Stellar Locus Regression
User Manual

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Chapter 1

Preliminaries

I encourage you to let us know about your thoughts, interest, questions, and usage of our code. Please email high@physics.harvard.edu.

1.1 Citations

If your work makes use of this code, please mention the version number you used and cite the original Stellar Locus Regression paper:

High, F. W., Stubbs, C. W., Rest, A., Stalder, B., & Challis, P. 2009, Astronomical Journal submitted, arXiv:0903.5302v1

Kevin Covey also requests that you cite his stellar locus paper because the code makes use of his data:

Covey, K. R., Ivezić, Ž., Schlegel, D., Finkbeiner, D., Padmanabhan, N., Lupton, R. H., Agüeros, M. A., Bochanski, J. J., Hawley, S. L., West, A. A., Seth, A., Kimball, A., Gogarten, S. M., Claire, M., Haggard, D., Kaib, N., Schneider, D. P., & Sesar, B. 2007, Astronomical Journal, 134, 2398

1.2 Validity of the Code, Validity of the Algorithm

Every piece of code comes with the statement:

```
SLR is free software: you can redistribute it and/or modify it under
the terms of the GNU General Public License as published by the Free
Software Foundation, either version 3 of the License, or (at your
option) any later version.

SLR is distributed in the hope that it will be useful, but WITHOUT
```

Only some aspects of our SLR algorithm were tested, and results vetted, in the peer-reviewed article of High et al. (2009). This code, however, has many features that are consistent with and allowed by the SLR algorithm, but whose results have not been explicitly tested. We expect SLR to have far broader applicability than what we explored in the paper, and we leave it to future work to test further applications formally.

So we urge the reader to peruse High et al. (2009) to understand the scope of tests we performed, and the possible circumstances under which SLR may be valid. Still, we make no warranty of validity nor accuracy, even in analyses similar or identical to those presented in the paper.

1.3 Scope

We made the scope of this implementation of SLR as narrow as possible so that its place within a photometric pipeline is well defined. Therefore, (1) to get SLR to work, you need to do some entirely conventional pre-processing of your data; and (2) you'll need to use and interpret the output of the code yourself. See §6 for a discussion on how to get your data in a state that SLR will like.

At base, SLR simply fits input colors to a standard line, such that the output colors match the line as well as possible. By its nature SLR has its own (in)sensitivities to the atmosphere, the dust in our galaxy, and stellar metallicity, for example. We explored all imaginable sensitivies in High et al. (2009) as deeply as we thought necessary to understand what SLR was doing on the whole. We think the result is something new and extremely useful, and we hope you do too.

Chapter 2

Introduction

Stellar Locus Regression (SLR) is a method of directly adjusting the instrumental broadband optical colors of stars to bring them into accord with a universal stellar color-color locus, producing accurately calibrated colors for both stars and galaxies.

We offer an implementation of SLR in the Interactive Data Language (IDL). This manual is a guide on getting, installing, and running our public IDL code.

The peer-reviewed paper of High et al. (2009) initially outlined the broad ideas behind the technique, established the mathematical formalism, and presented the first tests of the technique. We expect SLR to have even broader applicability to astronomy than we envisaged in that article.

2.1 What SLR Is

At it's core, SLR simply fits instrumental colors of stars to a standard line, delivering calibration parameters that can then be applied to all objects in the field.

Instrumental colors are differences in instrumental magnitudes. Instrumental magnitudes are the direct product of measuring photometry in bias-subtracted, flat-fielded images. Source Extractor (Bertin & Arnouts, 1996) is the common tool for measuring instrumental magnitudes. The distinctive stellar locus is seen immediately in instrumental color-color plots of stars in the field. The red points in the top panels of Figure 2.1 are a real example of this.

The instrumental stellar locus closely resembles the calibrated stellar locus, shown with the heavy line and gray density contours in Figure 2.1. If we align the two loci with simple shifts, we arrive at the middle panels of Figure 2.1. The two agree somewhat, although we see a systematic difference. This difference arises from using a different instrument (Magellan in Chile) than that used to make the standard stellar locus (Sloan Digital Sky Survey telescope in New Mexico). We measure and apply the usual instrumental color terms, re-measure the shift, and produce a stellar locus that matches the standard one nearly

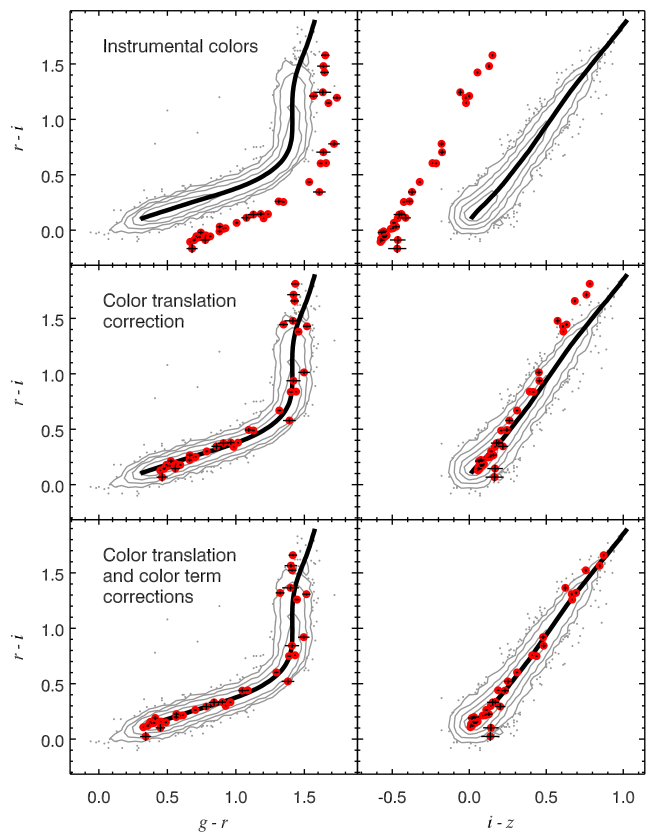

Figure 2.1: An illustration of Stellar Locus Regression (SLR). Colors are plotted on the SDSS photometric system. All panels show the standard stellar locus (black line and gray density contours), reproduced from Covey et al. (2007). Red points are stellar colors obtained from a Source Extractor analysis of flat-fielded Magellan 6.5 m IMACS images. *Top panels:* The instrumental IMACS colors are plotted, with a clear mismatch between them and the standard locus. *Middle panels:* SLR is performed with only a common translation vector applied to the instrumental colors. Note the color-dependent discrepancies in the upper right portions of the central panels. *Bottom panels:* Color terms are measured from a single, separate observation of a field containing standard stars. Fixing these color terms, a new best-fit translation is determined, which brings the observed colors onto the SDSS-calibrated color system, as defined by the stellar locus. This SLR analysis, when the corrections are then applied to all objects in the photometric catalog, allows us to rapidly obtain highly accurate colors on the SDSS system, directly from flat-fielded data, with a single correction step that accounts for atmospheric extinction, Galactic extinction and instrumental response differences.

perfectly. This is shown in the bottom panels of Figure 2.1.

The product is a color calibration that can be applied to all objects in the same field where the calibrator stars appeared. The SLR color calibration is achieved without first establishing individual zeropoints for each passband, can be performed in real-time at the telescope, and makes use of the stars from any field—they need not be standards. High et al. (2009) demonstrated how SLR naturally makes one wholesale correction for differences in instrumental response, for atmospheric transparency, for atmospheric extinction, and for Galactic extinction.

This all assumes that the standard locus is universal. We explored the extent to which this is true in High et al. (2009), both in theory and in practice. We found that SLR calibrations are repeatable with sub-percent systematic color uncertainty, that SLR re-calibrations of SDSS data are directly sensitive to reddening by Galactic dust at the 2% level for the fields we looked at, and SLR calibrations of red cluster galaxy colors were sufficiently accurate to deliver cluster photometric redshifts with 0.6% systematic uncertainty (which we found to be consistent with 2% color errors).

SLR is a simple and fundamentally different way of calibrating photometry. It works, and it works well.

Figure 2.2 schematically outlines how SLR fits into a typical calibration scheme. The core IDL tools we have developed are available at `http://stellar-locus-regression.googleco`
and this manual serves as a guide to that particular code.

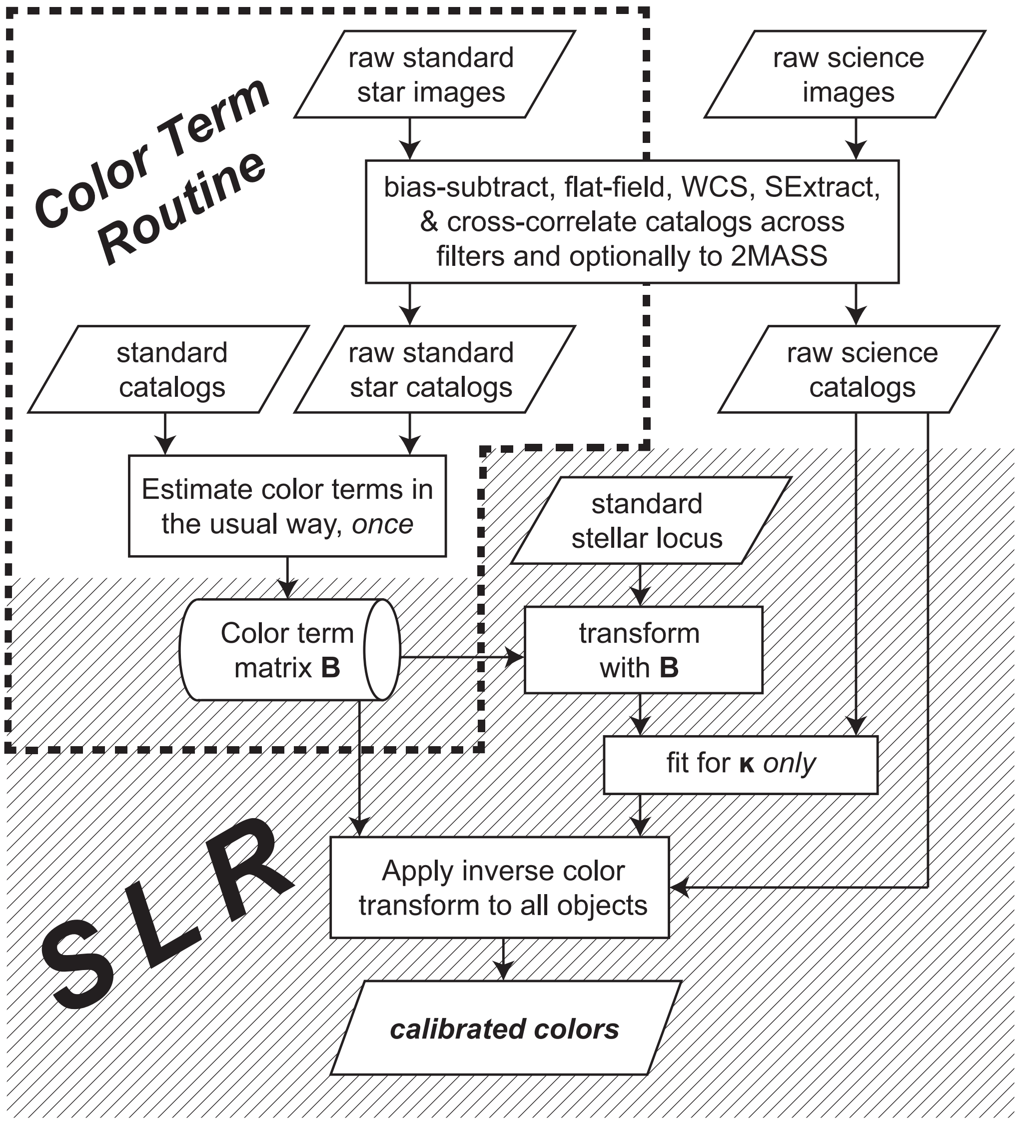

Figure 2.2: SLR flow chart for calibrating colors. The hashed region denotes parts of the algorithm that are unique to SLR, while the non-shaded region shows steps that are more traditional. The dotted region denotes the color term estimation routine, which need only be performed once per detector.

Chapter 3

Quick Start

1. Download the SLR code and unpack it in a directory of your choosing, <install-dir>.

2. Install and set up the Goddard astronomy IDL libraries, idlutils, and the Markwardt IDL libraries.

3. Download the stellar locus data of Covey et al. (2007) and put them in a directory <data-dir>/covey.

4. Set environment variables (here in tcsh):

   ```
   % setenv SLR_INSTALL <install-dir>/slr-v*
   % setenv SLR_DATA <data-dir>
   % setenv IDL_PATH {$IDL_PATH}:+$SLR_INSTALL/pro
   % setenv PATH {$PATH}:$SLR_INSTALL/bin
   ```

   where the version number v* corresponds to whatever you downloaded in step 1.

5. Verify your installation (see §5):

   ```
   % idl
   IDL> slr_docs
   IDL> exit
   % cd $SLR_INSTALL/example_data
   % slr.csh low_reddening.ctab low_reddening.slr.ctab
   % slr.csh high_reddening.ctab high_reddening.slr.ctab
   % idl
   IDL> slr_demo
   IDL> exit
   % cat low_reddening.slr.ctab
   % cat low_reddening.slr
   % cat high_reddening.slr.ctab
   % cat high_reddening.slr
   ```

Chapter 4

Installation

4.1 Download

First, go get the latest download at http://stellar-locus-regression.googlecode.com. Untar it with

```
tar xzvf slr-v*.tar.gz
```

where the version number v* corresponds to whatever you downloaded. Put the package in some directory <install-dir>. This can be /usr/local/idllibraries or $HOME or whatever you prefer. The package root directory will then be <install-dir>/slr-v*.

4.2 IDL Libraries

You'll need these idl libraries:

1. idlutils from http://www.astro.princeton.edu/~schlegel/code.html. Any installation procedure will do, but you probably want the latest idlutils tar file, e.g. idlutils-v5_3_0.tar.

2. *The latest* Goddard astro libraries from http://idlastro.gsfc.nasa.gov. Note that idlutils comes with an old version of the Goddard libraries that is *incompatible with this implementation of SLR*. Get the latest one.

3. Markwardt libraries from http://www.physics.wisc.edu/~craigm/idl. You want cmtotal.tar.gz.

Put them in your typical IDL directory. For example, use a directory you can remember <pro-dir>, like /usr/local/idllibraries.

Don't forget to add them to your IDL_PATH with shell startup file entries similar to:

```
% export IDL_PATH=$IDL_PATH:+<pro-dir>/idlutils:+<pro-dir>/markwardt
```

in bash or

```
% setenv IDL_PATH {$IDL_PATH}:+<pro-dir>/idlutils:+<pro-dir>/markwardt
```

in tcsh.

Of course all of this assumes you have properly initialized the IDL_PATH, for example in tcsh:

```
% setenv IDL_BIN /usr/local/itt/idl/bin
% source $IDL_BIN/idl_setup
% setenv IDL_PATH <IDL_DEFAULT>
```

4.3 Standard Stellar Locus

SLR gets the standard stellar locus data from the directory $SLR_DATA/covey.

Go get Kevin Covey's stellar locus data, which he makes available on his own website. You'll need the median locus line data:
http://www.cfa.harvard.edu/~kcovey/research/medianlocus.tbl
Put them in some directory <data-dir>/covey. We suggest putting them in the <install-dir>/example_data/covey subdirectory of your installation. Set SLR_DATA. If you used our suggestion, then you would issue

```
% setenv SLR_DATA <install-dir>/example_data
```

The directory $SLR_DATA/covey must exist and contain medianlocus.tbl and superclean.fits.

4.4 Environment Variables

Now set some environment variables in your cshrc or bashrc file. Remember to insert the appropriate directories. Example is for tcsh:

```
% setenv SLR_INSTALL <install-dir>/slr-v1.0
% setenv SLR_DATA <data-dir>
% setenv IDL_PATH {$IDL_PATH}:+$SLR_INSTALL/pro
% setenv PATH {$PATH}:SLR_INSTALL/bin
```

We've used the example directories mentioned in this install file. This should let the demo (see below) work properly. If you made different choices, you must make sure these environment variables reflect them.

Chapter 5

Usage

5.1 Verifying Your Installation

If everything is set up properly, you can run the demo by invoking IDL and running:

```
% cd $SLR_INSTALL/example_data
% idl
IDL> slr_demo
```

The first time you run it, it will take some time (it's reformatting the data to an optimal, IDL-friendly format). It will be faster the second time.

The demo will run SLR on the example Sloan Digital Sky Survey data that comes with your installation. You should see plots of the stellar locus (you must hit enter to continue), a visualization of the numerical regression, and results for best-fit parameters printed to screen.

5.2 Running slr.csh Using Example Data

Go to the directory $SLR_INSTALL/example_data, then issue at the commandline (you have to be in same directory as your input file):

```
% cd $SLR_INSTALL/example_data
% slr.csh low_reddening.ctab low_reddening.slr.ctab
```

This will run SLR on the example colortable we provided (first argument), and output SLR calibrations to another colortable (second argument). The output colortable is equal to the input colortable but with the additional appended columns GR, RI, etc, which are the calibrated colors g - r, r - i. Estimated color errors, with bootstrap errors added in quadrature, are also output.

Browse the output table of calibrated colors, and the log file that SLR generates, in this case lowext_stars3_fwhigh.slr. The latter contains the color calibration parameters with bootstrap errors.

```
% cat low_reddening.slr.ctab
% cat low_reddening.slr
```

If that works then you should also be able to run

```
% cd $SLR_INSTALL/example_data
% slr.csh high_reddening.ctab high_reddening.slr.ctab
```

Browse the output:

```
% cat high_reddening.slr.ctab
% cat high_reddening.slr
```

5.3 Running slr.csh with Your Own Data

To run SLR on your own data, issue the command (again, in the same directory as your input file):

```
% slr.csh input.ctab output.slr.ctab <config-file>
```

The configuration file can optionally be specified. If none is given, then the default file is used, $SLR_INSTALL/config/default.config.

This has the same output as the previous section. See §7 for requirements on acceptable input colortable formatting.

The code outputs a new colortable with calibrated colors and optionally magnitudes, with errors. The output filename is the input filename with the string "slr.ctab" appended. If the input filename had ".ctab" as the suffix, then this suffix is first removed in order to avoid duplication. The SLR log file is the input colortable file name with ".slr" appended. Again, ".ctab" is first removed if is the input file's suffix.

5.4 Writing Wrappers

At its core, SLR simply fits $ugrizUBVRIJHK$ colors to a standard locus. This is done with slr_pipe.pro. SLR doesn't care where the input magnitudes came from, nor whether they were previously calibrated fully, partially, or at all. SLR only knows how to make the input stellar locus look like the standard locus, thereby producing calibrated colors.

5.4.1 slr_pipe.pro

But the real power of SLR comes from writing wrappers to slr_pipe.pro. For example, if you have uncalibrated $griz$ magnitudes, with 2MASS J-band data for a subset of your stars, then you can make a wrapper that calls slr_pipe three times:

1. Calibrate only the colors $(g-r, r-i, i-z)$. This produces the vector of color translations $\boldsymbol{\kappa} = (\kappa_{gr}, \kappa_{ri}, \kappa_{iz})$.

2. Then calibrate only the colors $(i-z, z-J)$, but pass the calibration parameter κ_{iz} as an input and leave it fixed during the fit. This produces κ_{zJ}, which happens to be equal to your z-band zeropoint (which includes atmospheric extinction, Galactic extinction, the instrumental zeropoint, and so on).

3. Run it one more time, leaving $\boldsymbol{\kappa}$ fixed to the values you just measured, to produce a catalog that contains the calibrated colors $(g-r, r-i, i-z)$.

All three of these tasks are within the scope of slr_pipe, even though they have conceptually different results.

This is made possible by passing parameters on the IDL commandline. The best fit $\boldsymbol{\kappa}$ can be access via the IDL keyword kappa_out, and its error via kapperr_out. These can then be accessed then passed to the next call of slr_pipe using syntax like

```
IDL> slr_pipe,infile='low_reddening.ctab',$
IDL>          outfile='low_reddening.slr.ctab',$
IDL>          kappa_out=low_kappa, kapperr_out=low_kappa_err
IDL> slr_pipe,infile='low_reddening.ctab',$
IDL>          outfile='low_reddening.slr.ctab',$
IDL>          kappa_guess=low_kappa, kappa_guess_err=low_kappa_err, $
IDL>          nbootstrap=0
```

In this example we've run SLR twice, but the second time we changed the initial guess for $\boldsymbol{\kappa}$ used during the regression. We also decided not to do the bootstrap the second time, choosing instead to use the first bootstrap errors as our estimates for errors on the new $\boldsymbol{\kappa}$.

This works because any parameter that appears in the configuration file (§8) can be passed to slr_pipe, verbatim. Commandline parameters overwrite those parsed from the configuration file.

Wrapping around slr_pipe lets you loop over lots of data and/or run sophisticated calibrations, like the $grizJ$ scheme described above.

Chapter 6

Pre-Processing Your Data

Before you run SLR, you'll have to have multiband observations of a given field in hand. All images must be bias-subtracted and flat-fielded, including dome flats, fringe corrections, and ideally illumination corrections as well. You'll then run SExtractor or the equivalent to detect objects in each band, and identify unique stars, galaxies, and other objects between all bands. The result will be a list of instrumental magnitudes for each object in the field in each band. You can subtract instrumental magnitudes to arrive at intstrumental colors.

If you want to standardize your colors to a system using a different instrument than that originally used to establish the standard, then you'll probably have to measure color terms, as described in §9.

The final steps are to format your multi-band instrumental catalog into an SLR-readable colortable §7, and to tell SLR about your color terms using the config files (§8-9). You're now ready to run SLR.

Of course, you can also run SLR on photometry that has already been calibrated to any degree. When running SLR in this case, it will give you new calibrations such that the colors resemble the standard locus line as well as possible.

Chapter 7

The Colortable

SLR reads data from and outputs results to what we call *colortables.* These are simple ascii files with a single header that starts with # and one row of data per object. The header values are columns names, and each row corresponds to one object. Here's a simple (truncated) example:

```
# ID        RA       Dec type tmixed       g  g_err       r  r_err ...
   0 254.00649  34.33696    1      0  20.672  0.025  19.795  0.018 ...
   1 254.05269  34.36260    1      0  16.426  0.004  15.849  0.004 ...
   2 254.02026  34.34031    1      0  23.670  0.283  21.607  0.072 ...
   3 254.00436  34.36294    1      0  20.381  0.021  19.012  0.011 ...
   4 254.02655  34.34580    1      0  18.203  0.006  17.059  0.005 ...
...
```

The ellipses ... here mean there can be additional columns and rows.

The columns can be any fixed width, but they must be fixed. The header strings however need not be fixed width. Empty or erroneous data must generically be represented by the character "-" (dash).

While there is a minimal subset of columns that must be present for SLR to work properly, it is acceptable for there to be extra columns that the code doesn't formally recognize or use. This way you can carry extra information in the colortable, such as ID in the example above.

Table 7.1 lists the columns that are recognized and used by the SLR code.

Table 7.1: Colortable columns.

Column name	Type	Unit	Required?	Description
ID	*string*	J2000 deg	Yes	Object identifier.
RA	*float*	J2000 deg	Yes	Right ascension.
Dec	*float*	J2000 deg	Yes	Declination.

Continued on next page...

Table 7.1 continued: Colortable columns.

Column name	Type	Unit	Required?	Description
`type`	*integer*		Yes	1 = star. Only stars should be used. If an object has a different `type`, then the code will ignore it during regression, but will still apply calibrations to all objects when outputting the new colortable.
`tmixed`	*boolean*		Yes	Is the `type` ambiguous between the bands? Normally you'll want to run SLR on unambiguous stars (`tmixed` = 0, `type` = 1). If you are low on stars in your catalog, you can try setting `tmixed` to 1, in which case SLR will use all objects of the specified `type`.
`U`	*float*	mag	UNTESTED	U-band magnitude.
`U_err`	*float*	mag	If `U` present	Uncertainty in Johnson U-band magnitude.
`B`	*float*	mag	UNTESTED	B-band magnitude.
`B_err`	*float*	mag	If `B` present	Uncertainty in Johnson B-band magnitude.
`V`	*float*	mag	UNTESTED	V-band magnitude.
`V_err`	*float*	mag	If `V` present	Uncertainty in Johnson V-band magnitude.
`R`	*float*	mag	UNTESTED	R-band magnitude.
`R_err`	*float*	mag	If `R` present	Uncertainty in Johnson R-band magnitude.
`I`	*float*	mag	UNTESTED	I-band magnitude.
`I_err`	*float*	mag	If `I` present	Uncertainty in Johnson I-band magnitude.
`u`	*float*	mag	UNTESTED	u-band magnitude.
`u_err`	*float*	mag	If `u` present	Uncertainty in SDSS u-band magnitude.
`g`	*float*	mag	No	g-band magnitude.
`g_err`	*float*	mag	If `g` present	Uncertainty in SDSS g-band magnitude.
`r`	*float*	mag	No	r-band magnitude.
`r_err`	*float*	mag	If `r` present	Uncertainty in SDSS r-band magnitude.
`i`	*float*	mag	No	i-band magnitude.
`i_err`	*float*	mag	If `i` present	Uncertainty in SDSS i-band magnitude.

Continued on next page...

Table 7.1 continued: Colortable columns.

Column name	Type	Unit	Required?	Description
`z`	*float*	mag	No	z-band magnitude.
`z_err`	*float*	mag	If `z` present	Uncertainty in SDSS z-band magnitude.
`J`	*float*	mag	No	J-band magnitude.
`J_err`	*float*	mag	If `J` present	Uncertainty in SDSS J-band magnitude.
`H`	*float*	mag	UNTESTED	H-band magnitude.
`H_err`	*float*	mag	If `H` present	Uncertainty in SDSS H-band magnitude.
`K`	*float*	mag	UNTESTED	K-band magnitude.
`K_err`	*float*	mag	If `K` present	Uncertainty in SDSS K-band magnitude.

Chapter 8

Configuration Parameters

SLR reads ascii configuration files that the user can edit. Comments can be used with the character `#`. There must be at least one space between the parameter name and its value. Arrays (vectors) are comma-separated lists; there must be no spaces in such lists. Each parameter in the config file must have a corresponding value next to it. There can be no empty fields. All parameters must be present in the file.

Table 8.1 describes all configuration paramaters.

Table 8.1: Configuration parameters.

Parameter	Type	Description
	Colors to calibrate	
`colors2calibrate`	*string array*	Colors to be calibrate by SLR. Comma separated list, eg, `gr,ri,iz,zJ`
`kappa_fix`	*boolean array*	Fix $\boldsymbol{\kappa}$? There must be one entry for each `colors2calibrate`. Can be mixed, eg, `1,0,0,0`.
`kappa_guess`	*float array*	*Initial* values of $\boldsymbol{\kappa}$ for the fitting routine whenever `kappa_fix` is 0, or *fixed* values of κ whenever `kappa_fix` is 1. In magnitudes. There must be one entry for each `colors2calibrate`.
`kappa_guess_err`	*float array*	Values of errors for $\boldsymbol{\kappa}$, used when not bootstrapping or when only transforming the colors. In magnitudes.

Continued on next page...

Table 8.1 continued: Configuration parameters.

Parameter	Type	Description
`kappa_guess_range`	*float array*	Range of acceptable values of $\boldsymbol{\kappa}$, used by the fitting routine. In magnitudes. There must be one entry for each `colors2calibrate`.
	Color terms	
`colorterms`	*float array*	Color terms to use.
`colortermbands`	*string array*	Comma separated list of the bands that use the color terms. Each band here must appear somewhere in `colors2calibrate`, although not all magntiudes in `colors2calibrate` need have a `colortermband`. See §9. If `none`, then color terms are not used.
`colormult`	*string array*	Comma separated list of the colors that multiply the `colorterms`.
	Controlling the fitter	
`transform_only`	*boolean*	If yes, then don't do regression and just calibrate the data using the input $\boldsymbol{\kappa}$ and colorterms. If no, fit for $\boldsymbol{\kappa}$ and then perform the color transformation.
`weighted_residual`	*boolean*	Use the error-weighted residual?
`nbootstrap`	*integer*	Number of bootstraps to perform.
	Program behavior	
`force`	*boolean*	Force a re-read of ascii data? If not, then read from IDL .sav files if they exist.
`verbose`	*integer*	Verbosity level, 0, 1, or 2.
`plot`	*boolean*	

Continued on next page...

Table 8.1 continued: Configuration parameters.

Parameter	Type	Description
`postscript`	*boolean*	Write figures to postscript files instead of to screen? `plot` must also be set.
`interactive`	*boolean*	Prompt user for response periodically?
`animate_regression`	*boolean*	Plot each iteration of the fit?
`debug`	*boolean*	Debug mode?
`have_sfd`	*boolean*	Are the maps of Schlegel et al. (1998) available? Must exist in $DUST_DIR/maps.
	Ouput	
`write_ctab`	*boolean*	Write table of calibrated colors (and optionally magnitudes)?
`mags2write`	*string array*	What bands to write SLR-calibrated magnitudes for, or "none" if none. The bands must appear somewhere in `colors2calibrate`.
`mag_zeropoints`	*string array*	Which elements of $\boldsymbol{\kappa}$ are the magnitude zeropoints? There must be one entry for each `write_mags`.
	Conditions on the data	
`type`	*integer*	The type identifying stars, which are used in the fit.
`tmixed`	*boolean*	Whether to allow for point/extended source ambiguity in objects used in the fit.
`deredden`	*boolean*	Deredden the objects before fitting, using Schlegel et al. (1998)?
`cutdiskstars`	*boolean*	Cut out disk stars with Galactic $\|Z\| <$ `zeelow` before fitting, using Jurić et al. (2008)?

Continued on next page...

Table 8.1 continued: Configuration parameters.

Parameter	Type	Description
`zeelow`	*float*	Lower limit of allowable Galactic scale height Z for stars. Assumes they are main-sequence, and already calibrated. Only used if `cutdiskstars` is set. In parsecs.
`beelow`	*float*	Lower limit of allowable Galactic latitudes $\|b\|$, in deg.
`snlow`	*float*	Lower limit of allowable signal-to-noise in all bands used in the calibration.
`color_min`	*float array*	Hard lower limits on the colors. Each list entry is ordered to correspond to `colors2calibrate`. In magnitudes.
`color_max`	*float array*	Hard upper limits on the colors. Each list entry is ordered to correspond to `colors2calibrate`. In magnitudes.
`mag_min`	*float array*	Hard lower limits on the magnitudes. Each list entry is ordered to correspond to the ordered set of all magnitudes appearing in `colors2calibrate`. In magnitudes.
`mag_max`	*float array*	Hard upper limits on the magnitudes. Each list entry is ordered to correspond to the ordered set of all magnitudes appearing in `colors2calibrate`. In magnitudes.
`max_locus_dist`	*float*	Maximum distance to standard locus line allowable, in magnitudes.
`max_weighted_locus_dist`	*float*	Maximum error-weighted distance to standard locus line allowable. In magnitudes.
`magerr_floor`	*float*	Error to add to all magnitude errors in quadrature, in magnitudes.

Chapter 9

Color Terms

SLR allows for the use of color terms under a broad but still finite set of assumptions. We've attempted to make the assumptions as flexible as possible, without letting the code become too abstract and unwieldy. I'll go over the assumptions here so that you can get this code to produce better results than you would without using color term corrections.

9.1 The Procedure

9.1.1 Adopt Photometric Calibration Equations

First, understand that you must adopt a color term convention. You do this by adopting photometric calibration equations of the form

$$\text{instrumental mag} = \text{standard mag} + \text{zeropoints} + \tag{9.1a}$$
$$(\text{color term}) \times (\text{standard color}). \tag{9.1b}$$

Here the instrumental mag is what is measured after bias subtraction and flat-fielding, and the standard mag is the standardized measure of flux that we're ultimately after. The zeropoints have contributions from atmospheric extinction and Galactic extinction, from instrumental sensitivivity, from aperture corrections, and from anything else additive. The color term is a constant to be determined, and the standard color that it multiplies must be chosen. The value of the color term constant depends on the standard color that it multiplies.[1]

There is one equation of this form for each magnitude that you are considering during Stellar Locus Regression. So for N magnitudes you must adopt N photometric calibration equations, and N different color terms. Each color term can multiply a different standard color.

These equations are entirely standard, so there should be no surprises here.

[1]See High et al. (2009) for further discussion of the form of the photometric and color calibration equations that we use.

9.1.2 Measure Your Color Terms

It is your job to measure the color terms yourself. Although it is critical to use color term corrections when calibration data between different instruments using SLR, we do not provide procedures to do this for you. Our goal has been to keep the scope of our SLR code as narrow as possible so that its place within a larger photometric calibration pipeline is well defined. Also, we just don't want to support more code that we have to!

Typically you will measure color terms by matching catalogs of observed standard stars to a standard catalog, plotting the difference of instrumental mags and standard mags versus the standard color you adopted in Step 1, and measuring the slope of a best-fit line.

9.1.3 Put the Results in an SLR Config File

The final step is to tell SLR what conventions you adopted, and the values of the color terms you measured. See §8 while reading the following.

The SLR parameter `colortermbands` is a list of characters signifying the instrumental mags that require color term corrections. *Each band you list here must appear somewhere in* `colors2calibrate`. However it's not necessary to have all bands appearing in `colors2calibrate` to have an entry in `colortermbands`, because not all bands need color term corrections in practice. So make sure you don't include any extra bands in the list that just aren't being used in the color calibration in the first place.

For each entry of `colortermbands` you will need to specify one value for `colorterms` and `colormult`. The latter two configuration parameters are lists that must have the same length as `colortermbands`, and the lists are ordered. The colorterms you measured in Step 2 are placed in `colorterms`, and the standard color you chose in each passband calibration equation is placed in `colormult`.

Here's another important assumption to understand: *Each color you list in* `colormult` *must appear in* `colors2calibrate`. Your adopted standard colors must live in the vector space that you are calibrating. They cannot be linear combinations of `colors2calibrate`. They must be a subset of `colors2calibrate`. While this may be a more restrictive assumption, we take it to be entirely reasonable under most circumstances.

9.2 An Example

For example, in High et al. (2009) we took data in the *griz* Sloan passbands using instruments on the Magellan telescopes. We noticed that the color term corrections were significant, so we adopted some color term equations of the form

$$g = g_0 + a_g + E_g + A_g + b_g(g_0 - r_0) \tag{9.2a}$$
$$r = r_0 + a_r + E_r + A_r + b_r(r_0 - i_0) \tag{9.2b}$$
$$i = i_0 + a_i + E_i + A_i + b_i(i_0 - z_0) \tag{9.2c}$$
$$z = z_0 + a_z + E_z + A_z + b_z(i_0 - z_0) \tag{9.2d}$$

We observed some standard star fields in Stripe 82 and measured the color terms b. Then for all subsequent observations, we calibrated our instrumental colors using the same color term values. We did this by setting the color term parameters as follows:

```
colors2calibrate        gr,ri,iz
colortermbands          g,r,i,z
colorterms              -0.11,-0.01,-0.17,-0.01
colormult               gr,ri,iz,iz
```

In a subsequent step we matched all of our observed stars to the 2MASS database. After making a new input colortable that inluded the J-band data from 2MASS, we re-ran SLR with the following color term configuration to calibrate our Magellan i-band data:

```
colors2calibrate        iz,iJ
colortermbands          i,z
colorterms              -0.17,-0.01
colormult               iz,iz
```

Note that we had to remove the g and r band entries from the color term parameters because those bands don't appear in the new list of `colors2calibrate`. Also note that the J-band needed no color term correcton. This is because the J magnitudes were already calibrated!

9.3 Higher Order Corrections

It's possible of course to make color-airmass and other higher order corrections. The current implementation of SLR that we present here doesn't allow for these, but this is an obvious generalization that we intend to pursue.

Chapter 10

Frequently Asked Questions

Is there documentation of each IDL function? Yes, you can generate the html documentation for all IDL function with:

```
IDL> slr_docs
```

This will make the SLR IDL help page $SLR_INSTALL/docs/www/idl_help.html, which you can open in a web browser.

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