

Određivanje masa crnih rupa u aktivnim galaktičkim jezgrima pomoću polarizacije u širokim emisionim linijama

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- O supermasivnim crnim rupama (SMCR)
- Metode za određivanje masa SMCR
- Aktivna galaktička jezgra (AGJ)
- Reverberaciono mapiranje
- Polarizacija kod AGJ
- Merenje masa SMCR iz polarizacije
- Modelovanje STOKES-om
- Rezultati
- Zaključak

Supermasivne crne rupe

- Tipičan opseg masa $10^6 - 10^9 M_{\odot}$ (Kormendy & Richstone 1995)
- $E_{\text{bh}}/E_{\text{gal}} > 80$ (Fabian 2012)
- Jak uticaj SMCR na okolinu
- Zagrevanje i izbacivanje međuzvezdanog gasa
- Prestanak formiranja zvezda u centralnom ovalu
- Posmatrane korelacije $M_{\text{bh}} - \sigma_*$, $M_{\text{bh}} - L_{\text{bulge}}$ (Kormendy & Ho 2013)
- Koevolucija SMCR i galaksije domaćina (Heckman & Best 2014)

Direktne

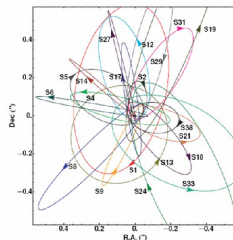
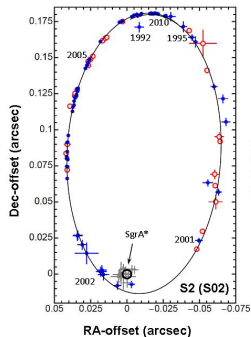
- Kretanje individualnih zvezda oko SMCR (Genzel et al. 2010; Meyer et al. 2012)
- Dinamika gasa (Miyoshi et al. 1995)
- Reverberaciono mapiranje kod AGJ (Blandford & McKee 1982; Bentz & Katz 2015)
- Iz polarizacije u širokim emisionim linijama kod AGJ (Afanasiev & Popovic 2015; Savic et al. 2018)

Indirektne

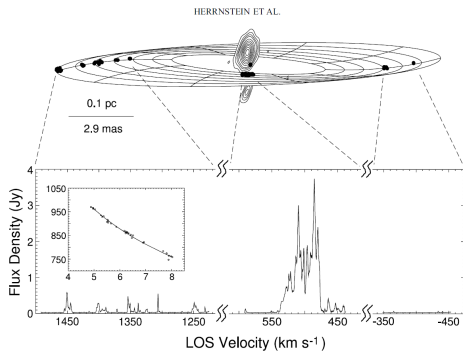
- Veličine koje su usko korelisane sa masom SMCR
- $M_{\text{bh}} - \sigma_*$ relacija (Ferrarese & Merritt 2000; Gebhardt et al. 2000a)
- $M_{\text{bh}} - L_{\text{bulge}}$ relacija (Kormendy & Richstone 1995; Magorian et al. 1998)
- $R - L$ relacija kod AGJ

Kretanje zvezda oko SMCR

- Metoda za sada moguća samo za našu galaksiju
- Posmatranja dugi niz godina sa Keck-a i VLT-a
- $M_{\text{bh}} = (4.30 \pm 0.20) \times 10^6 M_{\odot}$
- Genzel et al. 2010; Meyer et al. 2012

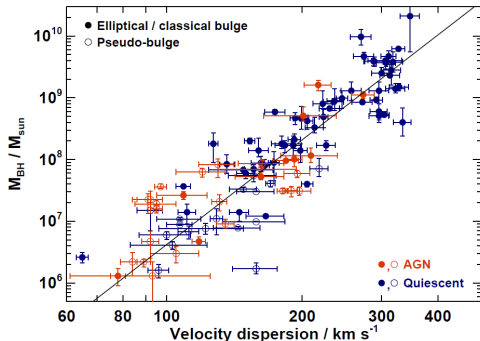


- NGC 4258
- Sopstveno kretanje i radialne brzine individualnih megamaserskih izvora
- Zakrivljen rotirajući disk
- $M_{\text{bh}} = (3.82 \pm 0.01) \times 10^7 M_{\odot}$ (Herrnstein et al. 2005)



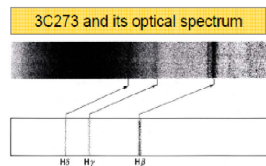
$M_{\text{bh}} - \sigma_*$ relacija

- Posmatra se disperzija brzine
- $M_{\text{bh}} \propto \sigma_*^{5.1}$
(McConnell et al. 2011)
- Stepen zavisi od tipa galaksija
- Posmatranje u jednoj epohi



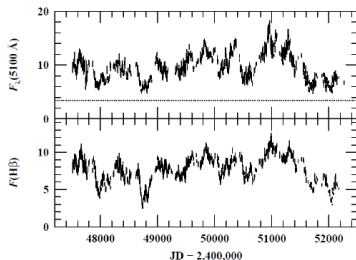
Heckman & Best 2014

- Karl Sajfert 1943.: Široke visoko jonizovane emisione linije kod nekih galaksija
- Marten Šmit 1963.: 3C273 je objekat sa $z = 0.158$
- Svega par procenata svih galaksija pokazuje jaku aktivnost u jezgru



Fizičke karakteristike

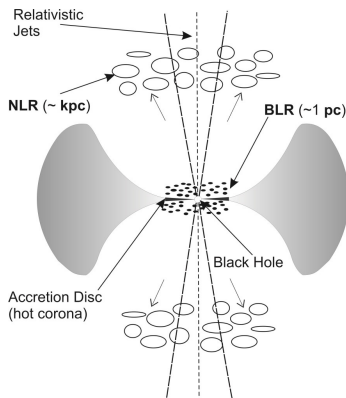
- Kompaktni objekti. Zapremina emitujućeg regiona je $\ll 1\text{pc}^3$
- Visoke luminoznosti: $L \sim 10^{42} - 10^{48} \text{ erg/s}$
- Pojačan kontinuum od gama i rentgenskog, do radio-zračenja
- Uočljive široke i uske emisijske linije
- Promenljivo zračenje
- Polarizovano zračenje
- Mnogo različitih tipova



NGC5548 Peterson et al. (2002)

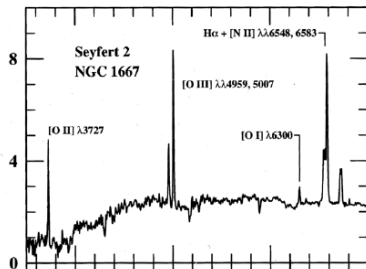
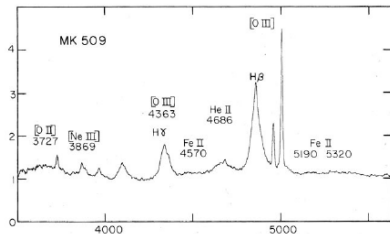
Objedinjeni model

- U centru je supermasivna crna rupa oko koje se vrši akrecija.
- Širokolinijski i uskolinjski regioni.
- Torus od prašine.
- Mlazevi.
- U zavisnosti od pravca posmatranja, vidimo različite objekte.
- Antonucci 1993; Urry & Padovani 1995



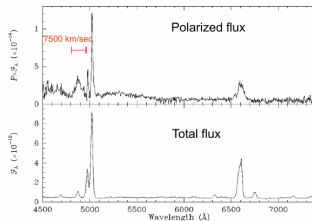
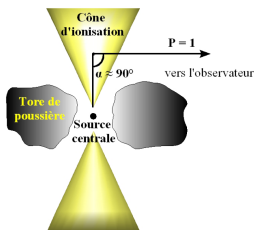
Optički pektar Sajfertovih galaksija

- Spiralne galaksije, izrazito sjajno jezgro.
- Najčešće tipa Sb ili SBb.

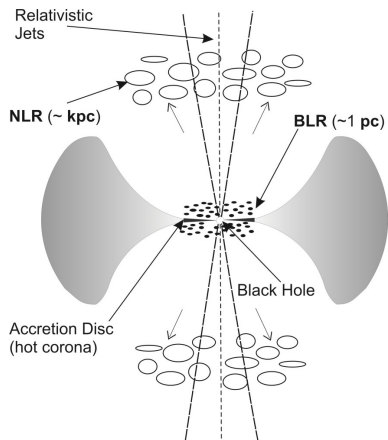


Posmatranja u polarizaciji

- Široke linije u polarizacionom spektru objekta NGC1068 (Antonucci & Miller 1985)
- Pogled kroz periskop u polarizovanom spektru.



Objedinjeni model

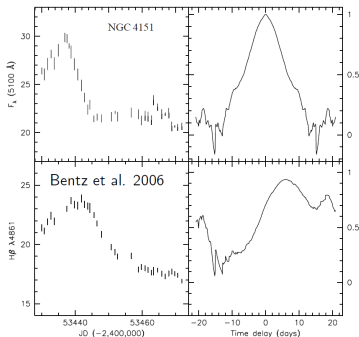


- BLR nije zaklonjen - tip-1 objekti, široke + uske emisione linije
- BLR je zaklonjen - tip-2 objekti, samo uske emisione linije

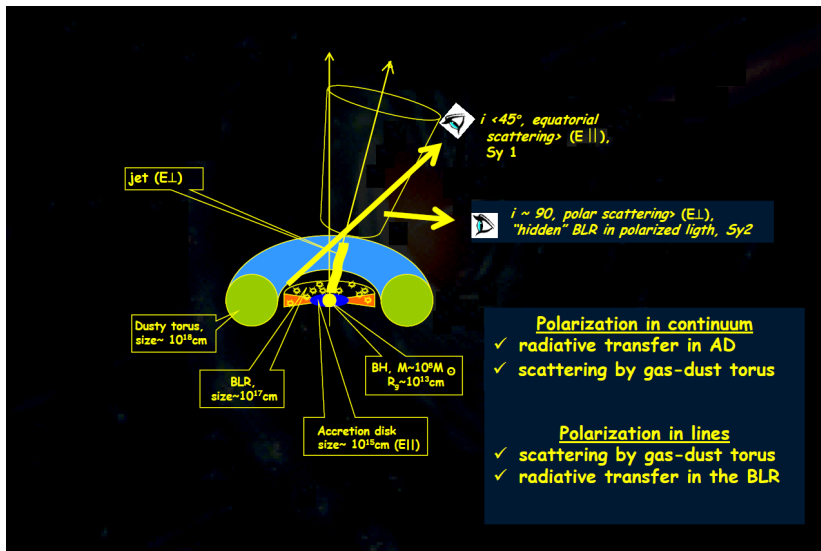
Reverberaciono mapiranje AG

- Matematički aparat Blandford & McKee (1982)
- Emisija BLR-a reaguje na emisiju kontinuuma
- Merenje vremenskog kašnjenja
- Jedna od najtačnijih metoda

$$M_{BH} = f \frac{c\tau V^2}{G}$$

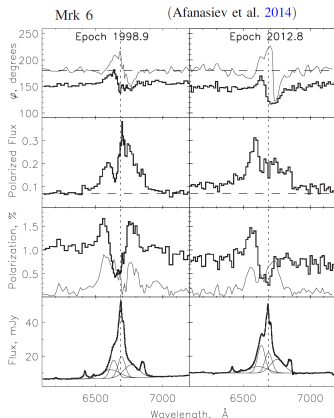


Ekvatorijalna i polarna polarizacija



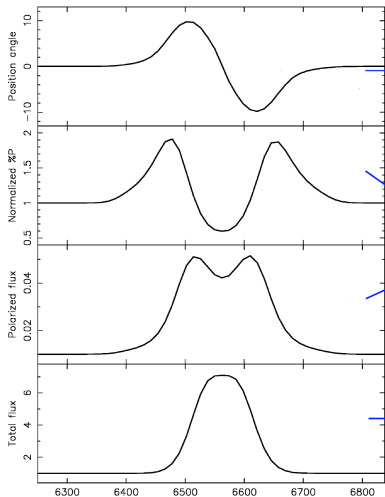
Polarizacija kod objekata tipa-1

- Rotacija polarizacionog pozicionog ugla ψ kao dokaz ekvatorijalnog rasejanja za objekte tipa-1
- Diskoliki BLR sa dominantnim Keplerovskim kretanjem
- Koplanarni rasejavajući region
- Slaba polarizacija, tipično nekoliko procenata



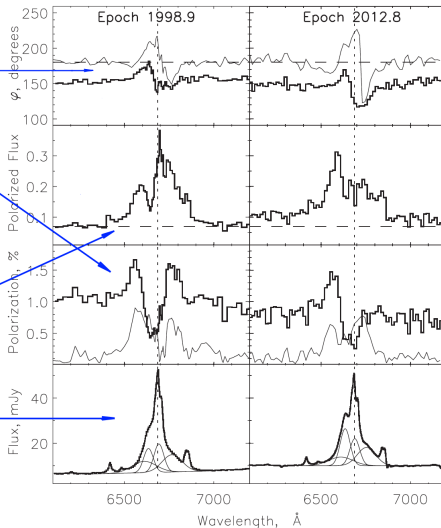
Polarizacija kod objekata tipa-1

Smith et al. 2005

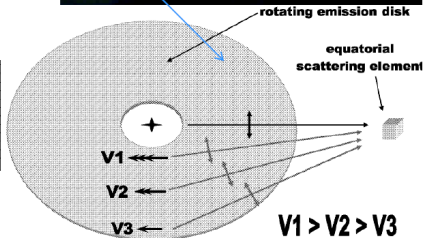
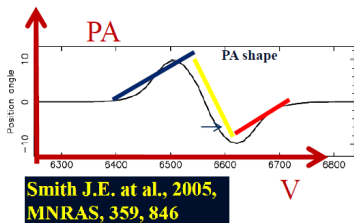
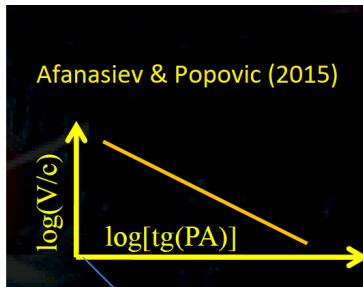
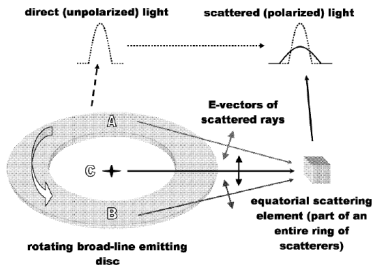


Mrk 6

Afanasiev et al. 2014

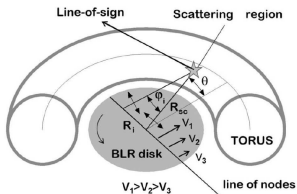


Polarizacija u širokim emisionim linijama



Određivanje masa SMCR iz polarizacije

- Afanasiev & Popovic (2015)
- Diskoliki BLR
- Aproksimacija jednog rasejanja

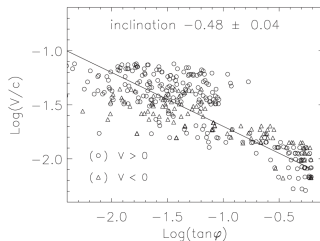
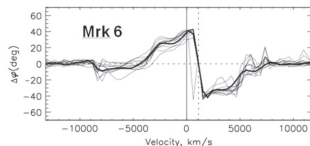


$$V_i = V_i^{\text{rot}} \cos(\theta) = \sqrt{\frac{GM_{\text{BH}}}{R_i}} \cos(\theta), \quad R_i = R_{\text{sc}} \tan(\varphi_i),$$

$$M_{\text{BH-kep}} = 10^{2a} \frac{c^2 R_{\text{sc}}}{G \cos^2(\theta)} = 1.78 \times 10^{2a+10} \frac{R_{\text{sc}}}{\cos^2(\theta)} M_{\odot},$$

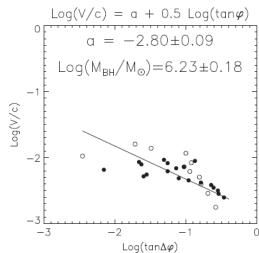
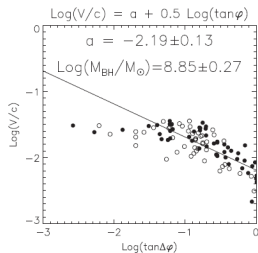
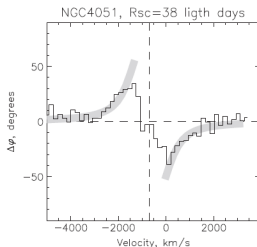
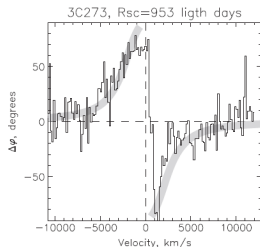
$$\log \frac{V_i}{c} = a - 0.5 \log(\tan(\varphi_i))$$

$$a = 0.5 \log \frac{GM_{\text{BH}} \cos^2 \theta}{c^2 R_{\text{sc}}}$$



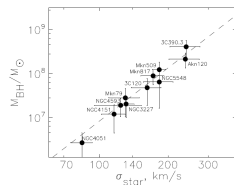
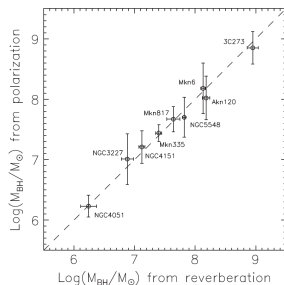
$$M_{\text{BH-kep}} = 1.53 \times 10^8 M_{\odot}$$

Određivanje masa SMCR iz polarizacije



Određivanje masa SMCR iz polarizacije

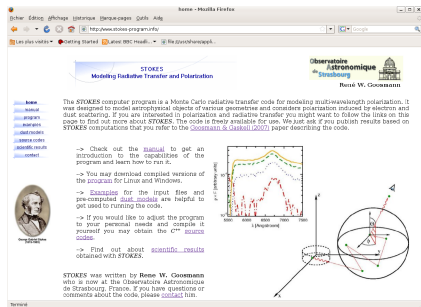
- Posmatranja u jednoj epohi.
- Dobro slaganje sa reverberacionim mapiranjem.
- Katalog od 30 objekata Afanasiev et al. 2018.
- Dobro slaganje sa $M_{\text{bh}} - \sigma_*$ relacijom.
- Primena na linije u drugom spektralnom opsegu.



- Proveriti mogućnosti i granice metode.
- Četiri generička modela sa zadatim masama: $10^6, 10^7, 10^8, 10^9 M_{\odot}$.
- Direktno modelovanje za NGC 4051, NGC 4151, 3C 273 i PG0844+349 sa posmatračkim podacima.
- Poređenje sa rezultatima iz posmatranja.

Modelovanje programom STOKES

- 3D MonteCarlo prenos zračenja sa kinematikom.
- Različite geometrije za emisione rasejavajuće regione.
- Polarizacija usled višestrukih rasejanja na elektronima (Tomsonovo) i prašini (Mievo).
- Goosmann & Gaskell (2007); Marin et al. (2012, 2015); Rojas et al. (2018)



The screenshot shows the homepage of the STOKES program. At the top, it says "STOKES Modeling Radiative Transfer and Polarization". Below this, there is a list of links: [HOME](#), [NEWS](#), [INSTALL](#), [EXAMPLES](#), [PARAMETERS](#), [ABOUT STOKES](#), [SCIENTIFIC RESULTS](#), and [CONTACT](#). The main text describes the program as a Monte Carlo radiative transfer code for modeling multi-wavelength polarization. It includes a small portrait of a man and a diagram of a sphere with coordinate axes and a path. There is also a graph showing intensity versus wavelength.

The STOKES computer program is a Monte Carlo radiative transfer code for modeling multi-wavelength polarization. It was designed to model astrophysical objects of various geometries and considers polarization induced by electron and dust scattering. If you are interested in polarization and radiative transfer you might want to follow the links on this page to find out more about STOKES. The code is freely available for use. We just ask if you publish results based on STOKES computations that you refer to the [Goosmann & Gaskell \(2007\)](#) paper describing the code.

- > Check out the [manual](#) to get an introduction to the capabilities of the program and learn how to run it.
- > You may download compiled versions of the program for Linux and Windows.
- > [Examples](#) for the input files and pre-compiled [dust models](#) are helpful to get used to running the code.
- > If you would like to adjust the program to your personal needs and compile it yourself you may obtain the [C++ source code](#).
- > Find out about [scientific results](#) obtained with STOKES.

STOKES was written by [Rene W. Goosmann](#) who is now at the Observatoire Astronomique de Strasbourg, France. If you have questions or comments about the code, please [contact](#) him.

Modelovanje programom STOKES

$$S_0 = I$$

$$S_1 = Ip \cos 2\psi \cos 2\chi$$

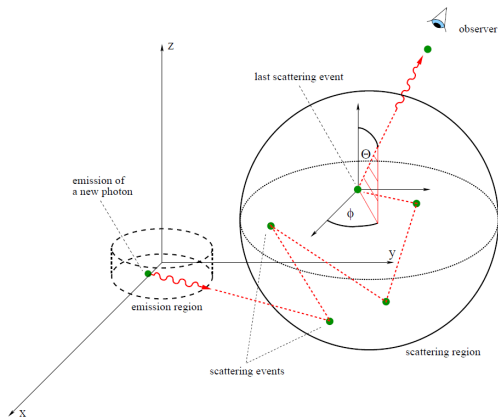
$$S_2 = Ip \sin 2\psi \cos 2\chi$$

$$S_3 = Ip \sin 2\chi$$

$$\begin{pmatrix} I^{out} \\ Q^{out} \\ U^{out} \\ V^{out} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{44} \end{pmatrix} \begin{pmatrix} I^* \\ Q^* \\ U^* \\ V^* \end{pmatrix}$$

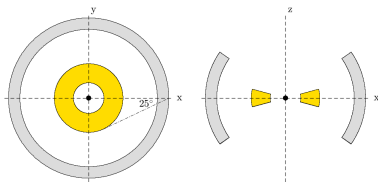
$$P = \frac{\sqrt{\hat{Q}^2 + \hat{U}^2 + \hat{V}^2}}{\hat{I}}$$

$$\psi = \frac{1}{2} \arctan \frac{\hat{U}}{\hat{Q}}$$



Modelovanje programom STOKES

- Tačkasti izvor izotropnog zračenja u kontinuumu, $F_\nu \propto \nu^{-2}$.
- Ugao poluotvora za BLR i SR su 15° and 35° respektivno.
- Unutrašnji radijus za BLR iz reverberacije u optičkom (Peterson et al. 2004, Kaspi et al. 2005, Bentz et al. 2006).
- Spoljašnji radijus za BLR usled sublimacije prašine $R_{\text{out}}^{\text{BLR}} = 0.2 L_{\text{bol},46}^{0.5}$. Bolometrijska korekcija iz Runnoe et al. (2012).
- Unutrašnji radijus za SR iz reverberacije prašine (Kishimoto et al. 2011, Koshida et al. 2014).



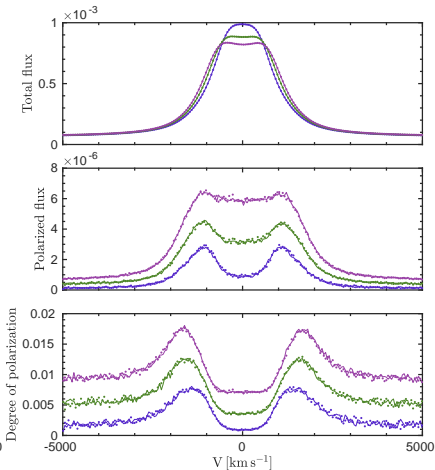
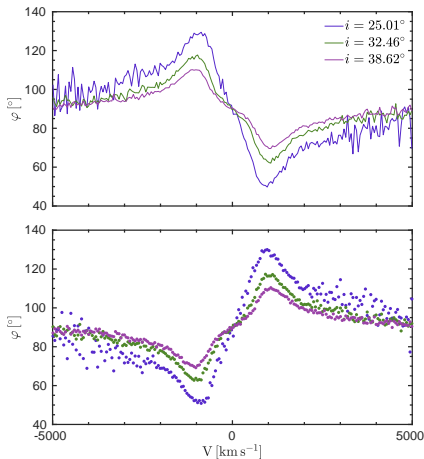
Modelovanje programom STOKES

- 14 AGJ sa poznatim masama, unutrašnjim i spoljašnjim radijusom BLR and SR.
- Relacija masa-radijus kao stepeni zakon.

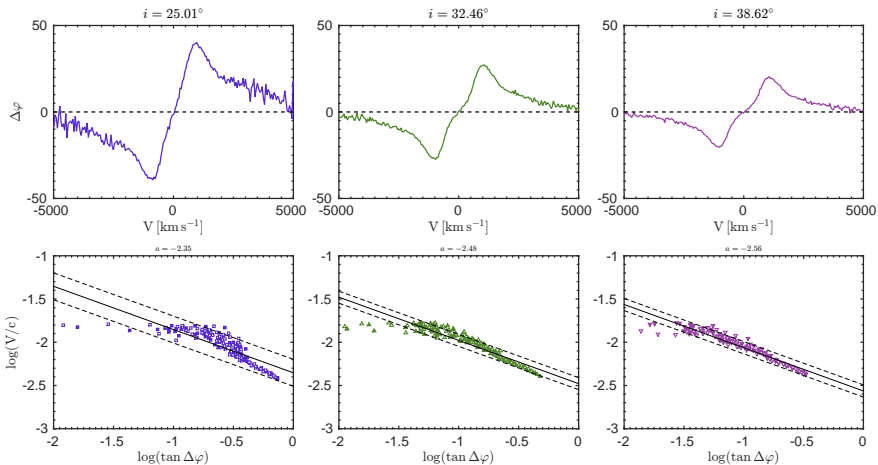
Mass	r_{in} (BLR)	r_{out} (BLR)	R_{in} (SR)	R_{out} (SR)
M_{\odot}	ld	ld	ld	ld
10^6	1.597	4.385	13.968	20.262
10^7	7.681	16.076	51.372	74.277
10^8	36.944	58.934	188.939	272.288
10^9	177.700	216.043	694.893	998.170

- Korišćen klaster Fermi na AOB sa 120 procesora.
- Mesocenter, za HPC u Strazburu, oko 30 procesora.

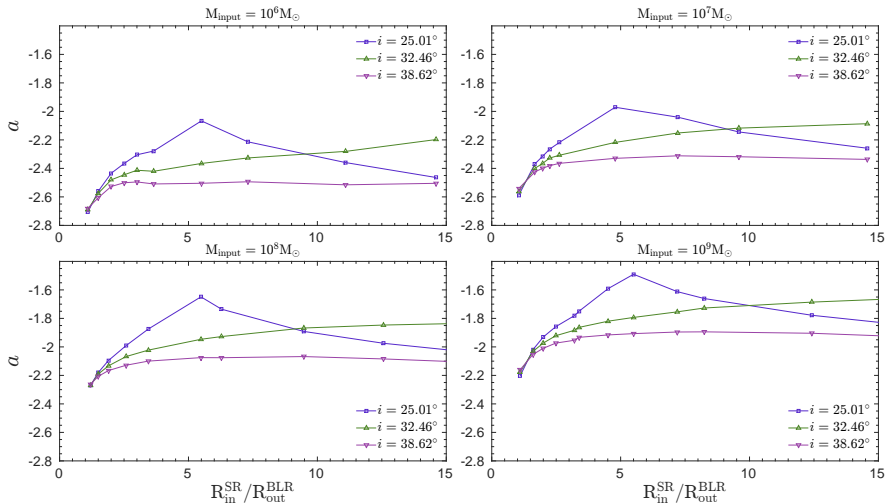
Generički model za $10^6 M_{\odot}$.



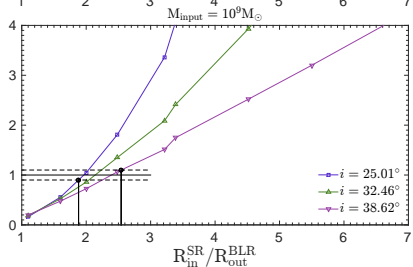
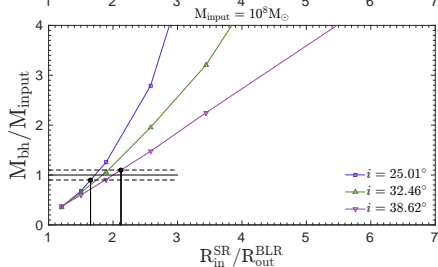
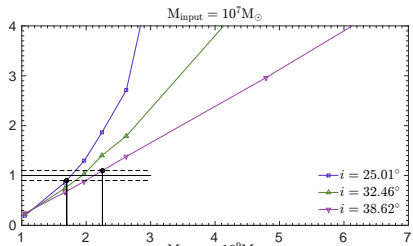
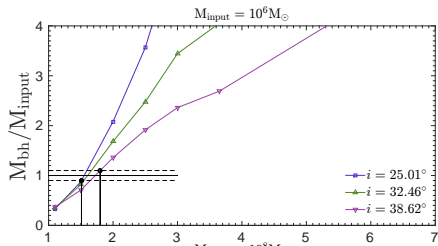
Generički model za $10^6 M_{\odot}$.



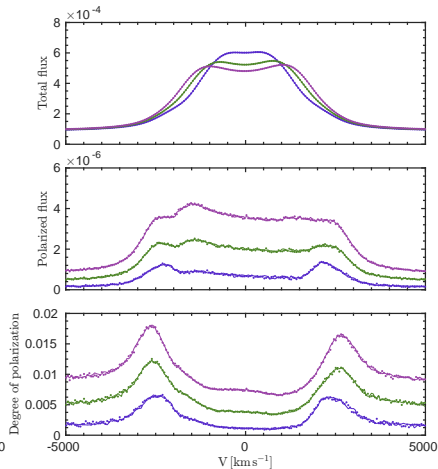
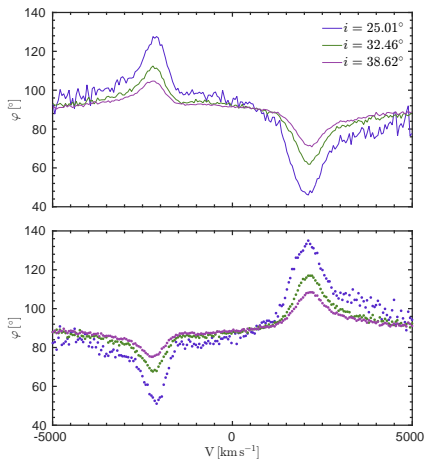
Uticaj međusobnog rastojanja između BLR i SR



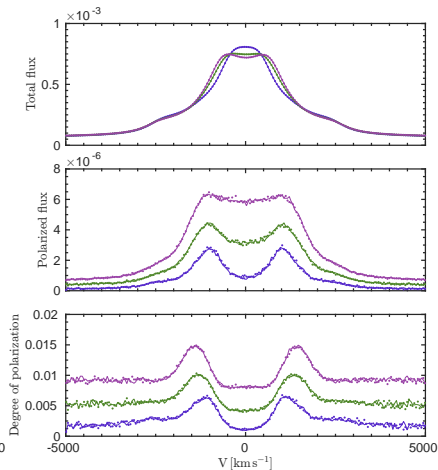
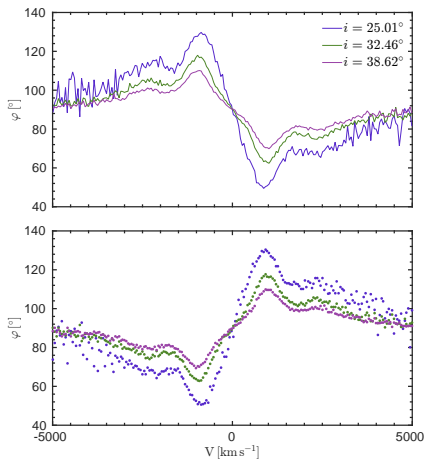
Uticaj međusobnog rastojanja između BLR i SR



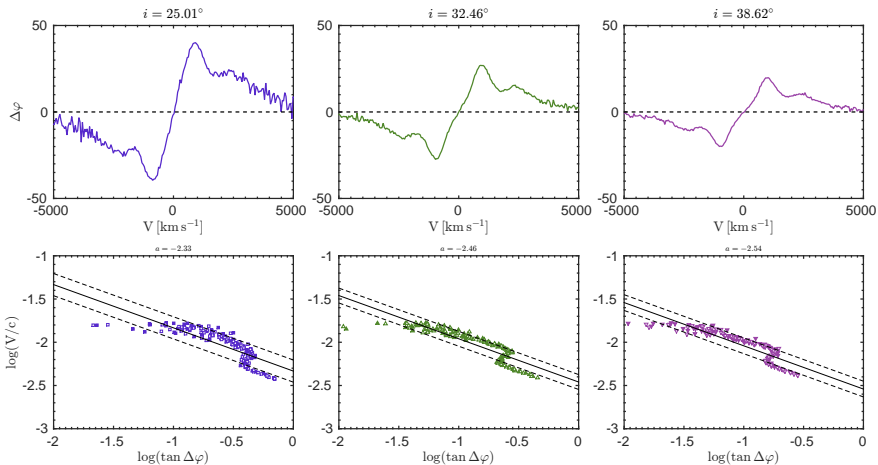
Uticaj radijalnih priliva



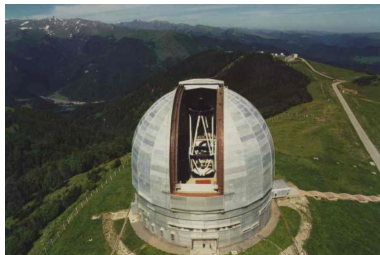
Uticaj verikalnih oticanja



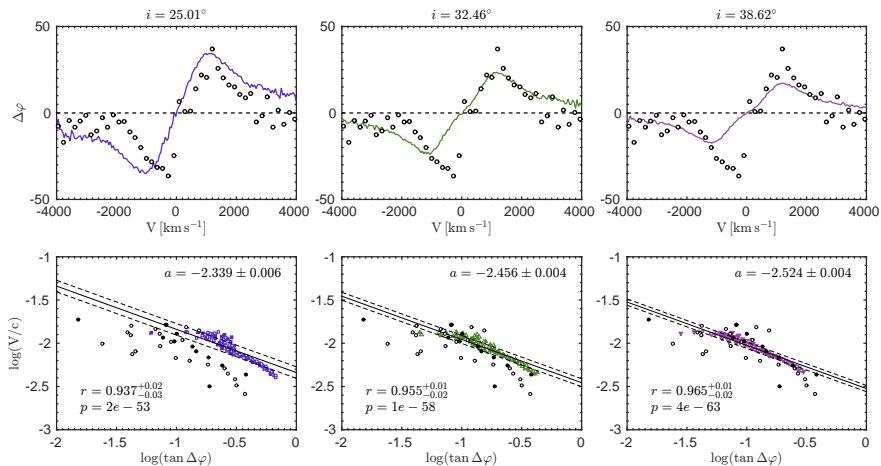
Uticaj verikalnih oticanja



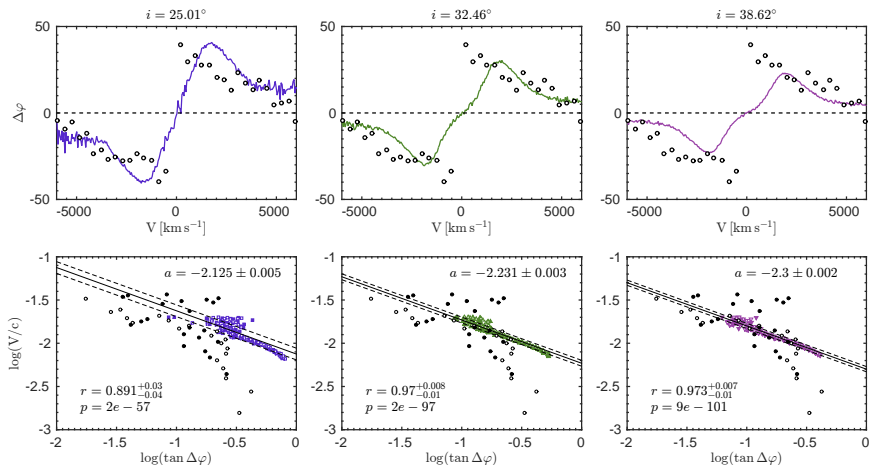
- Spektropolarimetrija sa 6 m-skim teleskopom na SAO RAS sa montiranim SCORPIO spektrografom (see Afanasiev & Moiseev 2005, 2011).
- Obračunat uticaj međuzvezdane polarizacije Afanasiev & Amirkhanyan (2012)



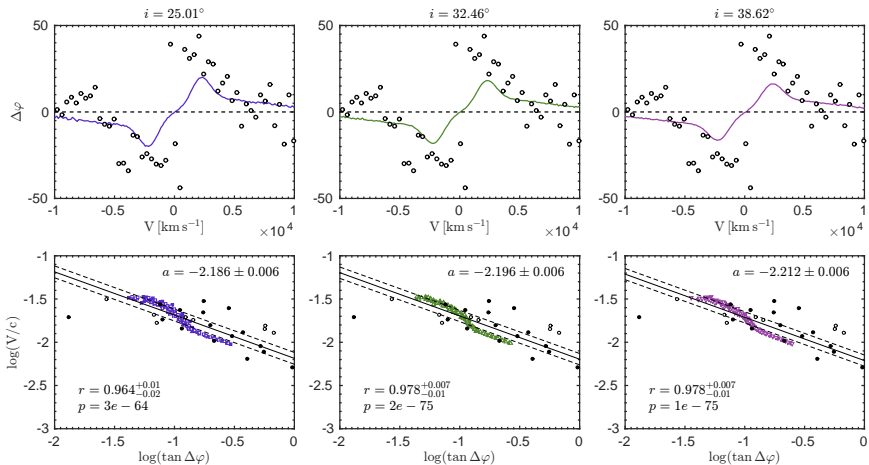
NGC4051 - model



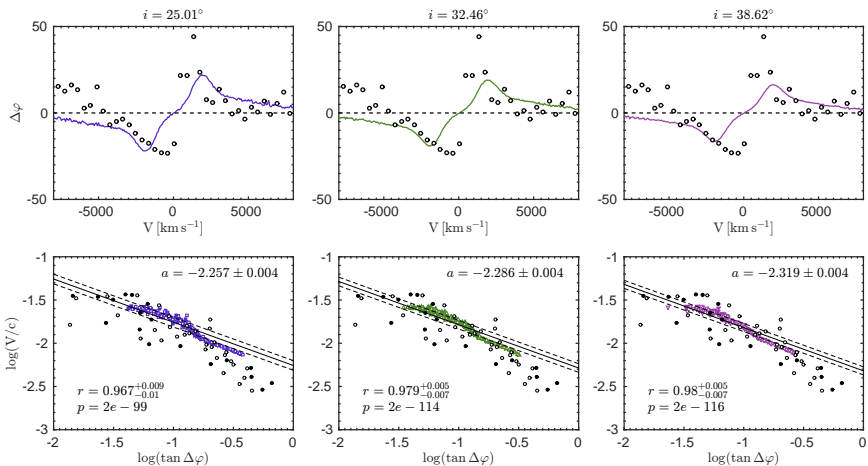
NGC4151 - model



3C273 - model



PG0844+349 - model



Poređenje rezultata i modela

Object	$\theta(^{\circ})$	$\log(M_{\text{MOD}}/M_{\odot})$	$\log(M_{\text{POL}}/M_{\odot})$	$\log(M_{\text{REV}}/M_{\odot})$
NGC 4051	25.01	7.2 ± 0.2	6.69 ± 0.21	6.24 ± 0.13
	32.46	6.92 ± 0.09		
	38.62	6.78 ± 0.06		
NGC 4151	25.01	7.56 ± 0.07	7.21 ± 0.27	7.12 ± 0.05
	32.46	7.40 ± 0.03		
	38.62	7.27 ± 0.04		
3C 273	25.01	8.94 ± 0.09	8.85 ± 0.27	8.83 ± 0.11
	32.46	8.90 ± 0.09		
	38.62	8.87 ± 0.08		
PG0844+349	25.01	8.00 ± 0.08	7.70 ± 0.23	7.85 ± 0.21
	32.46	7.95 ± 0.06		
	38.62	7.88 ± 0.06		

- Prost model za rešavanje prenosa zračenja
- Ispraćeno keplerovsko kretanje u profilima polarizacionog ugla
- Dobijene mase su nešto veće, ali se slažu sa postojećim vrednostima

Za budući rad

- Testirati metodu za druge široke linije npr Mg II 2800Å (u progresu)

Hvala na pažnji