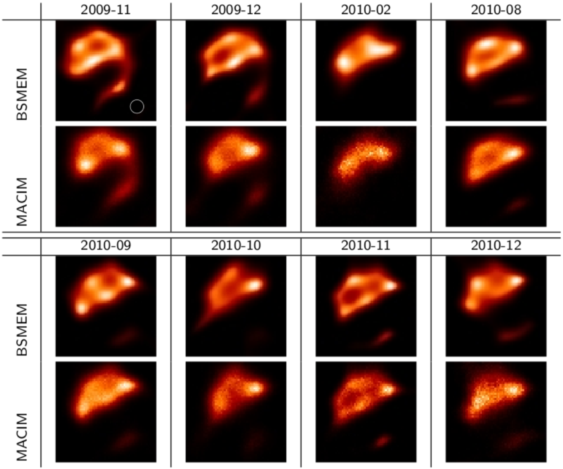
Can interferometry resolve the mass ratio in all single line spectroscopic eclipsing binary stars?

Brian Kloppenborg

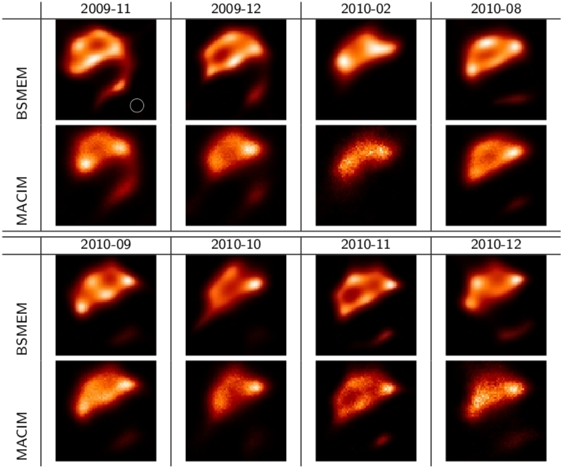
University of Denver

Tuesday, Mar. 29, 2011

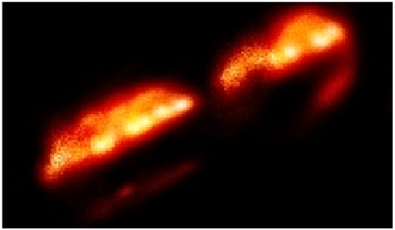
Motivation

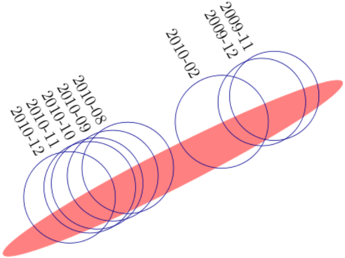

2009-11
2009-12
2010-02
2010-08
BSMEM
MACIM
2010-09
2010-10
2010-11
2010-12
BSMEM
MACIM

Motivation


2009-11
2009-12
2010-02
2010-08
BSMEM
MACIM
2010-09
2010-10
2010-11
2010-12
BSMEM
MACIM

Motivation





Outline

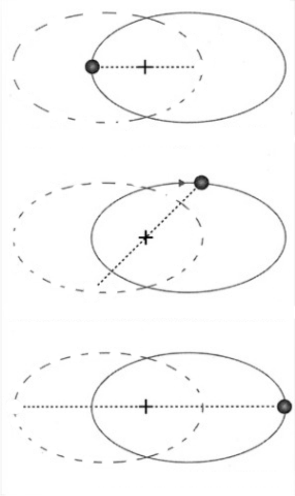
Binary Stars

Four Classes

- Visual Binaries
  - Can be observed as a binary system by eye/binocular/or telescope
- Spectroscopic Binaries
  - Shows doppler effect in it's emitted light
  - Two classes: SB2, SB1
- Eclipsing Binaries
  - Binary star system whose orbital plane is in the line of sight
  - Periodic dimming of one or both components
- Astrometric Binaries
  - Stars appear to orbit something in space, but no companion is visible

Why care about SB1s?

- Some inequality in the system
- Different Evolutionary States
- Mass Exchange
- Fun Physics



Orbital Solution Methods

Radial Velocity

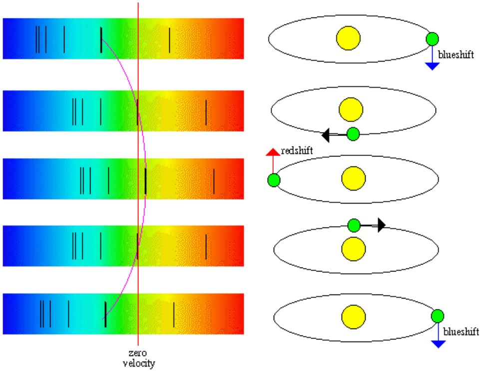
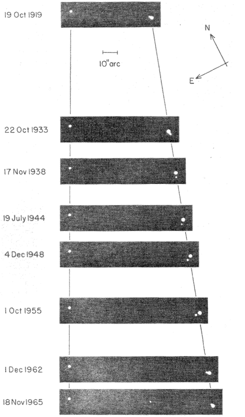


Figure: James Schombert (University of Oregon)

Astrometry

(photographic plates, interferometry)



Krüger 60: Van de Kamp, 1978

Orbital Solution Methods: RV

Radial Velocity:

$$V_z = \gamma + \frac{n\, asin(i)}{1 - ecos(E)} \left[\sqrt{1 - e^2} cos(\omega) cos(E) - sin(\omega) sin(E) \right]$$

Orbital Parameters Revealed:

γ, ω, a sin(i), e, T, τ

where $n = \frac{2\pi}{T}$, $n * (t - \tau) = E - esin(E)$

Orbital Solution Methods: Astrometry

After Plate Solutions, solve for the orbital parameters:

$$
\begin{aligned}
X &= c_x + \mu_x t + \dot{\mu}_x t^2 + \pi P_\alpha + ORBIT_x(\Omega, \omega, \alpha, e, i, T, \tau) \\
Y &= c_x + \mu_y t + \dot{\mu}_y t^2 + \pi P_\delta + ORBIT_y(\Omega, \omega, \alpha, e, i, T, \tau)
\end{aligned}
$$

Orbital Solution Methods: Astrometry

Thiele-Innes Constants:

- Yields: $\Omega \pm 180$, $\omega \pm 180$, α, e, i, T, τ
- Convention is to take $\Omega < 180$ if no distinction possible.
- Can also get π, μ_x, μ_y, $\dot{\mu}_x$, $\dot{\mu}_y$ with astrometric plates

Positions come from:

$$\Delta X = Bx + Gy, \Delta Y = Ax + Fy$$

where,

$$\begin{aligned} B &= a(cos(\omega)sin(\Omega) + sin(\omega)cos(\Omega)cos(i)) \\ A &= a(cos(\omega)cos(\Omega) - sin(\omega)sin(\Omega)cos(i)) \\ G &= a(-sin(\omega)sin(\Omega) + cos(\omega)cos(\Omega)cos(i)) \\ F &= a(-sin(\omega)cos(\Omega) - cos(\omega)sin(\Omega)cos(i)) \end{aligned}$$

and the angular parameters are derived from

$$\begin{aligned} tan(\omega + \Omega) &= (B - F)/(A + G) \\ tan(\omega - \Omega) &= (-B - F)/(A - G) \\ cos(i) &= (AG - BF)/a^2 \end{aligned}$$

Equations from Van de Kamp, 1978

Orbital Solution Methods: Astrometry

Full Orbital Equations:

- Yields Ω, ω, α, e, i, T, τ
- Can also get π, μ_x, μ_y, $\dot{\mu}_x$, $\dot{\mu}_y$

Positions and velocities are found/fitted by

$$
\begin{aligned}
x &= a(L_1 cos(E) + \beta L_2 sin(E) - eL_1) \\
y &= a(M_1 cos(E) + \beta M_2 sin(E) - eM_1) \\
z &= a(N_1 cos(E) + \beta N_2 sin(E) - eN_1) \\
V_x &= \frac{na}{\eta}(\beta L_2 cos(E) - L_1 sin(E)) \\
V_y &= \frac{na}{\eta}(\beta M_2 cos(E) - M_1 sin(E)) \\
V_z &= \frac{na}{\eta}(\beta N_2 cos(E) - N_1 sin(E))
\end{aligned}
$$

where,

$$
\begin{aligned}
\beta &= (1 - e * cos(E)) \\
\eta &= 1 - e * cos(E) \\
L_1 &= cos(\Omega)cos(\omega) - sin(\Omega)sin(\omega)cos(i) \\
M_1 &= sin(\Omega)cos(\omega) + cos(\Omega)sin(\omega)cos(i) \\
N_1 &= sin(\omega)sin(i) \\
L_2 &= -1 * cos(\Omega)sin(\omega) - sin(\Omega)cos(\omega)cos(i) \\
M_2 &= -1 * sin(\Omega)sin(\omega) + cos(\Omega)cos(\omega)cos(i) \\
N_2 &= cos(\omega)sin(i)
\end{aligned}
$$

Direct Orbital Equations (equations from Roy, 2005)

Combining Solutions

RV

γ, ω, a sin(i), e, T, τ

Astrometry

Ω, ω, α, e, i, T, τ [, π, μ_x, μ_y, $\dot{\mu}_x$, $\dot{\mu}_y$]

RV + Astrometry

Ω, ω, α, a, e, i, T, τ, $\boxed{d = a/tan(alpha)}$

A problem with SB1s

A Full orbital solution for binaries requires 8 parameters

Ω, ω, α, $a = a_1 + a_2$, e, i, T

For SB1's we're missing a_2! How can we find it?

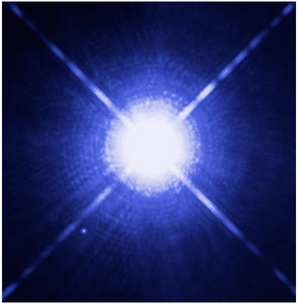
Interferometry to the rescue!

Three ways interferometry can help solve the problem

- Resolve out the companion
- Observe an eclipse in action (or part of it)
- Exploit deep absorption lines with interferometric spectroscopy

Resolve out the companion

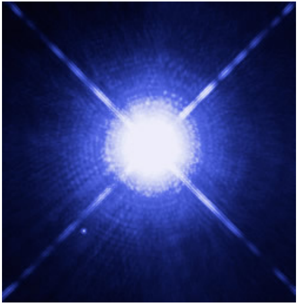
- Taylor, S (The CHARA Catalog of Orbital Elements of Spectroscopic Binary Stars, probably a few here)



Sirius AB: NASA, ESA, H. Bond (STScI) and M. Barstow (University of Leicester)

Resolve out the companion

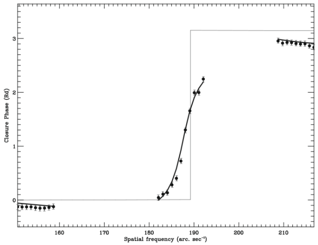
- Taylor, S (The CHARA Catalog of Orbital Elements of Spectroscopic Binary Stars, probably a few here)
- Koubsk, P et. al. 2010 (NPOI, Be STAR o Cas, 3 mag fainter, directly resolved)



Sirius AB: NASA, ESA, H. Bond (STScI) and M. Barstow (University of Leicester)

Resolve out the companion

- Taylor, S (The CHARA Catalog of Orbital Elements of Spectroscopic Binary Stars, probably a few here)
- Koubsk, P et. al. 2010 (NPOI, Be STAR o Cas, 3 mag fainter, directly resolved)
- Duvert, G (AMBER/VLTI, HD 59717, 5 mag K fainter, using closure phase nulling)



HD 59717 via. Closure Phase Nulling: Duvert, G. et. al 2008

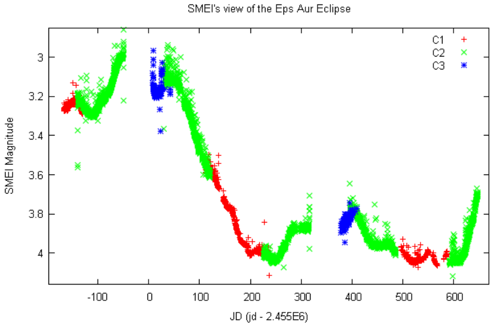
Interferometry to the rescue!

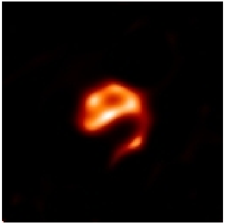
Three ways interferometry can help solve the problem

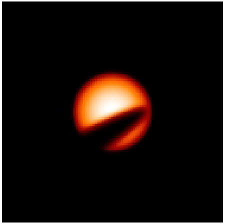
- Resolve out the companion
- Observe an eclipse in action (or part of it)
- Exploit deep absorption lines with interferometric spectroscopy

Observing an Eclipse

- Either catch ingress / egress
- Models with light curves

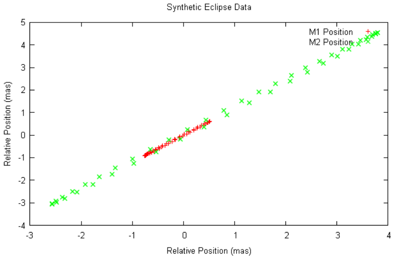


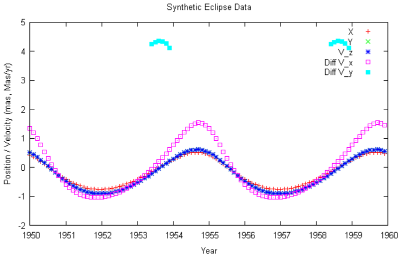




Kloppenborg et. al. (2010, 2011)

Synthetic ingress / egress





$\rightarrow$

A Test Case:

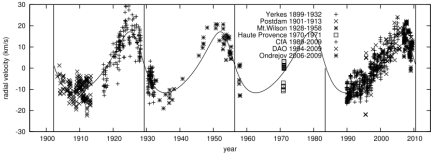
- System treated as SB1
- M1 visible, along with transit
- M2 otherwise unknown

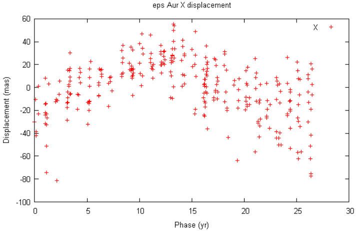
$$\begin{aligned}
\Omega &= 50.0 \\
\omega &= 32.0 \\
a1 &= 1.0 \\
a2 &= 5.0 \\
e &= 0.227 \\
i &= 89.0 \\
T &= 5.0 \\
\tau &= 1950.0
\end{aligned}$$

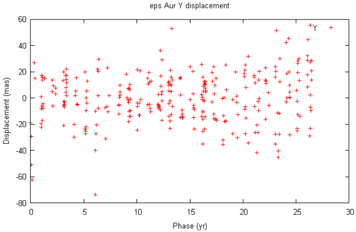
Real ingress / egress

ϵ Aur

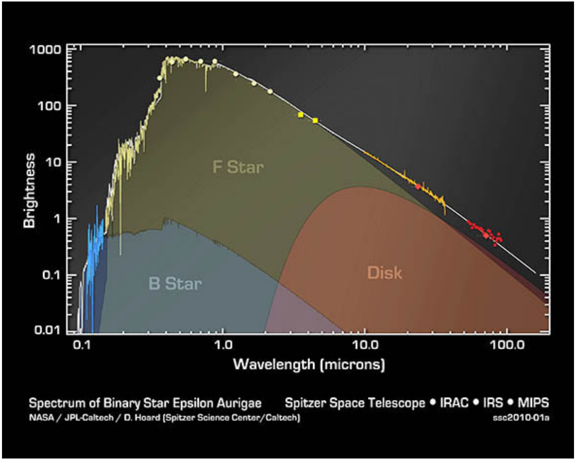
- Astrometric data noisy
- Hipparcos Parallax: $\pi = 1.53 \pm 1.29$
- RV Data plentiful





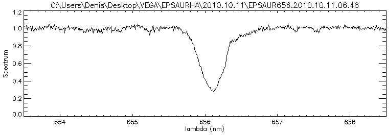


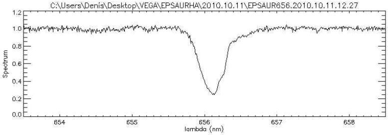
ϵ Aur SED



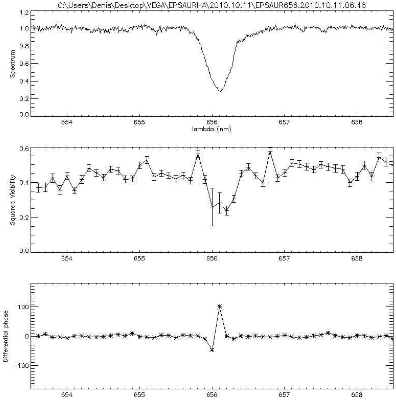
ϵ Aur SED: Hoard, Howell, Stencel (2010)

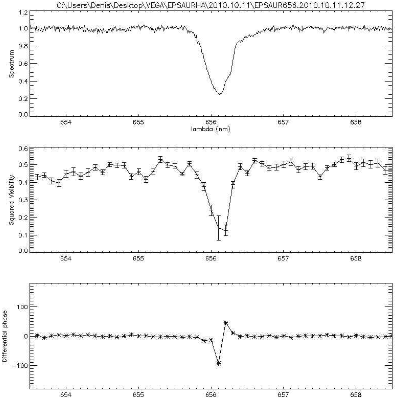
Finding Hidden Spectral Featuers



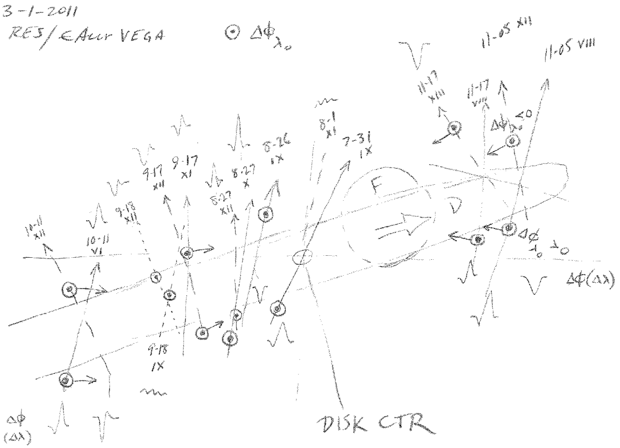


Finding Hidden Spectral Featuers





Interpreting the data



Extending to planets

- May not be necessary as you can apply normal methods, just like binary stars
- But then you run into limb darkening problems
- Kepler gives planet candidate host stars

Software

GPAIR / GPAOI

- Collaboration with Fabien Baron
- GPAOI: Library written in C that provides common routines for interferometry
  - Acceleration via. OpenCL
  - CPU and GPU
  - Implements Common OI Functions (Image $\rightarrow$ Vis, Vis $\rightarrow$ V^2, T3, χ^2)
- GPAIR: Image Reconstruction using GPAOI
  - 280x faster than CPU
  - Fabien will discuss results

OIFITS Simulator

- Collaboration with Fabien Baron
- Rewrite of the MROI Simulator
- Define your own interferometer / instrument
- Samples images with
  - Equal Hour Angle increments
  - User-defined hour angles
  - Using existing OIFITS data
- Add/drop telescopes from array configuration
- Uses a realistic noise model (Tatulli, E. Chelli, A. 2005)

New Modeling Code

- Yet another collaboration with Fabien Baron
- General purpose OI model fitting software
- Uses Levmar for minimization (soon: mpfit, multinest)
- Several defined objects (UDD, rectangles, ellipses with and without LD)
- Permits obscuring / semi-transparent modeling
- Automatic switching between analytic and image-based modeling
- Permits external constraints to be applied (orbits, photometry)
- Validation of orbit fitting routines against WDS grade 1 orbits
- Diff vis and diff phases coming soon

Conclusion

- SB1 Observation Methods
    - Resolve out the Binary in continuum
    - Observe an eclipse
    - Find spectral emission, track it