ECLIPSING BINARIES: THE ROYAL ROAD

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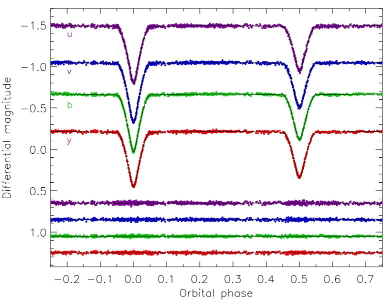
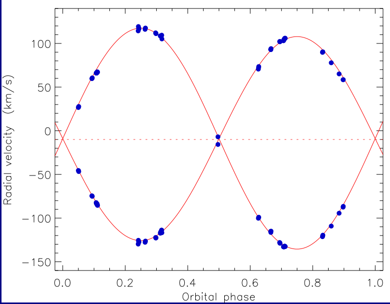
Historical context

- John Goodricke (1783) suggested that β Persei underwent eclipses
- Herschel (1802RSPT...92..477H christened the term "binary star"
- Savary (in 1827) established the equations of an astrometric orbit
- Pickering (in 1889) found that Mizar shows moving and doubled spectral lines
- Vogel (1890PASP....2...27V) proved the binary nature of β Persei: "spectroscopic binary"
- Stebbins (1911ApJ....34..112S): first measurement of mass and radius of an EB (β Aur)

The importance of eclipsing binaries

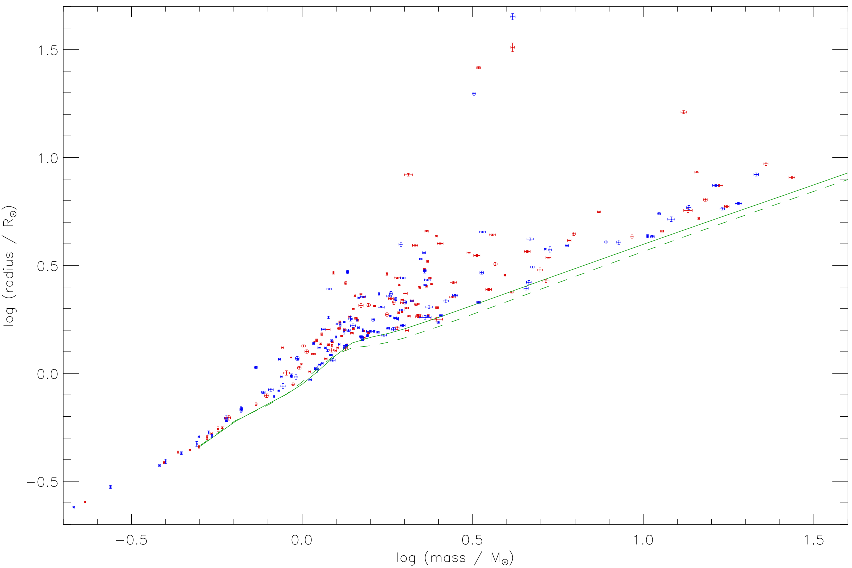
- Light curve analysis gives: $\frac{R_1}{a}$ $\frac{R_2}{a}$ inclination i $e\cos\omega$
- Radial velocity analysis gives: $M_1 \sin^3 i$ $M_2 \sin^3 i$ $a \sin i$ $e \sin\omega$
- Combine: masses to 1% radii to 1% $\log g$ to 0.01 dex
- Add in $T_{\rm eff}$: luminosity to 0.04 dex distance to 2%
- Abundance analysis using the spectra and known $\log g$





WW Aurigae (Southworth et al., 2005MNRAS.363..529S)

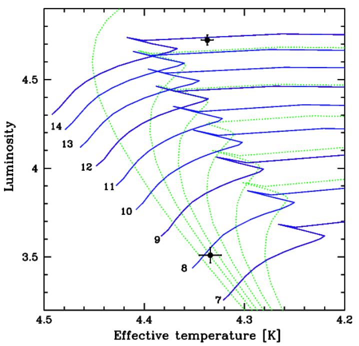
Well-studied eclipsing binaries



http://www.astro.keele.ac.uk/~jkt/debcat/

Uses of eclipsing binaries: (1) stellar theory

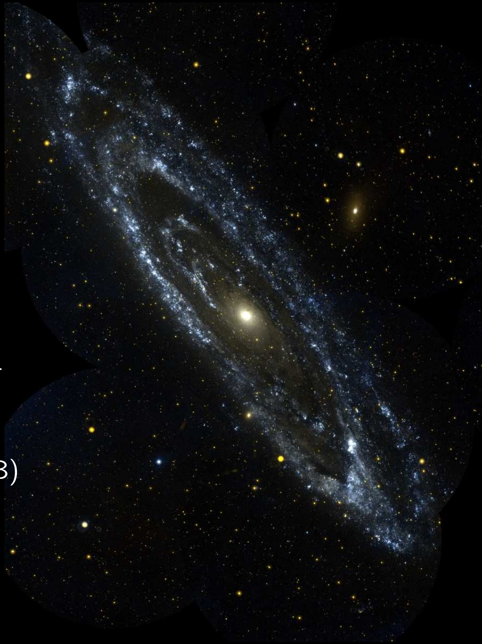
- Test theoretical stellar models
  (e.g. Pols et al. 1997MNRAS.289..869P)
- Apsidal-motion test of stellar structure
  (e.g. Claret 2007A+A...475.1019C)
- Investigate the chemical enrichment law
  (Ribas et al. 2000MNRAS.313...99R)
- Test model atmospheres via limb darkening
  (see Howarth arXiv:1106.4659)
- Star and binary star formation scenarios
  (e.g. Albrecht et al., 2009Natur.461..373A)
- Host stars of transiting extrasolar planets
  (Southworth 2009MNRAS.394..272S)



Components of V380 Cygni:
$M_1 = 13.13 \pm 0.24 \, \mathrm{M}_\odot$
$M_2 = 7.779 \pm 0.095 \, \mathrm{M}_\odot$.
Figure taken from Pavlovski et al. (2009MNRAS.400..791P).

Uses of eclipsing binaries: (2) distance scale

- HD 23642 in the Pleiades (e.g. Southworth et al., 2005A+A...429..645S)
- HV 2274 in the LMC (Guinan et al. 1998ApJ...509L..21G)
- M31V J0044380+41292350 in M 31 (Ribas et al., 2005ApJ...635L..37R)
- D33 J013346.2+304439.9 in M 33 (Bonanos et al., 2006ApJ...652..313B)

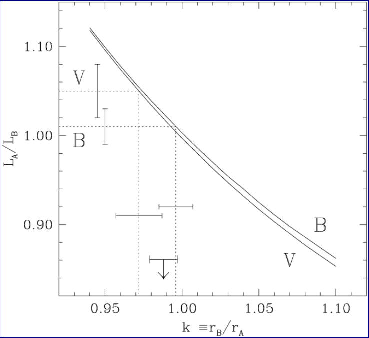


Photometric observations of eclipsing binaries

- Need a nice light curve covering both eclipses
  - standard passbands good for limb darkening and light ratios
- Need a geometrical model
  - well-separated stars: JKTEBOP code is fast and simple
    http://www.astro.keele.ac.uk/~jkt/codes/jktebop.html
  - full Roche model: Wilson-Devinney requires more effort
  - PHOEBE is a graphical interface to Wilson-Devinney
    http://phoebe.fiz.uni-lj.si/
- Nuisance parameter: limb darkening
  - simple linear law is enough for ground-based data
  - for good data you should fit for the coefficients
  - http://www.astro.keele.ac.uk/~jkt/codes/jktld.html
- Results: Orbital period $\frac{R_1}{a}$ $\frac{R_2}{a}$ inclination i $e\cos\omega$

Problem: solution degeneracy

- Partial eclipses can look roughly Gaussian for a wide range of parameters
  - eclipse duration constrains $\frac{R_1+R_2}{a}$
  - ratio of eclipse depths constrains surface brightness ratio
  - ratio of radii $k = \frac{R_2}{R_1}$ becomes poorly constrained
  - $\Rightarrow$ individual radii poorly known
- Solution: light ratio from spectroscopy



Light ratio for GG Orionis (Torres et al., 2000AJ....120.3226T, fig. 3)

Problem: error analysis

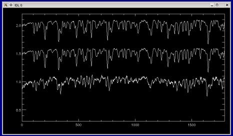
- Eclipsing binary light curves: multi-dimensional parameter space with strong correlations
  - correlations are intrinsic to the situation
  - can have many local minima
  - red noise in data
- Formal errors are optimistic, i.e. wrong
- Good error analysis
  - Monte Carlo or MCMC simulations (white noise)
  - residual-permutation or wavelet analysis (red noise)
  - genetic algorithm for initial minimisation
  - χ^2-chase for robust errorbars

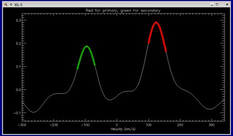
Spectroscopic observations of eclipsing binaries

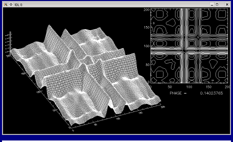
- Need high-resolution spectroscopy covering all orbital phases
  - standard requirement: 30 spectra and $1\,\mathrm{km\,s^{-1}}$ accuracy
  - late-type stars: planet-search spectrographs are excellent
  - early-type stars: no substitute for S/N
- Fit a Keplerian spectroscopic orbit
  - Period fixed from eclipses
  - Get out: K_1 K_2 $e\sin\omega$
- Result: masses and radii of two stars
  - $e\cos\omega + e\sin\omega \Rightarrow e + \omega$
  - $K_1 + K_2 + e + i \Rightarrow \boxed{M_1} + \boxed{M_2} + a$
  - $a + \frac{R_1}{a} + \frac{R_2}{a} \Rightarrow \boxed{R_1} + \boxed{R_2}$
  - $M + R \Rightarrow \boxed{\log g} + \boxed{\text{density}}$
- All this from just geometry!

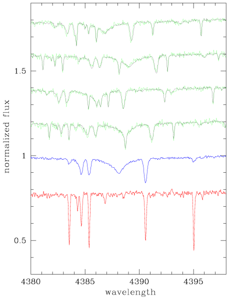
Radial velocity measurements

1. Gaussian fitting works well for many stars
   - good for well-spaced lines
2. Cross-correlation good for multiple lines
   - needs template spectrum
   - suffers from line broadening twice
3. TODCOR is two-dimensional cross-correlation
   - Zucker & Mazeh (1994ApJ...420..806Z)
   - works well when two stars are different
4. Spectral disentangling
   - Simon & Sturm (1994A+A...281..286S) + others
   - no template spectrum needed
   - line blending not a problem
   - returns K_1 and K_2 and individual spectra
   - Fourier space: sensitive to continuum level
   - Pixel space: may require much CPU time



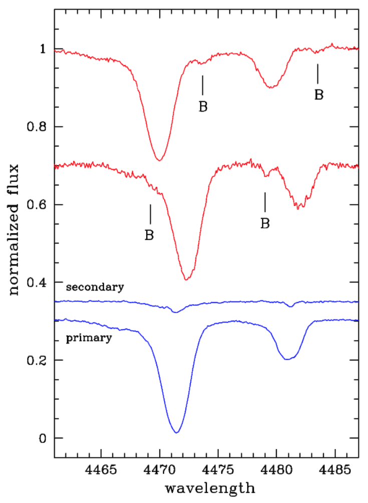






Problem: low light ratio

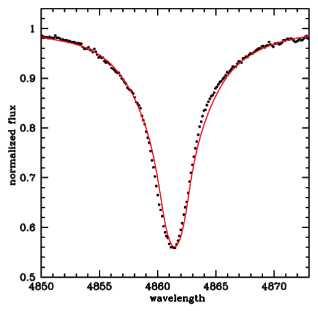
- Brightness-limited: bias towards binaries with evolved stars
- Evolution causes brighter star to become even brighter
- Example: V380 Cyg (B1.5 III + B2 V)
  - Pavlovski et al., (2009MNRAS.400..791P)
  - Light contribution of secondary star: 6%
- Secondary lines only visible on our best few spectra
- Disentangling gives:
  - spectra of both objects
  - K_1 and K_2 and e

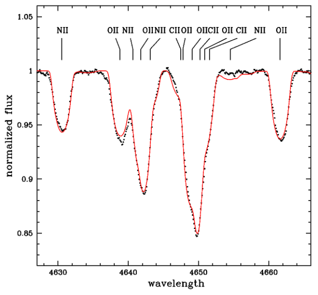


V380 Cygni (Pavlovski et al., 2009MNRAS.400..791P)

Atmospheric parameters

- Effective temperature needed for comparison to theoretical models
  - from colour indices (OK)
  - from spectral types (iffy)
  - from spectral analysis (good)
- Spectral disentangling gives individual spectra of both stars suitable for standard analyses
  - Renormalisation needed (Tamajo et al. 2011A+A...526A..76T)
  - Get individual chemical abundances
- Example (again): V380 Cyg
  - Abundances of C, N, O, Mg, Al, Si
- Luminosity $\Rightarrow$ $M_{\rm bol}$ $\Rightarrow$ distance



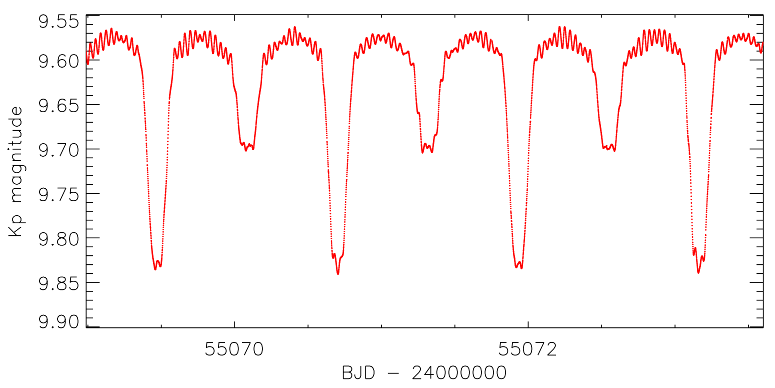


Eclipsing binaries: current and future

- Traditional analysis: 123 eclipsing binaries done well
  - 100 years of effort
- GCVS: 1982 EA-type systems as of 2011/10/06
- AAVSO VSX has 5900 EA for $V \leqslant 14$
- SuperWASP probably has 50 000 EB light curves
  - Up to 70 000 datapoints each
  - We don't have time to find them
- GAIA will produce 10^6 EBs of which 10^5 will be useful
- LSST will get 24 million EBs (Prša et al. 2011AJ....142...52P)
  - 6.7 million will have useful light curves
  - 1.7 million will have double-lined spectra
- Statistical properties become vital

Eclipsing binaries: the best available now

- *Kepler* has found 2165 EBs (Slawson et al. arXiv:1103.1659)
  - most are long cadence (1765 s sampling)
  - we have some at short cadence (59 s sampling)
- Example: KIC 10661783 (Southworth et al. 2011MNRAS.414.2413S)
  - Algol-type with δ Scuti pulsations



Eclipsing binaries: what next?

- Vast numbers of new eclipsing binaries
  - Statistical studies important
  - Automated analysis necessary

- Cherry-pick the best systems
  - metal abundances
  - low-mass (M-type)
  - high-mass (O-type)
  - pulsating
  - giant stars
  - members of clusters
  - in external galaxies

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