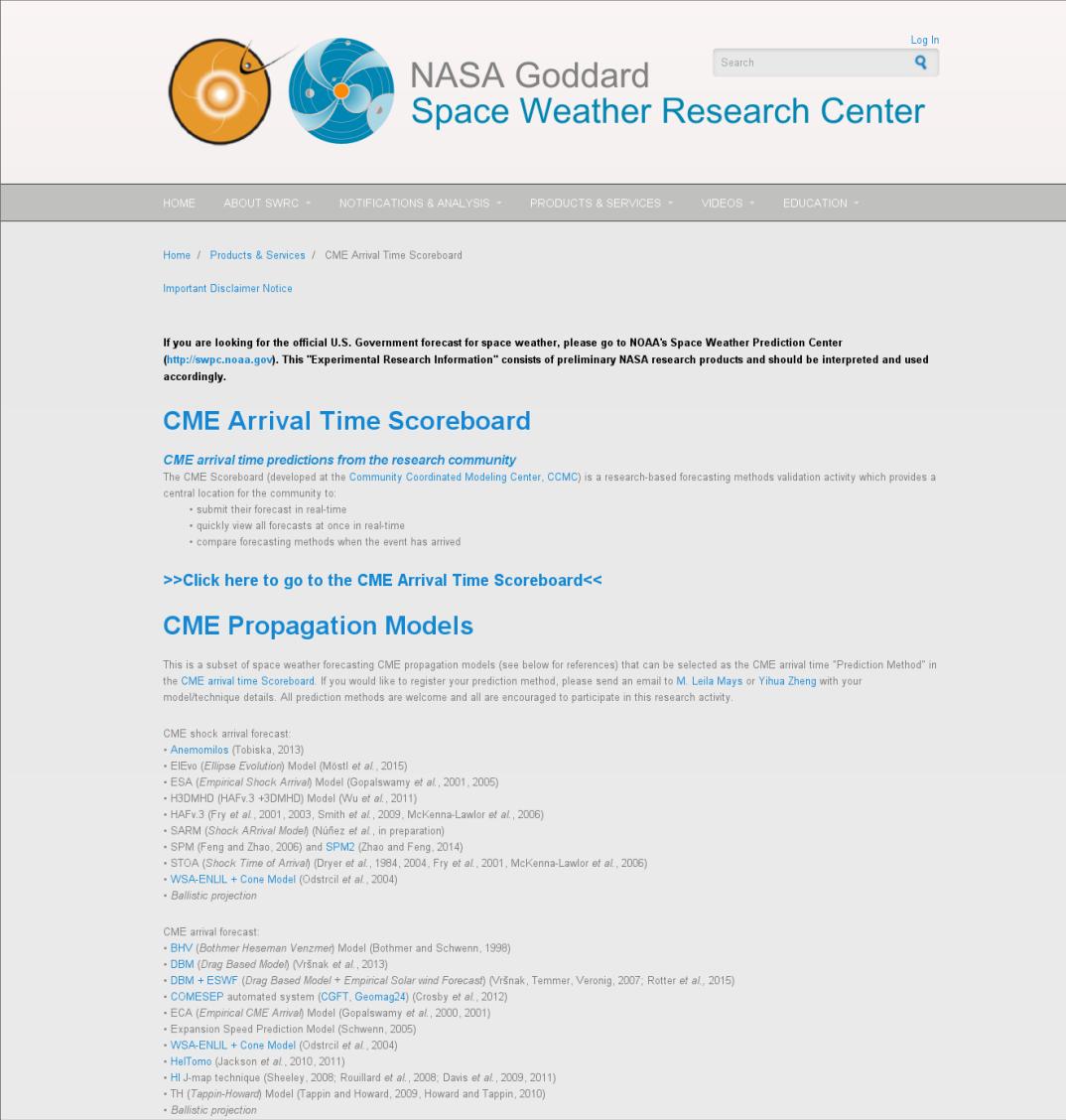


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[Follow @halocme](#)

Primjena DBM s $w=konst.$ i SS-širenjem na međunarodnim stranicama za prognostiku

NASA Space Weather Research Center – CME Arrival Time Scoreboard:
<http://swrc.gsfc.nasa.gov/main/cmemodels>



The screenshot shows the homepage of the NASA Goddard Space Weather Research Center. At the top, there are two circular icons: one orange with a sun-like center and one blue with a spiral pattern. To the right of these icons, the text "NASA Goddard" and "Space Weather Research Center" is displayed. A search bar and a "Log In" button are also present. Below the header, a navigation menu includes links for HOME, ABOUT SWRC, NOTIFICATIONS & ANALYSIS, PRODUCTS & SERVICES, VIDEOS, and EDUCATION. The main content area has a breadcrumb trail: Home / Products & Services / CME Arrival Time Scoreboard. It features a section titled "Important Disclaimer Notice" with a link to the official U.S. Government forecast at NOAA's Space Weather Prediction Center. Below this, a section titled "CME Arrival Time Scoreboard" contains a sub-section for "CME arrival time predictions from the research community". It describes the CME Scoreboard as a research-based forecasting methods validation activity and lists several prediction models. A link "=>Click here to go to the CME Arrival Time Scoreboard<<" is provided. Another section, "CME Propagation Models", discusses a subset of space weather forecasting models. A list of CME shock arrival forecasts is provided, including models like BHV, DBM, and EISWF. A "CME arrival forecast" section lists various models such as HIJ-map technique, TH (Tappin-Howard) Model, and Ballistic projection.

Primjena DBM s $w=konst.$ i SS-širenjem na međunarodnim stranicama za prognoziku

NASA Space Weather Database Of Notifications, Knowledge, Information (DONKI):
<http://kauai.ccmc.gsfc.nasa.gov/DONKI/>

Related Links | Frequently Asked Questions | Community Feedback | Downloads | Sitemap

About | Models at CCMC | Request A Run | View Results | Instant Run | Metrics and Validation | Education | R2O Support | Mission Support | Community Support |

Request Procedures | Generate Input Data Files & Parameters | Movies on Request | About the Run Process | Publications Policy

**Forecasting the Arrival of ICMEs:
The Drag-Based Model with constant w and y**

CME take-off date: May 23 2016

CME take-off time (UTC): 16 h 02 min

y - drag parameter: 0.2 $\times 10^{-7} \text{ km}^{-1}$

w - asymptotic solar wind speed: 450 km/s

R_\odot - starting radial distance of CME: 20 r_\odot

v_\odot - speed of CME at R_\odot : 1000 km/s

Select target from the list: Earth

© Tomislav Žic, Hvar Observatory, 2013

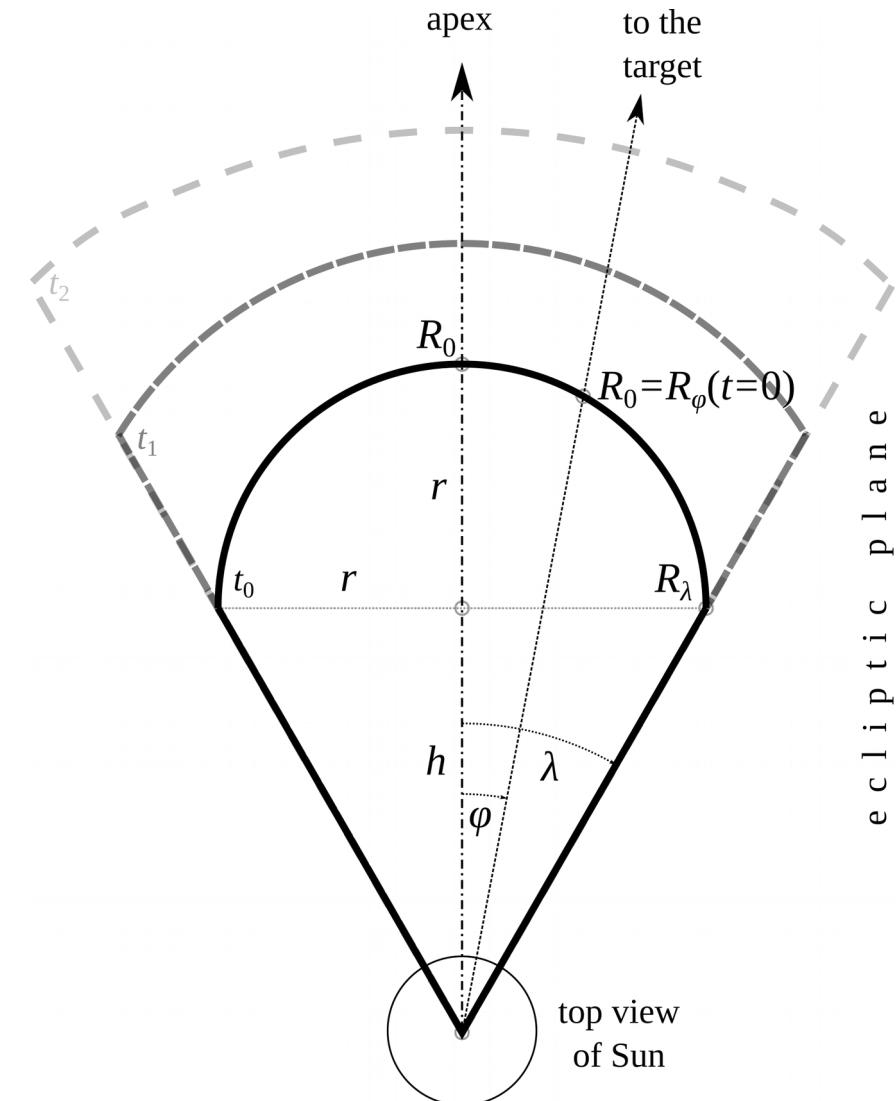
NASA NOAA NSB MDR

Curator: Anna Chulaki | NASA Official: Dr. Masha Kuznetsova | Privacy, Security Notices

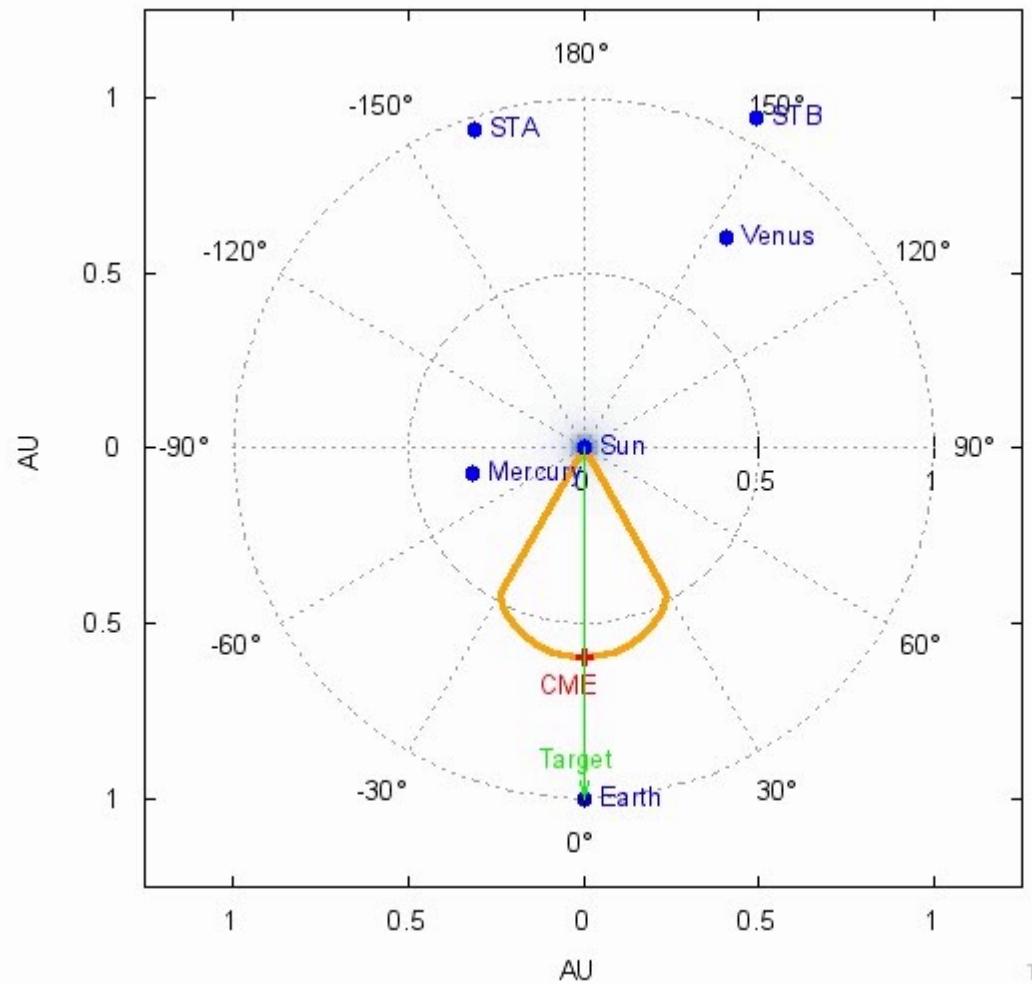
CCMC logo designed by artist Nana Bagdavadze

DBM s heliocentričnom funkcijom $w(R)$ i izravnjavanjem vodećeg luka CME-a

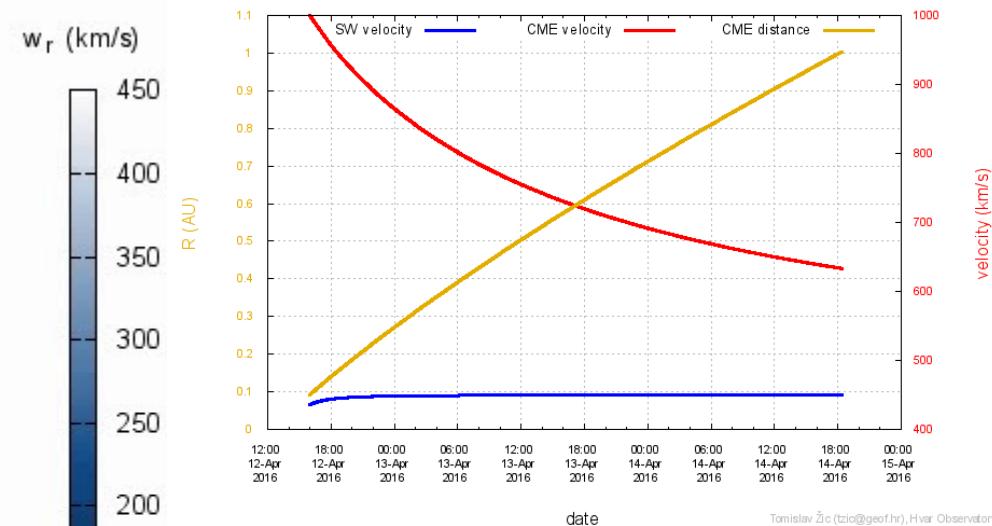
- Sunčev vjetar, w :
 - ovisi o heliocentričnoj udaljenosti R : $w(R)$
 - → parametar γ postaje također ovisan o heliocentričnoj udaljenosti: $\gamma(R)$
- svaki segment vodećeg luka (VL) CME-a giba se nezavisno
 - početna konusna konfiguracija se izravnava
 - suglasno s opažačkom činjenicom



Prikazi izračuna (za $w(R)$ i izravnjavanje VL) (<http://oh.geof.unizg.hr/~tomislav/DBM/>)



Tomislav Žic (tzic@geof.hr)



Rezultat:

- Dolazak CME do odabranog položaja (datum): 14.04.2016 u 18h:20min
- Vrijeme putovanja: 50.35 h
- Udarna brzina (at 1 AU): 633 km/s

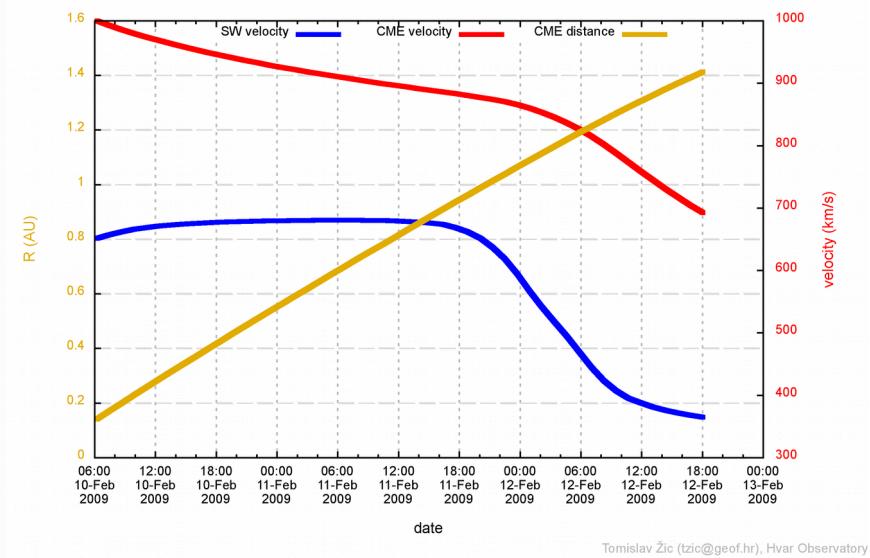
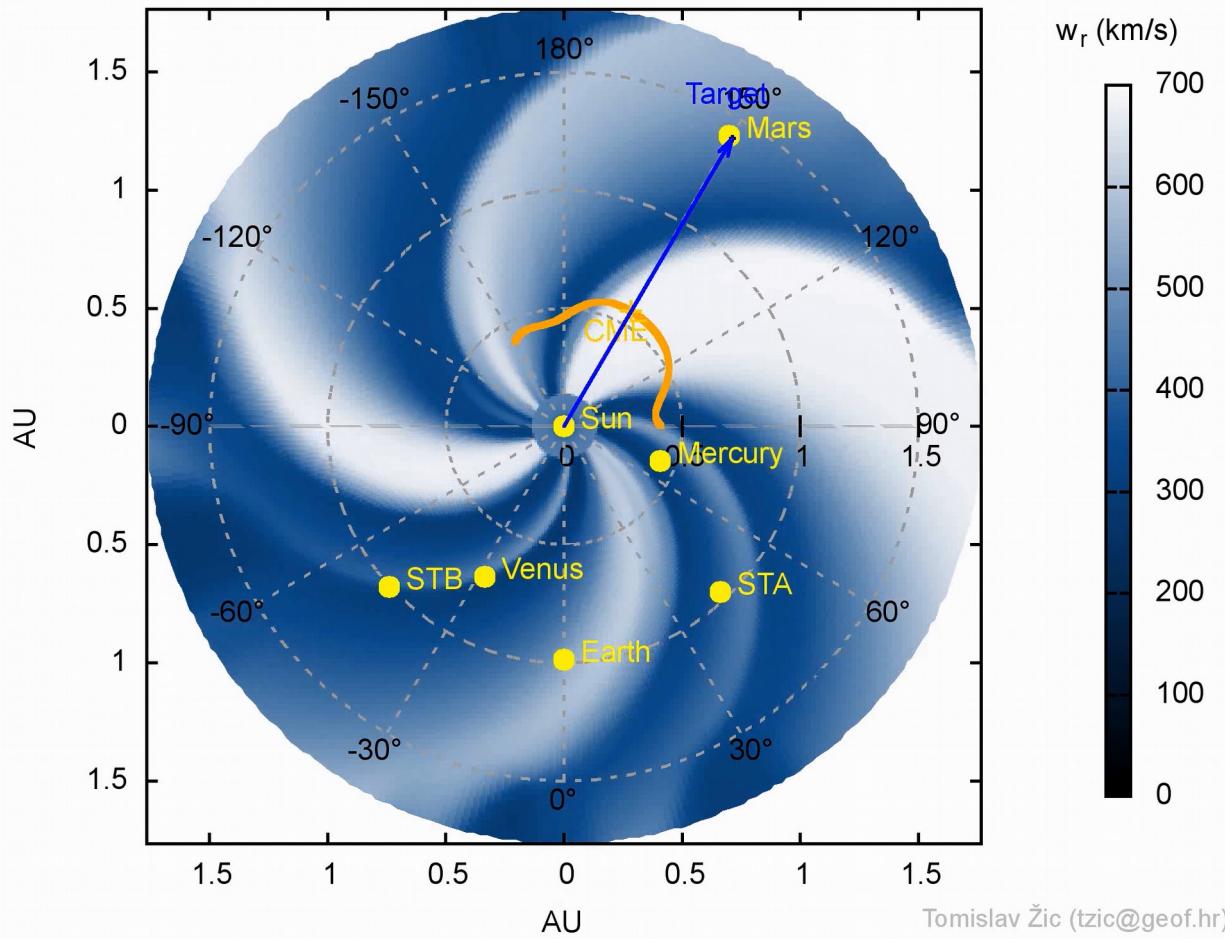
Ulagani parametri:

- Vrijeme početka erupcije: 12.04.2016 u 16h:00min
- $\gamma_\infty = 0.2 \times 10^{-7} \text{ km}^{-1}$, $w_\infty = 450 \text{ km/s}$,
- $R_0 = 20 r_S$, $v_0 = 1000 \text{ km/s}$,
 $\lambda = 30^\circ$, $\varphi_{\text{CME}} = 0^\circ$
- $R_{\text{target}} = 1 \text{ AU}$, $\varphi_{\text{target}} = 0^\circ$

Izračunato za 13.48 sekundi.

- LIJEVO: Širenje presjeka CME u eklitici
- DESNO: Kinematika '+ CME' segmenta u ekliptici

Primjer integracije DBM + ENLIL modela (<http://oh.geof.unizg.hr/~tomislav/DBM-ENLIL/>)



Tomislav Žic (tzic@geof.hr), Hvar Observatory

Općeniti model: $w(R)$, $\gamma(R)$ → pozadinski Sunčev vjetar intenzivno utječe na širenje CME

- parametar: $\Gamma = 0.2$
- početna CME udaljenost: $R_0 = 31 r_s$
- početna brzina CME-a: $v_0 = 1000 \text{ km/s}$
- kutna poluširina CME-a: $\lambda = 60^\circ$
- početna longituda erupcije CME-a: $\varphi = 150^\circ$
- „meta“: Mars

- LIJEVO: Presjek gibanja vodećeg luka CME-a u ekliptici. Erupcija započinje: 10. veljače 2009. u 06:13 UT.
- DESNO: Kinematika '+ CME' segmenta prema „meti“ (Marsu).

Minimizacija kvadratnog odstupanja

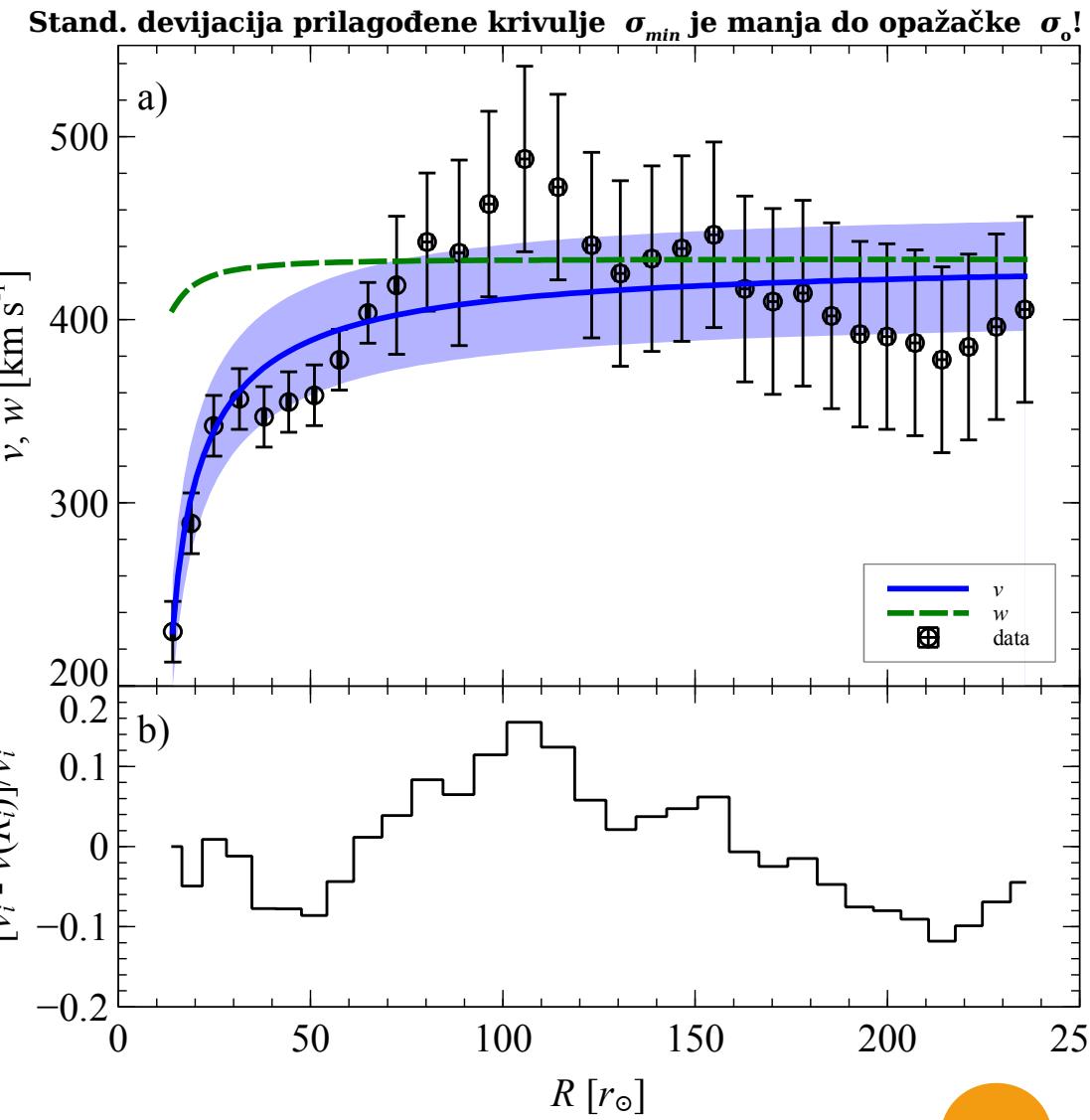
- ULAZNI parametri: skup vrijednosti opaženih ICME položaja i brzina $\{(R_0, v_0), \dots, (R_N, v_N)\}$
- IZLAZNI parametri: DBM vrijednosti $(\Gamma, w_\infty, R_0, v_0)$
- Metodom minimizacije kvadratnog odstupanja (engl. *the least-square fitting*):
– uzastopnom varijcijom DBM parametara
→ minimalno odstupanje između opaženih v_i i izračunatih vrednosti brzina $v(R_i)$ DBM metodom:

$$\sigma(\Gamma, w_\infty, R_0, v_0) = \sqrt{\frac{1}{(N+1)} \sum_{i=0}^N [v_i - v(R_i)]^2}$$

$$\rightarrow \sigma_{\min} \rightarrow$$

→ najbolji skup DBM vrijednosti:
 $(\Gamma, w_\infty, R_0, v_0)$

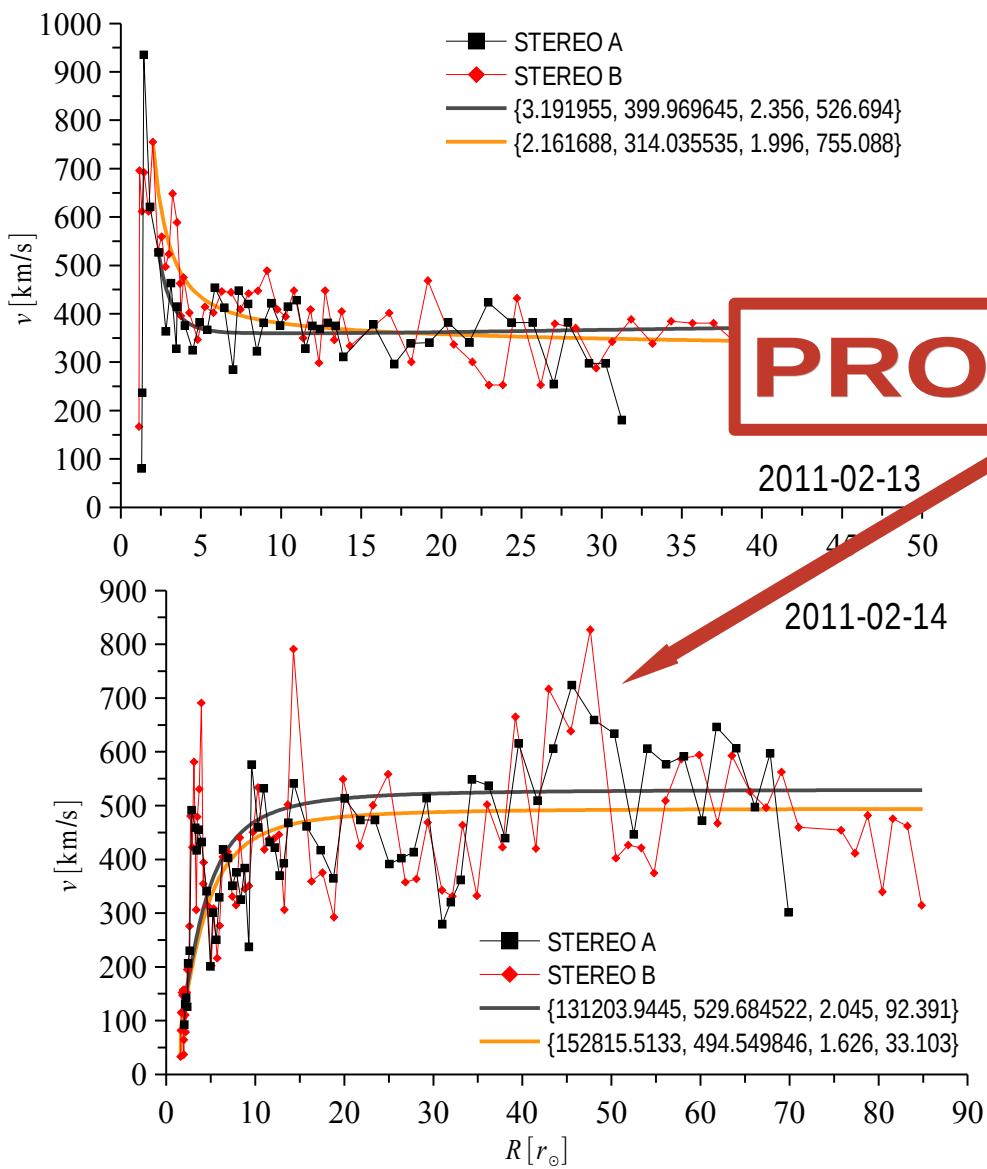
- pogodno za svemirsku prognostiku u realnom vremenu:
uzastopnim prilagođavanjem DBM krivulje podacima kako ICME propagira



Zaključak - općenita DBM propagacija izbačaja

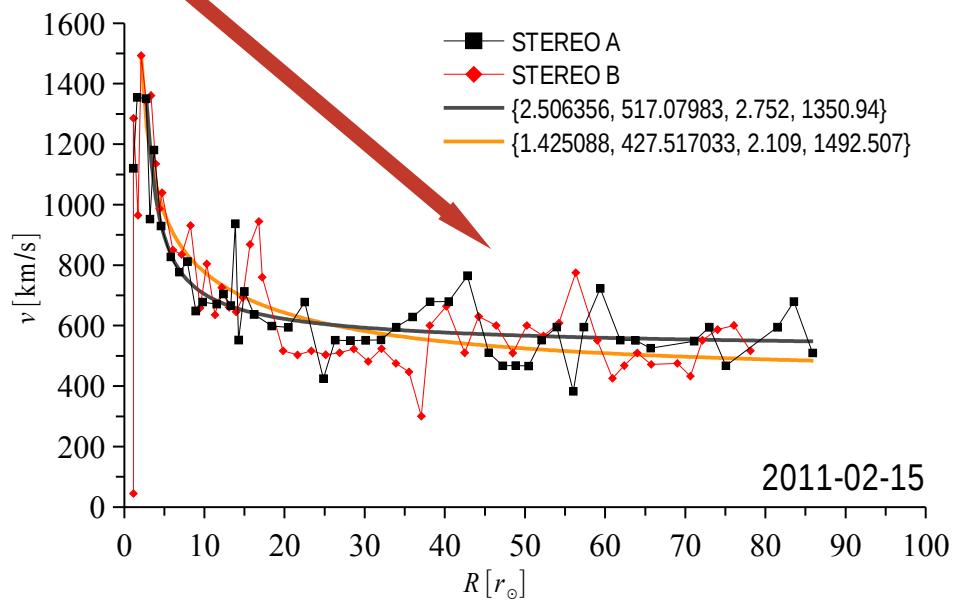
- Pogodnosti modela MHD otpora (The Drag-Based Model DBM):
 - jednostavan je, brz i prilagodljiv različitim situacijama
 - njegova točnost nije bitno lošija u usporedbi s drugim „naprednijim“ modelima (Vršnak et al., 2014)
 - prilagođen je brzom proračunu svemirske prognostike u realnom vremenu (Žic et al., 2015)
- Nedostaci:
 - magnetsko polje i Lorentzova sila nije uključena u model
 - CME-CME međudjelovanje je problematično za proračun
 - DBM nije potpuno prilagođen uporabi u kompleksnom i turbulentnom heliospeferskom okolišu
 - Hoće li DBM + ENLIL integracija dati bolje prognostičke rezultate?

Primjer na STEREO-A i STEREO-B podacima

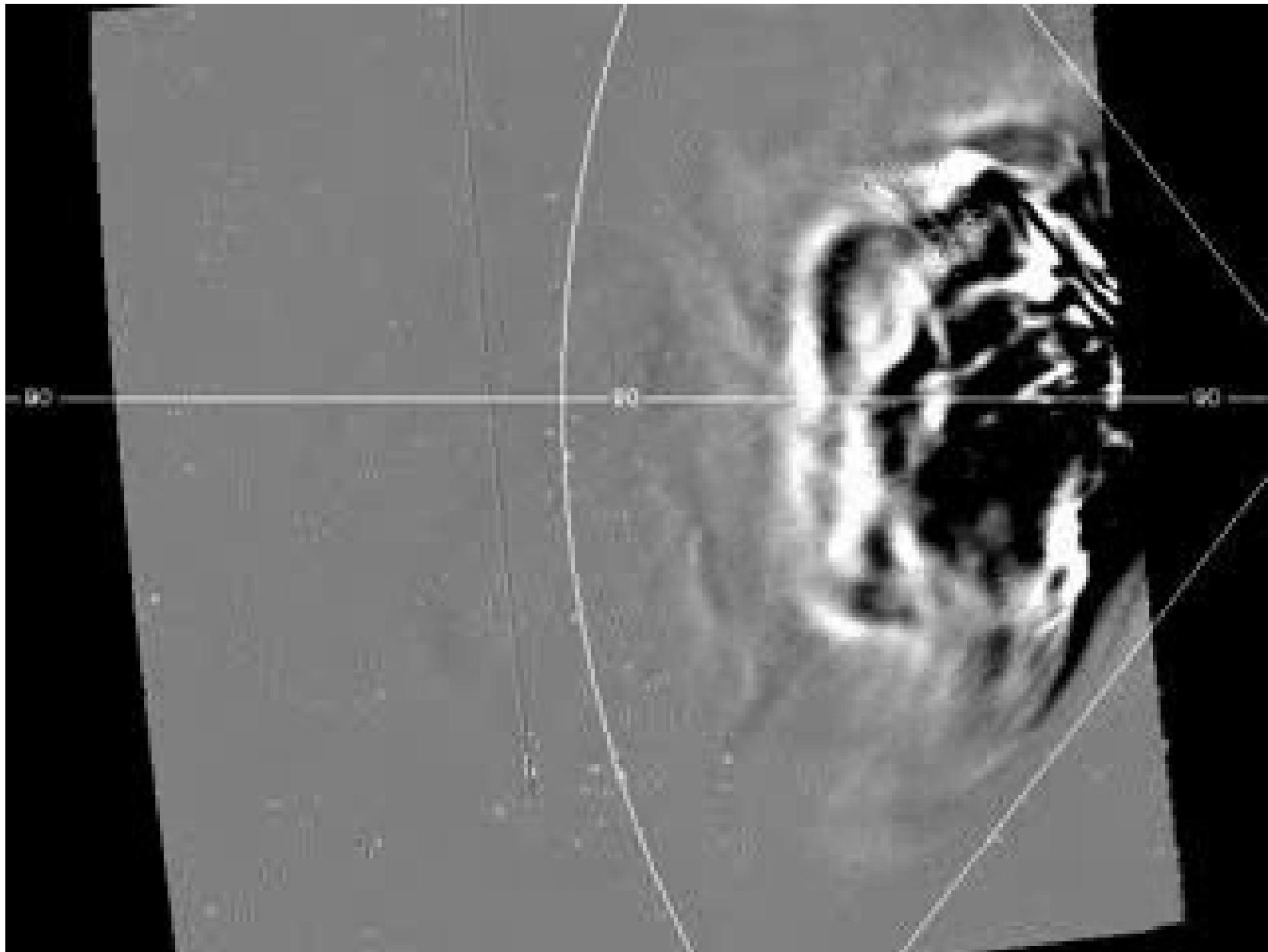


- **automatizacija:** minimizacijom kvadratnog odstupanja računske $v(R)$ krivulje i podataka s obzirom na bilo koju kombinaciju nepoznatih ulaznih parametara ($\Gamma, w_\infty, R_0, v_0$)

em nepoznatih parametara i
čkim traženjem minimuma
takve ukupne greške $E(\Gamma, w_\infty, R_0, v_0) \rightarrow$
parametri, kinematicka krivulja, tranzitne
vrijednosti



CME-CME međudjelovanje



Numerički izračun

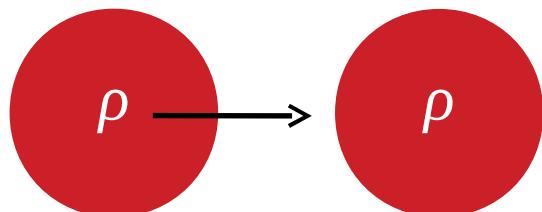
- VAC (Versatile Advection Code)
 - MHD, 2.5-D $[f(x,y); B = B_z]$, $\beta = 0$, Sunčev vjetar je u sustavu mirovanja
 - okolina: jednoliko polje: $B_0 = 1$, $\rho_0 = 1$, $v = 0$
(CME se giba u Sunčevom vjetru)



1)

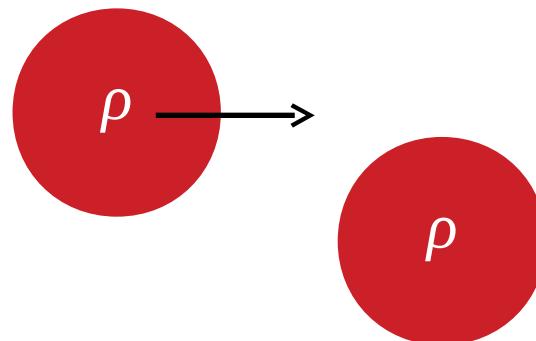
- udarni val \rightarrow CME u mirovanju:
- inicijacija udarnog vala: grad B
- **a)** $\rho = 10$; **b)** $\rho = 0.1$

c) CME \rightarrow CME direktni udar



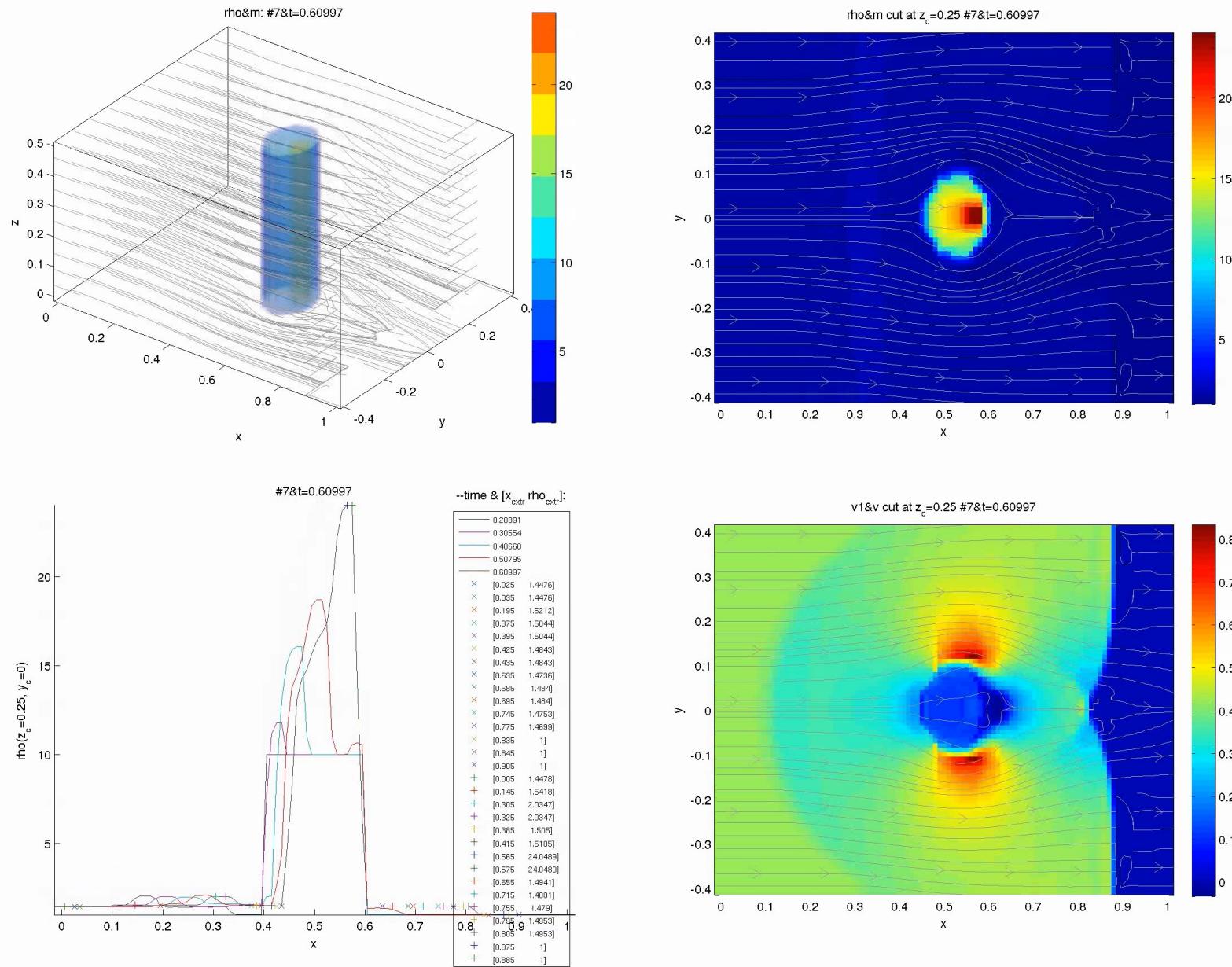
d) CME \rightarrow CME bočni udar

$$\rho = 2$$

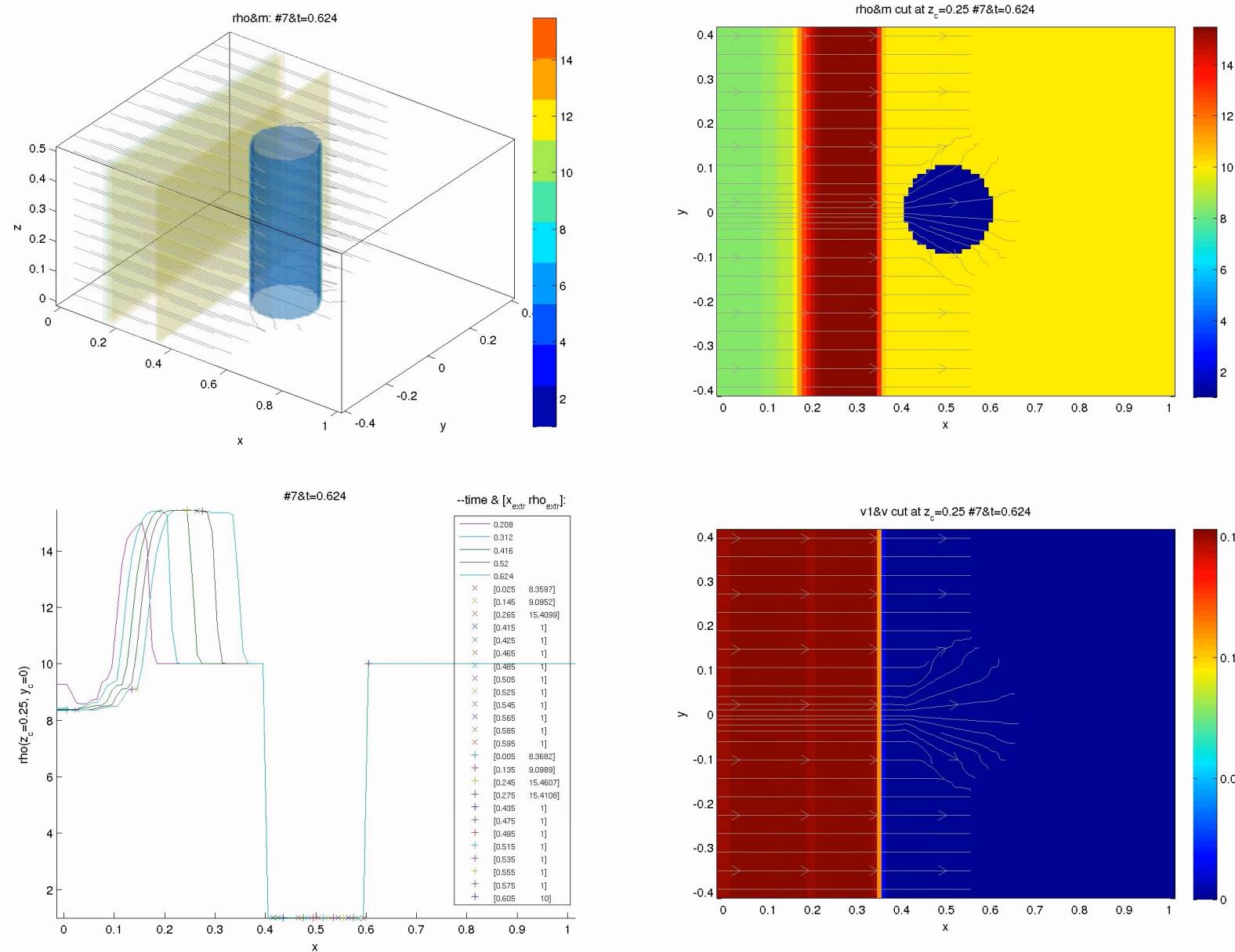


2)

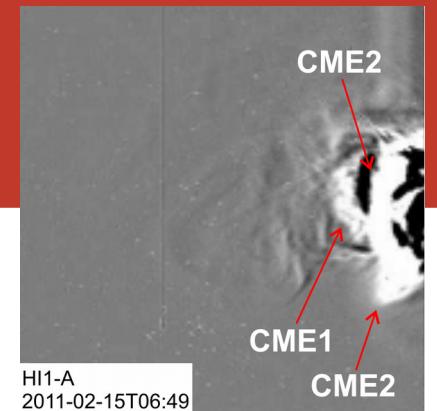
Udarni val nalijeće na „gusti“ CME



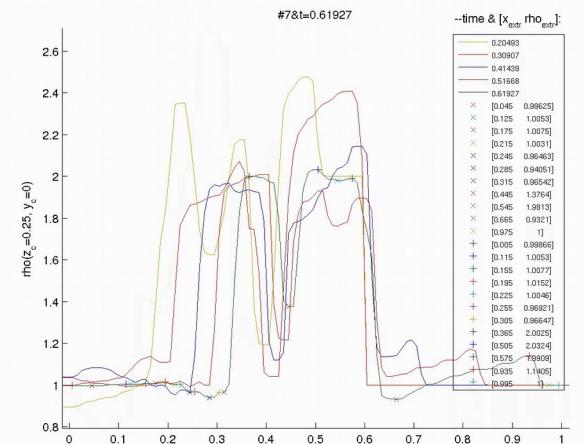
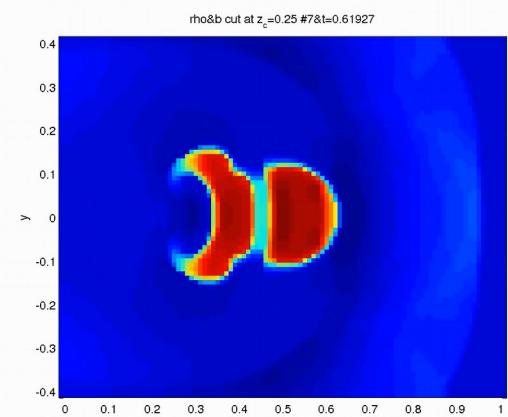
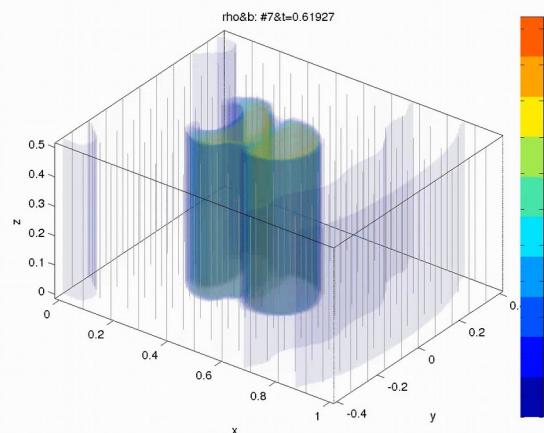
Udarni val nalijeće na „rijetki“ CME



CME-CME međudjelovanje

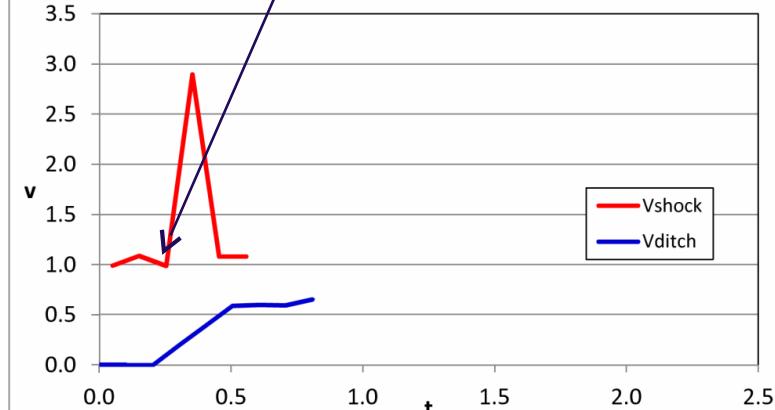
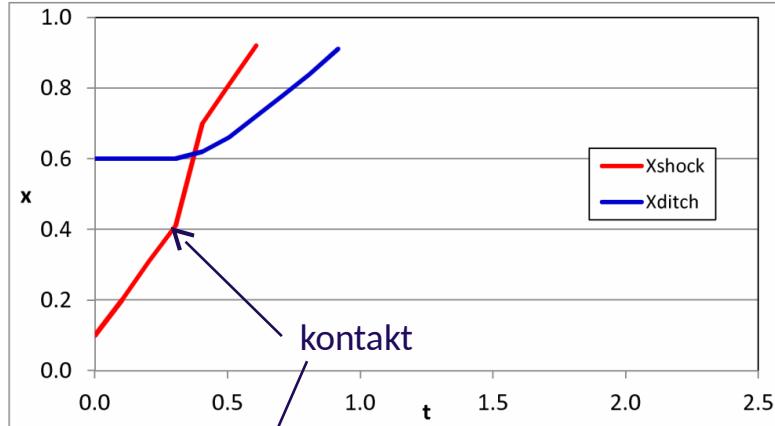
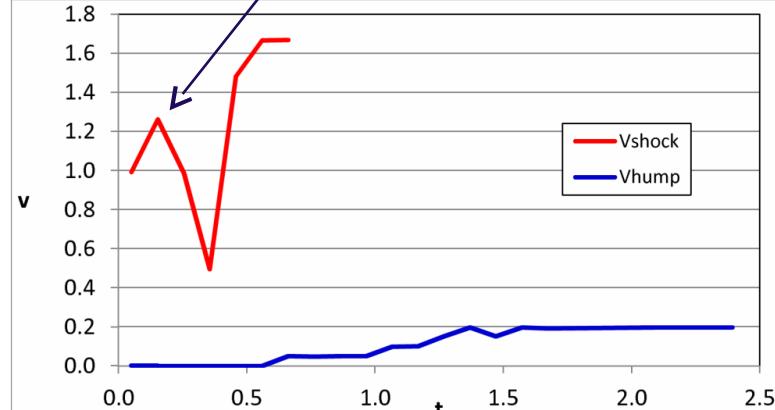
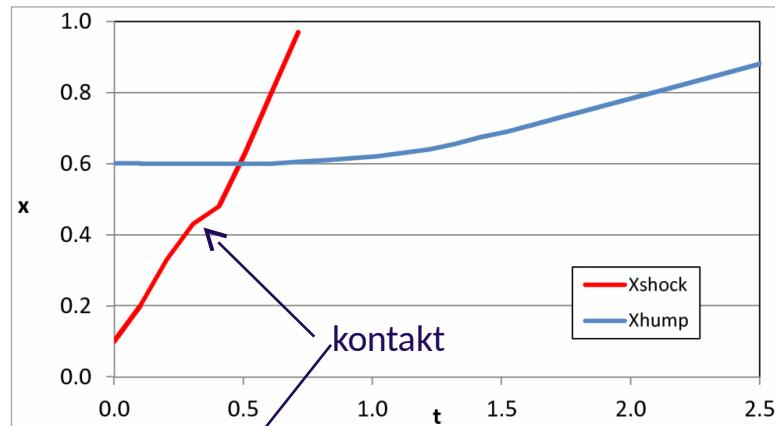
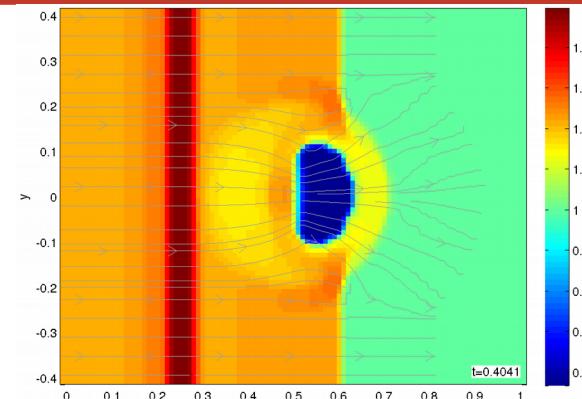
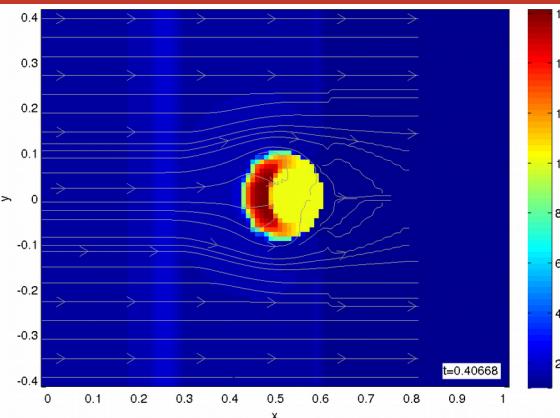


2c) direktni nalet



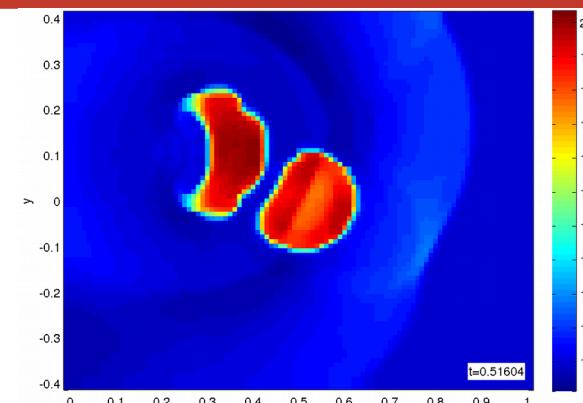
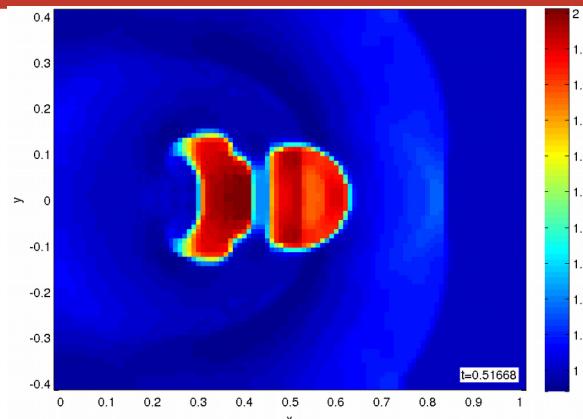
Udarni val → CME (gušći i rijedji)

CME je
gušći od
okoline

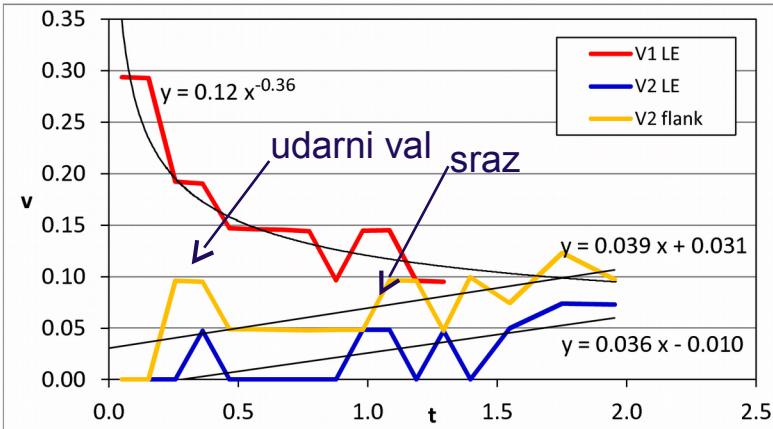
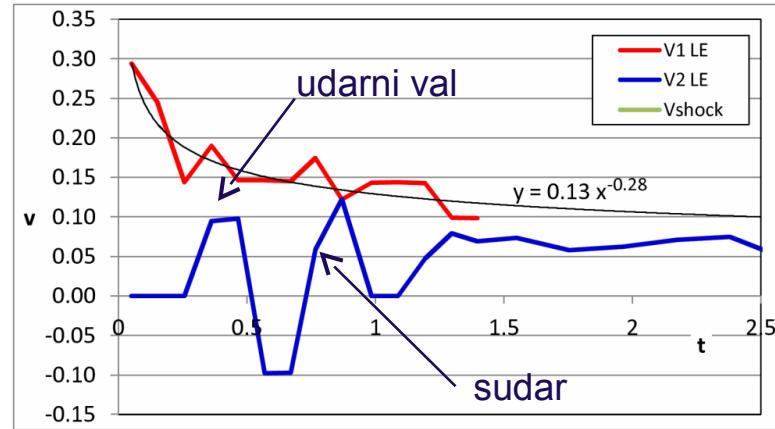
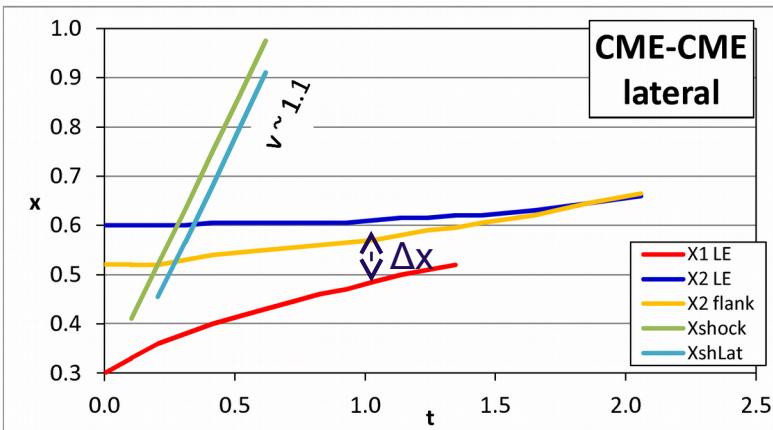
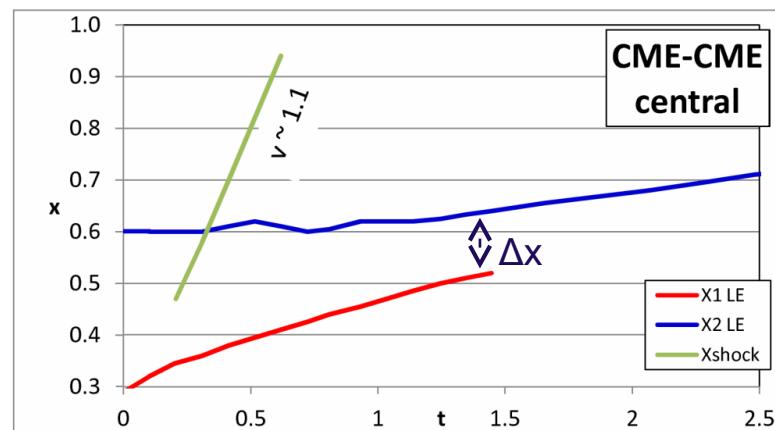


CME → CME (direktni i bočni sraz)

direktni
sraz



bočni
sraz



Zaključak - CME međudjelovanja

- nove era satelita za opažanje Sunce (npr. STEREO-A i -B) pokazala a su međudjelovanje između više CME-a češća nego što se mislilo
- potrebno nadograditi DBM model na osnovu numeričkih računa kako bi ugrubo uključio i posljedične efekte CME međudjelovanja
- očigledno, ovisno o masama ovisan im i sraz CME
- mase CME (odnosno γ parametre moguće je odrediti) iz početne kinematike („automatskom prognostikom“)
 - → dobiti γ parametre nakon sraza
 - → odrediti novu kinematiku CME-a

Hvala na
pažnji!