Stellar Motion: Spectroscopy of Binary and Pulsating Stars

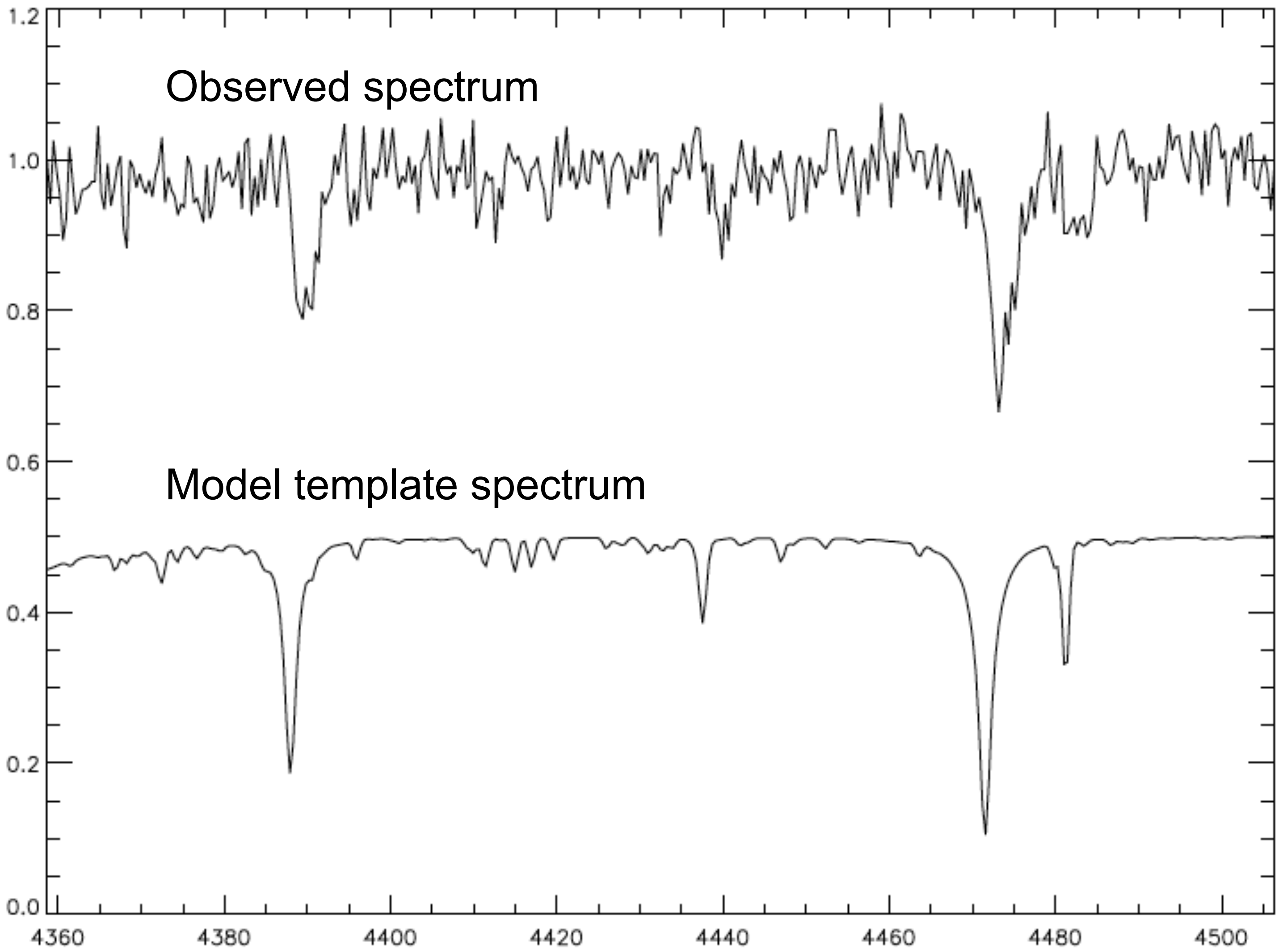
Binary stars:
radial velocities
spectral reconstruction
orbital elements
eclipsing binaries

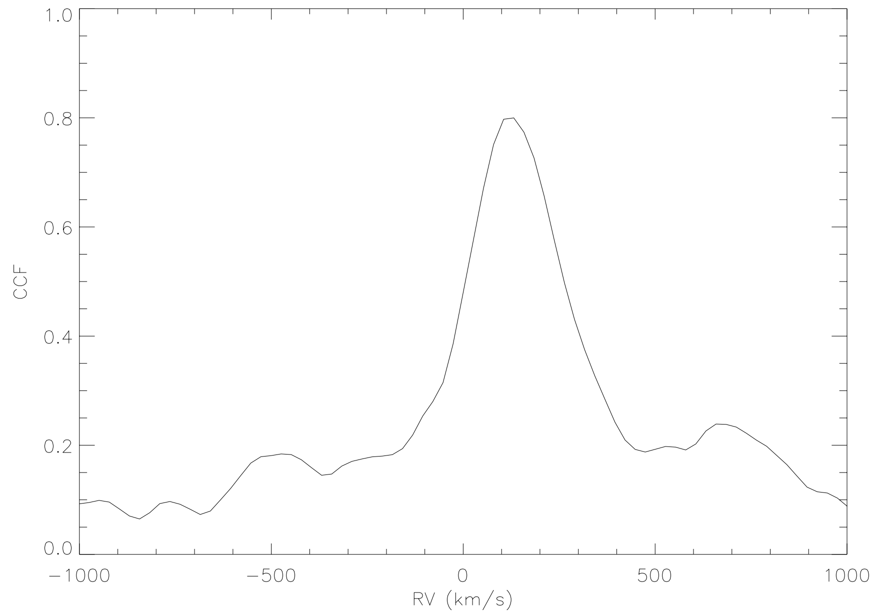
Pulsating stars:
radial pulsation
nonradial pulsation

Radial Velocity

- Ideally need high spectral resolving power and high signal-to-noise spectra
- For individual lines, form difference from rest wavelength (vacuum <200 nm, air >200 nm)
- Simple methods: centroid, parabola, Gaussian
- Better: cross-correlation function to use all the available spectral data; use data/template on a log lambda grid

$$\Delta v = c\frac{\Delta\lambda}{\lambda_0} = c\Delta \ln \lambda$$


Observed spectrum
Model template spectrum
1.2
1.0
0.8
0.6
0.4
0.2
0.0
4360
4380
4400
4420
4440
4460
4480
4500



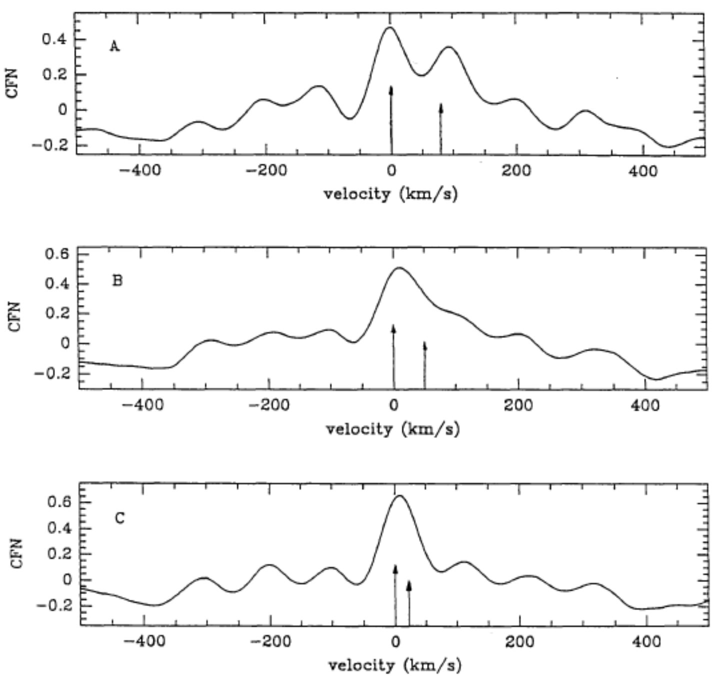
$$ccf(v) = \sum s(x)t(x+v)$$

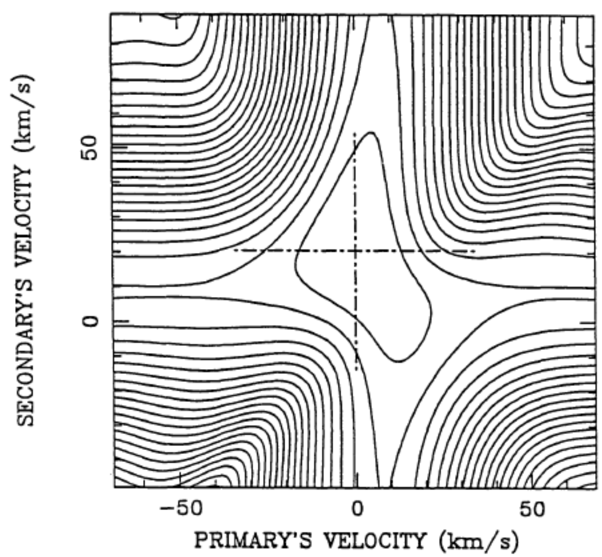
Peak occurs where shift *v* produces best match.

Blends in Double-lined Binaries

TODCOR: Zucker & Mazeh 1994, ApJ, 420, 806

Use two templates (one for primary, one for secondary) and then seek the CCF maximum as a function of velocity shifts for both stars.





Spectrum Reconstruction

- Doppler tomography (Bagnuolo et al. 1994): Derive individual spectra using known shifts and a flux ratio F_2/F_1.
- Uses iterative scheme and optional starting values.
- Apply to all spectra, so result has higher S/N.

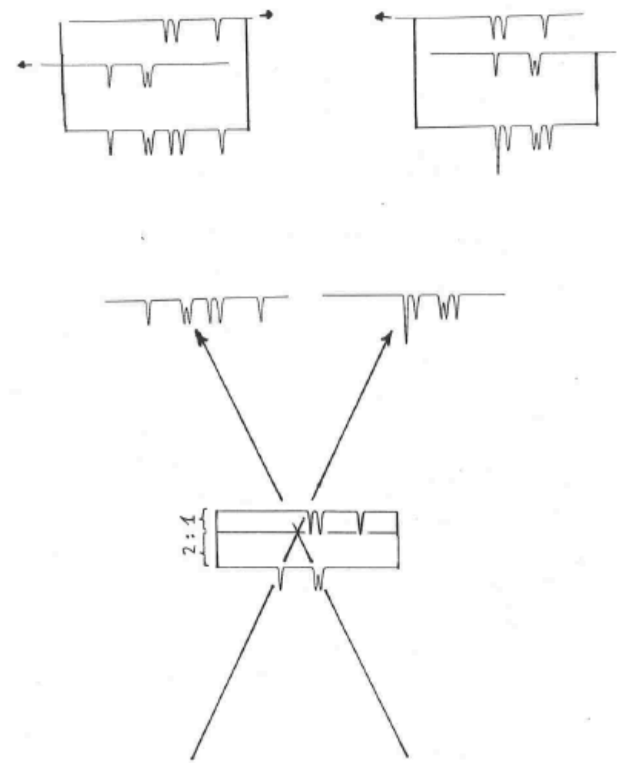


FIG. 1.1 – Cartoon of composite spectra, blended from a primary and a secondary with mass ratio Q=2 at opposite phases, represented by 'viewing angles' whose tangent is proportional to the Doppler shift.

Wiemker 1992

Spectrum Disentangling

- Derive individual spectra and the associated velocities using an adopted flux ratio F_2/F_1.
- Fourier Transform method: Hadrava 1995
- Gaussian Processes method: Czekala et al. 2017
- In each method, compare the individual spectra to models to revise flux ratio and estimate effective temperature, gravity, projected rotational velocity, and abundances

Orbital Elements

- γ = systemic velocity
- K_1, K_2 = velocity semiamplitudes
- e = eccentricity
- ω = longitude of periastron
  (advance in omega for apsidal motion)
- T = epoch of periastron or
  T_0 = epoch of maximum velocity for $e = 0$
- P = orbital period

Orbital Elements

- Period estimation can be difficult (sampling):
  DFT periodogram (Lomb 1976; Scargle 1982)
  Phase Dispersion Min. (Stellingwerf 1978)
- Keplerian motion solver:
  RVFIT (Iglesias-Marzoa et al. 2015)
  www.cefca.es/people/~riglesias/rvfit.html
- SB1: $\mathcal{F} = M_2^3(\sin i)^3/(M_1 + M_2)^2$
- SB2: $M_1(\sin i)^3$ and $M_2(\sin i)^3$
- Find inclination by visual orbit or eclipses

Eclipsing Binaries

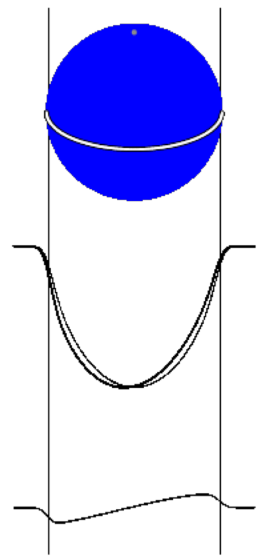
- Need detailed models to fit light curves:
  ELC (Orosz & Hauschildt 2000)
  PHOEBE (Prsa 2018, http://phoebe-project.org)
- Details sensitive to temperature ratio, tidal distortion, radii/a, and **inclination**
- Beaming binaries (asymmetry due to relativistic beaming, $\frac{F_2}{F_1} \neq 1$; Zucker et al. 2007)
- Rossiter-McLaughlin effect; spin of occulted star

Stellar Pulsation

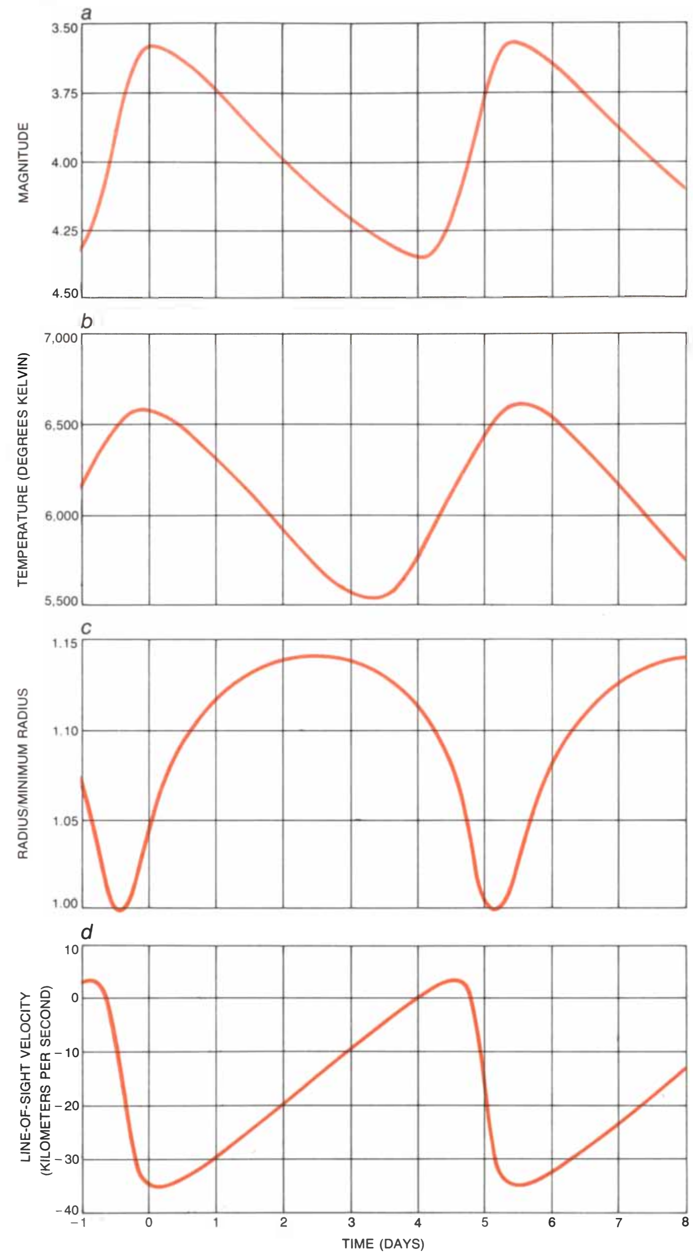
- Radial pulsator (Cepheid) will show periodic radial velocity variations that represent the sum of motions over the visible hemisphere

- Integrating radial velocity curve gives the change in radius (Baade-Wesselink)

- Combining with angular size variation yields distance (Merand et al. 2005)



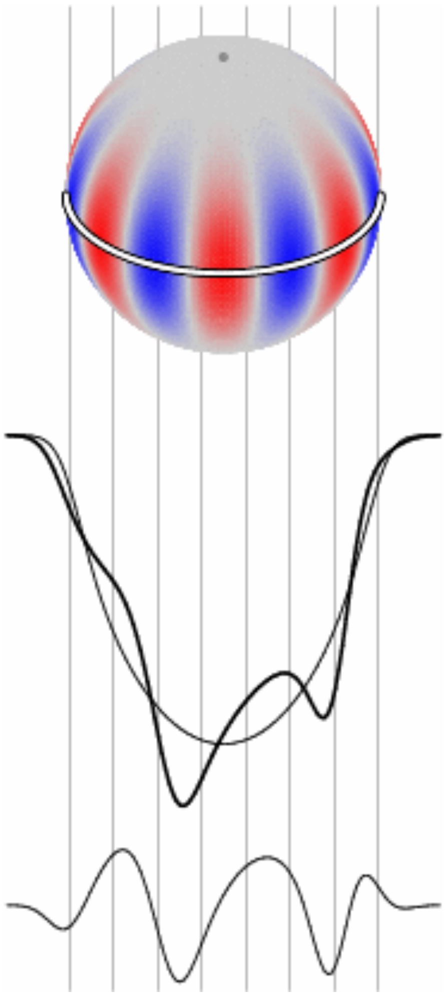
Percy 1975



VARIATION IN BRIGHTNESS COINCIDES with other changes in a pulsating star, as is shown here in the case of Delta Cephei. The light curve (*a*) of the star shows that its brightness varies regularly, with a period of 5.366341 days and a range of .9 magnitude. The changes in brightness are due mainly to variations in the star's temperature (*b*) and to a lesser extent to variations in its radius (*c*). As the star expands and contracts, the radiating layers alternately approach the observer and then recede from him. The line-of-sight velocity of the layers can be measured by the Doppler shift of the lines in the star's spectrum (*d*).

Nonradial Pulsation

http://staff.not.iac.es/~jht/science/



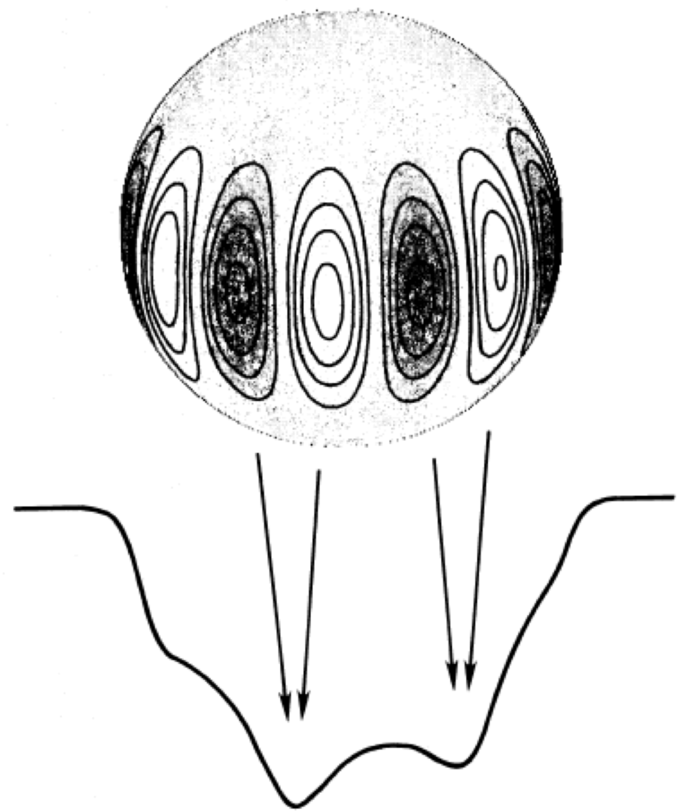


FIG. 16.—Illustration of the formation of distortions in the line profiles of a rapidly rotating nonradially oscillating star. This is a velocity map of the star with the resultant line profile shown below. The width of the line profile has been scaled to match the diameter of the star, thus reflecting the mapping which occurs between position across the disk and position across the line profile. The darkest shaded regions correspond to material moving away from the observer, while the lightest regions represent material moving toward the observer. Contours are drawn every 5 km s^{-1}.

Vogt & Penrod 1983, ApJ, 275, 661

Example of ϵ Per (Gies et al. 1999)

- At least four modes
- P Cyg lines grow as beating increases
- Pulsationally driven mass loss