Nightfall User Manual

by R. Wichmann
(rwichman@lsw.uni-heidelberg.de)

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1 Introduction

NIGHTFALL is an interactive application that introduces into the fascinating realm of eclipsing binary stars. Apart from their light variations that make them interesting objects for observations, eclipsing binaries are of fundamental importance for astrophysics, e.g. for measuring the mass of stars. NIGHTFALL is capable of producing:

- animated views of eclipsing binary stars,
- lightcurves and radial velocity curves,
- best-fit binary star parameters for a given set of observational data.

It is, however, not able to fry your breakfast egg on your harddisk.

Eclipsing binary stars are most often very close systems. In such systems, owing to tidal forces, the shapes of both stars can be highly nonspherical, up to the possible formation of an 'overcontact' system, where both stars form a single, dumbell-shaped object.

NIGHTFALL is a mildly ultramundane program of baroque complexity (I like Verdi and Händel on lazy sunday mornings - friday evenings are better with Iron Maiden and a good whisky). NIGHTFALL is based on a physical model that takes into account the nonspherical shape of stars in close binary systems, as well as mutual irradiance of both stars, and a number of additional physical effects.

NIGHTFALL can handle a large range of configurations, including overcontact systems, eccentric (non-circular) orbits, surface spots and asynchroneous rotations (stars rotating slower or faster than the orbital period), and the possible presence of a third star in the system.

NIGHTFALL supports the GNOME desktop (if installed), but does *not* require it.
Also, NIGHTFALL supports *internationalization*. Currently, besides the default language (english), only german is supported. The language is selected by the environment variable LANG (must be set before starting the program, in sh, bash: `LANG=de; export LANG`
in csh, tcsh: `setenv LANG de`).

1.1 Remarks

NIGHTFALL is not part of my research work - rather it is the result of a recreational activity aimed at distracting myself from daily research work.

I have tested NIGHTFALL with published data on several binary stars. Data for these systems are included in the source code distribution. As no two light curve programs use exactly the same algorithms, results are never identical; however, results from NIGHTFALL appear to be within the range of similar light curve programs used in the literature. I hope that I have found most flaws in the logic of the code, at least in the 'scientific' part. If you want to use NIGHTFALL for a publication, you may want to evaluate its performance by yourself. NIGHTFALL comes WITHOUT ANY WARRANTY (see also Section 1.3 for more information).

1.2 Bugs

Several, probably. If you find a bug and can eliminate it, send me a diff. If you find a bug and can't cope with it, send me a report, and wait for the next version. If you would like a feature, tell me.

1.3 Copyright

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This document is considered part of the NIGHTFALL program.

2 Requirements and Installation

2.1 Requirements

NIGHTFALL has been developed with the aim of being able to compile and run the program on a typical Linux system without any need of downloading/installing additional libraries or programs. Although I have not tested this, NIGHTFALL should compile on other Unix systems as well.

For command line use/file output, all you need is a C compiler (e.g. gcc). For interactive use and plotting, NIGHTFALL requires additional libraries/programs, which, however, should already be included in your Linux distribution (most probably). All required libraries/programs are available for a wide variety of Unix systems.

- For interactive use of NIGHTFALL, a GUI is provided, which is based on the GTK library (available at http://www.gtk.org, GNU Library General Public License). GTK should compile on most Unix systems. If you have a recent Linux distribution, GTK should already be included. To see whether GTK is installed, try to run

  $ gtk-config –libs

  which should yield something like: '-L/usr/lib -L/usr/X11R6/lib -lgtk -lgdk -lglib -lXext -lX11 -lm' (might be different for your system). If you get a message like 'sh: gtk-config: not found', you might need to install GTK. (On SuSE Linux – and maybe other distributions –, GTK is split in two packages. For running GTK applications, you need only the 'gtk' package. For compiling applications (like NIGHTFALL), you also need the 'gtkdev' package).

- For plots and graphs, NIGHTFALL requires either

  – GNUPLOT, version 3.5 (pre 3.6) patchlevel beta 347, or higher. Earlier versions may or may not work. You need a version with 'multiplot' support. To verify this, try:

    $ gnuplot
    gnuplot$ set multiplot

    If you get an error message, you have to update your GNUPLOT.
    You also need write permission to the directory '/tmp' on your system. To test this, try:

    $ touch /tmp/foo

  – or the PGPLOT Fortran graphics subroutine library (available at:

    http://astro.caltech.edu/ tjp/pgplot

    free for non-commercial use). You need a Fortran compiler (g77 is fine) to compile it. You have to compile it with the Xserver and postscript drivers, and also have to compile the C wrapper library that comes with PGPLOT.

- If you have installed the Gnome Desktop on your system, NIGHTFALL will build with support for it. However, Gnome is *not* required for NIGHTFALL - it compiles just as well without Gnome.

Note: With GNUPLOT, plots are not that nice sometimes, but animated mode runs much smoother with GNUPLOT than with PGPLOT. GNUPLOT does not support incremental plotting and display of images, thus a few options are only available with PGPLOT.

2.2 Installation

After downloading the source code, do:

$ gunzip -c nightfall-*(version number)*.tar.gz | tar -xvf -
$ cd nightfall-*(version number)*
$ ./DoInstall.sh

The 'DoInstall.sh' script will query you for some information (e.g. where to install the program), and then (optionally) build, test, and install the application. If you want to do it by hand, instead of './DoInstall.sh' run the following sequence of commands:

$ ./configure
$ make
$ make install

If you want to use PGPLOT, 'configure' might find it by itself; otherwise you might need the 'configure' option
'–with-pgplot-include=PFX' (where PFX should be the directory where the PGPLOT header file cpgplot.h is installed), and '–with-pgplot-lib=PFX' (where PFX should be the directory where the PGPLOT library files libpgplot.a, libcpgplot.a are installed).

By default, the binary is installed to /usr/local/bin, the data/help/configuration files to /usr/local/share/nightfall. If you don't like this, use the 'configure' option '–prefix=/where/to/install', where '/where/to/install' will replace '/usr/local'.

2.3 Compile/configure problems

- Have gnuplot, but configure does not find it
  - is gnuplot in your path ? if no, update your PATH environment variable
  - does it support 'set multiplot' ? (start interactively by typing 'gnuplot', then type 'set multiplot' to test) if no, update your gnuplot
  - does 'gnuplot_x11 -persist' work, or does it give an error message like: gnuplot: bad option: -persist ? if error, update your gnuplot
  - There was at least one gnuplot version that supports the required 'multiplot' option, but does not list it as supported. In this case, enforce gnuplot support with:
    `./configure --with-gnuplot`
- Have gnuplot and pgplot, want gnuplot support
  - enforce gnuplot support with:
    `./configure --with-gnuplot`
- Have pgplot, but configure does not find it
  - do you have a fortran compiler (required) ?
  - the following files are required: cpgplot.h, libcpgplot.a, libpgplot.a
    Use `./configure --with-pgplot-include=/my/pgplot/include/dir --with-pgplot-lib=/my/pgplot/li`
    where '/my/pgplot/include/dir' is the directory where cpgplot.h is located, and '/my/pgplot/lib/dir' is the directory where libcpgplot.a, libpgplot.a are located.
- Have pgplot, get compile error

  - maybe your fortran compiler does not understand the link options required by Gtk. upgrade to a recent version of g77.
  - maybe pgplot was compiled with a different fortran compiler. recompile.

- Other compile errors

  - There might be problems related to internationalization, that may be caused by a broken installation of a respective utility on your system. For solving this, you should choose one of the following switches for the 'configure' script:
    `--disable-nls`
    `--with-included-gettext`
    like, e.g.: `./configure --with-included-gettext`
    The first switch will completely disable internationalization, i.e. only the english version will be available. The second switch will use the internationalization program that is included in this source code distribution, thus bypassing any preinstalled, maybe broken, utility on your system.

2.4 Compile-time configuration

Several aspects/limits of NIGHTFALL can be configured at compile time. Mostly, these are related to fixed array sizes. For most users, the defaults should be sufficient.
To configure, edit the file 'Light.h' and change the default value(s) of the '#define ITEM' statement(s) in the first section of this file (where 'ITEM' stands for any of the bold words on the list below). Configuration options include (but are not limited to):

- NIGHTFALL_PLOTFILE – the name of the output plot file (default is 'Nightfall.ps').
- STEPS_PER_PI, MAXELEMENTS – the number of surface elements for stars. This number cannot be set exactly, as the algorithm determines it at run time, trying to achieve a more or less constant area per surface element (for the lightcurve computation, of course the exact surface area is taken into account). You can, however, set the number of steps per one Pi (= 180 degree) on the equator, which is STEPS_PER_PI. You also have to adjust the size of the array holding the surface, which is MAXELEMENTS.
- MAXOBS – the maximum number of observational data per filter
- PHASESTEPS – the maximum number of steps for a full orbit
- N_SPOT – the maximum number of spots per star
- GNU_GEOMETRY – the default plot window geometry, if you use GNUPLOT as plotting program
  You can override the default with the environment variable GNUPLOT_GEOMETRY
  Please note: it is not possible to fully specify the PGPLOT plot window geometry from within the program. It can be defined (in pixels) by:
  X resource: pgxwin.Win.geometry: WIDTHxHEIGHT+X+Y
  or environment variable: PGPLOT_XW_WIDTH [fractional display width].
  PGPLOTS's default is width=867, height=669 and aspect=8.5/11.
  If PGPLOT_XW_WIDTH is undefined, NIGHTFALL will set it to scale down the window width to the GNU_GEOMETRY width.
  Set PGPLOT_XW_WIDTH to 1.0, if you don't like this
  (bash, ksh: 'PGPLOT_XW_WIDTH=1.0; export PGPLOT_XW_WIDTH'
  csh, tcsh: 'setenv PGPLOT_XW_WIDTH 1.0').

- OUT_FILE, OUT_SIMPLEX – the names of output files for the lightcurve (OUT_FILE) and eventual fit results (OUT_SIMPLEX).
- PROFILE_ARRAY, PROFILE_RES – the size of the array for line profile computation (PROFILE_ARRAY) and the default resolution (PROFILE_RES).

3 Usage

3.1 General

If used in non-interactive mode, unless a configuration file is read in at startup (see Section 3.5), NIGHTFALL requires at least the following six numerical arguments on the command line (in that order):

- (1) the mass ratio of both stars (mass(Secondary)/mass(Primary), allowed range 0.0001 – 10000.0. For Roche lobe fill factors (see below) above one, the mass ratio is restricted to 0.003 - 50.
- (2) orbital inclination (= viewing angle of orbital plane, range 0 – 90 degree), where 0 deg corresponds to face-on view (no eclipse possible), and 90 deg to edge-on view (eclipse guaranteed). For angles in between, the occurence of an eclipse depends on the mass ratio and the Roche fill factors (see below).
- (3,4) Roche lobe fill factors. The *Roche lobe* is the maximum volume a star can fill in a binary system. Its size is, in general, different for the two stars, and depends on the mass ratio (see Section 4.1 for an explanation). The Roche lobe fill factor is in units of the polar radius of the *Roche lobe*. The allowed range is 0.001 – 1.3. For values above 1.0, both stars merge into a *common envelope/overcontact* system.
- (5,6) surface temperatures of both stars (in Kelvin, range 350 – 350000; Kelvin = degree Celsius + 273.15). Just for comparison, the surface temperature of the sun is 5780 K. If you use the 'model atmosphere' option, the allowed range shrinks to 3000 – 35000 K.

These six numerical arguments are always required, if NIGHTFALL **is used in command-line (i.e. non-interactive) mode without reading in a configuration file** (see below)

$ nightfall -U -C ty_boo.cfg

will read parameters from a configuration file and start NIGHTFALL in interactive mode. The configuration file is a simple text file that can be edited by hand. In interactive mode, you can also write out the current parameters to a configuration file.

$ nightfall (without arguments) will produce a full list of options (many).

By default, NIGHTFALL **will do nothing more than run in non-interactive mode, compute the lightcurve, write it to an output file 'NightfallCurve.dat', and exit silently. If you want more (nifty plots, etc.), read on.**

3.2 Plotting, Graphics

requires that NIGHTFALL has been compiled with support for PGPLOT or Gnuplot.
In interactive mode, there are several menu options available to produce plots. In non-interactive (command-line) mode, you can choose from the following:

- For a real-time animation of the two stars orbiting each other, use **-A**
- To select plotting of the output light curve, use **-G**
- To select the filter for the plottted lightcurve, use **-Bfilter** where 'filter'is one of UBVRIJHKuvby (see Section 5.4)

- To visualize the geometry, use **-V**.
  There are four sub-options (-Va, -Vi, -Vc, -Vv):
  - -Vc for a contour plot of the potential,
  - -Vi for an image of the potential,
  - -Vv for viewing the stars,
  - -Va for all in one plot.

  The default is 'c'. Only 'c' and 'v' are supported by GNUPLOT (GNUPLOT cannot display images).
- To obtain a hardcopy, use **-H**.

Detailed output is always written to a file 'NightfallCurve.dat'.

3.3 Interactive usage - the graphical user interface (GUI)

Use command line option **-U** to choose this option (note that if you do not give a config file - see above - you still need the six minimum arguments listed above). A GUI will (hopefully) come up.

In the menu bar, there is a **File** menu for reading data/configuration files. Please note that you need to reset the data memory [**Reset Memory**] before reading in data for another binary, otherwise you will end up in a mess ...
The **Output** menu allows to choose between several facilities for viewing the output of a computation and visualizing the binary system. Some of them allow interactive change of parameters like viewing angle etc. Please read the online help for more details.

In the toolbar below, there are buttons for computing a lightcurve [**Compute**], toggling animated view of the binary [**Animate**] while computing, writing out the current binary configuration [**Write**], and getting help on the currently active notebook page [**Context**].

The rest of the GUI is layed out as a 'notebook' with several different pages for setting options:

- **Basic** Here you can define the basic configuration of the binary - mass ratio, inclination, fill-out ratios and temperatures. I know, reading manuals is not much fun, but you should read at least Section 4 to know what's going on. Use animated mode for 'learning by doing'.
- **Advanced** For advanced options like asyncroneous rotation, non-circular orbit, etc. See Section 6.
- **Plot Options** for the selection of output filter (see Section 5.4), and plot window for lightcurve, as well as options for geometry visualization.
- **Data Fiting** Computation of best-fit parameters. Also: definition of absolute system parameters (for radial velocity). See Section 7.
- **Spots** Here you can interactively define up to two spots per star (additional spots can be defined on the command line or in a configuration file). Both spots can be switched on/off independently. See Section 6.7.
- **Third Light** For definition of the brightness of an (eventual) third star in the system. Third Light is just added to the total brightness, never eclipsed, i.e. it only has an effect on the relative depth of the eclipses. See Section 6.10.

On the bottom of the GUI, there is a status/progress bar.

3.4 Problems

- The GNUPLOT PS-driver apparently does not support the 'multiplot' option.
- For eccentric (non-circular) orbits, very small fill factors produce strong numerical artifacts in the light curve.
- There seem to be some numerical artifacts also in the line profiles sometimes, preferentially at quadrature.

3.5 Configuration File

NIGHTFALL comes with a set of configuration files, each of which will set the system parameters for a particular (real) binary system, and automatically load some data files with observed data for this particular binary star (see next section).

For the file format, see the commented example file 'ty_boo.cfg' in the source code distribution. To read in such a file, on the command line use:

-C path/to/config/file

If you don't give the full path, NIGHTFALL will search (in this order of priority) the present working directory, an eventual subdirectory './cfg', and the default data directory set at compile time. If the configuration file is in one of these, only the name, not the full path is required.

3.6 Data files

NIGHTFALL comes with a set of sample observational data for several different eclipsing binaries. For each included binary system, the data comprise lightcurves in several filters, as well as radial velocity curves. Also, for each of these systems there is a configuration file (see Section 3.5). Loading this configuration file will set the appropriate parameters for that particular system, and also read in the data. You can then compute the lightcurve and visualize the binary, with the observed data overlayed on the lightcurve.

E.g. you might call NIGHTFALL as 'nightfall -U -C data/ty_boo.cfg', then press 'ANIMATE' to switch on the real-time animation, and press 'COMPUTE' to compute the lightcurve. With 'PlotCurve' you can then get a plot of the final lightcurve, with the data overlayed.

Of course, you can also experiment by yourself and try to fit the lightcurve by varying the system parameters, or use the automatic fitting option.

To read in a single data file, use

-I path/to/data/file.

If you don't give the full path, NIGHTFALL will search (in this order) the present working directory, an eventual subdirectory './data', and the default data directory set at compile time. If the data file is in one of these, only the name, not the full path is required. For details on the format of the files, see Section 7.1.
Data are available for the following systems:

- **TY Boo:** a 'common-envelope' ('overcontact') system with two cool stars. This is a so-called 'shallow' overcontact system, as the stars are only slightly overfilling their Roche lobes (for the explanation of the term 'Roche lobe' see Section 4.1). The two stars have slightly different temperatures.
- **MR Cyg:** a semi-detached system (the cooler fills its Roche lobe) with two stars of very different temperature (but both much hotter than the Sun). Lightcurve should be computed with some advanved options: model atmosphere fluxes, detailed reflection (2-3 iterations), quadratic limb darkening.
- **DD Mon:** another semi-detached system (the cooler star fills its Roche lobe). The cooler star is slightly cooler than the Sun, the other one slightly hotter than the Sun. The total

mass is very low – both stars together have only about 0.6 solar masses. It seems difficult to fit the lightcurve without spots (did not try as yet).

- **BH Vir:** a detached system with two stars, one slightly hotter, the other slightly cooler than the Sun. At least one of the stars has surface spots, which cause a slight, but noticeable distotion of the lightcurve. The config file includes two spots on the cooler star. The BV lightcurves and the uvby lightcurves are from different years. As the stars exhibit some variability, you might want to use either the BV or the uvby lightcurves, but not all six simultaneously.

- **LZ Cen:** a detached, but near-contact system with two rather similar stars, both very hot. The stars are rotating very slightly faster than synchroneously. Lightcurve should be computed with some advanved options: model atmosphere fluxes, detailed reflection (2-3 iterations), quadratic limb darkening.

- **ER Vul:** a detached system of two stars that are both slightly hotter than the sun, and also have masses only slightly higher than the sun. The stars show strong and variable activity, i.e. large starspots that are varying with time. Thus the derived parameters of the spots can vary a lot from one observation to the next.

- **V541 Cyg:** a well-detached (i.e. wide) binary system with an eccentric (i.e. non-circular) orbit. As the binary is very wide, the eclipses are narrow, and it is **important** to set the number of steps for the lightcurve to a high value (say, 600, instead of the default of 80) in order to resolve the eclipses.

- **51 Peg:** an extrasolar planetary system. Only the radial velocity curve of the primary is known, thus for the planet only the product $m \times \sin(i)$ is known (0.45 Jupiter masses). Depending on the unknown inclination angle, the mass may be as high as 15 Jupiter masses, while higher masses are probably ruled out, because a higher-mass companion would have synchronized the primary, which is not the case (the rotation period of 51 Peg is 29-37 days, while the orbital period of the planet is 4.23 days). The model assumes an inclination angle of 25 deg, and a density similar to Jupiter's for the planet. The parameters of the star (mass, radius, temperature) are well known; the temperature of the planet can be calculated from its distance to the star. No eclipses (by the planet) have been observed, but the amplitude would be at the limit of even the most sensitive measurements.

3.7 Environment variables

The run-time behaviour of the program can be modified by the value of some *environment variables*. To set an *environment variable* to some value, depending on your shell the following command is required:

in csh, tcsh: `setenv VARIABLE=value`

in sh, bash: `VARIABLE=value; export VARIABLE`

- **HOME** your home directory, usually automatically set by your shell

- **TEMPDIR or TMPDIR** location for temporary files (should not be on NFS mounted filesystem). If these variables are not set, NIGHTFALL will use /tmp as default.

- **LANGUAGE or LC_ALL or LC_MESSAGES or LANG** (in this order of priority) will be used to determine your language. The default is English. At the time of this writing, the only other supported language is German (LANG=de).

- **NIGHTFALL_DATAROOT** the root directory to search for the data/, cfg/, and doc/ subdirectories (containing data, config, and help files, respectively). Only needed if this directory has been moved after installation.
- **NIGHTFALL_DATA_DIR** the directory where data are located. Only needed if these have been moved after installation, and **NIGHTFALL_DATAROOT** is not set or data are not in **$NIGHTFALL_DATAROOT**/data.
- **NIGHTFALL_CFG_DIR** for location of config files. See **NIGHTFALL_DATA_DIR**.
- **NIGHTFALL_DOC_DIR** for location of help files. See **NIGHTFALL_DATA_DIR**.
- **NIGHTFALL_LOCALE_DIR** for location of data for localization. Only important if you use internationalization to support your language. See **NIGHTFALL_DATA_DIR**.
- **NIGHTFALL_PLOTFILE** the name of the output file for plots. Default is nightfall.ps.
- **GNUPLOT_GEOMETRY** the display geometry for Gnuplot (default is "550x424+300+20").
- **PGPLOT_XW_WIDTH** fractional display width for PGPLOT X window.
- **NIGHTFALL_RADIATIVE** limiting upper temperature for stars with convective envelope (default is 7000; unit is Kelvin). Above that temperature the envelope will be considered radiative.
- **NIGHTFALL_SMAP_PATH** base path to the surface map. To this, the index for the bandpass and the current phase will be appended. No surface map will be output if this environment variable is not set.
- **NIGHTFALL_SMAP_BAND** bandpass (0..11 for UBVRIJHKuvby) for which surface map is output.
- **NIGHTFALL_MONO_WAVE** a comma-delimited list of up to twelve monochromatic wavelengths (unit: micrometer) to replace the effective wavelengths for the blackbody approximation.

4 Introduction to Binary Stars

This section (and the next) provide(s) an introduction to the problem (at a popular science level, hopefully), the options, and the algorithm(s) used. More technical aspects are in italics. If you find the less technical part too arcane, feel free to supply (constructive) suggestions.

4.1 The Roche Geometry

Imagine two lakes, seperated by a ridge. There are about three possible configurations:

- In both lakes, the water level is well below the level of the ridge. This is a **detached system**.
- One of the lakes reaches up to the lowest point of the ridge, and water may spill over to the other lake. This is a **semi-detached system**.
- Both lakes overflow the ridge and form one single lake. This is a **contact / overcontact system**.

Replace 'water' by 'gas', 'lake' by 'star', and you have the possible configurations of a close binary star system.

The stellar shapes in such a system are given by the sum of the gravitational forces, and the centrifugal force due to the orbital motion. Instead of using the forces, it is easier to use a **potential** (forces can then be expressed as the derivative of the potential, if needed). In the case of binary stars, this potential is called the **Roche potential**, named after the French mathematician Edouard Albert Roche (1820-1883). The stellar surface is then given by an **equipotential surface** (a surface, on which the potential is constant). Thus, the introduction of the potential makes the computation of any forces superfluous in this particular application.

The largest size a single star can have in a binary system is given by the **Roche lobe** - a teardrop-shaped equipotential surface, whose cusp touches the cusp of the Roche lobe of the other star at a point called **Lagrange 1 (L1)** (there are four more Lagrange points, which are of less interest here). L1 is located between both stars, on the line connecting their centres. At L1, the sum the forces is zero, thus, if a star fills its Roche lobe, at L1 matter can flow into the Roche lobe of the other star (provided it is not filled as well).

Thus, L1 would correspond to 'lowest point of the ridge' in the two-lake example above, and the Roche lobes would correspond to the two valleys below that point, that potentially can be filled by the two lakes. But just as the two lakes in the example above may be smaller than their maximum size (before flowing together), also the stars in a binary system may be smaller than their respective Roche lobes. A star that completely fills its Roche lobe will assume its teardrop-like shape. A star filling only a small fraction of its Roche lobe will be more spherical - distortion increases with the **Roche lobe filling factor**.

Note that the *relative* size of the Roche lobe of the two stars in the system depends on their mass ratio. The *absolute* size of the Roche lobe also scales with the separation of the two stars. Thus, with a fixed mass ratio and fixed absolute sizes of the stars (e.g. in kilometers), a star may fill its Roche lobe (and have a highly distorted figure), if the stars are rather close, but the same star might fill just a tiny fraction of its Roche lobe (and thus would be nearly spherical) if the binary separation would be rather large.

To define the sizes of stars in NIGHTFALL, you have to give the 'Roche lobe filling factor', which is defined in units of the Roche lobe (actually, its polar radius). NIGHTFALL uses a dimensionless potential, i.e. the distance between both stars is arbitrarily set to unity. Thus, for a fixed absolute size of the stars, decreasing the 'Roche lobe filling factor' would be equivalent to increasing the distance.

4.2 Shape of the lightcurve

The shape of the lightcurve depends mainly on three factors:

- temperatures - as the eclipsed areas are equal for the eclipse of the Primary and the eclipse of the Secondary, the depths of the eclipses are only different if the temperatures of both stars differ. See Section 5.3 for details on temperature and brightness.
- relative sizes and shapes of the stars, which are determined by the mass ratio (that determines the relative sizes of both Roche lobes) and the Roche lobe filling factors (see Section 4.1).
- temperature distribution on the stellar surface. If the Roche lobe filling factor is large, the star is very nonspherical, and its temperature can vary significantly over its surface. This effect is known as gravity brightening (see Section 5.5). The result is that the lightcurve varies strongly, even if there is no eclipse.
- mutual irradiation of both stars (see Section 6.2).
- cool/hot surface spots (like sunspots, but can be much larger in some stars, see Section 6.7).

4.3 Suggested experiments

- to begin, set the mass ratio to 1.0, both stars to equal fill factor and both temperatures to equal values. You will find that both eclipses have the same depth, as the eclipsed areas are equal (and have the same limb darkening).
- as soon as one star is hotter than the other, the depth of the eclipses will become different.
- the width of the eclipses depends on the sizes of the stars
- the 'textbook' case of a flat lightcurve between eclipses is very rare. The reason is that due to the aspherical shape of stars in close binary systems, the visible surface area of the star varies during the orbit. Also, this aspherical shape causes strong temperature (= brightness) variations over the surface of the star an effect called 'gravity brightening' (or 'gravity darkening'). For more details, see Section 5.5. You will see that the lightcurve only becomes flat between eclipses if the Roche lobe fill factors (and thus the aspherical distortions) of the stars are very small. Which means that the distance of the two stars is large compared to their sizes, and an eclipse con only be observed if the orbital inclination is very close to 90 degrees - a rather rare case.
- on the other hand, the aspherical shape of the stars can cause deep throughs in the lightcurve even if there is no eclipse at all ! To see this, set the mass ratio to 0.9, the Primary fill factor to 1.0, the Secondary fill factor to 0.1, and the inclination to 40 degree (just as an example). In animated mode, you can verify that there is no eclipse at all, but still you see deep throughs in the light curve.
- the 'bottom' of an eclipse only becomes (more or less) flat if the star is eclipsed for a prolonged time, i.e. if it is significantly smaller than the other, eclipsing star.
- in an eccentric (non-circular) orbit, the velocity of the stars is not constant. Thus, also the width of both eclipses may be different, and the times between them as well (see Section 6.5). There is a config file 'v541_cyg.cfg' for the binary system V541 Cygni, which shows both effects.

- the shape of the stars can vary a lot in an eccentric orbit, because the varying distance is equivalent to a varying Roche lobe filling factor. To demonstrate this, set the mass ratio to 1.0, and both Roche lobe filling factors to 1.0. Set the eccentricity to a large value (say, 0.6), and the orbital inclination to 0.0, to see what's going on (don't forget to switch on 'eccentric orbit', if you are in interactive mode). Use animated mode and enjoy.

5 More details

5.1 Which star is which ?

Stars in binary systems are labelled 'Primary' and 'Secondary'. In NIGHTFALL, the star called 'Primary' is the star which is *eclipsing* first, i.e. the star that passes *in front* of the other one at orbital phase zero (orbital phase indicates the position of the stars in the orbit on a scale from zero to one). The secondary is the star that is *eclipsed* first. In animated view, at start the Primary is left, the Secondary right. Note that this labelling of 'Primary' and 'Secondary' is inverse to the usual convention ... mea culpa. Maybe I fix it sometime.

To exchange the stars (if needed), you can either (i) swap the eclipses in your data, or (ii) swap the stars themselves.
For (i), add half an orbital period to the phase zeropoint in your datafile (for a circular orbit), or the time lag of the second eclipse (for an eccentric orbit).
For (ii), swap temperatures and Roche lobe fill factors, and replace the mass ratio q by 1/q. Don't forget to swap spots, if you have. For an eccentric orbit, add or subtract 180 deg to/from the Periastron length.

For a circular orbit, NIGHTFALL starts at orbital phase -0.25 – which is identical to +0.75 –, and calculates up to +0.75. In a circular orbit, eclipses are at orbital phase 0.0 and 0.5.).

NIGHTFALL uses a dimensionless potential, i.e. the distance between both stars is arbitrarily set to unity. The relative size of both Roche lobes then depends only on the mass ratio of both stars. The size of both stars has to be given as a fraction of the Roche lobe (actually, its polar radius). This fraction might be larger than one, if you want to specify an overcontact system. To specify a semi-detached system, set the Roche lobe filling fraction to 1.0 for one star, less for the other.

5.2 How is eclipse testing done ?

NIGHTFALL divides each stellar surface into a grid of a few thousand elements. Eclipse testing is done by checking - for each surface element individually- whether the line of sight towards that surface element intersects the other star. For overcontact systems, a star might eclipse its own throat region (the region connecting both stars). This condition is tested as well.
Although simple tests based on orbital phase or intersection of sperical regions suffice in most cases, still sometimes a rigorous and expensive test is needed.

5.3 Temperature and Brightness

Stellar surface temperatures can range from a few 1000 Kelvin to several 10000 Kelvin. The respective brightness can be calculated from the so-called blackbody law (a blackbody is an idealized thermal radiation source). The blackbody law is applicable to thermal radiation, such as infrared radiation of your own body, or radiation by stars; it is not applicable to non-thermal radiation sources like lasers.

By default, NIGHTFALL uses the blackbody law, which is neither terribly good nor terribly bad. It is possible to use, instead, light fluxes from detailed numerical computations of stellar atmospheres. Contrary to blackbody fluxes, these model atmosphere fluxes (like real stellar fluxes) depend not only on temperature, but also (mildly) on surface gravity, and on the chemical composition of the stellar atmosphere. As actual atmosphere calculations would be prohibitively expensive, model atmosphere fluxes are taken from tables that cover only a limited range in temperature (3000 K to 35000 K). Tables are hardcoded, and only available for one surface gravity value (a compromise value that should be ok for most cases), and solar chemical composition.

To switch on model atmosphere fluxes, use

-M

5.4 Output Lightcurves

Lightcurves are output in eight commonly used broad-band filters (UBVRIJHK from near-UV to near-infrared), and four narrow-band filters (Stroemgren uvby). The shape of the lightcurve depends on the filter passband.

The human eye itself also is not equally sensitive to all wavelengths of light – it also is a kind of 'filter' for light. To create a lightcurve that looks like the human eye would see it, you have to choose an output filter that matches as close as possible the sensitivity of the human eye. For broadband filters, the V filter gives the best match to the human eye. In the Stroemgren filter system, you might want to choose Stroemgren v.

Lightcurves are output in **magnitudes**. This is a relative unit commonly used in astronomy, and defined as

$$m_1 - m_2 = -2.5 \times \log \frac{flux_1}{flux_2}.$$

(For magnitude differences smaller than about 0.4, the difference in magnitude times 100 is nearly equal to the percentage difference in flux, i.e. 0.1 mag is about 10 per cent difference.) The brighter an object, the smaller its magnitude (Sun is -26.7 in the V filter, while the faintest stars visible by naked eye are about +6). NIGHTFALL uses the brightness at quadrature (phase -0.25 in a circular orbit, both stars fully visible) as normalization (i.e. as $flux_2$ in the equation above).

Output goes to a file 'NightfallCurve.dat'. To select plotting of output light curve, use

-G

To select the filter for the plotted lightcurve, use

-Bfilter,

where **filter** should be one of UBVRIJHKuvby. The default for plotting is the V filter, which is the best match to the human eye. If you read in data files with observed lightcurves (see Section 7.1 for more info), the default will be the filter of the first lightcurve read in.
To obtain a hardcopy (i.e. PS file), use

-H

5.5 Gravity Brightening

The nonspherical shape of both stars causes a non-constant surface gravity. This, in term, causes brightness variations, with regions of higher surface gravity having higher brightness. This effect is called gravity brightening or gravity darkening (depending on which article you read). Gravity brightening can produce deep minima in the lightcurve, even if there is no eclipse at all !! NIGHTFALL always takes care of this effect - there is no option to switch it off.

6 Advanced Options

6.1 Fractional Visibility

As eclipse testing is only done for the centres of surface elements, the coarse surface grid introduces numerical artifacts that are readily visible sometimes. To fix this problem, it is possible to compute **fractional visibilities** for the surface elements (i.e. compute what fraction of a surface element is eclipsed). To switch on, use

-F

6.2 Reflection

Due to the mutual irradiance of both stars, in addition to its own light, each star will also reflect light of its companion. This can be a very important effect, especially if the two stars are close (large Roche fill factor) or the temperature difference is large. NIGHTFALL offers two options:
(1) by default, the irradiating star is treated as a point source. This is ok for low Roche lobe filling factors, but not very accurate for stars filling a large fraction of the Roche lobe. It is rather fast, however.
(2) it is possible to compute the mutual irradiance of all pairs of surface elements, with up to nine iterations (usually, two to three are sufficient). This is an N^2 algorithm (N the number of surface elements), and thus computationally very expensive. To switch on, use

-Rn

where 'n' is the number of iterations.

6.3 Overcontact systems

For overcontact systems, the second Lagrange point (L2) comes into play. It is located behind the less massive star (as seen from the more massive), and has the same property as L1, i.e. the force vanishes there, and matter might flow out of the common envelope of an overcontact system (I suppose, by now you know where L3 is. L4 and L5 are in the orbital plane, left and right of the line connecting the centres of both stars. L3-5 are not terribly important for binary stars.)

Thus, the surface of the common envelope of an overcontact system has to be between the two equipotential surfaces given by the potentials of L1 and L2 (remember, the force is the derivative of the potential, thus if the net force is zero, the potential can still have a non-zero value - it just has to be 'flat' locally).

To have an overcontact system, set the Roche lobe filling factor of one star larger than 1.0 (as there is only one surface now, the smaller Roche lobe filling factor will be ignored). If you choose a too large value, NIGHTFALL will adjust it. (The largest possible value depends on the mass ratio. Anything larger than about 1.3 is rather unreasonable for any mass ratio.)

The combination of overcontact and non-circular orbit or asynchroneous rotation (see below) is not supported. It would be rather unphysical anyway, as the strong interaction (tidal forces and friction) would circularize and synchronize the system extremely rapidly.

6.4 Asynchroneous Rotation

Tidal forces in close binaries will tend to enforce synchroneous rotation (both stars rotating with the orbital period, thus showing each other always the same side) on a timescale usually shorter than stellar lifetimes.

There are, however, occasions when stars might rotate asynchroneously, e.g. young stars that are not yet rotating synchroneously, or massive stars that have short livetimes anyway, too short for synchronization to occur during their lifetime. Also, tidal forces fall off very rapidly with increasing distance, thus wide binaries are likely candidates for asynchroneous rotation (the tidal force is inverse proportional to the cube of the distance - unlike e.g. gravity, which is inverse proportional to the square of the distance and thus falls off much less rapidly).

A (nonstellar) example for synchronization is the Earth-Moon system, where Moon's rotation has been synchronized already, while Earth's rotation is known to slow down gradually. This would eventually lead to Earth's synchronization as well, but I suspect it might take longer than the lifetime of our solar system ...

To switch on asynchroneous rotation, use

-fP fratio or **-fS fratio**

[-fP for Primary, -fS for Secondary). 'fratio' is the ratio between stellar rotation period and orbital period.

Asynchroneous rotation modifies the Roche potential (see Section 4.1), and hence the equipotential surface which defines the stellar shape. One effect is a 'flattening' of the star for faster rotation. Another effect is that the 'critical lobe', i.e. the largest possible surface, is modified. For faster rotation, it becomes smaller than the Roche lobe (which is the 'critical lobe' for a synchroneously rotating star, as discussed in Section 4.1). In this situation, you might have two binary component, both filling their 'critical lobes', but well separated from each other.

For slower rotation, the 'critical lobe' can become larger than the Roche lobe... NIGHTFALL will check (and complain), if both stars intersect. (While an overcontact system with synchroneous rotation is no problem, asynchroneous rotation, with contact, will cause heavy friction, I would think, presumably leading to rapid synchronization. Thus a contact system with asynchroneous rotation probably is unrealistic.)

Surface spots (if there are any) will move with the stellar rotation rate (just as they should).

6.5 Eccentric Orbit

According to Keplers laws, the shape of the orbit is an ellipse. Often, it is close to a special case of an ellipse - a circle. However, sometimes binary orbits are markedly eccentric, i.e. non-circular. In an eccentric orbit, the distance and the orbital velocity is not constant. The stars will gain velocity, as they fall toward each other, and move fastest at Periastron (closest approach). They will lose velocity again as they move away from each other, and move slowest at Apastron (largest distance). Thus the time between first and second eclipse in general is different from the time between second and first. Also, the width of the eclipses may be different, as in general the stars will move with different velocities during the two eclipses. NIGHTFALL comes with sample data for the star 'V541 Cygni', an eccentric binary system where you can observe both effects.

Similar to asynchroneous rotation, the comment applies that tidal forces will act towards circularization of the orbit. Eccentric orbits are more likely in wide binaries than in close ones.

The problem is, that in an eccentric orbit the changing distance is equivalent to a changing Roche lobe filling factor, and thus a changing shape of the star (remember, the larger the Roche lobe filling factor, the larger also is the nonspherical distortion of a star's shape). While in a circular orbit the stellar surface is calculated only once, and then just rotated in space, in an eccentric orbit the stellar surface must be re-calculated at each step in orbital phase, thus causing substantial computational overhead.

To switch on this option, use

-e eccentricity periastron_length

where 'eccentricity' (range 0-1, 0 is circular orbit) is defined as

$$e = \frac{r_2 - r_1}{r_2 + r_1},$$

with r_2 is the largest and r_1 the smallest distance. Clearly, $e = 0.0$ if $r_2 = r_1$, which is the case for a circular orbit. $e = 1.0$ is a degenerate case (a parabola), which cannot be handled by the program. 'periastron_length' is the length (in degree) of the periastron, i.e. the point of closest approach in the orbit. To find out how it is counted, you may set the Roche lobe filling factor to 1.0, and e to a high value, like 0.5, Then, using the animation option (-A), you can identify the periastron easily, as the star will fill the Roche lobe at closest approach.
The input Roche lobe filling factor is assumed at Periastron. Due to the variable orbital velocity, 'synchroneous' rotation is not really synchroneous - rotation will lag behind the orbital motion for part of the orbit, and advance for the other part of the orbit. Surface spots (if there are any) will move accordingly.

6.6 Limb Darkening

The depth to which you can see into a star's atmosphere (where the visible light comes from) varies with the viewing angle. As the temperature (which determines the light flux) increases with depth, you can see hotter (= brighter) layers of the atmosphere towards the centre of the star's disk, where you can look deeper. Towards the limb, you see shallower, cooler, and thus less bright layers of the atmosphere. This results in the limb of a star being darker than the centre of its visible disk, an effect that can be seen readily on good (!) photographies of the Sun.

Limb darkening, as a function of the cosine of the viewing angle towards the stellar surface, is well aproximated by simple expressions. NIGHTFALL offers four different options, with expressions that are linear or include additional square or square root terms. The fourth option calculates limb darkening individually for each surface element (using the square root law). The square root law is probably most accurate, but you will find that there is not much difference.

The default is the linear law. To change this, use

-Ln

with 'n' a number in the range 0-3 (0 = default).

6.7 Surface Spots

Cool stars like the sun (i.e. stars with surface temperatures of a few thousand Kelvin only) often have surface spots, which are regions of somewhat lower temperature on the surface. Among such stars, some are known to have surface spots ('starspots') much larger than those shown by the Sun. In extreme cases, spots may cover a few tenths of the stellar surface. Usually, these are cool spots (i.e. a few 100 K cooler than the surrounding area), caused by magnetic activity (like on the Sun).

To include spots, use

-sP longitude latitude radius dimfactor or

-sS longitude latitude radius dimfactor

(-sP for a spot on the Primary, -sS for a spot on the secondary). Spots are circular. The arguments are longitude and latitude of the spot's centre, the radius (all in degree) and the factor, by which the surface temperature is changed in the spot area. You can have multiple spots on each star. For overlapping spot areas, 'dimfactor' is averaged.

It is possible, but physically very unrealistic, to set 'dimfactor' to rather low or high values (0.5 - 2.0). Temperature deviations of more than about 1000 K may be not realistic. Hot spots are seen only in exceptional cases.

6.8 Radial Velocities

Unlike lightcurves, which can be expressed in a relative unit, radial velocity curves only make sense in absolute units (km/s in NIGHTFALL). Thus, they require absolute dimensions as input for the system. (NIGHTFALL supplies default values, however, if you don't want to bother about this.) Use

-tP period or

-tM mass or

-tD distance

('period' in days, 'mass' (= total mass of both stars) in solar masses, 'distance' in solar radii.) You need to give two of these; the third can (and will) be calculated from Kepler's third law.

Radial velocities are computed as the sum of the orbital velocity of a point mass plus corrctions (flux-weighted contributions from each surface element). In animated view, you can see the resulting sum as well as the correction term (the latter multiplied by 2).

6.9 Line profiles

NIGHTFALL can calculate spectral line profiles at each phase step, which are output to files (one for each phase step). You can specify the rest wavelength 'lambda_zero' for the line. The luminosities (of individual surface elements) used to compute the profile are those for the passband with the closest effective wavelength. To switch on, use

-Plamda_zero

In interactive mode, you have the option to view the line profiles, and change the phase interactively.

Some numerical artifacts present, probably due to finite surface grid.

6.10 Third Light

The presence of an additional light source in the system (e.g. a third star) will decrease the contrast between eclipsed and non-eclipsed parts of the lightcurve. To include this effect, use

-3filter fraction

where 'filter' is one of the supported filters (UBVRIJHKuvby) and 'fraction' is the relative contribution of third light to the total system luminosity. I.e.:

$$L1 + L2 + L3 = 1.0,$$

where $L1 + L2$ is the combined light flux from Primary and Secondary, and $L3$ is 'third light'.

This option is not tested yet.

7 Fitting observed data

NIGHTFALL offers the possibility of determining a best-fit model for observed data. Several datasets can be fit simultaneously. Both a local and a global optimization algorithm are available. **Fit results** are written to a file 'NightfallFitted.dat'.

7.1 Reading in the data

In order to determine a best-fit model to observed data, you first have to read them into memory. Use

-I path/to/data/file.

Only one file is read. To read more files, prepend each of them with a **-I**. You can read in (only) one datafile for each filter.

Each row in the file should consist of two or three numbers. The first is the date of the observation (as decimal number, in any unit you like), the second the measurement value (in magnitudes for brightness, in km/s for radial velocity), and the third (optional) the estimated error of the measurement.

Lines starting with a '#' are ignored, with the following exceptions (no blank after '#' !!):

#P period gives the orbital period of the system (same unit as dates). The program will use this value to fold the data into orbital phase. The default is 1.0 (thus assuming that your data are already folded in phase).

#Z zeropoint gives the zeropoint for orbital phase, i.e. the time of Primary eclipse (same unit as dates). The default is 0.0 (again assuming that your data are already folded in phase).

#Bfilter gives the filter in which your data have been observed. Default is V. For radial velocities, use '1' for Primary, '2' for Secondary.

#W error gives the average estimated error of measurements (if you do not have individual ones). Default is 0.01 (brightness) or 1.0 (radial velocities). You can mix individual and average error estimates (e.g. if you have individual error estimates only for some of your data).

#V system_velocity For radial velocity curves, use this parameter to set the system velocity. Radial velocities will be set to $data - system\_velocity$.

#N normalisation_phase Use this parameter to set the phase at which to normalize the light curve. The default is the starting point of the lightcurve.

#S shift This is a particular important parameter that requires some care. As noted in in Section 5.3, NIGHTFALL will normalize its lightcurves to light at the normalisation_phase (see above), which by default is the starting point of the lightcurve (the leftmost in the plotted lightcurve). Thus, at this point, the brightness is zero magnitudes. For a meaningful fit, your observed lightcurve must be shifted up/down to have the value zero at this point as well (within the measurement errors). NIGHTFALL will try to do it automatically, but some correction may be required. Plot the lightcurve (data will be overplotted, if there are any), and check. Note: incorrect use of this parameter may make a fit look better, but the fitted parameters might be meaningless. Do not shift to anywhere else than the starting point of the lightcurve.

The source code distribution includes example files for the binaries TY Boo (an overcontact system) and some more. If in doubt, look into them.

7.2 Finding a local optimum

Determining a best-fit model means to optimize the parameters (like inclination, temperature, mass ratio, etc.) in such a way that the mismatch between model and observation is minimized. This mismatch is measured by a suitable **merit function** (sometimes also called **cost function**). NIGHTFALL uses the chi-square function as merit function.

General problems of determining best-fit parameters are:

(1) uniqueness: there may be several/many (nearly) equally good solutions. Do a few trials. **Restart** fitting with last best-fit as starting point.

(2) overfitting: the information content of a lightcurve is limited. Fitting too many parameters might produce good-looking, but meaningless results. Use as few free parameters as are sufficient for a good fit.

(3) local vs. global optimum: just that you find a valley, doesn't mean this is the deepest valley on Earth. The same applies to optimization problems. Any local optimization algorithm will only find a local optimum. If the problem is well-behaved, this will be the one and only, global, optimum. If the problem is badly-behaved, you might need a few trials with different starting points to find (hopefully) the global optimum. If the problem is even worse, you might need an awful lot of computing time to find the global optimum. Most examples in textbooks are nice. Most real-world optimization problems turn out to be bad or even ugly.

NIGHTFALL uses the so-called Simplex algorithm for local optimization. This is a direct search algorithm that is not terribly fast (and not terribly slow either), but very robust. To switch on optimization, use

-Xparameters tolerance

where 'parameters' is a string of characters indicating the parameters you want to fit (all others kept fixed), and 'tolerance' is the stopping criterion (something like 0.1 or less would be appropriate - 0.001 has a special meaning, see Section 7.4). Use 'nightfall' without options to get the character codes for fit parameters.

If more than one data file is input (e.g. lightcurves in different filters), NIGHTFALL will fit all data simultaneously. This will probably work well only if different datasets are properly weighted - i.e. if the error estimates (or at least their ratios) are ok.

Have a cup of coffee ready. Use the **-Db** option (switch on 'Busy' in interactive mode) to see what is going on meanwhile.

IMPORTANT: Restart fit with last best-fit as starting point. Continue this until you are sure that the solution has converged and does not improve anymore, i.e. the value of 'SDV (Chi square)' does not significantly change anymore. Otherwise, your results may be **completely meaningless**. (swich on the -Db option to see 'SDV (Chi square)' for each iteration – see Section 8.1.

Output is always written to a file 'NightfallFitted.dat'.

7.3 Goodness-of-fit

To evaluate how good a fit is, NIGHTFALL offers the following options:

(1) if you plot the lightcurve, residuals will be plotted as well. Look at them to check whether there are systematic trends (= bad fit).

(2) for a good fit, the residuals should scatter randomly around the model, with no systematic trends. This can be quantified by computing the 'runs statistic' (the number of runs = occurences of two or more **consecutive** residuals above or below the model curve). Obviously, a large number of runs would occur for a strictly alternating sequence, which is very unlikely for a random sequence. Likewise, only two runs would occur for the first half of the data below, the second above the model curve - also suspiciously non-random. The expected number of runs can be calculated analytically. NIGHTFALL will print out the actual number of runs, and the lower and upper limits for a 90 percent confidence interval.

(3) in theory, the goodness-of-fit can be evaluated from the χ^2 (Chi Square) value of the fit (the function actually minimized in parameter fitting), which should be close to unity for a good fit. However, this only works if the error estimates for the measurements are realistic - neither to high nor to low. This is very rarely the case in astronomy ...

7.4 Finding a global optimum

To find a global optimum, basically a stochastic search strategy is required (or an exhaustive seach of the complete parameter space ...). There are different possibilities, ranging from complete random search to some 'intelligent' variation of random search. NIGHTFALL offers 'Simulated Annealing', which is a kind of mathematical implementation of the cooling of matter (leading to crystallization, i.e. an energy optimum, if cooling is slow enough). Switch on by setting the fit tolerance to 0.001 (in command-line mode).

Be prepared for a computing time on the order of a day or more (if you have no other CPU-expensive job running).

I am not sure whether the algorithm is correctly implemented. In the present implementation, cooling might be too fast, or might stop at a too high 'temperature'. However, my own experiments were rather satisfactory most of the time.

Apparently, 'Simulated Annealing' does not mathematically guarantee that the global optimum is indeed found, unless 'cooling' proceeds infinetely slow ...

7.5 Mapping the Chi-Square function

This option will create a two-dimensional map of the merit function (i.e. in the case of NIGHTFALL the Chi-Square function that measures the goodness of a fit) with respect to two parameters. Start values are the current values, step values can be entered. The gridsize is fixed at compile time (default 16 x 16, i.e. 256 lightcurves will be evaluated). To switch on this option, use

-Xparameters step1 step2

Parameters are coded like in the fitting option (see above), but only two parameters should be chosen.

8 Miscellaneous

8.1 Debug options

-Dcharacterstring

Most debug options (selected by 'characterstring') are of little use unless you know the code rather well. Some will produce excessive (and excessively messy) output.

Exceptions are:

- **b** ('busy'), which keeps your screen somewhat busy in case you do something computationally expensive (data fitting, elliptical orbit).
- **w** ('warning'), which will print out warnings. Usually, these refer to problems that the program can deal with, and thus you can ignore them. If you do not get the output you expect, you might want to turn them on to see what the program complains about.
- **v** ('verbose'), which will print out a moderate amount of information (will grow excessive during data fitting ... use 'b' instead if you just want to see what's going on).

8.2 Output of the surface map

It is possible to obtain the 2D surface map of the stars, as seen by an observer, i.e. the map displayed in animated mode. You have to set the environment variable NIGHTFALL_SMAP_PATH to the path of the map file (the program will append the index of the phase to this, i.e. you will get a seperate file for each step in orbital phase). If NIGHTFALL_SMAP_PATH is undefined, no map will be printed.

By default, the map will be output for the V band; you can change that with the environment variable NIGHTFALL_SMAP_BAND (0..11 for UBVRIJHKuvby).

The map includes for each *visible* surface element:
(1) the index of the star,
(2) the index of the surface element,
(3, 4) x, y coordinates in the viewing plane of the observer, with the star at (0, 0),
(5, 6) x, y coordinates as above, but with the centre of mass at (0, 0),
(7) $\cos\gamma$, the line-of-sight angle,
(8) temperature,
(9) dimensionless gravity,
(10) area,
(11) flux.

The flux is not normalized to the area; it is the flux that this surface element contributes to the total flux.

8.3 User-defined wavelenghts

It is possible to compute monocromatic fluxes at up to twelve different, user-defined wavelengths. These wavelengths (unit: micrometer) must be provided as a comma-seperated list in the environment variable NIGHTFALL_MONO_WAVE. They will replace the wavelenghts used in the blackbody approximation.

- If less than twelve wavelengths are given, the remaining ones will be filled in with the wavelengths of the corresponding passbands.
- For each wavelength, NIGHTFALL will use the limb darkening coefficients of the passband whose wavelength matches best the monochromatic one.

- Blackbody approximation must be selected (i.e. the 'model atmosphere' option must be switched off), otherwise these user-defined wavelengths do not take effect.

9 Technical details

This section is intended as a technical reference for experts who want to familiarize themself with the nasty details and the algorithms used.

9.1 Geometry

The geometric setup is based on a paper [9] by Djurašević (1992). In a cartesian coordinate system (x, y, z), the stars are located at $(0, 0, 0)$ and $(1, 0, 0)$, and the z-axis is perpendicular to the orbital plane. A normalized, dimensionless Roche potential is used, which at a point $P(x, y, z)$ is given by the value C as

$$C = \frac{1}{r_1} + q(\frac{1}{r_2} - x) + \frac{q+1}{2}(x^2 + y^2)f^2,$$

with $r_1 = x^2 + y^2 + z^2$, $r_2 = (x - 1)^2 + y^2 + z^2$, mass ratio $q = m_2/m_1$, and nonsynchronism parameter $f = w/w_k$ (i.e. the ratio of the angular velocity to the Keplarian angular velocity). For practical purposes, a spherical coordinate system (r, η, ϕ) is used, which is defined by

$$\begin{aligned} x &= r\ \cos\eta, \\ y &= r\ \sin\eta\ \cos\phi, \\ z &= r\ \sin\eta\ \sin\phi. \end{aligned}$$

The surface of the star is then divided into elementary areas by a grid in (η, ϕ), and for each surface element the gravity acceleration $g(r, \eta, \phi)$, the area $dS(r, \eta, \phi)$, and the normal vector (l, m, n) is computed as outlined in [9].

Notes: **(i)** Equation (1-16) in [9] has a minor typo (wrong sign for l).
(ii) Djurašević [9] apparently uses equidistant steps in ϕ, thus leading to very unhomogeneous elementary areas. NIGHTFALL avoids this by adjusting the number of steps N_ϕ as

$$N_\phi = 10 + N_\eta sin\eta,$$

with N_η a (compile-time) constant.

9.2 Reflection and gravity darkening/brightening

There are two options available for the treatment of limb darkening. Both are *bolometric* corrections, in the sense that the bolometric flux of the irradiating component is used to modify the temperature distribution on the irradiated component. See [20] for a discussion of this issue.

The 'simple' option for the treatment of reflection is described in [9]. The correction should be exact for spherical stars.

The 'detailed' reflection treatment loops over all pairs of surface elements (dS_1, dS_2) and sums up, for each surface element dS_1, the irradiation by all visible surface elements dS_2 of the other star. Again, *bolometric* irradiation is computed. Of course, the true temperature of the irradiating surface elements (including reflection) is not known, thus it is necessary to iterate the algorithm. Convergence is typically reached after 2-3 iterations. The algorithm is described in [10].

For both treatments, for convective stars (below 7000 K) an albedo of 0.5, and for radiative stars an albedo of 1.0 is used.

Gravity darkening is computed by

$$T(r,\eta,\phi) = T_{eff}(\frac{g(r,\eta,\phi)}{g_{eff}})^{\beta}.$$

For convective stars (below 7000 K) a temperature-dependent gravity brightening exponent is used [1]. For radiative stars, the Von Zeipel (1924) exponent of 0.25 is used. The transition is sharp, without any interpolation.

Notes: **(i)** The 'simple' reflection treatment in [9] has been supplemented by a penumbral correction for the partial visibily of the other star, if it is at the horizon. This penumbral correction assumes that the horizon is flat and that the other star is spherical, i.e. that the visible part is a segment of a circle.
(ii) For the 'detailed' reflection treatment, instead of the quadratic limb darkening law used by [10], a square root law ([8])

$$I(\mu) = I(1)[1 - c(1-\mu) - d(1-\sqrt{\mu})]$$

is used (where μ is the cosine of the angle subtended by the emergent radiation and the direction perpendicular to the stellar surface), and bolometric limb darkening coefficients for $\log g = 4.0$ are taken from [19]. The normalization factor for the square root law was calculated as

$$\frac{1}{\pi\ (1 - c/3 - d/5)}.$$

(iii) The temperature limit of 7000 K dividing stars with convective/radiative envelopes can be changed by the environment variable NIGHTFALL_RADIATIVE (within the range 4000 – 12000 K).

9.3 Spots

Spots are always circular, and characterized by four parameters: longitude λ, latitude β, radius r, and a 'dimming' factor $A_p = T_p/T$, i.e. the ratio of the (local) temperature T_p with spot to the temperature T without spot. A detailed discussion of the trigonometric expressions used to identify surface elements within the spot area can be found in [9], section I-3. In the 'detailed' reflection treatment, reflection is calculated with spots, i.e. the spots are applied first, then the reflection is calculated. For overlapping spots, in the overlap area the mean value of their A_p is used.

9.4 Output flux

In the blackbody approximation, for each stellar component and each filter a (temperature-dependent) effective wavelength is computed, following Equation 3.30 in [4]:

$$\lambda_{eff} = \lambda_0 + \frac{5\mu_2(\lambda_p - \lambda_0)}{\sqrt{\lambda_0}},$$

where λ_0 is the filter wavelength, and λ_p the wavelength of the blackbody peak for the effective temperature of the respective component. The required second moments μ_2 of the filter passbands are computed following the prescription by [21], Equation 12:

$$\mu_2 \simeq \frac{FW(0.05)}{4.4},$$

where $FW(0.05)$ is the full width at the 0.05 level.

For the 'model atmosphere' option, fluxes for temperatures below 9800 K are from Hauschildt et al. (1999) NextGen models ([11, 12]), otherwise flux tables from Kuruzc models (1991) as given by [19] are used. The (originally monochromatic) fluxes have been integrated over the filter passbands (as given in [16]). Only $\log g = 4.0$ is used.

Three different limb darkening approximations are available, a *linear*, a *quadratic*, and a *square root* one, which are given by the following expressions, respectively:

$$\begin{aligned} I(\mu) &= I(1)[1 - u(1 - \mu)], \\ I(\mu) &= I(1)[1 - a(1 - \mu) - b(1 - \mu)^2], \quad \text{and} \\ I(\mu) &= I(1)[1 - c(1 - \mu) - d(1 - \sqrt{\mu})], \end{aligned}$$

where μ is the cosine of the angle subtended by the emergent radiation and the direction perpendicular to the stellar surface. Limb darkening coefficients are from [6, 7]. Only $\log(g) = 4.0$ is implemented. A discussion of the relative merits of these three approximations can be found in [8].
Notes: **(i)** For the linear limb darkening, the polynomial approximations given by [6] are used for U, B, V, Str uvby. In all other cases, the tabulated values are used.
(ii) When tabulated values are used, for temperatures out of range (below 3500 K and above 35000 K) the lowest/highest value is used (i.e. no extrapolation is attempted).

9.5 Eclipse testing

Eclipse testing follows the method proposed in [9]. First, the contact angle of the Roche lobes is used to exclude eclipses, if possible.
If an eclipse is possible, for each surface element dS the line of sight (LOS) towards dS is tested for intersection with the smallest sphere enclosing the eclipsing star (no intersection = not eclipsed). Then the LOS is tested for intersection with the largest sphere within the eclipsing star (intersection = eclipsed). This procedure takes advantage of the simplicity of testing the intersection of a line with a sphere.
If the LOS intersects the outer, but not the inner sphere, as a last (and computationally expensive) resort, the minimum of the Roche potential along the LOS is searched, and compared against the surface potential of the eclipsing star.

Notes: **(i)** In [9], the osculating cone (i.e. the tangent cone to the Roche surface at the inner Lagrangian point L_1) is used as the first eclipse criterion. According to [5], this can lead to serious errors for mass ratios very different from unity, as the larger Roche lobe is concave at the L_1. NIGHTFALL uses tabulated values from [5] (the cone angle $\phi_{\max}$ as given in their Table 2). **(ii)** In [9], the coordinate frame of the eclipsed star is used, for eclipse testing, which seems not to work for asynchroneous rotation. NIGHTFALL therefore uses the coordinate frame of the eclipsing star, following [2]. **(iii)** In [9], it is proposed to evaluate the potential along the LOS at six steps only. NIGHTFALL uses a more rigorous approach with a minimum finding routine (Brent's algorithm [3]).

9.6 Fractional visibility

The eclipse testing routine assigns to each surface element a visibility of 0 (eclipsed) or 1 (visible). However, the visibility is only evaluated for the centre of the element. This can lead to 'spikes' in the light curve, if large numbers of surface element centres become visible at once. Therefore, an option is provided to compute a *fractional* visibility for surface elements on the shadow limb.

The algorithm first searches all pairs of elements on the shadow limb (i.e. pairs with one element eclipsed, the adjacent element uneclipsed), and determines the potential minimum along the LOS towards them (which is typically already available from the eclipse test). Then, a linear approximation is made: for each pair, the distances d_i to the shadow limb are taken as proportional to the differences between the minimum Roche potential p_i^{LOS} along the LOS and the surface potential p_* of the eclipsing star:

$$f = \frac{d_1}{d_2} = \frac{p_1^{LOS} - p_*}{p_2^{LOS} - p_*}.$$

The surface element with the larger distance is assumed to be completely eclipsed or visible, and the other one of the pair is assigned a fractional visibility $(1/2 + |f|)$ based on the above approximation. This is not exact for individual surface elements, as the dividing line between them may not be parallel to the shadow limb. However, averaged over all surface elements on the limb, the error should be negligeable.

9.7 Eccentric orbits

In an eccentric orbit, the complete geometry and temperature distribution is re-calculated at each step (= step in mean anomaly). As the Roche potential is used in a dimensionless form, the change in distance is equivalent to a change in the Roche volume filling factor (= surface potential) with an unchanged unit distance.

This implies that the correct new surface potential must be found as a function of the stellar volume, which is scaled up/down with the distance. To avoid an iterative numerical integration of the stellar volume (i.e. varying the surface potential until the correct volume is found), which would be prohibitively expensive, the algorithm uses analytical approximations from [15] to derive the new surface potential.

The following procedure is used:

1. Solve the Kepler equation to determine the distance of the stars (and their position in the orbit).
2. Re-scale the distance to unity.
3. Scale the stellar volume by the the cube of the distance scale factor.
4. Find the 'mean radius' as the root of an analytical expression for the stellar volume (of 11th order in this 'mean radius').
5. Compute the new surface potential as a function of the 'mean radius'.

Numerical details, including the definition of the 'mean radius', can be found in [15].

9.8 Optimization

For local optimization, the Simplex algorithm is used. This is a direct search algorithm that does not require derivatives. For N free parameters, the simplex is a polyhedron with $(N + 1)$ vertices (or points) in the N-dimensional parameter space. At each step, the simplex moves through this parameter space according to some rules, basically moving away from its worst point. Details of the algorithm can be found in [14, 18].

For global optimization, an implementation of the 'simulated annealing' method is provided. Basically, 'simulated annealing' does a stochastic search of the parameter space. Replacing the current best point with a better point (i.e. a downhill step) is always allowed, replacing it with a worse point (an uphill step) is allowed with some probability depending on the (steadily decreasing) 'temperature' of the system.

The implementation is based on the 'Very Fast Simulated Re-Annealing' algorithm [13], however, the 're-annealing' part is not included. For random number generation, the 'Mersenne Twister' random number generator (period length $2^{19937} - 1$) by Makoto Matsumoto and Takuji Nishimura [17] is used. It has a Mersenne prime period of $2^{19937} - 1$ (about 10^{6000}) and is equi-distributed in 623 dimensions. Mainly for debugging purposes, the seed is fixed, thus the generated sequence is always the same, and the results are reproducible.

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A Command line Options

Mandatory:	
(q)	mass(Secondary)/mass(Primary)
(i)	inclination angle (degree)
(rf1)	Primary Roche fill factor
(rf2)	Secondary Roche fill factor
(t1)	Primary temperature
(t2)	Secondary temperature
Interactive:	
-U	Interactive mode
Graphic Output:	
-A	Animated view
-V[v,i,c,a]	Visualize geometry (default: v) v: view of stars i: image of potential c: contourmap of potential a: all of the above
-G[P,S,1,2]	Graph of lightcurve (default: 1) P,S: close-up of Primary/Secondary eclipse 1,2: display 1/2 orbital cycles
-B[U/B/V...]	Bandpass to display in graph (default: V)
-H	Hardcopy (postscript plot)
Files:	
-I datafile	Read in a data file containing observed data
-C cfgfile	Read in a configuration file
Advanced System Parameters:	
-f[P/S] F	asynchroneous rotation ratio (Period/Period_Orbit)
-s[P/S] longitude latitude radius dimfactor	Spot on Primary/Secondary
-e e w	eccentric orbit, e = eccentricity, w = periastron length
-t[P/M/D] value	period/total mass/separation in days/solar masses/solar radii
Debugging Options:	
-D[vwb]	Debug [verbose,warn,busy]
Computation Options:	
-Plamda_zero	Profile of absorption line at rest wavelength lamda_zero (nm)
-Nnn	nn steps for lightcurve (default 80)
-M	use Model atmosphere
-F	compute Fractional visibility
-L[0-3]	Limb darkening method (default: linear = 0) 0: linear 1: quadratic 2: square root 3: square root, individual surface elements
-R[1-9]	Reflection treatment 0: Point source 1-9: iterations for mutual reflection
-3CM	Third light, C: colour code, M: magnitude

Data Fitting:	
-X[..] Tolerance	Fit the parameters coded in string [..]
	012345: q, i, rf1, rf2, t1, t2
	67: e, w (eccentric orbit)
	89: F(Primary),F(Secondary) (asynchroneous rotation)
	A-H: 2 Spots (Primary)
	I-P: 2 Spots (Secondary)
	QR: Mass, Separation
	a-l: Third Light (UBVRIJHKuvby)
	(Tolerance = 0.001 to use Simulated Annealing)
-Y[as above] Step1 Step2	Chi Square Map (2 Parameters)