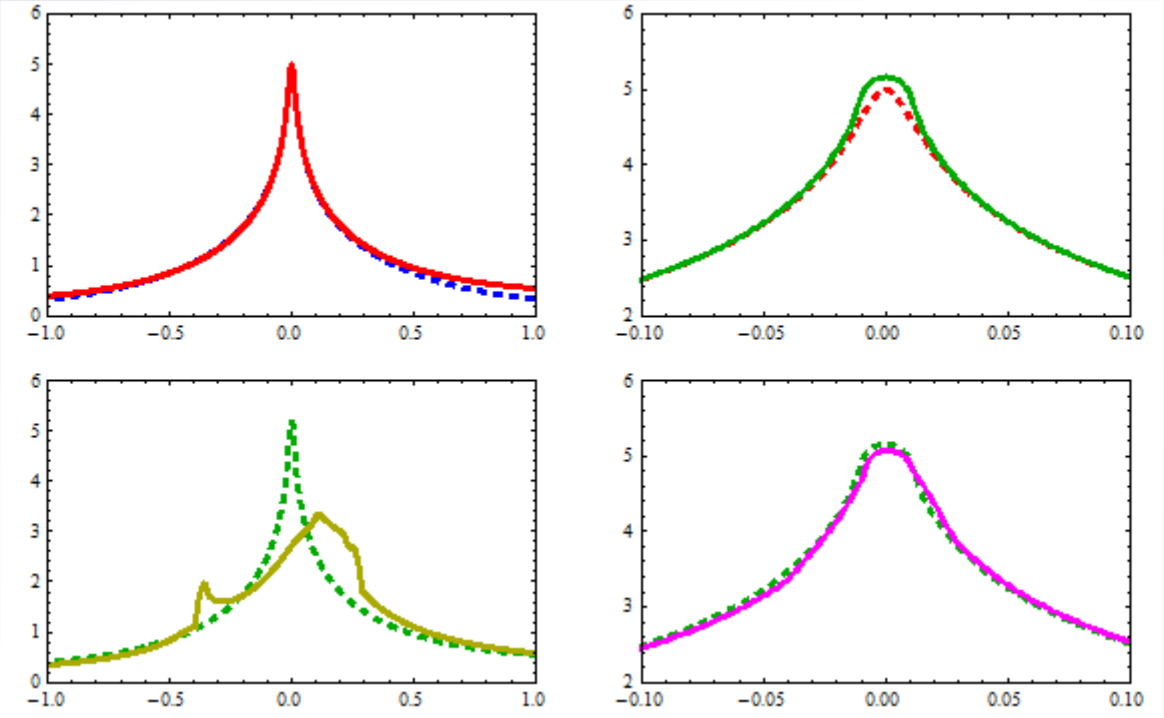
VBBinaryLensing

A public code for binary microlensing computation



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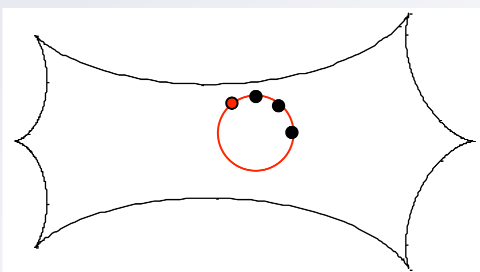
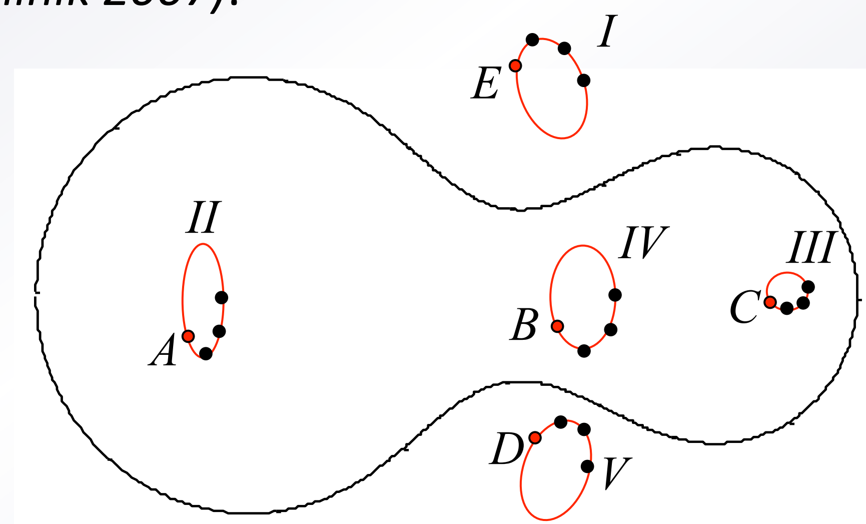
What is VBBinaryLensing

- **VBBinaryLensing** is a code for the calculation of **microlensing light curves**.
    - Point-Source Point-Lens
    - Extended Source Point-Lens
    - Binary Source Point-Lens
    - Extended Source Binary Lens
- **Higher order effects** implemented:
    - Linear limb darkening
    - Annual and space parallax
    - Circular orbital motion
- C++ library.
- Tested on Windows, Linux, Mac OS.
- Importable in Python.
- Source code is public (but no specific standard has been adopted!).

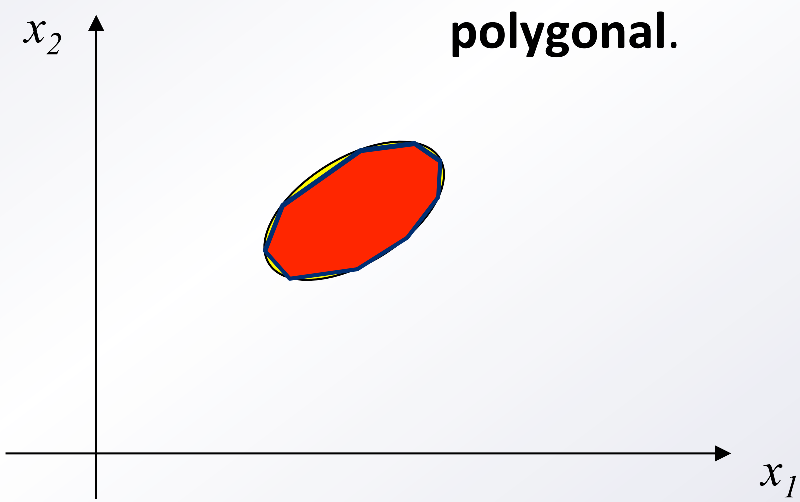
Magnification in Binary Lensing

- Magnification by binary lenses is calculated with the **contour integration** method *(Schramm & Kayser 1987; Dominik 1993; Dominik 1995; Gould & Gaucherel 1997; Dominik 1998; Dong et al. 2006; Dominik 2007)*.





- Area traditionally estimated by a **polygonal**.



- Area is typically underestimated.
- Uniform sampling is insufficient and/or inefficient.
- Ambiguities in case of source crossing a caustic.
- No limb darkening.

Advanced Contour Integration

(Bozza, MNRAS 408, 2188 (2010))

Parabolic correction:

- The simple trapezium formula can be corrected by a third order term:

$$A = \sum_{i=0}^{n-1} \frac{1}{2} \mathbf{x}_I(\theta_i) \wedge \mathbf{x}_I(\theta_i + \Delta\theta) + \frac{1}{24}\left[\left(\mathbf{x}_I' \wedge \mathbf{x}_I''\right)\Big|_{\theta_i} + \left(\mathbf{x}_I' \wedge \mathbf{x}_I''\right)\Big|_{\theta_i+\Delta\theta}\right]\Delta\theta^3 + O(\Delta\theta^5)$$

- The same accuracy can be reached with much fewer sampling points, saving computational time.

Error control:

- For each boundary arc we can estimate the error in our approximation with three indicators working in complementary ways:

$$E_{I,i,1} = \frac{1}{48}\left|\left(\mathbf{x}_I' \wedge \mathbf{x}_I''\right)\Big|_{\theta_i} - \left(\mathbf{x}_I' \wedge \mathbf{x}_I''\right)\Big|_{\theta_i+\Delta\theta}\right|\Delta\theta^3$$

$$E_{I,i,2} = \frac{3}{2}\left|\Delta A_I^{(p)}\left(\frac{\Delta\tilde{\theta}^2}{\Delta\theta^2} - 1\right)\right|$$

$$E_{I,i,3} = \frac{1}{10}\left|\Delta A_I^{(p)}\right|\Delta\theta^2$$

- The total error in the magnification is

$$E = \sum_{i=0}^{n-1}\sum_{I}\sum_{k=1}^{3} E_{I,i,k}$$

- The target accuracy $\delta\mu$ is reached if

$$\frac{E}{\pi\rho_*^2} < \delta\mu$$

Advanced Contour Integration

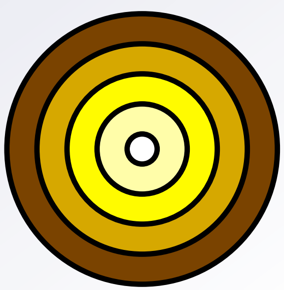
(Bozza, MNRAS 408, 2188 (2010))

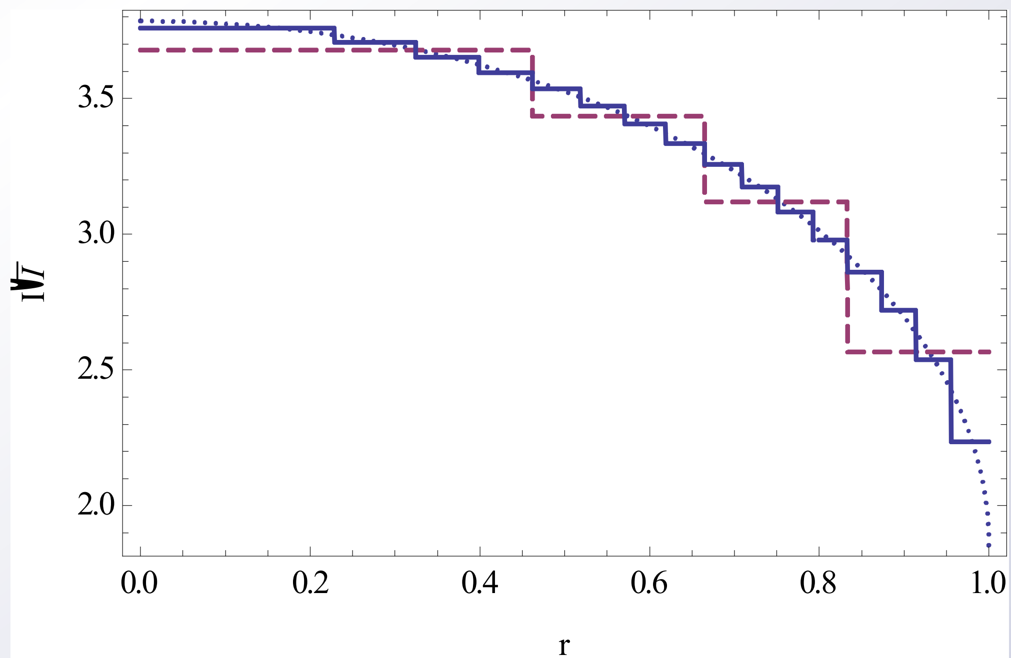
Optimal sampling:

- We increase the sampling where the error is largest (optimal sampling).
- We stop when the target accuracy is reached.

Limb darkening:

- In contour integration, limb darkening can be taken into account by calculating the magnification in concentric annuli and weighing them by the brightness profile.





- We sample uniformly in the integrated flux rather than radius.
- We use estimators for the residual error and thus **introduce optimal sampling**.

Testing Advanced contour integration

- Advanced contour integration is at the core of **RTModel**, the real-time modelling platform at Salerno University *(http://www.fisica.unisa.it/GravitationAstrophysics/RTModel.htm).*
- It has thus been extensively **tested in 5 years of real-time modelling** with any kind of binary events.
- It has been used in the **analysis of two specific events**:
  OGLE-2008-BLG-510: first automated real-time detection of a weak microlensing anomaly - brown dwarf or stellar binary, Bozza et al. (2012)
  Spitzer Observations of OGLE-2015-BLG-1212 Reveal a New Path toward Breaking Strong Microlens Degeneracies, Bozza et al. (2016)
- More testing has come in the last few months after the public release of VBBinaryLensing.

Release of VBBinaryLensing

- **VBBinaryLensing** is available at *http://www.fisica.unisa.it/GravitationAstrophysics/VBBinaryLensing.htm.*
- The **zip file** contains:

readmeVB.txt	Generic introductory information
VBBinaryLensingLibrary.h	C++ header
VBBinaryLensingLibrary.cpp	C++ source
main.cpp	Sample code with examples and instructions.
Makefile.dat	Example of a makefile (courtesy of Zhu)
howtopython.txt	Instructions for wrapping the library in Python code (courtesy of Hundertmark)
OB151212coords.txt	Sample coordinate file for an event (used in the examples in main.cpp)
satellite1.txt	Table for the positions of a satellite for space parallax calculation (Spitzer)
satellite2.txt	Same for Kepler.

Example of use

```
#include <stdio.h>
#include "VBBinaryLensingLibrary.h"

int main()
{
    VBBinaryLensing VBBL;

    double Mag,s,q,y1,y2,Rs,accuracy;
    s=0.8; //separation
    q=0.1; // mass ratio
    y1=0.01; // source position
    y2=0.3;
    Rs=0.01; // source radius

    accuracy=1.e-2; // Required accuracy of the result
    Mag=VBBL.BinaryMag(s,q,y1,y2,Rs,accuracy);

    printf("Magnification = %lf\n",Mag);

    return 0;
}
```

Methods

```
class VBBinaryLensing
{ ...
   public:
       double BinaryMag(…);
       double BinaryMagDark(…);

       void SetObjectCoordinates(char *,char *);

       double PSPLCurve(double *,double);
       double PSPLParallaxCurve(double *,double);
       double ESPLCurve(double *,double);
       double ESPLParallaxCurve(double *,double);

       double BinaryLightCurve(double *,double);
       double BinaryLightCurveParallax(double *,double);
       double BinaryLightCurveOrbital(double *,double);
       double BinSourceMag(double *,double);
       double BinSourceParallaxMag(double *,double);
       double BinSourceXallarapMag(double *,double);
}
```

Parallax and orbital motion

- **Parallax** is specified by two components of the parallax vector π_1 , π_2.
- Two possible **reference frames** are implemented:
  - Earth acceleration and its perpendicular direction.
  - North-East direction. (just set `VBBL.parallaxsystem=1;`)
- Parallax is calculated using the JPL calculator http://ssd.jpl.nasa.gov/txt/aprx_pos_planets.pdf.
- The magnification as seen from a **spacecraft** is obtained by setting

```
VBBL.satellite=1; // or 2 or 3 if you have more than one
```

- Satellite ephemeris tables are accepted in the NASA Horizons format.

- Circular **orbital motion** is implemented.
- Parameters are

$$\omega_1 \equiv \frac{1}{s}\frac{ds}{dt}, \quad \omega_2 \equiv \frac{d\alpha}{dt}, \quad \omega_3 \equiv \frac{1}{s}\frac{ds_z}{dt}$$

- All other quantities can be derived from these:

$$\omega = \sqrt{\omega_1^2+\omega_2^2+\omega_3^2}\,\frac{\omega_3}{\sqrt{\omega_1^2+\omega_3^2}}; \quad \cos i = \frac{\omega_2}{\sqrt{\omega_1^2+\omega_2^2+\omega_3^2}}\,\frac{\omega_3}{\sqrt{\omega_1^2+\omega_3^2}}$$

Conclusions and perspectives

- VBBinaryLensing is a new **public library** for the calculation of microlensing light curves.
- It is much **faster** than any other contour integration codes thanks to its advanced tricks.
- It has a very reliable **accuracy control**.
- It comes with **many functions** already implementing **higher order effects**.
- In general, inverse ray shooting codes are advantaged for large sources, while contour integration works better for smaller sources.
- Continuous **feedback from users** since the first release has widened the testing, thus increasing the reliability of the code.
- Many suggestions from the community have already been incorporated.

http://www.fisica.unisa.it/GravitationAstrophysics/VBBinaryLensing.htm.

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