Neutron star masses in X-ray Binaries

Science with SALT workshop

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Neutron star masses

- Theoretical masses of neutron stars are not well defined
- Neutron stars in binary radio pulsars have well constrained masses ~1.4 solar mass
- Masses of neutron stars in accretion powered systems are not accurately determined

Outline of talk

- Eclipsing X-ray Pulsars in general
- Centaurus X-3
- Vela X-1
- Improved neutron star masses with SALT
- OAO1657-415 with SALT?

- Other research areas of OU astronomers

Eclipsing X-ray Pulsars

Giant companion / mass donor star

+

Accreting neutron star

Eclipsing X-ray Pulsars

- Knowing:
    - RV of mass donor (optical spectroscopy)
    - RV of neutron star (X-ray pulse timing)
    - Inclination (eclipse duration)
    - Plus a few other assumptions…
- Allows masses of components to be determined

Eclipsing X-ray Pulsars

$$q = \frac{M_x}{M_o} = \frac{K_o}{K_x}$$

$$M_o = \frac{K_x^3 P \left(1 - e^2\right)^{3/2}}{2\pi G \sin^3 i} \left(1 + q\right)^2 \qquad M_x = \frac{K_o^3 P \left(1 - e^2\right)^{3/2}}{2\pi G \sin^3 i} \left(1 + \frac{1}{q}\right)^2$$

$$\sin i = \frac{\left(1 - \beta^2 \left(\frac{R_L}{a'}\right)^2\right)^{1/2}}{\cos \theta_e} \qquad \frac{R_L}{a'} = A + B \log q + C \log^2 q$$

$$\beta = R_o / R_L \qquad A, B, C = f\left(\Omega\right) \qquad \Omega = P_* / P$$

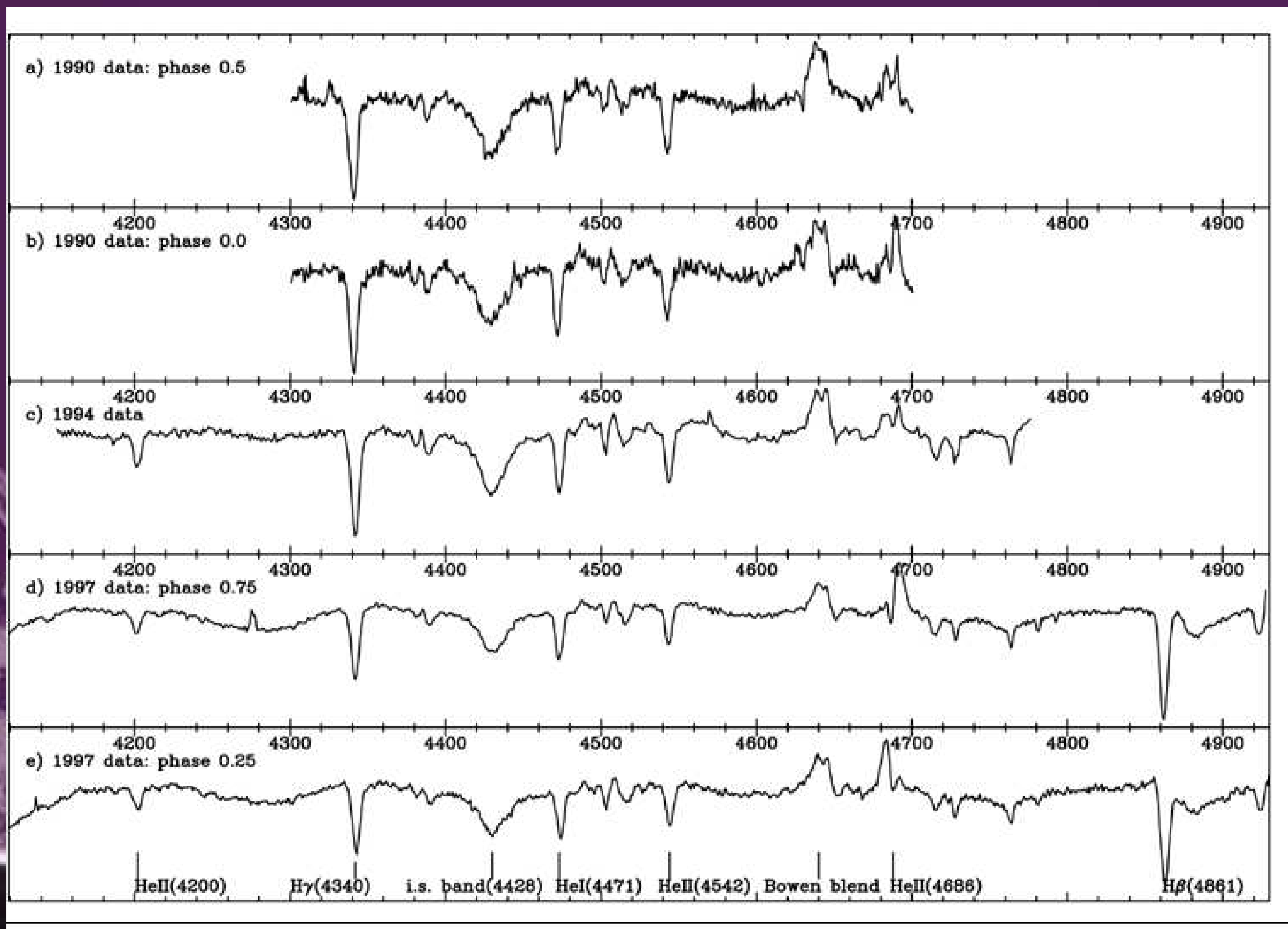
Eclipsing X-ray Pulsars

- Only 7 known eclipsing X-ray pulsars (6 of them at southern declinations)
  - Vela X-1 / GP Vel P=8.97d V=6.9
  - Hercules X-1 / HZ Her P=1.7d V=13.0
  - Norma X-2 / QV Nor P=3.7d V=13.5
  - Cen X-3 / V779 Cen P=2.09d V=13.4
  - LMC X-4 P=1.4d V=15
  - SMC X-1 P=3.9d V=13.3
  - OAO1657-415 P=10.4d V>23

Centaurus X-3

- Ash, Reynolds, Roche, Norton, Still & Morales-Rueda, 1999, MNRAS, 307, 357
- Known:
  - $K_x = 414.1 \pm 0.9$ km/s (Nagase et al 1992)
  - $\Theta_e = 32.9 \pm 0.5$ deg (Clark et al 1988)
  - $\beta = 1$ (Roche lobe overflow)
  - $\Omega = 1$ (Synchronous rotation)
  - $P = 2.087$ day, $e = 0$ (Circular orbit)
- 50 spectra @AAT in 3 runs; 0.75Å/pix (~50 km/s/pix); V ~ 13.4, spectral type ~ O 6-7 II-III

Centaurus X-3



Centaurus X-3

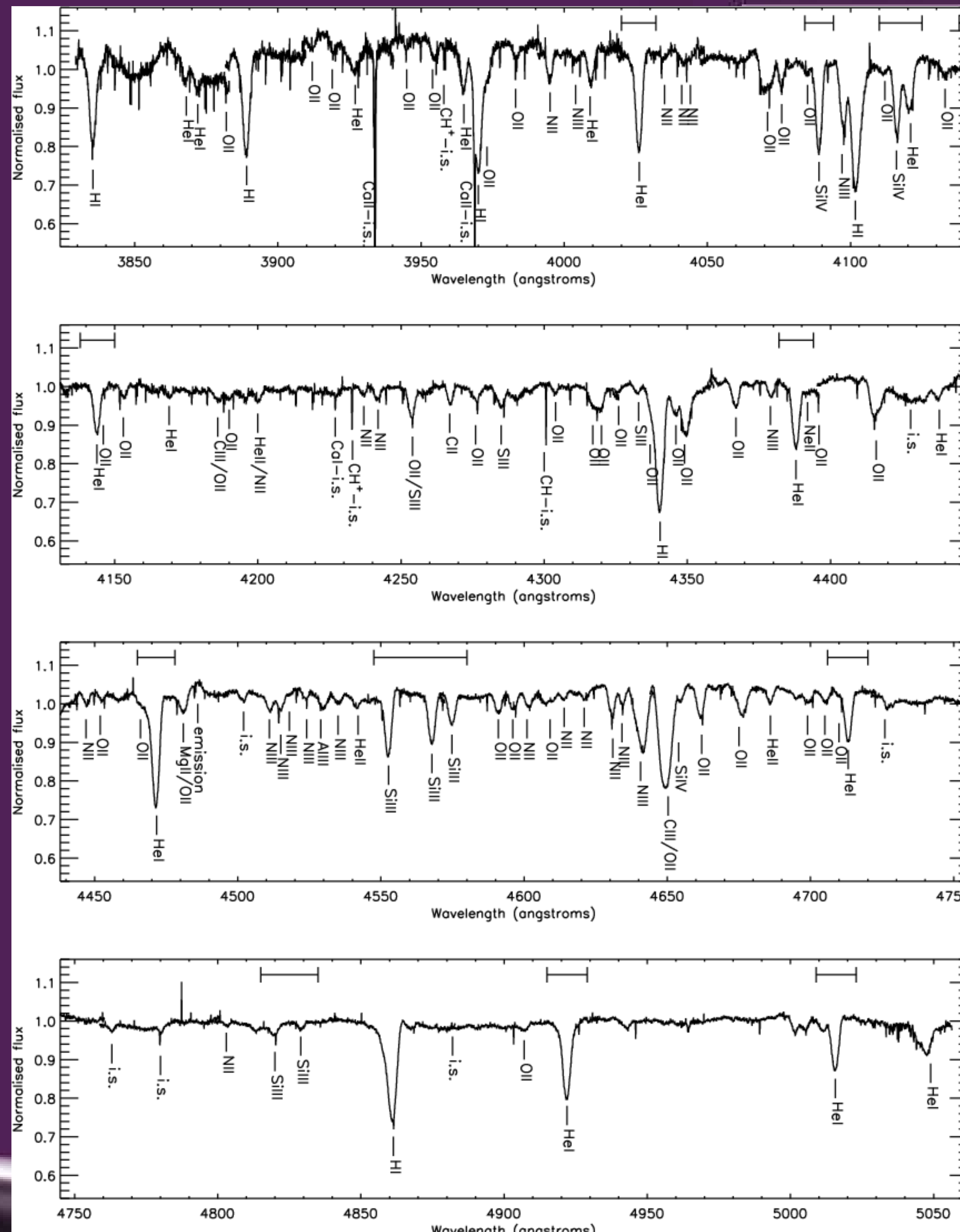
- Calculated:
  - K_o = 24.4 ± 4.1 km/s
  - q = 0.059 ± 0.010
  - i = 70.2 ± 2.7 degrees
  - M_o = 20.5 ± 0.7 solar mass
  - M_x = 1.21 ± 0.21 solar mass
- In agreement with canonical neutron star mass

Vela X-1

- Quaintrell, Norton, Ash, Roche, Willems, Bedding, Baldry & Fender, 2003, A&A, 401, 313
- Known:
  - $K_x = 278.1 \pm 0.3$ km/s (Bildsten et al 1997)
  - $\Theta_e = 33.8 \pm 1.3$ deg (Watson & Griffiths 1977)
  - $\Omega = 0.67 \pm 0.04$ (Zuiderwijk 1995)
  - $P = 8.964$ day, $e = 0.0898$ (Bildsten et al 1997)
- 180 echelle spectra @Mt Stromlo over 21 continuous nights; 0.06Å/pix (~4 km/s/pix); V ~ 6.8, spectral type ~ B0.5Ib

Vela X-1

Average spectrum



Vela X-1
fitting the RV curve

$$v = \gamma + \frac{4\pi a_1 \sin i}{P\left(1-e^2\right)^{1/2}} \frac{e\cos\omega + \cos(\nu+\omega)}{2}$$

Radial velocity
ω = periastron angle

$$\tan\left(\frac{\nu}{2}\right) = \left(\frac{1+e}{1-e}\right)^{1/2} \tan\left(\frac{E}{2}\right)$$

True anomaly

$$E - e\sin E = M = \frac{2\pi}{P}\left(t - T_0\right)$$

Eccentric anomaly

$$T_0 = T_{\pi/2} + \frac{P(\omega - \pi/2)}{2\pi}$$

Time of periastron passage

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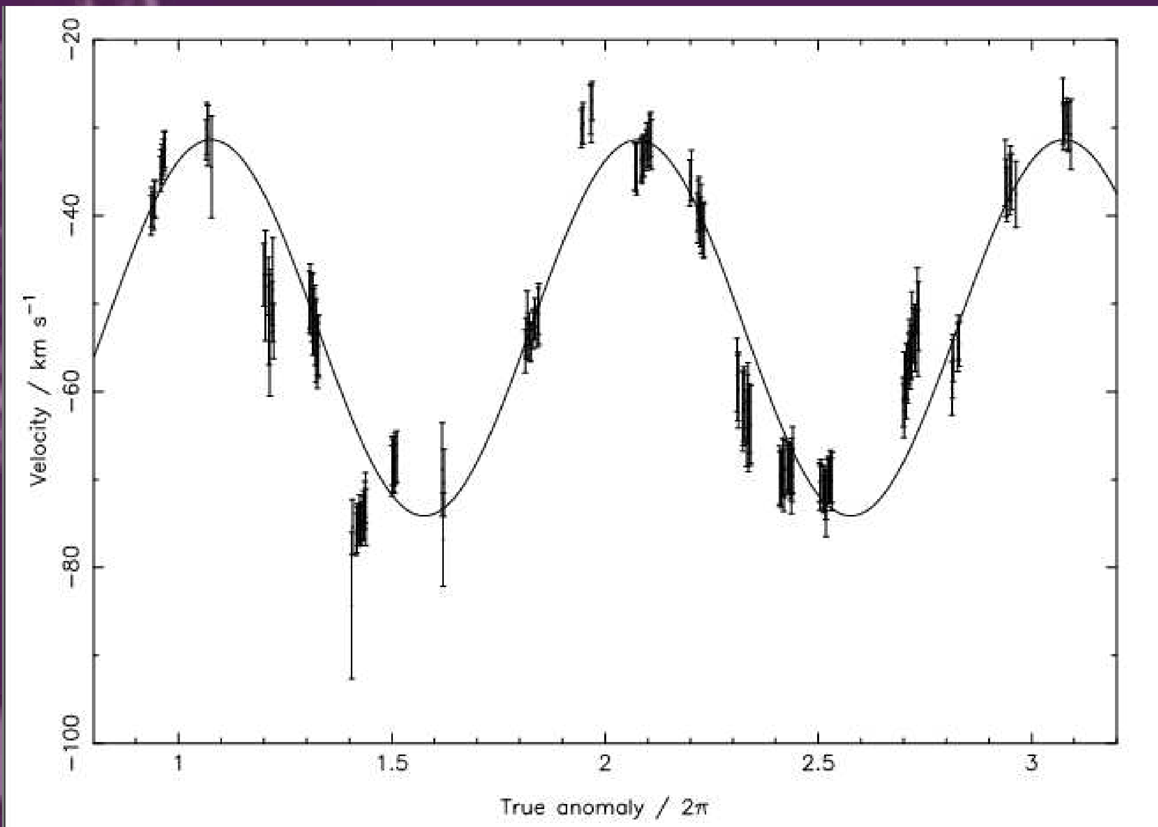
Vela X-1: First fit



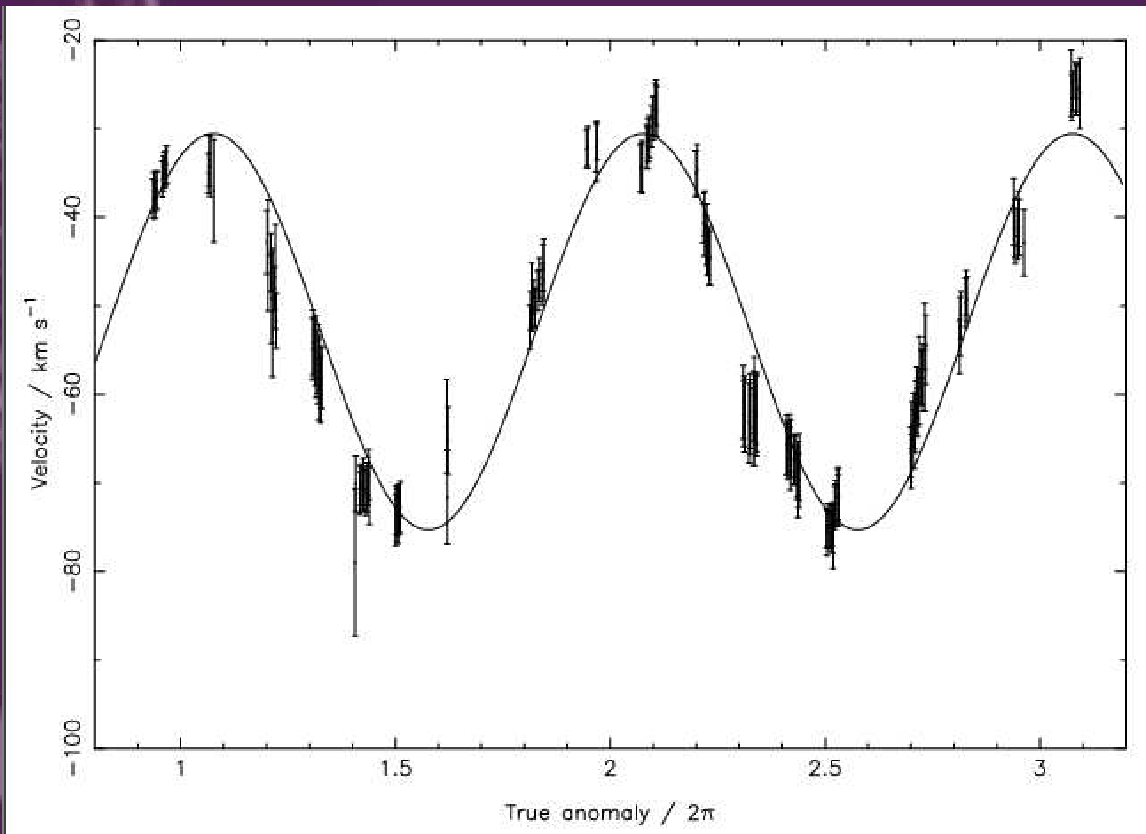
K_o = 21.4±0.5 km/s

But note residuals!

Power spectrum of residuals shows peaks @ 9 ± 1 day & 2.18 ± 0.04 day

'phase-locked' deviations as seen by others?

Vela X-1: Second fit

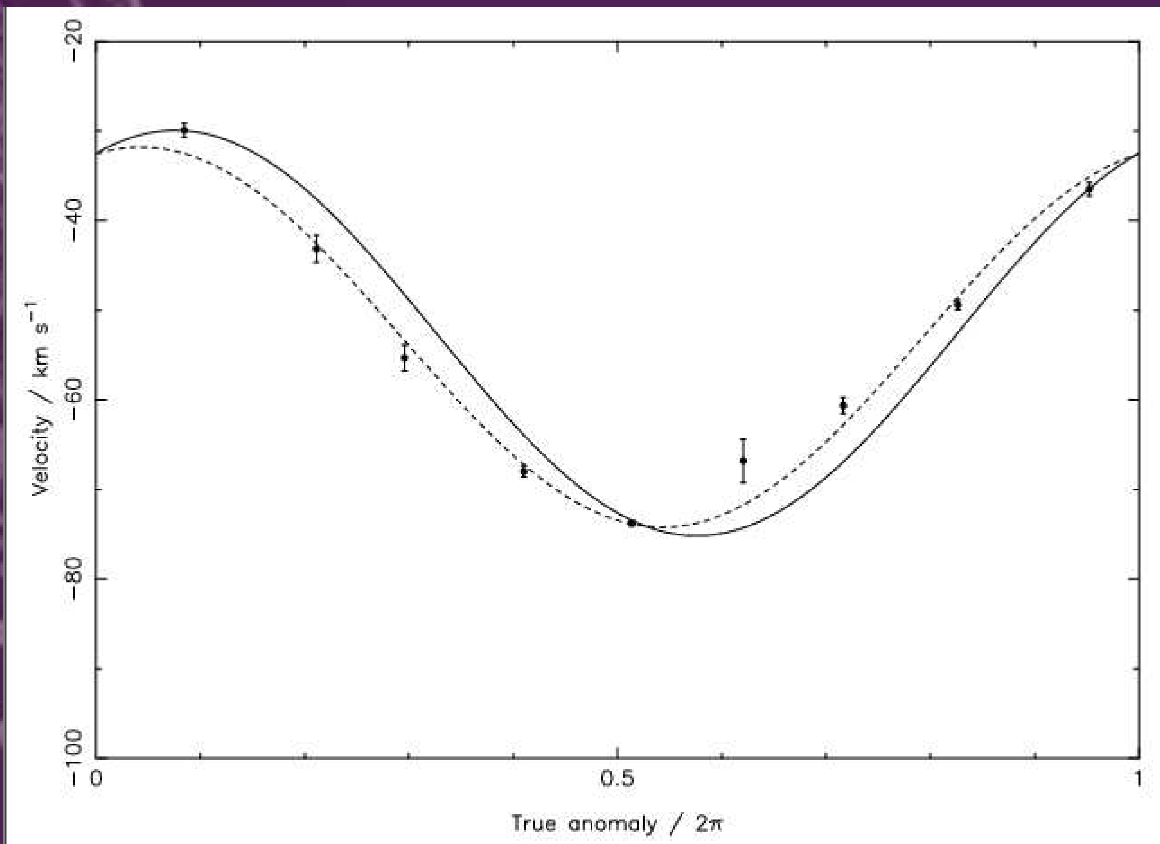


As well as RV curve, simultaneously fit a 2.18d sinusoid.

K_o = 22.4±0.5 km/s
$K_{2.18}$ = 5.4±0.5 km/s

Residuals still show further modulation at ~9 day period.

Vela X-1:
Fit to phase-binned means



Subtract the best fit 2.18d curve. Rebin into 9 daily phase bins.
K_o = 22.6±1.5 km/s

Residuals still show better fit possible allowing zero phase as free parameter (~7 hour shift req.)

Vela X-1: results

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- 2.18d and out-of-phase 9d modulation imply presence of non-radial pulsations in GP Vel @ ~f_{orb} and ~4f_{orb}
- May also be an *in-phase* non-radial pulsation at orbital period
- In which case RV amplitude, and hence neutron star mass, is over-estimated

Vela X-1 results

- Monte Carlo approach to propagate uncertainties
- β and i cannot be solved for simultaneously. Limits $\beta < 1$ and $i < 90$.
- Then solve the equations described earlier.

Vela X-1 results

Parameter	Value	
Observed		
$a_x \sin i$ / light sec	113.98 ± 0.13	
P / d	8.964368 ± 0.000040	
$T_{\pi/2}$ / MJD	48895.2186 ± 0.0012	
e	0.0898 ± 0.0012	
ω / deg	152.59 ± 0.92	
θ_e / deg	33.8 ± 1.3	
Ω	0.67 ± 0.04	
K_o / km s^{-1}	22.6 ± 1.5	
Inferred		
K_x / km s^{-1}	278.1 ± 0.3	
T_0 / MJD	48896.777 ± 0.009	
q	0.081 ± 0.005	
β	1.000	0.89 ± 0.03
i / deg	70.1 ± 2.6	90.0
M_x / $M_\odot$	2.27 ± 0.17	1.88 ± 0.13
M_o / $M_\odot$	27.9 ± 1.3	23.1 ± 0.2
a' at periastron / $R_\odot$	51.4 ± 0.8	48.3 ± 0.3
R_L at periastron / $R_\odot$	32.1 ± 0.6	30.2 ± 0.2
R_o / $R_\odot$	32.1 ± 0.6	26.8 ± 0.9

Implies *over-massive* neutron star, *if* there is no in-phase non-radial pulsation contributing to the RV curve

Neutron star masses with SALT

- Queue scheduled spectroscopy will allow effective phase coverage of the ~few days orbit for each system
- High sensitivity will allow improved accuracy of RV amplitudes to <0.1 km/s ?
- Therefore improved accuracy of mass estimates to <0.01 solar masses ?
- Should be possible for Roche lobe-filling systems in circular orbits (e.g. Cen X-3), and allow to better characterise eccentric systems (e.g. Vela X-1) by better modelling of non-radial pulsations

OAO1657-415

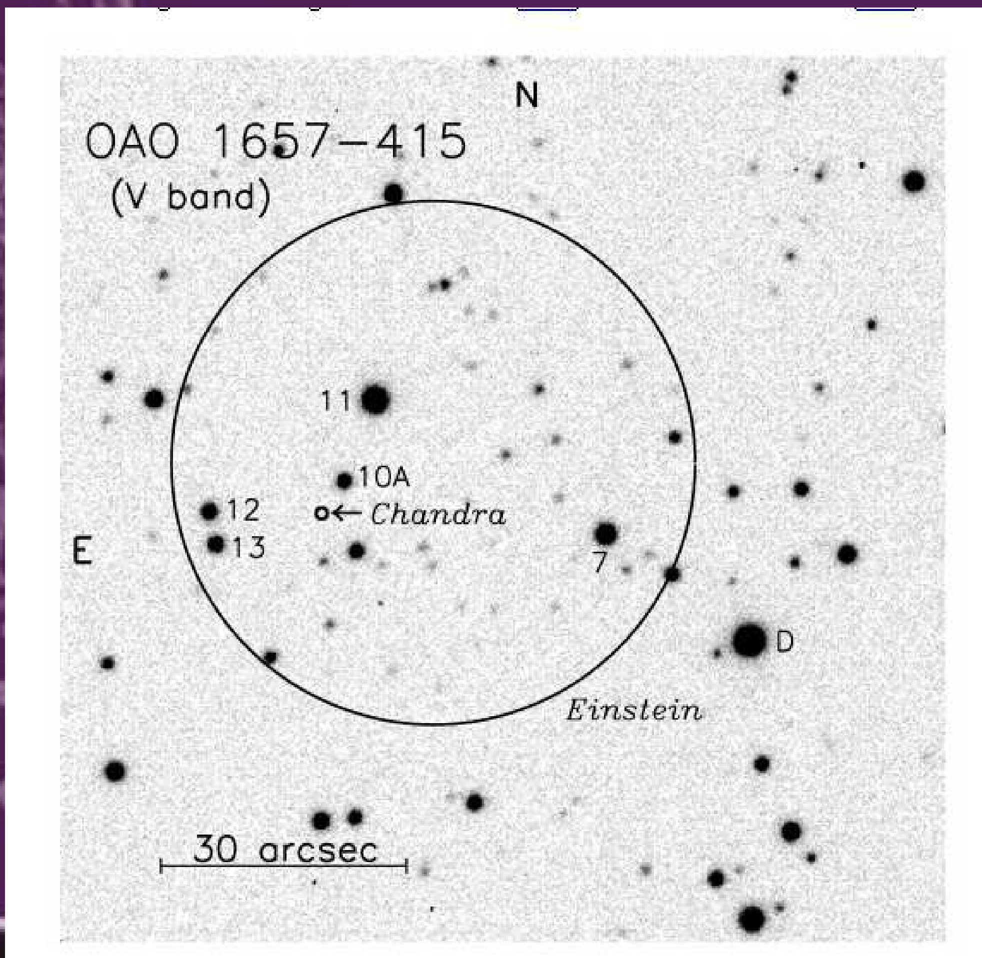
- From BATSE (Chakrabarty et al 1993)
- But no RV curve – no optical counterpart!

TABLE 1

OAO 1657−415 PARAMETERS

Parameter	Symbol	Value[a]
Best-fit orbital parameters and eclipse measurements:		
Orbital period	P_{orb}	$10^{d}.4436 \pm 0^{d}.0038$
Projected semimajor axis	$a_x \sin i$	106.0 ± 0.5 lt-sec
Eccentricity	e	0.104 ± 0.005
Longitude of periastron	ω	$93° \pm 5°$
Orbital epoch	$T_{\pi/2}$	JD 2,448,516.49 $\pm$ 0.05 TDB
Eclipse ingress[b]	$l_{e,in}$	$57°.1 \pm 1°.8$
Eclipse egress[b]	$l_{e,out}$	$116°.5 \pm 1°.8$
Derived quantities:		
Pulsar mass function	$f_x(M)$	$11.7 \pm 0.2\ M_\odot$
Eclipse half-angle	θ_e	$29°.7 \pm 1°.3$
Inferred constraints:[c]		
Orbital inclination	i	$\gtrsim 60°$
Companion mass	M_c	14–18 $M_\odot$
Companion radius	R_c	25–32 $R_\odot$
R_c-Roche radius ratio	R_c/R_L	$\gtrsim 0.85$

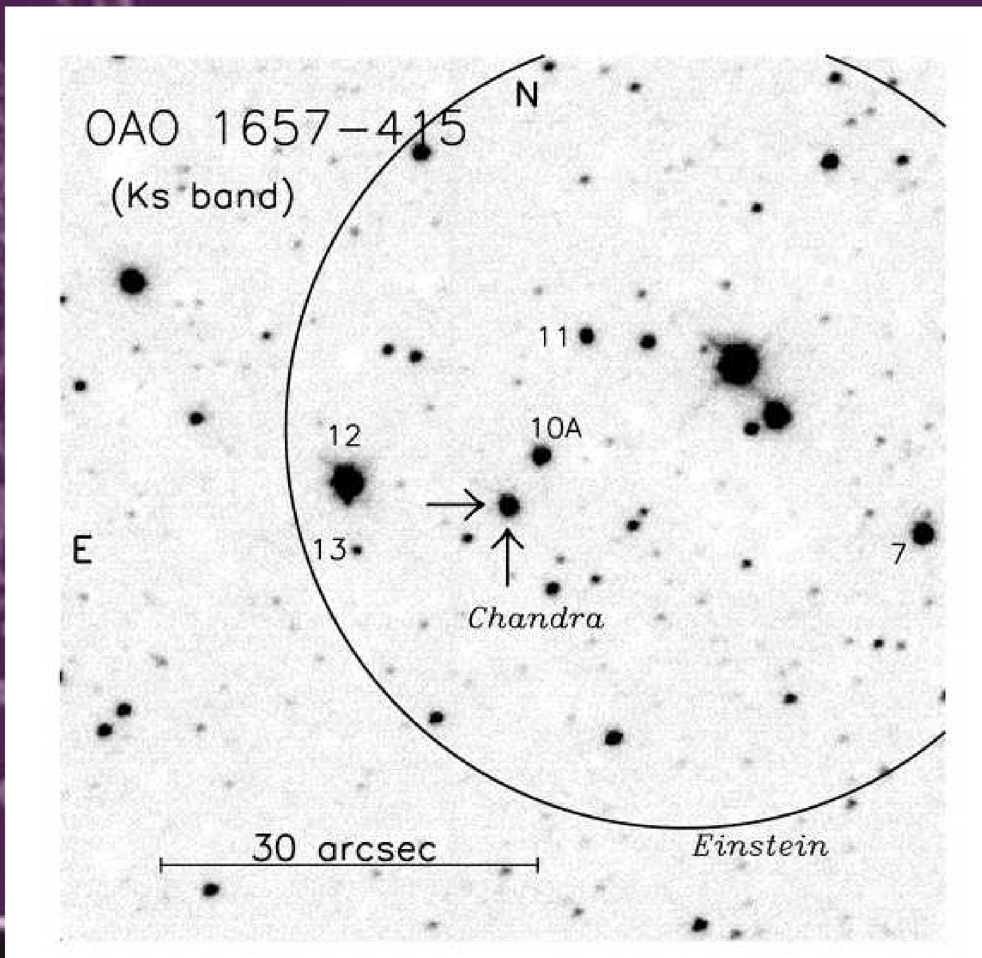
OAO1657-415



No optical counterpart within Chandra X-ray error circle, V > 23 (Chakrabarty et al 2002)

Previous candidate 'D' spectral type B5III now excluded by Chandra location

OAO1657-415



Infrared counterpart clearly seen at K = 10.67, H = 11.93, J = 14.08 (Chakrabarty et al 2002)

Similar parameters to those of Vela X-1
Need to measure ~20 km/s amplitude RV curve.

OAO1657-415

- Target for SALT?
- Counterpart (probably) has R (700 nm) ~ 20 and I (900 nm) ~ 17
- Feasible with current PFIS? Certainly with proposed IR upgrade.
- Measure only the 7th neutron star mass in an X-ray binary system. Only the 2nd in an eccentric orbit.

Other OU SALT interest

- Astronomy Research Group:
  - Carole Haswell
  - Ulrich Kolb
  - Barrie Jones
  - Andy Norton
  - Sean Ryan
- Planetary & Space Science Res. Inst.
  - Simon Green
  - Neil McBride
  - John Zarnecki

Other OU SALT interest

- Cataclysmic variables – time resolved spectroscopy, tomography, accretion disc physics, magnetic systems, population studies (Haswell, Kolb, Norton)
- Black Hole X-ray transients – multiwavelength monitoring through outbursts, accretion disc physics (Haswell, Norton)

Other OU SALT interest

- X-ray binaries in M31 – XRB population studies, LMXBs, ULXs (Kolb)
- Galactic chemical evolution – synthesis of the elements, high-resolution spectroscopy, stellar abundance analysis, pop II & III objects (Ryan)

Other OU SALT interest

- Exoplanets – transiting exoplanet search using WASP (2nd camera to be at SAAO?), stability of orbits of known exoplanets (Haswell, Jones, Norton)
- Solar system – near Earth objects, comets, Edgeworth-Kuiper belt objects, early Solar system (Green, McBride, Zarnecki)