1 Abstract

- Benefit of probing UV (Foley 2016) and IR (Krisciunas 2009)
- Current lack of SED extrapolation into UV and IR
- We're taking sampling of type II and I supernovae to get a time-dependent distribution of UV and IR colors:
  - U-B
  - r'-J
  - r'-H
  - r'-K
- Color curves are then being used to extrapolated SEDs into UV and IR
- spectroscopic features added
- What will UV-IR extrapolated SEDs provide the SN research community?

2 Introduction

3 Photometric Data

- Data are taken from Hicken et al. and Bianco et al. (Table 1)
- Paritel J,H,K bands created and registered in SNCOSMO for IR extrapolation
- Used SNCOSMO bessell bandpasses for UBVR, sdss for u',g',r'

SNID	Type	Color(s)	MW E(r'-V)	Redshift	Peak (Measured)	Reference
$SN2002bx$	II	$U-B$	0.0106	0.007539	52368.27 ± 0.25	*Hicken*
$SN2004aw$	Ic	$U-B$	0.0180	0.015911	53089.79 ± 0.08	*Bianco*
$SN2004gq$	Ib	$U-B$	0.0627	0.006401	53357.59 ± 0.21	*Bianco*
$SN2005bf$	Ib	$U-B, r'-J, r'-H, r'-K$	0.0385	0.018913	53496.29 ± 0.05	*Bianco*
$SN2005hg$	Ib	$U-B, r'-J, r'-H, r'-K$	0.0901	0.021308	53667.10 ± 0.05	*Bianco*
$SN2005kd$	IIn	$U-B$	0.2142	0.015040	53698.41 ± 0.21	*Hicken*
$SN2005mf$	Ic	$U-B, r'-J, r'-H, r'-K$	0.0153	0.026761	53734.02 ± 0.57	*Bianco*
$SN2005nb$	Ic	$U-B$	0.0320	0.023773	53739.68 ± 0.01	*Bianco*
$SN2006aj$	Ic	$U-B, r'-J, r'-H, r'-K$	0.1267	0.033529	53792.94 ± 0.14	*Bianco*
$SN2006ca$	II	$U-B$	0.1990	0.008903	53866.30 ± 0.16	*Hicken*
$SN2006cd$	IIP	$U-B$	0.0407	0.037116	53852.51 ± 0.56	*Hicken*
$SN2006F$	Ib	$U-B$	0.1635	0.013999	53749.72 ± 0.52	*Bianco*
$SN2006fo$	Ib	$r'-J, r'-H, r'-K$	0.0250	0.020728	53991.88 ± 0.18	*Bianco*
$SN2006T$	IIb	$U-B$	0.0647	0.007992	53765.11 ± 0.05	*Bianco*
$SN2007C$	Ib	$r'-J, r'-H, r'-K$	0.0363	0.005894	54114.10 ± 0.20	*Bianco*
$SN2007ce$	Ic	$r'-J, r'-H, r'-K$	0.0200	0.046332	54218.70 ± 0.26	*Bianco*
$SN2007D$	Ic	$r'-J, r'-H, r'-K$	0.2881	0.023163	54119.68 ± 0.61	*Bianco*
$SN2007gr$	Ic	$U-B, r'-J, r'-H, r'-K$	0.0535	0.001727	54339.81 ± 0.06	*Bianco*
$SN2007I$	Ic	$r'-J, r'-H, r'-K$	0.0250	0.021638	54118.55 ± 0.74	*Bianco*
$SN2007rt$	II	$r'-J, r'-H, r'-K$	0.0138	0.022365	54443.33 ± 0.24	*Hicken*
$SN2007uy$	Ib	$r'-J, r'-H, r'-K$	0.0194	0.007004	54464.46 ± 0.04	*Bianco*
$SN2008aj$	II	$U-B$	0.0128	0.024963	54484.47 ± 0.01	*Hicken*
$SN2008bj$	II	$U-B$	0.0233	0.018965	54553.23 ± 0.36	*Hicken*
$SN2008bn$	II	$U-B$	0.0154	0.024220	54555.05 ± 0.47	*Hicken*
$SN2008D$	Ib	$r'-J, r'-H, r'-K$	0.0194	0.007004	54474.28 ± 0.03	*Bianco*
$SN2008in$	II	$r'-J, r'-H, r'-K$	0.0193	0.005224	54828.26 ± 0.23	*Hicken*
$SN2008ip$	II	$r'-J, r'-H, r'-K$	0.0136	0.015124	54812.33 ± 0.51	*Hicken*
$SN2009ay$	II	$r'-J, r'-H, r'-K$	0.0342	0.022182	54901.63 ± 0.84	*Hicken*
$SN2009er$	Ib	$r'-J, r'-H, r'-K$	0.0389	0.035024	54966.59 ± 0.11	*Bianco*
$SN2009iz$	Ib	$u'-B, r'-J, r'-H, r'-K$	0.0729	0.014199	55115.14 ± 0.04	*Bianco*
$SN2009jf$	Ib	$u'-B, r'-J, r'-H, r'-K$	0.0971	0.008148	55121.97 ± 0.08	*Bianco*
$SN2009kn$	IIn	$u'-B$	0.0964	0.015798	55147.00 ± 2.60	*Hicken*
$SN2010bq$	II	$r'-J, r'-H, r'-K$	0.0191	0.030988	55295.10 ± 0.34	*Hicken*

Table 1: Summary of the SNe used in this analysis from Bianco et al. and Hicken et al. The colors listed for each SN are used in the extrapolations, and the peaks were measured in the course of this work.

4 Methodology

- SNe without U, u', J, H, and K data are removed from the dataset, then SNe are separated into II+IIP,IIn,Ib,Ic
- Run initial SNCOSMO fit to get initial time of peak, using bounds on t_0 of ± 20 days from first point
- Clip points more than 50 days from peak, repeat process and tighten clipping range if necessary for each SN until all time of peaks are reasonable to within ± 5 days

- Select best color to use for extrapolation based on number of points, quality of fit, etc.
- Run snsedextend program to get color tables after selecting color for each SN (set peak and have ±3 days)
- Calculate and minimize Bayesian Information Criterion (BIC) to determine best fit polynomial order
- Create posterior predictive fits showing best fit to color curve measured data

4.1 Color Table Generation

- A list of SNe with U,u',J,H, or K and optical data are provided to the snsedextend package with the following dictionaries used for fitting:
  - SN:Redshift
  - SN:Color to use for extrapolation
  - SN:E(B-V)
  - SN:Type
  - SNCosmo Model:Type
- redshift, host r_v, milky way r_v, and milky way E(B-V) are set as constants for SNCOSMO fitting
- Host E(B-V) is given bounds of ±1, t_0 is given a bound of ±3 days
- Magnitude data are translated to flux for SNCOSMO fitting
- All Optical (BVRg'r') data are fit using each model in SNCOSMO corresponding to the SN Type given, best model is taken
- Best fit model is translated to time and magnitude vectors for band in color chosen for extrapolation (i.e. B for U-B), which are interpolated using a 1D interpolation
- The time grid for the extrapolation band (i.e. U,u',J,H or K) is used to define magnitude values for the second color (i.e. B for U-B) so that we have UV or IR and optical data (i.e. U,B or r,J) values at the same epochs. They are then subtracted to get colors
- Colors are de-reddened using coefficients from O'Donnell 94
- Color table is generated (See table 2) from these data points

Days After Peak	U-B	U-B Error	U-V	U-V Error	V-J	V-J Error	V-H	V-H Error	V-K	V-K Error	B-J	B-J Error	B-H	B-H Error	B-K	B-K Error
−2.7134	−−	−−	−0.80	0.05	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−
−2.7097	−−	−−	−0.84	0.05	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−
1.2693	−−	−−	−0.45	0.06	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−
1.2730	−−	−−	−0.54	0.06	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−
1.3150	−0.56	0.06	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−
1.9837	−−	−−	−−	−−	−−	−−	−−	−−	1.97	0.19	−−	−−	−−	−−	−−	−−
1.9837	−−	−−	−−	−−	−−	−−	1.98	0.10	−−	−−	−−	−−	−−	−−	−−	−−
1.9837	−−	−−	−−	−−	1.39	0.08	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−
2.3312	−0.54	0.06	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−
2.4487	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	0.63	0.04	−−	−−	−−	−−
	...							...							...	
53.8437	−−	−−	−−	−−	−−	−−	−−	−−	2.25	0.03	−−	−−	−−	−−	−−	−−
53.8437	−−	−−	−−	−−	−−	−−	2.12	0.06	−−	−−	−−	−−	−−	−−	−−	−−
54.8337	−−	−−	−−	−−	−−	−−	2.05	0.04	−−	−−	−−	−−	−−	−−	−−	−−
54.8337	−−	−−	−−	−−	1.68	0.04	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−
56.8337	−−	−−	−−	−−	−−	−−	−−	−−	2.19	0.03	−−	−−	−−	−−	−−	−−
56.8337	−−	−−	−−	−−	−−	−−	2.03	0.03	−−	−−	−−	−−	−−	−−	−−	−−
56.8337	−−	−−	−−	−−	1.70	0.02	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−
64.8237	−−	−−	−−	−−	−−	−−	1.88	0.07	−−	−−	−−	−−	−−	−−	−−	−−
64.8237	−−	−−	−−	−−	1.63	0.02	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−
64.8237	−−	−−	−−	−−	−−	−−	−−	−−	2.01	0.26	−−	−−	−−	−−	−−	−−

Table 2: Example of Type II color table (abbreviated) generated by the snsedextend package. A similar table is created for each SN type, which is then read and binned before being fit with a polynomial. For more information on how these color tables are used, see sections 4.2 and 5.1.

4.2 Polynomial Fits to Measured Color Curves

- Description of BIC calculation and minimization
- Description of Posterior Predictive Fitting

4.3 SED Extrapolation

- Color curve(s) created/described in sections 4.1 and 4.2 is sent to SED extrapolation function
- Color is calculated from color curve best fit polynomial for each epoch in SED
- Color at each epoch is used to define a linear extrapolation into the UV or IR
    - Iterative process is used to define the endpoints/slope of the extrapolation so that area under line is equal to the color at that epoch
    - This process was tested and verified by Rick Kessler
- Endpoints were chosen based on UV and IR range that will be used (These are variables in the package that can be changed by a user):
    - UVrightBound=4000
    - UVleftBound=1200
    - IRleftBound=9000

    - IRrightBound=55000

- SED is extrapolated linearly such that it reaches zero at these endpoints

4.4 SED Spectroscopic Features

- Find a set of observed or model UV / NIR spectra from objects within each SN class.
    - Type Ib / Ic: We may have some nice composite spectra (or at least a few isolated spectra) from M. Modjaz's SNYU group
    - Type II, IIn, II-P: We may have some from the CfA team. Possibly from CSP. Possibly some are available on the online SN data repositories like the Open Supernova Catalog
- Pick the best available spectra (highest S/N ratio)
    - For any observed spectra that are noisy, run a Savitzky-Golay smoothing filter over them. Should not be needed for template spectra, which are effectively noiseless.
    - Flatten the spectra by fitting with a simple polynomial, as is done in SNID. The flattenened spectra should have a median flux values close to 0 for any wavelength bin.
- * Add flattened spectra on to the linear extrapolations. This should effectively "paint on" the spectral features, while maintaining the broad-band colors to be the same as what was set with the current snsedextend procedure.

5 Results and Discussion

5.1 Supernova Fitting

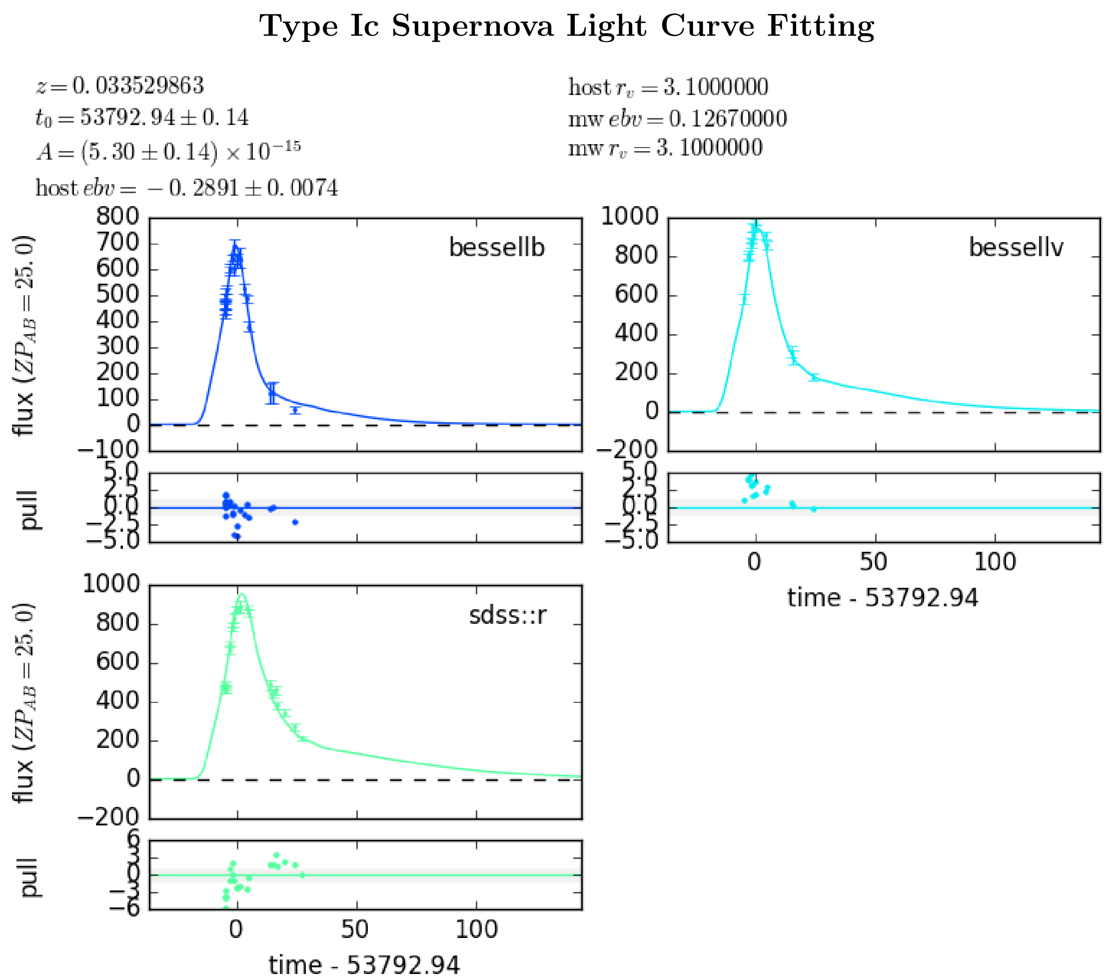


Figure 1: Example SNCOSMO fitting results of optical colors (B,V,r') for a SN Type Ib (SN 2005hg, see Table 1). For all SN fits see the appendix (I'll add them after tweaking).

5.2 Color Curve Fitting

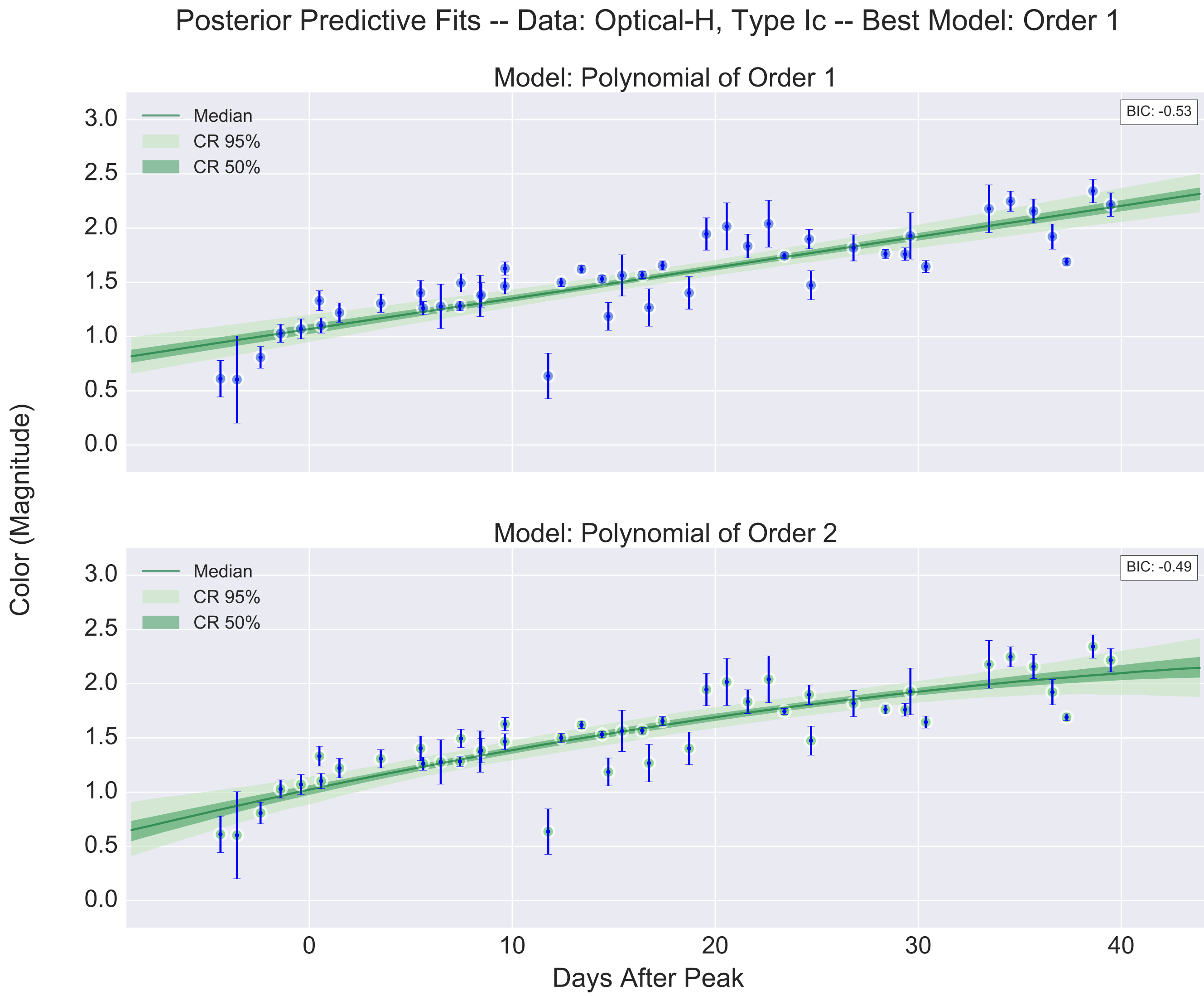


Figure 2: Example Posterior Predictive fitting results for U-Optical colors measured from Type Icand Type IIP templates. The blue points represent binned data, while the red points represent the whole of the dataset (see section 3). The best fit model was chosen by minimizing the Bayesian Information Criterion. All fits to Optical-J,H,K for all SN types are shown in the appendix.

5.3 SED Extrapolation

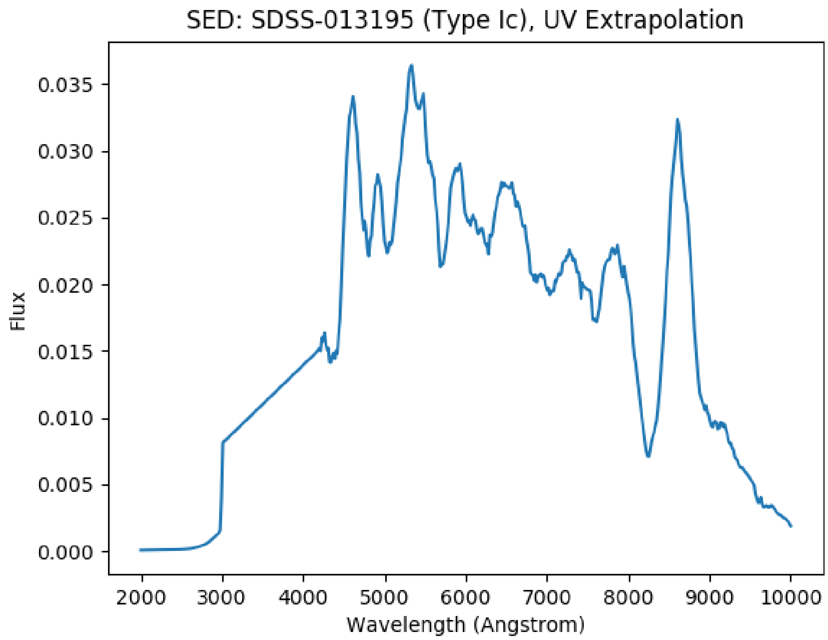
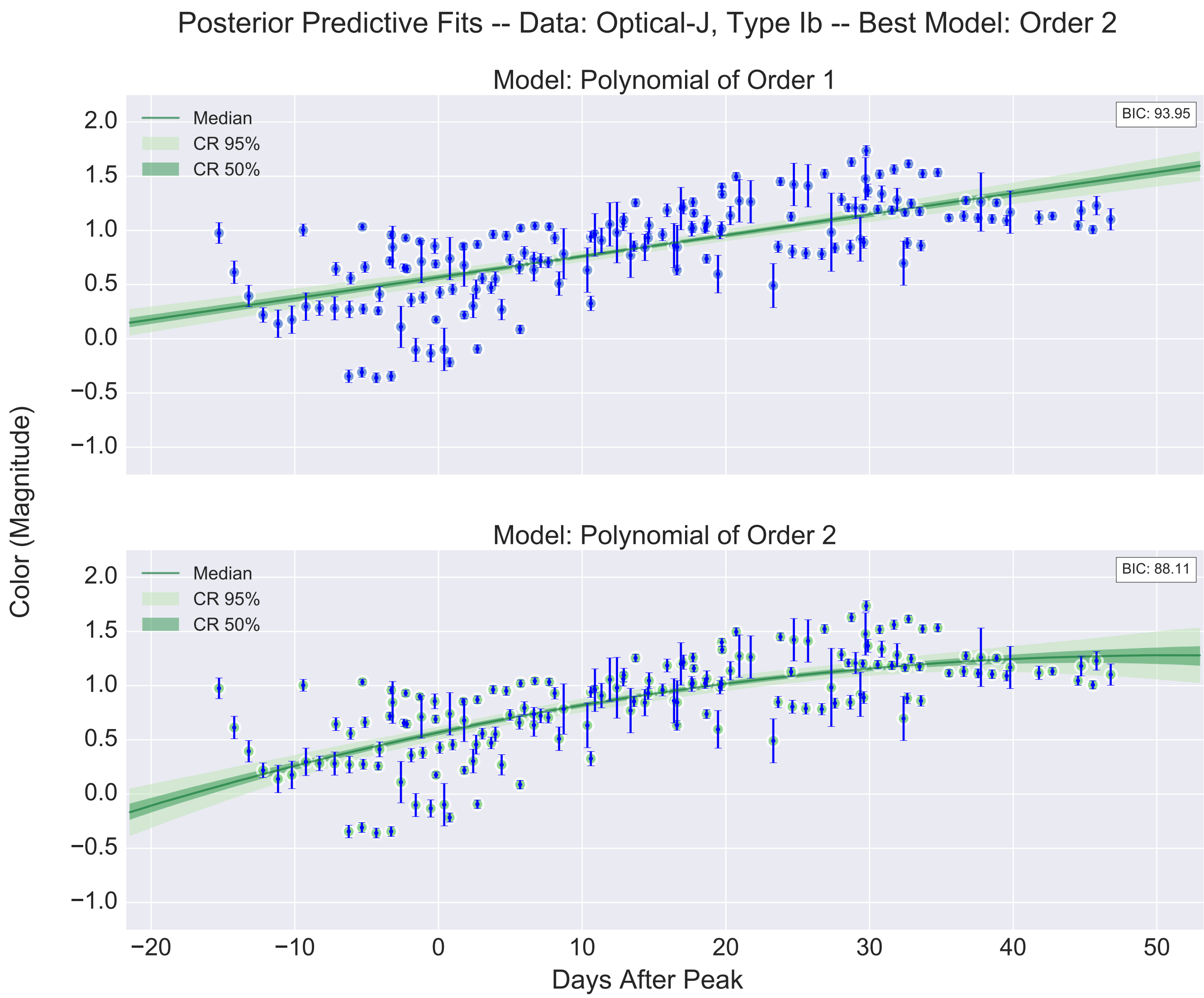
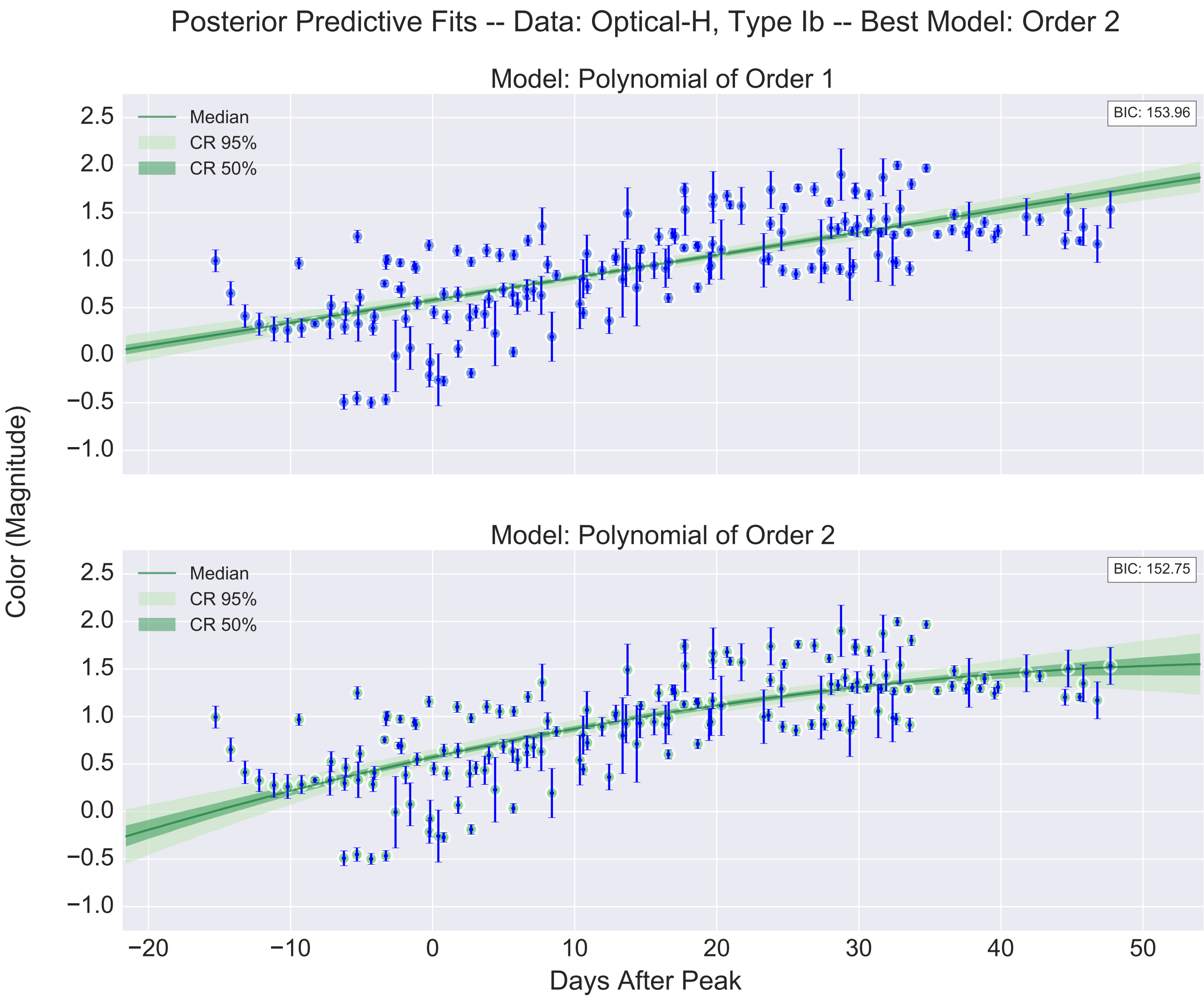


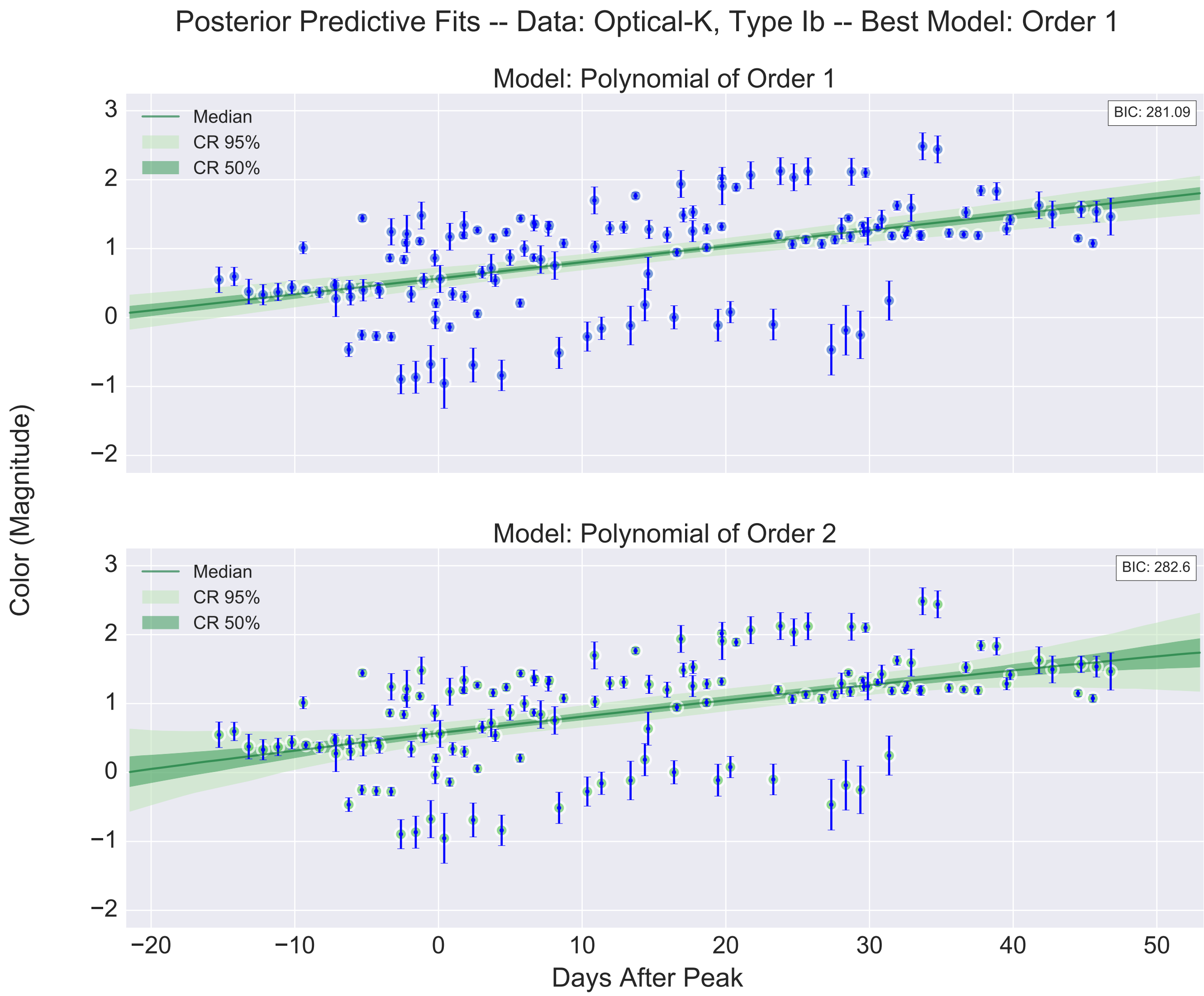
Figure 3: Example of extrapolated SED into the UV using the color curve generated by the snsedextend package.

Appendix

Type Ib



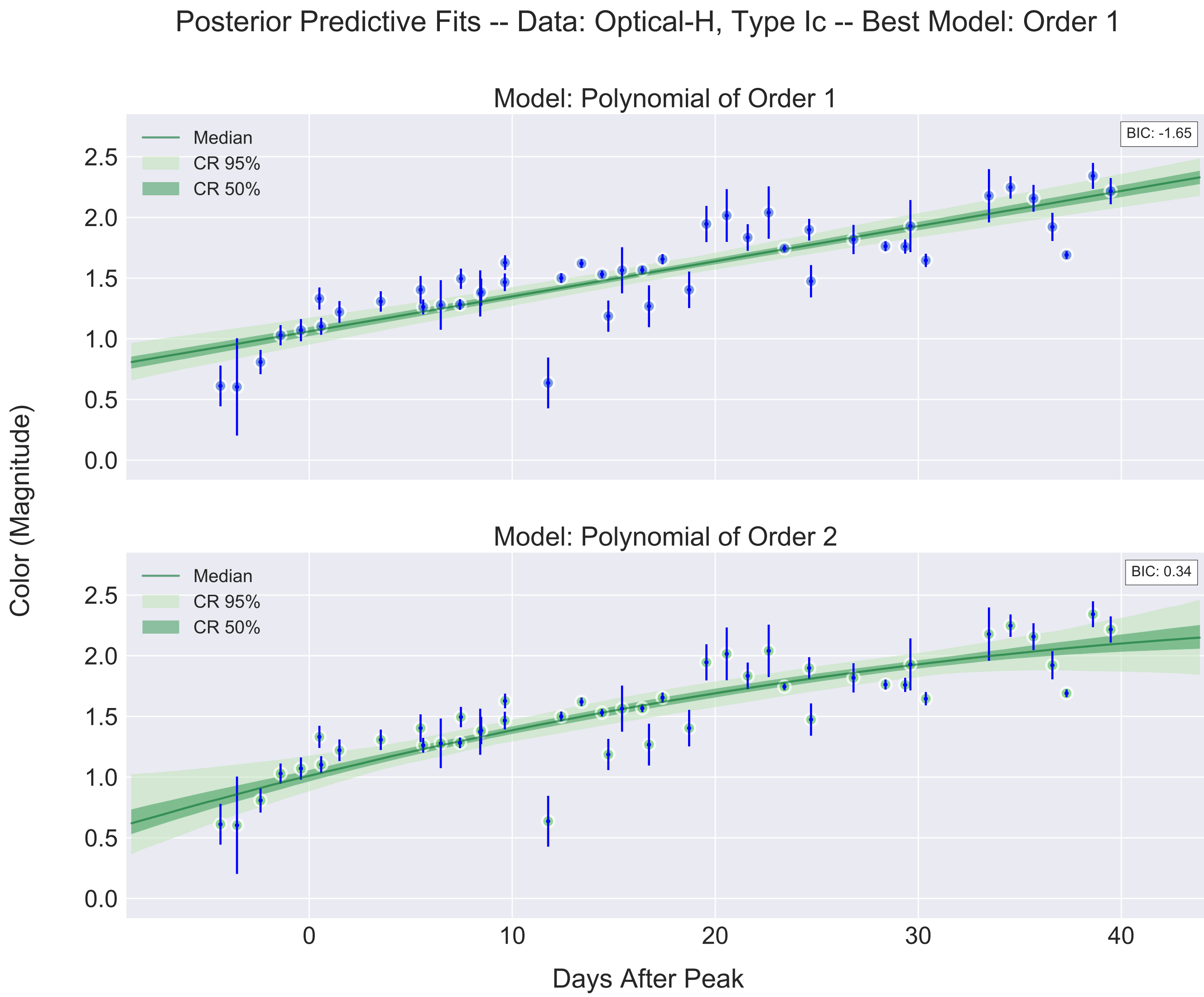

Posterior Predictive Fits -- Data: Optical-H, Type Ib -- Best Model: Order 2
Model: Polynomial of Order 1
Median
CR 95%
CR 50%
BIC: 153.96
Model: Polynomial of Order 2
Median
CR 95%
CR 50%
BIC: 152.75
Color (Magnitude)
Days After Peak


Posterior Predictive Fits -- Data: Optical-K, Type Ib -- Best Model: Order 1
Model: Polynomial of Order 1
Median
CR 95%
CR 50%
BIC: 281.09
Model: Polynomial of Order 2
Median
CR 95%
CR 50%
BIC: 282.6
Color (Magnitude)
Days After Peak
−20
−10
0
10
20
30
40
50
3
2
1
0
−1
−2


Posterior Predictive Fits -- Data: U-Optical, Type Ib -- Best Model: Order 2
Model: Polynomial of Order 1
Median
CR 95%
CR 50%
BIC: 141.3
Model: Polynomial of Order 2
Median
CR 95%
CR 50%
BIC: 138.93
Color (Magnitude)
Days After Peak
2
1
0
−1
−10
0
10
20
30

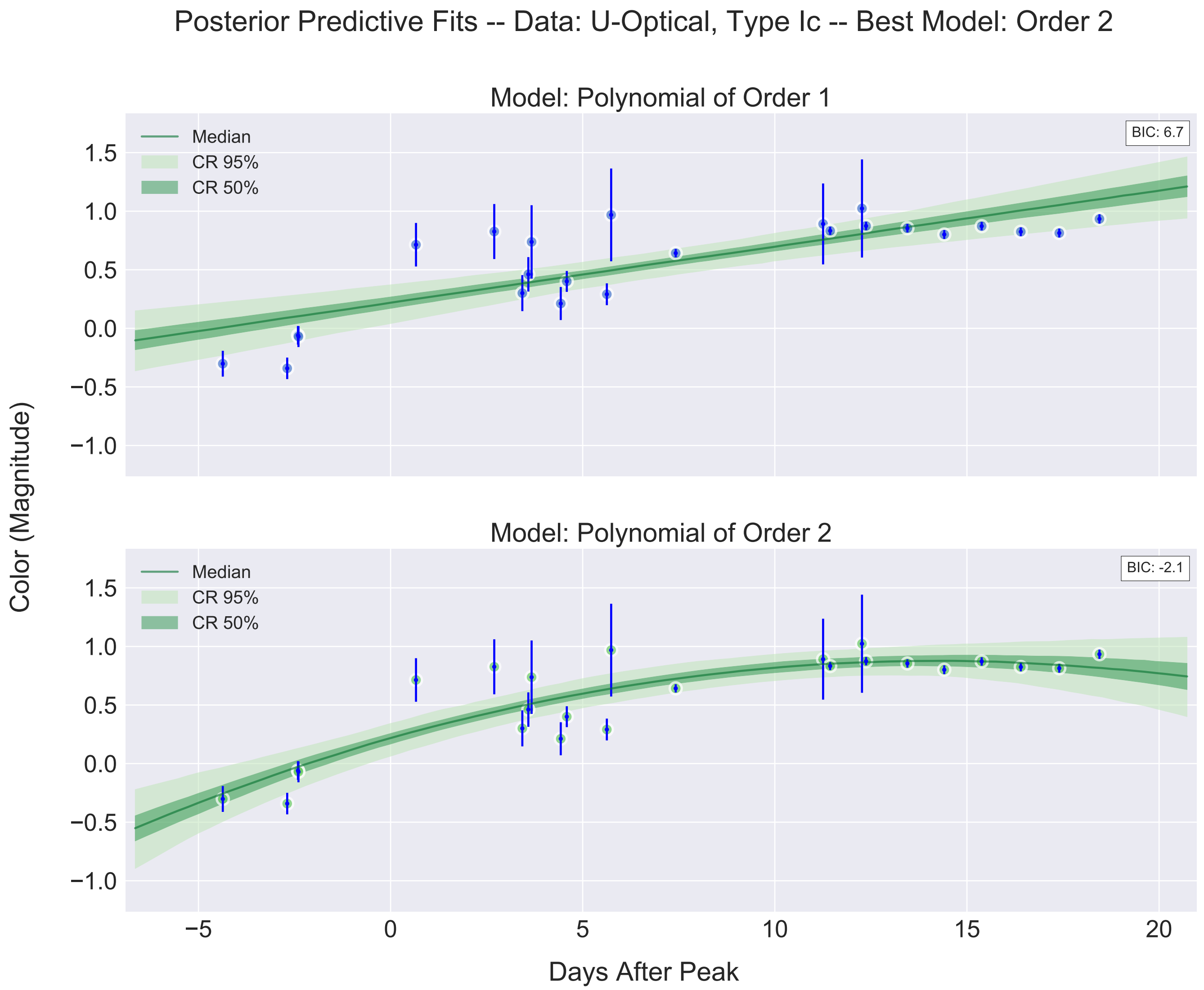
Type Ic

Figure 4: My fig



Posterior Predictive Fits -- Data: Optical-H, Type Ic -- Best Model: Order 1
Model: Polynomial of Order 1
Median
CR 95%
CR 50%
BIC: -1.65
Model: Polynomial of Order 2
Median
CR 95%
CR 50%
BIC: 0.34
Color (Magnitude)
Days After Peak
0.0
0.5
1.0
1.5
2.0
2.5
0
10
20
30
40


Posterior Predictive Fits -- Data: Optical-K, Type Ic -- Best Model: Order 1
Model: Polynomial of Order 1
Median
CR 95%
CR 50%
BIC: 11.85
Model: Polynomial of Order 2
Median
CR 95%
CR 50%
BIC: 12.53
Color (Magnitude)
Days After Peak
0.5
1.0
1.5
2.0
2.5
3.0
0
10
20
30
40


Posterior Predictive Fits -- Data: U-Optical, Type Ic -- Best Model: Order 2
Model: Polynomial of Order 1
Median
CR 95%
CR 50%
BIC: 6.7
Model: Polynomial of Order 2
Median
CR 95%
CR 50%
BIC: -2.1
Color (Magnitude)
Days After Peak
1.5
1.0
0.5
0.0
−0.5
−1.0
−5
0
5
10
15
20

Type II+ IIP

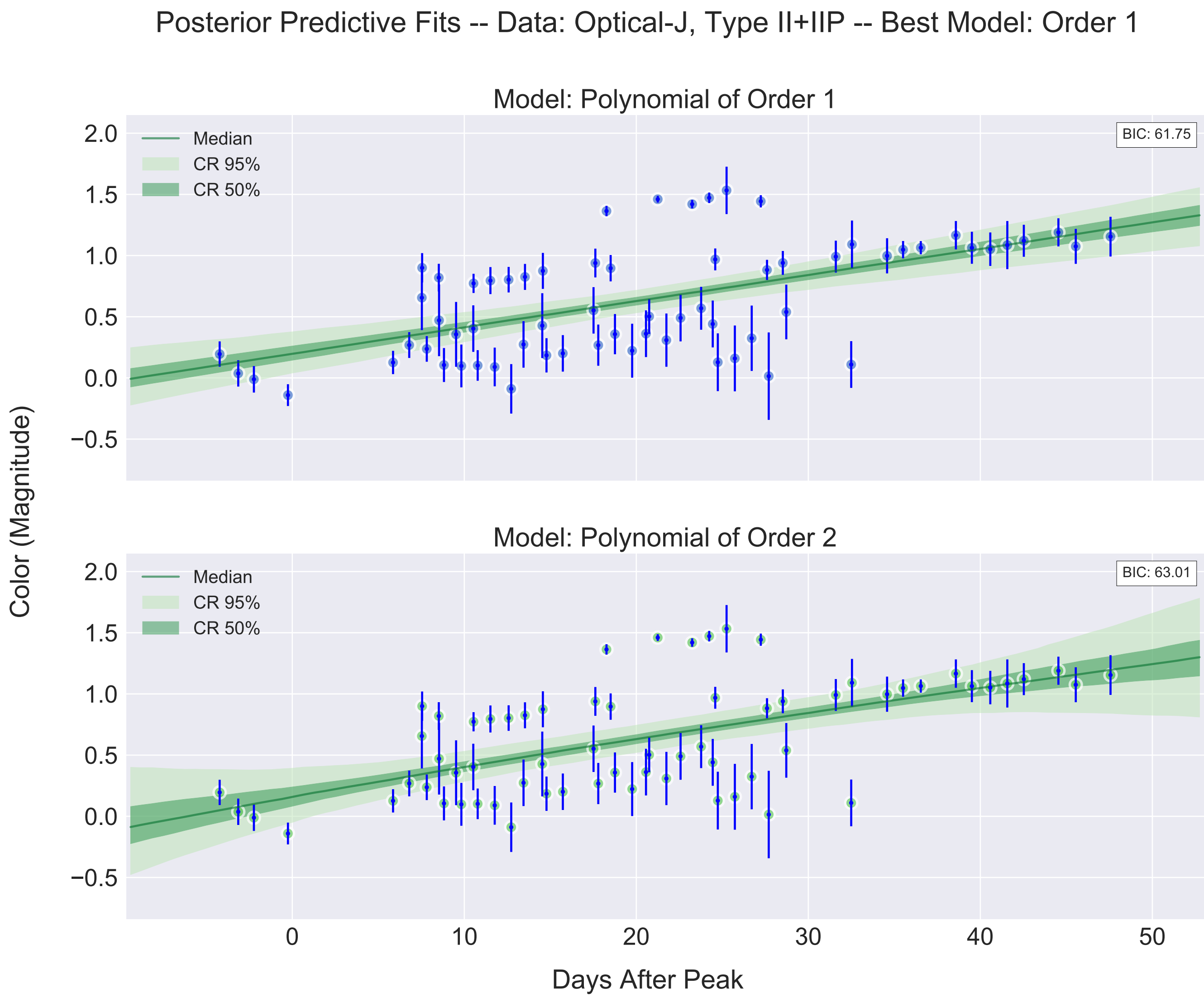
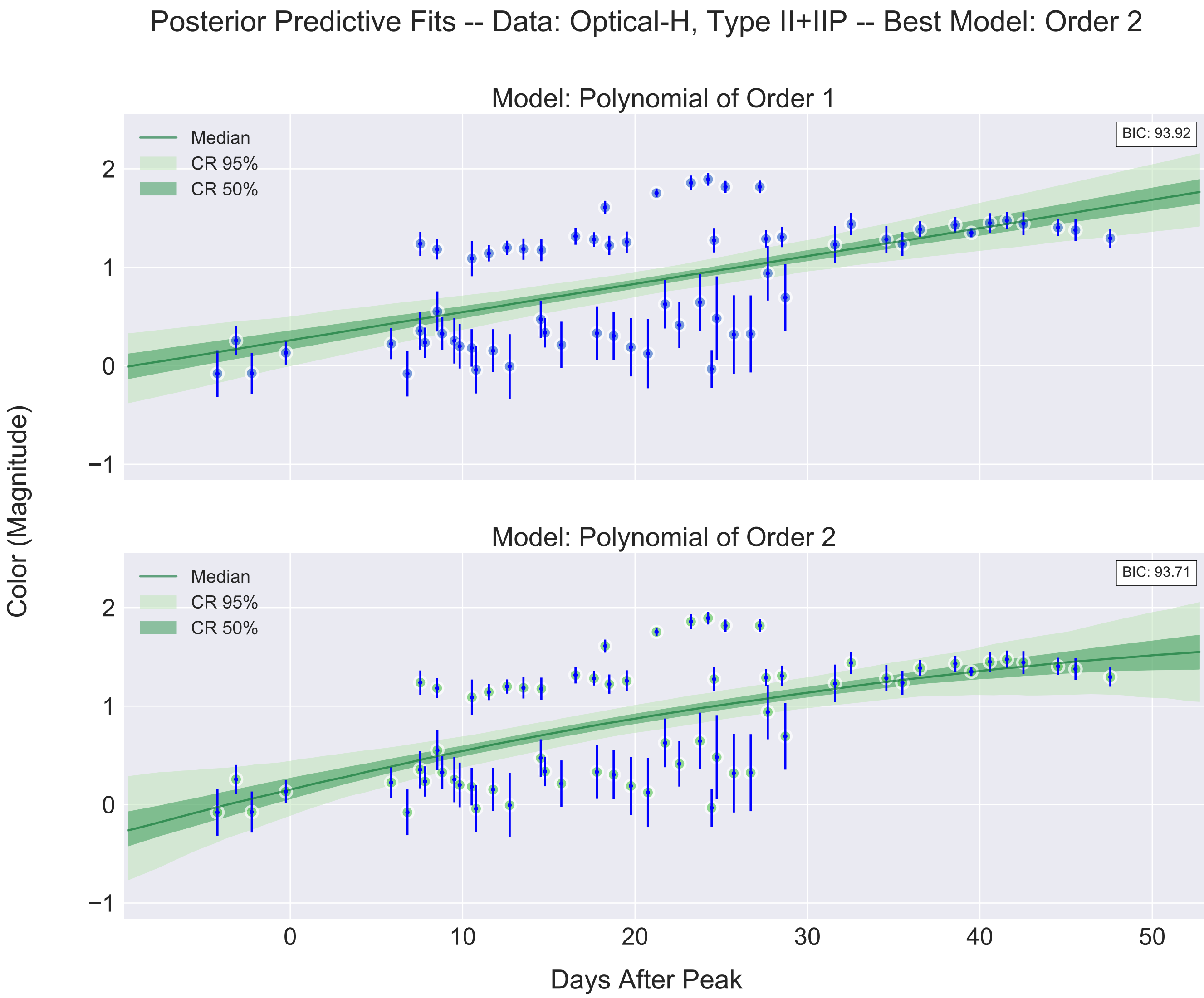
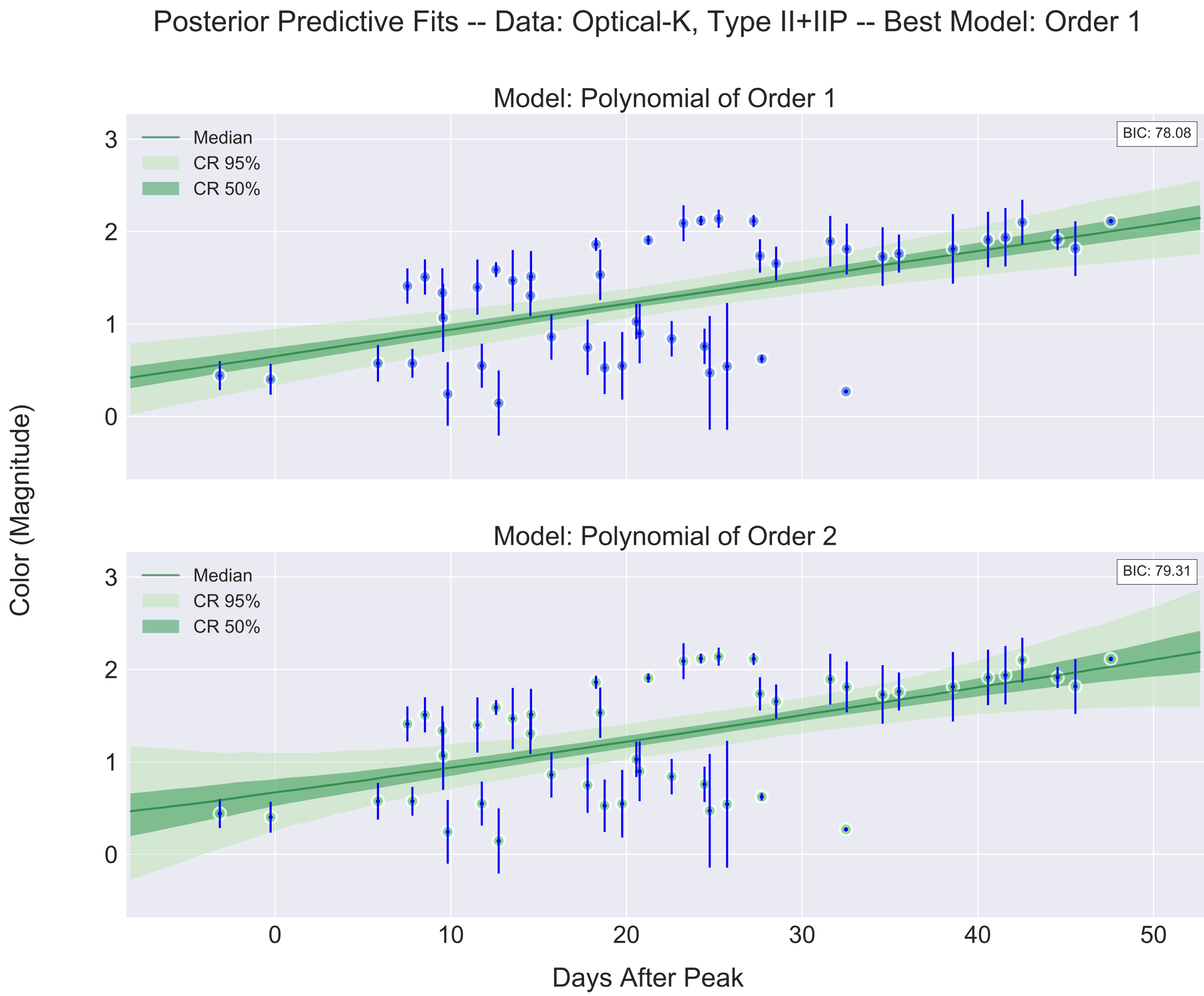
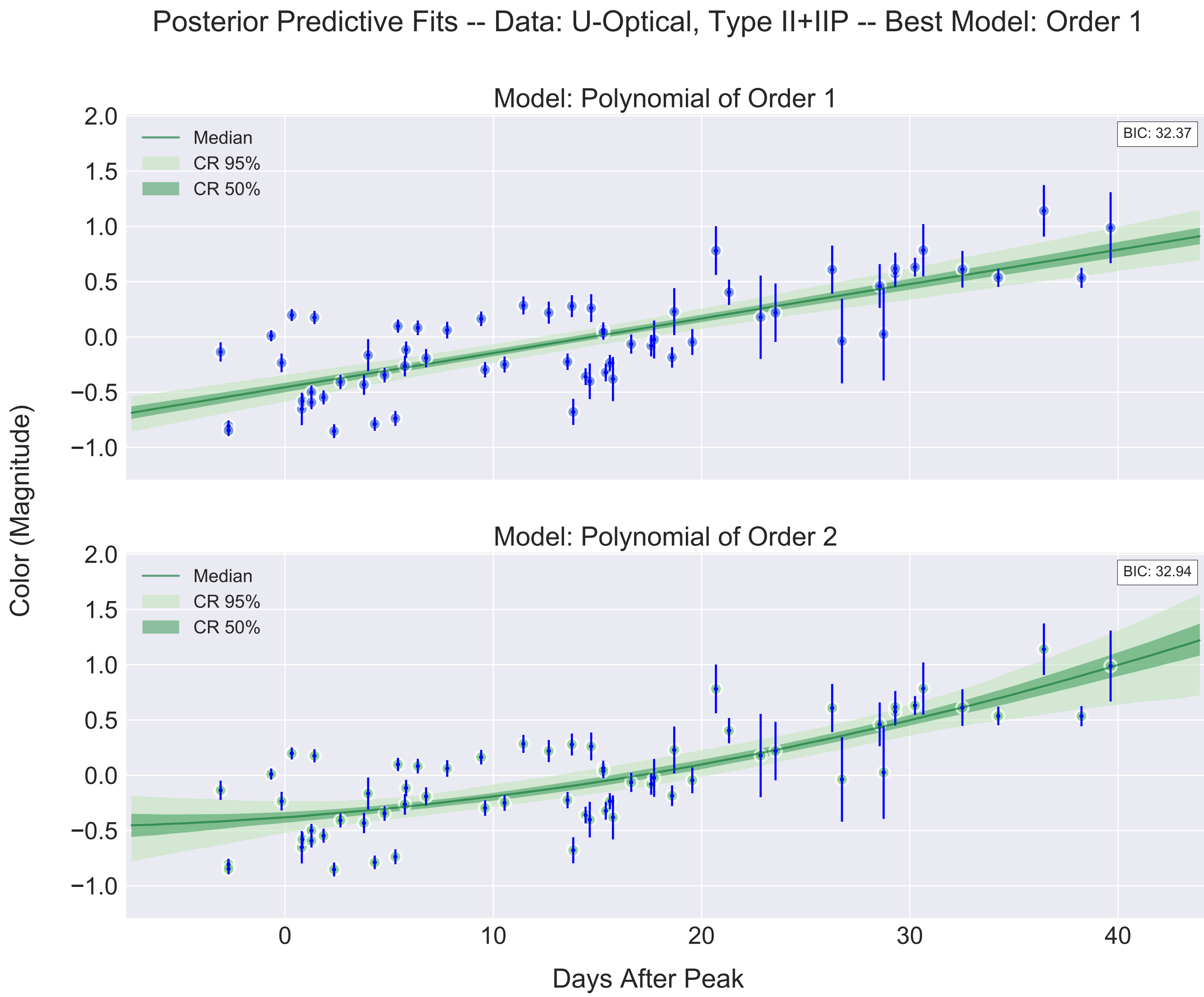


Figure 5: My fig


Posterior Predictive Fits -- Data: Optical-H, Type II+IIP -- Best Model: Order 2
Model: Polynomial of Order 1
Median
CR 95%
CR 50%
BIC: 93.92
Model: Polynomial of Order 2
Median
CR 95%
CR 50%
BIC: 93.71
Color (Magnitude)
Days After Peak
2
1
0
−1
0
10
20
30
40
50


Posterior Predictive Fits -- Data: Optical-K, Type II+IIP -- Best Model: Order 1
Model: Polynomial of Order 1
Median
CR 95%
CR 50%
BIC: 78.08
Model: Polynomial of Order 2
BIC: 79.31
Color (Magnitude)
Days After Peak


Posterior Predictive Fits -- Data: U-Optical, Type II+IIP -- Best Model: Order 1
Model: Polynomial of Order 1
Median
CR 95%
CR 50%
BIC: 32.37
Model: Polynomial of Order 2
BIC: 32.94
Color (Magnitude)
Days After Peak