BREAKING THE MMAG BARRIER

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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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  - interacting binaries (CVs, X-ray binaries, black hole binaries)
- Studying these variations is a basic tool of astronomy:
  - physical properties of stars (eclipsing binaries, pulsations)
  - distance scale (eclipsing binaries, δ Cepheids, RR Lyrae)
  - studying accretion (Algols, CVs, quasars)
  - validating theoretical predictions

High-quality photometry needed

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- Low-amplitude pulsations need good data for detection (β Cep, spB, ZZ Ceti, solar-like oscillations)

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- 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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- Atmospheric effects
  - extinction depends on elevation and wavelength
  - changes in seeing
  - clouds
- Sky background

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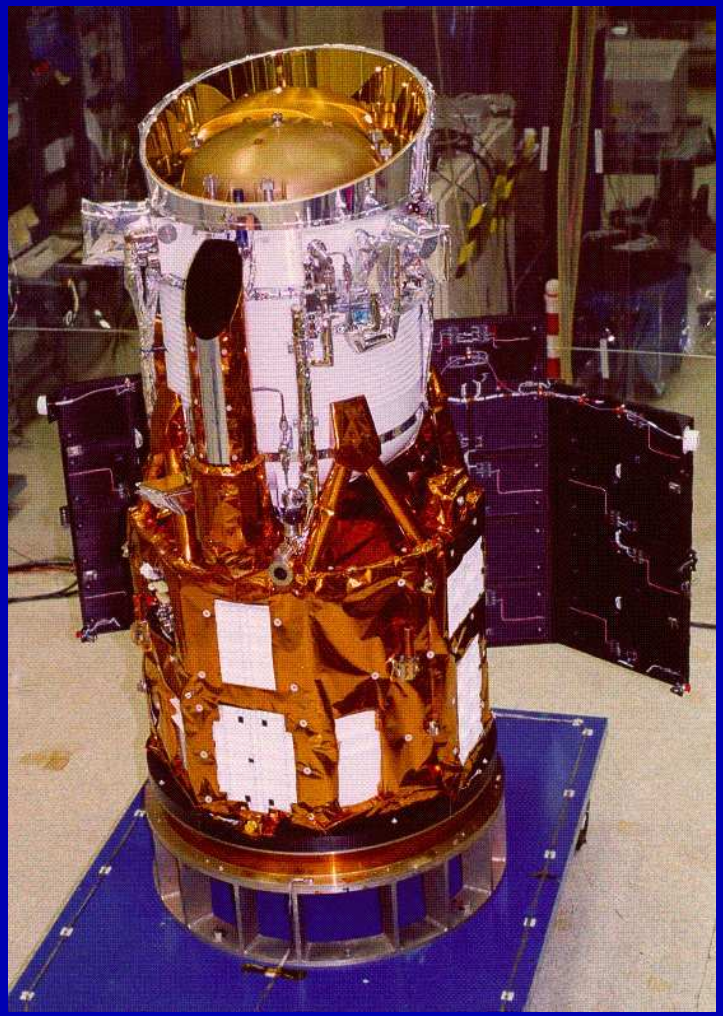

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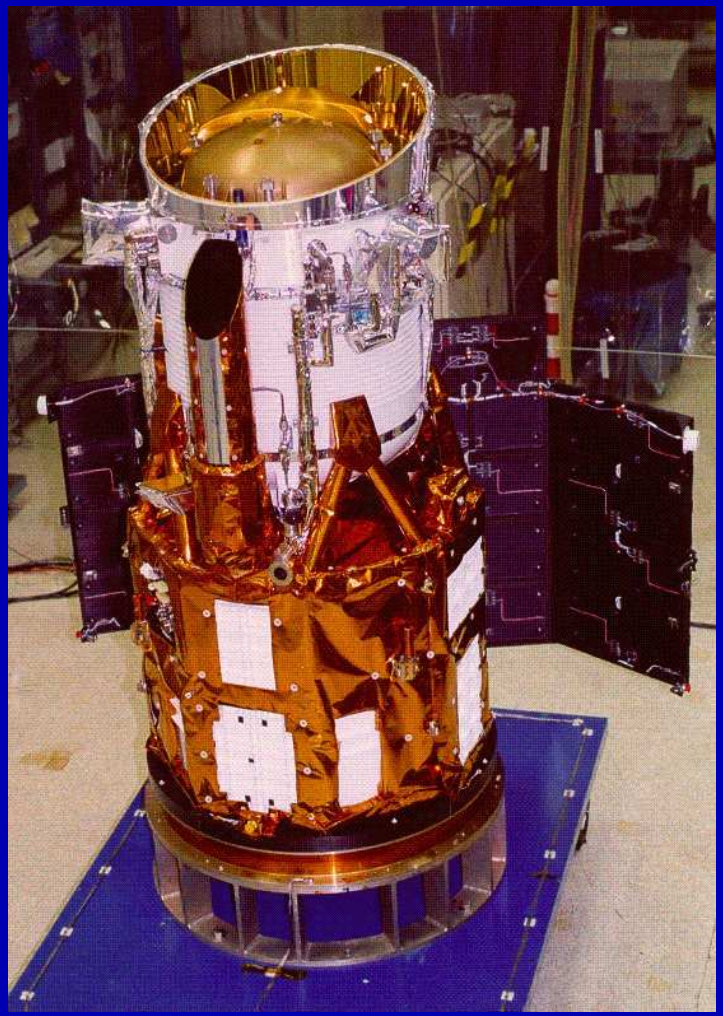
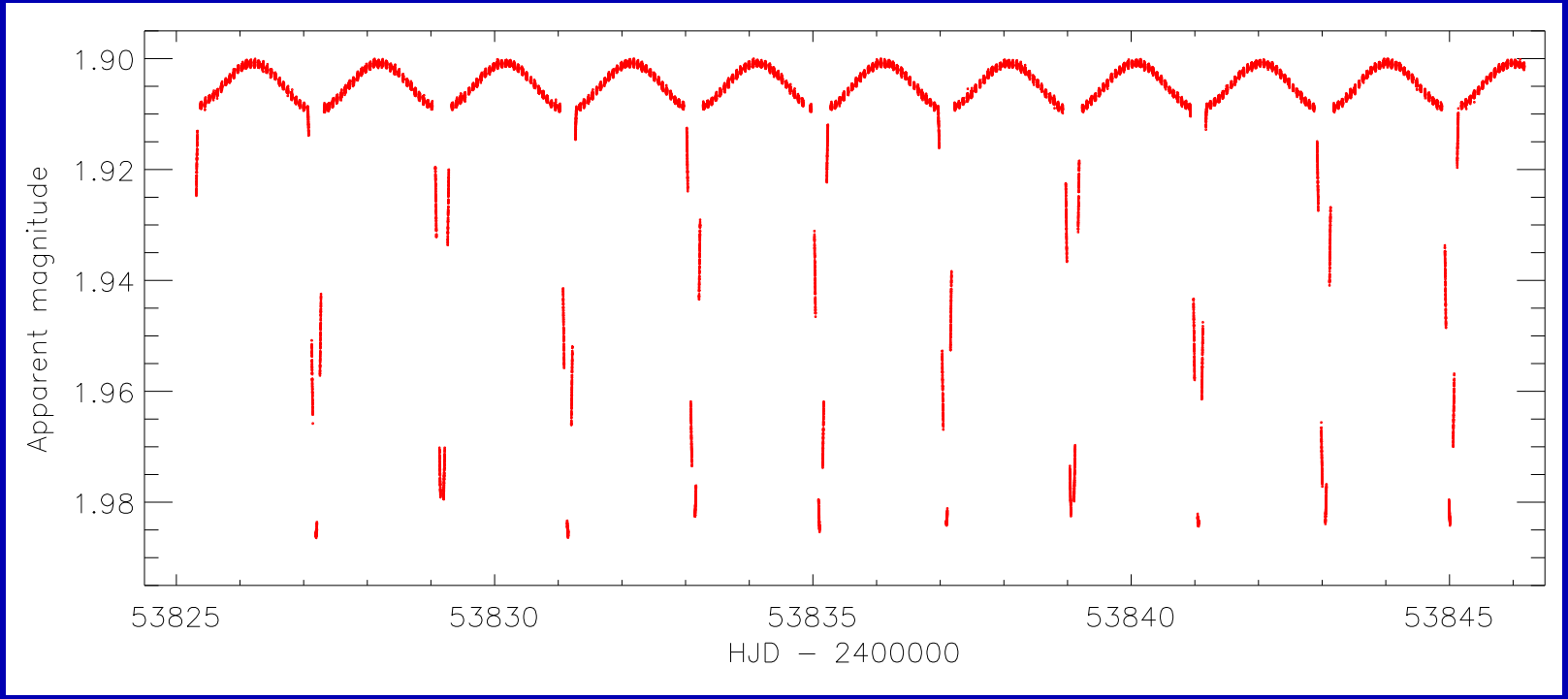


WIRE satellite: launched in 1999 to do an IR survey of galaxies but broke. The star tracker has since been used as a high-speed photometer.

- aperture: 5 cm
- cadence: 2 Hz
- targets: 5 at once ($V < 6$)

β 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

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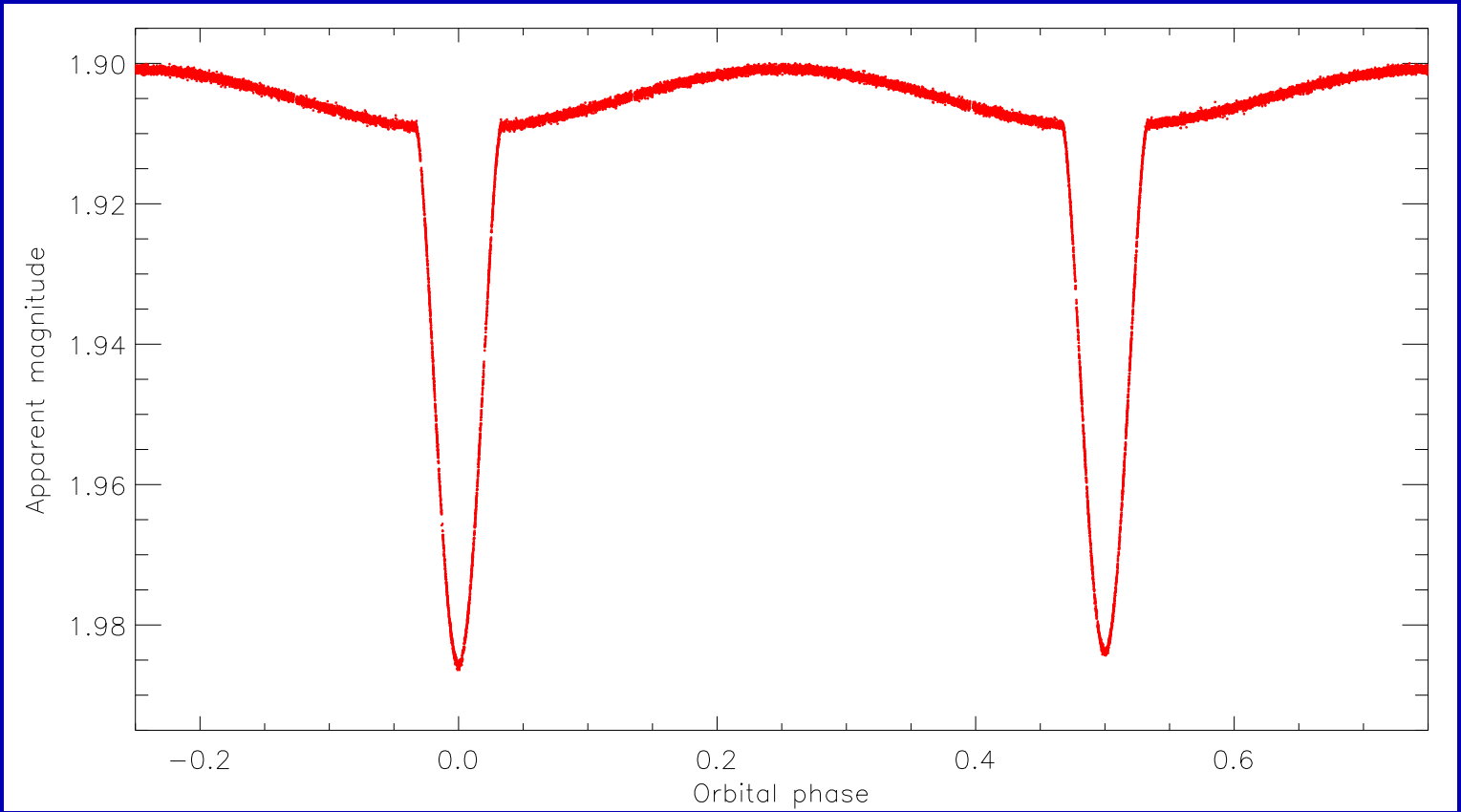
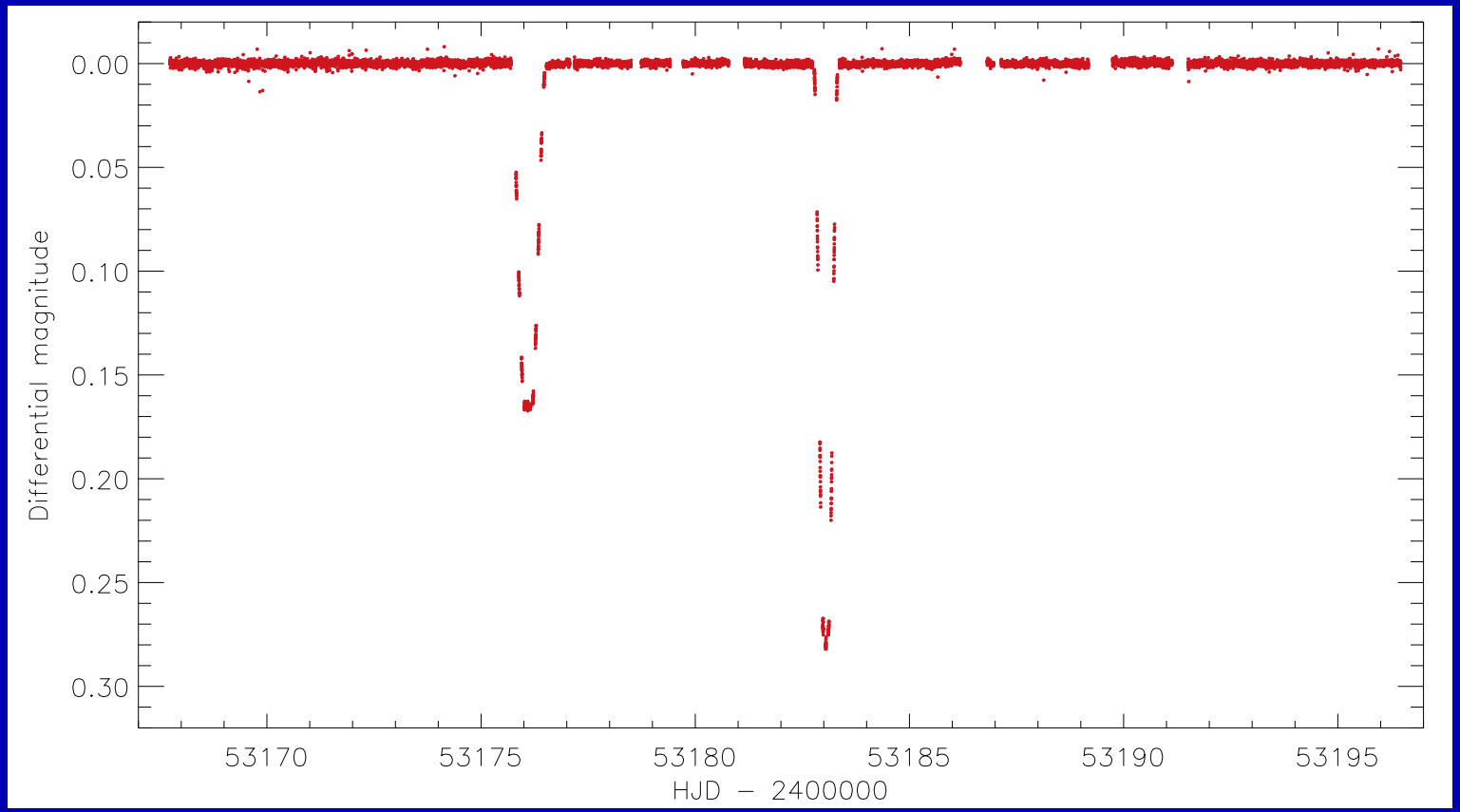


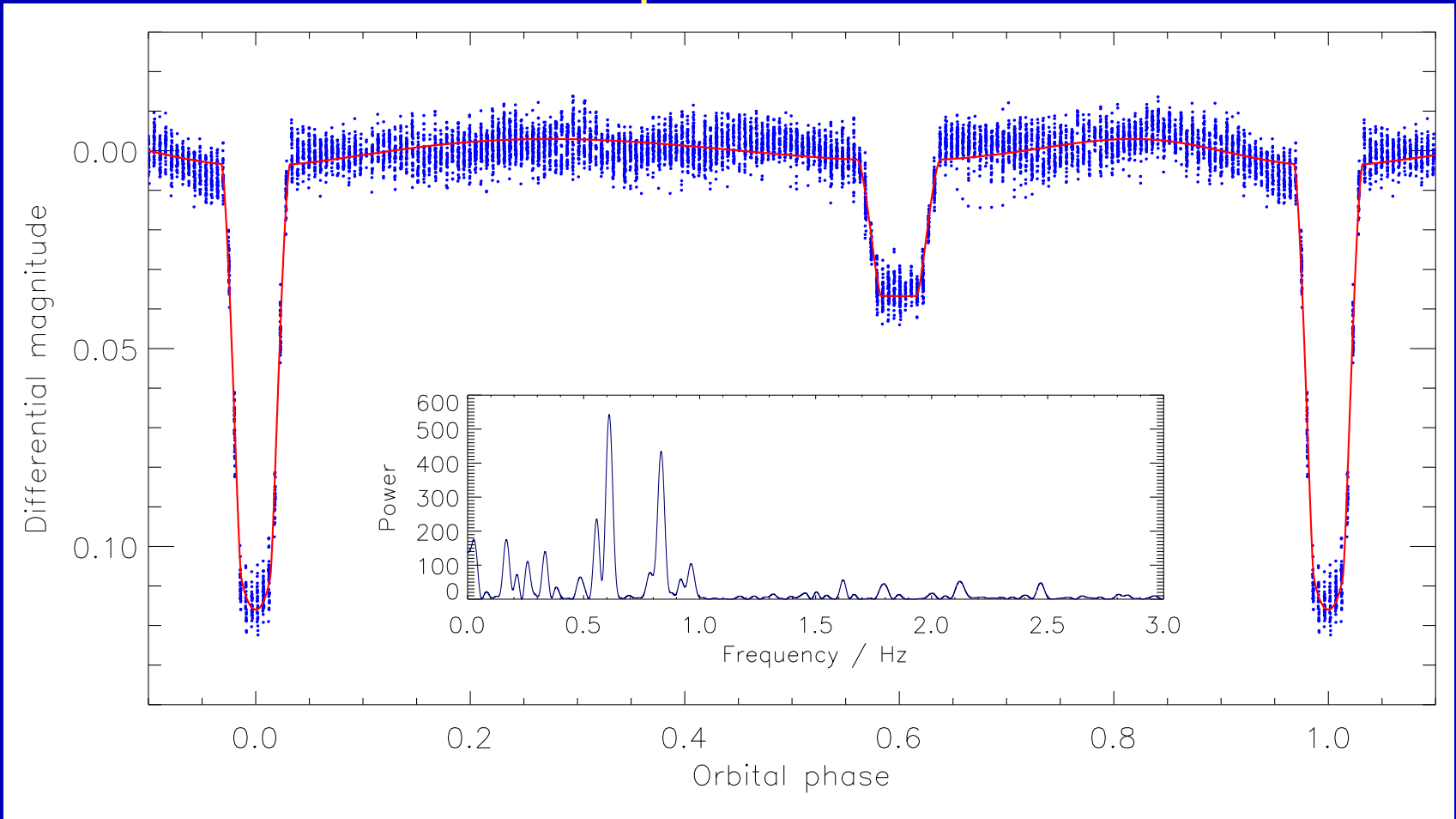
- Masses: $M_{\rm A} = 2.38 \pm 0.03\,{\rm M}_\odot$ $M_{\rm B} = 2.29 \pm 0.03\,{\rm M}_\odot$
- Radii: $R_{\rm A} = 2.76 \pm 0.02\,{\rm R}_\odot$ $R_{\rm B} = 2.57 \pm 0.02\,{\rm R}_\odot$
- Distance: 25.0 ± 0.4 pc (*Hipparcos* found 25.2 ± 0.5 pc)
- Southworth, Bruntt & Buzasi (2007, A&A, 467, 1215)

ψ Centauri with WIRE



- Secondary target discovered to be an eclipsing binary
- $V = 4.0$ $P_{\rm orb} = 38.81$ days Spectrum: B9 V + A2?
- WIRE light curve has 41 000 points with 2 mmag scatter
- Bruntt, Southworth et al. (2006, A&A, 456, 651)

AR Cassiopeiae with WIRE



- $V = 4.9$ $P_{\rm orb} = 6.07$ 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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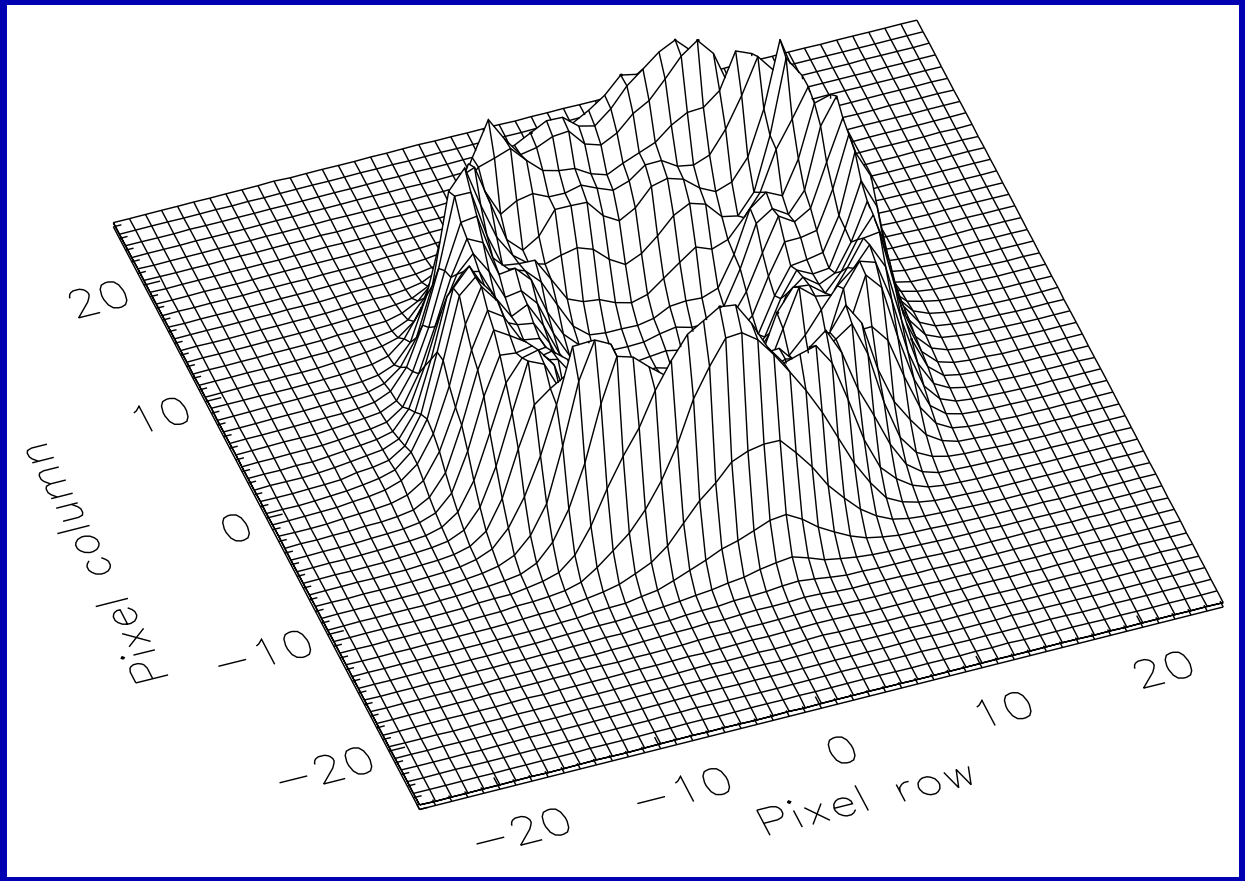
- Sky background increases, but is unimportant for bright stars
- Still need good comparison stars and good weather

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)

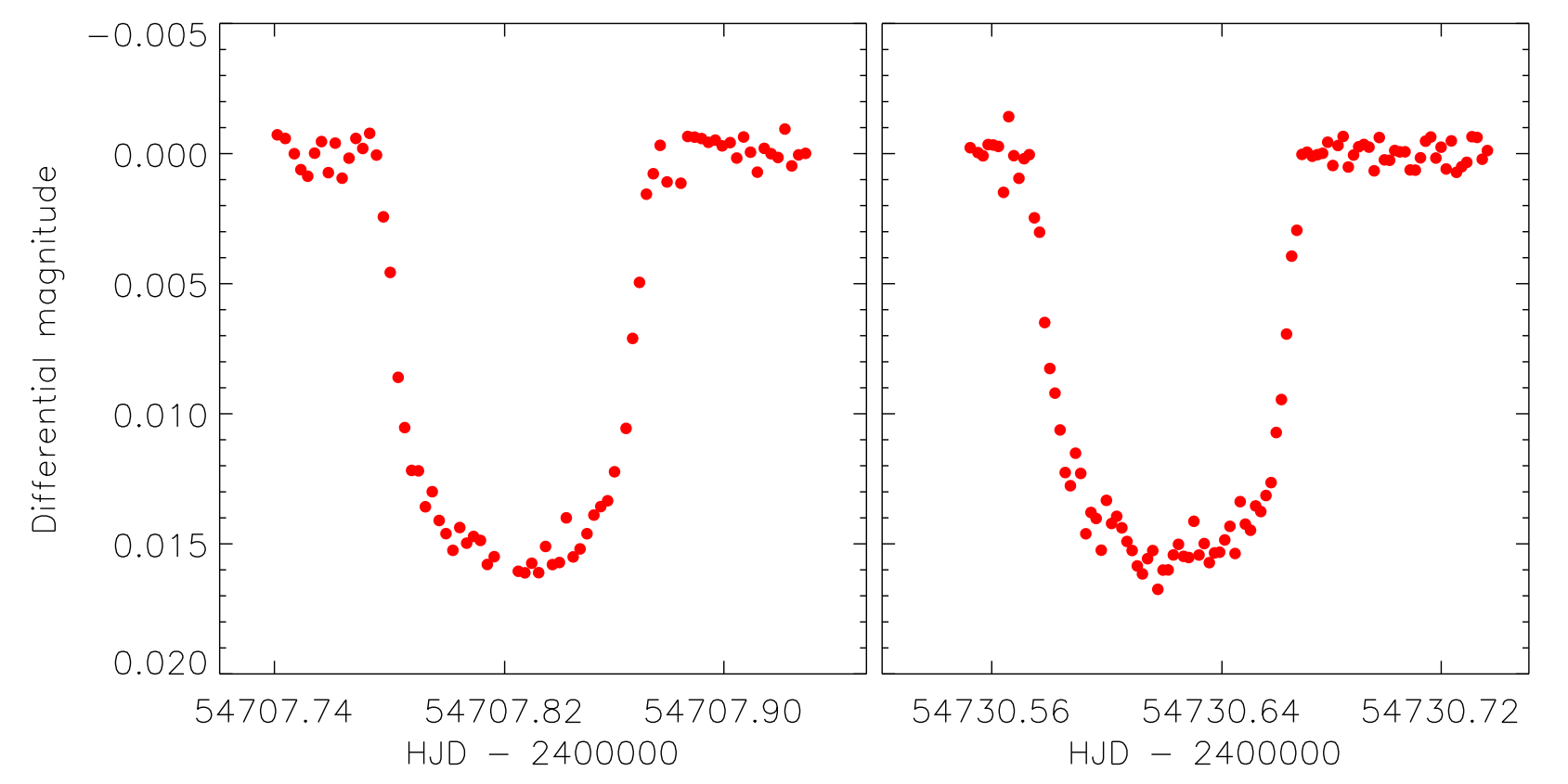


Example PSF for WASP-5

Defocussed photometry of WASP-5

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

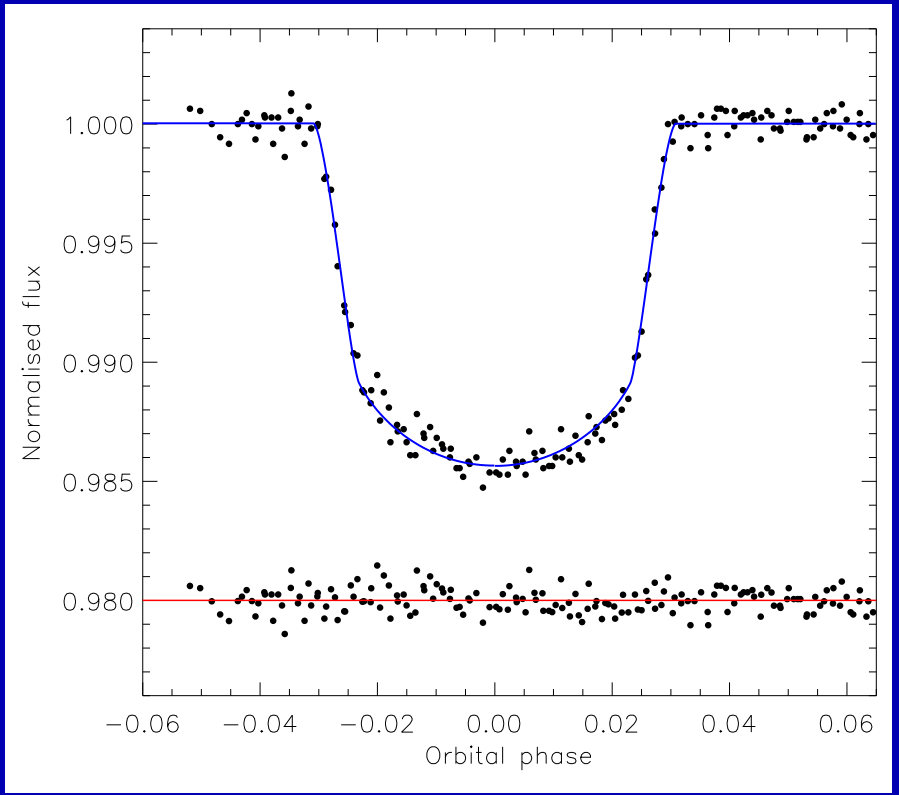
Defocussed photometry of WASP-5



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

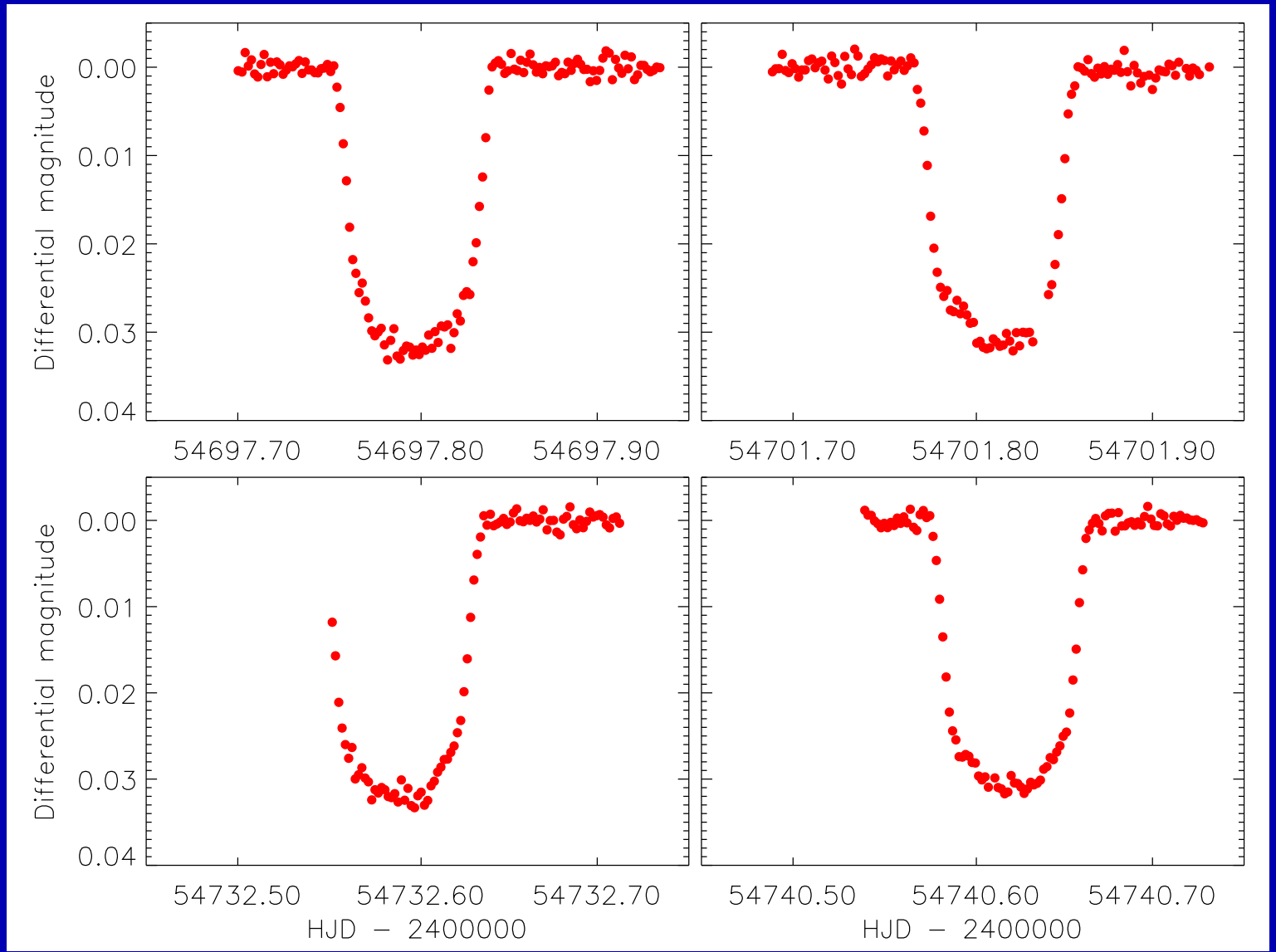
Physical properties of WASP-5

- JKTEBOP fit to transit light curve (Southworth, 2008, MNRAS, 386, 1644)
- Add in stellar model predictions (Southworth, 2008, MNRAS in press, `arXiv:0811.3277`)
- Mass of the planet ($\mathrm{M_{Jup}}$): $M_{\mathrm{b}} = 1.60 \pm 0.11 \pm 0.02$
- Radius of the planet ($\mathrm{R_{Jup}}$): $R_{\mathrm{b}} = 1.157 \pm 0.062 \pm 0.007$



JKTEBOP *fit to defocussed-photometry light curve*

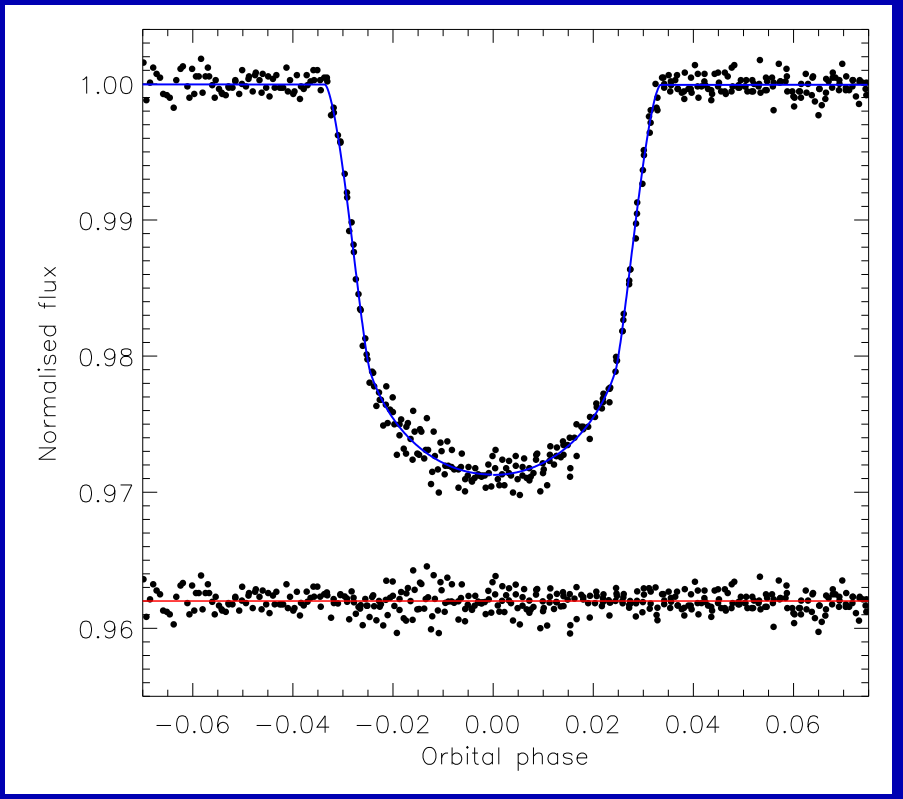
Defocussed photometry of WASP-4



- 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 ($\mathrm{M_{Jup}}$): $M_\mathrm{b} = 1.252 \pm 0.075$
- Radius of the planet ($\mathrm{R_{Jup}}$): $R_\mathrm{b} = 1.359 \pm 0.033$
- Surface gravity: $b_\mathrm{b} = 16.8 \pm 0.8 \ \mathrm{m\,s^{-2}}$ (independent of models)



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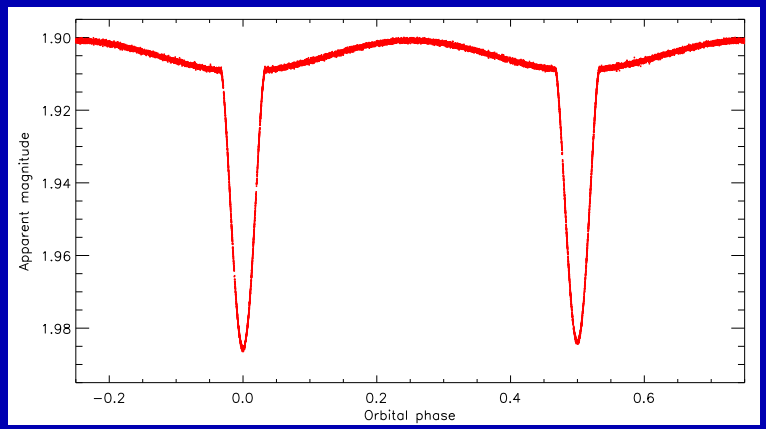

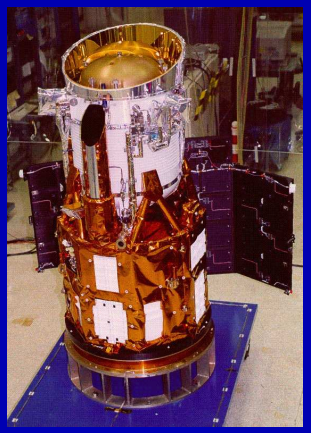

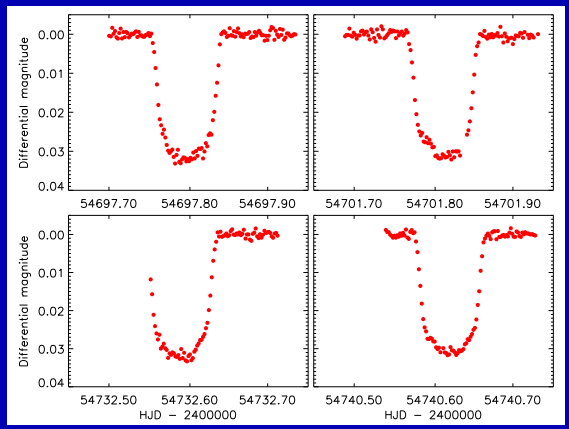

- Astronomical photometry has problems with scintillation, CCD response, atmospheric effects
- Go to space: no atmosphere but a very large cost
- Go to ground: defocus your telescope