Analysis of Spectroscopic Binaries

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3. How to determine binary orbits from measured RVs?
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1. Introduction:

Types of binary stars

classified by
- their appearance on the sky
- the orientation of their orbits
- their physical composition
By the Appearance On The Sky

- **Optical binaries:** Two stars that falsely appear to be binary stars, judging from their closeness on the sky are called *optical binaries.*

- **Visual binaries:** A system that can be resolved through the use of telescopes (including interferometric methods) are called *visual binaries.*

- **Astrometric binaries:** Only one component is visible that shows a wave-like motion on the sky
By the Appearance On The Sky

- **Spectroscopic binaries**: Stars that orbit so close to each other (or are so far away), that their components can't be resolved through telescopes but their orbital motion can be recognized in their spectra are called *spectroscopic binaries*.

- Example: *Mizar* in *Ursa Major* is a visual binary where both components are spectroscopic binaries.

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*Observed Spectrum*

- single lined: **SB1**
- double lined: **SB2**
On the Spectrum of Zeta Ursae Majoris*
Edward C. Pickering
[American Journal of Science, 3rd Ser., vol. 39, pp. 46-47, 1890]

- In the Third Annual Report of the Henry Draper Memorial, attention is called to the fact that the K line in the spectrum of Zeta Ursae Majoris occasionally appears double. The spectrum of this star has been photographed at the Harvard College Observatory on seventy nights and a careful study of the results has been made by Miss. A. C. Maury, a niece of Dr. Draper. The K line is clearly seen to be double in the photographs taken on March 29, 1887, on May 17, 1889 and on August 27 and 28, 1889. On many other dates the line appeared hazy, as if the components were slightly separated, while at other times the line appears to be well defined and single. An examination of all the plates leads to the belief that the line is double at intervals of 52 days, beginning March 27, 1887, and that for several days before and after these dates it presents a hazy appearance.

→ The first spectroscopic binary!
By the Orientation of the Orbit

Eclipsing Binaries:
We decide between primary and secondary and between total, annular, and partial eclipses. EBs are important to determine the fundamental parameters of the stars from photometry (lightcurves) and spectroscopy. Eccentric orbits lead to non-equidistant spacings of the primary and secondary eclipses in the lightcurves.
By the Physical Composition

→ We need some basics
The Roche lobe

Lagrangian points:
Force-free points $L_1$ to $L_5$

Roche lobe:
equipotential surface through $L_1$

Filling factors (substellar points $x_1$, $x_2$):

$$f_1 = \frac{x_1}{L_1}$$
$$f_2 = \frac{1-x_2}{1-L_1}$$

normalized potential (stars at [0,0,0] and [1,0,0], $q=m_2/m_1$)

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

Co-rotating (non-inertial) frame
gravitational + centrifugal force

By the Physical Composition

- **Detached binary**: No physical contact between the both stars. None has filled its Roche lobe, both spherical in shape.

- **Semi-detached binary**: One star fills its Roche lobe and has a non-spherical shape due to the gravitational distortion by a very close companion, mass transfer may occur.

- **Contact binary**: Both stars fill their Roche lobes, are non-spherical and have a common envelope.
2. Measurement of stellar radial velocities

$$\text{RV} = \text{velocity component towards the observer}$$

$$v_r = c \frac{(\lambda - \lambda_0)}{\lambda_0}$$

Here, $\lambda$ is the observed wavelength of the lines in a spectrum measured from

- centroid or first order moment
- Gaussian or other profile fit
- cross-correlation with a template
- other methods (see KOREL)
In the case of LPV, RVs are not well defined

- observation of variable RV surface fields in disk-integrated light (pulsating stars)
- observation of varying parts of stellar surfaces (EBs)

Define what you mean by RV (centroid, deepest point, ...)!
RV measurement for SB2 stars

SB2 \rightarrow \text{composite spectra}

RVs can be measured by

a) fitting \text{multiple Gaussians} or \text{synthetic line profiles} to
   - selected lines
   - the \text{CCF} obtained from cross-correlation with a template
   - \text{LSD} profiles

b) Advanced methods like \text{KOREL}

$H\alpha$ of $\beta$ Aur (two white subgiants of about equal masses).

Figure based on O. Thizy,
The problem can be more complex...

Time series of spectra of two B-type stars in an eclipsing, close binary

(Pavlovsky et al., 2011BSRSL..80..714P)

Spectra of the components after decomposition and renormalization
Fit of single lines

Fit single lines by one or more Gaussians or other profiles. Calculate RVs by averaging the results from many lines.

**Advantages**
- RVs of individual chemical elements
- Careful selection of unblended lines
- Error statistics

**Disadvantages**
- Does not use the full information
- Multiple Gaussians fail around $\gamma$-velocity

Simulation of measured (crosses) and calculated (solid curves) RVs of an eclipsing binary.
Cross-correlation

\[ CCF(v) = \int S(x+v)T(x) \, dx, \quad x = c \ln \lambda \]

Cross-correlate the spectrum with a template like a
- synthetic spectrum
- spectrum of a comparison star
- spectrum of the same star (mean spectrum, iteration, d-functions)

*Fit the CCF as in the case of single lines*

**Advantages**
- uses the full information from the spectra
- gives more precise RVs

**Disadvantages**
- no RVs of individual elements
- blends
- symmetry and shape of the CCF depend on the distribution of lines
- fails around \( \gamma \)-velocity

J. Harlow 2000 (thesis, Univ. of Toronto)

Gliese 372 (SB2 M-dwarf)
**LSD = Least Squares Deconvolution**
*(Donati et al. 1997)*

www.ast.obs-mip.fr/users/donati/multi.htm

**Basic assumption:** observed profile = convolution of a line pattern with one common, average line profile $P$

**Basic approximations:**
- wavelength-independent limb darkening (valid for weak lines)
- self-similar local profile shape
- linear addition of blends

**Determination of $P$** = linear deconvolution problem
→ search for the least squares solution

**Improvements:**
- recover the individual line strengths
- use line lists for multi-component atmospheres
Example: 250 nm of a K1-type spectrum $\rightarrow$ gain factor of 32 $\rightarrow$ corresponds to 7.5 mag
Summary: RV determination

- Single line fit (e.g. multi-Gaussian) is based on the S/N in the lines but allows to investigate lines of single elements, ions, and multiplets.

- CCF enhances the S/N by using information from all lines in the spectrum but is influenced by blends and the distribution of lines of different elements in the spectrum.

- LSD is basically an improved version of CCF that gives more accurate line profiles of higher resolution.

- In the case of SB2 stars, all these methods fail around $\gamma$-velocity.

- In the case of LPV (pulsation, eclipses), one has to define what exactly RV means.
3. Orbital solutions

For celestial mechanics, see
Karttunen, Kröger, Oja, Poutanen, Donner: „Fundamental Astronomy“
# Elements of the relative orbit

<table>
<thead>
<tr>
<th>geometry</th>
<th>semi-major axis</th>
<th>( a )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>eccentricity</td>
<td>( e )</td>
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<tr>
<td>orientation</td>
<td>inclination</td>
<td>( i )</td>
</tr>
<tr>
<td></td>
<td>nodal length</td>
<td>( \Omega )</td>
</tr>
<tr>
<td></td>
<td>length of periastron</td>
<td>( \omega )</td>
</tr>
<tr>
<td>motion</td>
<td>time of periastron passage</td>
<td>( T )</td>
</tr>
<tr>
<td></td>
<td>true anomaly</td>
<td>( \nu(t) )</td>
</tr>
<tr>
<td></td>
<td>orbital period</td>
<td>( P )</td>
</tr>
</tbody>
</table>

**RV**

|           | semi-amplitude | \( K \) |
|           | system velocity | \( \gamma \) |
Orbital phase diagrams

RV curves folded with the orbital period, phase zero at $t = T$

→ only $K$, $e$, and $\omega$ effect the shape of the RV curves
The true anomaly as a function of the eccentric anomaly

From the definitions of $\nu$ and $E$, we get

\[ r_x = r \cos \nu = a(\cos E - e) \quad (1) \]
\[ r_y = r \sin \nu = b \sin E \]

The distance follows to

\[ r = \sqrt{r_x^2 + r_y^2} = a(1 - e \cos E) \quad (2) \]

From the ellipse, we know

\[ b = a \sqrt{1 - e^2} \quad (3) \]

From (1) to (3), we obtain

\[ \cos \nu = \frac{\cos E - e}{1 - e \cos E} \quad (4) \]
\[ \sin \nu = \frac{\sin E}{1 - e \cos E} \sqrt{1 - e^2} \]

or

\[ \tan \frac{\nu}{2} = \sqrt{\frac{1 + e}{1 - e}} \tan \frac{E}{2} \quad (5) \]
The eccentric anomaly as a function of time

Second Keplerian law:

\[ \frac{a^2 M}{2} = \frac{a^2 E}{2} - \frac{a \varepsilon \cdot a \sin E}{2} \]

Kepler’s equation

\[ E - e \sin E = M \]

Mean anomaly: \( M = \frac{2\pi t}{P} \)

Iterative solution:

\[ E_{i+1} = M + e \sin E_i \]
Spectroscopic orbital solutions

The Keplerian orbital equations

\[ \gamma = \text{systemic velocity} \]
\[ K = \text{RV semi-amplitude} \]

spherical trigonometry
(see the link to J.B. Tatum below)

\[ v_r(t) = \gamma + K (e \cos \omega + \cos [\omega + \nu(t)]) \]

\[ \tan \frac{\nu}{2} = \sqrt{\frac{1 + e}{1 - e}} \tan \frac{E}{2} \]

\[ E - e \sin E = \frac{2\pi}{P} (t - T) \]

The method of differential corrections

(Schlesinger 1908, Allegheny Publ. 1, 33)

\[ O = v_r, \quad C = \gamma + K (e \cos \omega + \cos[\omega+v(t)]) \]

- **linearization** in \( p_i = P, \gamma, K, e, \omega, T: \quad O - C = dv_r, \quad \delta v_r = \sum \frac{\delta v_r}{\delta p_i} dp_i \)

- **least squares fit** to determine the corrections \( dp_i + \text{iteration} \)

- inverse matrix gives the errors
The method of differential corrections

Improvements:

- light time effects in hierarchical systems, \( t \rightarrow t - dt \)
- timely variable elements, \( p \rightarrow p + (t-T) \frac{dp}{dt} \)

\( N \) spectra, 10 differential corrections \( dD_k \) for \( P, \gamma, K, e, \omega, T \), and for the time derivatives of \( P, K, e, \) and \( \omega \):

\[
M = \left( \sum_{i=1}^{N} \left[ dRV(t_i) - \sum_{k=1}^{10} f_k(t_i) dD_k \right] \right)^2 \rightarrow \text{Min.} \quad \frac{\delta M}{\delta dD_k} = 0
\]

\( P, K, \) and \( e \) may be variable due to
- circularization of orbits (synchronization orbit-rotation)
- angular momentum transfer in interacting binaries
\( \omega \) may be variable due to apsidal motion (e.g. third component)
FOTEL 4

- FOTEL 4 is an advanced computer program to determine the orbital elements of SB2 stars
- The FORTRAN code was written by P. Hadrava, the program is described in detail in [www.asu.cas.cz/~had/fotel.pdf](http://www.asu.cas.cz/~had/fotel.pdf)
- It is able to combine photometric (lightcurves and times of minima in EBs), spectroscopic (RVs), and interferometric (positions) data of binaries and triple systems
- For triple systems, it considers the light-time effect
- It assumes triaxial ellipsoids for the star configurations as an approximation of its Roche-shapes in the case of contact and semi-detached binaries
55 UMa, an example

spectroscopic triple system with strong apsidal motion

RVs measured from TLS spectra taken in 1998, 1999, and 2003 by using triple Gaussians, folded with the best period of the close orbit.
Orbital solution including apsidal motion and the third body
4. Why are SB2s important?
Mass determination!

Single lined (SB1): Determine $K$, $P$, and $e$ spectroscopically

→ the mass function* $f(M_2) = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} = 1.036 \cdot 10^{-7} K_1^3 P (1 - e^2)^{3/2}$

This gives a lower limit for $M_2$ - but only if we know $M_1$, $M_1 + M_2$, or $M_2/M_1$

Double lined (SB2): $f(M_2) = M_2 \sin^3 (i) \frac{q^2}{(1+q)^2}$, $q = M_2/M_1 = K_1/K_2$

$f(M_1), f(M_2) \rightarrow$ lower limits for $M_1$ and $M_2$

Double lined EBs: $i \sim \pi/2 \rightarrow$ masses approximately known

+ lightcurve analysis $\rightarrow$ masses precisely known

## DISTANCE DETERMINATION FOR ECLIPSING DOUBLE-LINED BINARY STARS

<table>
<thead>
<tr>
<th>System</th>
<th>MEASURED DISTANCE (pc)</th>
<th>Hipparcos parallax</th>
<th>Binary analysis^a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>min</td>
<td>aver.</td>
</tr>
<tr>
<td>V505 Per</td>
<td></td>
<td>62</td>
<td>66</td>
</tr>
<tr>
<td>V781 Tau</td>
<td></td>
<td>73</td>
<td>81</td>
</tr>
<tr>
<td>UV Leo</td>
<td></td>
<td>83</td>
<td>91</td>
</tr>
<tr>
<td>V570 Per</td>
<td></td>
<td>103</td>
<td>117</td>
</tr>
<tr>
<td>V432 Aur</td>
<td></td>
<td>100</td>
<td>119</td>
</tr>
<tr>
<td>UW LMi</td>
<td></td>
<td>114</td>
<td>129</td>
</tr>
<tr>
<td>GK Dra</td>
<td></td>
<td>233</td>
<td>362</td>
</tr>
<tr>
<td>CN Lyn</td>
<td></td>
<td>304</td>
<td>445</td>
</tr>
</tbody>
</table>

^aFrom Munari et al. (2001b), Zwitter et al. (2003), Marrrese et al. (2004).
## TABLE 1

SUMMARY OF CAPABILITIES OF HIPPARCOS, SIM AND GAIA MISSIONS

<table>
<thead>
<tr>
<th></th>
<th>Hipparcos</th>
<th>SIM</th>
<th>GAIA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>agency</strong></td>
<td>ESA</td>
<td>NASA</td>
<td>ESA</td>
</tr>
<tr>
<td><strong>mission lifetime</strong></td>
<td>4 yrs</td>
<td>5 yrs</td>
<td>5 yrs</td>
</tr>
<tr>
<td><strong>launch</strong></td>
<td>1989</td>
<td>end of 2009</td>
<td>2010</td>
</tr>
<tr>
<td><strong>No. of stars</strong></td>
<td>120,000</td>
<td>10,000</td>
<td>1 billion</td>
</tr>
<tr>
<td><strong>mag. limit</strong></td>
<td>12</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>astrometric accuracy</strong></td>
<td>1 mas (at V= 10)</td>
<td>3$\mu$as (at V= 20)</td>
<td>3$\mu$as (at V= 12) 10$\mu$as (at V= 15) 200$\mu$as (at V= 20)</td>
</tr>
<tr>
<td><strong>photometric filters</strong></td>
<td>3 (BBP)</td>
<td></td>
<td>5 (BBP$^b$), up to 16 (MBP$^c$)</td>
</tr>
<tr>
<td><strong>radial velocity</strong></td>
<td>not available</td>
<td>not available</td>
<td>$\sigma \sim$1 km s$^{-1}$ (at I$_C$ = 14) $\sigma \sim$10 km s$^{-1}$ (at I$_C$ = 16)</td>
</tr>
<tr>
<td><strong>epochs on each target</strong></td>
<td>~ 110</td>
<td>pointed</td>
<td>~ 82 (astrometry, BBP$^b$) ~ 200 (MBP$^c$) ~ 100 (spectroscopy)</td>
</tr>
</tbody>
</table>

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*a Adapted from ESA-SCI(2000)4, Jordi et al. (2003), and Munari et al. (2003).

$^b$ broad-band photometry.

$^c$ medium-band photometry.
Composite spectra as a general problem

- Mass determination is most important (and the most simple task)
- Besides that, we need information about the fundamental parameters of the components
- We want to disentagle the RV variations and LPV originating from orbital motion (+eclipses) and other, physical processes like stellar activity (planet search), pulsations, magnetic fields, etc.

→ Spectral disentangling
5. Decomposition of composite spectra

Historically, SB spectra have been analysed by the following techniques:

- Cool giant + hotter, less evolved star (very different stars):
  subtract template for cool giant (Griffin & Griffin 1986)
- Tomographic separation (Bagnulo & Gies 1991)
- Disentangling in velocity space (Simon & Sturm 1994)
- Disentangling in Fourier space (Hadrava 1995)

see K. Pavlovski & Hensberge in arXiv:0909.3246v1 for a review
Tomographic separation

- Consider a row of erratically spaced trees with a similar row a fixed distance behind. By moving parallel to the rows from some distance away and observing the trees, you can mentally separate the two rows by noting which shift relative to the others. This is tomographic separation.

For orbiting spectroscopic binaries, it is the orbital motion which provides the change in perspective. Hence, the orbital velocities must be known a priori (+ the flux ratio).

see e.g. Bagnulo et al. 1991ApJ...376..266B
Iteratively correlate – shift – co-add

The basic idea is to use alternately the spectrum of one component to calculate the spectrum of the other one. In each step, the calculated spectrum of one star is used to remove its spectral features from the observed spectra and then the resulting single-lined spectra are used to measure the RV of the remaining component and to compute its spectrum by combining them appropriately.

Gonzalez & Levato, 2006A&A...448..283G
Spectrum decomposition with KOREL
(see P. Hadrava 2004, www.asu.cas.cz/~had/pakorelpdf)

Simultaneous solutions based on a given time series of composite spectra for the

- orbital elements
- radial velocities
- decomposed spectra
- timely variation of line strengths

using **Fourier transformation and simplex method**
KOREL basics

- $M$ composite spectra of $N$ stellar components
- coordinates are $x = c \ln(\lambda)$
- observed spectrum at time $t$:
  \[
  I(x, t) = \sum_{j=1}^{N} s_j(t) I_j(x) \delta[x - v_j(t)]
  \]
- Fourier transformation ($x \rightarrow y$):
  \[
  \mathcal{I}(y, t) = \sum_{j=1}^{N} s_j(t) \mathcal{I}_j(y) \exp[iv_j(t)]
  \]
- least squares method:
  \[
  \delta S = 0 \quad \text{with} \quad S = \sum_{l=1}^{M} \int \left| \mathcal{I}_l(y) - \sum_{j=1}^{N} s_{jl} \mathcal{I}_j(y) \exp iv_{jl} \right|^2 dy
  \]
- system of equations for $M$ spectra and $N$ components that is
  - linear with respect to the transformed spectra and line strengths
  - non-linear with respect to the radial velocities
How KOREL works

**KOREL input**
- time series of composite spectra
- definition of a hierarchical system
- guess values of parameters

**KOREL does**
- FFT of input spectra
- $v_{jl} = v(p_j,t)$ → starting with guess values of orbital elements $p_j$
- system is linear in $s_{ji}$ and $I_j(y)$ → direct solving
- System is non-linear in $v_{jl}$ → simplex method

**KOREL output**
- **Non-normalized**, decomposed spectra of up to 5 components
- timely variation of line strengths (e.g. eclipses, pulsations)
- orbital elements, optimized together with the radial velocities
Example: removing of telluric lines

- 55 UMa: three stellar components

- telluric lines: plus one fourth component of negligible mass

- spectra include heliocentric RV correction → fourth component in a solar orbit
Normalization of the output spectra

From KOREL (similar from other programs) we get the decomposed spectra $R_j$ normalized to the common continuum $C_1+C_2=1$ of the input spectra.

The spectra normalized to the individual continua $C_j$ are

$$N_j = 1 + \frac{(R_j - 1)}{C_j}$$

Assuming that the flux ratio of the two stars in the given wavelength band is $a = C_2/C_1$, we obtain

$$N_1 = 1 + (R_1 - 1)(1+a) \quad \text{or, in line depths} \quad n_1 = r_1(1+a)$$

$$N_2 = 1 + \frac{(R_2 - 1)(1+a)}{a} \quad n_j = 1 - R_j \quad n_2 = \frac{r_2(1+a)}{a}$$
Normalization of the output spectra

The normalization of the decomposed spectra can be done if we know the flux ratio of the components in the given spectra range (e.g. from photometry) or by fitting the decomposed spectra by synthetic spectra including the flux ratio as an additional free parameter.
Comparison of derived orbits

55 UMa - Results

- spectral analysis of disentangled spectra → $T_{\text{eff}}$, $\log g$, $v \sin i$
- orbital analysis + photometry → absolute masses, apsidal motion
- in combination → $L$, $R$ of all components + model of the orbit

precession of the close orbit with a period of 5300 yr

Lehmann et al. 2004, ASPC 318, 248
Lehmann & Hadrava 2005, ASPC 333, 211
Comparison KOREL - LSD

From the tomographic separation, like with KOREL, you will get, from a time series of spectra, the mean spectra of the components. The S/N depends on the number of included spectra.

From LSD, you will get, from a time series of spectra, a time series of mean line profiles. The S/N depends on the number of included lines per spectrum.

Time series of LSD profiles of the oEA star TW Dra showing high-degree non-radial pulsations (Lehmann et al. 2008CoAst.157..332L).
6. The Rossiter-McLaughlin Effect

The component that crosses the disk of the eclipsed star during primary or secondary eclipse blocks off the light from the approaching and then from the receding parts (or vice versa) of the rotating stellar surface. This produces a distortion in the line profiles (the symmetry of the rotational broadening is lifted) during the transit in a time-dependent manner, leading to an anomaly in the RV curve.
The RME in RZ Cas (observations in 2006)

The RME strongly depends on the radii and separation of the stars, the inclination of the orbit, and on the position angle of the rotation axis. Its modelling allows to determine these values.

Trinity – detected by the Kepler satellite

triple system, primary + close binary
eclipses within the close binary (0.9\,\text{d}) and
between the close binary and the primary (45\,\text{d})

1 transit = 2.7 \, \text{d}
Detection of planets

star: $1.69 \, M_{\text{sun}}, 1.42 \, R_{\text{sun}}, \, \text{vsini} = 48 \, \text{km/s}$
planet: $1.00 \, M_{\text{jupi}}, 0.15 \, R_{\text{sun}}$
orbit: $440 \, R_{\text{sun}}$
Detection of earth-like planets

star: $1 \, M_{\text{sun}}, 1 \, R_{\text{sun}}, P_{\text{rot}} = 25.38 \, \text{d} \rightarrow v \sin i = 2 \, \text{km/s}$
planet: $1 \, R_{\text{earth}}$
orbit: $a = 1 \, \text{AU}, P_{\text{orb}} = 1 \, \text{year}, i = 90^\circ$

$\rightarrow K_{\text{RV}} \sim 9 \, \text{cm/s}$
$K_{\text{RME}} \sim 50 \, \text{cm/s}$

but $K_{\text{RME}} \sim 26 \, \text{m/s}$ for $v \sin i = 100 \, \text{km/s}$!

<table>
<thead>
<tr>
<th>Spt.</th>
<th>G0</th>
<th>F5</th>
<th>F0</th>
<th>A0</th>
<th>B5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v \sin i$ (km/s)</td>
<td>12</td>
<td>25</td>
<td>95</td>
<td>190</td>
<td>210</td>
</tr>
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</table>
Discovery and Rossiter-McLaughlin Effect of Exoplanet Kepler-8b


ABSTRACT

We report the discovery and the Rossiter-McLaughlin effect of Kepler-8b, a transiting planet identified by the NASA Kepler Mission. Kepler photometry and Keck-HIRES radial velocities yield the radius and mass of the planet around this F8IV subgiant host star. The planet has a radius \( R_P = 1.419 \, R_J \) and a mass, \( M_P = 0.60 \, M_J \), yielding a density of 0.26 g cm\(^{-3}\), among the lowest density planets known. The orbital period is \( P = 3.523 \) days and orbital semimajor axis is 0.0483 \(+0.0006\,-0.0012\) AU. The star has a large rotational \( v \sin i \) of 10.5 \pm 0.7 km s\(^{-1}\) and is relatively faint (\( V \approx 13.89 \) mag), both properties deleterious to precise Doppler measurements. The velocities are indeed noisy, with scatter of 30 m s\(^{-1}\), but exhibit a period and phase consistent with the planet implied by the photometry. We securely detect the Rossiter-McLaughlin effect, confirming the planet’s existence and establishing its orbit as prograde. We measure an inclination between the projected planetary orbital axis and the projected stellar rotation axis of \( \lambda = -26.9 \pm 4.6^\circ \), indicating a moderate inclination of the planetary orbit. Rossiter-McLaughlin measurements of a large sample of transiting planets from Kepler will provide a statistically robust measure of the true distribution of spin-orbit

\( R \sim 1.5 \, R_J \)
\( M \sim 0.6 \, R_J \)
\( P \sim 3.5 \, d \)

\( v \sin i = 10.5 \, \text{km/s} \)

RME\(_{\text{max}} \sim 65 \, \text{m/s} \)
7. Spectroscopic eclipse mapping in asteroseismology

- The surface of the eclipsed disk is screened by the eclipsing star like in the case of the RME, rotation → pulsation
- First applied by Gamarova & Mkrtichian (2003, ASP Conf. Ser. 292, 369) to the lightcurves of pulsating stars (spatial filtration)


Amplitude amplification during the eclipses!
Numerical simulations (A. Tkachenko, thesis in 2010)

Figure 6.1: The radial velocity field on the surface of the primary for a sectoral $l=4$ mode during primary eclipse, shown for the orbital phases -0.05 (left) and +0.05 (right). Yellow and blue regions indicate positive and negative RVs, respectively.

Figure 6.5: The radial velocity field on the surface of the primary for a sectoral $l=4$ mode at the center of the primary eclipse for orbital inclinations of $68^\circ$, $75^\circ$, and $82^\circ$ (from left to right).
Figure 6.3: Time series of line profiles computed over one pulsation cycle of a sectoral $l=3$ mode (left) and the corresponding RVs measured from these lines (right) at out-of-eclipse phases (top) and at in-eclipse phases (bottom).
Figure 6.4: RV curves corrected for the Rossiter effect and folded with the orbital period. The primary minimum occurs at phase zero. **Left:** For a zonal \((l,m) = (1,0)\) mode. **Right:** For a sectoral \((l,m) = (3,3)\) mode.
Results

Normally, the sectoral modes of lowest degree show the largest amplitudes. In contrast, during the eclipses, the tesseral modes of higher degree are mostly amplified.

→ Eclipse mapping can be used
   - to detect non-radial modes that are not visible outside the eclipses
   - to identify the modes by their wavenumbers comparing the observed behavior with the predicted one
Summary

- Spectroscopic binaries are in general important for the determination of fundamental stellar parameters. More important: SB2 stars. Most important: eclipsing SB2 stars.
- Composite spectra require, besides the determination of the orbit, the decomposition of the spectra of the components.
- The investigation of timely variable physical processes in SBs requires to disentangle the effects due to orbital motion.
- The eclipse phases in EBs can be used to screen the surface of the eclipsed star spectroscopically for the structure of its surface velocity field (e.g. pulsation) or to determine the stellar parameters (rotation, RME).