BREAKING THE MMAG BARRIER

John Southworth

Department of Physics, University of Warwick
Astronomical photometry

- The majority of stars are variable in some way:
  - eclipsing binaries
  - transiting extrasolar planets
  - pulsating stars (δ Cep, β Cep, spB, γ Dor, roAp, RR Lyrae, δ Scuti, ZZ Ceti, solar-like oscillations)
  - interacting binaries (CVs, X-ray binaries, black hole binaries)
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- Studying these variations is a basic tool of astronomy:
  - physical properties of stars (eclipsing binaries, pulsations)
  - distance scale (eclipsing binaries, $\delta$ Cepheids, RR Lyrae)
  - studying accretion (Algols, CVs, quasars)
  - validating theoretical predictions
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- Low-amplitude pulsations need good data for detection ($\beta$ Cep, spB, ZZ Ceti, solar-like oscillations)
- Good photometry is vital for studying transiting extrasolar planets:
  - even the best transits are only 3% deep
  - many transits are 1% deep or less
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  - flat-field structure
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- Atmospheric effects
  - extinction depends on elevation and wavelength
  - changes in seeing
  - clouds
- Sky background
Solution 1: go to space!

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- Atmosphere is not a problem!
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WIRE satellite: launched in 1999 to do an IR survey of galaxies but broke. The star tracker has since been used as a high-speed photometer.

- aperture: 5 cm
- cadence: 2 Hz
- targets: 5 at once ($V < 6$)
\( \beta \) Aurigae with the WIRE satellite

- \( V = 1.9 \)  

  Period = 3.960 days  

  Spectrum: A1m + A1m

- First known double-lined spectroscopic binary: 1889 (Maury)

- First known double-lined eclipsing binary: Stebbins (1911)

- WIRE light curve: 30,015 points with 0.3 mmag scatter
Masses: $M_A = 2.38 \pm 0.03 \, M_\odot$  $M_B = 2.29 \pm 0.03 \, M_\odot$

Radii: $R_A = 2.76 \pm 0.02 \, R_\odot$  $R_B = 2.57 \pm 0.02 \, R_\odot$

Distance: 25.0 ± 0.4 pc (Hipparcos found 25.2 ± 0.5 pc)

• Secondary target discovered to be an eclipsing binary
• $V = 4.0 \quad P_{\text{orb}} = 38.81$ days \quad Spectrum: B9V + A2?
• WIRE light curve has 41 000 points with 2 mmag scatter
• \( V = 4.9 \)  \( P_{\text{orb}} = 6.07 \) days  Spectrum: B4 V + A6 V
• Variation at the primary star rotation period
• Also several pulsation frequencies
• Analysis ongoing with JKTEBOP
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- Sky background increases, but is unimportant for bright stars
- Still need good comparison stars and good weather
Defocussed photometry of WASP-5

- Transiting extrasolar planetary system
- Two transits observed with Danish 1.54m telescope
- Exposure time 120 seconds
- $R$ filter: $10^7$ counts per exposure for WASP-5
- PSF diameter 40 pixels (16 arcsec)

Example PSF for WASP-5
Defocussed photometry of WASP-5

- Standard aperture photometry (IDL version of DAOPHOT)
- Flat-fielding helps, but not by much
- Debiasing is totally unimportant
- Optimal combination of \( \sim 10 \) comparison stars
- Paper almost submitted...
Defocussed photometry of WASP-5

- Scatter of data: 0.50 mmag (2008/08/28) and 0.59 mmag (2008/09/20)
- Limited by telescope aperture (scintillation, collecting area)
Physical properties of WASP-5


- Mass of the planet ($M_{\text{Jup}}$): $M_b = 1.60 \pm 0.11 \pm 0.02$

- Radius of the planet ($R_{\text{Jup}}$): $R_b = 1.157 \pm 0.062 \pm 0.007$
Defocussed photometry of WASP-4

- Scatter: 0.60 mmag (dark time) to 0.89 mmag (grey time)
Physical properties of WASP-4

- Jktebop fit to transit light curve
- Add in stellar model predictions
- Mass of the planet ($M_{\text{Jup}}$): $M_b = 1.252 \pm 0.075$
- Radius of the planet ($R_{\text{Jup}}$): $R_b = 1.359 \pm 0.033$
- Surface gravity: $b_b = 16.8 \pm 0.8 \text{ m s}^{-1}$ (independent of models)

Jktebop fit to defocussed-photometry light curve
• Astronomical photometry has problems with scintillation, CCD response, atmospheric effects

• Go to space: no atmosphere but a very large cost

• Go to ground: defocus your telescope